

Fluids and halogens at the diagenetic-metamorphic boundary: evidence from veins in continental basins, western Norway

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ABSTRACT

Seven vein types are recognized in three continental Devonian molasse basins (the Hornelen, Kvamshesten and Solund basins) in western Norway. These include calcite-, quartz- and epidote-dominated veins. The salinities of fluid inclusions from quartz-dominated veins in the Hornelen and Kvamshesten basins are close to or slightly higher than those for modern seawater, whereas the fluids from quartz- and calcite-dominated veins in the Solund basin range from seawater values to 20 wt % NaCl equivalent. Minerals such as biotite, amphibole, titanite, chlorite and epidote are abundant in the latter veins, and are important constituents of the authigenic mineral assemblages. A combination of fluid inclusion and petrological data suggest that at least some of the veins formed at depths around 12–14 km. The Cl/Br ratios and the salinity of the fluid inclusions can be explained by interactions with evaporites, implying that the sedimentary environment forming the basin fill had the strongest influence upon low-grade metamorphic fluid Cl and Br contents. Differences in the Cl/I and Na/Br ratios between the Solund basin and the Hornelen and Kvamshesten basins are best explained by local mass transfer between pore fluids and the surrounding rock matrix during burial and increasing temperatures.

Key-words: continental basins, diagenetic-metamorphic boundary, fluid inclusions, halogens, western Norway

Received 5 June 2000; accepted 29 September 2000

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Geofluids (2001) 1, 53–70

INTRODUCTION

Samples of modern basinal brines generally represent waters from the upper ≈ 4.5 km of the basin (see Worden 1996); thus the geochemical evolution of brines during high-temperature (i.e. $> 150^\circ\text{C}$) diagenesis and low-grade metamorphism is poorly known. However, this is of importance for understanding how fluids and minerals interact during the early stages of progressive metamorphism. Very deep burial of sedimentary basins to depths exceeding 12–13 km is indicated by seismic studies worldwide (e.g. Breivik *et al.* 1998; Brune *et al.* 1992; Curray 1991). One way to fill the observational gap between diagenesis and metamorphism is to study ancient brines trapped as fluid inclusions in veins from deeply eroded basins. Examples of such basins formed during, and shortly after, the Caledonian orogeny in western Norway.

The aim of this work is to characterize the composition of fluids associated with veins in the Hornelen, Kvamshesten

and Solund basins in western Norway (Fig. 1). Both major and trace element compositions of the inclusion fluids have been studied in order to determine effects of fluid-rock interactions on pore fluid compositions close to the diagenetic-metamorphic boundary. Fluid inclusions have been analysed using a range of single inclusion and bulk techniques: microthermometry, scanning electron microscopy-energy dispersive analysis (SEM-EDA) of fluid inclusion decrepitates, liquid ion chromatography, gas chromatography (GC), atomic absorption spectroscopy (AAS), inductively coupled plasma (ICP) spectroscopy and Raman spectroscopy. In addition, this work presents a petrographic characterization of the veins in the Devonian basins. Neither the vein mineralogy nor the fluid inclusions have been previously described.

Geological setting

The onshore sedimentary molasse basins of western Norway are situated in the hanging-wall of a regional extensional

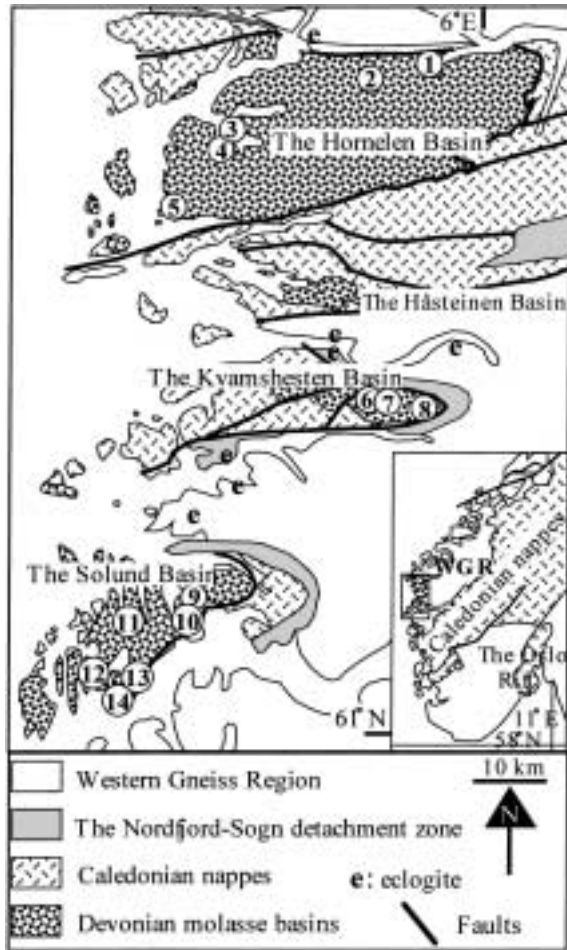


Fig. 1. Geology of western Norway with sampling localities (modified from Hartz & Andresen 1997).

detachment zone. This detachment zone separates the basins from the eclogite-bearing Western Gneiss Region (WGR) and was active from the late stages of the Caledonian orogeny (Andersen & Jamtveit 1990) until at least the early Cretaceous (Eide *et al.* 1997). Extensional tectonics caused ductile deformation in the basal parts of the basins (Seranne & Seguret 1987). Late movements along this detachment zone juxtaposed the basins onto the high-grade WGR rocks. The sedimentation was probably controlled by listric, ramp-flat normal faults rooted in the extensional mylonite zone (Hossack 1984; Osmundsen *et al.* 1998, 2000). The preserved sedimentary stratigraphy is 25 km in the Hornelen basin (Bryhni 1964; Kolderup 1926) and 6–7 km in the Kvamshesten and Solund basins (Seranne & Seguret 1987). This is considerable considering the modest horizontal extension of the basins. Seranne & Seguret (1987) argued that the maximum burial of the Hornelen basin did not exceed 5–10 km, a depth sufficient to reach greenschist facies metamorphic conditions. Still, the (meta-) sedimentary rocks are virtually undeformed, except along basal zones. The

present vertical thickness of the basins is estimated to be about 1500 m in the Hornelen basin (Seranne & Seguret 1987) and up to 3000 m in the Kvamshesten basin (Osmundsen *et al.* 1998).

The basins comprise continental alluvial and fluvial deposits (e.g. Bryhni 1964, 1978; Nilsen 1968; Osmundsen *et al.* 1998, 2000; Steel 1976; Steel *et al.* 1985). The Hornelen basin primarily comprises cycles of sandstones and siltstones, with coarse conglomerates along the basin margins (Steel 1976), whereas the Kvamshesten basin comprises sediments ranging in composition from coarse conglomerates to red/green sandstones and siltstones (Osmundsen *et al.* 1998). The conglomerates are present along the basin margins and the basal parts. The siltstones are interpreted to represent overbank or shallow lacustrine sedimentation (Bryhni 1978; Osmundsen *et al.* 1998; Skjerlie 1969). The Solund basin differs from the two others: it is dominated by coarse conglomerates, with only minor horizons of sandstones (Nilsen 1968), and metavolcanic material is abundant in parts of the basin (Grünhagen & Jamtveit, 2000). Seranne & Seguret (1987) argue that the Solund basin represents the deepest exposed level of the Devonian basins in western Norway.

Epidote and chlorite were previously identified as authigenic minerals in the metasediments from the Solund basin (Seguret *et al.* 1989; Seranne & Seguret 1987), but the rocks have not been examined by modern petrological methods. A summary of the authigenic petrography of the metasediments from the basins, based on H. Svensen *et al.* (in preparation), is given in Table 1. Also included in Table 1 are summaries of vein settings and mineralogy. The authigenic minerals in the Solund basin include epidote, amphibole, biotite, sphene, K-feldspar, albite, haematite and quartz. This suite of minerals is diagnostic of low-pressure hydrothermal/contact metamorphic settings with temperatures ranging from 230 to 320°C (e.g. Caruso *et al.* 1988; Franzson 1998; McKibben *et al.* 1988; Ruggieri *et al.* 1999; Schiffman *et al.* 1984, 1985). Thus the Devonian basins are potentially well suited for studying fluid composition, fluid sources and processes close to the diagenetic-metamorphic boundary.

ANALYTICAL METHODS

Table 2 gives an overview of the analytical methods applied to the vein samples from the basins.

Microthermometry

Microthermometric analyses were performed at the Mineralogical-Geological Museum, University of Oslo, using a Linkam THM600 heating-freezing stage. The stage was calibrated in the range –56.6–230°C; the analytical precision is in the range $\pm 0.1^\circ\text{C}$ for temperatures between –60 and +10°C.

Table 1 Overview of vein types and mineralogy.

