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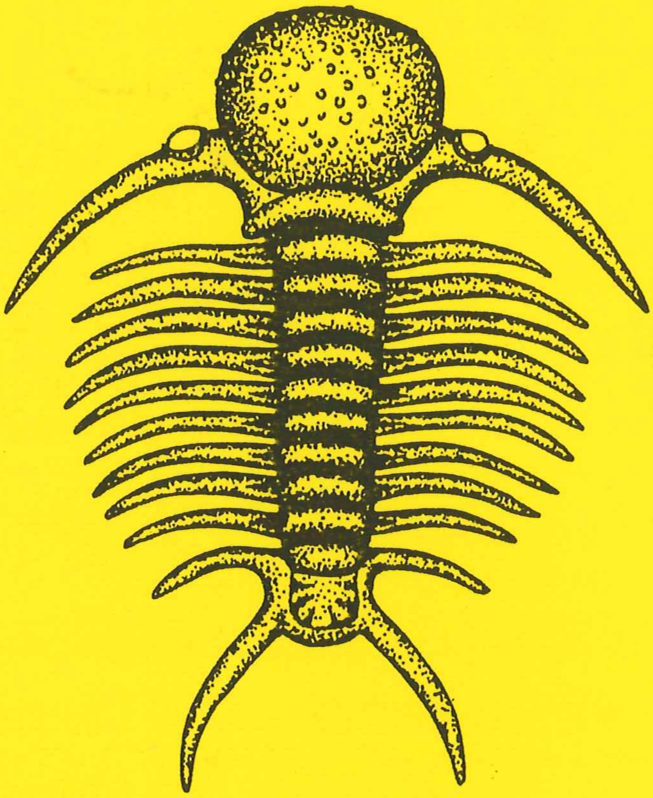

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Lund 2001 Examensarbete, 20 p Nr 138
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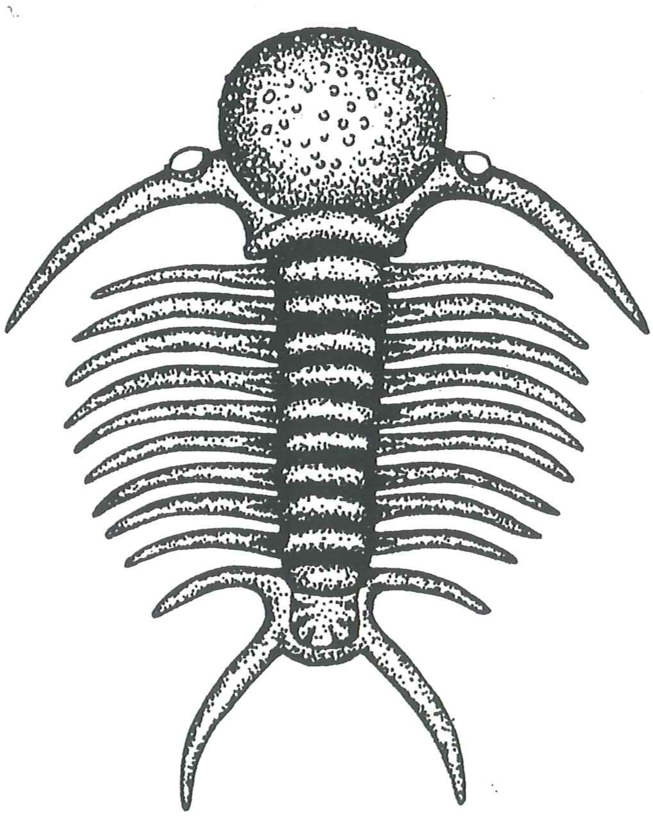

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CHRISTINE KARLSSON

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The Lower Cambrian strata of the Caledonian foreland of southern Sweden consist mainly of quartzitic sandstones with thicknesses of approximately 35 meters in Västergötland and 120 metres in Skåne. In the distal, moderately buried western members of the File Haidar Formation of Västergötland porosity and permeability was higher than in the proximal deeply buried units of the Hardeberga Formation of Skåne. In the sandstones from Västergötland the quartz cement contents were lower than in the sandstones from Skåne. Although the sedimentary successions in the proximal Caledonian foreland were moderately to deeply buried (< 5 km) no signs of pressure solution and subsequent silica redistribution were observed. The grain-minus-cement porosities suggest that quartz cementation occured during deep burial presumably due to the Caledonian foreland basin infill and subsidence. The Lingulid sandstone can be divided into two groups; one with measurable permeability and one without measurable permeability, probably due to hydrothermal influence. The gas expansion porosimeter and the digital gas permeameter prooved best for porosity and permeability measurements. The CL microscopy method was used for quartz overgrowths identification and quantification, whereas the BSE microscopy was the best method for detection of feldspars. PPL microscopy was prefered for detrital mineral identification.

Keywords: Diagenesis, petrography, sandstone, burial, Lower Cambrian, Caledonian foreland, Västergötland, Skåne, Sweden

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The main goal of this thesis is to document the burial diagenesis and the petrophysical properties of the moderately deeply buried Lower Cambrian sandstones of Västergötland, compared with the deeply buried contemporaneous sandstones of Skåne in the more proximal parts of the Caledonian foreland (Fig. 1).

According to Samuelsson (1999) the maximum palaeotemperature experienced by the Alum Shale in Västergötland is 100°C. For example in Jämtland the corresponding maximum temperature is 165°C. These data have been used to quantify burial depths of the Caledonian foreland basin (Samuelsson 1997). The study implied that a mountain range with about 7 km high peaks must have existed to accommodate a foreland basin fill fitting the palaeotemperature constraints. The maximal burial depth of the Alum Shale Formation and the Cambrian sandstones in Västergötland was estimated to about 2 km.

The burial history of Skåne is very complex. The Caledonian burial event and the post-Hercynic subsidence from Permian times until recent times are the two major events of the burial history of Skåne (Buchardt et al. 1997). The Alum Shale Formation of Skåne is well documented in various works and has an established vitrinite reflectance between 1.40% and 2.70% (Buchardt et al. 1997).

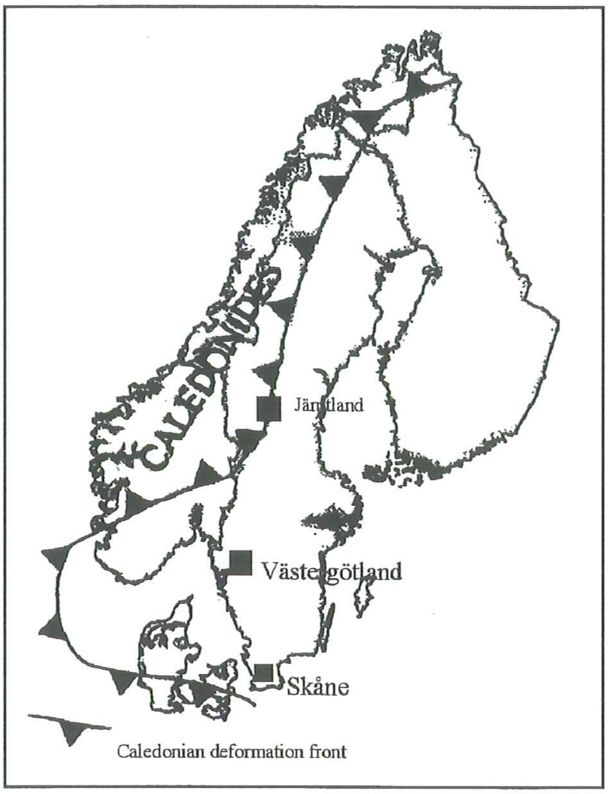


Fig. 1. Caledonian deformation front. From Samuelsson, 1999.

The Cambrian sediments of Västergötland were deposited during a transgression (Fig. 2). The transgression led to the deposition of basal conglomerates upon the Precambrian basement. A succession of quartzitic sandstones and mica-rich siltstones with thin mud parties, the Mickwitzia sandstone, overlie the conglomerate (Lindstöm 1991). A succession of fine-grained quartzitic sandstone follows, i.e. the Lingulid sandstone. The sandstones were buried in the foreland basin during the Caledonian orogeny, presumably sometime during Llandovery to Wenlock (Lindström et al. 1991). The Mickwitzia sandstone and the Lingulid sandstone form the western members of the File Haidar Formation (Fig. 3). These members have a total thickness of about 15 – 35 m (Jensen 1997). The 10 m thick Mickwitzia sandstone was probably deposited in a shallow marine setting, as opposed to the 25 m thick Lingulid sandstone which was deposited in a slightly deeper marine setting (Jensen 1997). A thick Permo-Carboniferous dolerite cap has preserved these sedimentary rocks, which are forming the plateau hills Kinnekulle, Lugnås, Billingen, and Halle- and Hunneberg of Västergötland (Jensen & Ahlberg *in* Ahlsens, 1998) (Fig. 2).

The transgression mentioned above was a result of an increase in plate tectonic activity. This transgression also influenced the deposition in Skåne (Bergström & Gee 1985) (Fig. 4). The Lower Cambrian sediments of Skåne are divided into four formations and reach a thickness of about 120 m (Lindström & Staude 1971). The Cambrian lithostratigraphy of Skåne was recently investigated by Kleman (2000), who argues that the formation names (Hardeberga Sandstone Formation, Norretorp Sandstone Formation and Rispebjerg Sandstone Formation) are misguiding since lithologies within the formations well could be other than sandstones. Kleman (2000) suggested a future formal lithostratigraphic classification including: the Hardeberga Formation, the Norretorp Formation, the Rispebjerg Formation and the Gislöv Formation. The Hardeberga Formation is suggested to be subdivided into the informal Lunkaberg unit, Vik unit, Brantevik unit and Tobisvik unit (Fig. 3). Since these units have not yet been formally established they should not be called members (Kleman 2000).

