Note on the composition and mineralogy of Wenlock Silurian bentonites from the Ringerike District: Implications for local and regional stratigraphic correlation and sedimentary environments

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Six bentonite samples from the Silurian (Wenlock) Steinsfjorden Formation collected in the Ringerike District of Norway have been mineralogically and compositionally characterised. The results are used to stratigraphically correlate three bentonites in the Ringerike District. The bentonites crop out in rocks deposited in widely varying sedimentary environments in a relatively small geographic region highlighting dynamic and varied sedimentary environments in the area during middle Silurian times. Correlation with bentonites from rocks of similar age along the north-south axis of the Oslo paleo-rift was not possible. A potential correlation between one bentonite at Ringerike with bentonites in the Slite Formation on the island of Gotland is proposed. This suggests that although there is evidence of significant volcanic activity preserved in the Lower Palaeozoic rocks of Scandinavia and northern Europe, spatial distribution and preservation of ash is highly variable.

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Introduction

The Lower Palaeozoic sediments of the Oslo Region, southern Norway, expose a broad range of sediment types. This demonstrates a dynamic tectonic environment, and a diversity of contemporaneous sedimentary environments occurring over a relatively small geographical region. Correlation over small distances is sometimes possible by careful mapping, facies analysis and biostratigraphy. However, this cannot be assured because many sedimentary rocks in the area are biostratigraphically barren (e.g. Worsley et al. 1983; Ribecai et al., 2000). Broader regional correlation of Lower Palaeozoic sediments along the north-south axis of the Permian Oslo rift structure is also difficult due to differential basin subsidence and rates of sea-level progression and regression. This results in simultaneous deposition of contrasting sediment types (Worsley et al., 1983). Also, thermal metamorphism and associated recrystallisation of the sediments after emplacement of rift-related magmatic rocks removed evidence of sedimentary structures and fossil assemblages. Therefore, the identification of key marker horizons, that are not necessarily fossil-bearing, but which may be traceable over long distances, is critical to correlation studies in the Oslo Region.

Amongst the most powerful marker horizons in correlation studies are volcanic glass and ash layers (Christidis & Huff, 2009) and clastic sediments that contain highly characteristic and/or diagnostic material (e.g. Cherns & Karis, 1995). There are several exposures of lower Silurian volcanics in the Ringerike District (Batchelor & Evans, 2000; Batchelor et al., 1995), as well as many other localities with Ordovician and Silurian bentonites in Northern Europe (Batchelor, 1999; Batchelor & Jeppsson, 1994; Batchelor & Jeppsson, 1999; Batchelor & Weir, 1988; Huff et al., 1997; Kiipli et al., 2001; Merriman & Roberts, 1990; Obst et al., 2002; Odin et al., 1986; Pearce, 1995; Romano & Spears, 1991; Teale & Spears, 1986). Many are geochemically and palaeontologically well characterised and their value for regional stratigraphic correlation has been abundantly demonstrated (Batchelor, 2003; Batchelor et al., 2003; Batchelor & Jeppsson, 1994; Batchelor & Jeppsson, 1999).

However, there are few reported bentonite occurrences in Silurian sediments of Wenlock age. Two bentonite suites, one in the M. *belophorus* – *C. ellesae* biozone and the other in the *G. nassa* – *M. dubius* biozone, on Gotland were reported by Batchelor & Jeppsson (1999). Bentonites in the *Cyrtograptus lundgreni* Zone on Bornholm (Obst et al., 2002) and between the top of the

Telychian and the lower Gorstian in the eastern Baltic (Kiipli et al., 2008a) have also been described. In the Oslo region one metabentonite horizon of late Wenlock to early Ludlow age from the Bjørntvet quarry near Porsgrunn in the southwest part of the Oslo Region has been reported (Hetherington et al., 2004). Other Silurian bentonites from the Wenlock period have been recognised in the appropriate sediments of Ringerike and Bærum (Jørgensen, 1964; Worsley et al., 1983), but few data on their mineralogy, composition, or biostratigraphy has been reported.

The microfossil assemblage found in the Bjørntvet quarry limestone is sparse and only constrains those bentonites to the *Sheinwoodian – Homerian* units of the Wenlock period (Hetherington et al., 2004). No strong geochemical correlation between the Bjørntvet bentonite and the bentonites of the Slite or Mulde formation on Gotland or from Bornholm could be established (Hetherington et al., 2004). Meanwhile, the absence of detailed palaeontological and geochemical information for the Silurian bentonites from Ringerike (Jørgensen, 1964; Worsley et al., 1983) prohibits meaningful correlation studies along the length of the Oslo rift.

A mineralogical and geochemical description of bentonites in the Wenlock Steinsfjord Formation rocks of the Ringerike District (Fig. 1) is presented, and the data compared to bentonites of equivalent age from the rest of Scandinavia. The implications for both short- and long-range stratigraphic correlations and the dynamic sedimentary environments of the Ringerike District during the Wenlock period of the Silurian are discussed.

Analytical Methods

Four outcrops of bentonites of Wenlock age in the Ringerike district were studied (Fig. 1) and samples weighing at least 1 kg collected.

Major and trace element analyses were completed by Activation Laboratories (Ancaster, Canada) using the *4-Litho Research* routine. Samples were mixed with a flux of lithium metaborate and lithium tetraborate and fused in an induction furnace. The molten glass was poured into 5% nitric acid solution with an internal standard and mixed continuously until completely dissolved. Aliquots of the solution were analysed for major and selected trace elements on a Thermo Jarrell-Ash ENVIRO II inductively coupled plasma mass spectrometer. Additional trace elements in the same solution were analysed by adding a second standard to cover the entire mass range and analysed in to a Perkin Elmer SCIEX ELAN 6000

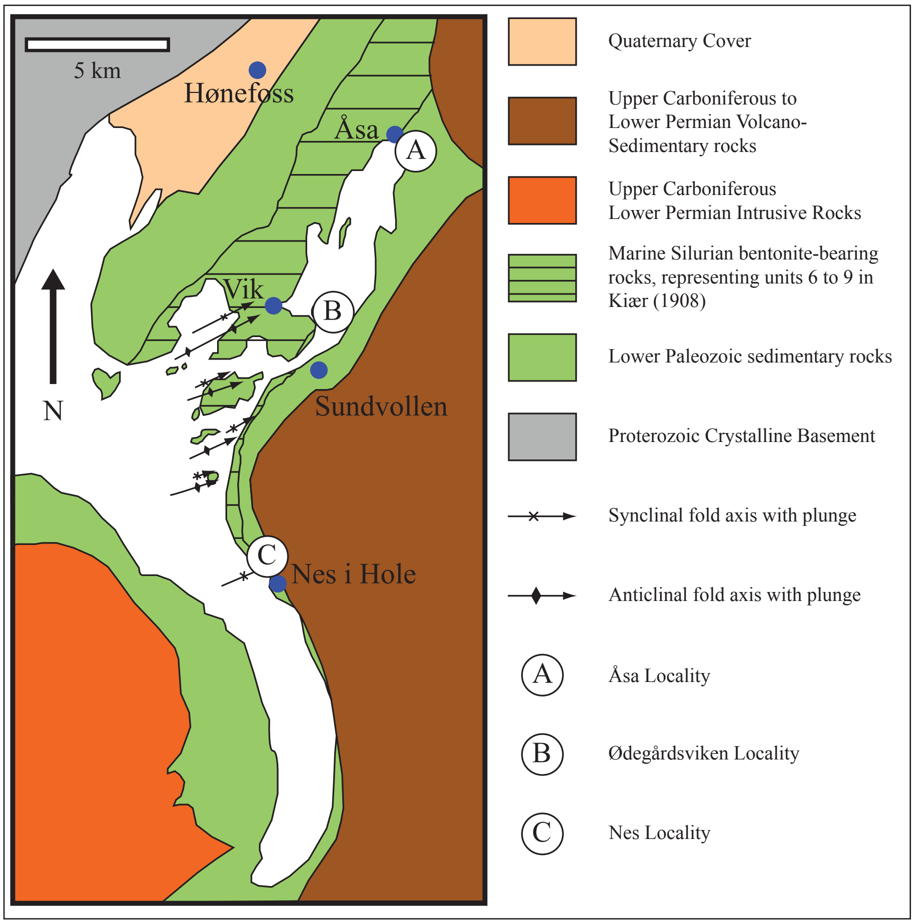


Figure 1 – Sketch map of the Ringerike District showing sample localities and major structural features.

inductively coupled plasma mass spectrometer. Calibration of instruments was completed using 7 prepared USGS and CANMET certified reference materials.