Vein type	Basin	Vein mineralogy	Auth. mineralogy	Samples*	Vein setting	Comments
H1	Hornelen	Qtz, Cal, Chl, Ttn, Ep, Kfs	Qtz, Cal, Chl,, Ttn, Ep, Ab, Kfs Phe, Hem, Ap	12	Occur throughout the basin. Less than 5 cm wide and 5 m long	Blocky quartz veins with calcite along margins. Vermicular chlorite is intergrown with quartz. K-feldspar is found on wall-rock feldspar. Euhedral epidote is locally abundant
K2	Kvamshesten	Qtz, Cal, Chl, Ttn, Ep, Kfs, Ab	As above	12	Occur in central parts of the basin. Less than 5 cm wide and 2 m long	Blocky quartz veins with sporadically occurring calcite. Vermicular chlorite is intergrown with quartz. K-feldspar and epidote are common accessories
K3	Kvamshesten	Qtz, Cal, Chl, Ttn, Ep	As above	3	These veins are found at high stratigraphic levels in the basin. Less than 2 cm wide and 1 m long. Postdate K2 veins	Quartz-dominated veins with some epidote and chlorite. Recrystallized quartz along vein margins, but no evidence for shear deformation from vein geometries
S4	Solund	Qtz, Cal, Chl, Ttn, Ep, Amph, Bt, Hem	Qtz, Cal, Chl, Ttn, Ep, Ab, Kfs, Bt, Amph, Hem, Ap	–	Occur throughout the basin. Both in regular veins up to several metres long, and in swarms and fracture networks. The veins are locally associated with faulting	Dominated by epidote crystals grown across vein. Show complex vein textures and mineral zoning (epidote). Where present in sandstones, the veins show alteration zones up to 10 cm wide (caused by K-feldspar dissolution and calcite precipitation)
S5	Solund	Qtz, Cal, Chl, Ttn, Kfs, Ab, Ep, Amph, Bt, Hem, Ap	As above	14	Occur throughout the basin. Steeply dipping (80–90°) veins, up to 2 m long, and have a consistent orientation of 30°N. Cut vein type S4	Comprise fibrous quartz and calcite, and show typical crack-seal textures. The fibrous habit is restricted to sandstone horizons, where in conglomerates the veins comprise blocky crystals. Vein minerals include chlorite, epidote, K-feldspar, amphibole, titanite and apatite
S6	Solund	Qtz, Cal, Chl, Ttn, Ccp	As above	4	Occur in central parts of the Solund basin. May exceed 10 m in length, but usually less than 2 cm long. The veins locally have a breccia-like appearance	Dominated by calcite, with fluid inclusion bearing euhedral quartz crystals. Other minerals are chlorite and chalcopyrite
S7	Solund	Qtz, Cal, Chl, Ttn, Ccp	As above	1	Veins are related to a shear zone in basal parts of the basin	Calcite-dominated veins with fracture networks of quartz, chalcopyrite and pyrite

*Number of samples studied by fluid inclusion techniques (see Table 2 for details).

Crush-leach analyses

Bulk fluid analyses were carried out at the University of Leeds. Quartz from the veins was crushed to a grain size of 500–1000 µm, followed by hand-picking under a binocular microscope, and then boiled in double distilled water to remove impurities and adsorbed ions. Three samples (SO-5, SO-8 and KO97-6) were boiled in HNO₃ prior to double distilled water to remove calcite. The purity of the cleaned quartz samples varied between the different vein types. The purity of the samples from the blocky quartz veins was close to 100%, whereas quartz from the Solund basin (S5–S7) contains mineral intergrowths, resulting in a purity sometimes as low as 80–90 vol %. Thus the analysed material may be regarded as bulk vein samples (especially samples from S5 veins; SOL98-4A–9A). The crush-leach analyses were carried out using methods described by Bottrell *et al.* (1988) and Banks & Yardley (1992). Detection limits for I and Br are ≈ 0.1 and 0.5 p.p.b., respectively.

A Varian 3500 GC-FID gas chromatograph at the University of Oslo was used to analyse light hydrocarbon gases from

selected samples. Between 10 and 15 g of quartz was crushed in a sealed steel chamber, and 2 mL of extracted gas from the chamber was analysed using a 30-m DB-1 column. The sensitivity of the gas chromatograph is high, and readily detects CH₄ concentrations down to 1 p.p.m.

SEM-EDA

Analysis of fluid inclusion decrepitates was carried out using a JEOL-840 scanning electron microscope, with a Link AN 10/55 S analyser, at the Department of Geology, University of Oslo. Polished wafers were cleaned using acetone, double distilled water and ethanol, prior to heating to ≈ 500°C to decrepitate the fluid inclusions. Additionally, some of the samples were decrepitated at 400°C. The wafers were then immediately mounted on glass-slides, carbon coated and analysed by SEM.

The semiquantitative analyses were conducted using natural and synthetic standards: Na, albite; Ca, wollastonite; K, KBr; Cl, RbCl; S, FeS₂. A beam current of 1.0 nA was used with a voltage of 15 kV. Decrepitates were analysed using a

Table 2 Overview of samples and analytical methods.

Sample	Loc. *	Nondestructive		Crush-leach						Decrepitates		
		Microtherm.	Raman	LIC				AA		ICP	GC	SEM-EDA
		NaCl	Gases	Cl/Br	Cl/I	Cl/F	Cl/SO ₄	Na/K	Na/Li	Metals	C ₁ -C ₅	Na, K, Ca, Cl, S
Vein type H1												
HOR97-1	3			x	x	x	x	x	x		x	
HOR97-3	2										x	
HOR97-4	2										x	
HOR97-5	2	x		x	x	x	x	x	x	x	x	
HOR97-6	1			x	x	x	x	x	x		x	
HOR97-7	1	x		x	x	x	x	x	x	x	x	x
HOR97-10	1	x		x	x	x	x	x	x		x	x
HOR97-11	1	x		x	x	x	x		x		x	
HOR97-12	4										x	
HOR97-16	4										x	
HOR97-17	4										x	
HOR-98	5	x		x	x	x	x	x	x			x
Vein type K2												
KV97-5	7										x	
KV97-21	7	x	x									
KV97-25	7	x	x	x	x	x	x	x	x		x	x
KV97-29	6	x										x
KV97-30	6	x										x
KV97-32	6	x		x	x	x	x	x	x			
KV97-34	6			x	x		x	x	x	x		x
KV97-36	6										x	
KV97-38	6	x		x	x	x	x	x	x			x
KV97-40	6			x	x	x	x	x	x		x	
KV97-42	6										x	
KV97-45	6	x		x	x		x		x	x		
Vein type K3												
PT-7	8			x		x	x				x	
PT-11	8	x										x
PT-13	8			x		x	x		x			
Vein type S5												
LO-4	10	x										
LO-6	10	x	x									x
SOL98-4A	9			x	x	x	x	x	x			
SOL98-4D	9	x		x	x	x	x	x	x			
SOL98-9A	9	x										
SOL98-9B	9	x		x	x	x	x		x			
SOL98-23B	10			x	x	x	x	x	x			
SOL98-23C	10			x	x	x	x		x			