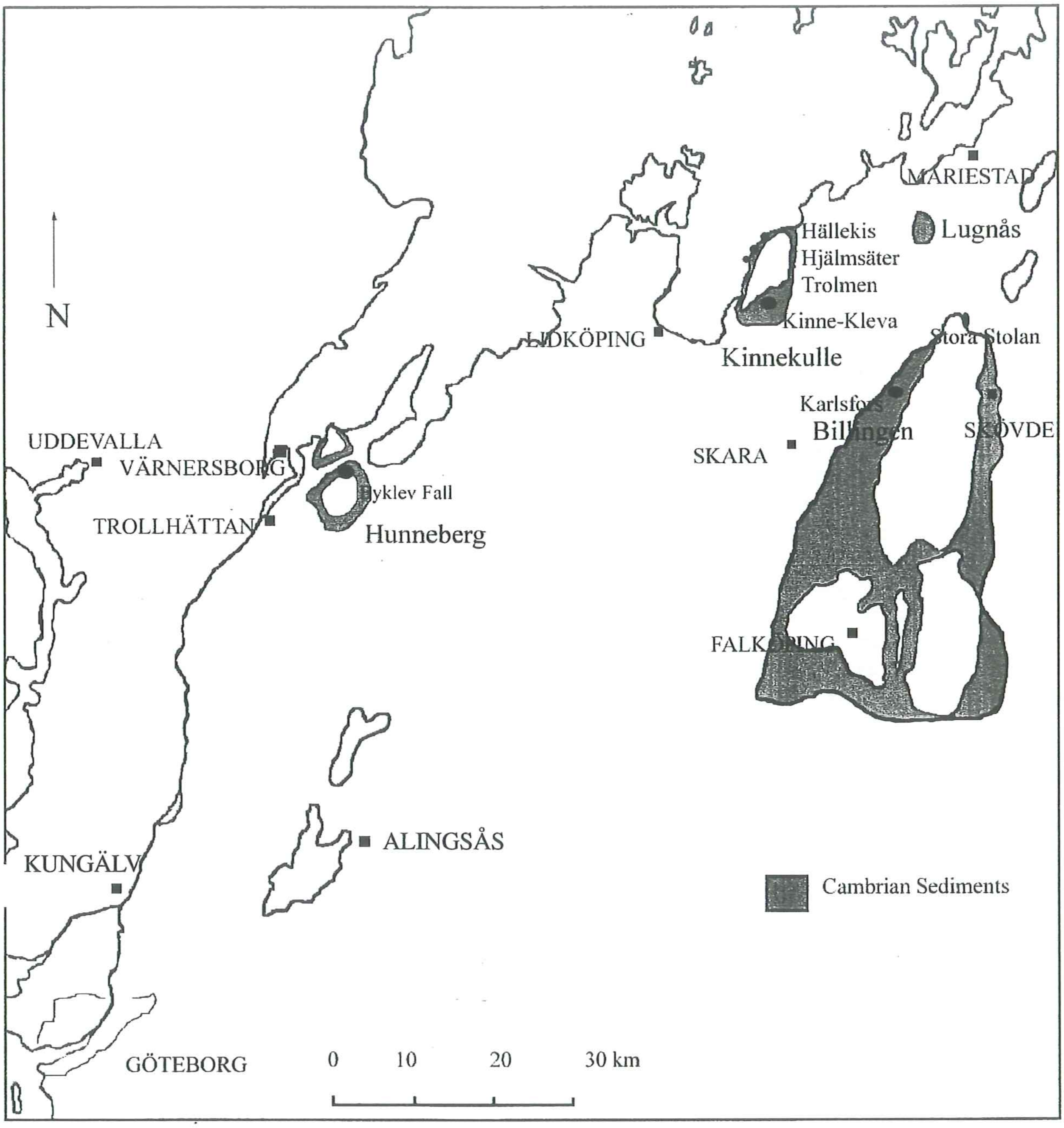


Fig. 2. Map of Västergötland with localities. From Martinsson (1974).

Materials and methods

Localities

The material was collected at eight localities in Västergötland (Fig. 2). At present time the localities are mostly small outcrops with varying accessibility (Table 1). In Skåne the material was collected at five localities (Fig. 4; Table 2).

Material

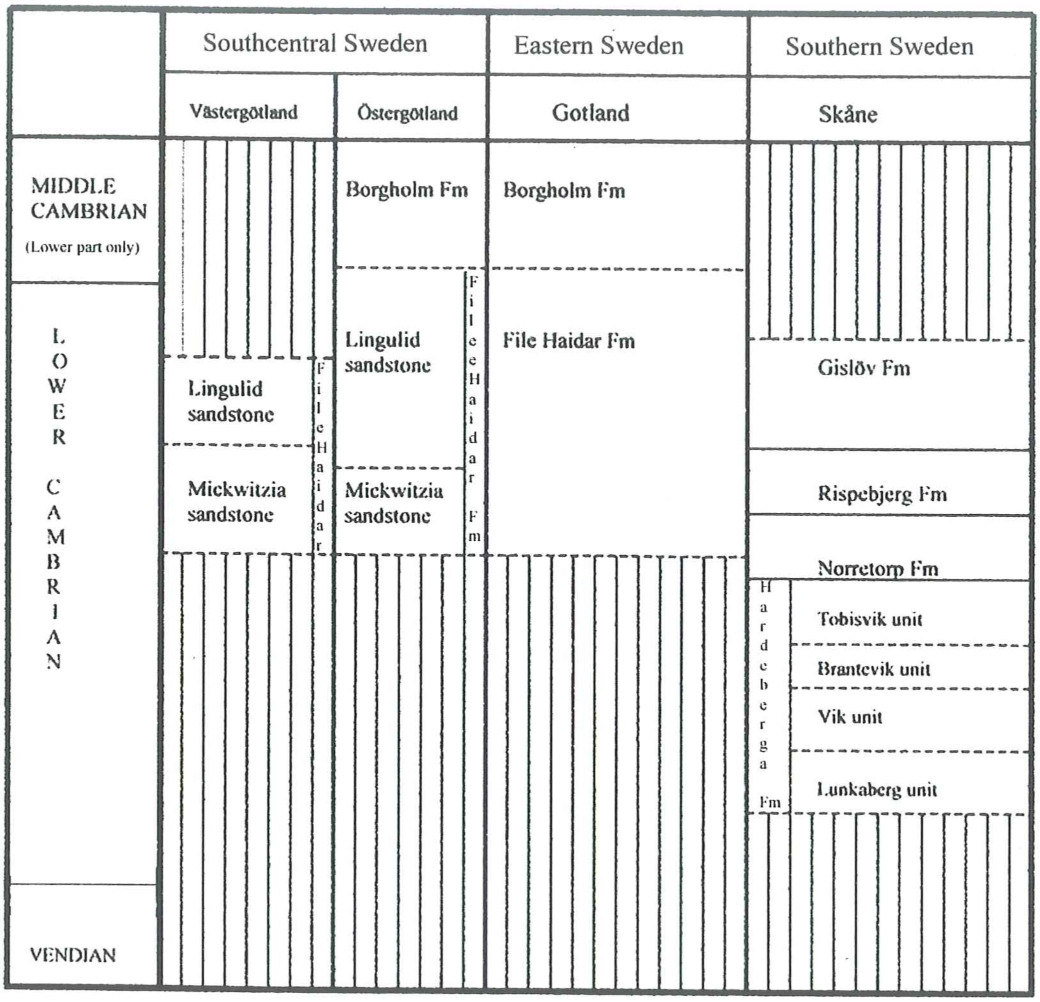
Thirty samples were collected from the localities in Västergötland (Table 1). Polished thin sections of the samples were made for petrological microscopic analysis. These thin sections were then subsequently used for the Cathodoluminisence microscopy (CL), 11 of the thin sections were used for Back scatter electron analysis (BSE). Eleven stubs were prepared for Scanning Electron Microscopy (SEM). Twenty-six plugs were drilled for porosity and permeability measurements .

Polished thin sections were prepared from seven samples from five localities in Skåne. They were used for polarization microscopy, CL microscopy and BSE microscopy (Table 2).

Polarization microscopy (PPL)

Polarization microscopy and point counting (300 points per thin section, with suitable stage length) was utilised, to determine detrital and diagenetic mineral compositions. The classification system follows Pettijohn et al. (1987).The overgrowth's preference for different types of detrital quartz such as unstrained and strained monocrystalline quartz and polycrystalline quartz and the features of the pore systems was also studied.

Fig. 3. The Lower cambrian lithostratigraphy of the Caledonian foreland, southern Sweden. From Jensen (1997) and Kleman (2000).



Cathodoluminescence microscopy (CL)

Luminescence is the emission of light from a solid which can be excited by energy. For geological studies the emission of light in the visible spectrum is the most used. The current density of a specimen and the voltage used of the electron beam controls the intensity of cathodoluminescence. When working with CL of quartz, the voltage used for the electron beam was set to about 20kV and 500 mA (Tucker 1988). Cathodoluminescence microscopy and image analysis was used to distinguish quartz cement from detrital quartz, and to detect feldspars. Quartz cement was quantified by means of point counting on high resolution CL images. A camera with a 3200 ASA film was used, and the film was exposed for 8 minutes with a 10x lens and for 6 minutes with a 4x lens. The CL point counting was performed with a digitally overlay grid system. Due to the restricted size of the thin sections the points counted varied from 261 to 362.

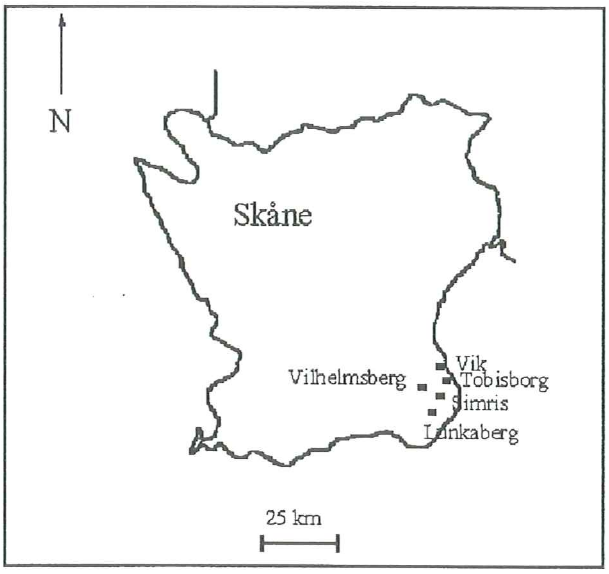


Fig. 4. Map of Skåne with localities. From Kleman, 2000.

