DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2002/80

Petrographic investigation of granites from the Metro stations in Copenhagen II

Additional data on granite panel discolouring, based on petrographical analysis and testing porosity and permeability properties

Stig A. Schack Pedersen, Sandra Piazolo and Niels Springer

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MINISTRY OF THE ENVIRONMENT

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Summary

Non-miscoloured Chinese Granite from mock-up (MK)

1. Medium to coarse grained stone
2. Texture of stone is only slightly anisotropic i.e. shows some preferred orientation of dark minerals
3. Slightly irregularly surfaced biotite and chlorite
4. Largely “closed” grain boundaries in stone providing reduced surface area for erosion and pathways for fluid
5. Chlorine presence within biotite and chlorite
6. Lower porosity/permeability
7. Combination of reduced porosity/permeability and reduced surface areas of biotite/chlorite to be eroded, lower risks of ferrous elements being transported to stone surface where they would oxidize

Non-miscoloured Chinese Granite from Frederiksberg Station (FK) – additional SEM data

1. Fine to medium grained stone
2. Texture of stone is anisotropic i.e. shows a preferred orientation of minerals
3. Abundant fine grained, iron rich minerals (biotite and chlorite) within matrix of stone which show an irregular surface and partly “edged, open” grain boundaries
4. Chlorine presence within biotite and chlorite
5. High porosity and permeability relative to the reference Finnish granite from Nørreport
6. Magnetite particles do not appear to be eroded

Jetburned Chinese Granite (KJ)

1. Fine to medium grained stone
2. Texture of stone is only very weakly anisotropic i.e. shows minor preferred orientation of minerals
3. Abundant fine to medium grained, iron rich minerals (biotite and chlorite) within matrix of stone which show an smooth surface and “closed” grain boundaries
4. Chlorine presence within biotite and chlorite
5. Low porosity and permeability in line with the reference Finnish granite.

Introduction

After completion of GEUS report 2002/26: *Petrographic investigation of granites from the Metro stations in Copenhagen: Investigation of granite panel discolouring, based on petrological analysis and testing porosity and permeability properties* by Stig A. Schack Pedersen, Sandra Piazolo, Christian Høier and Niels Springer, the Geological Survey of Denmark and Greenland, GEUS was asked by Ørestadsselskabet I/S (ref.: Jesper Brink Malmkjær) to inspect one more sample of the Chinese granite. This sample was given to Ørestadsselskabet I/S as a type example used for a mock-up before the installation of the main granite panels. Furthermore additional SEM analyses of a relatively unaffected sample from Frederiksberg Station and petrographic investigations of a jetburned sample have been carried out. This report presents the new data and should be regarded as a continuation of the previous investigations published in the first report (GEUS2002/26).

Petrographic investigation:

General remarks:

The samples characterised and examined in detail are:

1) MK1: Granite (Chinese) without discoloration taken from a mock-up
2) KJ: Granite (Chinese), jetburned, to be used as floor and step tiles.

The sample already described in the first report is:

3) FK: Granite (Chinese) from Frederiksberg Station which is partly discolored

From MK1 two petrographic thinsections (thickness 30 μm) were prepared. The orientation of the different thinsections is shown in Figure 2. From all samples small blocks with a honed top surface were cut out and their surface analysed in the SEM (Scanning Electron Microscope).

Granite panel from Mock-up: MK1

Macroscopic description:

The rock is medium grained (grain size between 0.5 and 2.5 mm) and shows an igneous texture with only a slight noticeable preferred orientation of dark minerals such as biotite and associated chlorite laths (Figs. 1 & 3).

Figure 1. *Photograph of a cut-out hand specimen of the granite panel representing an example for Chinese granite panels. Note the only slight preferred orientation of mafic minerals in the panel.*

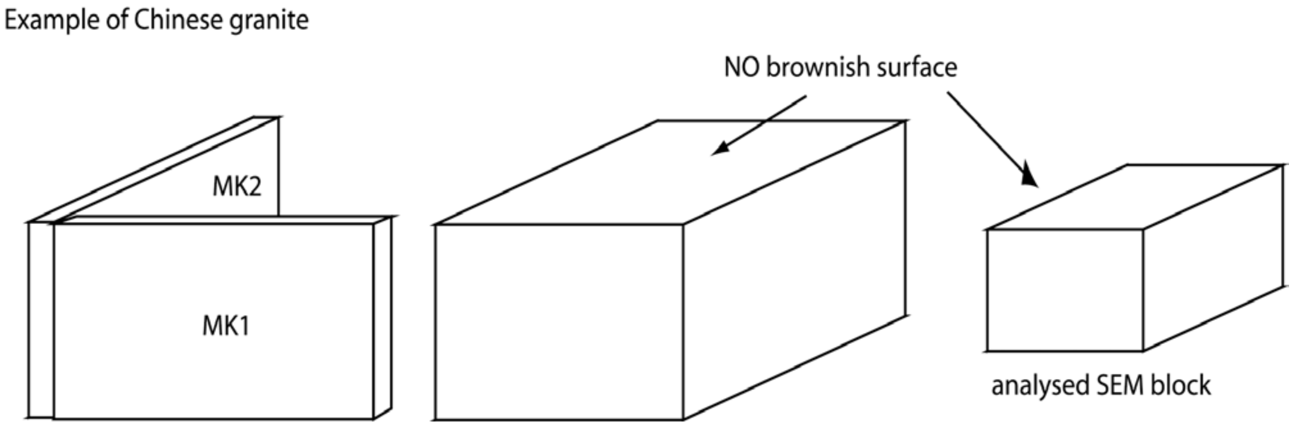


Figure 2. *Sketch of the orientation of the different thinsections obtained from the investigated granite samples.*

Microscopic description:

The general appearance of the thinsections which were cut at different orientation to the surface and fabric are shown in Figure 3. The rock is medium grained and exhibits largely an igneous texture (Fig. 4). These show only a slight preferred orientation of biotite (< 2 mm) and chlorite (see red line in Fig. 5). The main constituents of the rock are quartz, feldspar, biotite and chlorite, accessories are magnetite and muscovite. Most feldspar crystals (up to 2.5 mm) are characterized by a chemical zonation from core to rim which is typical for feldspars of igneous origin (Fig. 4). Chlorite replaces commonly partly or completely biotite and is also frequently associated with magnetite. Magnetite crystals (0.1 – 0.5 mm) are idiomorph and often associated with biotite and chlorite (Fig. 6). In addition, sericite and muscovite laths which are often aligned along crystallographic planes are abundant in the core of the feldspar crystals (Fig. 4). Quartz shows in places curved, irregular boundaries (Fig. 4).

