Development of the Fe-Ti-oxides in the Koster dyke swarm during amphibolite facies metamorphism

AAGE JENSEN

Jensen, Aa.: Development of the Fe-Ti-oxides in the Koster dyke swarm during amphibolite facies metamorphism. *Bull. geol. Soc. Denmark,* Vol. 38, pp. 109–118. Copenhagen, April 25th, 1990.
https://doi.org/10.37570/bgsd-1990-38-11

The 1421 Ma old Koster dyke swarm is part of the late Proterozoic Kattsund-Koster dyke swarm running from Bohus Län in Sweden into Oslofjord in Norway. On the basis of the degree of amphibolite facies deformation and recrystallisation, Hageskov (1984) has divided the dyke swarm into three sectors, where sector I is the southernmost part of the dyke swarm consisting of undeformed tholeiitic dolerites, sector III dykes are transformed to amphibolites, and sector II is transitional.

From a number of miroscopically investigated dykes 5 dykes from sector I, 5 dykes from sector II and 4 dykes from sector III have been selected for electron microprobe analyses of the Fe-Ti-oxides.

No significant differences could be found between the titanomagnetite groundmass in sector I and sector II, but in sector III the titanomagnetite groundmass is completely altered to turbid titanite.

Some of the dykes in sector II have an ilmenite composition similar to the sector I dykes, but other dykes from sector II have clearly lost Fe_2O_3 and are correspondingly richer in Ti; in sector III the ilmenite no longer contains Fe_2O_3.

Based on the composition of coexisting ilmenite and titanomagnetite, temperature and fO_2 have been determined for sector I and sector II dykes, but they cannot be determined for sector III dykes as no titanomagnetite is left here.

The dykes of sector I give temperatures between 1100° and 1280°, and fO_2 between 10^{-10} and 10^{-8}. The least altered dykes of sector II give similar values of temperature and fO_2 as sector I dykes, whereas the more altered dykes of sector II show considerably lower values of temperature and fO_2. These values, however, are not meaningful as they neither indicate temperature and fO_2 of interoxide reequilibration nor temperature and fO_2 of metamorphism; they are the result of ilmenite loosing Fe_2O_3 during meta-morphism.

Aage Jensen, Institute of Mineralogy, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark, October 26th 1989.

Introduction

The 1421 Ma old Koster dyke swarm, Hageskov & Pedersen 1988, which forms part of the Kattsund-Koster dyke swarm zone running from the archipelago of Bohus Län in Sweden into Oslofjord in Norway, is a very dense dyke swarm and extremely well exposed in the Koster archipelago.

This dyke swarm is late Proterozoic and consists in the south of tholeiitic dolerites trending NNE-SSW and dipping 67 ± 8°W. Here in the south the exposed width of the dyke swarm is about 8 km and the crust is regularly cut by about 700 dykes. Northwards, however, the tholeiitic dolerites have undergone progressive deformation under amphibolite facies metamorphic conditions.

The NNE-SSW trend found in the southern part of the dyke swarm changes northwards as the dyke swarm shows a major bend in which the dykes have been rotated anticlockwise, and the distance between the dykes decreases progressively northwards as the result of constrictional deformation following the formation of the major bend.

On the basis of the degree of the amphibolite facies deformation and recrystallisation of the dykes, Hageskov (1984) has divided the dyke swarm into three sectors.

Sector I comprises the southernmost part of the dyke swarm and consists of undeformed and only very slightly altered tholeiitic dolerites. Most dykes are aphyric, but some olivine- and plagioclase-porphyritic dykes are also seen. The percentage of recrystallised grains in the dykes of sector I is generally below 10.

Sector II is a transitional zone between the dolerites of sector I and the amphibolites of sector III. Almost all dykes of sector II are metadolerites with well preserved doleritic texture, but the igneous mineralogy is altered to varying

Table 1. Ilmenite analyses of sample 41112 from sector I.

Column I: Ilmenite as free grains
Column II: Ilmenite in irregular areas inside titanomagnetite
Column III: Ilmenite lamellae

	I	II	III
Number of analyses	22	4	10
MgO	0.05±0.01	0.20±0.09	0.09±0.04
Al_2O_3	0.02±0.03	0.03±0.02	0.02±0.01
TiO_2	49.28±0.48	49.81±0.23	49.59±0.38
V_2O_3	0.30±0.04	0.39±0.16	0.35±0.06
Cr_2O_3	0.05±0.10	0.00±0.00	0.01±0.01
MnO	0.91±0.10	0.93±0.10	0.95±0.06
FeO	43.36±0.39	43.46±0.40	43.50±0.38
Fe_2O_3	5.89±0.78	4.65±0.35	5.22±0.73
NiO	0.02±0.03	0.00±0.00	0.00±0.00
Sum	99.88±0.51	99.47±0.35	99.73±0.53
Cations based on 3 O			
Mg	0.002±0.001	0.008±0.003	0.003±0.002
Al	0.001±0.001	0.001±0.000	0.001±0.000
Ti	0.939±0.008	0.951±0.005	0.946±0.007
V	0.007±0.001	0.010±0.004	0.009±0.002
Cr	0.001±0.002	0.000±0.000	0.000±0.000
Mn	0.020±0.002	0.020±0.002	0.020±0.001
Fe^{++}	0.919±0.006	0.922±0.008	0.922±0.008
Fe^{+++}	0.112±0.015	0.089±0.007	0.099±0.014
Ni	0.000±0.001	0.000±0.000	0.000±0.000
Sum	2.001±0.001	2.001±0.001	2.000±0.000
Ti/Fe^{+++}	8.38	10.69	9.56

degrees, and the percentage of recrystallized grains varies strongly from about 15 to nearly 100.

In sector III all dykes are transformed to amphibolite and practically all dykes, with a few exceptions in the west, have a lineated fabric throughout, with or without a foliation. The dykes of sector III are totally recrystallised and enriched in H_2O, but otherwise no important alteration of the igneous chemistry has taken place (Hageskov 1987).