Scanning Electron Microscopy (SEM) and Backscattered Electron Image Microscopy (BSE)

Scanning Electron Microscopy (SEM) was used for observation of pore geometry, grain boundaries and quartz overgrowths. The magnification of the SEM ranges from x20 up to x100 000. To produce a small demagnified image of the electron source on the gold coated specimen the beam of electrons, which is produced from an electron gun, passes through a series of two or more electromagnetic lenses. A scanning raster deflects the electron beam so that it scans the surface of the specimen before it passes through the final electromagnetic lens. The picture built up of the scanned area of the stub is the scan synchronized with a cathode ray tube. Due to variation in the reflectivity across the surface of the specimen

Table 1. Localities and samples in Västergötland.

Locality	UTM coordinates	Lithofacies	Thickness	Samples
Mickwitzia sandstone				
Hällekis	VE 07510015	bioturbated	—	HC1a, HC1b, HC2
Hjälmsäter	VE 0319595495	—	—	HJ1, HJ2
Kinne-Kleva	VE 0795590702	—	1.5 m	KK1
Lugnås	VE 2667599590	—	7 m	LU1, LU2, LU3, LU4
Trolmen	VE 0345096395	crossbedding	30 m	TRA, TRB, TRC, TRD, TRD2, TRE2
Lingulid sandstone				
Hunneberg	UE 48955251	—	15 m	BH1, BH2, HB1, HB2, HB4a, HB4b
Karlsfors	VE 26758455	—	20 m	KR1, KR2
Stora Stolan	VE 30208780	—	6 m	ST1, ST2, ST3, ST4, ST5

a contrast in the cathode ray is acquired. The electrons reflected from the surface of the specimen from striking of the electron beam, are divided into backscattered electrons (BSE) and liberated low energy secondary electrons (SE). The BSE and the SE electrons reflected and emitted are then detected by a collector which emits a pulse of light at the arrival of an electron. The emitted light is converted to an electrical signal and then amplified by a photo multiplier and a video amplifier to produce an image (Tucker 1988).

When the Scanning Electron Microscope is set in Backscattered Electrons (BSE) mode, the low energy secondary electrons (SE) are inhibited to reach the collector. Therefore only the high energy reflected electrons (BSE) are collected and visualised. The thin sections were studied for detection of feldspars and photographed for point counting. The point counting was done digitally with an overlay grid system.

Permeability measurements

The equipment used in this procedure was a digital gas permeameter designed by Edinburgh Petroleum Services (DGP200) which measures absolute permeability based on Darcy's Law reads:

$$q = Q / A = -k\, Dp / (m\, L) \quad [1]$$

where q is the flow velocity, Q is the flow rate, A is the cross-sectional area, k is the permeability, Dp is the change in pressure over the sample, m is the fluids viscosity and L is the length over which the pressure drop occurs. Darcy's Law is applicable for laminar flow only and will not be reliable in cases of non laminar flow. Nitrogen (N_2) was used as the measurement gas, and compressed air was used for sample holding in the chamber. With a gas permeameter the gas permeability of a sample can be measured and with a series of measurements the theoretical fluid permeability can be calculated using the Klinkenberg-correction. The measured gas permeability is plotted in a Klinkenberg diagram and the three or more plots best aligned to a straight line gives the theoretical fluid permeability. According to standard procedures at DTU.

Porosity measurements

For the porosity measurements the equipment used was an EPS Helium Gas Expansion Porosimeter designed by Edinburgh Petroleum Services (HGP100) which is based on the principle of Boyle's Law. Boyle's Law states that for an ideal gas, at constant temperature, the product of its pressure and volume is constant. Therefore if a given quantity of gas expands into a larger volume, the expanded pressure will be equal to initial pressure and volume at constant temperature (Umland 1993).

$$(P_1 V_1)/T_1 = (P_2 V_2)/T_2 \quad T_1 = T_2 \quad [2]$$

The gases used in this method were helium (He), and nitrogen (N_2). The HGP100 consist of a core chamber which seals the cleaned, dried and measured cylindrical sample from the atmospheric pressure. The volume in the chamber is defined and the equipment is supplied with two known reference volumes for calibration measurements. After the compression a reference chamber is set with helium gas. The gas in the core chamber is there after allowed to expand and the increasing pressure is compared to the pressure in the reference chamber. According to standard procedures at DTU.

Grain density calculations

The grain density is achieved through calculations once the porosity analysis is terminated using Boyle's Law (see equation [2]) and used for an estimation of porosity measurements.

Results

Petrological microscopy

The samples KR1 and ST5 are of very poor quality and not suitable for analysis, therefore were they excluded from this method. Due to problems making the thin sections the pores of some samples were destroyed. Where they could be studied the porosity is intergranular but in some samples secondary porosity in feldspars were noticed. Furthermore it was noticed that the quartz overgrowths are preferentially present on unstrained mono-

Table 2. Localities and samples in Skåne.

Locality	Sample no	Unit
Hardeberga Formation		
Vik	JK3	Vik unit
Vik	JK4	Vik unit
Vilhelmsberg	JK7	Tobisvik unit
Lunkaberg	JK8	Lunkaberg unit
Lunkaberg	JK13	Lunkaberg unit
Simris	JK15	Tobisvik unit
Tobisborg	JK19	Tobisvik unit

Table 3. Permeability, porosity and grain density of Mickwitzia and Lingulid sandstones of Västergötland.

Sample no	Permeability (mD)	Porosity (%)	Grain density (g/cm³)
Mickwitzia sandstone			
HC1a	12	—	—
HC2	0	—	—
HJ1	36	—	—
HJ2	4	—	—
KK1	37	13	2.648
LU1	0	15	2.827
LU2	0	3	2.711
LU3	0	9	2.658
LU4	4	17	2.640
TRA	0	4	2.644
TRB	0	11	2.670
TRC	64	10	2.642
TRD	0	14	2.648
TRE2	0	11	2.647
Lingulid sandstone			
BH1	0	4	2.639
BH2	0	3	2.827
HB1	0	4	2.628
HB2	0	6	2.634
HB4b	0	6	2.634
ST1	251	17	2.640
ST2	119	15	2.645
ST3	245	16	2.646
ST4	151	15	2.645
ST5	120	17	2.642

crystalline detrital quartz grains in all samples where quartz overgrowths were notable. Quartz overgrowths were not present on any of the detrital feldspars, and where polycrystalline detrital quartz grains were present the overgrowths were absent. In samples BH1, BH2, HB4a, HC2, HJ1, HJ2, KR2, LU1, LU2, LU4, ST2, ST3, TRD, TRD2 and TRE carbonate cement was present for a variable degree ranging from 0.3% to 34.3%. The carbonate cements were not evenly distributed over the whole thin section, and in the hand specimens they resembled fissure fillings. Glauconite was present in HB4a, HB4b, HC2, HJ1, Hj2, KR2, ST1, ST2, ST3, ST4 and all samples from Trolmen except TRD. Of these 16 samples iron hydroxide was present in 12, and in four samples where glauconite was not present. Iron hydroxide is usally present in samples with glauconite (Personal communication A. Ahlberg). No signs of pressure solution were noticed when studied under PPL. In samples BH2 and HB1 from Hunneberg, some monocrystalline detrital quartz grains showed Boehm lamellas, but these are believed to be features of the parent rock and not derived from the deformation of the sediment.

Sandstone Classification

The results from the point counting in the PPL microscope showed that of the 17 samples collected from the Mickwitzia sandstone, 7 can be classified as quartz arenites and the remaining 10 as subarkoses. Of the 11 Lingulid sandstone samples 7 can be classified as quartz arenites, 3 as subarkoses and 1 as a sublitharenite. The samples from Skåne consist of 4 quartz arenite, 2 subarkoses and 1 quartz wacke (Table 4, Figs. 5, 6 & 7).

Cathodoluminescence microscopy

The point counting results of cathodoluminescence (CL) microscopy images are presented in Table 5. The quartz overgrowths of the Mickwitzia sandstone of Kinnekulle and Lugnås plateau hills ranges from 3% to 14 %. From Kinnekulle the sample number HJ1 and TRD show 3 % of quartz overgrowths and sample number HC1b contains 14% of quartz overgrowths. At Billingen the Lingulid sandstones show 4% to 8 % of quartz overgrowths and at Hunneberg 12% to 14 % of quartz overgrowths. In the Hardeberga Formation in Skåne the samples show results of quartz overgrowths ranging from 3% to 15%. Sample number JK13 from the Lunkaberg unit shows the lowest result, 3% compared to JK3 from Vik unit which shows the highest results, 15%.