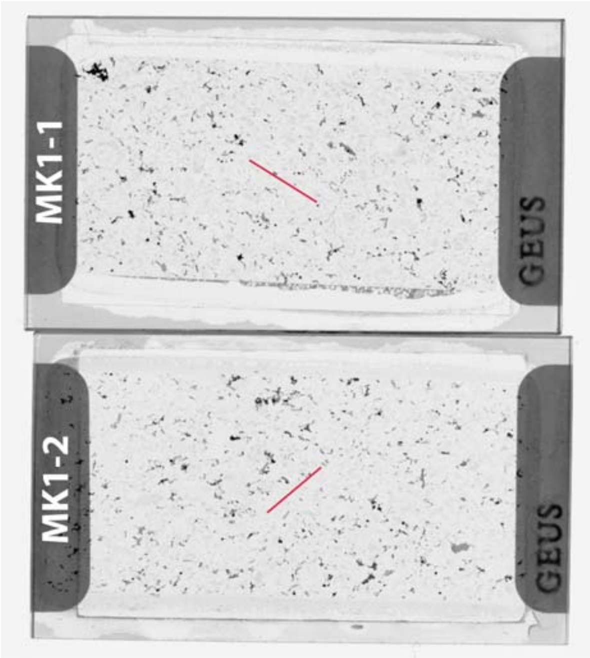


Figure 3. *Scanning image of the 2 thinsections made from sample MK1. Note that there is only a minor shape preferred orientation of biotite and that the crystals are coarse grained. For orientation of thinsections see Figure 2. Length of slides ca. 5 cm*

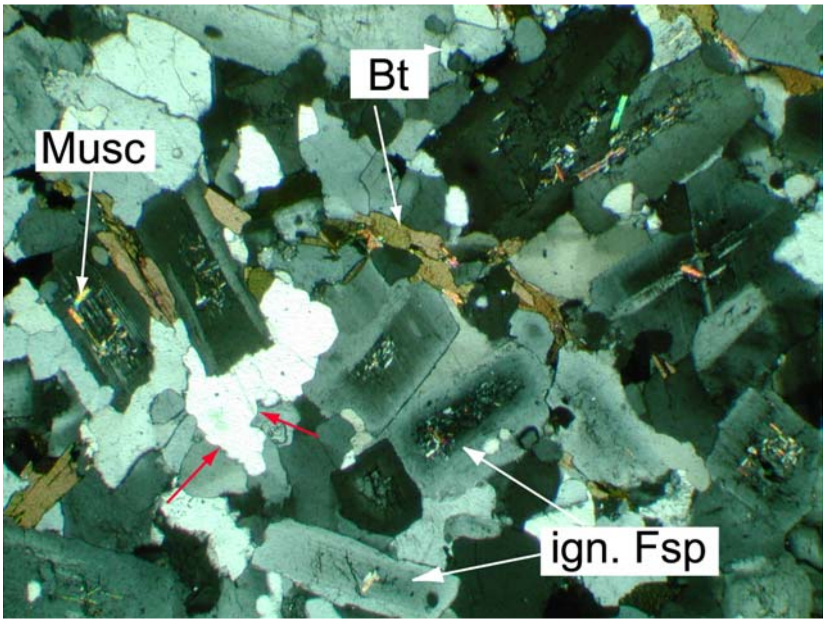


Figure 4. *General appearance of MK1 (thinsection MK1-2) under the microscope. The igneous feldspar (ign. Fsp) shows a well-developed chemical zonation from core to rim, sericite/muscovite (Musc) laths in the core and biotite (Bt) and chlorite (Chl) in the matrix. Quartz shows no undulatory extinction pointing to no noticable deformation after crystallization. Grain boundaries are slightly curved to straight (red arrows). Note that no dominant shape preferred orientation is seen in this sample. Micrograph is taken with crossed nicols and width of view is 7 mm.*

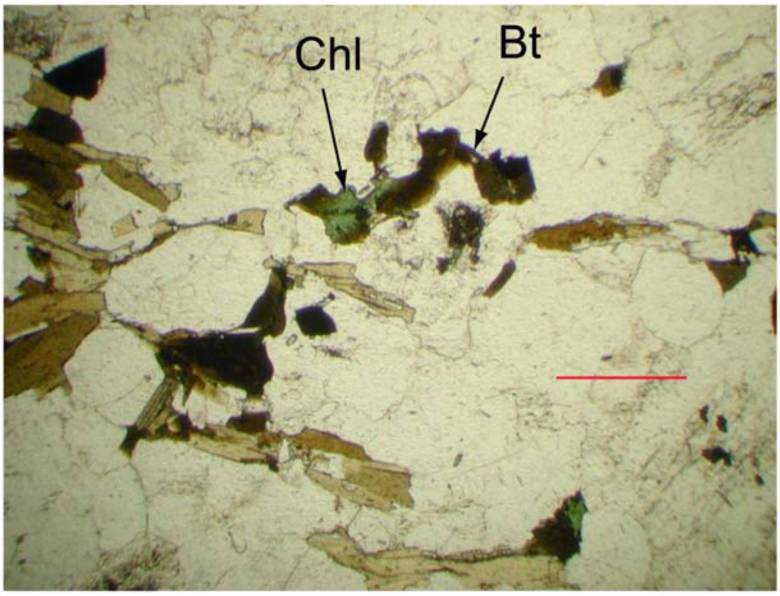


Figure 5. *Photomicrograph showing the slight preferred orientation (red line) of biotite and chlorite seen in MK1 (thinsection MK1-2). Note also the partial replacement of biotite by chlorite. Micrograph is taken in plain light and width of view is 6 mm.*

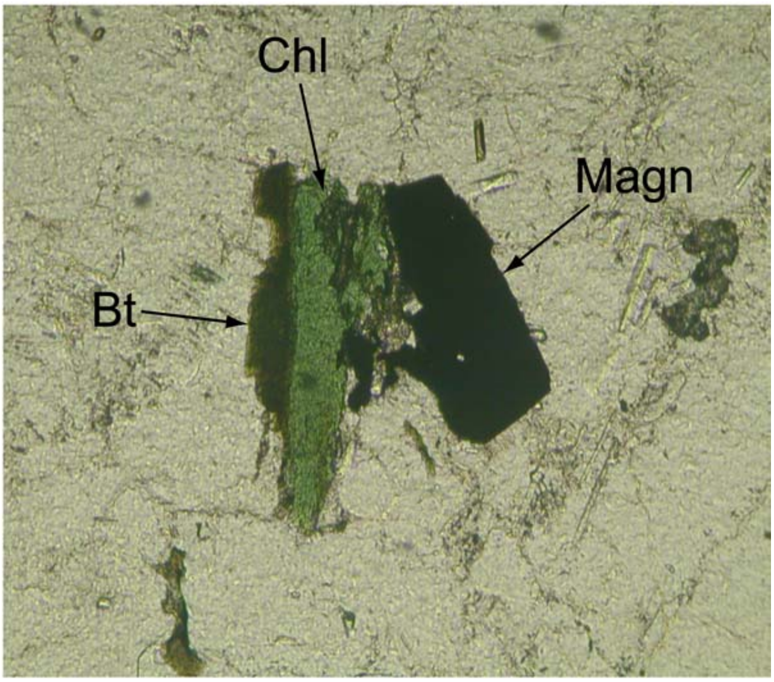


Figure 6. *Photomicrograph showing the association of biotite, chlorite and idiomorphic magnetite (Magn) seen in MK1 (thinsection MK1-2). Note also the partial to complete replacement of biotite by chlorite. Micrograph is taken in plain light and width of view is 1.5 mm.*

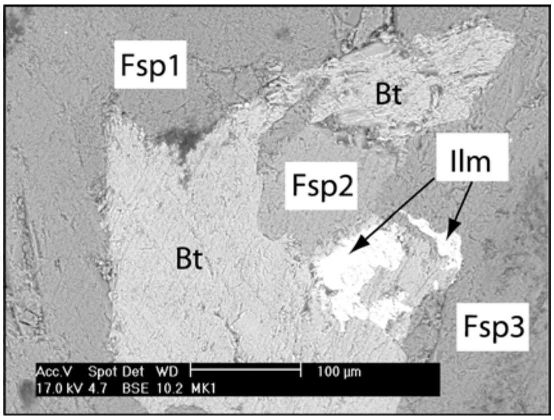


Figure 7. *Biotite next to an ilmenite crystal; Feldspar numbers correspond to feldspar analyses given in Table 3; BSE image.*

Scanning electron microscope investigations

In the SEM the crystallogaphic basal <a > planes of biotite are well seen in the SE and BSE images (Figs. 7 & 8). Chlorite exhibits an irregular surface (Fig. XX). The surface of feldspars is generally smooth (Fig. 7 and Fig. 8). Ilmenite and apatite show subidiomorphic shapes and the surface is characterised by concave, shallow, bowl-shaped ditches (Fig. 9). Grain boundaries in the vicinity of chlorite and biotite aggregates are hardly visible in the SE images. They are characterized by small pits (Fig. 8).
Examples of the composition of chorite, biotite and feldspar are given in Tab. 1, 2 and 3. Biotite and chlorite are Fe-rich and show some traces of Cl^- which replaces the OH^- groups in these minerals. The feldspars are generally of Na- to K-feldspatic composition. The element spectrum obtained from a quartz shows not only a Si peak but also traces of S, Cl and Ca. No significant traces of Fe are detected (Fig. 13).