The petrology, geochemistry and structural geology of the Koster dyke swarm has been thoroughly dealt with by Hageskov (1985, 1987). The purpose of this paper is to try to follow the development in the Fe-Ti-oxides from the dolerites through the metadolerites to the amphibolites.

Microscopic investigation

The microscopic investigation comprises 20 samples from 16 dykes in sector I, 12 samples from 12 dykes in sector II and 15 samples from 15 dykes in sector III. Five dykes from sector I were selected for electron microprobe analyses; amongst these was a 10 m wide dyke where samples from both contacts and samples 0.5 m and 6 m from the east contact were investigated. From sector II 5 dykes were selected and from sector III 4 dykes.

Concerning Fe-Ti-oxides the dykes are of two different types. One type carries ilmenite as the only Fe-Ti-oxide whereas the other type has titanomagnetite as well. In the 10 m wide dyke from sector I the contact samples have only ilmenite, but the samples from the interior of the dyke also contain titanomagnetite. One of the dykes from sector I differs from all the other dykes in that the titanomagnetite is rich in Cr and Al and has cores of chrome spinel; this dyke will be dealt with later in a separate paper.

These two types of dykes are found in sector II as well as sector I, but in sector III no unaltered titanomagnetite is left. Some of the dykes in sector III have only ilmenite which microscopically appears unchanged, and these dykes are thought to correspond to the dykes of sectors I and II with ilmenite as the only Fe-Ti-oxide. Other dykes from sector III have small rounded remnants of

Table 2. Ilmenite analyses of sample 41131 from sector I.

Column I: Mg-rich ilmenite as free grains
Column II: Ilmenite as free grains
Column III: Ilmenite lamellae

	I	II	III
Number of analyses	5	10	6
MgO	1.31±0.26	0.19±0.04	0.28±0.06
Al_2O_3	0.02±0.01	0.02±0.02	0.03±0.04
TiO_2	50.45±0.65	49.75±0.32	50.33±0.43
V_2O_3	0.11±0.06	0.13±0.07	0.24±0.04
Cr_2O_3	0.01±0.01	0.06±0.08	0.08±0.03
MnO	0.75±0.07	0.67±0.10	0.94±0.07
FeO	42.30±0.32	43.72±0.33	43.84±0.41
Fe_2O_3	5.26±0.35	5.99±0.58	2.76±0.98
NiO	0.01±0.02	0.01±0.02	0.02±0.02
Sum	100.22±0.93	100.54±0.45	98.52±0.32
Cations based on 3 O			
Mg	0.049±0.009	0.007±0.001	0.011±0.002
Al	0.001±0.000	0.001±0.001	0.001±0.002
Ti	0.948±0.004	0.941±0.004	0.969±0.010
V	0.003±0.002	0.003±0.001	0.006±0.001
Cr	0.000±0.000	0.000±0.001	0.002±0.001
Mn	0.016±0.002	0.015±0.002	0.020±0.002
Fe^{++}	0.884±0.008	0.919±0.006	0.938±0.010
Fe^{+++}	0.099±0.007	0.114±0.010	0.053±0.019
Ni	0.000±0.000	0.000±0.000	0.001±0.001
Sum	2.000±0.000	2.000±0.000	2.001±0.001
Ti/Fe^{+++}	9.58	8.25	18.28

Table 3. Ilmenite analyses of samples 41136 and 41142 from sector I.

Column I: 41136 Ilmenite as free grains
Column II: 41136 Ilmenite in irregular areas inside titanomagnetite
Column III: 41136 Ilmenite lamellae
Column IV: 41142 Ilmenite as free grains
Column V: 41142 Ilmenite lamellae

	I	II	III	IV	V
Number of analyses	6	4	5	4	6
MgO	0.05±0.02	0.05±0.03	0.03±0.01	0.02±0.02	0.03±0.02
Al_2O_3	0.01±0.01	0.01±0.01	0.05±0.07	0.01±0.01	0.04±0.06
TiO_2	50.72±0.35	50.33±0.20	50.22±0.57	50.93±0.53	50.49±0.37
V_2O_3	0.16±0.04	0.30±0.03	0.29±0.02	0.23±0.04	0.23±0.04
Cr_2O_3	0.00±0.01	0.01±0.01	0.03±0.03	0.10±0.17	0.01±0.01
MnO	0.74±0.14	0.76±0.09	0.81±0.06	1.23±0.16	1.16±0.06
FeO	44.73±0.33	44.38±0.24	44.25±0.50	44.50±0.64	44.16±0.26
Fe_2O_3	3.17±0.44	3.63±0.56	4.05±0.97	3.49±0.72	3.89±0.40
NiO	0.01±0.02	0.00±0.00	0.01±0.03	0.04±0.05	0.00±0.01
Sum	99.59±0.47	99.47±0.85	99.74±0.30	100.55±0.68	100.01±0.27
Cations based on 3 O					
Mg	0.002±0.001	0.002±0.001	0.001±0.001	0.001±0.001	0.001±0.001
Al	0.000±0.001	0.000±0.000	0.002±0.002	0.001±0.001	0.001±0.002
Ti	0.968±0.004	0.962±0.005	0.957±0.010	0.963±0.008	0.960±0.005
V	0.004±0.001	0.007±0.001	0.007±0.001	0.005±0.001	0.006±0.001
Cr	0.000±0.000	0.000±0.000	0.001±0.001	0.002±0.004	0.000±0.000
Mn	0.016±0.003	0.016±0.002	0.017±0.002	0.026±0.004	0.025±0.001
Fe^{++}	0.950±0.006	0.944±0.008	0.938±0.010	0.937±0.010	0.934±0.004
Fe^{+++}	0.061±0.009	0.070±0.010	0.077±0.019	0.066±0.014	0.074±0.008
Ni	0.000±0.000	0.000±0.000	0.000±0.000	0.000±0.001	0.000±0.000
Sum	2.001±0.001	2.001±0.001	2.000±0.000	2.001±0.001	2.001±0.001
Ti/Fe^{+++}	15.87	13.74	12.43	14.59	12.97

ilmenite inside larger masses of turbid titanite. These dykes are thought to almost certainly correspond to the dykes of sector I and II with titanomagnetite as well as ilmenite.

