DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2004/61

Comparison of reservoir material from well separator with reservoir cores in order to investigate the reason for reservoir deterioration around the ST-13 well

Stenlille underground gas storage

Troels Laier

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

GEUS

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G E U S

Abstract

Sands that accumulated in well separators of the injection/withdrawal wells of the Stenlille Underground Gas Storage during gas withdrawals were carefully examined in order to find the reason for the injection problems encountered in one of the wells. Several injection/withdrawal cycles have been completed since the drilling of the 8 wells at well site B from 1990 to 1996, but in 2003 the injection problems in ST-13 got serious, so action was needed to solve the problem. Samples from four well separators were examined by microscopy and scanning electron microscopy (SEM) including microprobe analysis, after having removed salty formation water using methanol. The results of the investigation were compared with results of similar examinations on reservoir rock samples from zone 3, represented by 6 plugs obtained from core#1 of ST-12.

The sand from well separators consist mostly of quartz with small amounts of feldspars and pyrite being present in minute quantities. The same composition was found for the reservoir rock. No indication of mineral overgrowth was observed on the sand grains of the separator samples, that could point to a beginning of precipitation of salts, which was anticipated to be the reason for the injection problems. The chloride content in the methanol used for removing formation water residues did not indicate the presence of solid salt either.

It is concluded that the injection problems are most likely due to blocking of the well by sand that accumulated in the well during the preceding gas withdrawal. Part of zone 3 of the sandstone reservoir rock is very poorly cemented and could have moved into the well during withdrawal. In accordance, the sand collected from the ST-13 well in which injection problems were encountered had the highest quartz content of all separator samples. Furthermore, larger volumes of sand appear to have accumulated in the ST-13 well compared to the other wells.

Knowing the conclusion of this report DONG decided to clean-up the well bore of ST-13, thereby solving the problems with low injection rates. A sample of well bore sand was analysed and based on these results it was concluded that the sand originated from the reservoir rock matrix. Total volume of sand produced during clean-up was in the order of 2-3 cubic metres.

Contents

Background and purpose

The underground gas storage facility at Stenlille was put into operation in 1989, approximately two years after the completion of the first injection well, ST-2, figure 1. From 1990 to 1996, eight more injection/withdrawal wells (I/W) were drilled at well site B. The reservoir area covered by these closely spaced wells is, however, larger than what might be judged from figure 1, as most of the wells are deviated. Using these wells natural gas is being stored temporarily in the Late Triassic/Early Jurassic Gassum Sandstone Formation (*c*. 1500 metres below surface), which forms a dome-like structure above a Zechstein salt-pillow. The casing of each well has been perforated at the levels of the most permeable zones of the Gassum formation, and several cycles of injection and withdrawal of gas have taken place since the completions of the wells.

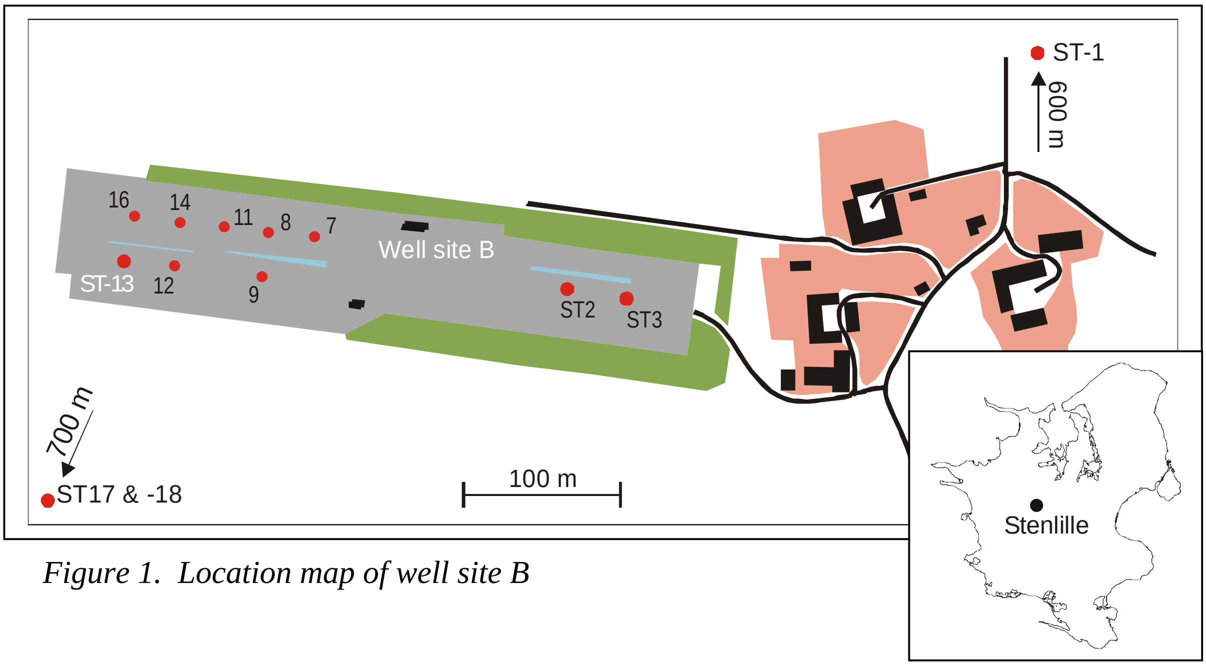


Figure 1. Location map of well site B

However, during the summer of 2003 difficulties with gas injection into the ST-13 well occurred /1/. Therefore, DONG A/S considered it necessary to re-perforate the ST-13 well. Before doing so, DONG A/S wanted more information as to reason for the injection problems in that particular well. DONG A/S, therefore, asked the Geological Survey of Denmark and Greenland (GEUS) for help to clarify the possible reasons for the injection problems in the ST-13 well.

It was agreed that GEUS should undertake an investigation of the reservoir material which was known to accumulate in the well separator during withdrawal of the gas in order to look for possible differences between this material and original reservoir rock material known from reservoir cores, which might explain the injection difficulties.

In this report a description of reservoir material from the well separator of ST-13 is given using microscopy, and scanning electron microscopy (SEM) including microprobe elemental analysis. This information has been compared with similar information for reservoir material obtained from well separators of three other wells at well site B, together with information obtained from six polished sections of core#1 from the ST-12 well. Based on these observations a brief discussion is given as to how the injection/withdrawal operations may have affected the reservoir properties leading to a diminished injection efficiency in ST-13.

A pre-print of the report was submitted to DONG who decided to clean-up the well. The results of analyses of the sand produced during the clean-up is described in an addendum to this report.

Description of samples collected from well separators

Samples, mostly sandy reservoir material, obtained from well separators of 10 injection wells were stored in glass bottles (figure 2) and sent to GEUS on June 14th, 2004.

Figure 2. Photo of all samples obtained from well separators (above) and samples selected for further investigation (below)

The labels on the glass bottles refer to the well ID's used by the well site personnel, and may be translated into the well numbers shown in figure 1, using the information given in table 1.

Table 1. List of injection/withdrawal wells.

Well No.	ST-1	ST-2	ST-7	ST-8	ST-9	ST-11	ST-12	ST-13	ST-14	ST-16	ST-17	ST-18
Well ID	A6	B9	B4	B3	B6	B2	B8	B10	B1	B11	D1	D2
Gas zone	1, 2b, 3	5	1, 2b, 3	5	1, 2b, 3	1, 2b, 3	3	3	5	5	2b, 3	5

For practical reasons DONG A/S devided the Gassum Sandstone Formation into a number of different zones, therefore, zones exploited by each well is also given in table 1. The cores taken while drilling the ST-13 well represent zones deeper than zone 3, perforated by this well. Therefore, it was decided to include in the present investigation reservoir material of zone 3 from well separator of the ST-12 well, which was cored in the zone 3 interval. The samples from the separatores of the two wells appeared to be fairly similar, as can be seen on the close-up photos of B8 and B10 of figure 2.

Two more samples of well separator material was selected for further investigation, namely B3 (ST-8) which represents zone 5, and B4 (ST-7) that contained large colorless crystals of what might be sodium chloride, figure 2. The rest of the samples consisted mainly of dark grey to black sandy material. Some samples had a slight petroleum like odour.

Investigation of samples collected from well separators

Four samples, out of the ten samples received by GEUS, were selected for further investigations. The moist samples of B3 (ST-8), B8 (ST-12) and B10 (ST-13) were studied by microscopy prior to rinsing (washing with methanol and drying) in order to check that no important information was lost due to sample cleaning prior to the SEM analysis. A number of micrographs of the moist samples were produced for documentation, two of which are shown in figure 3.

Dry matter and chloride content

The dry matter content of the moist sand samples of B3, B8, and B10 was determined by the weight loss upon drying the samples overnight (*c.* 12 h) at 105 ºC, table 2. No attempt was made to determine the dry matter content of sample B4, as the colourless viscous fluid in the bottle was suspected to be mainly glycol left-over from gas production. Glycol is added to some extend in order to avoid gas hydrate formation during the withdrawal of gas.

Moist samples were weighed and placed on a filter, washed 4-5 times with methanol (total volume 65 to100 ml) and dried overnight at room temperature.

Chloride concentrations in the methanol washings were determined by Mohr's titration, and the chloride content was then calculated as percentage sodium chloride of dry sample (table 2). In addition the sodium chloride deriving from formation water, was calculated assuming that the weight loss upon drying is all due to formation water having a sodium chloride content equivalent to 16.0 pct (known from the formation water production test of ST-1 in 1981).

Table 2. Weight loss upon drying selected samples plus NaCl content

Well ID	Well No.	Reservoir Zone	Sample weight	Pct. Weight loss upon drying, 105 ºC	Pct. NaCl	*) Formation water NaCl
B3	ST-8	5	33.5	20.8	0.7	3.7
B4	ST-7	1-3	25	not determined	(16)	
B8	ST-12	3	25.7	23.2	4.9	4.1
B10	ST-13	3	38.9	9.5	2.4	1.7

*) Assuming that weight loss is due to formation water (salinity=16.0 wt.pct NaCl)

The sodium chloride crystals in the B4 (ST-7) sample could not be completely dissolved by washing the sample with approximately 100 ml methanol. Therefore, care was taken to avoid the sodium chloride crystal in the following microscopic investigations of this sample. The sodium chloride content in the sandy material from the well separators of ST-12 and ST-13 appear to be a little higher than can be accounted for by formation water sodium chloride, table 2, indicating that a certain loss of water has occurred due to evaporation. However, the difference between percentage

NaCl found and NaCl percentage calculated from (formation water) weight loss is lower than what might have been expected if solid NaCl had been present in the moist samples, taking into account that NaCl saturation occur for 26 wt. pct solutions. Microscopic investigation of the moist samples did not indicate the presence of any solid sodium chloride either.