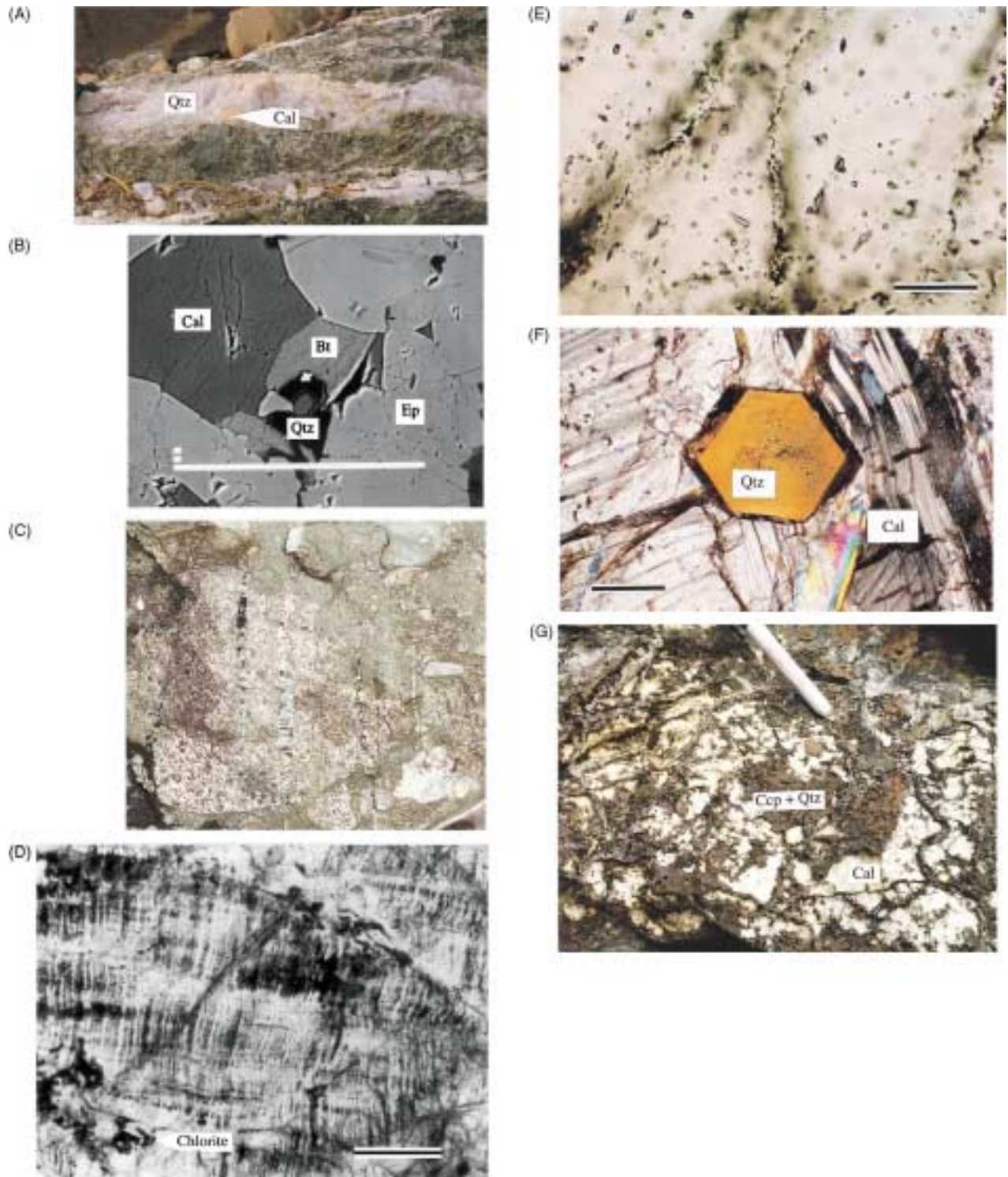


Fig. 2. Photomicrographs of veins and fluid inclusions. (A) Type 1 quartz-calcite vein from the Hornelen basin. The width of the biggest vein is ≈ 3 cm. (B) Backscatter photomicrograph from an epidote vein (type S4) in the Solund basin. The scale bar is 0.1 mm. Amph is amphibole. (C) Fibrous quartz-calcite veins (type S5) from conglomerates in the Solund basin. The width of the biggest vein is ≈ 1 cm. (D) Crack-seal bands in quartz from vein type S5, the Solund basin. The scale bar is 1 mm. (E) Primary fluid inclusions from vein type S5. The scale bar is 100 μm . (F) Quartz and calcite in type S6 veins from the Solund basin. The scale bar is 200 μm . (G) Chalcopyrite and quartz veinlets in calcite, the Solund basin. Abbreviations follow Kretz (1983).

Table 3 Fluid inclusion microthermometry.

Sample	Type	Status	#	<i>n</i>	<i>T_m</i> (°C)	Dev. (±)	<i>T_h</i> (°C)	Dev. (±)	Equiv.wt. % NaCl	Dev. (±)
Hornelen basin										
HOR97-5	H1	p	1	27	− 1.9	0.3	133	25	3.3	0.4
HOR97-7	H1	p	1	22	− 2.4	0.2	128	8	4.0	0.3
HOR97-10	H1	p	1	18	− 2.5	0.3	135	12	4.2	0.4
		s		3	− 1.1	0.1	214	21	1.8	0.1
HOR97-11	H1	p	1	3	− 2.9	0.1	151	6	4.8	0.1
		s		3	− 2.0	0.2	125	4	3.4	0.2
HOR98	H1	p	2	93	− 2.8	0.5	124	11	4.7	0.7
		s		15	− 1.9	0.4	204	17	3.2	0.6
Kvamshesten basin										
KV97-21	K2	p	1	8	− 2.2	0.3	123	9	3.6	0.5
KV97-25	K2	p	1	21	− 2.6	0.3	137	10	4.4	0.4
		s		6	− 4.9	0.4	175	23	7.7	0.6
KV97-29	K2	p	1	25	− 2.1	0.2	112	6	3.5	0.3
KV97-30	K2	p	1	18	− 2.3	0.1	123	7	3.8	0.2
KV97-32	K2	p	1	4	− 2.3	0.2	121	14	3.8	0.3
KV97-34	K2	p	1	46	− 2.1	0.3	135	12	3.6	0.5
KV97-38	K2	p	1	16	− 1.9	0.2	112	8	3.3	0.3
KV97-45	K2	p	1	5	− 2.1	0.3	132	13	3.6	0.5
PT-11	K3	p	1	38	− 1.0	0.2	132	8	1.8	0.3
Solund basin										
LO-4	S5	p	1	35	− 4.8	0.3	143	10	7.6	0.4
		s		10	− 13.9	0.6	146	13	17.7	0.5
LO-6	S5	p	1	33	− 4.6	0.2	139	6	7.3	0.3
		s		27	− 14.0	1.1	157	8	17.8	1.0
SOL98-4D	S5	p	1	9	− 5.4	0.4	142	20	8.4	0.5
SOL98-9A	S5	p	2	11	− 5.2	0.6	135	14	8.2	0.8
		s		6	− 1.8	0.1	125	12	3.1	0.2
SOL98-9B	S5	p	2	11	− 5.4	0.3	101	12	8.5	0.5
		s		6	− 7.1	0.3	93	13	10.6	0.3
NE97-6	S5	p	1	12	− 5.3	0.3	132	10	8.3	0.4
NE97-1	S5	p	1	29	− 8.0	0.6	144	5	11.7	0.7
NE97-2A	S5	p	2	11	− 7.7	1.9	146	5	11.2	2.2
		s		7	− 16.0	0.3	167	8	19.5	0.2
SO-2	S6	p		13	− 9.1	0.4	129	13	13.0	0.4
SO-3	S6	p		19	− 8.2	1.1	149	6	11.9	1.3
KO97-6	S7	p		15	− 9.2	0.4	127	7	13.1	0.5

#, Number of major fluid inclusion populations within a sample; p, primary; s, secondary.

inclusions from the three Devonian basins. The results of microthermometry are listed in Table 3, and shown in Fig. 3. Concentrations of NaCl were calculated using data from Bodnar (1993). Combining microthermometry and crush-leach analyses (Table 4) allows the recalculation of the inclusion fluid composition for the analysed elements (Table 5). To reduce the uncertainties of the calculations, only samples containing one dominant population of fluid inclusions (see Table 3) were used. The criterion for determining whether or not a population of primary fluid inclusions is dominant is qualitatively based on the volume of primary fluid inclusions relative to the volume of other generations of fluid inclusions.

Fluid inclusion ice-melting standard deviations are $< \pm 0.2$ in the Hornelen basin and ± 0.3 in the Kvamshesten basin, but reach ± 1.3 in calcite-dominated veins in the Solund basin. Fluid inclusions from the Hornelen basin often show

metastable behaviour during freezing–heating, i.e. some of the fluid inclusions appear to be single phase at room temperature, but nucleate a vapour phase during freezing followed by rapid heating ($> 10^\circ\text{C min}^{-1}$).

Type H1 veins

Fluid inclusions are common in quartz, as isolated inclusions (primary), as trails within quartz crystals (pseudo-secondary) or as secondary fluid inclusions. The H1 veins have a fluid inclusion petrography that is more complex than that of the other samples. Due to the relatively large size of quartz crystals, the status of some of the fluid inclusions is uncertain, i.e. it was difficult to distinguish between pseudo-secondary and secondary fluid inclusions. The size of the fluid inclusions ranges up to $\approx 40 \mu\text{m}$ in diameter. The fluid inclusion morphology ranges from spherical to irregular, with the irregular fluid inclusions being the largest.