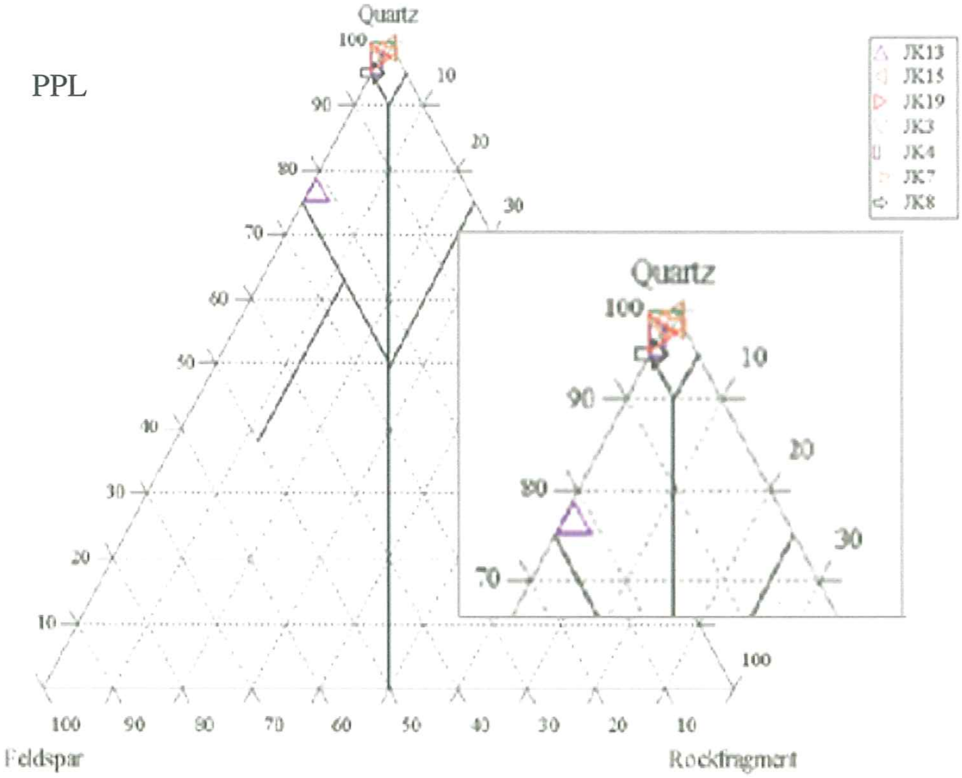
Scanning Electron Microscopy

Samples from the different localities are presented in Table 7. HC1a showed interconnected pores and quartz overgrowths on detrital quartz grains. HC2 on the other hand showed only few pores on the whole sample which did not seem to be interconnected with one another. In the Mickwitzia sample TRA there were even less porosity and not interconnected. The quartz overgrowths were also present on detrital quartz grains in the sample. The sample HB4a from Hunneberg shows no pores at all and was massive with detrital quartz grains covered in some parts with quartz overgrowths and in some parts in grain contact with other detrital quartz grains. The three samples of Billingen KR1, ST1 and ST3 all showed interconnecting pores and detrital quartz grains with quartz overgrowths. All samples of the Hardeberga Formation

Table 4. Results from point counting in plan poarized microscopy, and sandstone classification apeter Pettijoh et al (1987).

Sample no Classification	Quartz	Feldspar	Rock fragm	Qz-overgrowths	Carbonate	Mica	Fe-hydrox	glauconite	Porosity	Sandstone
Mickwitzia sandstone										
HC1a	79.9	6	0.6	13.6	0	0	0.3	0	2.3	quartz arenite
HC1b	84.6	1	0	12	0	0	1	0	1.3	quartz arenite
HC2	88.6	0.3	0	1.3	7.6	0	1	0.6	0.3	quartz arenite
HJ1	90.6	5.6	0	0	0	0	2.3	1	0.3	subarkose
HJ2	80.6	6.6	0.6	0.6	0.3	0.3	2.3	2	6.3	subarkose
KK1	86.9	2.3	0	7.3	0	0	1	0	2.3	quartz arenite
LU1	54.2	10.3	0	0	34.3	0	0	0	0	arkose
LU2	53.3	5.9	0	0	40	0	0.6	0	0	subarkose
LU3	95.6	5.9	0	0.6	0	0	0	0	0.6	quartz arenite
LU4	82.6	2.6	0	8	6	0	1	0	0.6	quartz arenite
TRA	87.6	7	0	1	0	0.6	0.6	0.3	1.6	subarkose
TRB	93.9	1.3	0.6	0	0	0.3	2.6	0	1	quartz arenite
TRC	74.3	5.6	0	8.6	0.3	0	9	0.6	1.6	subarkose
TRD	92.6	0	1	0	0.3	1.6	0	4.3	0	quartz arenite
TRD2	78.9	4.6	1.3	0	5.6	2	0	2.3	0	subarkose
TRE	81.6	2.3	1	0	0.3	0	12	2.6	0	quartz arenite
TRE2	87.6	8.6	0	0	0	0	2.3	1.3	0	subarkose
Lingulid sandstone										
BH1	84.2	3.3	5.6	0.3	5.6	0.6	0	0	0.3	sublitharenite
BH2	84.6	2.3	0.3	0	12.6	0	0	0	0	quartzarenite
HB1	90.2	6	3.3	0	0	0	0	0	0	subarkose
HB2	92.3	6	1.6	0	0	0	0	0	0	subarkose
HB4a	90	6	0	0	2.6	0	0	4.3	0.3	quartz arenite
HB4b	94.6	0.6	2.6	0	0	0	0.3	1.6	0	quartz arenite
KR2	61	5	0	2	23	1	6.6	1.3	0	subarkose
ST1	94.6	3.6	0	0	0	0	0	0.3	1.3	quartz arenite
ST2	92.6	1	0	0.6	0.3	0	0.3	4.6	0.3	quartz arenite
ST3	94.3	0.6	0	3	0.3	0	0	1	0.6	quartz arenite
ST4	92	3.6	0	0	0	0	0	1.6	2.6	quartz arenite
Hardeberga Formation										
JK3	77.8	1.3	0	20.6	0	0	0	0	0	quartz arenite
JK4	84.9	1.3	0	0	0	0	clay matrix12.3	0	0	quartz arenite
JK7	84.3	1.3	0	14.3	0	0	0	0	0	quartz arenite
JK8	87	4.6	0	9.3	0	0	0	0	0	quartz arenite
JK13	71.6	20.6	1.3	6	0.3	0	0	0	0	subarkose
JK15	72.2	1	0	26.3	0	0	0	0	0.3	quartz arenite
JK19	91	1.9	0	7	0	0	0	0	0	quartz arenite

PPL



BSE

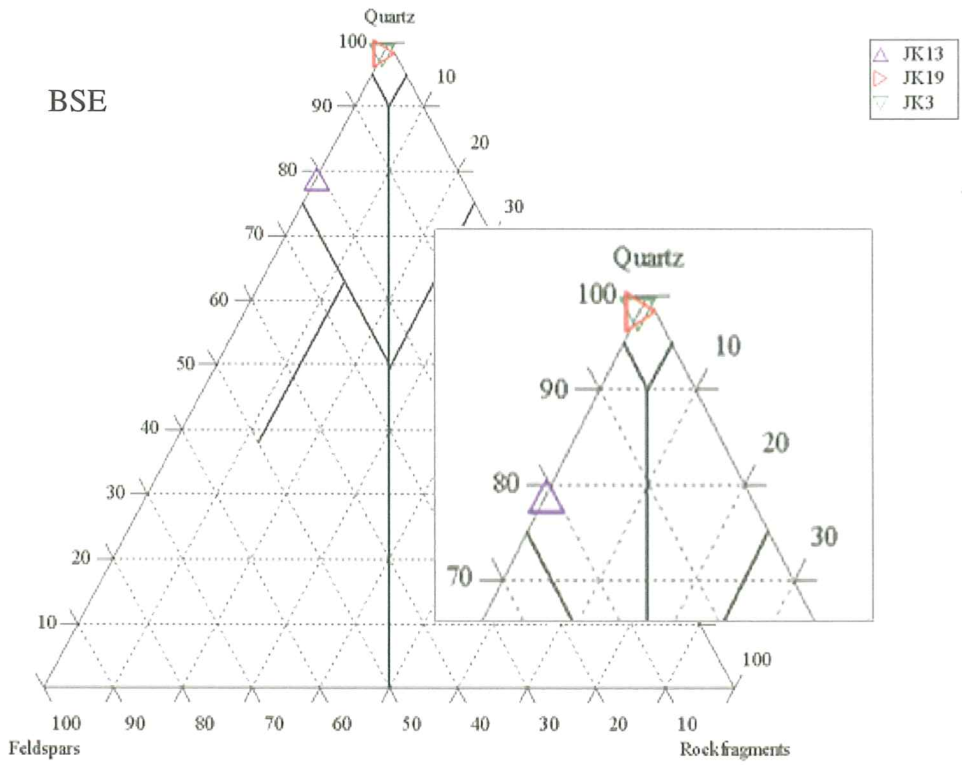
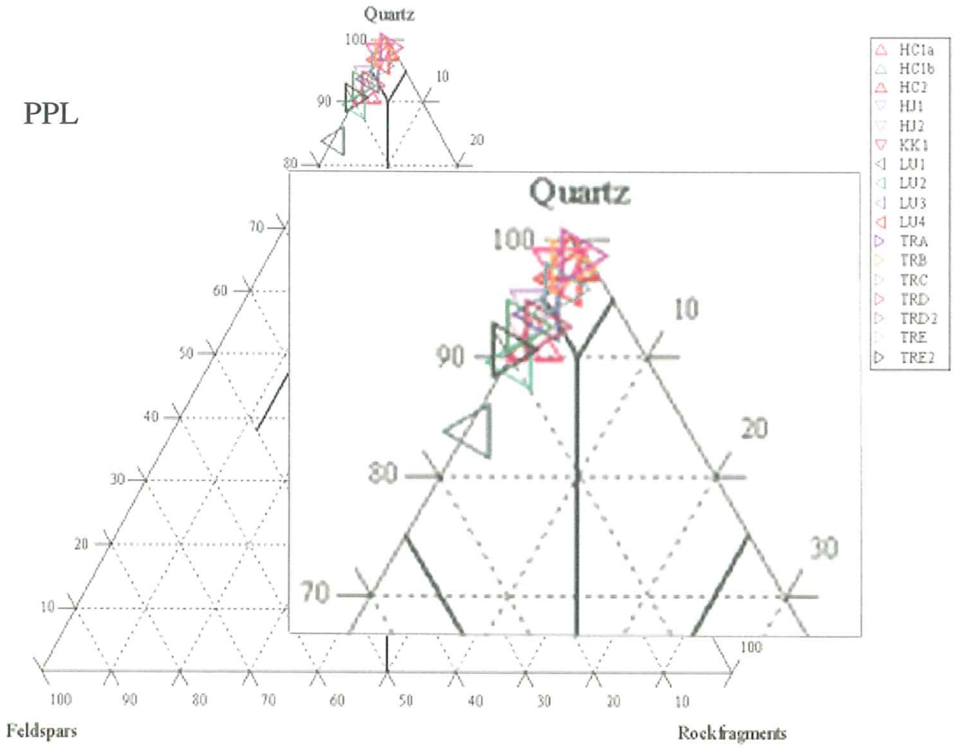


Fig. 5. Triangle diagrams illustrating sandstone classification of the Hardeberga Formation from PPL and BSE pointcounting.