Microscopy

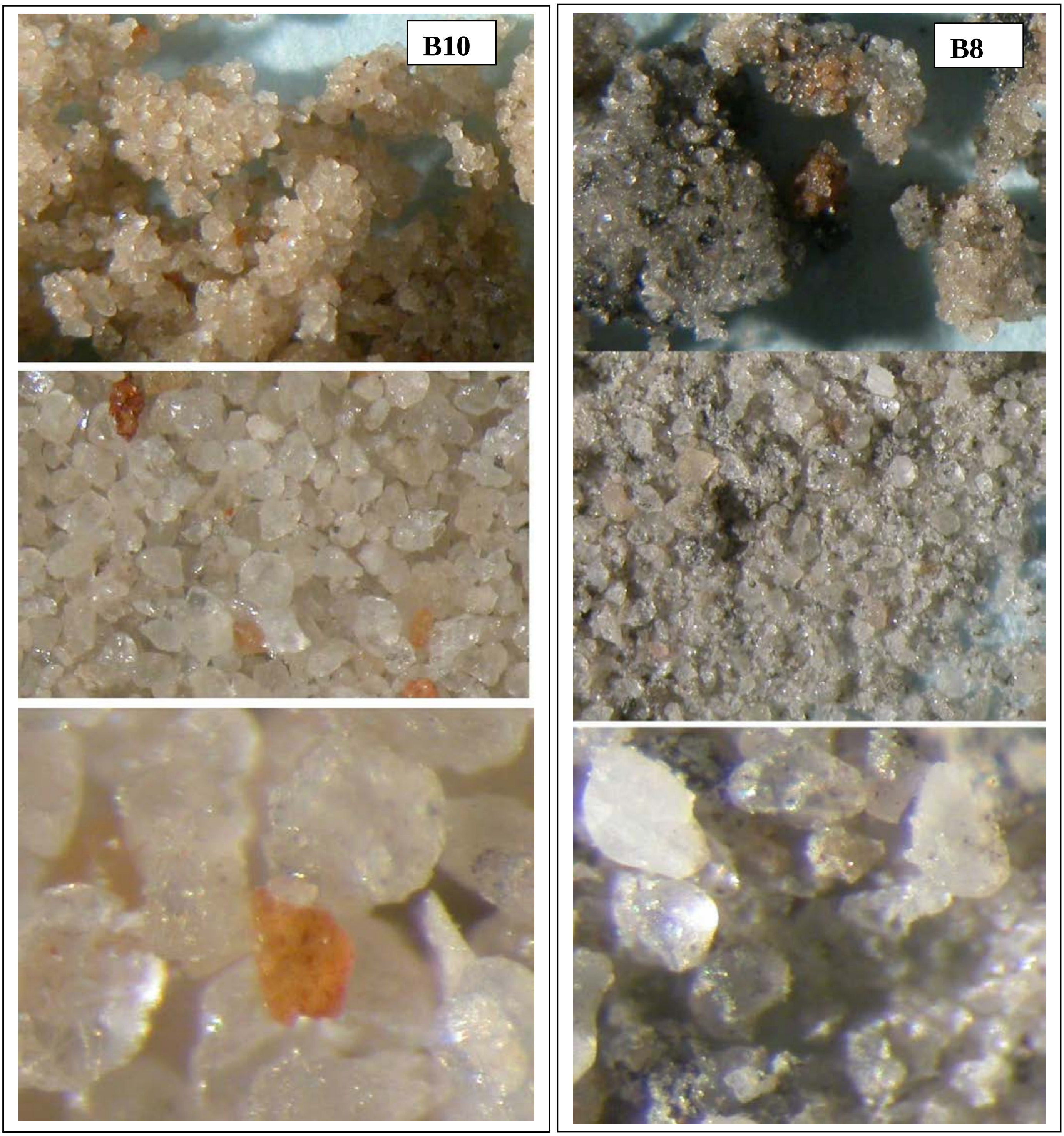


Figure 3. Micrographs of untreated moist samples (6x) top, washed and dried samples (12x) middle same (50x) below.

Microscopic investigations of separator material from B3 (ST-8), B8 (ST-12) and B10 (ST-13) moist as well as washed and dried samples were carried out using a Wild microscope. A few examples for the B8 and B10 samples are shown in the micrographs of figure 3.

The only difference between moist samples and washed and dried samples appear to be the difficulty in separating the particles one from the other of the former, as can seen from figure 3. Furthermore, the sand of B8 appear to be a little more fine grained that of B10.The sand of B3 (not shown in figure 3) appeared to be fairly similar to that of B10 although it contained more impurities observed as black stains on the colourless quartz grains. Darker particles (presumably corrosion products) also appeared to more numerous in B3 than in B10. The amount of impurities, such as particles of rust and metals, was much higher in B4 from ST-7 than in the other samples. Not to mention the fairly large amount of sodium chloride crystals in this sample, as also mentioned above.

SEM including microprobe analysis

Polished sections of washed and dried sands of B3, B4, B8 and B10 embedded into epoxy resins were prepared for the scanning electron microscopy. The polished sections were coated with carbon before being mounted in the chamber of the Philips XL-40 electron microscope.

Representative SEM micrographs of the 4 different samples are shown in figures 4-6, starting with B10 the sample from the ST-13 well, in which injection problems were encountered. The results of the microprobe elemental analysis are shown below each of the SEM micrographs. Based on the elemental analysis, the compound (mineral) composition were automatically calculated, omitting carbon which was used for coating the samples. Note that the carbon peak is less dominating for the more "dense" fine grained sample of B8, figure 5, compared to other more "open space" coarse grained samples. Microprobe elemental analysis was also applied to single particles in order to identify their elemental composition. A number of the particles identified using microprobe analysis have been marked on the SEM micrographs. From the SEM micrographs and the microprobe results, table 3, it appears that the material collected from the four well separators consist mostly of quartz, plus minor quantities of feldspars. Minute amounts of pyrite were observed in all samples, however the total amount of iron was below detection limit for bulk analyses of B3 and B10. The iron content of B4 and B8 is most likely due to iron-containing compounds other than pyrite, table 3

Table 3. Composition of bulk samples based on microprobe counting, as weight. pct

Sample	Figure	SiO2	Al2O3	K2O	CaO	SO3	TiO2	Fe2O3	MoO3	Cl
B3, ST-8	6	93.43	2.19	1.14		1.15				2.07
B4, ST-7	7	71.30	4.96	1.38	1.80	5,74		10.12		
B8, ST-12	5	91.16	2.70	1.21		1,38	1.08	1.70		0.55
B10, ST-13	4	97.76								2.24

The material of B8 from the ST-12 well separator contain a higher proportion of more fine grained material, and is also more rich in heavy minerals, figure 5 and table 3, than the other samples. The SEM micrograph of B4, figure 7, confirm together with the microprobe analysis that the material from the ST-7 well separator contain more impurities, such as rust particles and iron.

Studies of a number of individual mineral grains at greater magnification did not reveal any mineral overgrowth which could point to a beginning of cementation that had been anticipated to be the cause of the injection problems in the ST-13 well.

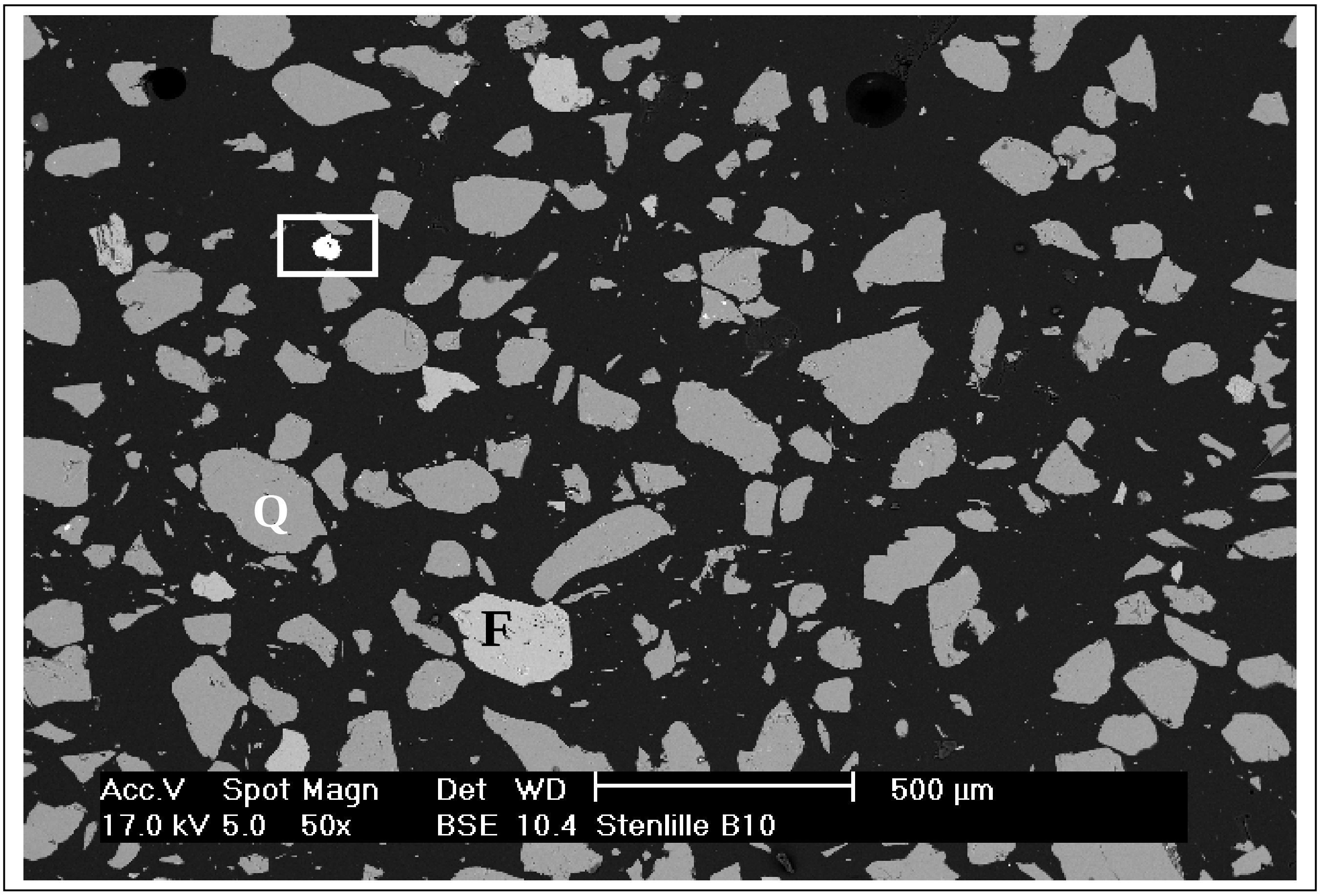
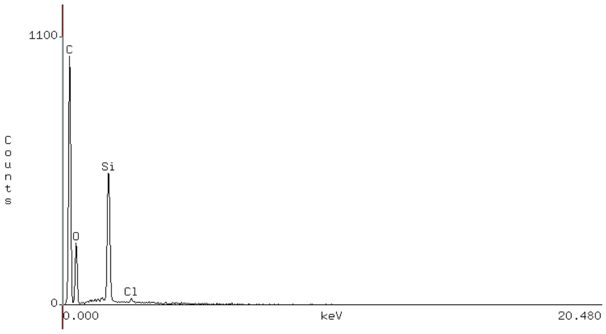