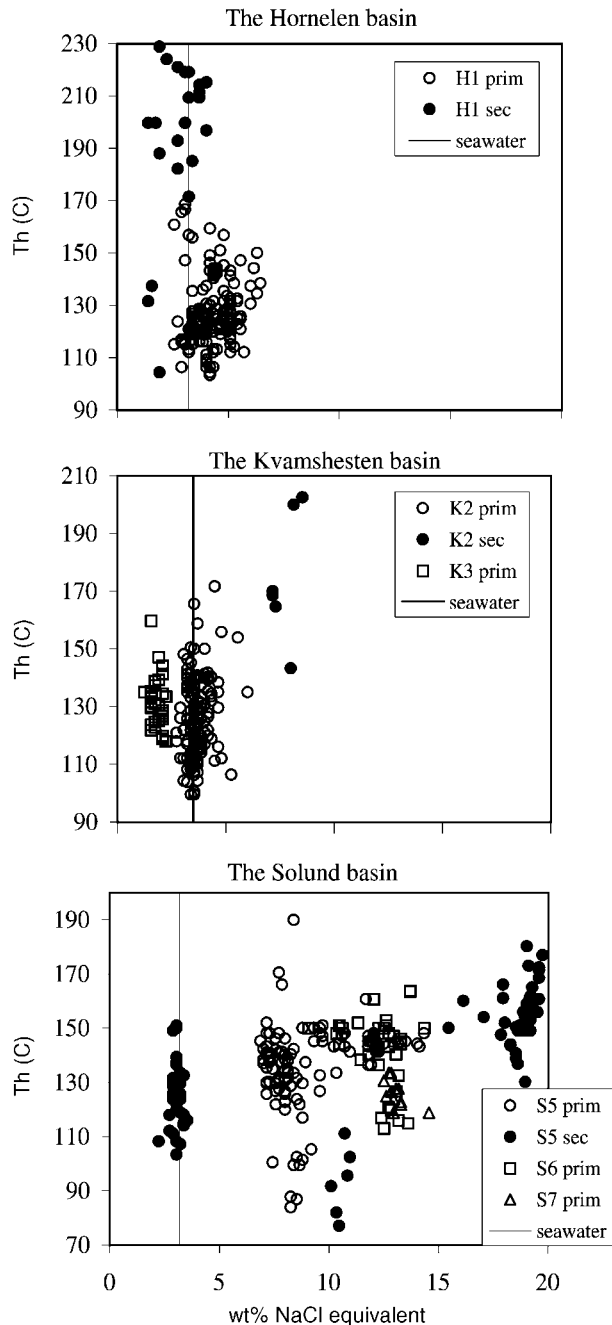


Fig. 3. Fluid inclusion microthermometry data from veins in the three basins.

Ice-melting temperatures for primary brine fluid inclusions vary from -1.9 to -2.6°C (average values), giving salinities between 3.3 and 4.8 wt % NaCl equivalent (Table 3 and Fig. 3). Homogenization temperatures of primary fluid inclusions range from 125 to 150°C . Secondary fluid inclusions in sample HOR97-11 homogenize at 125°C , whereas those in samples HOR97-10 and HOR-98 homogenize between 200 and 215°C .

Type K2 and K3 veins

The veins from the Kvamshesten basin are remarkably homogeneous with respect to populations of fluid inclusions. Fluid inclusions are dominantly primary, making these samples ideal for crush-leach studies. Secondary brine and N_2 fluid inclusions are present in sample KV97-25.

Ice-melting temperatures for primary brine fluid inclusions from veins in the Kvamshesten basin vary from -1.9 to -2.6°C (average values from K2 veins), giving salinities between 3.3 and 4.4 wt % NaCl equivalent (Table 3). Sample PT-11 (vein-type K3) shows significantly lower salinity (1.8 ± 0.3 wt % NaCl equivalent) than the samples from K2 veins. One K2 sample (KV97-25) contains secondary N_2 fluid inclusions and secondary brine inclusions. Heating of the N_2 inclusions from -190°C resulted in homogenization of liquid + vapour N_2 to vapour N_2 at $149.5 \pm 1.3^{\circ}\text{C}$ (40 measurements). The secondary brine fluid inclusions in sample KV97-25 are small (diameter $< 8 \mu\text{m}$) and rare, have salinities of 7.7 ± 0.6 wt % NaCl equivalent, and homogenization temperatures of $175 \pm 23^{\circ}\text{C}$.

Type S5 veins

Fluid inclusions from all vein types in Solund show lower ice-melting temperatures than inclusions from the Kvamshesten and the Hornelen basins. On average, the salinities of inclusion fluids in the fibrous S5 quartz veins are more than 3 wt % higher than those of the fluid inclusions in the H1 and K2 veins. Primary fluid inclusions in the S5 veins (Fig. 2E) have salinities between 7 and 8 wt % NaCl equivalent. One of these solids in the fluid inclusions was identified as epidote by Raman spectroscopy (peaks at 208, 355, 393, 429, 441, 465, 566, 600, 893, 920, 983 and 1086 cm^{-1}), suggesting trapping of epidote crystals during fluid inclusion formation and thus a primary origin of the fluid inclusions. Secondary fluid inclusions are high-salinity brines of 16–19 wt % NaCl equivalent (with eutectic melting close to -41°C , indicating the presence of Ca in the inclusion fluids), or have a salinity equivalent to seawater (sample SOL98-9A). In addition, secondary fluid inclusions in sample SOL98-9B have a salinity of 10.6 wt % NaCl equivalent.

Type S6 veins

Quartz crystals in the calcite matrix contain primary two-phase liquid-vapour fluid inclusions with ice-melting temperatures between -8.2 and -9.1°C , corresponding to 12–13 wt % NaCl equivalent. The average homogenization temperatures in the two analysed samples are 129 ± 13 and $149 \pm 6^{\circ}\text{C}$.

Veins related to chalcopyrite mineralizations (type S7)

Quartz intergrown with chalcopyrite contains primary two-phase liquid-vapour fluid inclusions with ice-melting temperatures of $-9.4 \pm 0.4^{\circ}\text{C}$, corresponding to 13.1 ± 0.5 wt % NaCl equivalent. The homogenization temperature is

Table 4 Crush-leach inclusion fluid element mass ratios.

Sample	Type	Cl/Br	Cl/F	Cl/SO ₄	Cl/I	Na/K	Na/Li
Hornelen basin							
HOR97-1	H1	335	602	5	4586	165	403
Split	H1	332	564	5	3021	147	395
HOR97-5	H1	985	197	10	7624	295	89
HOR97-6	H1	455	158	21	8100	21	205
Split	H1	550	146	20	6397	21	208
HOR97-7	H1	429	1844	7	4966	118	114
HOR97-10	H1	355	133	32	11698	29	472
HOR97-11	H1	271	101	13	11636		828
Split	H1	393	71	12	5414		811
HOR-98	H1	554	123	9	9627	16	109
Split	H1	497	120	9	7423	17	105
Kvamshesten basin							
KV97-25	K2	169	1989	9	6395	23	331
KV97-32	K2	325	304	19	3101	11	139
Split	K2	294	157	20	3804	10	154
KV97-34	K2	286		15	7943	18	195
KV97-38	K2	266	93	33	9542	53	242
Split	K2	254	97	34	7048	42	242
KV97-40	K2	323	481	2	5135	27	331
KV97-45	K2	192		12	6669		3310
PT-7	K3	337	21	5			106
PT-13	K3	316	31	12			94
Solund basin							
SOL98-4A	S5	488	265	54	24565	16	3626
Split	S5	523	240	43	28275	8	4261
SOL98-4D	S5	531	763	29	41114	5	3566
SOL98-9B	S5	525	659	48	29263		3730
SOL98-23B	S5	727	68	71	20811	5	5995
Split	S5	718	69	69	29847		6834
SOL98-23C	S5	851	69	78	22299		4746
SOL98-23D	S5	810	61	110	21734		5007
SOL98-25A	S5	731	48	151	13373		4971
NE97-1	S5	450	302	175	37210	12	1940
Split	S5	431	297	150	34600	12	1875
SO-5	S6	480	492	332	40992		1293
SO-8	S6	543	1910	357	82413		
Split	S6	478	1941	333	80401		535
KO97-6	S7	793	302	1	22184		365
Seawater		292	14615	11	316667	27	61765

127 ± 7°C, and thus these fluid inclusions are close to the S6 vein fluid inclusions in composition and density. The diameters of the fluid inclusions rarely exceed 10 µm.

Summary

In the Kvamshesten basin, the inclusion fluid salinities of most samples resemble the salinity of modern seawater (i.e. 3.2 wt % NaCl equivalent), ranging from ≈ 3–5 wt % NaCl equivalent. Two samples show deviating salinities: one sample from K3 veins has a salinity of ≈ 1.8 wt % NaCl equivalent, whereas the K2 vein KV97-25 contains primary fluid inclusions with ≈ 4.5 wt % NaCl equivalent, and secondary fluid inclusions with ≈ 8 wt % NaCl equivalent. Homogenization temperatures are higher for the secondary fluid inclu-

sions than for the bulk of the primary fluid inclusions from the basin (average of 130°C).

The Hornelen basin inclusion fluids have salinities close to or slightly higher than those of modern seawater (3.3–4.8 wt % NaCl equivalent). Fluid inclusions are dominantly primary. Secondary brine fluid inclusions have salinities similar to those of the primary fluid inclusions. Homogenization temperatures for the primary fluid inclusions range from 125 to 150°C, while those for the secondary fluid inclusions scatter from 125 to 215°C.