PPL



BSE

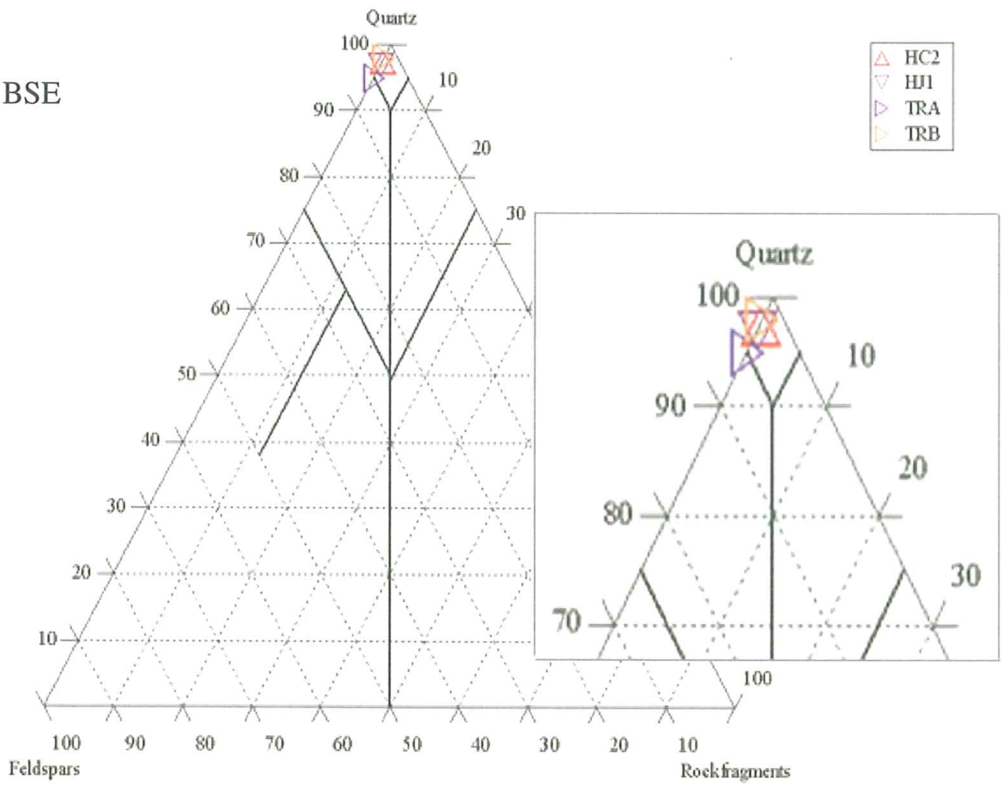
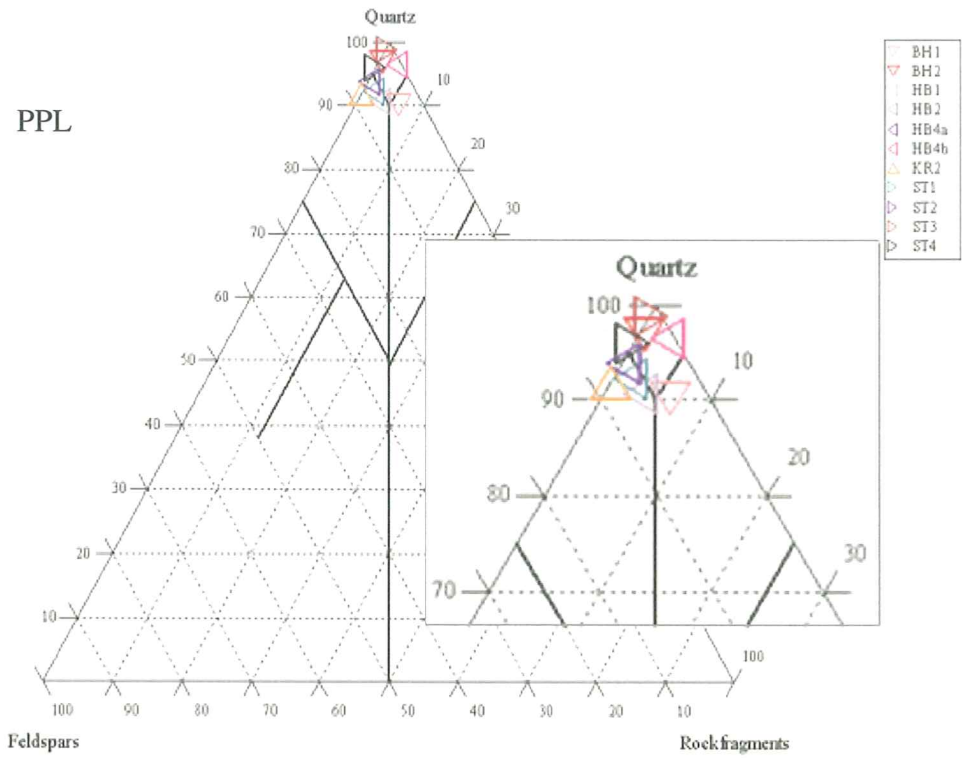


Fig. 6.Triangle diagrams illustrating sandstone calssification of the Mickwitzia sandstone from PPL and BSE pointcounting.



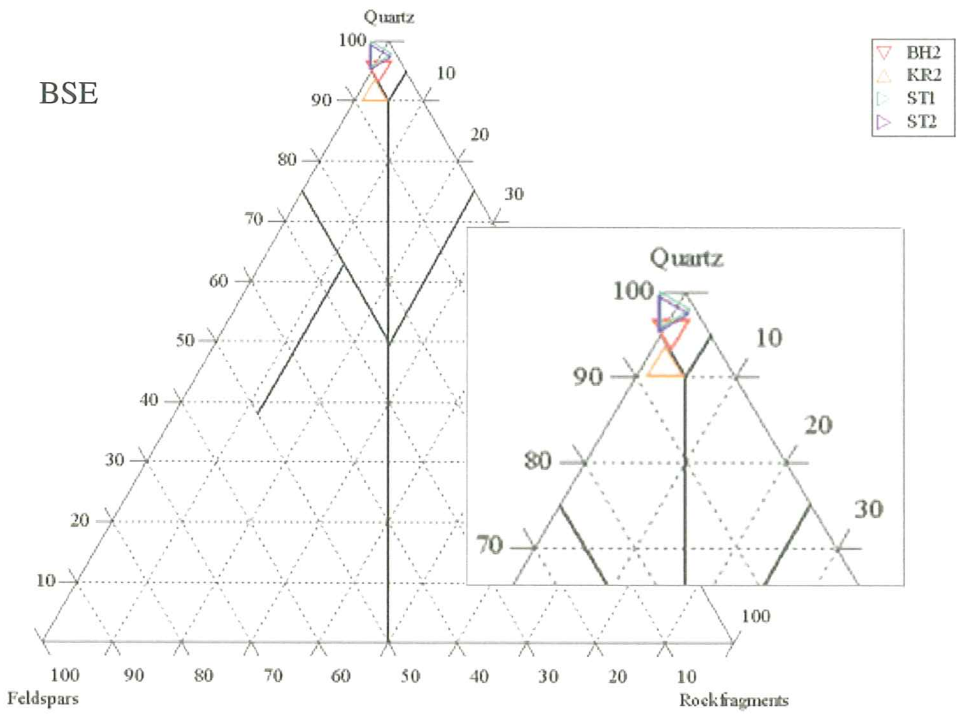


Fig. 7. Triangle diagrams illustrating sandstone classification of the Lingulid sandstone from PPL and BSE pointcounting.

showed detrital quartz grains covered with quartz overgrowths and few areas with direct detrital quartz grain contact. SEM images confirmed the features observed by other methods (Plate 1). For instance, The Mickwitzia sandstone samples from Västergötland, HC2 (Plate 1, image A) and TRA (Plate 1, image B) show pores and detrital quartz surrounded by quartz overgrowths. Furthermore, partly dissolved feldspars do not seem to have quartz overgrowths (Plate 1, image C). From Stora Stolan, samples show high permeabilities, and when studied in the SEM they show well interconnecting pores (Plate 1, image D). Furthermore sorting is good, and the detrital quartz with quartz overgrowths and small clay minerals growing everywhere, perhaps as a result of dissolved feldspars. The sample SEM-images from Karlsfors (Plate 1, image E) shows the sorted sandstone with the pores, the detrital quartz and the quartz overgrowths not as extensive as for example in the Mickwitzia sandstone sample from Hällekis Camping mentioned above. The dense sandstone of the plateau hill of Hunneberg (Plate 1, image F), HB4a, shows detrital quartz grains with quartz overgrowths filling the pores as well as clay minerals. The two samples studied in the SEM from the Hardeberga Formation are JK3 and JK19. The expected dense sandstone, with no or very little porosity and detrital quartz grains surrounded by quartz overgrowth, is shown on images G and H of Plate 3.

Back scattered reflection analysis

The results from the point counting of the images taken in BSE mode of the SEM are presented in Table 6 and seen in triangular diagrams in Figs. 5, 6 & 7. The samples HC2, HJ1 and TRB from the Mickwitzia sandstone are all classified as quartz arenites and sample number TRA was classified as a subarkose. From the plateau hill of Hunneberg the Lingulid sandstone sample BH2 is classified as a quartz arenite in contrast with the Lingulid sandstone samples from Billingen which includes one subarkose and two quartz arenites. From the Hardeberga Formation in Skåne samples JK3 and JK19 were classified as quartz arenites and the sample JK13 as a subarkose. BSE point counting results correspond well to the point counting done in PPL microscopy.

Permeability measurements

The permeability measurements show that half of the Lingulid sandstone at Stora Stolan had permeability results ranging from 120 to 250 mD. Furthermore, almost half of the Mickwitzia sandstone had permeability to 65 mD. The remaining Mickwitzia and Lingulid sandstones show no measurable permeability (Table 3).

Porosity measurements

Porosity in samples from Stora Stolan ranged from 14.9 % to 17.3 %. Furthermore the samples from Hunneberg

Table 5. Cathodoluminescence microscopy point counting.

