WHAT MAY WE LEARN FROM BRØGGER'S ESSEXITIC HURUM VOLCANO CONCERNING THE MAGMATIC DIFFERENTIATION

BY

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4 TEXTFIGS

From W. C. Brøgger's just published "Der große Hurumvulkan"[1] I abstract a summary of the chemical analyses[2] and the mineralogical composition[3] of the plutonic rocks with accompanying flows and melanocratic and leucocratic dykes (table I—III).

Table I.

Plutonic rocks.

	1	2	3	4	5	6	7	8	9	10
SiO_2	16.5	46.0	46.8	48.4	47.9	50.1	48.5	49.6	50.0	52.0
TiO_2	11.9	2.2	2.8	3.1	1.9	1.9	2.0	3.0	2.9	2.3
Al_2O_3	3.4	5.8	11.6	15.5	16.6	18.5	12.9	13.0	13.5	15.0
Fe_2O_3	28.8	5.5	4.3	4.3	5.7	3.3	7.4	3.5	3.0	3.4
FeO	22.1	8.3	9.7	7.9	7.5	5.6	8.2	9.8	9.5	7.7
MgO	12.9	12.7	8.4	4.6	4.4	3.1	5.8	5.1	5.2	4.2
CaO	1.0	16.4	10.9	9.6	9.4	8.7	9.2	9.3	8.8	7.0
Na_2O	}0.09	1.8	2.6	3.3	3.2	4.0	3.6	3.3	3.1	4.2
K_2O		0.5	1.3	1.7	2.1	2.8	1.7	2.3	2.4	2.7
Pyroxene	2.1	83.2[1]	35.5	21.6	24.6	23.3	33.4	35.9	35.2	21.5[4]
Bronzite.........	-	.	-	6.7	-	-	-	2.3	-	-
Olivine..........	29.6[2]	3.6	12.0[2]	-	6.5	-	6.8[2]	1.9[2]	-	-
Biotite	-	3.1	5.6	8.6	8.3	8.5[3]	3.1	6.5	10.0[3]	14.6

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[1] Die Eruptivgesteine des Oslogebietes. V. The Norwegian Acad. of Sci., mat.-naturv. class, 1930, no. 6 (printed 1931). The manuscript was in the main worked out as far back as in 1915.

[2] Only given with one decimal and H_2O, MnO BaO etc. neglected.

[3] From the details given by Brøgger I calculate the feldspar ratio Ab : An : Or.

Table I, continued	1	2	3	4	5	6	7	8	9	10
Quartz		-	-	-	-	-	-	-	-	1.7
Ilmen., magnet....	63.3	2.9	6.7	8.3	7.5	6.2	8.9	8.5	8.0	6.8
FeS₂	-	-	0.09	0.24	-	-	-	0.09	0.11	0.10
Apatite	0.0	tr.	0.76	1.77	0.78	0.70	1.13	1.27	1.14	1.24
Ratio { Ab.....	Ab₁₄	Ab	48	51	50	48	54	58	57	64
An	An₈₆	Ab₂	40	38	34	32	29	21	20	21
Or.....		An₁	12	11	16	20	17	21	23	15
Sum { Feldspar.....	5.7	6.5	38.6	52.3	52.3	60.3	46.9	42.8	43.6	53.5
Mg, Fe- silicate	31.8	90	53	37	39	32	43	47	45	36

1 Incl. 1 pc. hornblende.
2 Olivine and serpentine.
3 lncl. some chlorite.
4 Diopside inclusive 2.96 pc. hornblende.

Table I.

Plutonic rocks.

The analyses are arranged with combined regard to the increase of the sum of the alkalies and to the (calculated) decrease of An in the feldspar ratio.

No. 1—3, 6, 7—9 from Randvikholmen, no. 4, 5, 10 from Tofteholmen, two small islands in the Oslofjord, situated ab. 1.5 km from each other.

No. 1. Ultrabasic schliere of cumberlandite (ilmenite-magnetite olivinite) in pyroxenite. — No. 2. Schlieric facies of olivine yamaskite. — No. 3. Normal essexite gabbro (main rock). — No. 4. Boundary facies, essexite gabbro (main rock). — No. 6. Leucocrate facies of essexite. — No. 7. Half porphyric facies of essexite gabbro. — No. 8 and 9. Essexite gabbro, fine grained. — No. 10. Fine grained facies of essexite.

Table II.

Dikes.

	Melanocratic				Leucocratic				
	11	12	13	14	15	16	17	18	19
SiO₂	42.7	44.6	44.5	48.2	57.0	57.6	59.9	64.7	66.9
TiO₂	5.4	2.6	3.3	3.4	1.2	1.2	1.6	0.8	0.6
Al₂O₃	7.8	12.3	9.1	7.5	13.4	16.3	15.9	15.5	15.9
Fe₂O₃	5.5	1.6	5.2	5.8	0.6	0.6	0.2	3.4	2.1
FeO	10.8	11.8	8.7	8.0	3.8	4.3	5.9	0.9	1.0
MgO	11.6	9.2	7.6	10.1	3.0	2.4	2.2	1.0	0.6
CaO	12.6	10.0	9.7	12.8	8.7	3.8	4.5	1.5	2.9
Na₂O	1.6	2.5	3.6	2.1	3.2	5.1	2.9	5.2	6.0
K₂O	0.4	1.2	1.1	1.4	3.8	3.2	6.0	4.6	4.3

Table II, continued	Melanocratic				Leucocratic				
	11	12	13	14	15	16	17	18	19
Pyroxene	61.3	-	-	48.2	26.4	12.2[2]	6.8[1]	0.9[1]	-
Hornblende	10.9	-	-	-	1.0	-	-	-	2.6
Olivine (& serp.)	4.5	-	-	12.2	4.5	-	-	-	-
Biotite (& chlor.)	2.8	-	-	-	-	4.5[3]	12.3	2.6	1.7
Ilmen., magnet.	9.7	-	-	12.6	0.85	2.2	3.1	4.7	2.2
FeS$_2$	0.19	-	-	-	3.2	3.5	1.0	-	-
Apatite	0.52	-	-	0.83	0.69	0.86	0.19	0.61	0.46
Quartz	-	-	-	-	7.6	4.0	10.9	15.2	13.3
Ratio { Ab	-	-	-	-	45	62	35	58	57
An	-	-	-	-	15	10	21	6	11
Or	-	-	-	-	40	28	44	36	32
Sum { Feldsvar	8.8	-	ab. 30	27.2	56.5	69.7	66 1	73.8	78.7
Mg, Fe-silicate	79.4	-	-	60.4	31.9	16.7	19.0	3.5	4.3

[1] Diopside.
[2] Incl. hornblende.
[3] Chlorite and serpentine.