Primary fluid inclusions from the Solund basin have salinities higher than those of modern seawater, and fluid inclusions from veins with sulphide mineralizations have salinities from 12 to 13 wt % NaCl equivalent. Secondary fluid

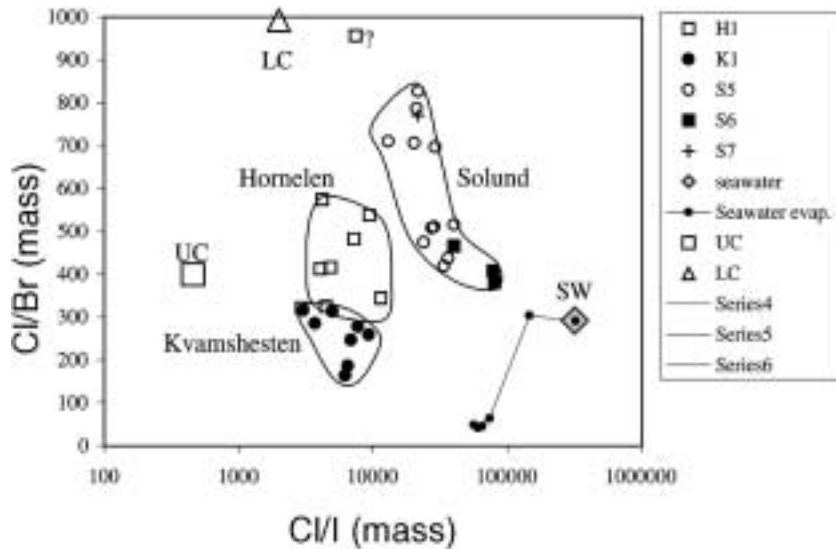


Fig. 4. Crush-leach-derived Cl/Br–Cl/I systematics. The seawater evaporation trend is from Fontes & Matray (1993), McCaffrey *et al.* (1987) and Zherebtsova & Volkova (1966). Upper (UC) and lower (LC) crustal bulk rock values are from Wedepohl (1995).

inclusions are either saline Ca-bearing, reaching 19 wt % NaCl equivalent, or have salinities similar to those of modern seawater. Homogenization temperatures for the primary fluid inclusions range from 140 to 160°C.

Crush-leach analyses

The compositions of the inclusion fluids are presented in Table 4 as mass ratios, with Cl^- and SO_4^{2-} as major anions. As shown in Table 4, some of the splits deviate with respect to element ratios; however, a 10% deviation is within the range of analytical uncertainties. The deviations between the splits from sample HOR97-11 indicate the presence of more than one dominant generation of inclusion fluids, and the sample has not been included in the fluid composition reconstruction.

The Cl/Br mass ratios of the inclusion fluids range from 169 (Kvamshesten) to 550 (Hornelen), and up to 850 (Solund basin). The average Cl/Br mass ratio of H1 is 469. K2 and K3 veins represent a relatively homogeneous population with the lowest measured Cl/Br ratios ranging from 169 to 337 (scattering around seawater Cl/Br at 292). Two K3 samples have values of 315 and 337. The Cl/Br–Cl/I compositions of the inclusion fluids from the three basins have distinct signatures (Fig. 4). The Solund veins have the highest Cl/I ratios, and the S6 veins are the most I-depleted and Br-enriched (relative to Cl). The Hornelen and Kvamshesten vein fluids have similar Cl/I ratios. Figure 5 shows the Cl–Br–Na systematics of the inclusion fluids. The K1 and K2 vein fluids plot close to seawater, whereas the H1 and Solund veins plot above, but parallel to, the trend derived when adding NaCl to seawater. The relatively low Solund and Hornelen Na/Br ratios could be explained by the removal of Na from the fluid by Na–Ca exchange reactions.

All analyses show enrichment of I relative to Cl compared to modern seawater. Inclusion fluids from the Kvamshesten basin have Cl/SO₄ ratios ranging from 2 to 34, whereas the inclusion fluids from the Solund basin all have Cl/SO₄ ratios much higher than that of seawater (11), and higher than the inclusion fluids from the Hornelen and Kvamshesten basins. All inclusion fluids have Na/Li ratios above those of seawater, with vein types S5 and S6 having ratios higher than 1000, and all the other vein types with ratios lower than 800.

Reconstructed inclusion fluid compositions

Inclusion fluid compositions have been reconstructed using the concentrations of Na derived from microthermometry and element mass ratios. The resulting anion and alkali concentrations are presented in Table 5, whereas the concentrations of Pb, Zn, Mg, Mn, Cu and Ba from H1 and K2 veins are presented in Table 6. Analyses with large deviations between repetitive leaches are not included here; neither are analyses of samples containing more than one dominant fluid inclusion population. For samples analysed for both cations and anions, there is a deficiency in negative charges, probably due to the presence of HCO_3^- , which was not analysed quantitatively. The other analyses show deficiencies in positive charges, which can be explained by the exclusion of Ca in the analyses. The uncertainties of the reconstructed fluid compositions are reduced by using the concentration of Na, as Cl concentrations are probably underestimated by microthermometry due to the presence of KCl, MgCl_2 , FeCl_2 and CaCl_2 .

Concentrations of Na, K, Li, Cl, I and F are all higher than those of modern seawater, except for a few samples in the Solund and Kvamshesten basins. Reconstructed concentra-

Table 5 Reconstructed inclusion fluid composition (all values are given in p.p.m.).

Sample	Type	NaCl*	Na*	K	Li	Cl*	Br	I	F	SO ₄	+/- [‡]
Hornelen basin											
HOR97-5	H1	3.3	13002	50	114	19998	26	3.4	133	2550	0.75
HOR97-7	H1	4.0	15760	125	65	24240	77	6.6	18	4984	0.69
HOR-98	H1	4.7	18518	1134	170	28482	62	3.8	279	3897	0.83
Split			18518	1116	177	28482	71	4.8	295	4120	0.81
HOR97-10	H1	4.2	16548	570	35	25452	80	2.4	214	898	0.92
Kvamshesten basin											
KV97-25	K2	4.4	17336	741	173	26664	186	4.9	16	3530	0.86
KV87-32		3.8	14972	1444	110	23028	65	8.1	69	1117	1.17
Split			14972	1532	96	23028	64	5.2	120	928	1.30
KV97-34	K2	3.6	14184	743	100	21816	88	3.2		1669	0.90
KV97-45	K2	3.6	14184		18	21816	111	3.2		1844	1.00
KV97-38	K2	3.3	13002	248	54	19998	66	2.0	190	530	1.15
Split			13002	310	53	19998	69	2.6	182	520	1.16
PT-11 [†]	K2	1.9	7092		65	10908	21		343	1359	1.00
Solund basin											
SOL98-4A	S5	8.4	33096	2028	9	50904	112	2.4	207	1017	0.97
Split			33096	3999	8	50904	101	2.0	221	1229	1.04
SOL98-4D	S5	8.4	33096	6160	6	50904	102	2.6	71	1869	1.04
SOL98-9B	S5	8.2	32308		9	49692	108	1.1	87	1197	0.88
SOL98-23B	S5	7.6	29944	11541	5	46056	91	3.1	973	936	0.85
Split			29944	9325	4	46056	91	2.2	950	937	0.83
SOL98-23C	S5	7.6	29944	12167	6	46056	68	2.5	838	731	0.99
SOL98-23D	S5	7.6	29944	13412	6	46056	70	2.7	923	511	1.02
SOL98-25A	S5	7.6	29944	15047	6	46056	69	3.8	1046	331	1.18
NE97-1	S5	11.7	46098	3957	24	70902	258	3.0	386	663	0.66
Split			46098	3732	25	70902	290	3.5	421	831	0.61
SO-5	S6	13	51220	7978	40	78780	274	3.0	268	396	0.67
SO-8	S6		51220		96	78780	140		35	201	–
KO97-6	S7	13.1	51614	14958	143	79386	153	5.8	403	149031	0.41
Seawater		3.2	10500	380	0.17	19000	65	0.06	1.3	1766	

*Average wt % NaCl from microthermometry. [†]Based on the crush-leach of sample PT-13. [‡]+/-, Charge balance.

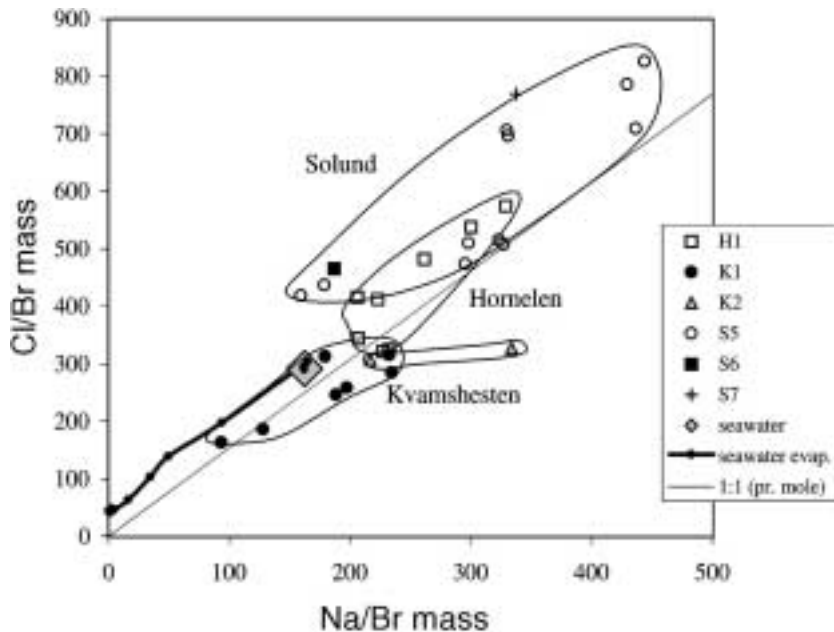

Fig. 5. Cl-Br-Na systematics of the inclusion fluids. Seawater evaporation trend is from Fontes & Matray (1993).