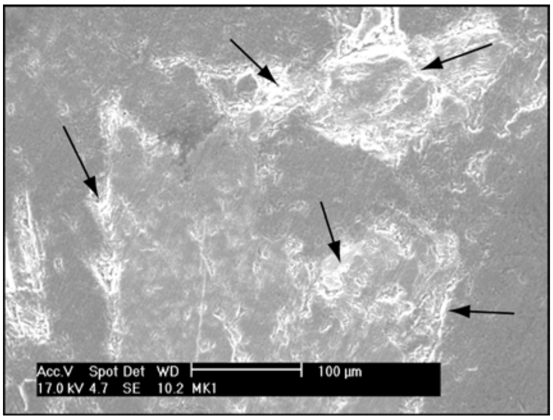


Figure 8. *Same area as Fig. 7; SE image. Note that feldspar –feldspar boundaries are not noticable, whereas biotite-feldspar and ilmenite – felspar boundaries are marked by small pitches pointing to some "chemical erosion", hence fluid flow along grain boundaries.*

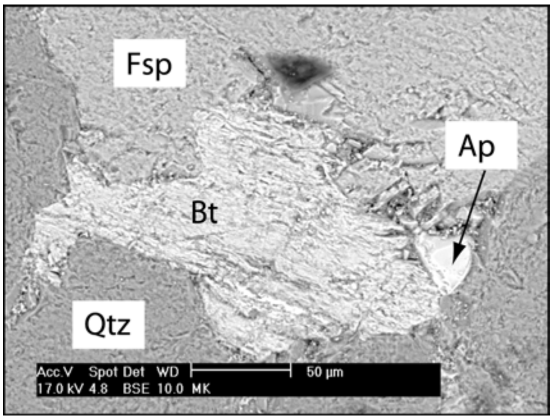


Figure 9. *Biotite next to an apatite crystal; BSE image*

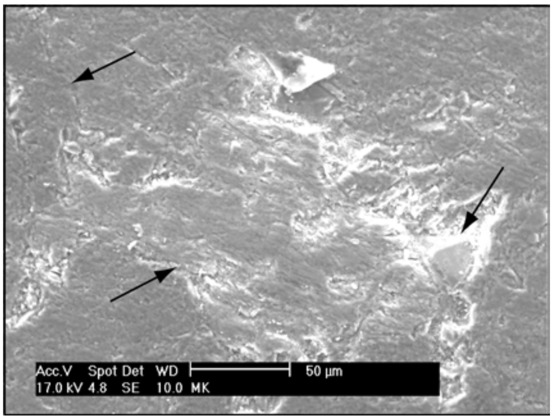


Figure 10. *Same area as Fig. 9; SE image. Note that feldspar –feldspar boundaries are not noticable, whereas biotite-feldspar and apatite – felspar boundaries are in places marked by pitches.*

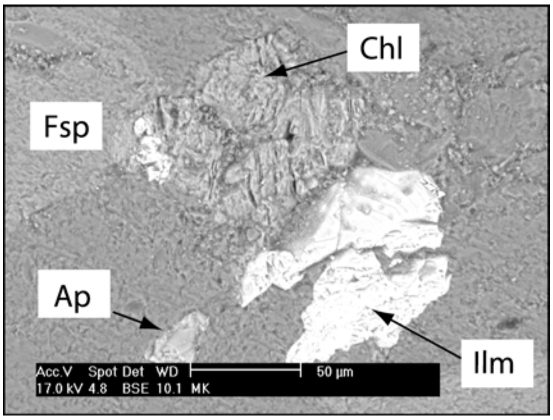


Figure 11. *Chlorite next to an ilmenite crystal; BSE image*

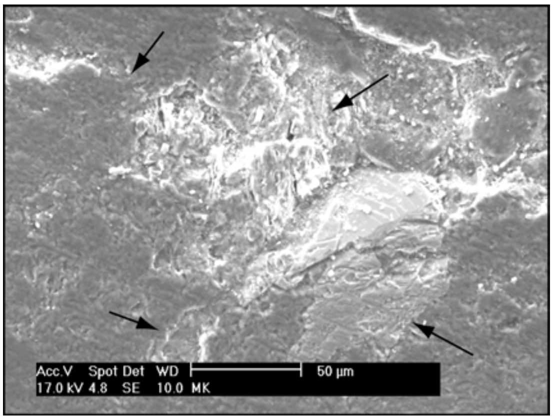


Figure 12. *Same area as Fig. 11; SE image. Note that the chlorite itself shows a very irregular surface pointing to some dissolution along its crystal planes. Boundaries to other minerals (ilmenite, quartz) are largely smooth; they are "closed". The ilmenite has a smooth surface.*

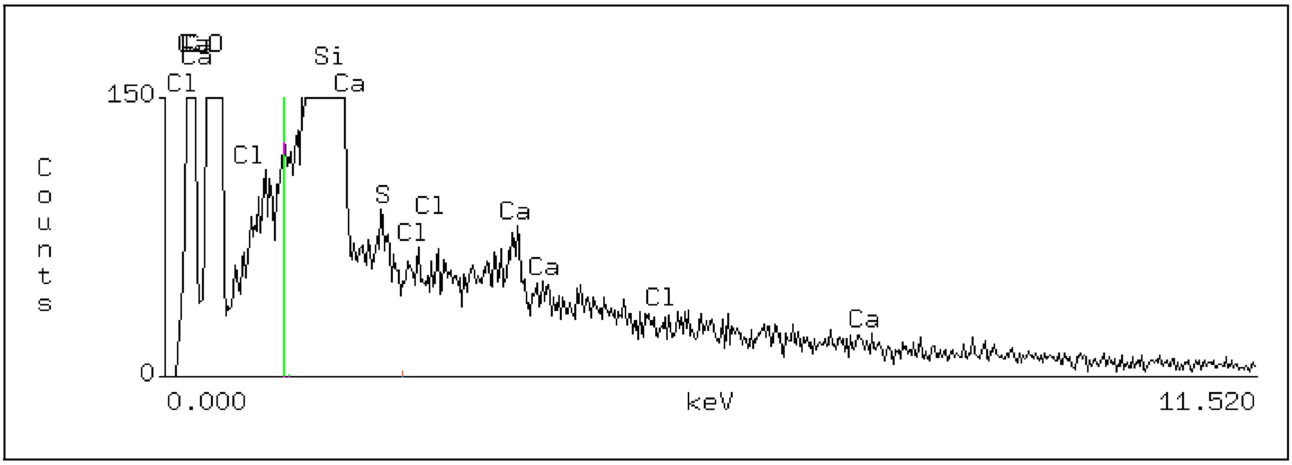


Figure 13. *EDX profile obtained in SEM. Analyses of a 0.2 * 0.2 mm area of quartz in the MK1 sample. Note the traces of Ca and Cl and S, no Fe peak is identified.*