Table II.

Melanocratic dikes.

No. 11—13 from Tofteholmen, no. 14 from Holm in Saude. No. 11. Madeirite. — No. 12. Camptonite. — No. 13. Pyroxene camptonite. — No. 14. Essexite melaphyre, intrusive.

Leucocrate dikes.

No. 15, 16, 19 from Tofteholmen, no. 17 from Vealøs, no. 18 from Randvik-holmen. — No. 15. Akerite (boundary facies with apophyse). — No. 16. Menaite. — No. 17. Hurumite. — No. 18. Windsorite (apophyse). — No. 19. Windsorite. — As to a quartz dike, "pyrite salite", from Tofteholmen, carrying 86 pc. quartz, 7.0 pc. pyrite, 0.14 pc. apatite, 4.0 pc. muscovite and carbonate, but no feldspar at all, I refer to Brøgger's work.

Table III.

From Holmestrand with environs; no. 21 lower, no. 22 middle and no. 23 upper bench in the lava series.

No. 20—23 are essexite melaphyres (no. 20 contact metamorphosed). — No. 24—25 are essexite porphyries.

Table III.

Flows.

	Essexite melaphyre				Essexite porphyrite	
	Melano-crate 20	21	22	23	24	25
SiO_2	42.0	45.8	48.2	44.8	48.8	52.5
TiO_2	3.0	3.0	2.3	2.5	2.8	2.4
Al_2O_3	9.5	13.4	11.0	12.2	16.6	12.1
Fe_2O_3	8.0	8.2	9.6	7.3	10.1	6.1
FeO	7.3	6.4	3.9	7.1	2.7	7.2
MgO...............	10.7	7.3	7.3	8.1	4.6	4.3
CaO	15.6	12.1	12.4	11.2	4.4	7.6
Na_2O	0.8	1.3	1.2	2.2	3.9	2.8
K_2O	1.9 [1]	0.9	0.9	1.35	2.2	2.3
Pyroxene	57.5	-	-	33.6	-	26.5
Olivine (& serp.)	-	-	-	8.2	-	3.1
Biotite (& chl.)......	24.3	-	-	-	-	.
Ilmen., magn........	5.8	-	-	12.4	-	11.7
FeS_2	-	-	-	0.7	-	0.15
Apatite	0.16	-	0.62	0.86	1.00	0.89
Quartz	-	-	-	-	-	8.9
Ratio { Ab...............	-	-	-	38	-	49
Ratio { An	-	-	-	44	-	22
Ratio { Or...............	-	-	-	18	-	29
Sum { Feldspar	9.8	Rel. little		43.3	-	46.3
Sum { Mg, Fe-silicate ...	81,9	Very much		41.8	-	29.6

[1] 1.87 pc. K_2O according to O. Røer. The rock is contact metamorphosed, and somewhat of the contents of K_2O is probably added by this process. (Brøgger).

Further — in particular as to the plutonics and the leucocrate dikes — I illustrated graphically (fig. 1) the ratio Ab : An : Or and the quantity of the Mg, Fe-silicates, this last quantity given by circles of varying size [1].

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[1] In this graph I neglect the plutonics no. 1 (without feldspar), and no. 2 with so small a quantity of feldspar that the determination of the ratio Ab : An : Or is too unsure. — Of the flows I include the essexite porphyry table III, no. 25.

At the essexites (the essexite gabbros included) from the numerous small plugs[1] in the Hurum district we meet with a series of variations. Thus these plutonics (illustrated by table I, no. 3—10) parallel with a decrease of An[2] in the feldspar mixture on the whole, yet in the details with some exceptions, show

an increase of Or in relation to Ab + An, and

a decrease of MgO in the ratio MgO : FeO, in the total rock as well as in the Mg, Fe-silicates[3].
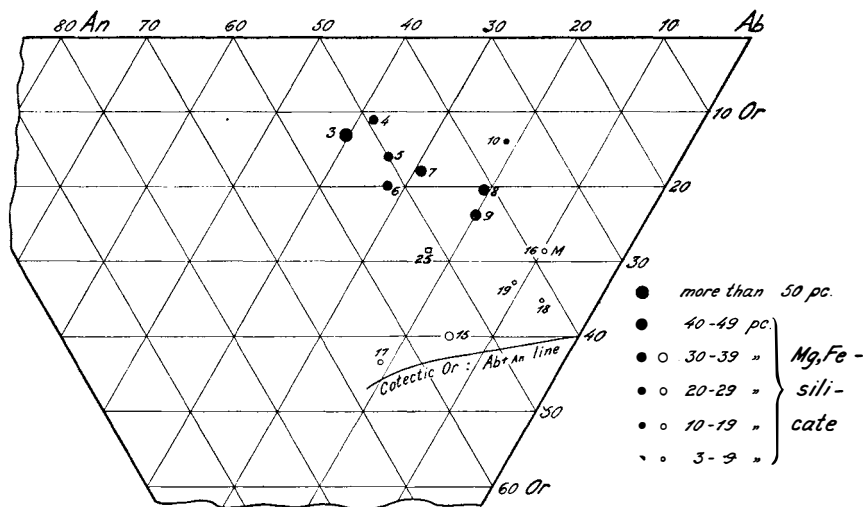
Fig. 1. The plutonics no. 3—10 are given by closed circles, the leucocrate dikes no. 15—19 by open circles, and the flow no. 25 by an open quadrangle. M = menaite. — "The cotectic Or : Ab + An-line" is copied from my previous papers.

The facies variations may be explained by the ordinary laws of crystallization differentiation; to this we shall come back below.