Table 6 Reconstructed cation and anion composition.

Type	KV97-34	KV97-45	HOR77-5	HOR97-7
	K2	K2	H1	H1
Cl	25248	21240	22945	28951
Br	91	114	24	70
I	3	3	3	6
F			120	16
SO ₄	1719	1891	2314	4523
Na	14184	14184	13002	15760
K	765		52	124
Li	90	20	113	65
As (\pm SD)	899 \pm 210	2522 \pm 751		152 \pm 160
Zn (\pm SD)	43 \pm 17	178 \pm 13	25 \pm 7	50 \pm 12
Pb (\pm SD)	709 \pm 491	2022 \pm 360	364 \pm 113	262 \pm 114
Mn (\pm SD)	29 \pm 6	49 \pm 15	13 \pm 4	434 \pm 6
Mg (\pm SD)	115 \pm 2	155 \pm 13	48 \pm 1	495 \pm 6
Ca (\pm SD)	5889 \pm 11	10903 \pm 91	3288 \pm 72	76484 \pm 638
Ba (\pm SD)	438 \pm 25	1204 \pm 49	427 \pm 9	30833 \pm 412
pos/neg	1.2	1.9	1.0	5.7

tions of Br range from 30 to 170 p.p.m. As seen from the Cl–Br relations in Fig. 6, the H1 and K2 inclusion fluids plot close to modern seawater, whereas the K3 inclusion fluids plot along the seawater dilution trend. The samples from the Solund basin are more saline, but are Br-depleted compared to the seawater evaporation trend. Cl-rich, Br-depleted fluids can be produced from a low-salinity fluid affected by halite dissolution. The concentrations of I and Br show a positive correlation ($R^2 = 0.94$) for the Hornelen (H1) samples. The concentrations of I show only small variations, and range from 1 to 7 p.p.m. The Hornelen samples also show a positive correlation between I and SO₄ ($R^2 = 0.91$). Sodium

is the most abundant cation in the Hornelen and Kvamshesten fluids, followed by Ca and Ba. Some of the analyses may, however, be contaminated, such as sample HOR97-7 which contains > 90 000 p.p.m. Ca and > 37 000 p.p.m. Ba. The concentrations of metals such as Pb (320–612 p.p.m.) and Zn (37–61 p.p.m.) in the K2 and H1 veins are comparable with those of inclusion fluids from basinal and low-grade metamorphic settings (cf. Banks *et al.* 1991; Kharaka *et al.* 1987; Meere & Banks 1997; Yardley *et al.* 1993), whereas one of the analyses shows elevated Pb, Zn and As concentrations (KV97-45). The concentration of Li ranges from 20 to 100 p.p.m., i.e. on the same order of magnitude as Br.

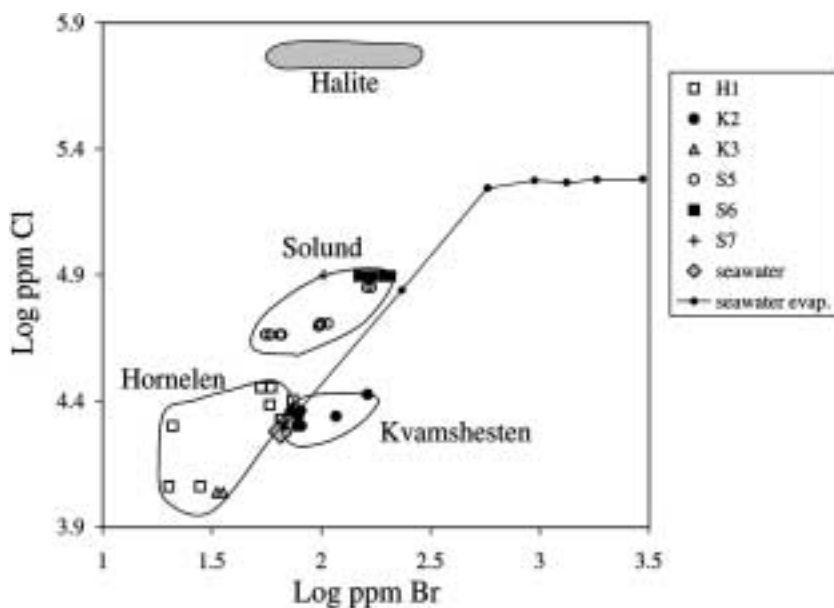
**Fig. 6.** Reconstructed inclusion fluid Cl–Br compositions. Halite data are taken from McCaffrey *et al.* (1987).

Table 7 SEM-EDA analyses (as average wt % elements).

Sample	Type	#	Na	K	Ca	Cl	S
Hornelen basin							
HOR-98 (\pm SD)	H1	44	37.5 \pm 1.2	1.9 \pm 0.4	1.9 \pm 1.3	56.6 \pm 1.1	0.2 \pm 0.3
HOR97-7 (\pm SD)	H1	19	36.1 \pm 2.6	1.8 \pm 0.9	2.9 \pm 3.8	58.9 \pm 1.6	0.3 \pm 0.4
Kvamshesten basin							
KV97-30 (\pm SD)	K2	20	38.4 \pm 2.1	3.7 \pm 1.4	0.7 \pm 2.5	57.1 \pm 1.3	0.3 \pm 0.1
KV97-38 (\pm SD)	K2	9	41.9 \pm 1.8	0.9 \pm 0.6	0.1 \pm 0.1	56.5 \pm 2.2	0.6 \pm 0.7
KV97-25 (\pm SD)	K2	20	41.6 \pm 4.8	2.6 \pm 1.2	0.5 \pm 1.9	54.7 \pm 4.7	0.7 \pm 0.4
KV97-29 (\pm SD)	K2	18	38.6 \pm 2.9	3.2 \pm 1.8	0.9 \pm 3.3	57.1 \pm 1.7	0.3 \pm 0.1
KV97-34 (\pm SD)	K2	43	39.8 \pm 6.3	3.8 \pm 2.8	2.7 \pm 5.4	53.1 \pm 3.2	0.5 \pm 0.3
PT-11 (\pm SD)	K3	11	38.3 \pm 3.4	3.8 \pm 1.8	1.3 \pm 2.9	55.9 \pm 2.5	0.8 \pm 0.9
Solund basin							
LO-6 (\pm SD)	S5	84	34.8 \pm 2.8	2.7 \pm 1.7	6.3 \pm 4.7	56.2 \pm 3.3	0.0 \pm 0.0
SO-2 (\pm SD)	S6	14	36.2 \pm 2.5	4.0 \pm 2.7	3.9 \pm 2.3	56.0 \pm 2.9	0.0 \pm 0.0

#, Number of analyses.

Analyses of decrepitates

Considering the semiquantitative nature of SEM-EDA decrepitate analyses, the results are primarily used to characterize the chemical system in the inclusion fluids, and to compare inclusion fluid compositions between vein types. The SEM-EDA analyses show, in agreement with the bulk analyses, that the major components in the inclusion fluids are Na, Cl, K and S (Table 7). The major elements found in decrepitates are: (i)

Na + K + C \pm Ca \pm S in the H1 and K2–3 veins; and (ii) Na + Ca + K + Cl in the S5 and S6 veins. The concentration of S is highest in the Kvamshesten samples (reaching an average of 0.9 wt %), whereas the Ca concentrations are highest in the Solund samples (up to 6.3 wt %). Figure 7 shows the systematics in the Ca–Na–K space. The SEM-EDA Na/Ca mass ratios are generally higher for the Kvamshesten basin samples than for the Hornelen and Solund samples, consistent with a correlation between Ca concentration and total fluid salinity. There is a