Chlorite MK1-1

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Al-K	0.1377	1.403	24.18	19.32	+/- 0.27
Si-K	0.2273	1.462	39.96	33.24	+/- 0.37
Ca-K	0.2684	1.094	24.72	29.35	+/- 0.40
Fe-K	0.1520	1.156	10.62	17.57	+/- 0.50
Mg-K	0.0010	1.671	0.24	0.17	+/- 0.09
K -K	0.0009	1.130	0.09	0.10	+/- 0.09
Cl-K	0.0006	1.330	0.07	0.08	+/- 0.09
Ti-K	0.0014	1.226	0.12	0.17	+/- 0.12
Total			100.00	100.00	

Chlorite MK1-2

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Mg-K	0.0670	1.750	16.08	11.72	+/- 0.14
Al-K	0.0949	1.675	19.64	15.90	+/- 0.15
Si-K	0.1860	1.595	35.20	29.66	+/- 0.21
P -K	0.0068	1.786	1.30	1.21	+/- 0.06
K -K	0.0238	1.164	2.36	2.77	+/- 0.08
Ca-K	0.0773	1.106	7.11	8.54	+/- 0.13
Ti-K	0.0074	1.159	0.60	0.86	+/- 0.07
Mn-K	0.0076	1.159	0.54	0.89	+/- 0.10
Fe-K	0.2467	1.131	16.65	27.90	+/- 0.34
Cl-K	0.0041	1.365	0.52	0.55	+/- 0.05
Total			100.00	100.00	

Table 1. *MK1: Chlorite composition; calculation of number of cations on the basis of 24 oxygens*

Biotite MK1-1

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Mg-K	0.0425	1.840	11.22	7.82	+/- 0.14
Al-K	0.0859	1.651	18.34	14.18	+/- 0.17
Si-K	0.1807	1.547	34.72	27.95	+/- 0.24
K -K	0.1296	1.143	13.22	14.81	+/- 0.19
Ti-K	0.0294	1.144	2.45	3.37	+/- 0.13
Fe-K	0.2808	1.121	19.66	31.47	+/- 0.45
Cl-K	0.0030	1.317	0.39	0.40	+/- 0.06
Total			100.00	100.00	

Biotite MK1-2

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Mg-K	0.0402	1.836	10.62	7.39	+/- 0.12
Al-K	0.0812	1.640	17.24	13.31	+/- 0.14
Si-K	0.1827	1.527	34.70	27.89	+/- 0.21
P -K	0.0023	1.703	0.45	0.40	+/- 0.05
K -K	0.1053	1.136	10.70	11.97	+/- 0.15
Ca-K	0.0517	1.120	5.04	5.79	+/- 0.12
Ti-K	0.0276	1.157	2.33	3.19	+/- 0.11
Mn-K	0.0088	1.155	0.65	1.02	+/- 0.11
Fe-K	0.2560	1.125	18.03	28.82	+/- 0.35
Cl-K	0.0018	1.313	0.23	0.24	+/- 0.05
Total			100.00	100.00	

Table 2. *MK1: Biotite composition; calculation of number of cations on the basis of 24 oxygens*

Feldspar MK1-1

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Al-K	0.1384	1.136	17.62	15.73	+/- 0.16
Si-K	0.4450	1.250	59.88	55.65	+/- 0.35
K -K	0.2260	1.224	21.38	27.66	+/- 0.28
Ca-K	0.0020	1.267	0.19	0.26	+/- 0.09
Na-K	0.0045	1.581	0.93	0.71	+/- 0.07
Total			100.00	100.00	

Feldspar MK1-2

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Al-K	0.1800	1.189	22.10	21.40	+/- 0.19
Si-K	0.4453	1.380	60.95	61.43	+/- 0.38
K -K	0.0034	1.274	0.31	0.43	+/- 0.08
Ca-K	0.0592	1.190	4.89	7.04	+/- 0.16
Na-K	0.0713	1.360	11.74	9.69	+/- 0.15
Total			100.00	100.00	

Feldspar MK1-3

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Al-K	0.1804	1.175	22.17	21.20	+/- 0.21
Si-K	0.4477	1.364	61.38	61.09	+/- 0.41
K -K	0.0048	1.265	0.44	0.61	+/- 0.08
Ca-K	0.0802	1.187	6.70	9.51	+/- 0.20
Na-K	0.0541	1.402	9.31	7.59	+/- 0.15
Total			100.00	100.00	

Table 3. . *MK1: Feldspar composition; calculation of number of cations on the basis of 24 oxygens*

Ilmenite MK1-1

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Ti-K	0.4549	0.973	47.34	44.24	+/- 0.28
Mn-K	0.1365	1.085	13.82	14.81	+/- 0.22
Fe-K	0.3746	1.051	36.12	39.36	+/- 0.36
Cl-K	0.0005	1.083	0.07	0.05	+/- 0.04
Total			100.00	100.00	

Table 4. *MK1: Ilmenite composition; calculation of number of cations on the basis of 24 oxygens*

Granite panel from Frederiksberg Station: FK

Macroscopic description:

The description is given in GEUS report 2002/26. The rock is fine to medium grained (grain size mostly between 0.2 and 2 mm) and shows an igneous texture with a recognisable fabric which is defined by biotite and chlorite. Both a foliation and lineation is present.

Microscopic description:

The description is given in GEUS report 2002/26: The general appearance of the thin-section show a preferred orientation of biotite and chlorite.

The rock is fine to medium grained (grain size between 0.2 and 2 mm) and exhibits an igneous texture. The main constituents of the rock are quartz, feldspar and biotite, accessories are chlorite, magnetite and muscovite. Chlorite is frequently associated with magnetite or in places partly to completely replaces biotite. Magnetite crystals (0.1 – 0.5 mm) are idiomorphic and often associated with biotite and chlorite. Feldspar (up to 2 mm) is characterized by a chemical zonation from core to rim which is typical for feldspars of igneous origin. In addition, sericite and muscovite laths are abundant in the core of the feldspar crystals.

The rock does exhibit a noticeable preferred orientations of the biotite (< 1 mm), feldspar and chlorite laths, which originates from a synmagmatic alignment of mineral phases. These now make up an igneous foliation and lineation of the rock.

Scanning electron microscope investigations

SEM investigations show that chlorite partly replaces biotite (Fig. 14). The crystallogaphic basal <a > planes of biotite are well seen in the SE and BSE images (Fig. 16). Chlorite has a relatively smooth surface appearance with some minor pits (Fig. 14). The surface of feldspars is irregular (Fig. 14 and Fig. 15). Magnetite shows idiomorphic to subidiomorrphic shapes and its surface is characterised by concave, shallow, bowl-shaped ditches (Fig. 14). Biotite-feldspar and chlorite-feldspar grain boundaries are hardly visible in SE images. In some cases, they are characterized by small pits (Fig. 16) which can be attributed to the mechanical treatment of the panel surface. Boundaries between feldspars in the vicinity of biotite and chlorite are smooth and appear ”closed”

Examples of the composition of chorite, biotite and feldspar are given in Tab. 5, 6 and 7. Biotite and chlorite are Fe-rich and show some traces of Cl^- which replaces the OH^- groups in these minearls. The feldspars are generally of Na- to K-feldspatic composition. The element spectrum obtained from a quartz shows not only a Si peak but also traces of Ca, Cl, Na and S, no Fe peak could be identified (Fig. 18).