Figure 4. SEM micrograph of B10 (ST-13, zone 3), polished section of separator material after washing with methanol, Q= quartz; F= feldspar; square = pyrite



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Peak Identification Results
Separator B10-Bulk Analysis
Tue Jun 22 16:49:57 2004

Element  k-ratio    ZAF    Atom %  Element  Wt % Err. Compound Compound    No. of
         (calc.)                     Wt %   (1-Sigma) Formula    Wt %    Cations
  Si-K    0.3746   1.220   32.91    45.70    +/- 0.70   SiO2     97.76     12.000
  Cl-K    0.0157   1.423    1.28     2.24    +/- 0.28   Cl        2.24      0.466
  O -K     ---     2.687   65.81    52.06 S     ---      ---      ---        ---
  Total                   100.00   100.00                       100.00     12.466

   The number of cation results are based upon 24 Oxygen atoms
   Table Symbols:  S -- Wt.% calculated by Stoichiometry
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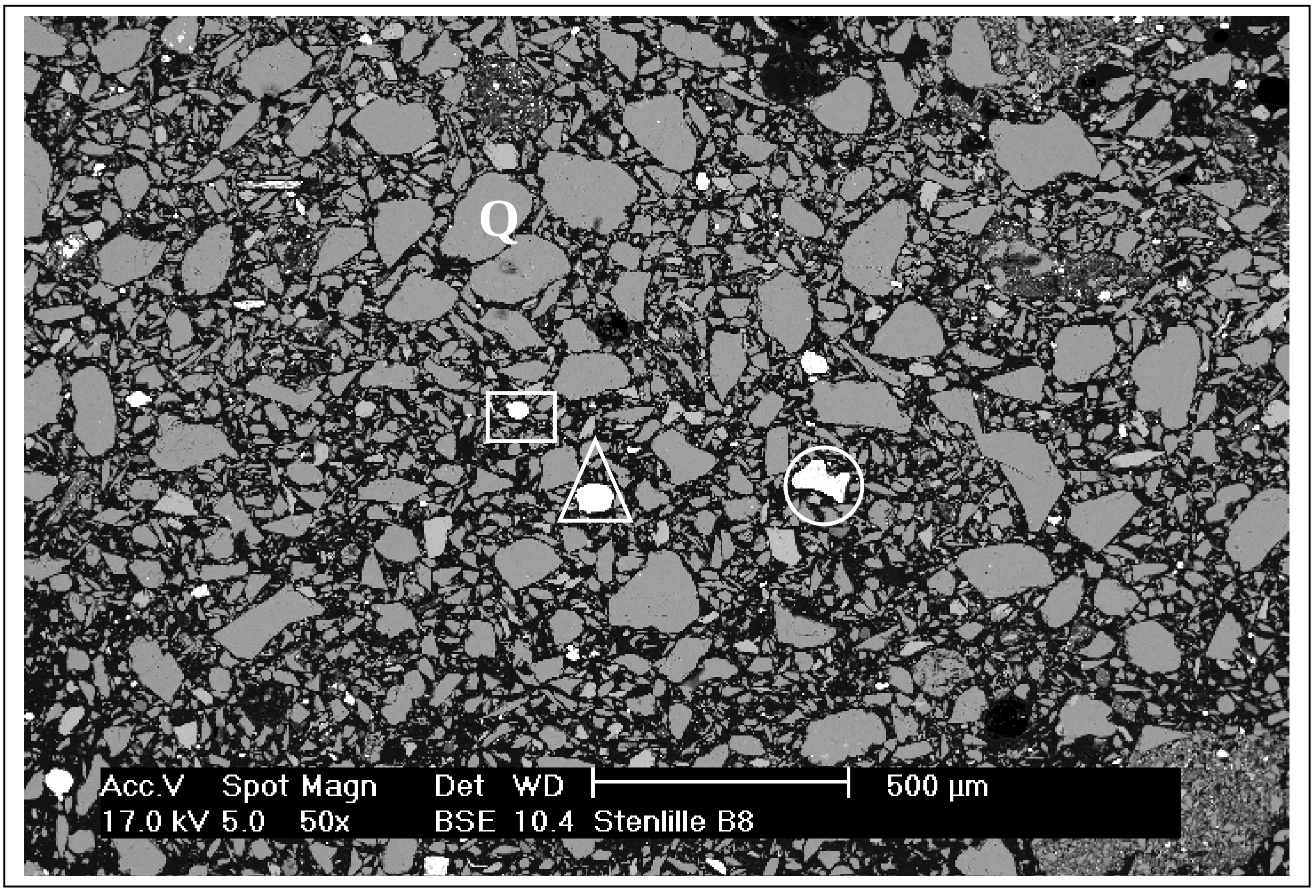
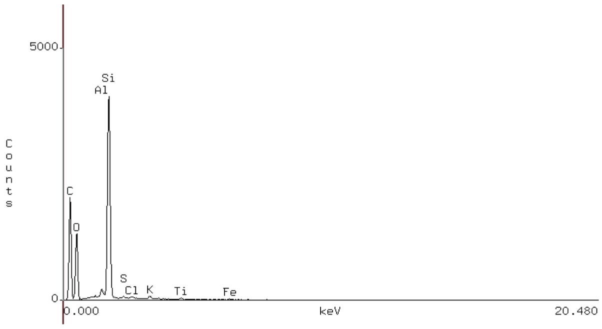


Figure 5. SEM micrograph of B8 (ST-12, zone 3), polished section of separator material after washing with methanol Q= quartz; square = pyrite; triangle = zircon; circle = ilmenite



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Peak Identification Results
Separator B8-Bulk Analysis
 Jun 22 17:01:07 2004
Quantitative Analysis
Element  k-ratio    ZAF   Atom %  Element  Wt % Err. Compound Compound    No. of
         (calc.)                    Wt %   (1-Sigma) Formula     Wt %     Cations
  Al-K    0.0102   1.409    1.08    1.43    +/- 0.10   Al2O3      2.70     0.393
  Si-K    0.3396   1.255   30.94   42.61    +/- 0.27   SiO2      91.16    11.241
  S -K    0.0037   1.495    0.35    0.55    +/- 0.07   SO3        1.38     0.128
  Cl-K    0.0039   1.415    0.32    0.55    +/- 0.07   Cl         0.55     0.116
  K -K    0.0081   1.250    0.53    1.01    +/- 0.07   K2O        1.21     0.191
  Ti-K    0.0052   1.249    0.28    0.65    +/- 0.09   TiO2       1.08     0.100
  Sm-L    0.0012   1.481    0.02    0.17    +/- 0.32   Sm2O3      0.20     0.008
  Fe-K    0.0097   1.232    0.44    1.19    +/- 0.18   Fe2O3      1.70     0.158
  O -K     ---     2.712   66.05   51.83 S     ---      ---       ---       ---
  Total                   100.00  100.00                        100.00    12.335
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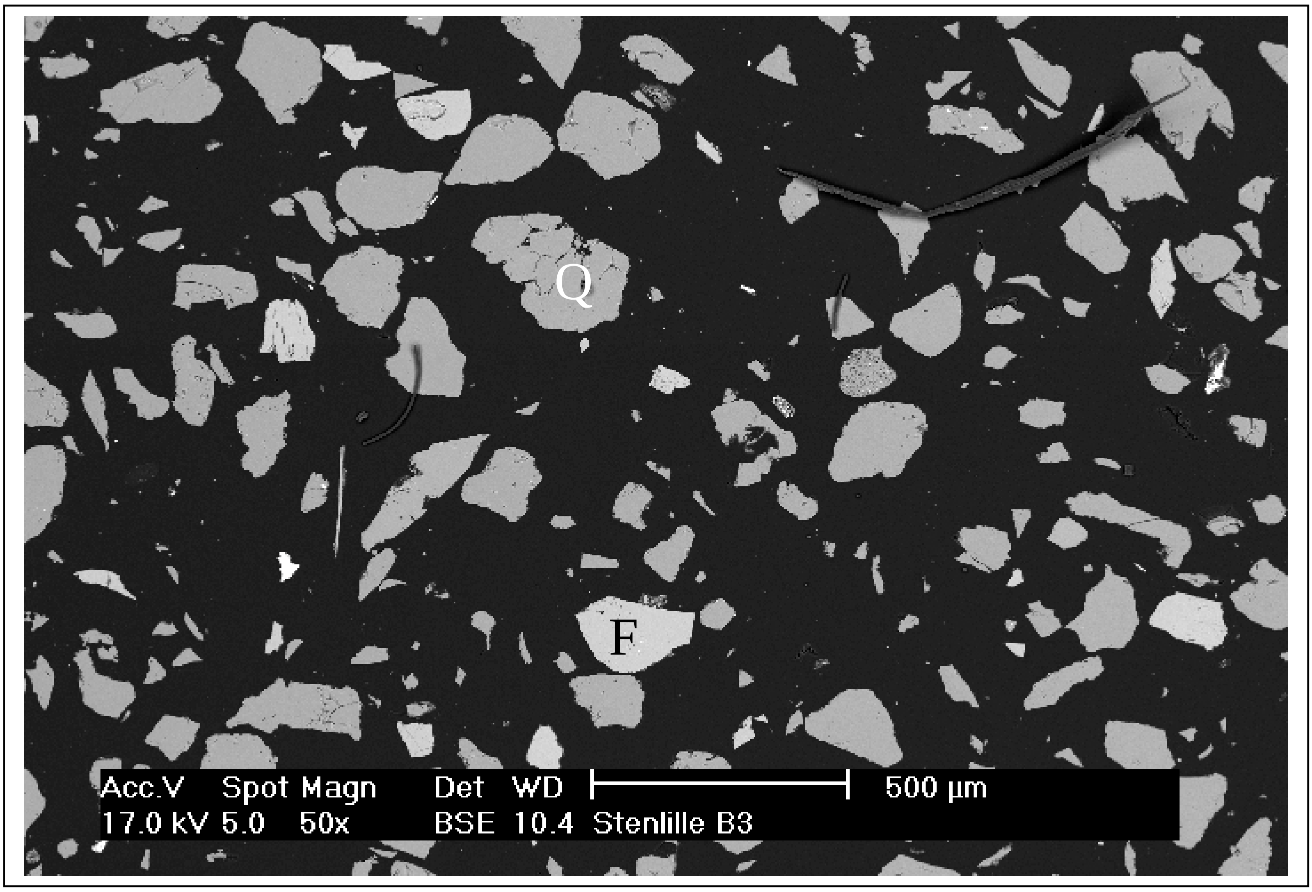
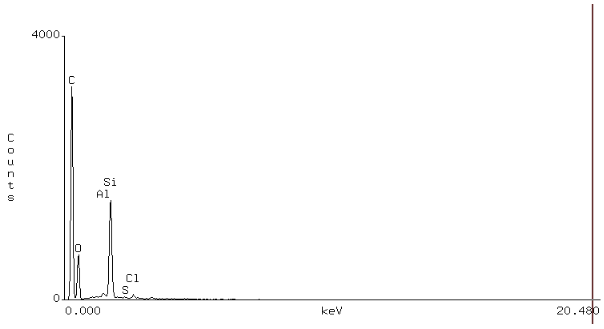