Clay mineral analyses were performed in laboratories at the University of Giessen. Samples were cleaned with a steel brush, crushed into small pieces with a hammer and ground in a tungsten-carbide swing-mill for a maximum of 30 seconds. An aliquot of the powder was analysed by X-ray diffraction (XRD) to identify the major silicate phases present. Carbonate was removed from the powders by treating with 5% acetic acid and washing with deionised water. The quantity of calcite present was estimated by calculating the weight loss of each sample. The <2μm fraction was obtained using settling tubes. Afterwards, the clay fraction was Ca-saturated with 2N $CaCl_2$. Oriented slices were prepared by pipetting suspension onto glass slides (5 mg/cm^2) and allowing to air-dry. Both air-dried and ethylene glycol-treated samples (in a vapour bath at 60°C overnight) were studied by XRD. Illite and chlorite crystallinity were measured on air-dried, glycolated and heated samples using a D501 Bruker-AXS (Siemens) diffractometer, CuKα radiation at 40 kV and 30 mA, and automatic divergence slits (primary and secondary V20) with a secondary graphite monochromator.

Illite crystallinity was calculated using the software DIFFRACPlus (Socabim) and Profil Fitting. The illite crystallinity index is defined as the full width at half maximum intensity of the first illite-muscovite basal reflection. Illite crystallinity values were transformed into Kübler index (KI) values using a correlation with the standard samples of Warr & Rice (1994) (KI_{CIS} = 1.343 * ICGiessen – 0.003). KI was used to define the limits of metamorphic zones, and the transition values were chosen as follows: KI = 0.25 Δ°2Θ to high anchizone boundary, KI = 0.30 Δ°2Θ for the high to low anchizone boundary and KI = 0.42 Δ°2Θ for the low anchizone to diagenetic zone. The same experimental conditions were used to determine chlorite crystallinity on the (002) peak (ChC(002)) expressing the full width at half maximum intensity values of the second (7 Å) basal reflection of chlorite. Furthermore, the ChC(002) measurements were calibrated with those of Warr & Rice (1994) and expressed as the Árkai index (ÁI) (Guggenheim et al., 2002): ÁI = 0,766* ChC(002) + 0,117. The anchizone boundaries for the Árkai index were defined by correlation with the Kübler index and are here given as 0.24-0.30 Δ°2Θ.

Sample Description

The four sampled localities, one each from Åsa and Nes and two at Ødegårdsviken, in the Ringerike district are road-cut exposures of Lower Palaeozoic sedimentary sequences (Fig. 1). All localities have been assigned to the Silurian Steinsfjorden Formation (Worsley et al., 1983). The Steinsfjorden Formation is Wenlock in age and equivalent to the *ellesae* and *lundgreni* graptolite zones (Worsley et al., 1983; Ogg et al., 2008).

Åsa

A single bentonite measuring ~5 cm is exposed in opposing walls of a road-cut at the eastern end of a tunnel at Norwegian Grid Ref (WGS84): NM74286695; Locality A on Figure 1; (the same bentonite is exposed at the western end of the tunnel and is depicted in Fig. 19a of Worsley et al. (1983)). The tunnel cutting exposes 30 m of sedimentary rocks. Underlying the bentonite are dolomitic limestones and calcareous dolostones. Above the bentonite is an amplexoporid bryozoan biostrome with some oncolites, nodular limestones with abundant brachiopods, bryozoans and minor corals; the exposure is capped by a favositid biostrome. The rocks were assigned to unit 9f by Kiær (1908) and Worsley et al. (1983), and are now recognised as part of the Brattstad Member of the Steinsfjorden Formation (Fig. 2) (Worsley et al., 1983; Olaussen, 1985). The Brattstad Member of the Steinsfjorden Formation is approximately 30 m thick and is overlain by the Ranberget Member. The transition is marked by a change in colour and the disappearance of the few remaining in situ marine faunas.

The bentonite has a distinctive green colour against the darker host-rock, is more strongly weathered, and typically recessed 4-5 cm into the rock wall. The outcrop has a north-south strike (008°) and dips 15° to the east. Sample material (Åsa-03-02A) was collected from the south side of the road, which is less weathered and friable, suggesting less post-diagenetic weathering and/or alteration. The mineralogy of the sample is illite + quartz + chlorite + albite. An illite crystallinity of 0.721 (Table 1) was measured indicating rock-forming conditions in the high diagenetic zone (100-150°C).

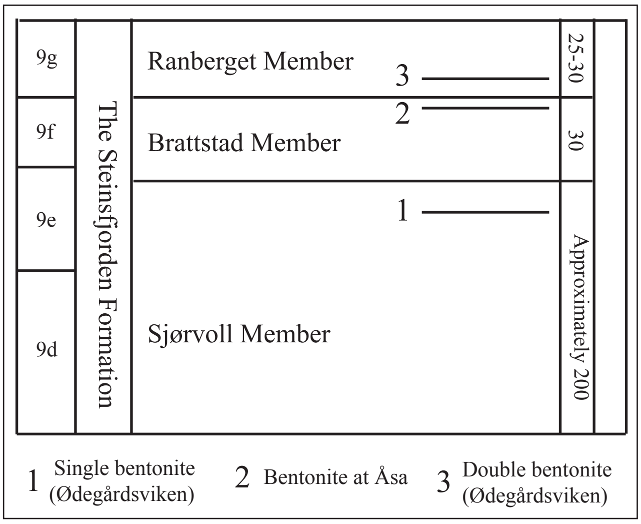


Figure 2 – Schematic representation of Steinsfjorden Formation stratigraphy and position of bentonites on the basis of literature descriptions (Kiær, 1908; Whitaker, 1977; Worsley et al., 1983).

Table 1: Overview of illite crystallinity values

	Assemblage	Illite Crystallinity	Zone	T Range (Approx.)
Åsa-03-02A	Ilt + Qz + Chl + Ab	0.72	High Diagenetic	100-150°C
Øde-03-01	Qz + Ab + Chl + Ilt + Ms-Pg*	0.82	High Diagenetic	100-150°C
Øde-03-02	Qz + Ab + Chl + Ilt + Ms-Pg* (ML)	0.58	High Diagenetic	150-200°C
Nes-03-03A	Qz + Ab + Ilt + Cal	1.55	Low Diagenetic	<100°C
Nes-03-03C	Qz + Ab + Ilt + Cal + Gp + Ber and/or Kln	1.01	Low Diagenetic	~100°C
Nes-03-03B	Qz + Ab + Ilt + Cal + Gln	1.59	Low-to-high Diagenetic	<100°C

*Notes: All mineral abbreviations at Whitney & Evans (2010), except Ber = berthierine. * - Muscovite and paragonite are identified as a mixed layer phase.*

Ødegårdsviken

Two localities at Ødegårdsviken were sampled (Norwegian Grid Ref (WGS84): NM72416036; Fig 1, Locality B). The first location was a single, 3-4 cm thick, green bentonite that crops out in marls of the Sjørvoll Member (Fig. 2, 3a); the unit was assigned to Kiær's unit 9d (Whitaker, 1977). The mineralogy of the bentonite was discussed by Jørgensen (1964), who assigned the rocks to stratigraphic unit "9c"; this assignation was recognized as erroneous and later corrected by Whitaker (1977). The equivalent graptolite age of the Ødegårdsviken rocks is *ellesae*, indicating that these units are stratigraphically below the outcrops investigated at Åsa (Fig. 2).