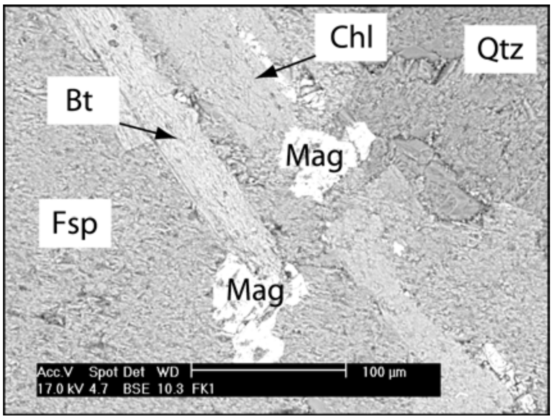


Figure 14. *Biotite next to a magnetite crystal; BSE image.*

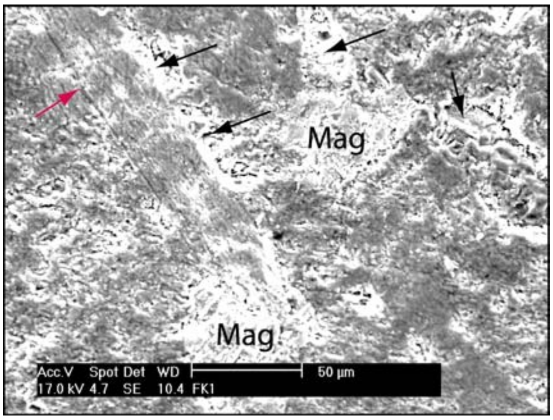


Figure 15. *Close-up of same location as Fig. 14; SE image. Note that the cleavage of biotite gives a noticable surface-pitch appearance to the biotite. The magnetite shows an irregular surface with some characteristic bowl-shaped structures. Grain boundaries to the right of the crystals are characterized by pitches, whereas on the left hand side (red arrow) grain boundaries appear mostly closed. The right hand pitches may be due to the cutting and polishing of the rock.*

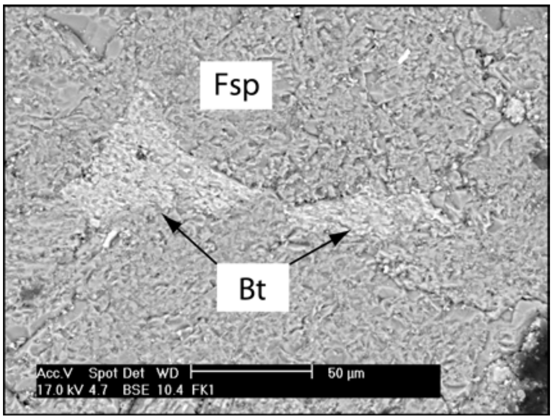


Figure 16. *Biotite crystals imbedded in feldspar; BSE image.*

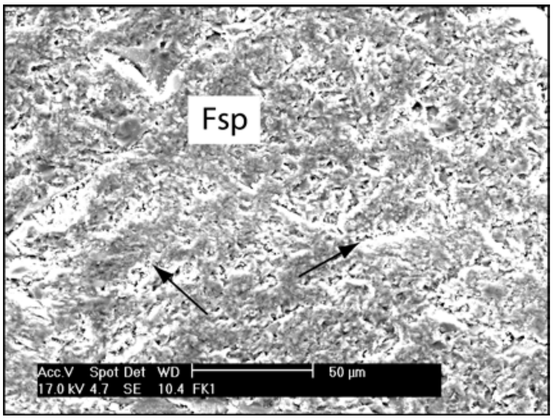


Figure 17. *Same as Fig. 16; SE image. Note that the boundaries between biotite and feld-spar not detectable (arrows). The whole surface is characterized by only minor indenta-tions.*

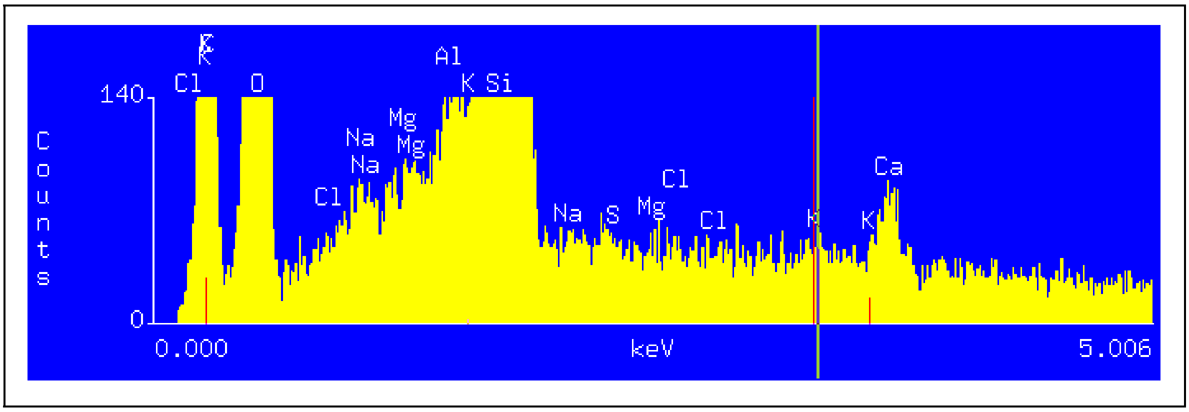


Figure 18. *EDX profile obtained in SEM. Analyses of a 0.2 * 0.2 mm area of quartz in the FK sample. Note the traces of Ca, Cl, Na and S, no Fe peak could be identified.*

Chlorite FK-1

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Mg-K	0.0785	1.887	20.62	14.81	+/- 0.19
Al-K	0.1030	1.830	23.65	18.85	+/- 0.20
Si-K	0.1477	1.738	30.92	25.66	+/- 0.24
Fe-K	0.3614	1.109	24.28	40.06	+/- 0.47
K -K	0.0041	1.167	0.42	0.48	+/- 0.07
Cl-K	0.0004	1.376	0.06	0.06	+/- 0.06
Ti-K	0.0007	1.103	0.06	0.08	+/- 0.07
Total			100.00	100.00	

Chlorite FK-2

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Mg-K	0.0965	1.755	22.65	16.93	+/- 0.19
Al-K	0.1202	1.789	25.90	21.50	+/- 0.21
Si-K	0.1539	1.757	31.30	27.04	+/- 0.24
Fe-K	0.3069	1.119	20.00	34.35	+/- 0.43
K -K	0.0011	1.183	0.11	0.13	+/- 0.06
Cl-K	0.0002	1.399	0.02	0.03	+/- 0.06
Ti-K	0.0003	1.121	0.03	0.04	+/- 0.07
Total			100.00	100.00	

Table 5. *FK: Chlorite composition; calculation of number of cations on the basis of 24 oxygens*

Biotite FK-1

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Mg-K	0.0574	1.812	14.64	10.40	+/- 0.16
Al-K	0.0850	1.686	18.15	14.32	+/- 0.17
Si-K	0.1891	1.574	36.21	29.75	+/- 0.25
K -K	0.0940	1.155	9.50	10.87	+/- 0.16
Ti-K	0.0209	1.139	1.70	2.38	+/- 0.12
Fe-K	0.2867	1.121	19.68	32.15	+/- 0.43
Cl-K	0.0009	1.342	0.12	0.13	+/- 0.05
Total			100.00	100.00	