The differentiation in the proto-direction has at places gone on so long that we get olivine yamaskite (table I, no. 2) consisting predominantly of pyroxene, and cumberlandite (= ilmenite-magnetite olivinite, no. 1).

[1] The greatest essexite, at Huseby, in the Hurum district — above the fjord — has according to the map in Brøggers paper an area of ab. 0.44 km2.

[2] Parallel with the decrease of An (with 43.3 pc. silica) and increase of Ab (with 68.8 pc. silica) and of Or (with 64.7 pc. silica) we get an increase of the percentage of silica in the total rock.

[3] As to the details see table V below.

The flows, according to Brøgger on the average of the same chemical composition, as the plutonics, show similar variations as the latter.

The melanocrate dikes (no. 11—14), compared with the ordinary plutonics (no. 3—10) demonstrate on the average

an increase of TiO_2, $FeO + MgO$, and CaO,

but on the other hand a decrease of the sum of the alkalies and of Al_2O_3,

demonstrating a decrease of the feldspars and an increase of ilmenite-magnetite and of the Mg, Fe-silicates (in particular pyroxene), thus a differentiation in the proto-direction.

As to the Brøgger's leucocrate dikes compared with the mother rock we note

a decrease of TiO_2, Fe_2O_3 and P_2O_5, further of MgO and CaO,

but on the other hand an increase of the sum of the alkalies, further a decrease of An in relation to Ab, but an increase of Or in relation to Ab + An and also separately to Ab.

The leucocrate dikes thus, as also pointed out by Brøgger, represent the residual magmas of the essexites, at the various stages of the differentiation in the restmagma-direction.

The menaites (see table II, no. 16 and divers analyses in Brøgger's papers from other localities in the Oslo district) often form dikes of rather great dimensions. This may be connected with the fact that the menaites represent the residual magma at the initial· stages of the crystallization of the essexites, thus at stages when the residual magma was present in a rather great quantity.

But on the other hand, the windsorite (no. 18, 19), representing the restmagma at very far advanced stages of the crystallization of the mother rock, when the restmagma was present only in a small quantity, form dikes of very small dimensions. We also meet with a similar phenomenon at many other igneous rocks.

We note that the residual magma dikes table II, no. 15—19 carry some quartz, the dikes with ab. 65 pc. silica even as much as 14—15 pc. I. e. a plutonic magma crystallizing as quartz free essexite (with ab. 49 pc. silica) delivers restmagma giving rise to dikes carrying notable quantity of quartz. As a parallel we mention that some — but not all — of the dikes of lestiwarite, representing the youngest

— and small — restmagma dikes of the lardalite (without quartz, and rather rich in nephelite) carry some quartz. And in quartz free gabbros we sometimes meet with quartz bearing restmagma dikes. This phenomenon may probably be explained by a dislocation of the magmatic equilibrium, due to some concentration of H_2O in the restmagma.

Referring to fig. 1 we emphazise that the relative increase of Or in the leucocrate dikes examined by Brøgger never is so considerable that the contents of Or in relation to Ab + An is greater than the cotectic Or : Ab + An line, previously determined by myself. This my be considered as a new argument for the correctness of the course of this line, very important for petrology.

On the formation of the Hurum essexite from a magma (ab. 49 pc. SiO₂) produced by magmatic differentiation of a parent magma much richer in silica (ab. 64 pc. SiO₂).

The Hurum essexite belongs to the comagmatic Oslo province, made classical by the studies of W. C. Brøgger. His renowned old catchword on *the parallellism between the sequence of crystallization and the sequence of eruption* was based on the sequence of eruption in the Oslo province, with the essexites as the oldest and the granites as the youngest igneous rocks.

Brøgger assumed long ago that the essexites with accompanying flows were ordinary igneous rocks, solidified from magmas, and that this is so, is proved without any doubt by his detailed studies, now (1931) published. The Hurum volcano is not a strato, but a "Schield" volcano, covering a very considerable area, of a length more than 40, perhaps even more than 50 km, and whose breadth may be measured with similar figures. The total thickness of the numerous single flows amounts, in the somewhat peripheric parts, in one place to ab. 100—110 m, and in another place to ab. 110—120 m, and is composed of a great lot — at least ab. 25 — of planeparallel single flows of varying thickness, some only 1 m or still less thick, many 2—3 or 5—10 m in thickness, and some 15 m or still somewhat more.

Brøgger — referring to other "Schield"volcanos (Hawaii, Iceland) — concludes that the considerable area of the Hurum flows, each single flow planeparallel and often of very small thickness only may be

explained by the fact that the lava was characterized even by a *great thin fluidity*.

Brøgger's arguments are so convincing that I believe that every geologist will agree in his conclusion.

Table IV gives the average compositions, no. 1 and 2 of the igneous rocks in general[1] (no. 1 according to my own calculation[2], no. 2 according to Clarke and Washington, this printed in brevier, as the errors here in my opinion are much greater than in my own calculation),

no. 3 Brøgger's old calculation[3] (1894) of the igneous rocks — plutonic rocks and flows, principally of rhomb porphyries — of the Oslo comagmatic province,

no. 4, Brøgger's average calculation (1931) of the Hurum essexites (plutonics and flows).

<div align="center">Table IV.</div>

	Average composition of the igneous rock[1]		Oslo comagm. province	Hurum essexite
	1	2	3	4
	Vogt	Clarke	Brøgger	Brøgger
SiO_2	64.9	59.85	64.2	49.1
TiO_2	0.55	1.05	-	2.5
Al_2O_3	15.55	15.55	17.2	13.6
Fe_2O_3	2.15	3.1	} 3.6	5.9
FeO	2.5	3.85	}	7.3
MgO	2.45	3.55	0.8	6.1
CaO	4.3	5.15	2.0	9.9
Na_2O	3.45	3.9	7.0	2.9
K_2O	3.65	3.15	4.6	1.8
P_2O_5	0.18	0.3	-	0.36
Divers	0.3	0.55	0.6[2]	0.5
Sum	100.0	100.0	100.0	100.0

[1] Without H_2O.

[2] TiO_2, ZrO_2, P_2O_5, H_2O etc.

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[1] In both cases H_2O and CO_2 disregarded.

[2] On the Average Composition of the Earth's Crust. Oslo Acad. of Sci. for 1931.

