SOME HORNFELSES FROM SAXONY AND THE PROBLEM OF METAMORPHIC FACIES

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The Mineralogical and Petrographical Collection of the Swiss Federal Institute of Technology (Zürich) owns a suite of contact-metamorphic rocks from the aureole around a granite strip belonging to the Lausitz Massif (Saxony), and lying to the south of Dresden on the left bank of the Elbe between Dohna and Zehista in the north and Berggiesshübel in the south. They belong to the greywacke formation of Culmic to Silurian age and are quite typical products of normal granite contact. With a view to clarifying some questions relating to the chemistry of metamorphic rocks, seven analyses were carried out at the writer's request by J. Jakob.

TABLE 1

	1	2	3	4	5	6	7
SiO_2	50.24	61.00	63.25	54.76	39.06	49.61	94.74
TiO_2	1.72	0.97	0.81	1.14	0.76	1.70	0.19
Al_2O_3	16.24	18.32	17.48	24.02	2.50	14.80	1.00
Fe_2O_3	3.49	1.95	1.26	1.86	{ 3.47	2.13	0.09
FeO	7.83	4.53	4.27	4.93	—	9.61	1.12
MnO	0.09	0.03	0.06	0.06	0.06	0.15	0.00
MgO	6.00	2.72	2.06	1.98	1.39	7.74	0.00
CaO	2.74	0.86	1.38	0.49	27.70	8.85	0.27
Na_2O	4.10	3.02	3.23	2.10	1.63	4.01	1.71
K_2O	1.56	4.93	4.38	5.98	1.17	1.33	0.93
H_2O+	3.08	1.80	2.00	2.82	0.77	0.20	0.30
H_2O-	0.15	0.00	0.00	0.00	0.00	0.00	0.00
P_2O_5	0.57	0.04	0.02	0.00	0.00	0.00	0.00
CO_2	2.10	0.00	0.00	some C	21.85	—	0.00
	99.91	100.17	100.20	100.14	100.36	100.13	100.35

1. Slate. Burkhardtswalde near Weesenstein (matrix of clay minerals with some quartz and calcite with carbonaceous pigment.)
2. Nodular andalusite mica schist. Seidewitztal near Zuschendorf. (Mineral composition mainly quartz, biotite, andalusite, some muscovite and ore.)
3. Cordierite-hornfels. Lockwitztal, near the chocolate factory. (Cordierite, feldspar, quartz, biotite, occasional garnet and tourmaline.)
4. Cordierite mica-hornfels. Prenskerschacht in the Lockwitz valley near Kreischa. (Very rich in cordierite, some zoisite, biotite, muscovite and little quartz.)
5. Calcic greywacke. Friedrichswalde in the Bahra valley near Pirna. (Consists chiefly of quartz and calcite with zoisite, epidote, feldspars.)
6. Amphibolite (schistose). Bahraberg, between Zehista and Friedrichswalde, (consists chiefly of hornblende and plagioclase).
7. Quartzite with hornfels structure. Nenntmannsdörfer Mühle, Seidwitztal near Zehista. (95% quartz, beside some feldspar and biotite.)

TABLE 2. MOLECULAR VALUES (NIGGLI-VALUES)

	si	al	fm	c	alk	k	mg	ti	c/fm	co_2
1	141	27	51	8	14	0.20	0.49	3.6	0.16	8.0
2	225	40	34.5	3.5	22	0.52	0.43	2.7	0.1	—
3	250	40.5	30	6	23.5	0.47	0.40	2.4	0.20	—
4	189	49	29	2	20	0.65	0.35	3.0	0.07	—
5	103	4	12.5	77.5	6	0.32	0.44	1.5	6.2	7.8
6	112	19.5	48	21.5	11	0.18	0.54	2.9	0.45	—
7	2285	14	24.5	7	54.5	0.26	0.0	3.5	0.29	—

Nrs. 1–4 show a large excess of alumina and belong (Niggli 1934) to the alumosilicate rocks. They undoubtedly were derived from argillaceous rocks with, at most, a very slight addition of alkalis.

Nr. 5 is a calc-silicate rock derived from a lime-rich greywacke.

Nr. 6 has the chemical composition of a rather alkali-rich calc-alumosilicate rock and may have been derived from a shale, tuff or eruptive rock of gabbrodioritic composition.

Mr. 7 is a SiO_2 rock derived from a quartz-sandstone.

In what follows, only the alumo-silicate rocks will be considered together with some problems of chemical petrology which they raise. The marginal areas of the Lausitz granites often contain zones rich in inclusions and characterized by an alteration of the biotite granite to two-mica granite. Many modern hypotheses tend to ascribe an important rôle to metasomatic and chemical alterations. In view of this fact it seems important to compare the chemical composition of metamorphic sediments (para-rocks) with those of rocks whose composition does not seem likely to have suffered any considerable chemical change. Molecular (Niggli-) values are well adapted to this purpose as they render conspicuous the alumina excess (al-(alk+c)) typical of pelitic rocks.