Sample no	Detrital-QZ	QZ-overgrowths	Other	Primary porosity	Number of points
Mickwitzia sandstone					
HC1b	77	14	3	6	333
HC2	86	11	0	3	346
HJ1	92	3	3	2	333
HJ2	81	10	4	5	323
KK1	88	5	2	5	337
LU1	89	4	5	2	261
LU2	85	6	7	2	274
LU3	87	6	5	2	309
LU4	80	10	10	0	288
TRA	84	11	2.5	2.5	345
TRC	86	8	3	3	333
TRD	87	3	8	2	313
TRE	88	5	5	2	331
TRE2	85	6	4	5	296
Lingulid sandstone					
HB1	80	12	8	0	323
HB2	75	14	11	0	359
KR1	91	5	0	4	269
ST1	85	8	0	7	305
ST2	88	4	2	6	323
ST3	91	4	0	5	341
ST4	86	6	0	8	321
ST5	85	5	4	6	308
Hardeberga Formation					
JK3	84	15	1	0	328
JK4	93	5	1	1	332
JK7	90	10	0	0	343
JK8	86	14	0	0	362
JK13	87	3	9	1	315
JK15	87	13	0	0	343

Table 6. BSE image point counting.

Sample no calssification	Quartz	Feldspars	Other	Porosity	No of points	Sandstone
Mickwitzia sandstone						
HC2	95	2.5	0	2.5	538	quartz arenite
HJ1	94	2	0	4	507	quartz arenite
TRA	93	5	0	2	566	subarkose
TRB	97	2	0	1	566	quartz arenite
Lingulid sandstone						
BH2	93	4	0.5	2.5	499	quartz arenite
KR2	91	6	1.5	1.5	564	subarkose
ST1	94	2	0	4	427	quartz arenite
ST2	93	2	0	5	498	quartz arenite
Hardeberga Formation						
JK3	98	2	0	0	558	quartz arenite
JK13	79	21	0	0	537	subarkose
JK19	98	1.5	0	0.5	556	quartz arenite

had porosity ranging from 3% to 6% and the sample from Karlsfors had a porosity result of 16 %. The Mickwitzia sandstone all ranged from 2.9% to 16.7% in porosity (Table 3).

Grain density

The majority of the samples from Västergötland shows results ranging from 2.628 to 2.670, which is close to the density of quartz (2.65 g/cm^3) (Klein and Hurlbut 1985). The samples from the localities Lugnås and Byklevfall, Hunneberg labelled LU1, LU2 and BH2 showed high density values from 2.711 to 2.827 which suggest that the measurements were inaccurate, or that abundant heavy minerals are present but not detected during point counting (Fig. 3).

Interpretation and Discussion

Evaluation of methods

During point counting in a PPL microscope one have to be aware, that the reliability is dependent on thin section quality, selected material, operator skill and finally the number of points counted (Cooper et al. 2000). Also the quantification of overgrowths volumes is difficult, due to the absence of identifiable boundaries between detrital quartz and quartz overgrowths (Cooper et al. 2000). When comparing different sandstones, samples with similar grain size should be used in order to get reliable results. The reason for using samples with similar grain size is that the lens of the PPL microscope and the stage length of the point counting apparatus are the same and therefore more representable. In this study the grain size vary and therefore it is important to verify results with other methods such as BSE analysis point counting, CL microscopy point counting, porosity measurements and SEM microscopy. The PPL miroscopy is an acceptable method to obtain the modal composition of the sandstones.

For the BSE and CL analysis it is important that the analysed area is representative for the whole sample. The BSE and CL point counting is yet another source of errors if measures to obtain representative images fail. When using CL microscopy for quartz detection, the voltage used is around 20 kV. The feldspars in a thin section will glow at such high voltages if hit with the beam, and conceal darker detrital quartz and quartz overgrowths. Therefore, during quartz CL photography, feldspars are avoided which may lead to lack of representativity. The quartz overgrowths were easier detected in a CL microscopy than in any other microscopy method. Unweathered detrital feldspars are much easier detected in BSE analysis compared to PPL microscopy (Plate 2).

The results of porosity and permeability measurements depend on the quality of the selected core and that it is absolutely dry. Also the physical measurements of the core are of vital importance, as are the data collecting. The most reliable method for measuring porosity is the use of a gas expansion porosimeter.

When using stubs for SEM microscopy, the stubs should be made of samples representative of the sandstone examined, carefully gold coated and dust free to avoid image distortions.

Method comparison

The detrital quartz and quartz overgrowths have been studied with all methods available during this study. The two best methods used for detecting quartz overgrowth are the PPL microscopy and the CL microscopy. The

Table 7. Samples studied in the SEM.

Sample no	Unit
JK3	Vik unit
JK7	Tobisvik unit
JK13	Lunkaberg unit
JK19	Tobisvik unit
HC1a	Mickwitzia sandstone
HC2	Mickwitzia sandstone
TRA	Mickwitzia sandstone
HB4a	Lingulid sandstone
KR1	Lingulid sandstone
ST1	Lingulid sandstone
ST3	Lingulid sandstone

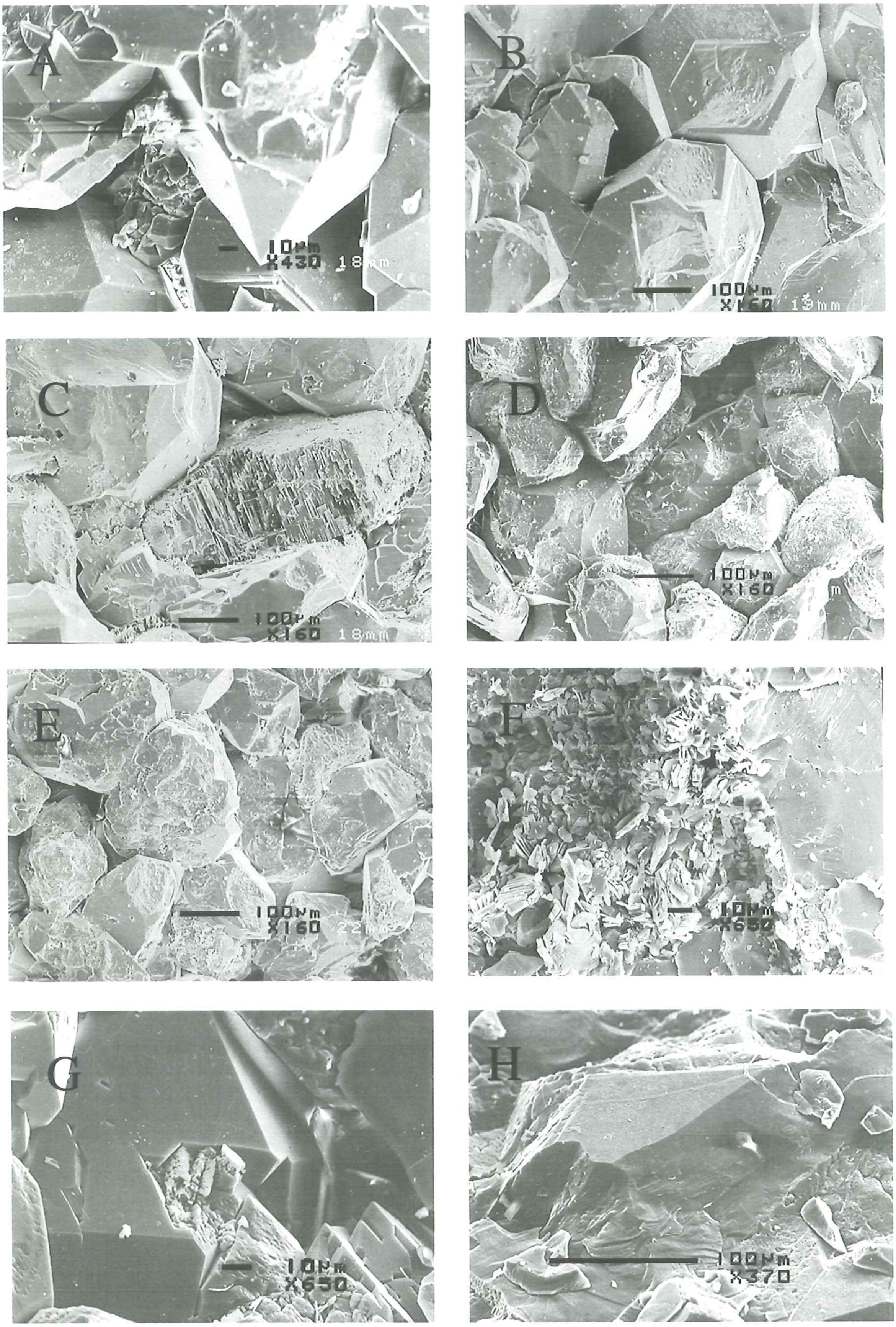


Plate 1. Images taken in SEM. *A*. HC2, pores and quartz overgrowths attached to detrital quartz grains in close-up. *B*. TRA, quartz overgrowths surrounding detrital quartz grains. *C*. TRA, a decaying feldspar showing no signs of quartz overgrowths attached. *D*. ST1, a permeable sandstone with detrital quartz grains in some parts surrounded by quartz overgrowths. *E*. KR1, yeet a porous snadstone showing detrital quartz grains surrounded by quartz overgrowths. *F*. HB4a, diagenetic clay minerals probably as a result of feldspar dissolution. *G*. JK19, quartz overgrowths on detrital quartz grain in close-up. *H*. JK3, dense quartz arenite with detrital quartz grains and some quartz overgrowths. Scales given on images.