[3] Die Eruptivgesteine des Kristianiagebietes, I.

Brøgger's old calculation of the average magma of the Oslo province was, in its days, a very important scientific progress, in spite of the fact that it only gave an approximative view. I believe that a future revision will show somewhat more MgO and less alkalies, in particular less Na_2O [1].

We point out, that the original magma (no. 3, with ab. 64 pc. silica) has by the magmatic differentiation given rise to the essexite *magma* (no. 4, with ab. 49 pc. silica), carrying more — and partly even much more — TiO_2, Fe_2O_3, FeO, MgO, CaO, P_2O_5 and on the other hand in particular much less alkalies.

This may be explained by an addition to the original magma in particular of Mg, Fe-silicates together with some titaniferous iron ore and apatite.

The Hurum essexites consist on an average of ab. 46 pc. feldspar, 45 pc. Mg, Fe-silicate, 8 pc. titaniferous iron ore and not quite 1 pc. apatite. Already this short summary compared with the average composition of the Oslo rocks (table IV, no. 3) indicates that the addition of Mg, Fe-silicate and titaniferous iron ore took place in a very great scale.

We shall render a calculation, based on the percentage of K_2O. The Hurum essexites carry on an average 1.80 pc. K_2O (Brøgger, table IV, no. 4). — We suppose as an average for the Oslo rocks 4.0 pc. K_2O (about middle of table IV, no. 1 and 3). If we suppose, that the added minerals did not contain any K_2O at all, the original magma should have constituted 45 pc. and the added minerals 55 pc. But in fact, also the added minerals may have contained some K_2O (say 0.1—0.2 pc. K_2O in the pyroxene-hornblende, much more in biotite, further somewhat in eventuel plagioclase). Supposing 1.6 pc. K_2O due to the rest of the original magma, we get a quantity of 40 pc. original magma and 60 pc. sum of the added minerals.

Starting from these figures and Brøgger's average composition (table IV, no. 4) of the Hurum essexite, and further supposing that the original Oslo magma carries

SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	P_2O_5
64	0.6	16.7	1.5	2	2	2.5	6	4	0.2

we calculate the following average composition of the added minerals (amounting to 60 pc.), recalculated to 100 pc.

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[1] The essexites according to Brøgger's old summary (1894) amount only to somewhat below 1 pc. of the total extension of the Oslo rocks.

SiO$_2$	TiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	FeO	MgO	CaO	Na$_2$O	K$_2$O	P$_2$O$_5$
39.1	3.9	11.5	8.9	10.9	8.8	14.8	0.9	0.33	0.47.

This may be calculated as ab. 1 (or 1.2) pc. apatite, 12 pc. titaniferous iron ores, and 87 pc. silicates, these last averagely with ab. 45 pc. SiO$_2$.

This calculation is indeed — and in particular as to Na$_2$O — rather unsure, but it may be justified to conclude that the added minerals, besides a little apatite and some iron ore, quite predominantly consisted of Mg, Fe-silicate, principally pyroxene (or hornblende), probably also a relatively small quantity of plagioclase, rich in An.

The minerals which by the addition to the parent magma gave rise to the essexite, are thus just the minerals separated at very early stages of the crystallization of the parent magma, and even at so early stages that the separation of the feldspar (plagioclase, very rich in An) only had begun to a slight extent.

Referring to statements in my previous papers — in particular The Physical Chemistry of the Magmatic Differentiation etc. III, First Half, 1929, p. 31 et seq. — we point out that at the stages when the here treated subsiding minerals were separated, the quantity of apatite must have been much greater than 1 (or 1.2) parts of apatite: ab. 12 parts of ilmenite-magnetite: ab. 87 (or a little less than 87) parts of Mg, Fe-silicates. I. a. somewhat of the subsiding apatite must have been subject to a fractional (or selective) resorption.

The relatively very considerable quantity (ab. 60 parts) of the added minerals must have been resorbed by the parent magma (about 40 parts), perhaps not by a single process, but by various consecutive processes, acting at a very great depth and during geological periods of considerable duration.

— Brøgger points out the almost complete agreement from a chemical point of view between the dike of bronzite kersantite at Hovland in the lardalite (Lardal) and the essexite table I, no. 4 occuring as a boundary facies at Tofteholmen. Further there is only a rather small chemical difference between the just mentioned dike of bronzite kersantite and several of the other essexites (in particular table I, no. 4 and 6) and Brøgger's average calculation (table IV, no. 4) of the Hurum essexites.

The dike of bronzite kersantite represents a rather far advanced stage of differentiation in the proto-direction[1] within the lardalite magma. This differentiation within the lardalite, in the sequence of eruption somewhat younger than the essexite, gave thus chemically a product almost identical with several of the essexites, resulting also from a differentiation in the proto-direction, but from the original parent magma.

On the petrogenetic relation between the essexites and the gabbros.

The graphs (fig. 2—4) illustrate the feldspar ratio Ab : An : Or of the essexites, the gabbros (and norites) and the anorthosites.

The graph of the *essexites*, representing the essexites in general, is worked out on the basis of the many analyses in Rosenbusch-Osann, Elemente der Gesteinslehre (1923, p. 218), in Brøgger's work and the average calculation in Daly's Igneous Rocks and their Origin (1914). The calcutation of the feldspar ratio in essexites, relatively rich in alkalies, on the basis of the analyses is in general encumbered with rather great uncertainty, due to the contents of nephelite etc. and the rather great quantity of the Mg, Fe-silicates. The minimum contents of Or in the ratio Ab : An : Or may be taken from Brøgger's mineralogical calculation of the Hurum essexites, with relatively low contents of the alkalies.

The graph of the *gabbros* and the diorites — the quartz gabbros and quartz diorites not included — is as to the gabbros (and norites) worked out on the basis of my own average calculations[2] of the gabbros (and norites), devided into subgroups with varying acidity of the plagioclase, and on a number of analyses of isolated plagioclases, some of these last analyses indicating the minimum and the maximum contents of Or at varying proportions between Or and Ab + An. The continuation of this graph up to ab. 65—70 Ab of the relatively small group of the quartz free diorites is based on the average analyses by Daly and on divers single-analyses. As to the graph (fig. 4) of the *anorthosites* — with up to 8—10 pc. Mg, Fe-silicate, thus the anorthosite-norites not included — I refer to the chapter "on the plagioclase of the anorthosites" in my just quoted paper (part I, 1924, p. 73—75).