Figure 6. SEM micrograph of B3 (ST-8, zone 5), polished section of separator material after washing with methanol, Q= quartz; F= feldspar



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Peak Identification Results
Separator B3-Bulk Analysis
Quantitative Analysis
Tue Jun 22 18:05:56 2004

Element  k-ratio    ZAF   Atom %  Element  Wt % Err. Compound Compound   No. of
         (calc.)                    Wt %   (1-Sigma) Formula     Wt %    Cations
  Al-K    0.0084  1.384     0.87    1.16    +/- 0.13   Al2O3      2.19     0.320
  Si-K    0.3534  1.236    31.57   43.67    +/- 0.43   SiO2      93.43    11.554
  Cl-K    0.0146  1.417     1.19    2.07    +/- 0.17   Cl         2.07     0.435
  K -K    0.0075  1.261     0.49    0.95    +/- 0.15   K2O        1.14     0.181
  S -K    0.0031  1.497     0.29    0.46    +/- 0.15   SO3        1.15     0.107
  O -K     ---    2.751    65.58   51.68 S     ---       ---       ---       ---
  Total                   100.00  100.00                        100.00    12.596
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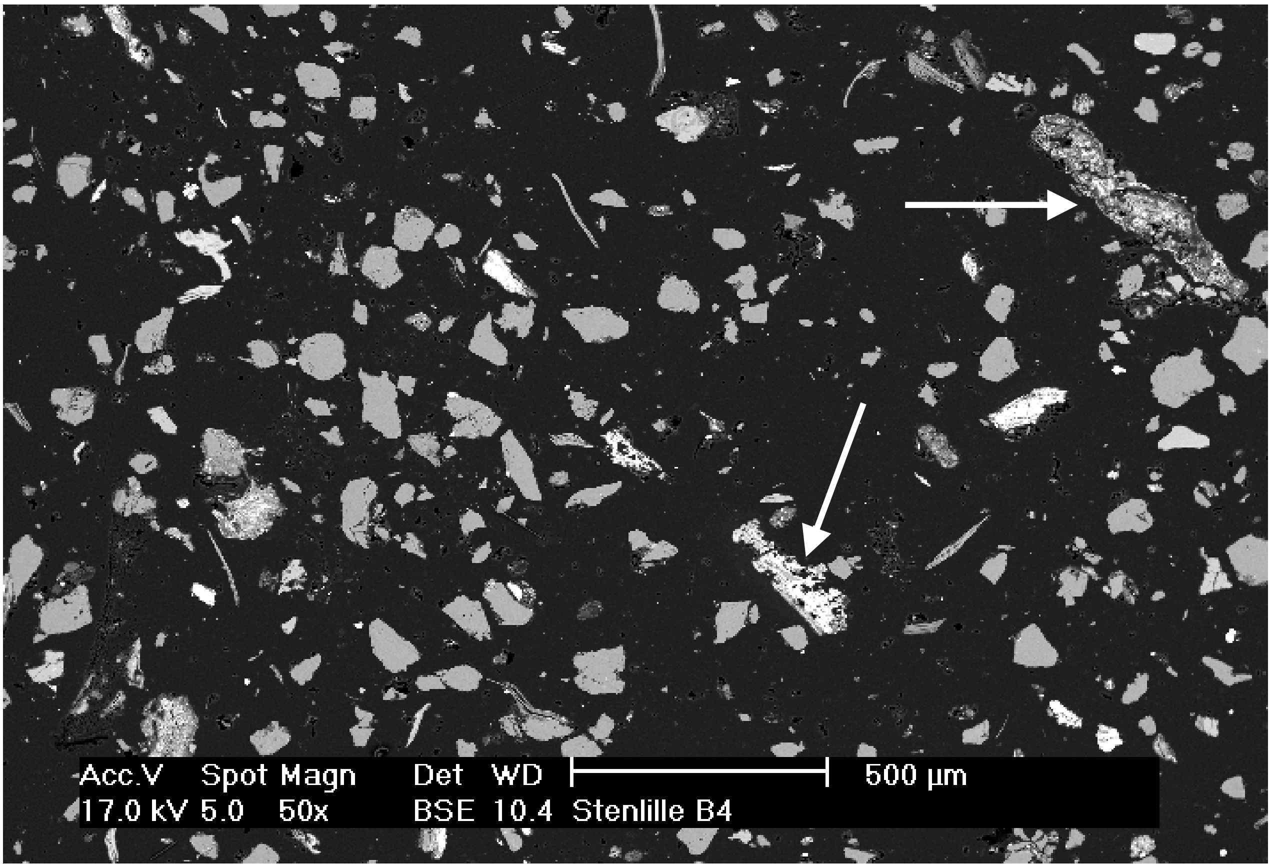
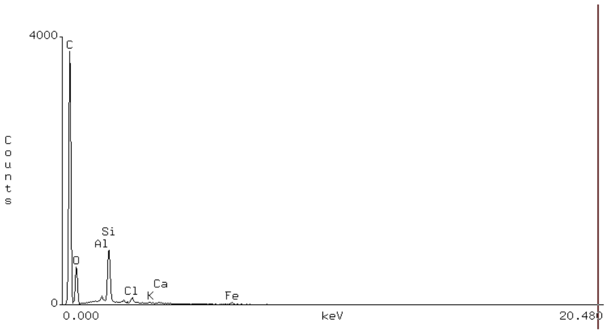


Figure 7. SEM micrograph of B4 (ST-7, zones 1-3), polished section of separator material after washing with methanol. Arrows = lumps of iron (oxide)



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Peak Identification Results
Separator B4-Bulk Analysis
Quantitative Analysis
Tue Jun 22 18:16:29 2004