The single bentonite is conformable with the host rocks, which strike to the northeast and dip steeply to the northwest. The northern end of the bentonite's exposure is truncated by two dykes; one with a pink colour, and the other with a grey colour (Fig. 3a). A sample was collected at the base of the outcrop at the maximum possible distance from the intrusive rocks (Øde-03-01A) (Fig. 3a). A second sample was taken 3 m further north, and 50 cm from the dykes (Øde-03-01B) (Fig. 3a)

The two samples are mineralogically characterised by quartz, albite, chlorite, illite and a mixed layer paragonite/muscovite species. An average illite crystallinity value for the two samples of 0.82 (Table 1) was calculated, indicative of high diagenetic zone conditions and temperatures >150°C (Merriman & Frey, 1999). These temperatures were supported by the Árkai Index (AI) of 0.41.

240 m southeast of the first locality, at a stratigraphically higher horizon in the succession and equivalent to the base of unit 9g in the *lundgreni* zone, two bentonites are exposed in the Ranberget Member of the Steinsfjorden Formation (Kiær, 1908; Whitaker, 1977) (Norwegian Grid Reference (WGS84): NM72496018). The top of unit 9f is marked by large exposures of oncolites capped by silicious limestones with mud cracks. Unit 9g is a lighter coloured limestone with two thin, green-coloured clay layers exposed on bedding planes (Fig. 3b). The stratigraphically lower bentonite is 2 cm thick and is exposed continuously along the bottom of a limestone step (sample Øde-03-02A) (Fig. 3b).

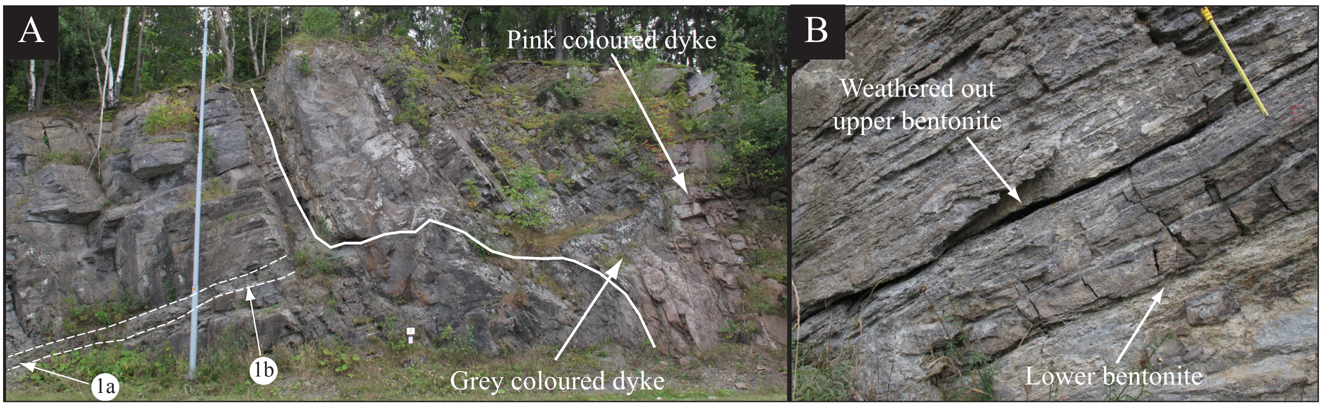


Figure 3 – Bentonite exposures at Ødegardsviken. A) Single bentonite at location Norwegian Grid Ref (WGS84): NM7241603. Solid line represents the boundary between sedimentary rocks and the intrusive dykes. Locations of sample Øde-03-01A and Øde-03-01B are marked. B) Double bentonite at Norwegian grid reference (WGS84): NM72496018. The stratigraphically lower bentonite was sampled (Øde-03-02A)

The mineral assemblage of the bentonite is quartz, albite, chlorite, illite and a mixed-layer paragonite/muscovite phase. Illite crystallinity values (KI) (Table 1) and chlorite crystallinity (ÁI) values of 0.58 and 0.43, respectively, have been measured. This equates with a temperature in the high-diagenetic zone, but the greater degree of crystallinity indicates that it has experienced higher temperatures than the single bentonite to the northwest (Øde-03-01A and 01B).

The second bentonite at this locality crops out 25 cm higher in the stratigraphic succession. It is <1 cm thick and commonly pinches out across the exposure. It is rarely exposed, with much material having been weathered out from its location at a step in the limestone that marks the transition between two bedding planes (Fig. 3b). Due to weathering and lack of exposure it was not possible to adequately sample this bentonite for mineralogical and compositional characterisation.

Nes

Three samples from two bentonites exposed in a roadcut along the former E16 north of Sønsterud collected during road construction by Nils Spjeldnæs (Department of Geosciences, University of Oslo) were studied (Locality C; Fig. 1; grid reference NM70995230). The bentonites are hosted in an exposure of limestone with inter-bedded mud and siltstone layers. The whole outcrop is approximately 5 m high and 25 m long.

The bentonites are conformable in the sedimentary rocks, strike 074° and dip variably, but steeply (~70°), to the north. Both bentonites are green-grey in colour at their base and lighten towards the top. Their steep inclination has resulted in their direct exposure to rainfall and weathering, which may have resulted in unquantifiable alteration of the clay-rich horizons.

Stratigraphically, the bentonites lie just below a thick bryozoan bed and 55 m above an oncolite bed. The latter is very distinct and believed to correlate with a similar bed identifiable at the 311-313 m point of the Ødegårdsviken section described by Whitaker (1977). This would place the bentonites at Nes either at the very top of the Brattstad Member or close to the bottom of the Ranberget Member (Fig. 2).

The stratigraphically lower bentonite (Nes-03-03A) is approximately 10 cm thick and consists of quartz + albite + illite + calcite. The calculated illite crystallinity value is 1.55, which is characteristic for low diagenetic conditions (<100°C). The second bentonite, which is stratigraphically 40 cm higher in the unit, is ~15 cm thick. Two samples were analysed: the first (Nes-03-03B), from the centre of the bed, consists of quartz + albite + illite + calcite + glauconite. An illite crystallinity value of 1.59 was measured, but this is influenced by the presence of glauconite. Peak deconvolution and modelling (after Lanson, 1997) provided a revised KI value of 1.01 (Table 1). This value is characteristic of the transition from the low to high diagenetic zones. A second sample from the bottom of the bentonite (Nes-03-03C), just above the bedding plane, consists of quartz, albite, illite, calcite, gypsum, berthierine and/or kaolinite, with a calculated illite crystallinity of 1.37 (Table 1), which is also characteristic of the low-diagenetic zone (<100°C).

Bentonite Compositions

The major oxide analyses of the bentonites show positive correlations between the concentrations of SiO_2 and Al_2O_3, and CaO and loss on ignition values (LOI) (Table 2) and reflect the host rock of each sample. Those deposited in limestone richer rocks have lower SiO_2 and Al_2O_3 concentrations and higher LOI and CaO values. The SiO_2/Al_2O_3 ratios are <3.0, and TiO_2/Al_2O_3 ratios are <0.04, which is a good indication of clays derived from the alteration of volcanic material (Table 2) (Teale & Spears, 1986). The exceptions are samples Øde-03-01B and Øde-03-02A (Table 2), which have SiO_2/Al_2O_3 approaching 3.5. Selected trace element ratios are plotted on diagrams that, although not primarily designed to discriminate between tectonic environments of volcanic eruption, have proven useful for comparing and contrasting bentonites of differing compositions (Fig. 4).

The three samples of bentonite from outcrops of a single bentonite horizon (Åsa-03-02A, Øde-03-01A and Øde-03-01B) have lower Zr/TiO_2 and Nb/Y ratios and lower (Y+Nb) concentrations and form a separate grouping (Fig. 4). Samples from the stratigraphically lower bentonite at Nes (Nes-03-03A) and Ødegårdsviken (Øde-03-02A) also correlate with one another (Fig. 4). In contrast, the two samples from the uppermost bentonite at Nes (Nes-03-03B and Nes-03-03C) have no geochemical correlation with the other samples. These samples have distinctly higher (Y+Nb) concentrations and Nb/Y ratios, although the Zr/TiO_2 ratio and Rb contents are similar to other samples.