The relative extension of the rocks with given ratio Ab : An : Or is as to the gabbros and anorthosites based on the number of analyses in the average calculations with varying Ab : An proportions.

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[1] See my paper on the phys. chem. of the magmatic differentiation, III, first half, 1929, p. 40 et sec.

[2] Phys. chem. of the magmatic differentiation of ign. rocks, I (1924), p. 125.

As to the anorthosites and the gabbros (plus diorites) the quantity of Or in relation to $Ab + An$ on the whole decreases with increasing An. This fact depends on the maximum quantity of Or which at the varying proportions between Ab and An may enter into the plagioclase [1].

As to the *Mg : FeO-ratio* of the Mg, Fe-silicates of the Hurum essexites and the gabbros in general I refer to the table V and VI.

A. The calculated (stoichiometrical) ratio MgO : FeO is worked out under the supposition that $3/4$ of the contents of TiO_2 and $1/2$ of Fe_2O_3 enters into ilmenite-magnetite; for getting the quantity of FeO in the Fe, Mg-silicates we thus from the total percentage of FeO may subtract a quantity of FeO = $65/100$ of the percentage of TiO_2 plus $21/100$ of the percentage of Fe_2O_3.

B. Brøgger has for the Hurum essexites on the basis of the chemical rock analyses and the microscopical examination calculated the quantity (table I) and the chemical composition of the various Mg, Fe-silicate. And on the basis of these figures I have calculated the MgO : FeO ratio in the total Mg, Fe-silicates.

Table V.

The Hurum essexites.

	3	4	5	6	7	8	9	10
SiO₂	46.8	48.4	47.9	50.1	48.5	49.6	50.0	52.0
FeO	9.7	7.9	7.5	5.6	8.2	9.8	9.5	7.7
MgO	8.4	4.6	4.4	3.1	5.8	5.1	5.2	4.2
K₂O	1.3	1.7	2.1	2.8	1.7	2.3	2.4	2.7

MgO : FeO in the Mg, Fe-silicates.
A. After subtraction of FeO for ilmenite-magnetite.

MgO : 31 FeO	MgO : 33 FeO	MgO : 39 FeO	MgO : 40 FeO	MgO : 34 FeO	MgO : 46 FeO	MgO : 44 FeO	MgO : 43 FeO
69	67	61	60	66	54	56	57

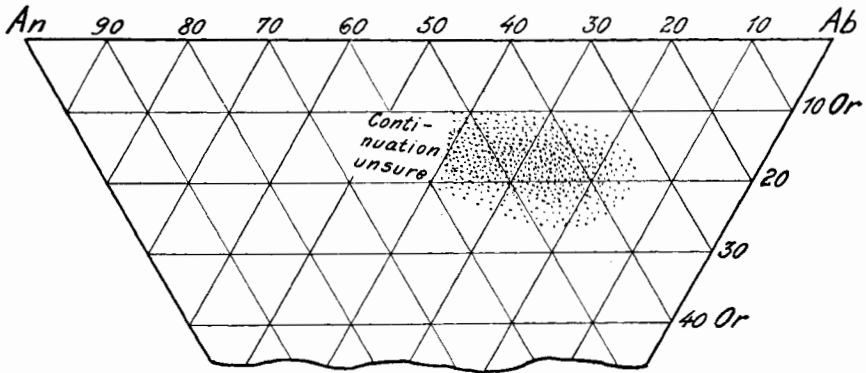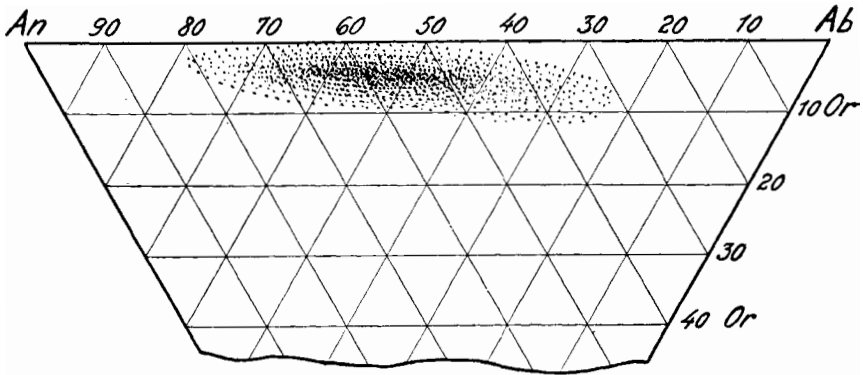[1] See the graph fig. 4 and accompanying text in my paper II, 1926, On the Feldspar Diagram.

Fig. 2. Essexites.

Fig. 3. Gabbros (and diorites).
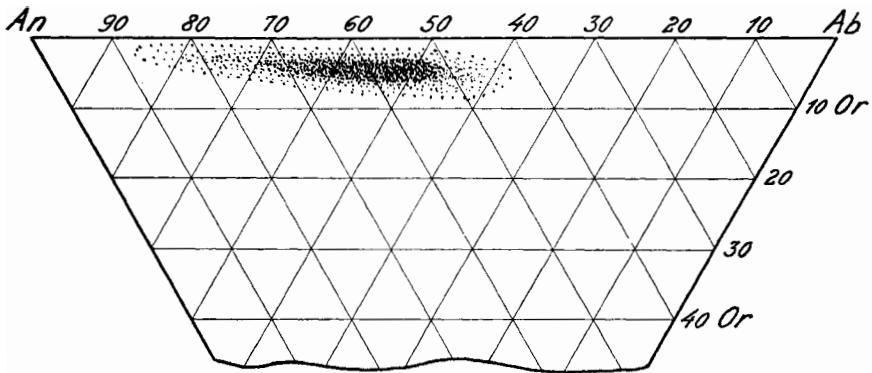

Fig. 4. Anorthosites.