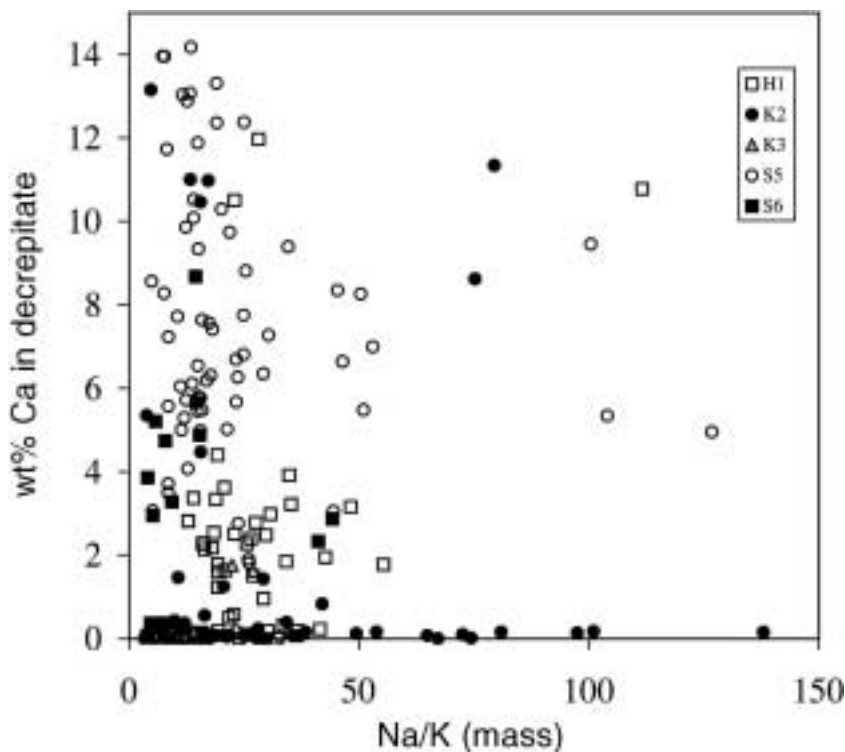

Fig. 7. SEM-EDA decrepitate Na–K–Ca relations.

Table 8 Light hydrocarbon gases in inclusion fluids.

Sample	Type	C ₁	C ₂	C ₃	i-C ₄	n-C ₄	i-C ₅	n-C ₅	C ₁ /C ₂ +	C ₂ /C ₃	C ₄ i/n
Hornelen basin											
HOR97-1	H1	90.0	10.0	0	0	0	0	0	9.0		
HOR97-3	H1	93.9	4.1	1.0	0	1.0	0	0	15.3	4.0	0
HOR97-4	H1	90.0	10.0	0	0	0	0	0	9.0		
HOR97-5	H1	80.3	14.6	3.6	0	1.5	0	0	4.1	4.0	0
HOR97-6	H1	79.5	14.1	3.8	0	2.6	0	0	3.9	3.7	0
HOR97-7	H1	89.8	5.5	3.1	0	1.6	0	0	8.8	1.8	0
HOR97-10	H1	85.1	6.4	4.3	0	4.3	0	0	5.7	1.5	0
HOR97-11	H1	78.1	21.9	0	0	0	0	0	3.6		
HOR97-12	H1	97.0	1.8	0.6	0	0.6	0	0	32.0	3.0	0
HOR97-16	H1	78.1	21.9	0	0	0	0	0	3.6		
HOR97-17	H1	83.3	16.7	0	0	0	0	0	5.0		
Kvamshesten basin											
KV97-5	K2	91.3	8.7	0	0	0	0	0	10.5		
KV97-25	K2	73.2	24.4	2.4	0	0	0	0	2.7	10.0	
KV97-36	K2	64.7	29.4	0	5.9	0	0	0	1.8		
KV97-40	K2	77.8	20.0	0	0	2.2	0	0	3.5		0
KV97-42	K2	91.9	4.9	1.6	0	1.6	0	0	11.3	3.0	0
PT-7	K3	66.7	15.0	5.0	0	8.3	0	5.0	2.0	3.0	0
Solund basin											
LI8	S5	68.3	21.7	0	3.3	3.3	1.7	1.7	2.2		1.0
NE97-2	S5	81.1	18.9	0	0	0	0	0	4.3		
Reference data*											
Modum veins		84.3	9.6	3.0	1.0	1.2	0.4	0.5	5.4	3.2	0.8
Ula field		72.7	12.9	8.9	1.4	3.2	0.5	0.4	2.7	1.4	0.4

*Karlsen *et al.* (1993).C₁, CH₄; C₂, C₂H₆; C₃, C₃H₈; C₄, C₄H₁₀; C₅, C₅H₁₂.

good agreement between Na/K ratios obtained by crush-leach analyses and SEM-EDA.

Gas chromatography

The results of gas chromatography show that methane and traces of ethane to pentane are present in the H1, K2 and K3 veins (Table 8, and Fig. 8 for an H1 vein). The gases are likely to be present in the vapour phase in the fluid inclusions, even though they have not been detected by Raman spectroscopy or by optical microscopy fluorescence. Thus they represent components probably present in the original vein fluids. CH₄ is the most abundant gas species present, comprising 65–97 mol % of the total hydrocarbons. The concentration of C₂ reaches 29 mol % of the total hydrocarbon content in the K2 veins, and all vein types contain traces of C₃₊. No attempts were made to detect CO₂, H₂S or N₂ in the fluid inclusions by gas chromatography.

DISCUSSION

Vein fluids and metamorphism

There is no direct way to link the composition of the studied vein-hosted inclusion fluids to the composition of the fluid

that occupied the rock pore space at the time of vein formation, since fluid inclusions are not found in authigenic minerals in the basins. Thus a combination of wall-rock petrography, vein petrography and field observations has been carried out to determine the timing of vein formation. The following observations give important clues regarding the vein fluid origin: K2–3 and S5 veins are present within individual sedimentary layers, and on relatively small scales compared to the individual sedimentary sequence and the size of the pebbles in the conglomerates; no wall-rock alteration is observed around H1, K2–3 or S5–6 veins; in contrast, S4 veins show extensive wall-rock alteration, indicating that the vein fluids were, if not externally derived, at least out of equilibrium with the surrounding rock matrix.

Isochores for the fluid inclusions in the H1, K2 and S5 veins have been calculated (using relations from Zhang & Frantz 1987) in order to constrain the depth of burial (Fig. 9), as there are no reliable barometers applicable to low-grade metamorphic settings. Samples from the Solund basin are particularly interesting as: (i) the Solund basin is believed to contain the sediments that experienced the deepest burial of the studied basins (Seranne & Seguret 1987); (ii) based on petrographic evidence, the veins were probably formed during maximum temperature conditions;

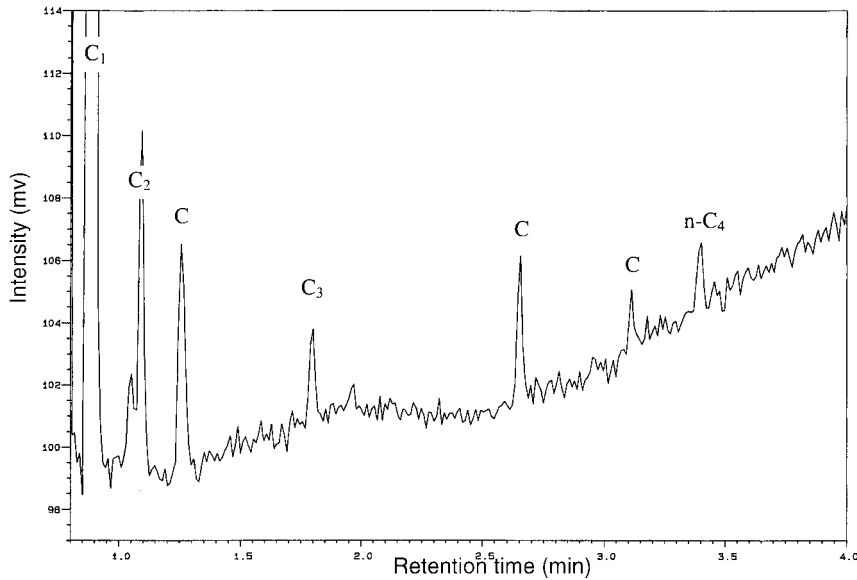


Fig. 8. Gas chromatogram from H1 vein HOR97-6. C: contaminant.

and (iii) the temperature of metamorphism is reasonably well constrained by the mineralogy of the S4 and S5 veins. Temperatures exceeding $\approx 300^\circ\text{C}$ are required to form biotite in hydrothermal systems (Cho *et al.* 1988; Schiffman *et al.* 1985); however, mineral isograd temperatures are strongly dependent on fluid composition. CO_2 was not detected by Raman spectroscopy in two selected samples, and chlorite thermometry gave temperatures in the range $305\text{--}330^\circ\text{C}$ (H. Svensen *et al.*, in preparation). Biotite and amphibole are not observed in the Kvamshesten basin, but the presence of epidote may indicate minimum temperatures of $\approx 230^\circ\text{C}$ (e.g. Cho *et al.* 1988; Schiffman *et al.* 1984; Sveinbjörnsdóttir 1992), whereas a lack of amphibole suggests $T < 270^\circ\text{C}$. Thus a temperature estimate of $250 \pm 20^\circ\text{C}$ for the Hornelen and Kvamshesten basins seems reasonable. Combining the temperature estimate (250°C for the H1 and K2 veins and

$315 \pm 15^\circ\text{C}$ for the S5 veins) with fluid inclusion isochores from these veins, pressures of 2.4 ± 0.4 kbar (1 bar = 105 Pa) and 3.4 ± 0.2 kbar, respectively, are obtained (Fig. 9). This corresponds to a depth of burial of 9.1 ± 1.6 km for the H1 and K2 veins, and 13.4 ± 0.6 km for the S5 veins, using a linear pressure gradient and a mean rock density of 2.6 g cm^{-3} .