Chondrite normalized rare earth element distribution plots (Figure 5, Table 2) have a shallow negative slope, and variable negative Eu anomalies. The light rare earth elements are more enriched in the stratigraphically lower samples (Åsa-0302-A, Øde-0401A and Øde-0401B). The strongest Eu anomalies were observed in the compositionally distinct and stratigraphically highest bentonite at the Nes locality (Nes-03-03B and Nes-03-03C). A normalisation of selected trace and rare earth elements against mid-ocean ridge basalt (MORB) (Figure 6) (Saunders & Tarney, 1984) shows that all of the bentonites are variably enriched in incompatible elements including the alkali and alkali-earths, Th, the light rare earth elements and selected high-field strength elements, but also relatively depleted in the heavy rare earths and the compatible transition series elements Ti, Ni and Cr.

Table 1: Overview of illite crystallinity values

SAMPLE	Åsa-03-02A	Øde-03-01A	Øde-03-01B	Øde-03-02A	Nes-03-03A	Nes-03-03B	Nes-03-03C
SiO_2	49.45	44.31	46.33	37.97	50.04	53.44	50.41
Al_2O_3	16.26	18.65	13.38	11.09	21.96	23.66	22.64
Fe_2O_3	4.35	2.85	4.32	3.68	2.71	1.40	1.45
MnO	0.037	0.038	0.058	0.062	0.009	0.003	0.013
MgO	4.97	3.15	3.99	5.09	2.86	3.69	3.43
CaO	5.77	9.00	11.31	16.93	2.98	1.27	3.97
Na_2O	0.73	0.39	0.84	0.59	0.32	0.24	0.20
K_2O	5.33	6.14	3.92	3.33	7.74	7.49	7.16
TiO_2	0.497	0.689	0.503	0.422	0.690	0.192	0.189
P_2O_5	0.13	0.10	0.13	0.11	0.17	0.03	0.03
LOI*	11.43	13.60	13.73	19.89	9.31	8.63	10.68
Total	98.95	98.90	98.52	99.16	98.79	100.02	100.18
Ba	376	318	346	234	264	71	74
Sr	189	628	589	390	200	196	378
Y	22	31	17	22	34	19	22
Sc	9	6	10	9	2	12	12
Zr	182	352	174	127	389	106	97
Be	4	4	3	3	4	5	4
V	56	62	81	52	85	<5	5
Cr	53	63	87	84	<20	<20	<20
Co	11	10	17	10	6	<1	1
Ni	52	41	62	58	<20	<20	<20
Cu	29	113	41	37	136	<10	<10
Zn	51	48	54	58	<30	<30	<30
Ga	20	25	20	19	17	30	28
Ge	2	2	2	1	2	1	1
As	7	15	10	<5	6	<5	<5
Rb	184	224	141	136	201	218	215
Nb	15	23	12	12	22	72	68
Sn	4	9	10	9	3	10	10
Cs	10	6	6	5	15	23	25
Hf	5	9	5	4	8	6	6
Ta	1	1	1	1	1	6	6
Pb	34	21	8	8	26	<5	8
Bi	1	4	1	5	0.8	1	1
Th	16	18	9	10	21	24	23
U	3	3	2	2	6	4	3
La	42.7	30.9	38.9	42.5	14.3	11.4	11.9
Ce	85.7	58.8	67.3	80.1	37.8	27.4	29.7
Pr	9.71	6.64	7.71	8.75	5.23	3.26	3.64
Nd	34.5	24.5	28.0	32.0	24.6	13.4	15.2
Sm	6.0	4.97	5.48	6.25	5.5	3.2	3.6
Eu	1.18	1.21	1.26	1.24	1.52	0.25	0.47
Gd	4.5	4.78	4.45	5.11	5.3	3.0	3.4
Tb	0.8	0.94	0.70	0.82	0.9	0.6	0.6
Dy	4.1	5.54	3.51	4.30	5.6	3.6	4.1
Ho	0.8	1.17	0.64	0.88	1.1	0.7	0.8
Er	2.4	3.65	1.99	2.77	3.0	2.2	2.5
Tm	0.38	0.529	0.290	0.413	0.41	0.33	0.36
Yb	2.5	3.06	1.87	2.50	2.3	2.0	2.2
Lu	0.36	0.425	0.285	0.360	0.30	0.29	0.32

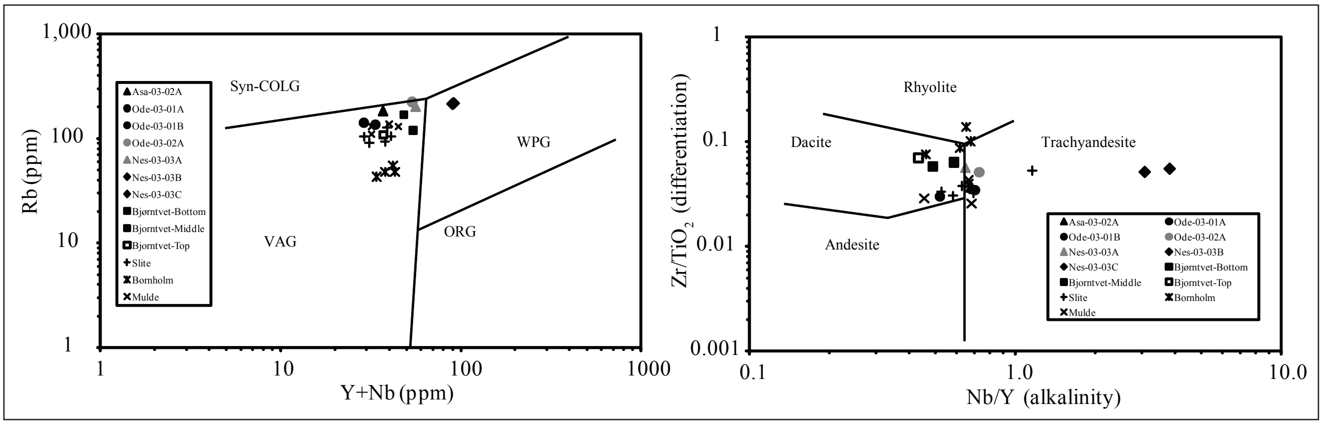


Figure 4: A) Trace element compositional data plotted on the tectonic discrimination diagrams for granites and alkali granites (Pearce et al., 1984). WPG = within-plate granite; ORG = ocean ridge granite; VAG = volcanic arc granite; Syn-COLG = syn-collision granite. B) Trace elementcompositional data plotted on the Nb/Y vs. Zr/TiO$_2$ geochemical grid of Winchester & Floyd (1977). Additional data from Batchelor & Jeppsson (1999) and Hetherington et al. (2004).

Figure 5: Chondrite-normalised rare earth element (REE) data for bentonite samples. Normalising values from Wakita et al. (1971). NASC – North American Shale Composition; PAAS – Post Archean Australian Shale.