Table 3 contains a number of examples selected at random from a large collection. It is evident that no great differences exist between these

TABLE 3

	si	al	fm	c	alk	k	mg	
clay, molasse	250	43	37.5	6	13.5	0.56	0.56	Horgen (Zürich), Switzerland
clay, molasse	250	43	35.5	4	17.5	0.63	0.47	Wettingen, Baden, Switzerland
green slate	206	43	31	6	20	0.28	0.35	Anglesey, England
roofing slate	240	43	38.5	1.5	17	0.63	0.36	Vermont, U.S.A.
Virginia slate	258	41.5	39.5	2	17	0.46	0.46	Mesabi, U.S.A.
slate rock	254	41	37	1	21	0.36	0.33	Anglesey, England
greywacke	300	42.5	30	5.5	22	0.38	0.47	Kamenz, Saxony

clays, shales and slates (pelitic sediments) and the rocks quoted above. A slight addition of alkalis seems likely, especially in the cases of nos. 2 and 3. Slight alterations such as these fall well within the scope of normal metamorphism and by no means justify considering these specimens as true metasomatic rocks.

The same molecular values may also be used to find metamorphic rocks which might be of similar mineral composition. For the SiO_2 value which has purposely been separated from the other molecular values remains practically unaffected by changes in mineral composition, except when the SiO_2 content is very low. Thus Table 4 contains a number of rocks whose compositions are closely related to those of rocks 1 to 4 in Table 2. It is immediately evident that the mineral composition can differ widely. Herein lies the problem of the relationship of metamorphic facies to temperature, pressure and water content. It has become usual nowadays to characterize the major units of the facies classification by special names instead of adhering to the historical method (Grubenmann-Becke) which used general definitions for this purpose.

It is not proposed to proceed on these lines here. For there seems to be little reason for including a staurolite-kyanite facies under the general concept of an amphibolite facies. It would surely be most inconvenient to assign a granite rock to the pyroxene gabbro facies, or to the sanidinite facies, and nobody would like to call a clay a limestone facies. We understand by rock facies a definite assemblage of minerals with a given structure and fabric. There is no justification in including in names such as green-schist facies, epidote-amphibolite facies, pyroxene hornfels facies, eclogite facies, etc., rocks with other minerals, structures and fabrics but formed under analogous physical conditions.

If it be desired to correlate facies of different mineral and chemical composition with respect to their conditions of formation, concepts such as Katafacies, Mesofacies and Epifacies with the necessary transitions are far more useful. Similar terms (in the main relating to temperature) have been applied in the treatment of ore deposits. They have long since (Grubenmann-Niggli 1924) been dissociated from any specific connection with depth or definite zones in the earth's crust as controlling factors. (The objections raised by Eskola and summarized by Turner (1948, p. 34) are less important than the objections given above.) The subfacies given in Table 5 which in principle all have the same chemical composition, can be arranged as shown in the tabulation at top of next page (some minerals may occasionally be absent).

In the case of an SiO_2 deficit the meso- to epifacies may also include emery subfacies with chloritoid, ores, diaspore, etc. (Oenay 1950).

In order to understand the connection between the various types, a

1. Cordierite-andalusite (sillimanite, mullite)-feldspars-pyroxene-subfacies (si-deficit: spinel, corundum)	
2. Cordierite-sillimanite (andalusite)-feldspars-biotite-subfacies	Katafacies (kata conditions)
3. Sillimanite (andalusite)-feldspars-biotite-subfacies	
4. Sillimanite-garnet-feldspars-biotite-subfacies (±cordierite)	
5. Garnet-biotite-feldspars-subfacies	Kata-mesofacies
6. Cordierite-feldspars-anthophyllite-biotite-subfacies	
7. Andalusite (sillimanite)-biotite-muscovite-(feldspars)-subfacies	Mesofacies (meso conditions)
8. Garnet-biotite-muscovite (feldspars)-subfacies	
9. Kyanite-staurolite-biotite-muscovite (feldspars)-subfacies	
10. Biotite (chlorite)-muscovite (feldspars)-subfacies	Meso-epifacies
11. Chloritoid (staurolite, biotite, andalusite, garnet)-sericite-subfacies	
12. Chloritoid (chlorite)-sericite (albite)-subfacies	Epifacies (epi conditions)
13. Sericite-albite-chlorite (glaucophane)-subfacies	
14. Sericite-chlorite-subfacies	

molecular base must be calculated and standard norms for kata-, meso- and epi conditions be deduced from it. As all compounds are given in formulae of a definite size, it is easy to express the connection between minerals and to calculate the modifications corresponding to any subfacies. The underlying principles have been explained elsewhere (Niggli 1936, Burri-Niggli 1945, Niggli 1948).

One example may here be treated more fully.