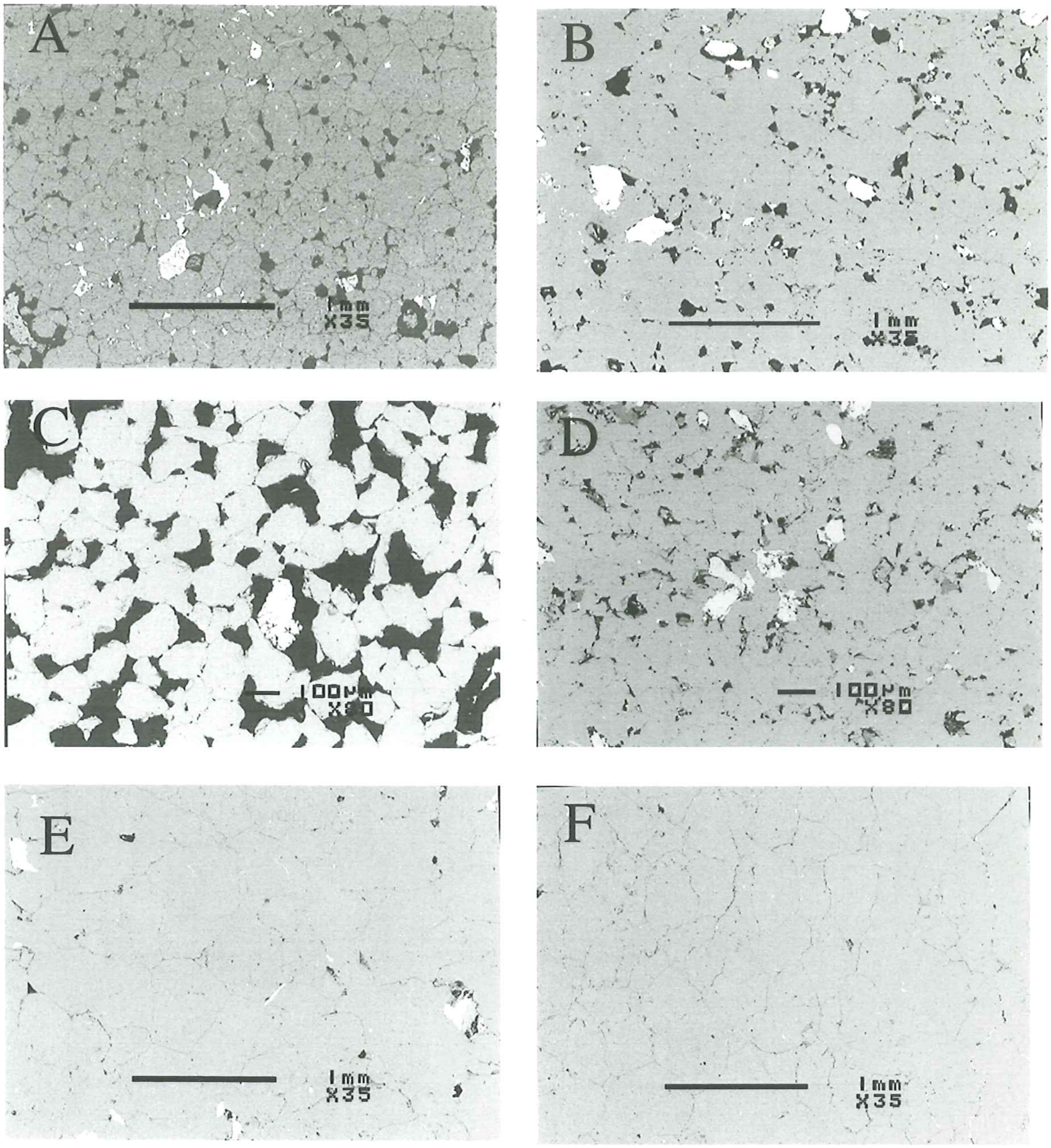


Plate 2. BSE microscope images showing mineral composition and porosity. Black colour represent porosity, grey represent quartz, light grey represent feldspar and smaller white areas represent heavy minerals. *A*. HC2, Hällekis Camping. *B*. TRA, Trolmen. *C*. ST1, Stora Stolan. *D*. BH2, Hunneberg. *E*. JK3, Vik. *F*. JK7, Vilhelmsberg. Scales are given on images.

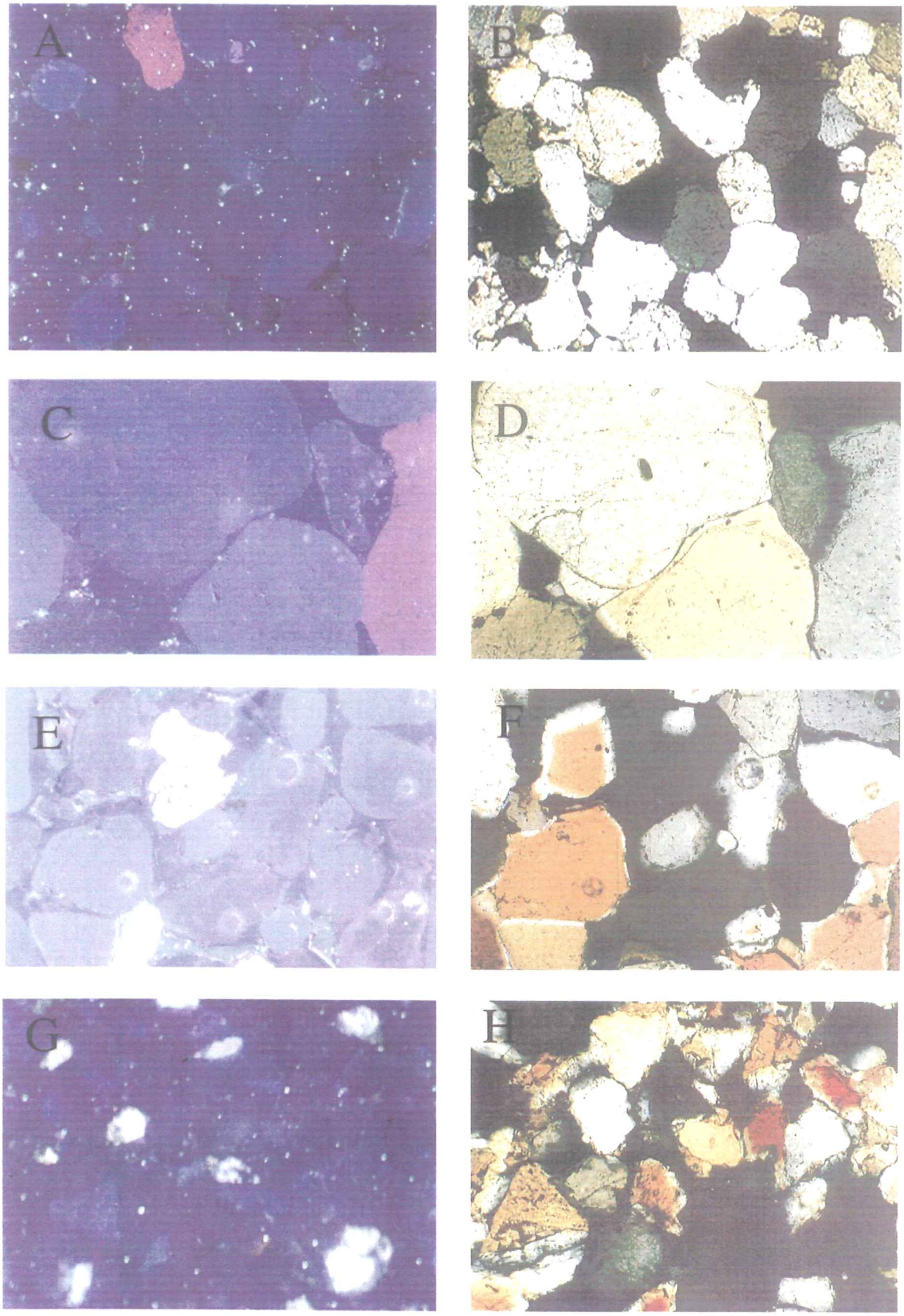


Plate 3. Images A, C, E and G are CL microscopy images showing detrital quartz grains, diffenrence in provenance of detrital quartz, quartz overgrowths, feldsparts and pores. Black colours represent pores, blue to light blue and dark pinkish represent detrital quratz, dark blue represent quartz overgrowths and white represent feldspars. Images B, D, F and H are taken in a polarization microscope and are pair phototgraphs to the CL images. *A*. CL, HC2. *B*. PPL, HC2. *C*. CL, JK15. *D*. PPL, JK15. *E*. CL, LU4. *F*. PPL, LU4. *G*. CL, HB2. *H*. PPL, HB2.

quartz overgrowths can in a PPL microscope be difficult to detect since the syntaxial overgrowths commonly have the same crystallographic orientation as the detrital quartz grain. In CL microscopy the quartz overgrowths are more easily distinguished and therefore more reliable. When comparing the results of quartz overgrowths from PPL microscopy and CL microscopy, the quartz overgrowths is notably higher in CL microscopy (Table 8). In samples, where the quartz percentage is above 90 in PPL point counting, the results are broadly corresponding to the CL microscopy results.

Results from PPL point counting and BSE point counting are used for comparison of feldspar contents and sandstone classification. The two methods correspond well (Table 9). Sample HJ1 is classified as a subarkose or a quartz arenite depending on whether PPL or BSE is used for point counting. This is probably due to that the area analysed with BSE microscopy is not representative for the whole sample. The total content of feldspar differs in sample HJ1 with 7 % feldspar in the PPL point counting and 2% feldspar in the BSE point counting. In sample ST1 the total content of feldspar is 4 % in the PPL point counting and 2 % in the BSE point counting. The broad correspondence of these results suggests that both point counting methods are acceptable.

Sandstone porosity and permeability are decreasing during burial due to diagenesis. Comparison of porosity measurements with BSE microscopy point counting, CL microscopy point counting and point counting in PPL microscopy was performed to establish which methods are the most reliable for different aspects of the reservoir properties. The results from the different methods vary extensively (Table 10). The method of measuring porosity with the gas expansion porosimeter was the most reliable. The point counted thin sections often had artificial additional pores (not counted) due to material loss during grinding and polishing. Therefore the actual porosity is higher than detected during point counting.

Petrophysical and diagenetic similarities of sandstones from Västergötland and Skåne

The mineral compositions of the sandstones from Västergötland and Skåne are similar. They consist mostly of detrital quartz and quartz overgrowths, K- feldspars, rock fragments and diagenetic carbonates. The sandstone composition is also very similar in the two areas, which were dominated by quartz arenites and subarkoses (Figs. 5, 6 & 7).