B. Vogt, on the basis of Brøgger's calculation of the Mg, Fe-silicates.

| 64 MgO : 36 FeO | 59 MgO : 41 FeO | 52 MgO : 48 FeO | Disregarded[1] | 62 MgO : 38 FeO | 52 MgO : 48 FeO | 55 MgO : 45 FeO | 59 MgO : 41 FeO |

The average compositions of the various subgroups of the gabbros and norites is taken from my above quoted paper (1924, I, p. 125), neglecting the quartz gabbros and quartz norites, and also neglecting the separate subgroups relatively rich in diallage, resp. hypersthen (and thus relatively poor in plagioclase).

Table VI.

Gabbros (and norites).

	Gabbros (and norites)					Rel. rich in TiO_2, Fe-oxydes, P_2O_5	
	N	Gb	Gb	N	Gb	Gb	N
Number of anal.....	28	61	25	10	22	22	13
	1	2	3	4	5	6	7
SiO_2	50.7	49.5	49.5	47.7	45.6	48.5	48.0
TiO_2	1.2	1.2	0.8	0.5	0.9	3.6	2.0
Al_2O_3	17.2	18.0	18.1	18.3	19.5	14.9	18.2
Fe_2O_3	2.0	3.6	2.1	2.1	4.0	3.4	3.6
FeO	7.6	6.8	5.6	6.9	6.3	10.4	8.5
MgO......	7.7	6.4	7.9	10.0	7.2	5.2	5.2
CaO	9.5	9.7	13.1	12.1	14.2	8.9	8.7
Na_2O	2.7	3.0	1.8	1.4	1.4	3.0	3.4
K_2O	0.9	1.1	0.5	0.6	0.4	1.4	1.2
P_2O_5	0.25	0.30	0.25	0.15	0.20	0.56	0.61

A. Calculated ratio n MgO : (1-n) FeO in the Fe, Mg-silicates.

| 68 MgO : 32 FeO | 68 MgO : 32 FeO | 75 MgO : 25 FeO | 74 MgO : 26 FeO | 73 MgO : 27 FeO | 56 MgO : 44 FeO | 60 MgO : 40 FeO |

[1] Due to the calculation giving 4.56 instead of (found) 5.93 pc. FeO (incl. MnO).

The essexites stay rather near the gabbros, and especially is this the case with many of the Hurum essexites which, as pointed out by Brøgger, for essexites are on the whole characterized by relatively low contents of alkalies. Many of the Hurum essexites may according to Brøgger be nominated as essexite gabbro.

In particular we meet with a very intimate aggrement between the essexite gabbros and the subgroups of gabbros (and norites) relatively rich in TiO_2, Fe-oxydes and P_2O_5. I refer to the average analyses (table VII a) of the essexites (or essexite gabbros) table I, no. 3, 4, 5, 7, 10 and the middle (table VII b) of the gabbro sub-group table VI, no. 6 and 7, representing not quite a fifth of the total number of analyses — or somewhat less than a fifth of the relative extension — of the proper (quartz free) gabbros (incl. norites).

Table VII.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	P_2O_5
a (ess. poor in K_2O)..	48.7	2.4	14.3	5.0	8.2	5.5	9.3	3.4	1.9	0.46
b (gb, rich in TiO_2 etc.)	48.25	2.8	16.5	3.5	9.4	5.2	8.8	3.15	1.3	0.58

We note the slightly smaller quantity of K_2O in the here treated subgroup of the gabbros.

The principal difference between the essexites and the gabbros, both with ab. 47—50 pc. SiO_2, lies in K_2O or in the relation between Or and Ab + An. The Hurum essexites (or essexite gabbros) poorest in K_2O show (see table I) 11, 12, 16, 17 Or : 100 Ab + An + Or, and the gabbros (with ab. 47—50 SiO_2) on an average ab. 6 Or, thus some samples a little less and other samples a little more than 6 Or : 100 Ab + An + Or.

For petrographical classification and geological mapping it may be desirable to have a boundary between the two categories of rocks, and as such a boundary, for rocks with ab. 47—50 p. SiO_2, I propose 10 Or : 100 Ab + An + Or.

The most extended essexites carry between 70—65 Ab : 30—35 An and 55—50 Ab : 45—50 An, and the bulk of the gabbros carry between 55—50 Ab : 45—50 An and 35 Ab : 65 An, thus the gabbros on the

whole more An in relation to Ab than the essexites, and — as
mentioned above — less Or in relation to 100 Or + Ab + An.

Further we meet with a difference as to the MgO : FeO ratio.

In the total rock the Hurum essexites (table I, no. 3—10) show
(stochiometrically) on an average — — — — 53 MgO : 47 FeO,

Daly's average calculation [1] of the essexites (20 anal.) gives
. . . 57 MgO : 43 FeO,

and Rosenbusch-Osann's average calculation [2] (13 anal.)
. . . 50 MgO : 50 FeO.

thus on the whole . . . 53 MgO : 47 FeO.

My own average calculations of the various subgroups of the
gabbros (table VI no. 1—7) give 65, 65, 72, 72, 69, 47, 55 MgO : 35,
35, 28, 28, 31, 53, 45 FeO, — thus on the whole, laying the stress
on the various ratios in proportion with the number of analyses
which they represent . . . 64 MgO : 36 FeO.

Turning now to the Mg, Fe-silicates, the calculation according
to the method table V, A on the average gives for the essexites
62 MgO : 39 FeO, and after method B on the average 58 MgO ; 42 FeO,
thus in the mean 59.5 MgO : 40.5 FeO. — The method A applied
to Daly's average calculation gives 67 MgO : 33 FeO,

and to Rosenbusch-Osann's average calculation . . . 60
MgO : 40 FeO,

thus on the whole according to these three determinations
. . . 62 MgO : 38 FeO.   ·

The average of the various subgroups of the Mg, Fe-silicates of
the gabbros (table VI, A) gives . . . 68 MgO : 32 FeO [3].

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[1] Igneous Rocks and their Origin. 1914.

[2] Elemente der Gesteinslehre. IV edit., 1923, p. 218.