The titanomagnetite never has cores of ilmenite. Most of the ilmenite is developed as typical {111} lamellae, but occasionally the titanomagnetite has areas of more or less irregularly shaped ilmenite, but these are strongly believed to be the result of oxyexsolution just like the ilmenite lamellae.

The titanomagnetite grains in the Koster dykes typically consist of a titanomagnetite groundmass which encloses ilmenite lamellae and occasionally some ilmenite in irregular areas.

Analytical results

The electron microprobe analyses were carried out with a Jeol Superprobe JCXA 733 with 15.0 kV accelerating voltage and a sample current of 20.0 nA using olivine, corundum, rutile, V_2O_3, Cr_2O_3, $MnTiO_3$, hematite and Ni as standards. Total iron was distributed between ferrous and ferric iron using the method suggested by Finger (1972).

The results are shown in tables 1 to 9 for ilmenite and tables 10 and 11 for groundmass titanomagnetite.

Analyses of ilmenite

Ilmenite analyses from sector I are shown in tables 1 to 3 for dykes carrying titanomagnetite as well as ilmenite, and in table 4 for dykes carrying only ilmenite.

It can be seen that the ilmenite does not contain Al, Cr and Ni and, with the exception of 41131 (table 2), Mg is very low or absent. In 41131 some Mg is present in all the ilmenite grains as well as in ilmenite lamellae in the titanomagnetite, but some of the free grains of ilmenite are considerably richer in Mg than others. With the exception of these Mg-rich grains the ilmenites investigated here are considerably poorer in MgO than the ilmenite analyses given by Haggerty (1976) (0.02–0.28% in the Koster dykes

Table 4. Ilmenite analyses from samples with ilmenite as the only Fe-Ti-oxide.

	Sector I 41167	Sector I 41135/41146	Sector II 41109	Sector III 41108	Sector III 41179	Sector III 51704
Number of analyses	20	10	11	8	12	17
MgO	0.05±0.02	0.05±0.03	0.05±0.03	0.05±0.04	0.08±0.05	0.04±0.03
Al_2O_3	0.01±0.01	0.02±0.02	0.01±0.01	0.02±0.02	0.03±0.08	0.03±0.07
TiO_2	51.19±0.31	49.83±0.61	53.36±0.57	52.36±0.56	52.69±0.27	52.55±0.56
V_2O_3	0.12±0.05	0.17±0.11	0.11±0.10	0.18±0.12	0.07±0.07	0.11±0.10
Cr_2O_3	0.01±0.01	0.00±0.01	0.01±0.02	0.01±0.01	0.03±0.04	0.04±0.04
MnO	0.94±0.10	0.81±0.26	1.24±0.06	1.18±0.09	1.70±0.09	0.73±0.11
FeO	45.12±0.30	43.91±0.78	46.08±0.43	45.55±0.34	45.20±0.23	46.23±0.35
Fe_2O_3	2.46±0.47	3.43±0.72	0.00±0.00	0.50±0.50	0.11±0.23	0.15±0.27
NiO	0.01±0.01	0.01±0.01	0.01±0.02	0.03±0.08	0.07±0.10	0.03±0.04
Sum	99.91±0.46	98.23±0.77	100.87±0.95	99.88±0.53	99.98±0.50	99.91±0.71
Cations based on 3 O						
Mg	0.002±0.001	0.002±0.001	0.002±0.001	0.002±0.001	0.003±0.002	0.002±0.001
Al	0.001±0.001	0.001±0.001	0.000±0.000	0.000±0.001	0.001±0.002	0.001±0.002
Ti	0.974±0.005	0.965±0.006	1.005±0.004	0.996±0.009	1.001±0.006	0.999±0.005
V	0.003±0.001	0.004±0.003	0.002±0.002	0.004±0.002	0.001±0.001	0.002±0.002
Cr	0.000±0.001	0.000±0.000	0.000±0.000	0.000±0.000	0.001±0.001	0.001±0.001
Mn	0.020±0.002	0.017±0.006	0.026±0.001	0.025±0.002	0.036±0.002	0.016±0.002
Fe^{++}	0.954±0.005	0.945±0.011	0.964±0.004	0.963±0.004	0.954±0.004	0.977±0.004
Fe^{+++}	0.047±0.009	0.066±0.014	0.000±0.000	0.010±0.010	0.002±0.004	0.003±0.005
Ni	0.000±0.000	0.000±0.000	0.000±0.000	0.001±0.002	0.001±0.002	0.001±0.001
Sum	2.001±0.001	2.000±0.000	1.999±0.001	2.001±0.001	2.000±0.000	2.002±0.001
Ti/Fe^{+++}	20.72	14.62	infinite	99.60	500.50	333.00

against Haggerty's 1.04–2.71%), and the finding of Haggerty that the MgO content of exsolved ilmenite tends to be higher than that of ilmenite found as free grains is not confirmed by this investigation.

Some Mn is present in all the ilmenite, MnO varying from 0.67% to 1.23%.

There is also some V present in all the ilmenites, V_2O_3 varying from 0.11% to 0.39%; in dykes with only ilmenite 0.17% is the highest value obtained. Except for 41142 (table 3) it can be seen that ilmenite lamellae and ilmenite in irregular areas inside titanomagnetite are somewhat richer in V than ilmenite occurring as free grains.

TiO_2 is generally about 50% but varies between 49% and 51%. When the MgO-rich ilmenite in 41131 which has only 42.3% FeO is excluded, FeO varies between 43.5% and 45%.

In dykes with only ilmenite, Fe_2O_3 in ilmenite lies between 2.5% and 3.5%, whereas in dykes with titanomagnetite as well as ilmenite Fe_2O_3 varies between 3% and 6%. It is striking that the ilmenite lamellae in 41131 have only half as much Fe_2O_3 as the ilmenite occurring as free grains.

Ilmenite analyses from sector II are shown in

Table 5. Ilmenite analyses of sample 41106 from sector II.