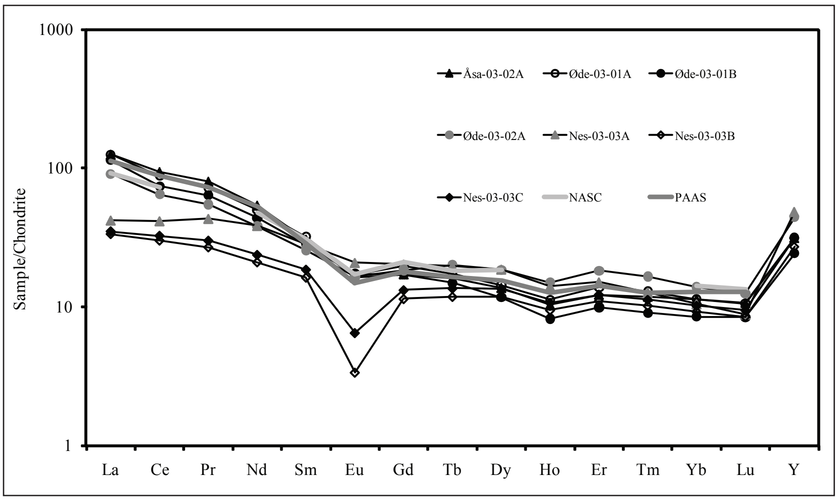
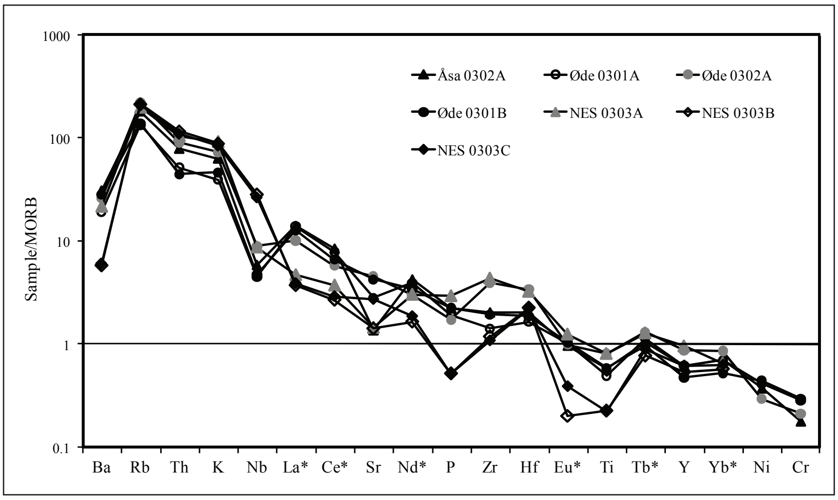


Figure 6: MORB-normalised trace and rare earth element data for the bentonite samples. Normlising values from Saunders & Tarney (1984).



Discussion

The mineralogy and compositional data for the samples in this study highlight some of the strengths and weaknesses of identifying and using sedimentary horizons that have a high volcanic ash content for correlation purposes. Perhaps of greatest importance is establishing whether a sample represents a volcanic rock or not. Bentonites are clay-rich rocks, consisting predominantly of smectite, formed by alteration of volcanically derived ash and glass. Other indicators, particularly in younger bentonites, are the presence of primary igneous minerals in the form of phenocrysts (Batchelor & Evans, 2000; Batchelor, 2003), presence of glass shards or alumino-silicate and/or crystal-rich layers in high-purity sandstone or limestone horizons (e.g. Batchelor & Prave, 2010), as well as compositional indicators, such as the distribution of rare earth elements (Christidis & Huff, 2009).

Compositionally, there are some indications that the samples represent bentonites. SiO_2/Al_2O_3 and TiO_2/Al_2O_3 ratios of <3.0 and <0.04 respectively are indicative of volcanic ash and glass derived material. Meanwhile, chondrite normalised REE plots for clastic sediments, especially clay and mudstones such as the North American Shale Composition (NASC) and Post-Archean Australian Shale (PAAS), which are rich in alumino-silicate minerals, typically have steep negative light rare earth element (LREE) and near horizontal heavy rare earth elemental chondrite normalised patterns (see plots of NASC and PAAS in Fig. 5) (Rollinson, 1993; McLennan et al., 2003).

Two samples have SiO_2/Al_2O_3 approaching 3.5 (Øde-03-01B and Øde-03-02A; Table 2) and lie outside the expected range for volcanogenic clays. In the case of Øde-03-01B, it is one of two samples collected within 3m of one another in a single horizon (Fig. 3a). Despite samples Øde-03-01A and Øde-03-01B being collected from the same horizon they have contrasting major element compositions (Table 2). However, they have comparable trace element compositions (Figs. 4-6). It is proposed that the primary SiO_2/Al_2O_3 ratio has been disturbed, possibly by processes related to intrusion of the nearby dyke (Fig. 2a); intrusion of this dyke may also have contributed to the higher illite crystallinity value (Table 1). The higher than expected SiO_2/Al_2O_3 ratio in Øde-03-02A has no apparent connection with igneous activity. Rather, it may have been caused by the introduction of SiO_2 from the siliceous limestone host rock during sedimentation, diagenesis, sediment reworking and/or bioturbation, post-lithification alteration during low-grade metamorphism, or a combination of these processes.

Interpretation of the REE plots is more complex. The pattern of chondrite normalised values for the single bentonite horizon collected at Åsa and Ødegårdsviken (Åsa-0302-A, Øde-03-01A and Øde-03-01B) closely mimics those of the chrondrite normalised values for NASC and PAAS with relatively steep LREE and near horizontal HREE patterns. The chrondrite normalised patterns for the samples collected at Nes are much more characteristic of material derived from volcanic ash. These have shallower LREE trends and pronounced negative Eu anomalies (Fig. 5). Despite the similarity between some samples and NASC and PAAS compositions, on the basis of outcrop relationships, each of the sampled localities is believed to represent a sedimentary horizon derived from volcanic ash and glass. However, it is highly probable that the Åsa and Ødegårdsviken samples contain a significant clastic component. Furthermore, the shallow negative trend in the chondrite normalised data, enrichment in alkali and alkali-earths and Th, and depletion in compatible transition series elements (Ti, Ni and Cr) compared to MORB indicate that the volcanic material was most probably derived from a calc-alkaline source. The distinctly higher (Y+Nb) concentrations and Nb/Y ratios measured in the uppermost bentonite at Nes (Nes-03-03B and Nes-03-03C) and the shallower chrondrite normalised LREE distribution may indicate that this bentonite is derived from more alkaline, potentially trachytic, volcanic material.

Mineralogically, the samples contain no smectite *senso stricto* (Table 1) and few potential phenocrysts were identified. With increasing temperature during burial and low-grade metamorphism the expected sequence of dioctahedral clay minerals is smectite → mixed layer illite/smectite → illite → muscovite (Frey & Robinson, 1999), and the regional presence of igneous rocks associated with rifting is a viable driver of such mineralogical transformations. Of further interest is the noted systematic variation in the assemblage and properties of the di-octahedral silicates. In the south, the phyllosilicates are dominated by mixed illite-smectite minerals with high illite crystallinity values (1.01-1.59) and no chlorite. Samples from progressively more northerly locations show a decrease in illite crystallinity (0.72 at Åsa), the absence of smectite or any mixed phase, and the occurrence of chlorite indicating a higher temperature of metamorphism. Conodont alteration index (CAI) values reported from localities close to each of the sampling localities in this study also show an increase in temperature from south to north (Aldridge, 1984). Samples collected close to the Åsa locality gave CAI values of 5, which indicate temperatures above 300°C. Meanwhile, samples from close to Ødegårdsviken gave CAI values of 4 (190-300°C) and a locality near Nes gave CAI values of 3 – 4 (150-250°C). These twin observations may have implications for the palaeo-extent of Permian lavas in the Oslo Rift. Permian granitic to syenitic intrusions associated with the Oslo Rift crop out to the northeast, and voluminous rhyolites and trachytes are exposed immediately to the east of these localities. Transformation of the alumino-silicate minerals from smectite to illite, driven by contact metamorphism, may be expected. If the sedimentary section containing the bentonites had been buried beneath lava flows then higher grades of thermal alteration and metamorphism may have been expected in the stratigraphically higher locations at Nes. However, both the CAI values and illite crystallinity values show that greater thermal heating occurred at the stratigraphically lowermost locality at Åsa. While it is possible that some of the thermal maturation was caused by burial, as was discussed, but discounted by Aldridge (1984), the geographic proximity of granitic to syenitic intrusive rocks associated with the Øyangen and Heggelia calderas (Larsen et al., 2008) is a more probable cause of the thermal maturation.