Element  k-ratio    ZAF   Atom %  Element  Wt % Err. Compound Compound    No. of
         (calc.)                    Wt %   (1-Sigma) Formula     Wt %     Cations
  Al-K    0.0178   1.474    2.09    2.63    +/- 0.20   Al2O3      4.96      0.786
  Si-K    0.2562   1.301   25.53   33.33    +/- 0.52   SiO2      71.30      9.585
  S -K    0.0162   1.417    1.54    2.30    +/- 0.23   SO3        5.74      0.579
  Cl-K    0.0342   1.371    2.85    4.69    +/- 0.26   Cl         4.69      1.069
  K -K    0.0092   1.238    0.63    1.14    +/- 0.21   K2O        1.38      0.236
  Ca-K    0.0110   1.174    0.69    1.29    +/- 0.23   CaO        1.80      0.260
  Fe-K    0.0583   1.215    2.73    7.08    +/- 0.67   Fe2O3     10.12      1.024
  O -K     ---     2.891   63.93   47.54 S     ---       ---       ---        ---
  Total                   100.00  100.00                        100.00     13.539
```

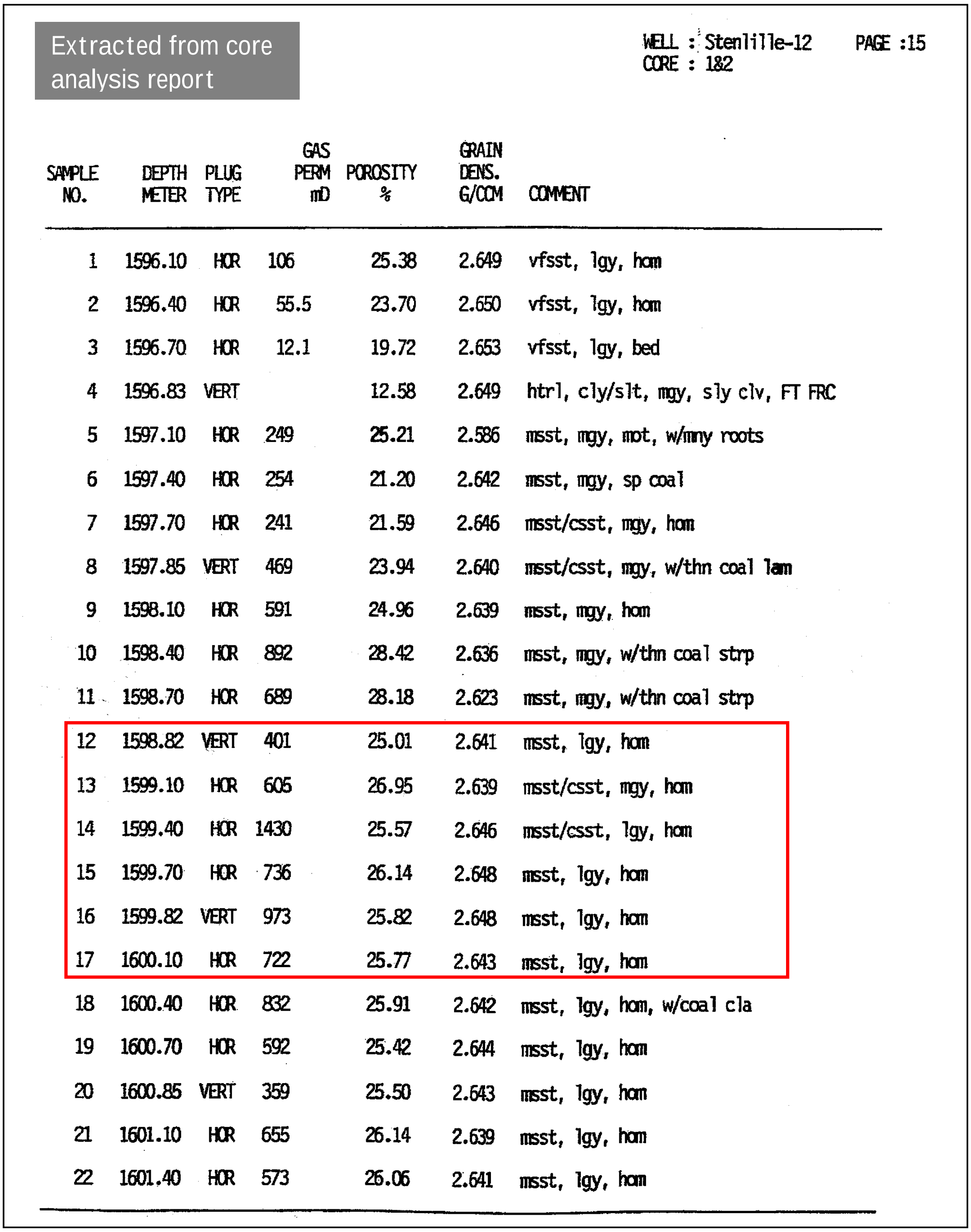
Study of core plugs for comparison

Figure 8. Core#1 from ST-12, representing part of zone no. 3. Selected plugs indicated by numbers

In order to compare the material collected from the well separators with the original reservoir rock, suitable samples were looked for in the GEUS core archive. The best choice appeared to be 6 plugs from core#1 of ST-12, shown on figure 8.

Data on selected core plugs

The 6 plugs had previously been used for permeability measurements with the results given below.



Extracted from core analysis report

WELL : Stenlille-12 PAGE :15
CORE : 1&2

SAMPLE NO.	DEPTH METER	PLUG TYPE	GAS PERM mD	POROSITY %	GRAIN DENS. G/CCM	COMMENT
1	1596.10	HOR	106	25.38	2.649	vfsst, lgy, hom
2	1596.40	HOR	55.5	23.70	2.650	vfsst, lgy, hom
3	1596.70	HOR	12.1	19.72	2.653	vfsst, lgy, bed
4	1596.83	VERT		12.58	2.649	htrl, cly/slt, mgy, sly clv, FT FRC
5	1597.10	HOR	249	25.21	2.586	msst, mgy, mot, w/mny roots
6	1597.40	HOR	254	21.20	2.642	msst, mgy, sp coal
7	1597.70	HOR	241	21.59	2.646	msst/csst, mgy, hom
8	1597.85	VERT	469	23.94	2.640	msst/csst, mgy, w/thn coal lam
9	1598.10	HOR	591	24.96	2.639	msst, mgy, hom
10	1598.40	HOR	892	28.42	2.636	msst, mgy, w/thn coal strp
11	1598.70	HOR	689	28.18	2.623	msst, mgy, w/thn coal strp
12	1598.82	VERT	401	25.01	2.641	msst, lgy, hom
13	1599.10	HOR	605	26.95	2.639	msst/csst, mgy, hom
14	1599.40	HOR	1430	25.57	2.646	msst/csst, lgy, hom
15	1599.70	HOR	736	26.14	2.648	msst, lgy, hom
16	1599.82	VERT	973	25.82	2.648	msst, lgy, hom
17	1600.10	HOR	722	25.77	2.643	msst, lgy, hom
18	1600.40	HOR	832	25.91	2.642	msst, lgy, hom, w/coal cla
19	1600.70	HOR	592	25.42	2.644	msst, lgy, hom
20	1600.85	VERT	359	25.50	2.643	msst, lgy, hom
21	1601.10	HOR	655	26.14	2.639	msst, lgy, hom
22	1601.40	HOR	573	26.06	2.641	msst, lgy, hom

Table 4. Data on permeability, porosity, density and lithology, from ref.2

The plugs had been rinsed with methanol in order to remove formation water residues prior to the permeability measurements /2/. Thus, it should be possible to use the plugs for microscopic investigation without any further cleaning. Inspection using a simple microscope also indicated that samples would be suitable for scanning electron microscopic investigation, figure 9.

Figure 9. Micrographs of plug No.14 from core#1 of ST-12 ,magnification 6x (upper) 25x (lower) Location of plug no. 14 shown is on figure 8.

Comparing the micrographs of plug no.14 with those of well separator sample B10, figure 3, the two samples appear to have similar composition.

SEM including microprobe analysis

Polished sections of the 6 core plugs were prepared for scanning electron microscopy by the same technique as was used for the well separator samples. Microprobe analysis was carried out on both bulk samples table 5, as well as for individual particles, indicated on the micrographs figures 10-14.

Table 5. Summary of microprobe bulk analyses of selected core plugs, as weight pct .

Plug No.	SiO2	Al2O3	K2O	CaO	SO3	MoO3	Cl
12	97.73	1.57	0.49				0.22
13	96.22	1.65	1.29	0.33		1.29	
14	98.33	1.16	0.28				0.23
15	97.55	1.12	0.27		1.06		
16	97.44	1.35	0.33	0.36	0.52		
17	96.37	1.64	0.47	0.39		0.86	0.28