Biotite FK-2

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Mg-K	0.0569	1.683	13.10	9.58	+/- 0.14
Al-K	0.0956	1.586	18.67	15.16	+/- 0.16
Si-K	0.2172	1.525	39.20	33.13	+/- 0.24
K -K	0.1202	1.166	11.91	14.01	+/- 0.17
Ti-K	0.0301	1.164	2.43	3.50	+/- 0.12
Fe-K	0.2158	1.135	14.57	24.48	+/- 0.35
Cl-K	0.0010	1.351	0.13	0.14	+/- 0.05
Total			100.00	100.00	

Table 6. *FK: Biotite composition; calculation of number of cations on the basis of 24 oxygens*

Feldspar FK-1

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	No. of Cations
Na-K	0.0264	2.178	5.12	5.76	+/- 0.09	1.975
Al-K	0.0854	1.468	9.50	12.55	+/- 0.10	3.664
Si-K	0.1992	1.454	21.08	28.97	+/- 0.17	8.129
Ca-K	0.0342	1.168	2.04	4.00	+/- 0.07	0.786
O -K	0.1765	2.760	62.25	48.72	+/- 0.47	---
Total			100.00	100.00		14.554

Feldspar FK-2

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Na-K	0.0374	1.500	7.06	5.61	+/- 0.29
Al-K	0.1373	1.181	17.38	16.21	+/- 0.35
Si-K	0.4789	1.295	63.90	62.03	+/- 0.68
Ca-K	0.1376	1.174	11.66	16.16	+/- 0.48
Total			100.00	100.00	

Table 7. *FK: Feldspar composition; calculation of number of cations on the basis of 24 oxygens*

Jetburned granite panel: KJ

Macroscopic description:

In handspecimen appears the rock medium grained (grain size between 0.5 and 2.5 mm) and shows a igneous texture with only a very weak preferred orientation of dark minerals such as biotite and associated chlorite laths. The upper surface is marked by a relief. The surface does not show any discolouration.

Microscopic description:

No thinsections where prepared from this sample.

Scanning electron microscope investigations

SEM investigations show the surface of this sample is ”clean” (Fig. 19 and Fig. 21). Chlorite and biotite have a smooth surface appearance (Fig. 22). The surface of feldspars is also smooth (Fig. 20 and Fig. 22). Grain boundaries in the vicinity of chlorite and biotite aggregates are hard to detect in the SE images (Fig. 22).
Examples of the composition of chorite, biotite and feldspar are given in Tab. 8, 8 and 10. Biotite and chlorite are Fe-rich and show some traces of Cl^- which replaces the OH^- groups in these minearls. The feldspars are generally of albitic to kalifeldspatic composition. The element spectrum obtained from a quartz shows not only a Si peak but also traces of S, Na, K. Only minor traces (if any) of Fe and Cl are seen (Fig. 24).

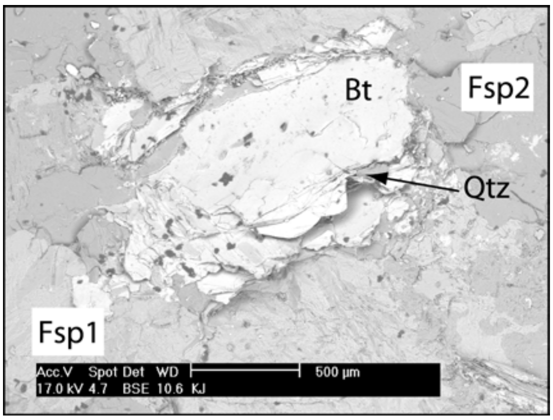


Figure 19. *Biotite, here seen as a stack of basal <a> planes subparallel to the surface imbedded in feldspar; BSE image. The surface has been jetburned and appears much “clearer” than the photographs taken from other samples. Even in this BSE the relief at the surface of the sample is seen.*

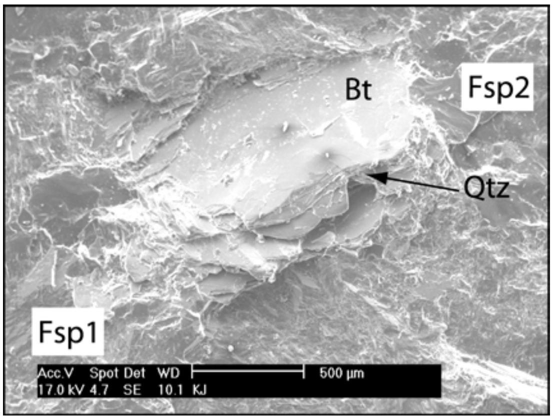


Figure 20. *Same location as Fig. 19; SE image. Note the relief of the sample, and the obvious cleavage of biotite. Grain boundaries are closed.*

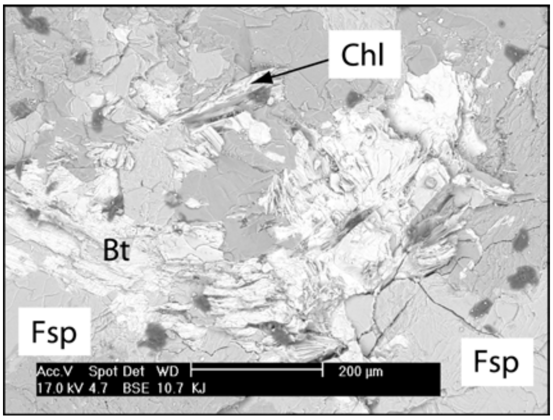


Figure 21. *Biotite-chlorite aggregate imbedded in feldspar; BSE image. The dark spots are artifacts of some chemical reaction triggered by the electron beam or possibly an artefact of the jetburning treatment.*

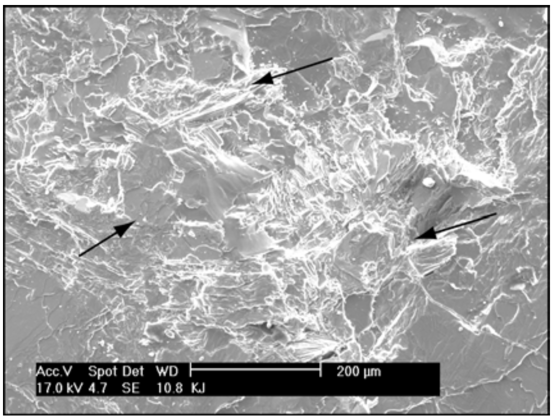


Figure 22. *Same location as Fig. 21; SE image. Note surface irregularities at the surface of biotite. The chlorite shows no profound irregular surface. Grain boundaries are showing only slight indentations.*

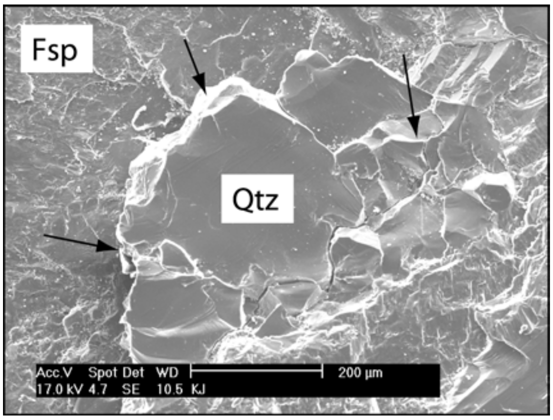


Figure 23. *Quartz cystal imbedded in feldspar; SE image. Note surface of the quartz is characterized by bowl-shaped pitches. The quartz crystal builds a surface high. Overall, the surface is exceptionally smooth in comparison with other samples (cf. Figs. 10 and 17)*