Local Stratigraphic Correlation and Sedimentary Environments at Ringerike

The single bentonite at Åsa (Åsa-03-02A) and the stratigraphically lower single bentonite at Ødegårdsviken (samples Øde-03-01A and Øde-03-01B) have similar chondrite normalised rare-earth element signatures (Fig. 5) and correlate with one another in the volcanic arc geo-tectonic field (Fig. 4). It is proposed that these two localities represent the same bentonite (Fig. 7). Similarly, the lowermost bentonite from the stratigraphically higher Ødegårdsviken locality (Øde-03-02A) positively correlates with the lowermost bentonite from Nes (Fig. 7)(Nes-03-03A). These samples have calc-alkaline rare-earth element distributions and plot in the volcanic arc field of the discrimination diagrams. The compositional correlation and stratigraphic relationship – the lowermost bed in a bentonite doublet – suggests that these two samples represent the same bentonite (Fig. 7). The uppermost bentonite from the Nes locality has contrasting compositional characteristics and does not correlate with any of the other studied samples. However, on the basis of its occurrence slightly above sample Nes-03-03A it is proposed that it correlates with the unsampled bentonite at Ødegårdsviken observed ~25 cm above sample Øde-03-02A.

The composition of the uppermost bentonite at Nes (Nes-03-03B and 03C) with its strong alkaline signature, compared to other samples, represents a bentonite horizon with a distinctive composition. This could make it a highly attractive marker horizon for correlation purposes. However, to date, such strong alkaline (trachytic) signatures have only been documented in the younger Carboniferous-Permian Oslo Rift-related volcanic rocks (Neumann et al., 2004). No evidence of similar rocks of Silurian age from elsewhere in Scandinavia or northern Europe has been reported.

Although there is geochemical and field evidence for correlating the Åsa locality with the stratigraphically lower bentonite at Ødegårdsviken, and the doublet of bentonites at Ødegårdsviken and Nes, a similar conclusion cannot be reached on the basis of mineral assemblage data, or by comparing host sediments, their relative thicknesses and currently assigned stratigraphic levels.

A positive correlation between these two localities suggests that the complex and dynamic nature of sedimentation in the tidal flat environment regressing from north-to-south described by Olaussen (1985) may be more complex. Here, lagoonal type environments represented by the rocks found at Åsa (Fig. 1) occur to the north of

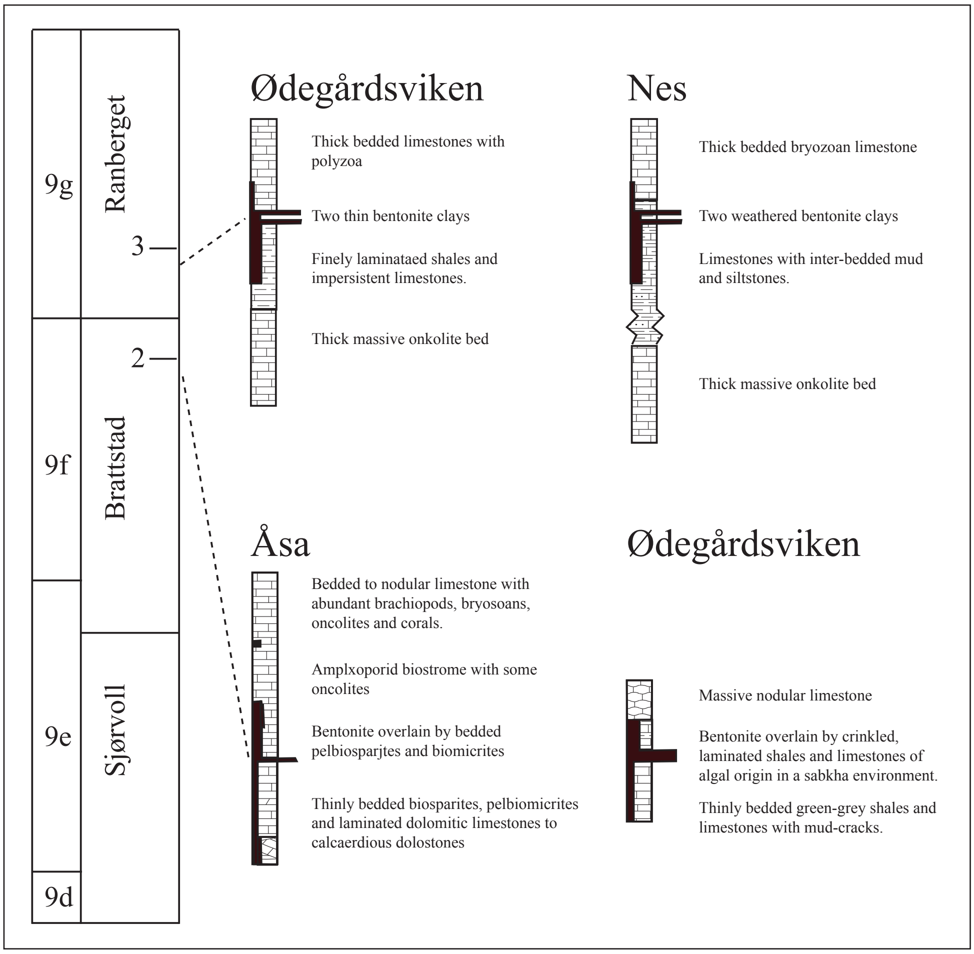


Figure 7: Stratigraphic correlation of the two bentonite-bearing horizons in the upper Steinsfjorden Formation at Ringerike.

sabkha and tidal flat environments represented by rocks found at the 520-530 m level in the Ødegårdsviken section of Whitaker (1977). Furthermore, the single bentonite at Ødegårdsviken has been assigned to the Sjørvoll Member of the Steinsfjorden Formation (Fig. 2; Whitaker, 1977) while the bentonite at Åsa was assigned to the younger Brattstad Member (Fig. 2; Worsley et al., 1983). Such assignations are now conflicting as these rocks have now been shown to be chronologically equivalent and the relative stratigraphy of these units may require resolution in the future. It is not the role of this contribution to favour one option over another, but the authors consider reassigning the older rocks of the Ødegårdsviken section to the Brattstad Member as a more logical option. This is based on greater biostratigraphic control at the Åsa locality, and the compositionally distinct marker horizon is considered to be more reliable than field correlation based on limited fossil assemblages and phyla that have a wider biostratigraphic range and hence are less reliable as index fossils.

Besides the positive geochemical correlation between the doublets of bentonites at Ødegårdsviken and Nes, there are correlations in the under- and overlying sediments. The underlying lithologies are laminated shales with occasional limestones at Ødegårdsviken, and limestones with interbedded muds and siltstones at Nes, with both localities capped by bryozoan-bearing massive limestones (Fig. 7). However, investigation of the greater sedimentary section also demonstrates significant variation in either the sedimentation rates between the two localities, or preservation of the section. At Ødegårdsviken the bentonite host-rocks are only a few metres above a massive and highly recognisable oncolite bed (Fig. 7). In contrast, an oncolite bed with similar features and thickness that is identifiable at Nes fully 50 m lower in the stratigraphic section. Although the two oncolite beds have not been positively correlated as a single horizon, and even accounting for a time lapse from north-to-south, the significant difference in stratigraphic thickness between the bentonites and the oncolites would suggest much higher rates of sedimentation at the more southerly location (Fig. 1).

As with the single bentonite, the positive correlation between these bentonites allows for tighter constraints to be placed on the stratigraphic location of the two localities. Prior to this study, the Nes location had not been positively assigned to a particular Member of the Steinsfjorden Formation. It is proposed that its sedimentological and geochemical correlation with the double bentonite at Ødegårdsviken positively equates with the stratigraphic height of the rocks at Nes and to the equivalent of the Ranberget Member of the Steinsfjorden Formation (Fig. 7).

Regional Stratigraphic Correlation

Volcanic ash-fall horizons, in geologic terms, represent instantaneous moments in time making them powerful tools for correlating sedimentary rocks over large distances. The stratigraphic positions of the bentonite horizons in the Brattstad and Ranberget Members of the Steinsfjorden Formation place graptolite-equivalent constraints on the timing of deposition. This information may be used to relate their stratigraphic position to other Silurian bentonites in Scandinavia and northern Europe. On the basis of stratigraphy, it is possible to discount regional correlation with Silurian bentonites reported from stratigraphically lower locations at Osmundsberg (Sweden) (Huff et al., 1998), Vik, just to the northwest of the sampled localities in this study (Batchelor et al., 1995), and the Lower Visby Formation on the island of Gotland, southeast Sweden (Batchelor & Evans, 2000).