Column I: Ilmenite as free grains
Column II: Ilmenite in irregular areas inside titanomagnetite
Column III: Ilmenite lamellae

	I	II	III
Numbers of analyses	7	6	6
MgO	0.05±0.03	0.04±0.02	0.09±0.03
Al_2O_3	0.02±0.03	0.01±0.01	0.01±0.01
TiO_2	48.62±0.49	50.39±0.19	51.25±0.40
V_2O_3	0.17±0.05	0.28±0.03	0.34±0.15
Cr_2O_3	0.03±0.03	0.04±0.03	0.09±0.04
MnO	1.41±0.32	1.13±0.08	1.33±0.41
FeO	42.21±0.58	44.07±0.10	44.58±0.49
Fe_2O_3	6.86±0.88	3.88±0.49	4.34±0.80
NiO	0.01±0.01	0.06±0.14	0.02±0.03
Sum	99.38±0.50	99.90±0.53	102.05±0.35
Cations based on 3 O			
Mg	0.002±0.001	0.002±0.001	0.003±0.001
Al	0.000±0.001	0.001±0.001	0.000±0.000
Ti	0.932±0.008	0.959±0.005	0.955±0.008
V	0.004±0.001	0.007±0.001	0.007±0.003
Cr	0.001±0.001	0.001±0.001	0.002±0.001
Mn	0.030±0.007	0.024±0.002	0.028±0.009
Fe^{++}	0.899±0.011	0.933±0.005	0.924±0.013
Fe^{+++}	0.132±0.017	0.074±0.009	0.081±0.015
Ni	0.000±0.000	0.001±0.003	0.000±0.001
Sum	2.000±0.000	2.002±0.001	2.000±0.000
Ti/Fe^{+++}	7.06	12.96	11.79

Table 6. Ilmenite analyses of sample 41155 from sector II.

Column I: Ilmenite as free grains
Column II: Ilmenite in irregular areas inside titanomagnetite
Column III: Ilmenite lamellae

	I	II	III
Number of analyses	6	6	3
MgO	0.03±0.03	0.03±0.03	0.06±0.03
Al_2O_3	0.02±0.02	0.02±0.03	0.01±0.01
TiO_2	49.97±0.63	51.80±0.42	51.79±0.28
V_2O_3	0.25±0.15	0.37±0.05	0.32±0.04
Cr_2O_3	0.02±0.02	0.10±0.17	0.05±0.02
MnO	1.19±0.09	1.04±0.23	1.23±0.02
FeO	43.69±0.64	45.48±0.23	45.23±0.23
Fe_2O_3	4.32±1.16	1.99±0.60	2.16±0.68
NiO	0.01±0.01	0.02±0.02	0.01±0.01
Sum	99.50±0.63	100.85±0.61	100.86±0.27
Cations based on 3 O			
Mg	0.001±0.001	0.001±0.001	0.002±0.001
Al	0.001±0.001	0.000±0.001	0.000±0.001
Ti	0.956±0.011	0.976±0.007	0.976±0.006
V	0.005±0.003	0.007±0.001	0.006±0.001
Cr	0.001±0.001	0.002±0.003	0.001±0.000
Mn	0.025±0.002	0.022±0.005	0.026±0.000
Fe^{++}	0.929±0.013	0.953±0.003	0.947±0.005
Fe^{+++}	0.083±0.022	0.038±0.011	0.041±0.013
Ni	0.000±0.000	0.000±0.001	0.000±0.000
Sum	2.001±0.001	1.999±0.001	1.999±0.001
Ti/Fe^{+++}	11.52	25.68	23.80

Table 7. Ilmenite analyses of sample 41147 from sector II.

Column I: Ilmenite as free grains
Column II: Ilmenite in irregular areas inside titanomagnetite
Column III: Ilmenite lamellae

	I	II	III
Number of analyses	6	7	11
Mg	0.05±0.03	0.02±0.02	0.02±0.02
Al_2O_3	0.00±0.01	0.01±0.02	0.01±0.02
TiO^2	52.89±0.37	53.12±0.62	53.08±0.38
V_2O_3	0.18±0.07	0.25±0.13	0.20±0.09
Cr_2O_3	0.02±0.04	0.03±0.04	0.04±0.04
MnO	0.96±0.10	0.87±0.07	0.94±0.10
FeO	46.41±0.25	46.78±0.36	46.73±0.36
Fe_2O_3	0.55±0.48	1.20±0.68	0.98±0.52
NiO	0.04±0.04	0.00±0.01	0.02±0.03
Sum	101.10±0.38	102.28±0.58	102.02±0.55
Cations based on 3 O			
Mg	0.002±0.001	0.001±0.001	0.001±0.001
Al	0.000±0.000	0.000±0.001	0.000±0.001
Ti	0.994±0.005	0.987±0.009	0.988±0.005
V	0.004±0.002	0.005±0.003	0.004±0.002
Cr	0.000±0.001	0.001±0.001	0.001±0.001
Mn	0.020±0.002	0.018±0.002	0.020±0.002
Fe^{++}	0.969±0.004	0.966±0.005	0.967±0.007
Fe^{+++}	0.010±0.009	0.022±0.013	0.018±0.010
Ni	0.001±0.001	0.000±0.000	0.001±0.001
Sum	2.000±0.000	2.000±0.000	2.000±0.000
Ti/Fe^{+++}	99.40	44.86	54.89

tables 5 to 8 for dykes carrying titanomagnetite as well as ilmenite, and in table 4 for dykes carrying only ilmenite.

The ilmenite does not contain Al and Ni, and free grains of ilmenite also seem to be devoid of Cr, whereas some of the ilmenite intergrown with titanomagnetite may contain a small amount of Cr.

Mg is absent or very low. Some Mn is present in all the ilmenite, MnO varying from 0.87% to 1.67%. There is also some V present in all the ilmenite, V_2O_3 varying from 0.11% to 0.38%. Ilmenite lamellae and ilmenite in irregular areas inside titanomagnetite are somewhat richer in V than ilmenite occurring as free grains.