[3] This ratio, calculated from the average gabbro analyses by subtracting the
quantity of FeO entering into magnetite-ilmenite (method A) agrees rather well
with the numerous direct (chemical and optical) determinations, giving for
for hypersthene in. the gabbros in most cases 30—36 pc. $FeSiO_3$, and for
olivine in the same rock on the average ab. 30 pc. Fe_2SiO_4 (see my paper on
the magmatic differentiation, part I, p. 11 and 35—36). — The analyses of separated
Mg, Fe-silicates in the gabbros, collocated in Rosenbusch-Osann, Elemente
der Gesteinslehre, IV edit. 1923, p. 198 give, — no. 1, 2, 3, 4, 7, 8, 15 (mono-
clinic pyroxene), — no. 9 (hypersthene), — 11, 12, 13, 14 (hornblende), —
no, 17 (olivine) 79, 77, 72, 67, 64, 71, 70, — 72 —, 69, 76, 59, 71, — 58 MgO :
21, 23, 28, 33, 36. 29, 30, — 28, — 31, 24, 41, 29, — 42 FeO,
thus averagely 70 MgO : 30 FeO.

Summary concerning the average of the MgO : FeO ratio:

In the total⎰ essexites 53 MgO : 47 FeO
   rock   ⎱ gabbros 64 MgO : 36 FeO

— — — — — —

In the Mg,⎰ essexites 62 MgO : 38 FeO
Fe-silicates⎱ gabbros 68 MgO : 32 FeO.

We conclude that the gabbros in the total rock as well as in the separated Mg, Fe-silicates on the whole carry somewhat more MgO in relation to FeO, than the essexites do.

The first in the magma separated plagioclase is characterized by an enrichment of An in relation to Ab, and the first separated Mg, Fe-silicate[1] is characterized by an enrichment of MgO in relation to FeO.

By the magmatic differentiation in the restmagma direction we thus get residual magmas characterized by relative decrease of An in the An : Ab ratio, and at the same time a relative decrease of MgO in the MgO : FeO ratio, and vice versa by the magmatic differentiation in the proto direction[2] with an addition of a notable quantity of silicates.

The average percentage of K_2O in the igneous rocks amounts according to Clarke and Washington's last calculation to 3.14 pc., and according to my own calculation (see table IV, no. 1), which in my opinion is more correct, to 3.65 pc. — And the average percentage in the proper gabbros (incl. norites) amounts according to my own calculation[3] (see table VI) to 0.90 (or 0.91) pc.[4].

Tschirwinsky (Nowotscherkask, 1929, rev. in N. Jahrb. f. Min. etc. 1931, p. 160) has calculated the average composition of the Mg, Fe-silicates of the gabbros (and norites),

      hypersthene (10 anal.) ...... 72 MgO : 28 FeO
      augite (diallage, 30 anal.).... 75 MgO : 25 FeO
      amphibole (10 anal.) .... 69 MgO : 31 FeO
      olivine (5 anal.)............ 53 MgO : 47 FeO

    thus on the whole 71 MgO : 29 FeO.

[1] Olivine, orthopyroxene, monoclinic pyroxene, biotite.
[2] I refer to the comprehensive explanations given in several places in The Physical Chemistry of Magmatic Differentiation of Igneous Rocks, part I (1924), II (1926), III (first half, 1929 and second half, 1930).
[3] Daly (1914) gives for "all gabbros" 0.90 and for "all norites" 0.81 pc. K_2O.
[4] The quartz gabbros (and quartz norites) and the subgroups very rich in diallage, resp. hypersthene are here neglected.

If we start from these figures (3.65, resp. 0.90 pc. K_2O), and further suppose that the added minerals did not contain any K_2O at all, the gabbros should have been built up by $^1/_4$ of the parent magma and $^3/_4$ of added minerals. But in fact, also the added minerals must have contained a little K_2O. If we — in relation to the present gabbros — suppose an addition of say $^4/_{10}$ or $^5/_{10}$ of plagioclase with 0.5 pc. K_2O and $^3/_{10}$—$^4/_{10}$ of Mg, Fe-silicate with 0.2 pc. K_2O (besides some iron ore), only $0.90 \div ab.\ 0.3 = ab.\ 0.6$ pc. K_2O in the present gabbros can come from the rest of the parent magma. The present gabbros should thus on the average have been built up of ab. $^1/_6$ of the parent magma, and ab. $^5/_6$ of added minerals.

If we start from these figures, and further from my average calculation of the parent magma (table IV, no. 1), and from the following average composition of the proper gabbros [1]

SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	P_2O_5
48.98	1.41	17.73	3.16	7.14	6.85	10.65	2.53	0.91	0.32

we calculate the following average composition of the added minerals (amounting to 83.3 pc.) recalculated to 100 pc.

SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	P_2O_5
45.7	1.6	18.2	3.35	8.1	7.75	11.9	2.35	0.35	0.35.

This may be calculated as 0.9 pc. apatite, 4.6 pc. ilmenite-magnetite, and 94.5 pc. silicates, these last averagely with ab. 48.5 pc. SiO_2, the silicates composed of somewhat more of a rather basic plagioclase than Mg, Fe-silicates.

The above calculations at the essexites and at the gabbros concerning the "added minerals" are indeed encumbered with very great sources of error. Yet — starting from the theory of the crystallization differentiation — we may be justified in concluding that the quantity of the added minerals is much greater, and thus the quantity of the parent magma much less at the gabbros than at the essexites.

The Hurum essexites carry on an average about the same quantity of feldspar and Mg, Fe-silicate, but the gabbros in general unquestionably more plagioclase than Mg, Fe-silicate [2]. — The added

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[1] Calculated from the subgroups table VI, no. 1—7 (thus the quartz gabbros and norites and the gabbros and norites very rich in Mg, Fesilicates disregarded).

[2] In accordance herewith the Hurum essexites according to the analyses in Brøgger's paper on an average contain 13.6 pc. Al_2O_3, and the various sub-

minerals at the essexites consist, according to our calculations, besides some apatite and titaniferous iron ore, quite predominantly of Mg, Fe-silicate only with a subordinate quantity of plagioclase. But at the gabbros we in the added minerals may have to deal with a very great quantity of plagioclase, in the same quantity as the Mg, Fe-silcates, or even in a still greater quantity.