Bentonites of comparable age at other Scandinavian localities include bentonite horizons described in the Slite and Mulde Formations on the island of Gotland (Batchelor & Jeppsson, 1999) and the Cyrtograptus Shale of Bornholm, Denmark (Obst et al., 2002). The bentonites from Bjørntvet Quarry were also deposited in the Steinsfjorden Formation, but their stratigraphic position is more poorly constrained (Hetherington et al., 2004).

In discrimination plots showing (Nb+Y vs Rb) and (Zr/TiO_2 vs Nb/Y) the composition of the bentonite in the Cyrtograptus Shale from Bornholm does not correlate with any of the samples presented in this study (Fig. 3). On the other hand, the stratigraphically lower bentonite at Nes (Nes-03-03A) and sample Øde-03-02A, which positively correlate with one another, have similar trace element compositions to the bottom and middle bentonite horizons at Bjørntvet. However, although the uppermost horizon at Bjørntvet has a loose correlation with the single bentonite layers collected at Åsa and Ødegårdsviken, the inverted stratigraphy of the horizons prohibits a positive correlation between the bentonites at Bjørntvet and those described here. Furthermore, the composition of the uppermost bentonite at Nes (Nes-03-03B and 03C) deviates significantly from the topmost bentonite at Bjørntvet, which is also less favourable for a positive regional correlation.

In contrast, the compositional data for the bentonites from the Slite and Mulde formations on Gotland (Batchelor & Jeppsson, 1999), show very similar trace element ratios to the single bentonite horizon at Åsa and Ødegårdsviken (Åsa-03-02A and Øde-03-01A and 01B). The metabentonites in the Slite and Mulde Formations were interpreted to be derived from a volcanic arc environment associated with waning subduction along the Tornquist-Teysseyre Zone. This was located 400 km to the SW of present day Gotland, and the equivalent of a location ~600km SSW of the Vik-Sundvollen Region where the current study has been conducted.

Chondrite normalised REE concentrations in apatite from the Slite and Mulde Formation bentonites show LREE enrichment over HREE with a gradual negative slope (Batchelor & Jeppsson, 1999). Although the whole-rock concentrations are not provided, rare earth elements (La, Ce, Pr, Sm Gd and Lu), as well as Y and Sr, have been shown to be compatible in apatite crystallising in silicate melts (Prowatke & Klemme, 2006). Therefore the apatite values presented by Batchelor & Jeppsson (1999) may be considered representative of whole-rock REE concentrations in the bentonites of the Slite and Mulde Formations. The data for apatite in the Slite and Mulde formations is characterised by strong LREE enrichment over HREE. However, only apatite from the four stratigraphically oldest bentonites in the Slite Formation show small negative Eu anomalies. These are representative of the REE distribution in the single bentonite horizons at Åsa and Ødegårdsviken. Furthermore, the stratigraphic position of the Slite Formation in the M. *belophorus – C. ellesae* is similar to the Brattstad and Ranberget Members of the Steinsfjorden Formation (Worsley et al., 1983), whereas the position of the Mulde formation is stratigraphically higher in the *Ozarkodina bohemica* biozone, which includes fauna typical of the *Gothograptus nassa-Monograptus dubius* biozone (Batchelor & Jeppsson, 1999).

Although there are compositional and stratigraphic similarities between the single bentonite horizon at Åsa (Åsa-03-02A) and Ødegårdsviken (Øde-03-01A and B) and bentonite horizons in the Slite Formation, there is a discrepancy between the numbers of bentonites identified. A potential correlation only exists between the single bentonite in the Ringerike District and one of the four oldest bentonites in the Slite Formation. If a correlation does exist then evidence for as many as six other bentonites identified in the Slite Formation (Batchelor & Jeppsson, 1999) is absent at Ringerike. This may be considered surprising for isopach schemes showing the distribution and thickness of K-bentonites in Scandinavia and northern Europe (Kiipli et al., 2008b; Kiipli et al., 2008c) suggest that the modern day location of potential volcanic ash clouds lies to the northwest of the Oslo region suggesting that preservation and thickness of bentonites may be expected to be greater in the Oslo Region compared to Gotland and regions further to the east. On the other hand, if the Oslo region was peripheral to the direction of ash transport by the prevailing winds, significant thicknesses of ash are not guaranteed in localities that are geographically closer to the source. Furthermore, the preservation of volcanic ash in the sedimentary record is not necessarily guaranteed, especially in dynamic sedimentary basins, where physical perturbation and mixing of ash with clastic derived material, including clays, may mask the presence of a volcanic component or obliterate its existence during sediment reworking, thus hindering long-term preservation of relatively short term events (Sadler, 1981; Sadler & Dingus, 1982).

Conclusions

Bentonite horizons from three localities in the Wenlock division of the Silurian Steinsfjorden Formation in the Ringerike District of southern Norway have calc-alkaline affinities and positive compositional correlations with one another. The horizons may be used to provide short range stratigraphic correlation between a diversity of rock types that were being deposited simultaneously in a relatively small, and clearly dynamic, geographic region. Medium range correlation with outcrops of bentonites of similar age in the south of the Oslo Rift was not possible.

Similar compositional characteristics between a single bentonite in the Ringerike District and bentonites that crop out in the Slite Formation of Gotland have been noted. However, differences in the number of identified bentonite horizons and the limited geochemical datasets upon which the correlation was based hinder a firm positive correlation being drawn. However, it is noted that, especially given the highly dynamic and changing environment of sediment deposition in the Ringerike District, conditions for preservation and/or identification of additional bentonites in the stratigraphic sections exposed at Åsa and Ødegardsviken are unfavourable.

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References

Aldridge, R. J. 1984: Thermal metamorphism of the Silurian strata of the Oslo region, assessed by conodont colour. *Geological Magazine 121*, 347-349.

Batchelor, R.A. 1999: Metabentonites from the Silurian inliers of the southern Midland Valley of Scotland: distribution and geochemistry. S*cottish Journal of Geology 35(1)*, 71-77.

Batchelor, R.A. 2003: Geochemistry of biotite in metabentonites as an age discriminant, indicator of regional magma sources and potential correlating tool. *Mineralogical Magazine 67(4)*, 807-817.

Batchelor, R.A. & Evans, J. 2000: Use of strontium isotope ratios and rare earth elements in apatite microphenocrysts for characterization and correlation of Silurian metabentonites: a Scandinavian case study. *Norsk Geologisk Tidsskrift 80*, 3-8.

Batchelor, R.A., Harper, D.A.T. & Anderson, T.B. 2003: Geochemistry and potential correlation of Silurian (Telychian) metabentonites from Ireland and SW Scotland. *Geological Journal 38*, 161-174.

Batchelor, R.A. & Jeppsson, L. 1994: Late Llandovery bentonites from Gotland, Sweden, as chemostratigraphic markers. *Journal of the Geological Society, London, 151*, 741-746

Batchelor, R.A. & Jeppsson, L. 1999: Wenlock metabentonites from Gotland, Sweden: geochemistry, sources and potential as chemostratigraphic markers. *Geological Magazine 136(6)*, 661-669

Batchelor, R.A. & Prave, A.R. 2010: Crystal tuff in the Stoer Group, Torridonian Supergroup, WM Scotland. *Scottish Journal of Geology 46(1)*, 1-6.

Batchelor, R.A. & Weir, J.A. 1988: Metabentonite geochemistry: magmatic cycles and graptolite extinctions at Dob's Linn, southern Scotland. *Transactions of the Royal Society Edinburgh Earth Sciences 79*, 19-41.

Batchelor, R.A., Weir, J.A. & Spjeldnæs, N. 1995: Geochemistry of Telychian metabentonites from Vik, Ringerike District, Oslo Region. *Norsk Geologisk Tidsskrift 75*, 219-228

Cherns, L. & Karis, L. 1995: Late Ordovician – early Silurian transgressive sedimentation in the Jämtland basin, central Swedish Caledonides. *Geologiska Föreningens i Stockholm Förhandlingar 117(1)*, 23-30.