Fluid composition and sources

Halogen geochemistry has often been used to provide clues about the source of fluids in sedimentary basins (e.g. Rittenhouse 1967; Worden 1996), based on the nonconservative nature of Cl and Br during evaporite formation or dissolution. In contrast, the conservative nature of Cl and Br in most other geological systems suggests that the halogens may be used to trace fluid sources in metamorphic systems as well. The Cl/I ratio is an indicator of fluid-rock interactions, and decreases in the fluid during decomposition and interaction with organic-rich material and with increasing temperature (e.g. Muramatsu & Wedepohl 1998; Worden 1996).

Effects of interaction with host rocks

The Kvamshesten and Hornelen basins contain mudstones (fossil-bearing) and, as iodine is enriched in muds, shales, iron oxides and organic-rich sediments (Fuge & Johnson 1986), the low Cl/I ratios from veins in these basins (Fig. 4) can be explained as a result of interaction between pore fluids and the rock matrix. Mudstones are not present in the Solund basin, and the inclusion fluids have higher Cl/I ratios than those of the other basins, but still lower than those of seawater. Interaction with organic material is also a likely source of N-rich fluids (present in a K2 vein).

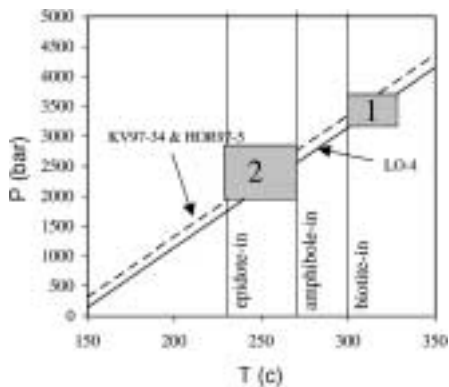


Fig. 9. P - T diagram showing isochores of fluid inclusions from K2 and S5 veins. The isochores are based on average fluid inclusion data. 1, Solund basin; 2, Kvamshesten and Hornelen basins.

The bulk of the light hydrocarbon gases are probably derived from finely disseminated organic matter during relatively high temperatures, at least above the gas window. A high temperature is supported by the absence of isobutane in all samples, except one K2 vein.

As large areas in the Solund basin contain metavolcanics (Grünhagen & Jamtveit, 2000), hydration may have resulted in increased pore fluid salinities. However, this process cannot explain the high Cl/Br ratios for many of the Solund samples, as hydration will eventually result in lowered Cl/Br ratios in the residual fluid.

The proposed temperature and pressure conditions during maximum burial of the basins make it likely that the pore fluids interacted strongly both with detrital grains and pebbles. Clasts are dominantly metamorphic and magmatic rocks, quartzite, gabbro, diorite and gneisses (Cuthbert 1991), but the formation of minerals like epidote and mica in plagioclase clasts could have occurred during retrogression *in situ* (i.e. in the sediment source rocks). There is some evidence for clast–pore fluid interactions, as clasts show alteration zones along the margins (in agreement with observations by Seranne & Seguret 1987). The concentrations of halogens in high-grade rocks is low (average lower crustal concentrations in p.p.m.: Cl, 278; Br, 0.28; I, 0.14; Wedepohl 1995), but interactions with Cl-bearing minerals could lead to higher Cl/Br ratios in pore fluids. This effect would be most pronounced in rocks with a small grain size (sandstones) rich in detrital mica and apatite. Some of the sandstone-hosted S5 veins show significantly higher Cl/Br ratios (Fig. 4) than the conglomerate-hosted veins. The enrichment of Br relative to Na in the S5–S7 vein fluids (Fig. 5) is best explained by Na–Ca exchange reactions between minerals (notably feldspars) and fluid.

The composition of the inclusion fluids from the chalcopyrite-bearing S7 veins (only one sample analysed) does not differ from that of the S5 and S6 inclusion fluids. Even though the geological setting points towards an external source for the mineralizing fluids, as the veins are present in a several hundred metres long shear zone (200–300 m) close to the detachment zone, leaching of Cu by saline fluids from volcanic material in the basin is still possible.

Salinity increase by interaction with evaporites

The Cl–Br–Na concentration of inclusion fluids has been widely used to constrain the source of salinity (i.e. Kesler *et al.* 1995, 1996; Walter *et al.* 1990). The vein fluids in all basins have compositional characteristics comparable to those of either modern seawater or basinal brines with solutes derived (at least partly) from dissolution of halite/evaporites.

As hydration reactions cannot explain the high Cl/Br ratios in the Solund basin, a high Cl/Br source has to be invoked. Halogen systematics show that the S5–7 vein fluids can be explained by adding NaCl to seawater-like composi-

tions, followed by removal of Na by mineral–fluid reactions (i.e. Na–Ca exchange). There is, however, no significant difference in the Cl concentration between the fluids with high and low Cl/Br ratios. Since evaporites are absent in the basin today, and metavolcanic material is present, it could be argued that the vein fluids have a saline hydrothermal component with a high Cl/Br ratio.

The vein fluids in the Kvamshesten and Hornelen basins have a lower salinity, and the K2 vein fluid compositions are comparable to those of modern seawater. The low-salinity inclusion fluids from K3 veins in the Kvamshesten basin, which plot along the seawater dilution trend in Fig. 6, could have been diluted by low-salinity (i.e. meteoric) fluids from other parts of the basin.

If the inclusion fluids have their salinity derived from the dissolution of evaporites, it would explain the elevated salinities, the Cl/Br–Na/Br systematics, and the Cl–Br systematics. Evaporites are not found in the stratigraphic record, but there are features which may be linked to evaporites. Non-marine evaporites are dominated by halite, gypsum and calcite (Hardie 1984). Halite and gypsum have not been found, but there are calcite-cemented layers and nodules in sandstones in both the Hornelen (Bryhni 1978) and Kvamshesten basins, siltstones in the Kvamshesten basin have calcite concretions, and siltstones in the Hornelen and Kvamshesten basins have mud cracks (Bryhni 1978; Skjerlie 1969). The siltstones were deposited in shallow lacustrine environments controlled by fluvial systems, floodplains and evaporation (Bryhni 1978; Osmundsen *et al.* 1998; Skjerlie 1969). The position of the basins in the Devonian was 20–25° south of the equator (Torsvik *et al.* 1986), supporting a theory of evaporite formation. Even though the basins were deposited in a continental setting, they were at some stage buried below seawater level as the maximum depth of burial is assumed to be around 13 km. This could have introduced seawater into the sediments, and the Kvamshesten vein fluids have salinities and Cl–Br compositions that resemble those of seawater. However, the data presented in this study do not conclusively discriminate between marine and non-marine fluids.

CONCLUSIONS

- (1) The salinity of the inclusion fluids ranges from 1.8 to 19.7 wt % NaCl equivalent, where fluids from the Hornelen and Kvamshesten basins have salinities close to those of modern seawater (3.2 wt % NaCl) and the veins in the Solund basin have salinities between 7 and 19.5 wt % NaCl. This is surprising as the available geological information about the basins clearly suggests that the sediments were deposited in fluvial and alluvial continental settings.
- (2) A combination of fluid inclusion densities and temperature estimates based on mineral assemblages indicates

that at least the Solund basin was buried to ≈ 13 km during vein formation.

- (3) Inclusion fluid halogen systematics suggest that vein fluid salinities were partly derived from the dissolution of evaporites.
- (4) The vein fluids had rock-buffered iodine concentrations and the Solund vein fluids were affected by Na–Ca exchange reactions. Cl/Br relations do not indicate that the vein fluids from the Solund basin were significantly affected by hydration of the metavolcanic material in the basin.
- (5) Our data suggest that local sediment composition had the greatest influence on pore fluid composition during burial through the diagenetic regime. The Cl/Br ratio was determined by interactions with evaporitic sequences, whereas the Cl/I and alkali to halogen ratios were modified during increasing temperatures and burial towards the metamorphic regime.

ACKNOWLEDGEMENTS

This work is part of H. Svensen's PhD Thesis, funded by the Norwegian Research Council, grant 70994/410 to B. Jamtveit. Analytical work at the School of Earth Sciences, Leeds, was supported by grant NERC GR3/11087. We would like to thank T. B. Andersen, P. T. Osmundsen, B. W. D. Yardley, H. Austrheim, M. Lynn, T. Winje, B. Løfken Berg, A. Bhullar, T. Andersen, C. Calvert-Smith, C. Brøman and two anonymous reviewers for contributions to this paper.

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