I. e., the added minerals at the gabbros may have resulted from more advanced stages of the crystallization of the parent magma than at the essexites. And in accordance herewith, the subsiding minerals at the formation of the gabbros in relation to the parent magma were present in a greater quantity than at the formation of the essexites.

The genetic difference between the essexites and the gabbros should thus depend on the facts

that the added minerals at the gabbros resulted from more advanced stages of the crystallization of the parent magma than at the essexites, — the subsiding minerals thus also being present in a greater quantity at the formation of the gabbros than at the formation of the essexites,

and the subsiding minerals at the gabbros being added to a percentic less quantity of the parent magma than at the essexites.

This last phenomenon seems to be a consequence of the first named phenomenon.

In connection with the just mentioned factors we must probably also consider the fact that the gabbros have a much greater extension than the essexites.

On the contents of P_2O_5, TiO_2 and Fe_2O_3.

Average	P_2O_5	TiO_2	Fe_2O_3
Essexites {Hurum, Brøgger	0.36	2.55	5.92
Daly (20 anal.)	0.66	1.88	4.37
Rosenb.-Osann (13 anal.)..	0.78	1.99	3.83
Gabbros (Vogt, table VI, no. 1—7)	0.32	1.41	3.35

groups into which I have divided the proper gabbros (table VI, no. 1—7) 17.2 18.0, 18.1, 18.3, 19.5, 14.9, 18.2, thus on the average 17.7 pc. Al_2O_3.

The essexites without any doubt on an average carry more TiO_2 and P_2O_5 than the gabbros, probably also the contents of Fe_2O_3 are somewhat greater.

As to the addition of the subsiding minerals, delivering the proto enriched rocks, we in general may take into account the following factors,

1. the stage of crystallization in the original magma, delivering the subsiding minerals,

2. the fractional (selective) separation (in my opinion as a rule resorption) of the subsiding minerals[1].

Due to the sequence of the beginning crystallization in the parent magmas the contents of apatite and magnetite-ilmenite are proportionally greater in the mixture of the subsiding minerals at the first stages than at the later stages of the crystallization. The subsiding minerals at the formation of the essexites may thus have carried more apatite and magnetite-ilmenite than at the formation of the gabbros. This may be the principal reason for the higher average contents of P_2O_5 and TiO_2 (probably also Fe_2O_3) in ihe essexites than in the gabbros.

Yet, we may also consider the selective resorption, in particular as to apatite[2]. The subsiding minerals, separated in the parent magma at a rather early stage of the crystallization, delivering the essexite magmas, may without doubt have contained more P_2O_5 than ab. 0.5 pc. The surplus must have been kept back at the subsidence of the separated minerals[3]. The same may probably also have been the case at the formation of the gabbro magmas.

The cumberlandite (ilmenite-magnetite olivinite) and the olivine yamaskite (table I, no.1—2), produced by differentiation in the proto-direction within the essexite magma are both practically without any

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[1] See in particular my paper on the magmatic differentiation, part III, first half (1929), p. 33 et seq.

[2] See in particular my paper on the magmatic differentiation, part III, first half (1929), p. 45 et seq.

[3] In this connection I mention that many of the intermediary-acid rocks — such as e. g. the alkali-lime syenites and monzonites with 50.0—54.9 pc. SiO_2 (according to my calculations averagely with ab. 0.52 pc. P_2O_5), the larvikites and lardalites (with ab. 0.4, resp. ab. 0.6 pc. P_2O_5) — are richer in P_2O_5 than the gabbros, probably also than the essexites. This may perhaps be due to an enrichment of P_2O_5 in the magmas delivering the magmas of these rocks, by a selective resorption of some apatite.

apatite at all or only with extremely low contents of apatite. This is also the case with numerous other ilmenite-magnetite olivinites spinellites etc. I refer to a paper which I am now preparing, and where I shall give a lot of observations in order to explain the selective resorption. — In this paper I shall also by other working methods come back to the problem of the resorption in a great scale of the subsiding minerals, delivering the proto-enriched rocks.

W. C. Brøgger's above treated work is of very high petrological interest, in particular as here decisive arguments are delivered for the fact that a magma(!) with ab. 49 pc. silica has been produced from a parent magma with ab. 64 pc. silica.

Starting from the theory of the crystallization differentiation — the correctness of whose main features may be accepted as proved — the essexites may be explained by an addition of minerals, separated at early stages of the crystallization of the parent magma, and added to a given quantity of the parent magma — in proportion approximatively $6/10$ minerals to $4/10$ magma, — and these minerals, perhaps by a repeated series of processes, may in the totality have been *transformed from the solid to the liquid phase*, thus together with the quantity of the parent magma delivering a new proto enriched magma.

N. L. Bowen in his later papers, in particular "The Evolution of Igneous Rocks" (1928), due to the considerable amount of the melting or resorption heat, considers a resorption on a very great scale as impossible, and further he supposes a parent magma of basaltic or gabbroidic composition (with ab. 50 pc. silica). On the other hand I have laid stress on the fact that numerous comagmatic provinces to a very great extent consist of granite. In a paper quoted above (see the text to table IV) I have demonstrated that the average parent magma must have carried as much silica as ab. 65 pc.

On the basis of geological and petrological observations of various kinds I have in previous papers emphasized that various proto-enriched rocks were solidified from magmas, produced by resorption of added (subsiding) minerals. Brøgger has now adduced new and very important arguments, and this is the main reason why I have written the present paper.

When observations furnish convincing proof in support of a certain theory, we cannot accept the objection that the theory for

one reason or other should he an impossibility. The latent heat of the silicates is indeed very considerable — I was the first, more than 25 years ago to demonstrate this experimentally, — but in order to explain the resorption on a great scale we must take into account that the resorption may have taken place at a great depth, during a period — or subsequent periods — of geological length, and under conditions where a conduct of heat from the neighbooring magmas may have been of predominant importance (perhaps partly due to the circulation of volatile compounds).

In the history of petrography Brøgger's brilliant and careful investigations of the Oslo comagmatic province has played an exceedingly important part. His new paper, on the Hurum volcano, is a worthy addition to his previous investigations, and I am certain that I constitute myself interpreter for a large number of colleagues when I express the hope that Brøgger may find time and opportunity to continue and conclude his investigations of the Oslo area.