From the SEM micrographs, figure 10-14, and the microprobe results, table 5, it can be seen that the reservoir rock of the very permeable part of core#1 from ST-12 consist mainly of quartz, plus minor quantities of feldspars. Minute amounts of pyrite was observed in all core plugs, however the total amount of iron was below detection limit for bulk analyses.

The reservoir rock consist of an open network of quartz grains, containing relatively little pore filling material. Bulk analysis of the pore filling material indicate the presence of feldspars, barite and pyrite, figure 12 and table 6.

Table 6. Result of microprobe analysis of filling material between large quartz grains, plug no. 14

SiO2	Al2O3	K2O	CaO	MgO	SO3	BaO	Fe2O3	Cl
43.13	20.18	2.38	19.69	1.51	3.98	6.18	5.56	0.39

The microprobe analyses indicate that the proportion of carbonate minerals in the reservoir is very low, if present at all.

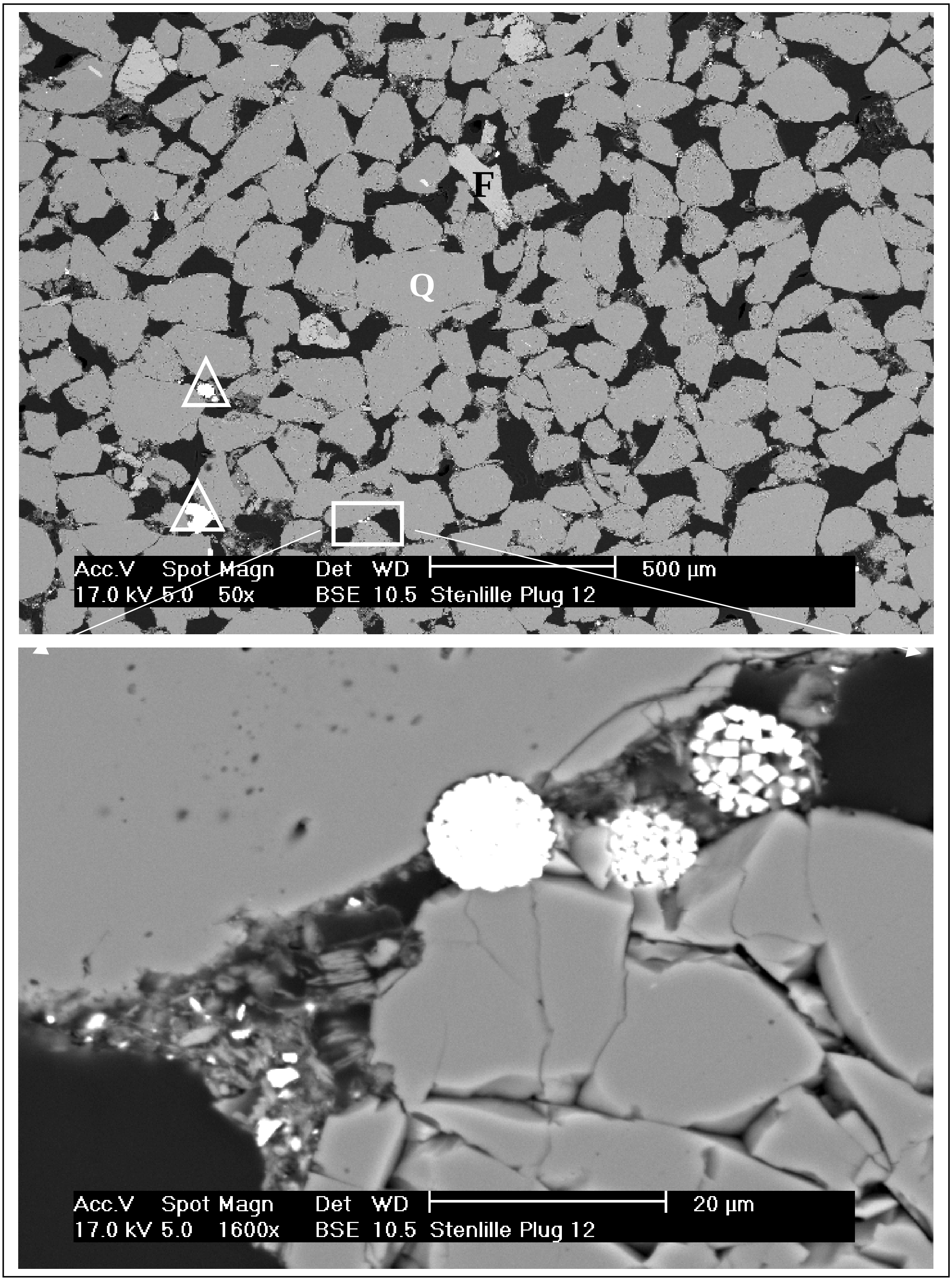


Figure 10. SEM micrograph of polished section of core plug 12; core#1, ST-12. ***.*** *Q = quartz; F = feldspar; square = pyrite; triangle = zircon*

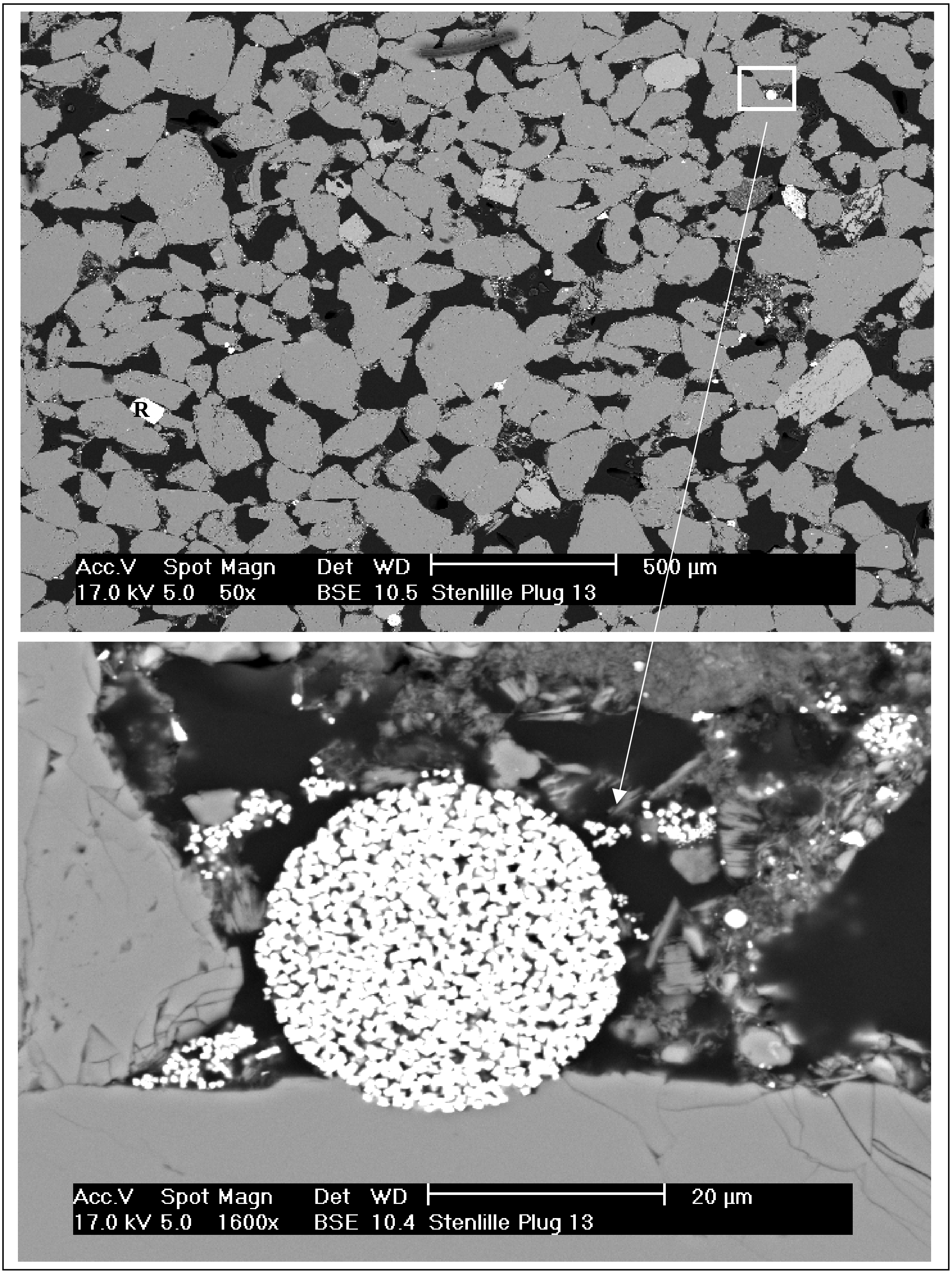


Figure 11. SEM micrograph of polished section of core plug 13; core#1, ST-12
R = Rutile; square = pyrite

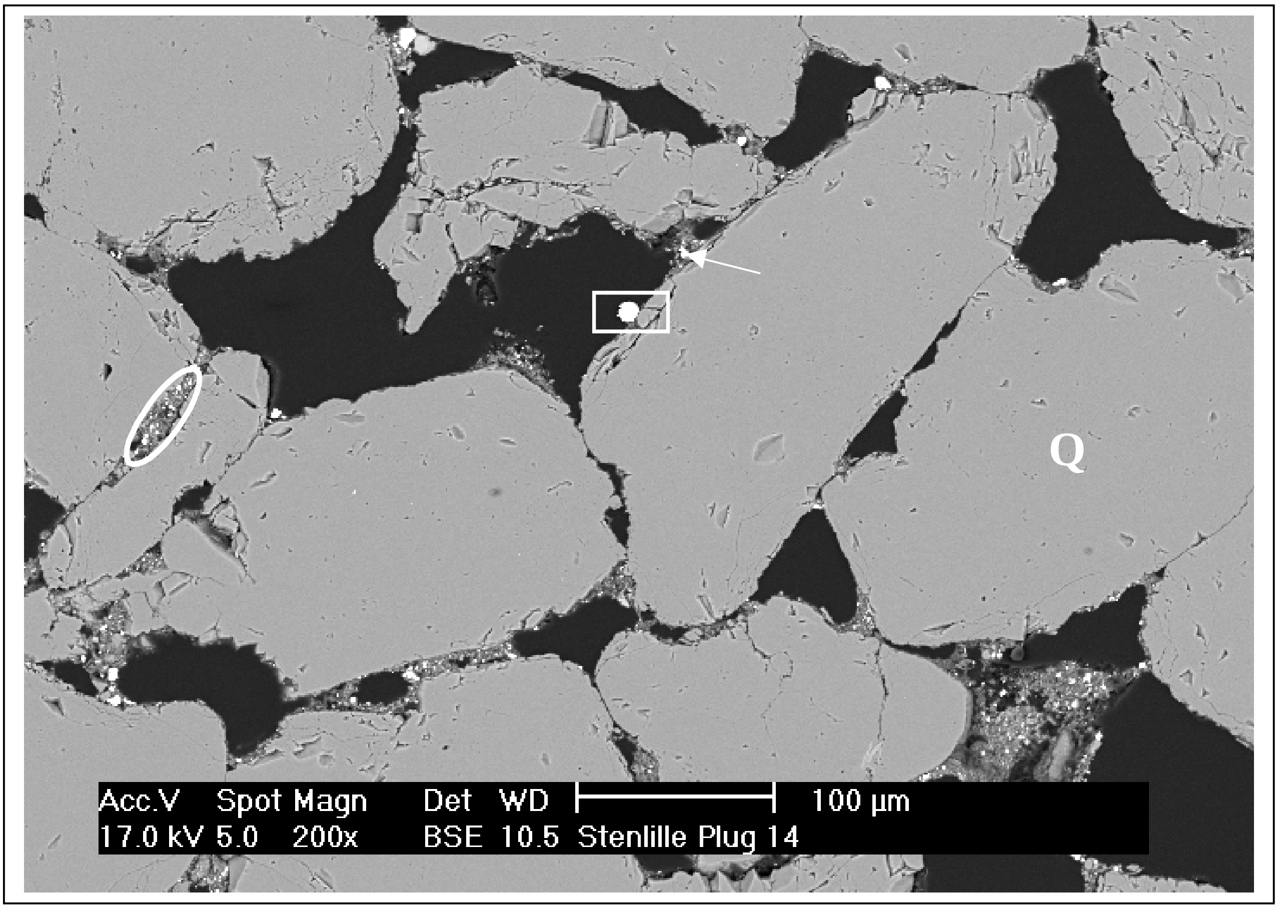
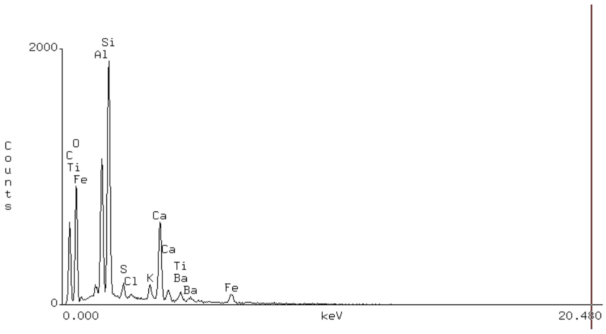


Figure 12. SEM micrograph of polished section of core plug 14 core#1, ST-12
Q= quartz; square = pyrite; arrow = barite; ellipse = filling, composition shown below.



`Peak Identification Results`

ST-12 core#1, Plug 14 Filling Material (indicated by ellipse on figure 12)

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Quantitative Analysis
Tue Jun 22 18:34:45 2004
Element  k-ratio   ZAF    Atom %  Element  Wt % Err. Compound Compound   No. of
         (calc.)                    Wt %   (1-Sigma) Formula    Wt %     Cations
  Mg-K    0.0049  1.855    0.86     0.91    +/- 0.07   MgO      1.51      0.335
  Al-K    0.0683  1.564    9.09    10.68    +/- 0.18   Al2O3   20.18      3.540
  Si-K    0.1371  1.471   16.49    20.16    +/- 0.22   SiO2    43.13      6.420
  S -K    0.0117  1.367    1.14     1.59    +/- 0.11   SO3      3.98      0.444
  Cl-K    0.0030  1.315    0.25     0.39    +/- 0.06   Cl       0.39      0.098
  K -K    0.0170  1.163    1.16     1.98    +/- 0.15   K2O      2.38      0.452
  Ca-K    0.1059  1.126    6.84    11.93    +/- 0.15   CaO     16.69      2.662
  Ba-L    0.0384  1.443    0.93     5.54    +/- 0.26   BaO      6.18      0.360
  Ti-K    0.0000  1.237    0.00     0.00    +/- 0.00   TiO2     0.00      0.000
  Fe-K    0.0322  1.206    1.60     3.89    +/- 0.38   Fe2O3    5.56      0.623
  Total                  100.00   100.00
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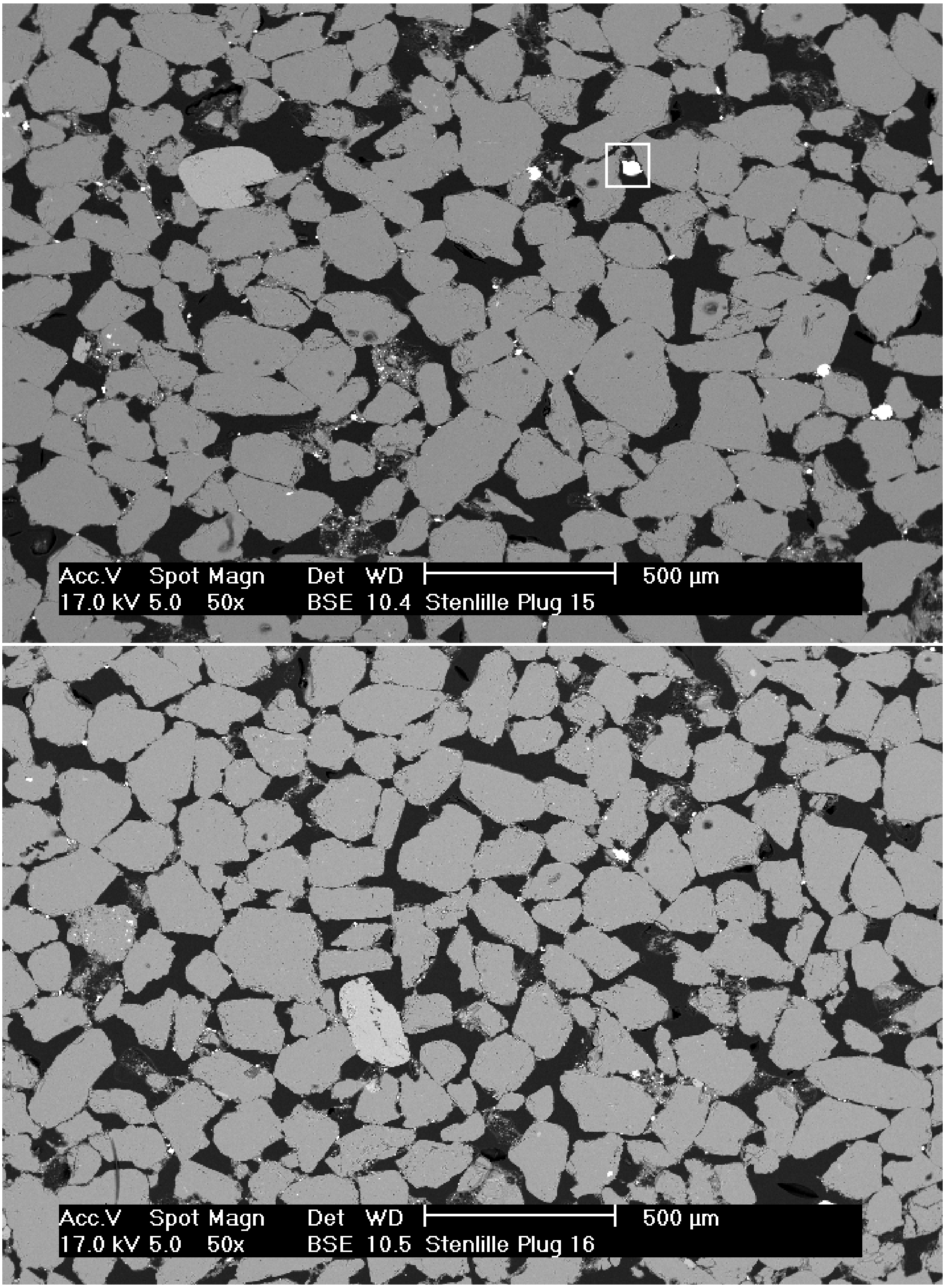


Figure13. SEM micrographs of polished sections of core plugs 15 & 16; core#1, ST-12
Square = pyrite

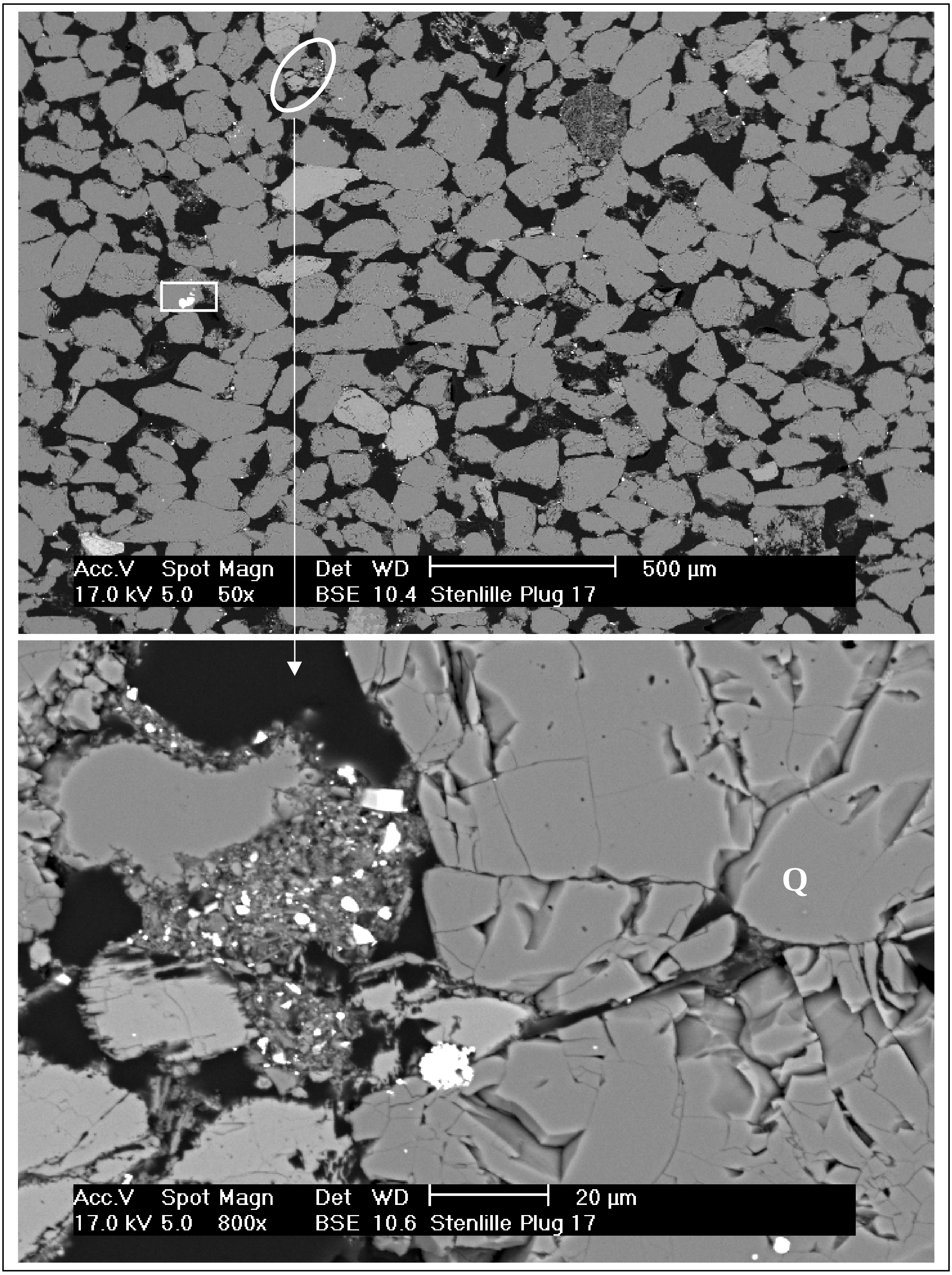


Figure 14. SEM micrographs of polished section of core plug 17 core#1, ST-12. Q = quartz, Square = pyrite; ellipse = filling.

Discussion of results

Examination of the sandy material that accumulated in well separators during withdrawal of gas from the underground gas storage at Stenlille was performed in order to reveal why problems with gas injection in the ST-13 arose after several injection/withdrawals cycles. The material collected from the well separators consist mostly of sand from the reservoir rock, as was shown by microscopy, figure 3, as well as scanning electron microscopy, figures 4-7, including microprobe analysis, table 3. However, no major cause for the injection problems could be deduced from the examination of well separator samples alone, as the material from the ST-13 well appeared to be not significantly different from that of the other wells which did not experience injection problems.