Concerning Ti the sector II dykes fall into two groups, one with high TiO_2 (41147 and 41154) and one with lower TiO_2 (41106 and 41155). The high TiO_2 group has close to 53% TiO_2 and shows no difference between free grains, irregular areas and lamellae. The group with lower TiO_2 has less than 50% TiO_2 in ilmenite in free grains, but shows increasing amounts of TiO_2 in irregular areas and lamellae.The dyke with only ilmenite belongs to the group with high TiO_2.

Table 8. Ilmenite analyses of sample 41154 from sector II.

Column I: Ilmenite as free grains
Column II: Ilmenite in irregular areas inside titanomagnetite
Column III: Ilmenite lamellae

	I	II	III
Number of analyses	6	3	3
MgO	0.05±0.04	0.06±0.06	0.03±0.03
Al^2O_3	0.03±0.02	0.01±0.02	0.02±0.02
TiO_2	52.76±0.17	52.28±0.02	52.55±0.18
V_2O_3	0.13±0.13	0.38±0.12	0.25±0.10
Cr_2O_3	0.08±0.05	0.26±0.25	0.16±0.02
MnO	1.67±0.10	1.25±0.06	1.42±0.18
FeO	45.67±0.25	45.62±0.16	45.78±0.37
Fe_2O_3	1.00±0.42	2.68±0.16	1.43±0.25
NiO	0.01±0.03	0.04±0.05	0.00±0.01
Sum	101.40±0.44	102.58±0.15	101.64±0.70
Cation based on 3 O			
Mg	0.002±0.002	0.002±0.002	0.001±0.001
Al	0.001±0.001	0.000±0.001	0.000±0.001
Ti	0.988±0.004	0.968±0.002	0.982±0.004
V	0.003±0.003	0.008±0.003	0.005±0.002
Cr	0.002±0.001	0.005±0.005	0.003±0.001
Mn	0.035±0.002	0.026±0.001	0.030±0.004
Fe^{++}	0.951±0.005	0.940±0.005	0.951±0.001
Fe^{+++}	0.019±0.008	0.050±0.003	0.027±0.004
Ni	0.000±0.000	0.001±0.001	0.000±0.000
Sum	2.001±0.001	2.000±0.000	1.999±0.001
Ti/Fe^{+++}	52.00	19.36	36.37

Table 9. Analyses of titanite and ilmenite remnants inside titanite of sample 41107 from sector III.

Number of analyses	6		7
SiO_2	30.93±0.11	MgO	0.03±0.02
TiO_2	38.18±0.68	Al_2O_3	0.01±0.02
Al_2O_3	1.12±0.23	TiO_2	50.85±0.49
Cr_2O_3	0.03±0.04	V_2O_3	0.21±0.19
Fe_2O_3	0.99±0.19	Cr_2O_3	0.04±0.04
MnO	0.08±0.02	MnO	2.17±0.26
NiO	0.02±0.02	FeO	43.47±0.39
MgO	0.01±0.01	Fe_2O_3	3.06±0.37
CaO	28.68±0.19	NiO	0.02±0.03
Na_2O	0.00±0.00	Sum	99.86±0.76
K_2O	0.00±0.00		
Sum	100.04±0.51		
Cations based on 20 O		Cations based on 3 O	
Si	4.013±	Mg	0.001±0.001
		Al	0.000±0.001
Al	0.171±	Ti	0.969±0.005
Fe^{+++}	0.094±	V	0.004±0.004
Mg	0.002±	Cr	0.001±0.001
Ni	0.002±	Mn	0.046±0.005
Cr	0.003±	Fe^{++}	0.921±0.006
Ti	3.725± Sum 3.997	Fe^{+++}	0.058±0.007
		Ni	0.000±0.000
		Sum	2.000±0.000
Mn	0.008±	Ti/Fe^{+++}	16.71
Ca	3.982± Sum 3.990		

The grouping established for TiO_2 holds also for FeO and Fe_2O_3. The group with high TiO_2 is correspondingly high in FeO but is low in Fe_2O_3, and there is as much Fe_2O_3 in irregular areas and lamellae as in free grains. The dyke with only ilmenite does not contain Fe_2O_3 at all. The group with lower TiO_2 is also lower in FeO but richer in Fe_2O_3. The amount of FeO increases and the amount of Fe_2O_3 decreases from the ilmenite of free grains to ilmenite in irregular areas and lamellae. Ilmenite occurring as free grains in the group with lower TiO_2 in sector II has a composition similar to the sector I dykes, but shows increasing amounts of TiO_2 and FeO and decreasing amounts of Fe_2O_3 when free grains are compared to ilmenite in irregular areas and lamellae. Thus one could say that ilmenite lamellae and irregular areas in the group with lower TiO_2 have a composition intermediate between the two groups.

Concerning differences between exsolved ilmenite and ilmenite found as free grains, it is seen that exsolved ilmenite is generally richer in V_2O_3 and sometimes poorer in Fe_2O_3 than the ilmenite of free grains.

Analyses of ilmenite from sector III are shown in table 4 for dykes with only ilmenite, and table 9 shows the composition of ilmenite remnants

Table 10. Analyses of titanomagnetite groundmass from sector I.

	41112	41131	41136	41142
Number of analyses	12	10	7	6
MgO	0.03±0.03	0.01±0.01	0.01±0.01	0.01±0.01
Al_2O_3	0.32±0.01	0.33±0.04	0.21±0.05	0.34±0.05
TiO_2	1.54±0.51	2.31±0.99	1.66±0.28	1.44±0.29
V_2O_3	1.44±0.39	1.32±0.07	1.70±0.07	1.42±0.10
Cr_2O_3	0.08±0.07	1.38±0.07	0.15±0.03	0.08±0.02
MnO	0.07±0.08	0.06±0.06	0.06±0.03	0.06±0.04
FeO	33.03±0.85	33.36±1.01	32.60±0.44	32.51±0.34
Fe_2O_3	65.37±1.21	61.17±1.78	63.17±0.76	64.20±0.51
NiO	0.02±0.03	0.03±0.02	0.00±0.01	0.02±0.02
Sum	101.90±0.55	99.97±1.29	99.56±0.70	100.08±0.35
Cations based on 32 O				
Mg	0.013±0.013	0.004±0.004	0.004±0.004	0.004±0.004
Al	0.114±0.004	0.120±0.015	0.076±0.019	0.123±0.018
Ti	0.349±0.116	0.532±0.228	0.385±0.065	0.332±0.066
V	0.347±0.094	0.324±0.017	0.421±0.017	0.348±0.024
Cr	0.020±0.016	0.335±0.017	0.037±0.007	0.020±0.006
Mn	0.018±0.020	0.015±0.015	0.015±0.007	0.015±0.011
Fe^{++}	8.318±0.214	8.552±0.260	8.406±0.113	8.338±0.087
Fe^{+++}	14.815±0.275	14.111±0.415	14.657±0.176	14.815±0.118
Ni	0.005±0.007	0.007±0.006	0.000±0.002	0.006±0.006
Sum	23.999±0.001	24.000±0.000	24.001±0.001	24.001±0.001
Ti/Fe^{+++}	0.024	0.038	0.026	0.022