Christidis, G.E. & Huff, W.D. 2009: Geological aspects and genesis of bentonites. *Elements 5(2)*, 93-98.

Guggenheim, S., Bain, D.C., Bergaya, F., Brigatti, M.F., Drits, V.A., Eberl, D.D., Formoso, M.L.L., Galan, E., Merriman, R.J., Peacor, D.R., Stanjek, H., & Watanabe, T. 2002: Report of the Association Internaional Pour L'Etude des Argiles (AIPEA) Nomenclature Committee for 2001: Order, Disorder and Crystallinity in Phyllosilicates and the use of the "Crystallinity Index". *Clays and Clay Minerals 50*, 406-409.

Hetherington, C.J., Nakrem, H.A. & Batchelor, R.A. 2004: The Bjørntvet Brudd metabentonite: A new Silurian correlation tool for the southwest Oslo Region. *Norsk Geologisk Tidsskrift 84*, 239-250.

Huff, W.D., Bergström, S.M., Kolata, D.R. & Sun, H. 1997: The Lower Silurian Osmundsberg K-bentonite. Part II: Mineralogy, geochemistry, chemostratigraphy and tectonomagmatic significance. *Geological Magazine 135(1)*, 15-26.

Jørgensen, P. 1964: Mineralogical compostion of two silurian bentonite beds from Sundvollen, Southern Norway. *Norsk Geologisk Tidsskrift 44*, 227-234.

Kiær, J. 1908: Das Obersilur im Kristianiagebiete. Eine stratigraphisch-faunistische Untersuchung. *Videnskapsselskapets Skrifter I. Matematisk-Naturvidenskapelig Klasse 1906 volume II*, Kristiania, 596 pp.

Kiipli, T., Jeppsson, L., Kallaste, T. & Söderlund, U. 2008a: Correlation of Silurian bentonites from Gotland and the eastern Baltic using sanidine phenocryst composition, and biostratigraphical consequences. *Journal of the Geological Society, London 165*, 211-220.

Kiipli, T., Männik, P., Batchelor, R.A., Kiipli, E., Kallaste, T. & Perens, H. 2001: Correlation of Telychian (Silurian) altered volcanic ash bed in Estonia, Sweden and Norway. *Norsk Geologisk Tidsskrift 81*, 179-194.

Kiipli, T., Orova, K., Kiipli, E. & Kallaste, T. 2008b: Use of immobile trace elements for the correlation of Telychian bentonites on Saaremaa Island, Estonia, and mapping of volcanic ash clouds. *Estonian Journal of Earth Sciences 57(1)*, 39-52.

Kiipli, T., Soesoo, A., Kallaste, T. & Kiipli, E. 2008c: Geochemistry of Telichian (Silurian) K-bentonites in Estonia and Latvia. *Journal of Volcanology and Geothermal Research 171*, 45-58.

Lanson, B. 1997: Decomposition of experimental X-ray diffraction patterns (profile fitting): a convenient way to study clay minerals. *Clays and Clay Minerals 45*, 132-146.

Larsen, B.T., Olaussen, S., Sundvoll, B. & Heeremans, M. 2008: The Permo-Carboniferous Oslo Rift through six stages and 65 million years. *Episodes 31*¸ 52-58.

McLennan, S.M., Bock, B., Hemming, S.R., Hurowitz, J.A., Lev, S.M. & McDaniel, D. 2003: The roles of provenance and sedimentary processes in the geochemistry of sedimentary rocks. *In:* Lentz, D.R. (Ed.) Geochemistry of Sediments and Sedimentary Rocks: Evolutionary considerations to mineral deposit-forming environments, Geotext 4, p. 184. Geological Association of Canada.

Merriman, R.K. & Roberts, B. 1990: Metabentonites in the Moffat Shale Group, Southern Uplands of Scotland: Geochemical evidence of ensialic marginal basin volcanism. *Geological Magazine 127(3)*, 259-271.

Merriman, R.K. & Frey, M. 1999: Patterns of very low-grade metamorphism in metapelitic rocks. *In:* Frey, M. & Robinson, D. (Eds.) Low-grade metamorphism. pp 61-107. Blackwell Science

Obst, K., Böhnke, A., Katzung, G. & Maletz, J. 2002: Pb-Pb zircon dating of tuff horizons in the Cyrtograptus Shale (Wenlock, Silurian) of Bornholm, Denmark. *Bulletin of the Geological Society of Denmark 48*, 1-8.

Odin, G.S., Hunziker, J.C., Jeppsson, L. & Spjeldnæs, N. 1986: Radiometric K-Ar ages of pyroclastic biotites deposited in the Wenlockian of Gotland (Sweden). *Chemical Geology 59*, 117-125.

Ogg, J.G., Ogg, G. & Gradstein, F.M. 2008: *The concise geologic time scale*. Cambridge University Press, Cambridge, 177 pp.

Olaussen, S. 1985: Sedimentology and lithostratigraphy of the tidal flat deposits of the Steinsfjorden Formation (Wenlock) of Ringerike, Southern-Norway. *Norges Geologiske Undersøkelse Bulletin 399*, 1-25.

Pearce, R.B. 1995: The geochemistry of Llandovery and Wenlock age K-bentonites in the Southern Uplands. *Scottish Journal of Geology 31(1)*, 23-28.

Prowatke, S. & Klemme, S. 2006: Trace element partitioning between apatite and silicate melts. *Geochimica et Cosmochimica Acta 70(17)*, 4513-4527.

Ribecai, C., Bruton, D.L. & Tongiorgi, M. 2000: Acritarchs from the Ordovician of the Oslo Region, Norway. *Norsk Geologisk Tidsskrift 80(4)*, 251-258.

Rollinson, H. 1993: *Using geochemical data: evaluation, presentation, interpretation.* Longman Group, Harlow, 352 pp.

Romano, M. & Spears, D.A. 1991: Bentonites from the Horton Formation (Upper Silurian) of Ribblesdale, Yorkshire. *Proceedings of the Yorkshire Geological Society 48(3)*, 277-285.

Sadler, P.M. 1981: Sediment accumulation rates and the completeness of stratigraphic sections. *Journal of Geology 89*, 569-584.

Sadler, P.M. & Dingus, L.W. 1982: Expected completeness of sedimentary sections: estimating a time-scale dependent limiting factor in the resolution of the fossil record. *Proceedings of the Third North American Paleontology Convention 2*, 461-464.

Saunders, A.D. & Tarney, J. 1984: Geochemical characteristics of basaltic volcanism within back-arc basins. *In:* Kokelaar, B.P. & Howells, M.F. (Eds.) Marginal Basin Geology 16, 322 pp. Blackwell Scientific Publications.

Teale, C.T. & Spears, D.A. 1986: The mineralogy and origin of some Silurian bentonites, Welsh Borderland, U.K. *Sedimentology 33*, 757-765.

Wakita, H., Rey, P. & Schmitt, R. A. 1971: Abundances of the 14 rare-earth elements and 12 other trace elements in Apollo 12 samples: Five igneous and one breccia rocks and four soils. *Proceedings of the Second Lunar Science Conference 2*, 1319-1329.

Warr, L.N. & Rice, A.H.N. 1994: Interlaboratory standardization and calibration of clay mineral crystallinity and crystallite size data. *Journal of Metamorphic Geology 9*, 141-152.

Whitaker, J.H.M. 1977: *A Guide to the Geology around Steinsfjord, Ringerike*. Universitetsforlaget, Oslo, 56 pp.

Whitney, D.L. & Evans, B.W. 2010: Abbreviations for names of rock-forming minerals. *American Mineralogist 95*, 185-187.

Worsley, D., Aarhus, N., Bassett, M.G., Howe, M.P.A., Mørk, A. & Olaussen, S. 1983: The Silurian succession of the Oslo Region. *Norges Geologiske Undersøkelse 384*, 57 pp.