Therefore, close examination was also carried out on core plugs of the reservoir rock representing zone 3 exploited by the ST-13 well, in order to check for minor differences that might give an answer to the problem. The sandy material of B10 recovered from the well separator of ST-13 appeared to be similar to that of the reservoir rock of zone 3 with respect to composition and grain size distribution, compare tables 3 and 5 and SEM micrographs of figure 4 and figures 10-14. The plugs selected for comparison were taken from core#1 of the ST-12 well, as the cores taken in the ST-13 represent deeper zones of the Gassum Sandstone Formation. The ST-12 well also exploit zone 3 of the reservoir, however injection problems were not reported for this well. Sands from well separators of both wells were examined. It is worth noticing that the material of sample B8 collected from ST-12 is more fine grained that of sample B10 from ST-13, figure 3, and have a little different mineral composition, table 3 and figures 4, 5. However, with the information at hand it is not possible to decide whether the difference between the two samples B8 and B10 is due to different parts of zone 3 being perforated in the two wells, or to differences in mode of operation of the two wells, ST-12 and ST-13. Conventional core analyses including rock permeability /2/ show that zone 3 of the reservoir is not completely homogeneous, and the plugs selected for comparison with the well separator sands were taken from the most permeable part of the zone, table 4.

Sample B3 recovered from the well separator of the ST-8 well that exploits the deeper zone 5 of the reservoir resembles B10 (ST-13), with respect to grain size, figures 4 and 6, but appear to have a little higher feldspar content compared to B10 which consist of almost pure quartz, table 3.

Hypotheses regarding causes for injection problems. One may imagine at least 3 ways in which injection problems could occur in the injection/withdrawal wells at Stenlille: 1) clogging of the reservoir rock due to precipitation of salts; 2) clogging due to migration of fines; 3) blocking due to accumulation of large volumes of sand in the well.

The first hypothesis, clogging due to precipitation of salt is not very likely, as one should expect cementation to stabilise the reservoir rock, thus less sand should be expected to accumulate in the ST-13 well in which injection problems occurred, contrary to what was observed. Furthermore, no sign of mineral overgrowth was observed on the reservoir sand recovered from the separator of the ST-13 well.

The second hypothesis is difficult to prove or disprove, however, if clogging due to fines migration was the main cause for injection problems one might expect such a problem more likely to occur in a rock type producing grain sizes present in the B8 sample of ST-12, figure 5, rather than in a more coarse rock producing the type of sand in B10 of ST-13, figure 4. Possibly, clogging due to fines migration would also lead to lower production of solids during gas withdrawal from such a well, opposite to what was observed.

Injection problems may possibly occur if fairly large volumes of sand accumulate in the well during the preceding gas withdrawal. Based on the information available to us including the results of the present investigation, this hypothesis is considered to be the most likely one for the injection problems encountered in the ST-13 well. The sand collected from the separator of ST-13 consist of almost pure quartz, and was most likely produced from an interval consisting a reservoir rock type represented by the most permeable plugs examined here. The rock type of these plugs is very poorly cemented, and one may imagine, that the quartz grains are fairly easily moved during the injection/withdrawal operation. Thus, fairly large volumes of sands may accumulate in the well during gas withdrawals.

Conclusions

Three hypotheses were considered for the reason of the injection problems encountered in the ST-13 well. The two hypothesis on clogging resulting from either precipitation or fines migration were considered to be less likely, because higher volumes of sand was observed for the well encountering injection problems compared to the other wells not having this problem, contrary to what might have been expected. Furthermore, no sign of mineral overgrowth was observed on the sand collected from the ST-13. Also, comparison of the grain size distribution of sands from different wells indicated that the type of sand from ST-13 would be the less likely to cause problems due to clogging with fines.