Table 11. Analyses of titanomagnetite groundmass from sector II.

	41106	41155	41147	41154
Number of analyses	12	4	9	5
MgO	0.01±0.02	0.03±0.02	0.03±0.04	0.00±0.00
Al_2O_3	0.16±0.03	0.30±0.05	0.54±0.09	0.32±0.03
TiO_2	1.61±0.71	1.16±0.22	0.90±0.11	1.58±0.39
V_2O_3	1.06±0.07	1.37±0.13	1.30±0.20	1.45±0.07
Cr_2O_3	1.11±0.09	0.21±0.05	0.27±0.12	2.11±0.07
MnO	0.05±0.05	0.05±0.07	0.04±0.06	0.08±0.05
FeO	32.81±1.13	32.31±0.07	32.26±0.18	32.79±0.46
Fe_2O_3	64.11±1.38	65.38±0.41	65.87±0.40	62.55±0.51
NiO	0.02±0.03	0.06±0.11	0.03±0.04	0.03±0.07
Sum	100.94±2.03	100.87±0.14	101.24±0.42	100.91±0.49
Cations based on 32 O				
Mg	0.004±0.009	0.013±0.009	0.013±0.018	0.000±0.000
Al	0.057±0.011	0.108±0.018	0.193±0.033	0.115±0.011
Ti	0.369±0.163	0.265±0.051	0.206±0.025	0.362±0.089
V	0.258±0.016	0.335±0.031	0.315±0.049	0.352±0.016
Cr	0.267±0.022	0.051±0.013	0.066±0.029	0.508±0.016
Mn	0.013±0.013	0.013±0.018	0.011±0.015	0.020±0.013
Fe^{++}	8.348±0.287	8.225±0.018	8.174±0.046	8.334±0.117
Fe^{+++}	14.679±0.316	14.976±0.093	15.016±0.091	14.302±0.117
Ni	0.005±0.007	0.015±0.027	0.007±0.009	0.007±0.016
Sum	24.000±0.001	24.001±0.001	24.001±0.001	24.000±0.001
Ti/Fe^{+++}	0.025	0.018	0.014	0.025

inside turbid titanite as well as the composition of the titanite.

Ilmenite from dykes with only ilmenite is compositionally similar to the sector II group with high TiO_2, whereas the ilmenite remnants inside titanite more resemble the sector II group with lower TiO_2. Ilmenite in sector II and III is somewhat richer in Mn than ilmenite from sector I, the highest amount of Mn being found in ilmenite remnants inside titanite in sector III.

Analyses of groundmass titanomagnetite

Analyses of groundmass titanomagnetite from sector I are shown in table 10, and from sector II in table 11.

The groundmass titanomagnetite in both sectors is very low in Mg, Mn and Ni. Al_2O_3 is generally about 0.3%, but in 41136 from sector I and in 41106 from sector II it is somewhat lower, and in 41147 from sector II it is somewhat higher.

TiO_2 is generally about 1.5%, but 41131 from sector I has more than 2%, and 41147 and 41155 from sector II have only about 1%.

V_2O_3 is about 1.3%, but 41136 from sector I is somewhat higher, and 41106 from sector II somewhat lower. Cr_2O_3 varies from near zero to about 2%. Cr-rich titanomagnetite is found in both sectors.

FeO is about 33% and sector II seems to be slightly lower than sector I, mainly due to 41147 and 41155. Fe_2O_3 varies between 61% and 66%; sector II is somewhat richer than sector I, again mainly due to 41147 and 41155.

41131 from sector I is enriched in Ti and depleted in Fe^{+++}, whereas 41147 and 41155 from sector II are depleted in Ti and enriched in Fe^{+++}.

Determination of the composition of the original titanomagnetite

The composition of the original titanomagnetite has been determined in two different ways: Method I and Method II. Both methods are based on microscopic investigation of the titanomagnetite, which has revealed that in all the samples the ratio of ilmenite lamellae and ilmenite in irregular areas on the one side and titanomagnetite groundmass on the other side is very close to 1/1 or 50/50. No visible deviation from this ratio can be detected, so the following calculations are based on the assumption that oxyexsolved ilmenite and titanomagnetite groundmass are present in the ratio 50/50.

Method I

By oxyexsolution of the original titanomagnetite ilmenite and magnetite are formed according to the formula: $3Fe_2TiO_4 + 1/2\ O_2 \rightleftharpoons 3FeTiO_3 + Fe_3O_4$, which corresponds to a volume ratio between ilmenite and magnetite of 2.2/1. The 50 parts of ilmenite is accordingly divided by 2.2, and the resulting 22.7 is withdrawn from the 50 parts of magnetite and added to the 50 parts of ilmenite, which changes the ratio of 50/50 to 72.7% ulvöspinel and 27.3% magnetite.

Then the microprobe analyses of the titanomagnetite groundmass are used to calculate how much of the groundmass is still ulvöspinel, and half this percentage is then taken from the magnetite percentage and added to the ulvöspinel percentage.