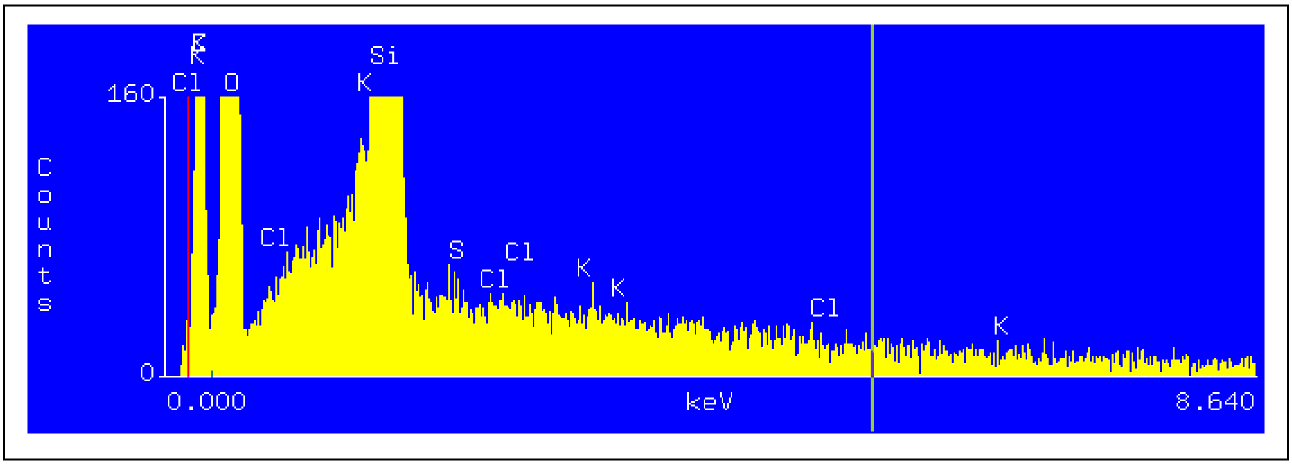


Figure 24. *EDX profile obtained in SEM. Analyses of a 0.2 * 0.2 mm area of quartz in the KJ sample. Note the traces of K, Cl and S, but no Fe peak could be identified.*

Chlorite KJ-1

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Al-K	0.1129	1.792	27.17	20.23	+/- 0.21
Si-K	0.1346	1.722	29.91	23.18	+/- 0.22
Ca-K	0.0011	1.062	0.10	0.12	+/- 0.06
Fe-K	0.4499	1.090	31.84	49.06	+/- 0.51
Cl-K	0.0009	1.342	0.12	0.12	+/- 0.05
Mg-K	0.0350	2.074	10.82	7.26	+/- 0.15
K -K	0.0003	1.143	0.03	0.03	+/- 0.05
Total			100.00	100.00	

Chlorite KJ-2

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Al-K	0.0767	1.783	17.58	13.68	+/- 0.18
Si-K	0.1817	1.625	36.45	29.52	+/- 0.25
Ca-K	0.0284	1.082	2.66	3.08	+/- 0.10
Fe-K	0.3610	1.110	24.88	40.06	+/- 0.48
Cl-K	0.0026	1.357	0.34	0.35	+/- 0.06
Mg-K	0.0616	1.919	16.88	11.83	+/- 0.18
K -K	0.0064	1.156	0.66	0.74	+/- 0.07
Ti-K	0.0067	1.112	0.54	0.75	+/- 0.09
Total			100.00	100.00	

Table 8. . *KJ: Chlorite composition; calculation of number of cations on the basis of 24 oxygens*

Biotite KJ-1

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Mg-K	0.0231	1.836	6.09	4.24	+/- 0.11
Al-K	0.0960	1.580	19.63	15.16	+/- 0.17
Si-K	0.2151	1.515	40.53	32.59	+/- 0.25
K -K	0.1109	1.151	11.40	12.76	+/- 0.17
Ti-K	0.0236	1.141	1.96	2.69	+/- 0.12
Fe-K	0.2904	1.119	20.33	32.51	+/- 0.43
Cl-K	0.0004	1.335	0.05	0.06	+/- 0.06
Total			100.00	100.00	

Table 9. *KJ: Biotite composition; calculation of number of cations on the basis of 24 oxygens*

Feldspar KJ-1

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Al-K	0.1417	1.133	18.09	16.05	+/- 0.16
Si-K	0.4353	1.252	59.01	54.50	+/- 0.34
K -K	0.2385	1.220	22.62	29.08	+/- 0.29
Ca-K	0.0029	1.270	0.28	0.37	+/- 0.08
Total			100.00	100.00	

Feldspar KJ-2

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Na-K	0.0407	1.485	7.60	6.05	+/- 0.15
Al-K	0.1749	1.184	22.16	20.70	+/- 0.23
Si-K	0.4146	1.358	57.93	56.32	+/- 0.43
K -K	0.0437	1.242	4.02	5.43	+/- 0.17
Ca-K	0.0966	1.192	8.30	11.51	+/- 0.24
Total			100.00	100.00	

Feldspar KJ-3

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)
Na-K	0.0767	1.341	12.41	10.28	+/- 0.15
Al-K	0.1776	1.190	21.73	21.14	+/- 0.19
Si-K	0.4524	1.376	61.47	62.24	+/- 0.38
K -K	0.0022	1.276	0.20	0.28	+/- 0.07
Ca-K	0.0508	1.191	4.19	6.05	+/- 0.15
Total			100.00	100.00	

Table 10. *KJ: Feldspar composition; calculation of number of cations on the basis of 24 oxygens*

Summary of petrography

In the light of the question what causes the discoloration in some of the granite types, the above investigations supplement earlier investigations and underline the characteristics described in the previous report.

Characteristics of granite with some discoloration (FK)

- fine to medium grained
- moderate to strong shape fabric of biotite, chlorite and igneous feldspar
- abundant and small grained biotite and chlorite
- irregular surface structure of chlorite and biotite
- surface irregularities (pits) along grain boundaries
- high Fe and Cl bearing biotite and chlorite

Characteristics of granite without discoloration (MK1)

- coarse grained
- no shape preferred orientation of mineral species
- lower amounts of large grained biotite and chlorite
- smooth surface of chlorite (MK1)
- no ”eroded, open” grain boundaries next to biotite and chlorite crystals

Finally it should be noted that the color index (amount of dark minerals as biotite, chlorite, magnetite and ilmenite) is only about 4 % in the unaffected mock-up granite, whereas the color index is about 7–8 % in all the investigated discolored granites from Kongens Nytorv and Frederiksberg.

Porosity and permeability tests of granite tiles

In this study four additional 25 mm diameter plug samples have been analyzed for porosity and permeability. They all originate from Chinese granite tiles – 2 samples were taken from a mock-up, and 2 samples were taken from the jetburned floor tiles. Results are highlighted in table 11 below; the previously measured Metro tile data have been included for comparison. Experimental conditions are identical to the previous study. However, the tiles received for analysis only had a thickness of 20 mm and this precluded the possibility of taking directional plugs. Therefore the 4 additional plugs taken for this study are cut perpendicular to the surface of the tiles.