Quartz is the principal cement in the Hardeberga Formation, the Mickwitzia sandstone and the Lingulid sandstone. These sandstones have been exposed to maximum temperatures well over 100°C, and were thus prone to be subjected to prominent quartz cementation (Samuelsson 1999; Fisher et al. 2000). Although, if exposed to lower temperature during longer time, smaller amounts of quartz cement is able to grow (Houseknecht 1984). For

Table 8. Comparison of total quartz overgrowths content in methods PPL and CL.

Sample no	PPL total qz-overgr content %	CL total qz-overgr content %
Mickwitzia sandstone		
HC1b	12	14
HC2	1.3	11
HJ1	0	3
HJ2	0.6	10
KK1	7.3	5
LU1	0	4
LU2	0	6
LU3	0.6	6
LU4	8	10
TRA	1	11
TRC	8.6	8
TRD	0	3
TRE	0	5
TRE2	0	6
Lingulid sandstone		
HB1	0	12
HB2	0	14
KR1	—	5
KR2	2	—
ST1	0	8
ST2	0.6	4
ST3	3	4
ST4	0	6
ST5	—	5
Hardeberga Formation		
JK3	20.6	15
JK4	0	5
JK7	14.3	10
JK8	9.3	14
JK13	6	3
JK15	26.3	13

Table 9. Comparison of feldspar content and sandstone classification in methods PPL and BSE.

Sample no	PPL Feldspar %	Sandstone classification	BSE Feldspar %	Sandstone classification
Mickwitzia sandstone				
HC2	1	quartz arenite	1	quartz arenite
HJ1	6	subarkose	2	quartz arenite
TRA	7	subarkose	5	subarkose
TRB	1.5	quartz arenite	2	quartz arenite
Lingulid sandstone				
BH2	2.5	quartz arenite	4	quartz arenite
KR2	7.5	subarkose	6	subarkose
ST1	4	quartz arenite	2	quartz arenite
ST2	1	quartz arenite	2	quartz arenite
Hardeberga Formation				
JK3	2	quartz arenite	2	quartzarenite
JK13	22	subarkose	21	subarkose
JK19	2	quartz arenite	1.5	quartz arenite

quartz cementation there are a few different silica sources available. Recent research has established that almost all silica sources are internal (derived from sources within the sediment pile)(Worden & Morad 2000). The external silica sources presumably require unrealistic transport distances (Worden & Morad 2000) and are here not believed to be the source. This is due to that external sources of silica require enormous fluxes of water due to the fact that silica is only sparingly soluble in water at diagentic temperatures (Worden & Morad 2000). The fact, that directly adjacent mudstones are not present and can therefore not be a silica source, is also a reason why external sources are not believed to be prominent (Barclay & Worden 2000; Giles et al. 2000). Internal sources of dissolved silica are dependent on the detrital grain exposure, amount of detrital feldspars, temperature and fluid chemistry history and type and amount of reactive clay minerals (Worden & Morad 2000). Different types of internal dissolved silica sources include detrital feldspar-related reactions, pressure dissolution, stylolites within sandstones and dissolution of amorphous silica (Worden & Morad 2000). For the examined sandstones of Västergötland and Skåne, the detrital feldspar-related reactions could be probable silica sources since no signs of pressure solutions or stylolites have been noticed. In some samples secondary intragranular porosity has been

Table 10. Comparison of measured and calculated prosity based on point counting in PPL, BSE, CL and measurements in a porosimeter.

Sample no	Porosity measurements (%)	PPL (%)	BSE (%)	CL (%)
Mickwitzia sandstone				
HC1a	—	2.3	—	—
HC2	—	0.3	2.5	3
HJ1	—	0.3	4	2
HJ2	—	6.3	—	5
KK1	13	2.3	—	5
LU1	15	0	—	2
LU2	3	0	—	2
LU3	9	0.6	—	2
LU4	17	0.6	—	0
TRA	4	1.6	2	2.5
TRB	11	1	1	—
TRC	10	1.6	—	3
TRD	14	0	—	2
TRE2	11	5	—	0
Lingulid sandstone				
BH1	4	0.3	—	—
BH2	3	0	2.5	—
HB1	4	0	—	0
HB2	6	0	—	0
HB4b	6	0	—	—
ST1	17	1.3	4	7
ST2	15	0.3	5	6
ST3	16	0.6	—	5
ST4	15	2.6	—	8
ST5	17	—	—	6

noticed due to complete or partial detrital feldspar dissolution associated with surrounding clay cement rims (Hartmann et al. 2000). It is thought that the abundance of feldspars decreases with increasing burial depth. Feldspars have higher Si/Al ratios than the clay minerals that replace them and this is the main reason why they are prominent silica sources for quartz cementation. Replacing clay minerals are controlled by the chemistry of the pore fluid as seen in reactions (A) and (B) (Worden & Morad 2000).

$2KalSi_3O_8 + 2H^+ + H_2O = Al_2Si_2O_5(OH)_4 + 4SiO_2 + 2\ K^+$ (A)

K-feldspar kaolinte quartz

$3\ KalSi_3O_8\ 2H^+ = Kal_3Si_3O_{10}(OH)_2 + 6SiO_2 + 2K^+$ (B)

K-feldspar Illite quartz

The presence of diagenetic clay minerals is clear in the SEM images (Plate 1, image F). It has not been determined which clay mineral is present in the samples of this study. The detrital minerals, entirely or partly surrounded by the quartz overgrowths, are mainly unstrained monocrystalline quartz grains. The reason for this could be that the polycrystalline quartz grains and monocrystalline quartz grains with undulose extinction are less suitable substrates for quartz cementation, due to their inconsistent lattice orientations (Pettijohn et al. 1987). Furthermore, the detrital quartz grains of the studied sandstones of both Västergötland and Skåne show in CL microscopy (Plate 3, images A, C, E and G) different shades of blue and dark pink, which probably are due to different provenance (Houseknecht 1991). The hydrothermal carbonate vein fillings in some samples possibly have appeared during nearby magmatic intrusions. They were presumably derived from associated hydrothermal pore fluids. Microcrystalline quartz cement has not been observed in any of the samples of Västergötland or Skåne.

Petrophysical and diagenetic differences between sandstones from Västergötland and Skåne

When studying the cementation of the sandstones of Skåne, the quartz overgrowths appear to be more evenly distributed in all samples compared to those in the sandstones from Västergötland. The quartz cement appears both as overgrowths and as outgrowths and are formed due to syntaxial growth with the same crystallographic orientation as the detrital quartz grain in most cases. The outgrowths are not rims around the detrital grains, but pronounced localised projections obstructing and destroying the adjacent pore (cf. Worden & Morad 2000).

The extent of the quartz overgrowths were generally larger in the sandstones of Skåne than in those from Västergötland. The sandstones of the Hardeberga Formation have greater contents of quartz cement than the sandstones of Västergötland. The clear differences in quartz cementaion between Skåne and Västergötland is due to that the sandstones of the Hardeberga Formation have been more deeply buried than the sandstones of Västergötland in a more proximal part of the Caledonian foreland basin. Sandstones buried deeper than 2700 m have a huge range in authigenic quartz volumes compared with sandstones buried to less than 2700 m with negligible quartz cement (Fisher et al. 2000; Walderhaug et al. 2000).

Data from all the methods used in this project points in the expected direction. Based on the permeability and porosity of the Lingulid sandstone, this unit could be divided into two groups, one group with expected high permeabilities of 251 to 119 mD and one group with no measurable permeability. It is plausible that the Permo-Carboniferous dolorite cap of the Hunneberg plateau hill has influenced the diagenesis of the Lingulid sandstone (c.f. Houseknecht 1984). The dolerite cap has at Hunneberg a thickness of about 90 m at times and at Billingen a thickness of about 45 m (Magnusson et al. 1962). The dolerite cap is also nearer the sandstone at Hunneberg than on Billingen. It is possible that the dolerite sills had a hydrothermal influence on the sandstones and that the pore fluids dissolved detrital feldspars which then released silica for growth of quartz cement on the detrital quartz grains .

Quartz overgrowths could appear as micro-quartz cement in areas with extensive intrusions or volcanic activity due to hydrothermal influence (Houseknecht 1984). The Permo-Carboniferous intrusions do not seem to have had that effect on the cementation of the Lingulid sandstone of the plateau hill of Hunneberg. Instead the cementation preferably grew as syntaxial quartz overgrowths on detrital monocrystalline quartz grains. At Billingen the quartz overgrowths grew as thin coatings on detrital quartz grains. In Skåne most of the NW-SE oriented Permo-Carboniferous dolerite intrusions are vertical dykes and not sills. In the sandstone of Skåne the quartz cementation appears occasionally as both overgrowths and outgrowths in the same sample, filling the adjacent pores. In the sandstones of Västergötland, with exceptions of the Lingulid sandstone from the plateau hill of Hunneberg, the cementations is dominated by overgrowths.

Conclusions

Compared to the deeply buried sandstones in Skåne, the Västergötland sandstones were shallower buried, and possibly less influenced by magmatic intrusions. This is shown by higher porosity and permeability values, and lower quartz cement contents.

· Although the investigated sedimentary successions were moderately to deeply buried in the Caledonian foreland (< 5 km, Buchardt 1997; Samuelsson 1999), no signs of pressure solution and subsequent silica redistribution were observed during CL and PPL microscopy.

· During this study, porosity was best measured with a gas expansion porosimeter and permeablility measured with a digital gas permeameter. Quartz cement was identified and quantified with CL microscopy, while the BSE microscopy was used to identify and quantify the feldspar content.

· Very low overall grain-minus-cement porosities (dense grain packing) suggest that quartz cementation occured during deep burial, presumably as a direct consequence of Caledonian foreland basin infill and subsidence.

· Neglible porosity and permeability and an increase in quartz cementation in the Lingulid sandstone at Hunneberg compared to the Lingulid sandstones at Billingen, were probably due to the closer and thicker dolorite cap at Hunneberg.

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