Method II

The cations of the microprobe analyses of ilmenite lamellae (and where irregular areas of ilmenite are also present the average of these analyses and the analyses of lamellae) are recalculated from a sum of cations 2 to sum of cations 3. Then the average of this and the cations from the microprobe analyses of the titanomagnetite groundmass is calculated. The result is calibrated to 4 oxygens with corresponding movement of Fe^{+++} to Fe^{++}. The ratio of ulvöspinel to magnetite is then determined from this result.

The agreement between the two methods is very good, the average difference being less than one percent relative.

The composition of the original titanomagnetite is found to vary between 75.4% Fe_2TiO_4, 24.6% Fe_3O_4 and 79.4% Fe_2TiO_4, 20.6% Fe_3O_4.

Temperature and fO_2 determinations from coexisting pairs of ilmenite and titanomagnetite

Temperature and fO_2 values are based on the curves of Andersen & Lindsley (1988). Andersen & Lindsley have two somewhat different sets of curves, one set based on the Akimoto model, and one set based on the spinel site mixing model. There is no great difference between the two models. However, Akimoto values seem to be 5–10° lower than spinel site mixing values at the high temperature end, and 5–10° higher than spinel site mixing values at the low temperature end. In the following only Akimoto values are given.

In determining temperature and fO_2 the percentage of $FeTiO_3$ present in the ilmenite is based on the percentage of Fe^{++} in the microprobe analyses of ilmenite. The values obtained by Method II are used for the composition of the original titanomagnetite, and the percentage of Fe_2TiO_4 is based on 100 minus the percentage of Fe_3O_4. This means that V, Al and Cr are calculated as equivalent to Ti. If the percentage of Fe_2TiO_4 is based only on the amount of Ti, the temperatures obtained are between 30° and 80° lower, depending mainly on the amounts of V, Al and Cr present, though the decrease in temperature is also larger for lower values of $FeTiO_3$ in ilmenite than for higher values.

The sector I dykes give temperatures between 1100° and 1280°C and fO_2 between 10^{-10} and 10^{-8}. In 41131 there are two different ilmenites one of which is Mg-rich. This Mg-rich ilmenite is believed to be early and might not be in equilibrium with titanomagnetite. However, if the Mg-rich ilmenite crystallised in equilibrium with titanomagnetite a temperature of 1375° and a fO_2 of 10^{-7} is indicated, whereas the other ilmenite in 41131 gives a temperature of 1280° and fO_2 of 10^{-8}. The fO_2 value for the Mg-rich ilmenite falls just on the FMQ buffer curve, whereas the other ilmenites lie between the FMQ and WM buffer curves, about 1/4 the distance below the FMQ buffer curve.

The curves for determining temperature and fO_2 were established for ilmenite and titanomagnetite crystallising in equilibrium. If this is disregarded, however, and the composition of the ilmenite lamellae is used instead of the ilmenite in free grains, it is interesting to see that for one of the dykes (41131) a temperature about 100°C lower is obtained, whereas the other dykes show no significant difference.

As for the sector II dykes, two of them give temperatures and fO_2 similar to the sector I dykes, namely 1170° and 1300° and 10^{-9} and $10^{-7.5}$, and also here the composition of ilmenite lamellae indicates a temperature about 100° lower. The fO_2 values for these two dykes lie between the FMQ and WM buffer curves, about 1/4 the distance below the FMQ buffer curve.

The remaining two dykes of sector II give temperatures of 870° and 1040° and fO_2 10^{-15} and $10^{-11.5}$ respectively, and the use of the composition of ilmenite lamellae instead of ilmenite in free grains gives no significant difference. However, the author does not consider these values meaningful, as the ilmenite has most probably lost Fe_2O_3 during metamorphism. It is not believed that the temperatures indicate the temperature of metamorphism. Firstly, the temperatures are too high for that. Secondly, it is not believed that the temperature of metamorphism can be determined in this way. The effect of metamorphism is to remove Fe_2O_3 from ilmenite, and it is believed that the higher the temperature of metamorphism the more Fe_2O_3 will be removed, and the more Fe_2O_3 that is removed the lower the temperature indicated by the curves.

Conclusions

Haggerty (1976) expected wide compositional variations between primary ilmenite and exsolved ilmenite, but only found that MgO tended to be higher in exsolved ilmenite. The ilmenite in the Koster dykes is considerably poorer in MgO than the analyses of Haggerty, and the preference of MgO for exsolved ilmenite cannot be confirmed. On the other hand the analyses of ilmenite from the Koster dykes have shown that exsolved ilmenite is generally richer in V_2O_3 and sometimes poorer in Fe_2O_3.

From table 4 which shows ilmenite analyses from dykes carrying only ilmenite it can be seen that whereas the ilmenites from sector I dykes contain Fe_2O_3, those in dykes from sectors II and III do not contain Fe_2O_3. This cannot be the result of interoxide reequilibration as there is no other Fe-Ti oxide present; the disappearance of Fe_2O_3 must be caused by metamorphism.

In the sector I dykes with titanomagnetite as well as ilmenite (tables 1–3), most of the dykes show no detectable difference in composition between ilmenite found as free grains and exsolved ilmenite, but in one dyke (41131) the ilmenite lamellae are clearly lower in Fe_2O_3 than the free ilmenites. This could be the result of intraoxide reequilibration with TiO_2 moving from the titanomagnetite groundmass to ilmenite lamellae in exchange for Fe_2O_3. However, the titanomagnetite groundmass in 41131 has a considerably higher ratio of Ti/Fe^{+++} than all the other dykes. It is therefore believed that the ilmenite lamellae in 41131 were born low in Fe_2O_3 because the oxyexsolution took place at temperatures where the ilmenite could not accommodate more Fe_2O_3.

Of the dykes from sector II the group with high TiO_2 has as much Fe_2O_3 in the exsolved ilmenite as in the ilmenite found as free grains. Free grains of ilmenite in this group are considerably lower in Fe_2O_3 than the free grains of ilmenite in the group with lower TiO_2, and it is believed that the low content of Fe_2O_3 is caused by migration of Fe_2O_3 due to metamorphism, although the low ratio of Ti/Fe^{+++} in the titanomagnetite groundmass in one of the dykes (41147) may indicate that interoxide reequilibration has also played a role.