Sample ID	Orientation	Porosity 1 %	2	Porosity, mean %	Grain density 1 g/cc	2	Grain density, mean g/cc
NP1	isotropic	0.71	0.45	0.58	2.643	2.636	2.639
KK1a	hz 1	0.85	0.80	0.82	2.668	2.667	2.668
KK1b	hz 2	1.08	1.14	1.11	2.665	2.667	2.666
KK1c	vert	1.34	1.53	1.43	2.669	2.677	2.673
KK2a	hz 1	1.03	1.02	1.03	2.667	2.667	2.667
KK2b	vert	1.05	1.09	1.07	2.668	2.669	2.669
FKa	hz 1	1.21	1.27	1.24	2.664	2.666	2.665
FKb	hz 2	1.18	1.22	1.20	2.664	2.665	2.665
FKc	vert	1.23	1.29	1.26	2.666	2.668	2.667
MK1a	no	0.98		0.98	2.668		2.668
MK1b	no	1.12		1.12	2.673		2.673
KJ1a	no	0.58		0.58	2.627		2.627
KJ1b	no	0.54		0.54	2.628		2.628

Abbr.: hz 1 – horizontal direction 1
hz 1 – horizontal direction 2
vert – vertical

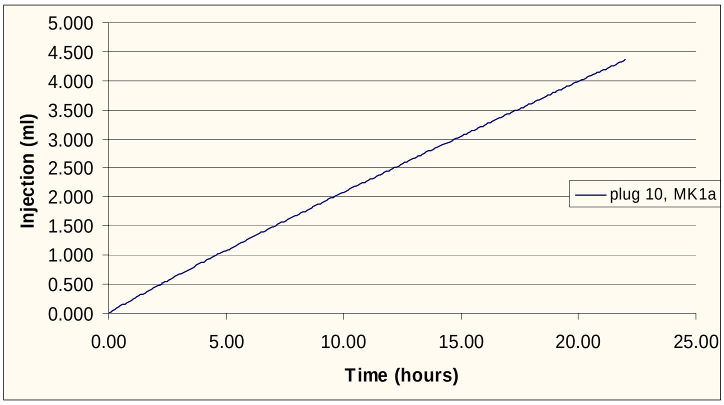
Sample ID	Diameter mm	Length mm	Temp C	Fluid vis-cosity cP	Cal. flow rate ml/h	Permeability µD	Hydraulic con-ductivity E-12 m/s
NP1	24.84	25.88	21	1.00	0.020	0.10	0.97
KK1a	24.81	38.87	21	1.00	0.139	1.05	10.1
KK1b	24.84	9.73	21	1.00	0.461	0.87	8.4
KK1c	24.84	9.24	21	1.00	0.538	0.96	9.3
KK2a	24.88	31.62	21	1.00	0.119	0.72	7.0
KK2b	24.84	36.34	21	1.00	0.067	0.47	4.5
FKa	24.85	39.39	21	1.00	0.273	2.08	20.1
FKb	24.87	39.33	21	1.00	0.206	1.56	15.1
FKc	24.86	30.00	21	1.00	0.176	1.02	9.9
MK1a	24.86	18.87	21	1	0.1995	0.73	7.0
MK1b						n.a.	n.a.
KJ1a	24.78	20.43	21	1	0.0299	0.12	1.2
KJ1b	24.78	20.43	21	1	0.0367	0.15	1.4
Steel	25.00	25.00	21	1.00	0.0001	0.0005	0.005
Steel	25.00	25.00	21	1.00	0.0002	0.0011	0.011

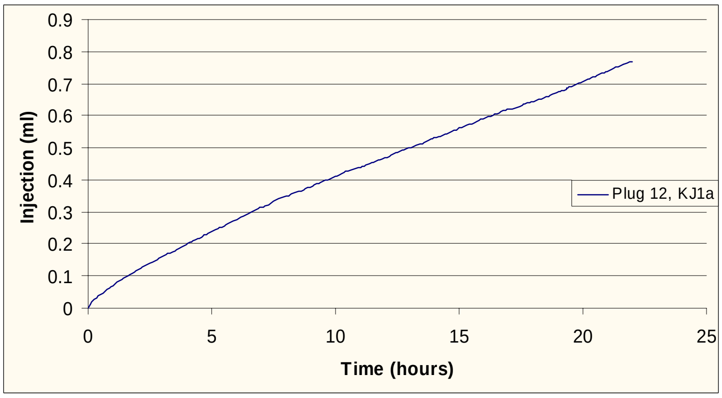
Table 11. *Copenhagen Metro granite tiles. Core analysis data measured for mock-up (MK1) and jetburned (KJ1) tiles are highlighted.*

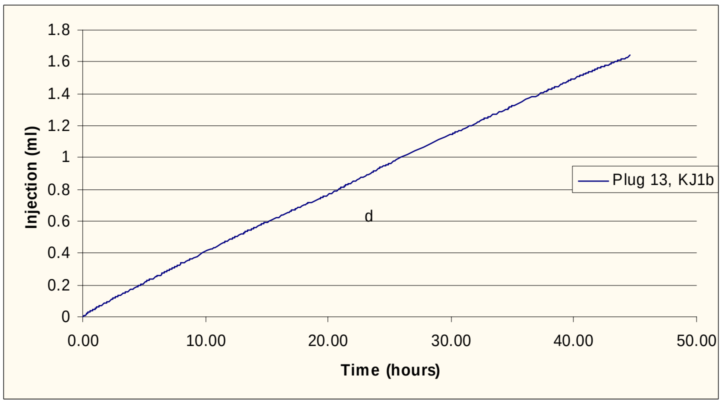
Summary of porosity and permeability measurements

The Chinese granite samples taken from the mock-up (MK1) have porosity and permeability very comparable to the Chinese granites formerly measured from Kongens Nytorv (KK), table 11. The jetburned tiles with no discoloration (KJ1) have very low porosity and permeability, comparable to the Finnish reference granite (NP1). It is therefore difficult to evaluate the effect of the jetburning. We believe that jetburning is mostly a surface modifying process and find it difficult to believe that this process could have diminished the porosity to half its original value. The most obvious conclusion is therefore that the low permeability measured for the jetburned tiles is a result of the low intrinsic porosity, and not a result of the jetburning process. This conclusion however, would benefit from further evidence obtained from more than just one jetburned tile.

Table 12. *Injection curves recorded by the computer controlled pumping system showing near to ideal flow conditions. The injection pressure was kept constant at 30 bars during the liquid permeability experiment.*







Analytical Methods

The following is a short description of the methods used by GEUS Core Laboratory. For a more detailed description of methods, instrumentation and principles of calculation the reader is referred to API recommended practice for core-analysis procedure (API RP 40, 2^{nd} ed. 1998).

4.1 Sampling

Plugs of diameter 25 mm were drilled from the granite tiles perpendicular to the surface of the tiles. Samples were then dried at 60 °C and analyzed for porosity.

4.2 He-porosity and grain density

The porosity is measured on dried samples. The porosity is determined by subtraction of the measured grain volume and the measured bulk volume. The Helium technique, employing Boyle's Law, is used for grain volume determination, applying a double chambered Helium porosimeter with digital readout, whereas bulk volume is measured by submersion of the plug in a mercury bath using Archimedes principle. Grain density is calculated from the grain volume measurement and the weight of the dried sample.

4.4 Liquid permeability

The water saturated plug is mounted in a hydrostatic Hassler core holder and a net confining pressure of 50 bar applied to the sleeve. The fluid upstream pressure of 30 bar is delivered from a computer controlled metering pump. Pressures and injected volume are recorded during a period of 24 hours. The liquid permeability is calculated from Darcy's equation for laminar liquid flow in porous media.

4.5 Precision of analytical data

The table below gives the precision (= reproducibility) at the 68% level of confidence (+/- 1 standard deviation) for routine core analysis measurements performed at GEUS Core Laboratory.

Measurement	**Range, mD**	**Range, %**	**Precision**
Grain density			0.003 g/cc
Bulk volume (Hg)			0.01 cc
Porosity		< 1 %	0.3 porosity-%
		> 1 %	0.15 porosity-%
Liquid permeability	> E-3		5 %