The most plausible explanation for injection problems encountered in the ST-13 well is that fairly large volumes of sand accumulated in the well during the preceding gas withdrawal, which could then block gas injection at a later time. The sand accumulated in the separator of the ST-13 consisted almost of pure quartz, which might have been produced from a poorly cemented reservoir rock, such as that represented by core plugs examined in the present investigation.

References

/1/ DONG A/S Stenlille Gas Storage – 2003 Annual Report.

/2/ Conventional Core Analysis For Dansk Naturgas A/S - Well: Stenlille -12; Core 1 and 2. DGU service report no. 22, 1994.

Addendum: Cleaning of ST-13 well bore

Based on the conclusions of the present report, DONG decided to clean up the well bore of ST-13. During the clean up 2 -3 cubic metres of sand was removed from the well bore, thereby solving the problems with low injectivity (oral information from DONG). The sand appeared to be rather fine grained, therefore DONG asked GEUS to examine a sample of this material to be able to decide whether the sand represents reservoir matrix material, or just a fine grained fraction of the reservoir. This information could help decide which precautions should be taken in order to minimise injectivity problems in the future.

A sample of well bore sand was examined for its water content, then washed with methanol and examined using scanning electron microscopy including microprobe analysis. Water content and chloride content removed by methanol washings are shown table 7, together with results for well separator sample (taken from table 2).

Table 7. Weight loss upon drying well bore and separator samples, plus NaCl content

Well ID	Well No.	Reservoir Zone	Sample weight	Pct. Weight loss upon drying, 105 ºC	Pct. NaCl	*) Formation water NaCl
ST-13	ST-13	3	47.6	16.7	0.8	3.0
B10	ST-13	3	38.9	9.5	2.4	1.7

*) Assuming that weight loss is due to formation water (salinity=16.0 wt.pct NaCl)

Last column of table 7 indicate the amount of sodium chloride that may derive from formation water. Comparing last two columns of table 7 it is obvious that the water present in the sample is less saline than the formation water of the Gassum Formation.

A polished section of the well bore sand was prepared for scanning electron microscopy on the Philips XL-40 instrument. Microprobe analysis of the bulk sample shown on figure 15 indicate that sample consist mainly of quartz, table 8. Microprobe analysis on single grains with a different appearance indicated that minor quantities of feldspars and iron filings are also present in the sample. Minute quantities of Barite were also observed.

Table 8. Composition of bulk samples based on microprobe counting, as weight. pct

Sample	Figure	SiO2	Al2O3	K2O	Fe2O3	Cl
ST-13 well bore	15	98.43				1.57
Plug 14, ST-12	12	98.33	1.16	0.28		0.23
ST-13 separator	4	97.76				2.24

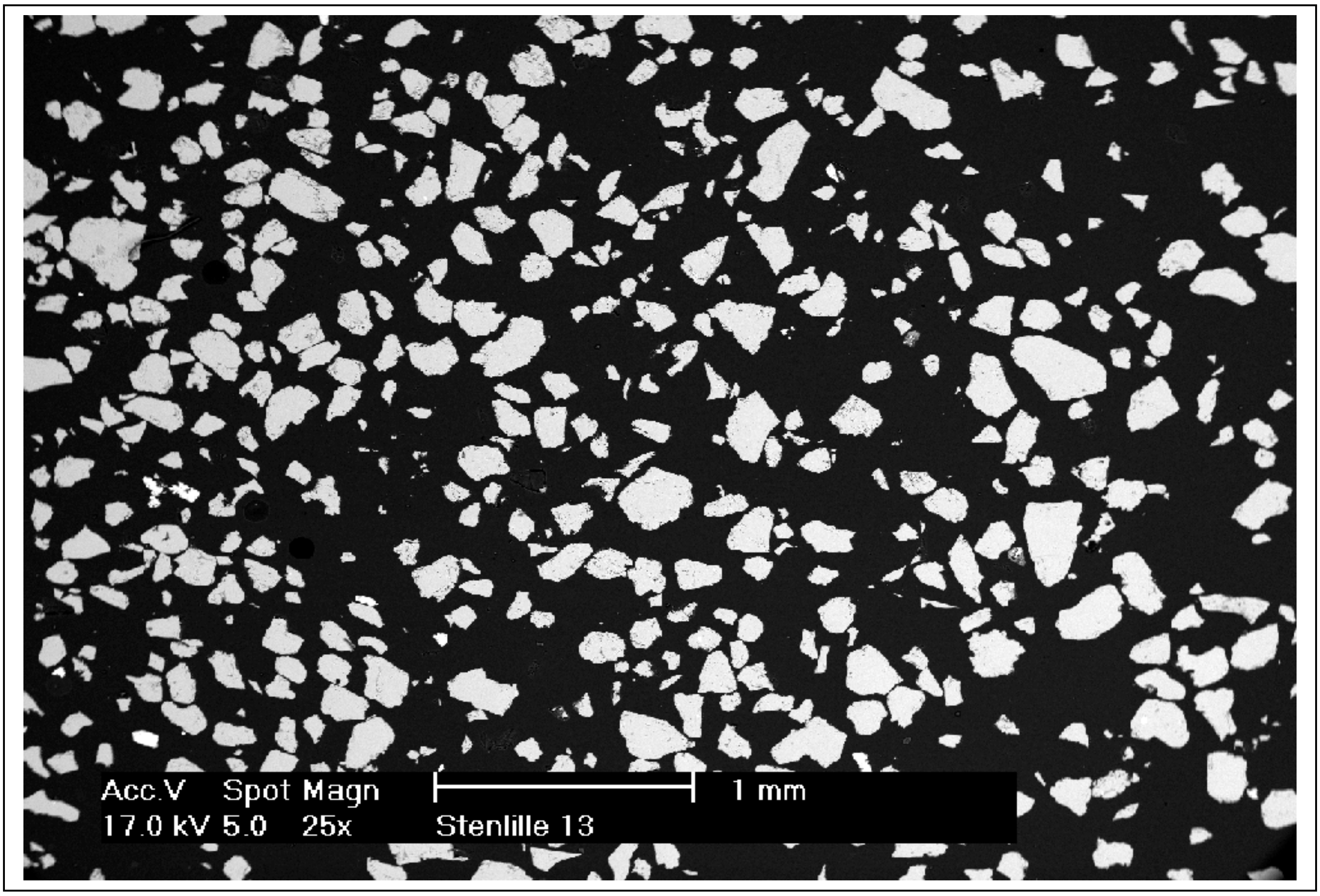
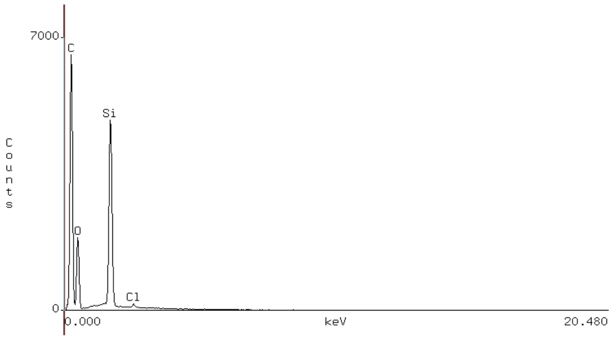


Figure 15. SEM micrograph of sand recovered from clean-up of ST-13



Peak Identification Results

St-13 well bore clean-up

Tue Aug 17 11:41:09 2004

Quantitative Analysis

```
Element  k-ratio    ZAF   Atom %  Element  Wt % Err. Compound Compound    No. of
         (calc.)                    Wt %   (1-Sigma) Formula     Wt %    Cations
  Si-K    0.3765   1.222   33.03   46.01    +/- 0.27   SiO2     98.43     12.000
  Cl-K    0.0110   1.428    0.90    1.57    +/- 0.15   Cl        1.57      0.325
  O -K     ---     2.668   66.07   52.42 S     ---      ---      ---        ---
  Total                   100.00  100.00                       100.00     12.325

   The number of cation results are based upon 24 Oxygen atoms
   Table Symbols:  S -- Wt.% calculated by Stoichiometry
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Comparing the analytical results of well bore sand with those of the core material, there can be little doubt that the sand accumulating in the well bore during gas withdrawal was coming from the reservoir matrix itself, and do not represent just a fine grained fraction of the reservoir.