In the sector II ilmenite group with lower TiO_2 contents, the ilmenite found as free grains has as much Fe_2O_3 as in the sector I dykes, and it is believed that the Fe-Ti-oxides in this group are unaffected by metamorphism. The exsolved ilmenite is considerably poorer in Fe_2O_3 than the ilmenite occurring as free grains; the difference is most striking in 41155, and the low ratio of Ti/Fe^{+++} in the titanomagnetite groundmass of this dyke might indicate intraoxide reequilibration between titanomagnetite groundmass and exsolved ilmenite without any change of composition of the ilmenite found as free grains. No such indication can be established for 41106, so the reason for the low content of Fe_2O_3 in the exsolved ilmenite could be the same as proposed for 41131 from sector I, namely that the oxyexsolution has taken place at temperatures where the ilmenite could not accomodate more Fe_2O_3.

Ilmenite and titanomagnetite crystallised in equilibrium at temperatures between 1100° and 1280° and fO_2 between 10^{-10} and 10^{-8}, whereas the oxyexsolution ceased at considerably lower temperatures and fO_2. Concerning the fO_2 values obtained with ilmenite as free grains, the value for the Mg-rich ilmenite in 41131 lies just on the FMQ buffer curve, whereas all the other values lie between the FMQ and WM buffer curves, about 1/4 the distance below the FMQ buffer curve.

Acknowledgements. The samples were collected by B. Hageskov and financially supported by S.N.F. (Danish Natural Science Research Council). The Jeol Superprobe on which the analyses were carried out was bought with funds from S.N.F. and is run under the supervision of J. Rønsbo, Institute of Mineralogy, University of Copenhagen, whose assistance with the analyses is greatly appreciated. Thanks are due to John Bailey for kindly improving the English of the manuscript.

Dansk sammendrag

Koster dyke sværmen er en del af den sen proterozoiske Kattsund-Koster dyke sværm, der strækker sig fra Bohus Län til Oslofjorden. Dyke sværmen er på grundlag af graden af amfibolitfacies metamorfose af Hageskov (1984) inddelt i tre sektorer, hvor sektor I omfatter uomdannede doleriter og sektor III er amfiboliter, medens sektor II er en overgangszone mellem de uomdannede doleriter og amfiboliterne.

Der er foretaget en mikroskopisk undersøgelse af Fe-Ti oxiderne i 20 prøver fra 16 gange i sektor I, 12 prøver fra 12 gange i sektor II og 15 prøver fra 15 gange i sektor III. Denne undersøgelse har vist at gangene er af to typer, hvoraf den ene har ilmenit som det eneste Fe-Ti-oxid, medens den anden type har såvel ilmenit som titanomagnetit. I sektor III er der dog ikke længere uomdannet titanomagnetit tilbage, men titanomagnetiten er fuldstændig omdannet til grumset titanit.

For at følge ændringen i sammensætningen af Fe-Ti-oxiderne med stigende metamorfose er der udvalgt 5 gange fra sektor I, 5 gange fra sektor II og 4 gange fra sektor III til mikrosondeanalyse. Resultatet heraf er vist i tabellerne 1–11. Tabel 1–3 viser sammensætningen af ilmenit i sektor I i gange, der indeholder såvel ilmenit som titanomagnetit. Tabel 4 viser sammensætningen af ilmenit i gange fra alle 3 sektorer med ilmenit som eneste Fe-Ti-oxid. Tabel 5–8 viser sammensætningen af ilmenit i sektor II i gange, der indeholder såvel ilmenit som titanomagnetit. Tabel 9 viser analyser af ilmenit og titanit fra sektor III. Analyser af titanomagnetit grundmassen er vist i tabel 10 og 11 for henholdsvis sektor I og II.

Medens der ikke har kunnet påvises nogen signifikant forskel i titanomagnetit grundmassens sammensætning i sektor I og II, så er det tydeligt at ilmeniten mister sit indhold af Fe_2O_3 under metamorfosen. Det er endvidere påvist at ilmenitlameller i titanomagnetit generelt har et højere indhold af V_2O_3 end ilmenit i frie korn, og i nogle tilfælde er ilmenitlamellerne tydeligt fattigere på Fe_2O_3 end ilmenit i frie korn.

Temperatur og ilttryk for den samtidige krystallisation af ilmenit og titanomagnetit er bestemt til 1100°-1280° og 10^{-10}–10^{-8}. Ilmenitlamellerne i titanomagnetit er formentlig dannet ved væsentlig lavere temperatur og ilttryk.

References

Andersen, D. J. & Lindsley, D. H. 1988: Internally consistent solution models for Fe-Mn-Ti oxides: Fe-Ti oxides. *Amer. Miner.* 73, 714–726.

Finger, L. W. 1972: The uncertainty in the calculated ferric iron content of a microprobe analysis. *Carnegie Inst. Wash. Yearb.* 71, 600–603.

Hageskov, B. 1984: Magnetic susceptibility used in mapping of amphibolite facies recrystallisation in basic dykes. *Tectonophysics* 108, 339–351.

Hageskov, B. 1985: Constrictional deformation of the Koster dyke swarm in a ductile sinistral shear zone, Koster islands, SW Sweden. *Bull. geol. Soc. Denmark* 34, 151–197.

Hageskov, B. 1987: Tholeiitic dykes and their chemical alteration during amphibolite facies metamorphism: The Kattsund-Koster dyke swarm SE Norway – W Sweden. *Sver. Geol. Unders.* Ser. C, Nr. 817, 1–61.

Hageskov, B. & Pedersen, S. 1988: Rb-Sr age determination of the Kattsund-Koster dyke swarm in the Østfold-Marstrand belt of the Sveconorwegian Province, W Sweden-SE Norway. *Bull. geol. Soc. Denmark* 37, 51–61.

Haggerty, S. E. 1976: Oxidation of opaque mineral oxides in basalts. 1–100 *In* Rumble, D. (*ed.*) Oxide minerals. *Min. Soc. Amer.*, Short course notes. Southern Printing Company, Virginia.