ROCK NR. 3, TABLE 1

	atomic numbers	Ru	Kp	Ne	Cal	Sp	Fo	Fa	Fs	Q	
Si	1053		93	104			2	30	8	816	
Al	342		93	104	50	95					
Fe‴	16								16		
Fe	60							61			
Mn	1										
Mg	51					47	4				
Ca	25				25						
Na	104			104							
K	93		93								
Ti	10	10									
	1755	10	279	312	75	142	6	91	24	816	1755
base (%)		0.6	15.9	17.8	4.3	8.1	0.3	5.2	1.4	46.4	100

To deduce the base from the kata standard norm, the following equations are required: (*see page 872*)

TABLE 4

	si	al	fm	c	alk	k	mg	
Plagioclase-cordierite-hornfels	203	36	42	8	14	0.67	0.41	Kolaas, near Oslo, Norway
Cordierite-hornfels	215	46	31.5	3.5	19	0.70	0.37	Mt. Ascutney, Vermont, U. S. A.
Andalusite-cordierite hornfels (leptite)	289	46	30.5	1	22.5	0.84	0.76	Långban, Sweden
Cordierite-andalusite-hornfels	286	46	28	3	23	0.91	0.31	Montana, U.S.A.
Cordierite-spinel-hornfels	131	45	42.5	4	8.5	0.44	0.34	Perthshire, Scotland
Cordierite-hornfels	229	40.5	47.5	0.5	4.5	0.84	0.50	Commando Neck, Vredefort, S. Africa
Gneiss with sillimanite, biotite, cordierite and garnet	107	41	54	1.5	3.5	0.68	0.40	Valpelline, Italy
Sillimanite-cordierite-hornfels	205	43	40	5.5	11.5	0.70	0.43	Mooifontein, Lydenburg, S. Africa
Sillimanite-gneiss	259	42.5	32	6.5	19	0.39	0.50	Langenbielau, Silesia
Andalusite-hornfels	143	42.5	43	1.5	13	0.68	0.34	Valdana, Elba
Andalusite-biotite-schist	197	47	29	3	21	0.51	0.28	Azegour, Marocco
Biotite-schist	319	37	40	5.5	17.5	0.30	0.45	Koltschak Isle, Sweden
Andalusite-mica-hornfels	227	45	32	4	19	0.38	0.36	Eichgrün, Auerbach, Saxony
Two-mica-gneiss	214	44.5	29.5	3	23	0.44	0.33	Simplon tunnel, Valais, Switzerland
Two-mica-schist	384	42	31	6.5	20.5	0.89	0.54	Lucomagno, Switzerland
Garnet-two-mica-schist	264	40	33.5	9	17.5	0.56	0.37	Stavanger, Norway
Garnet-gneiss	313	42	32.5	5.5	20	0.64	0.39	Nynäs, Sweden
Garnet-gneiss	257	38	36	10	16	0.20	0.39	Fort Ann, New York, U.S.A.
Garnet-mica-schist	230	41	35.5	7	16.5	0.60	0.32	Bru, Stavanger, Norway
Sillimanite-kinzigite	220	46.5	41.5	3.5	8.5	0.66	0.40	Valpelline, Italy
Staurolite-biotite-schist	154	35	45	8	12	0.52	0.44	Chittering Valley, W. Australia
Kyanite-mica-schist	400	43	38	1.5	17.5	0.65	0.89	Gastein, Austria
Sericite-albite-gneiss with glaucophane and chlorite	244	40	33	4	23	0.43	0.35	Val de Bagnes, Valais, Switzerland
Chlorite-sericite-albite-gneiss with glaucophane	231	40	38	4	18	0.65	0.37	Val de Bagnes, Valais, Switzerland
Chloritoid-schist	262	45	41.5	3.5	10	0.85	0.30	Reichenau, Grisons, Switzerland

$$2\ Fs+1\ Fa=2\ Mt+1\ Q$$
$$3\ Kp+2\ Q=5\ Or$$
$$3\ Ne+2\ Q=5\ Ab$$
$$3\ Cal+2\ Q=5\ An$$
$$6\ Sp+5\ Q=11\ Cord$$
$$3\ Fo+1\ Q=4\ En$$
$$3\ Fa+1\ Q=4\ Hy$$

The following kata standard norm (equivalent) is now obtained by calculation:

Ru	Or	Ab	An	Cord	Hy(+En)	Mt	Q
0.6	26.5	29.6	7.2	14.9	6.4	1.4	13.4

The rock could, therefore, be a cordierite hornfels with hypersthene and in this case the figures quoted would (although they are strictly speaking equivalent units) approximate closely to volume percentages. Now in reality the rock belongs to the cordierite-feldspars-biotite subfacies. This means that pyroxene and orthoclase are largely replaced by biotite+quartz. The equation which at once permits a calculation of the new mineral composition reads as follows (in terms of equivalent numbers):

$$10\ Or+12\ (En\ or\ Hy)+water=16\ Bi+6\ Q$$

in our case, therefore,

$$5.3\ Or+6.4\ Hy+water=8.5\ Bi+3.2\ Q$$

For rocks belonging to the cordierite-feldspars-biotite subfacies, we therefore have the following expression:

Ru	Or	Plag	Cord	Bi	Mt	Q
0.6	21.2	36.8	14.9	8.5	1.4	16.6

These figures give a close approximation of the observed mineral composition.

Other rocks of Table 4 contain andalusite in place of cordierite and much more mica (including muscovite). They, therefore, belong to the andalusite-biotite-muscovite subfacies. The following equations can now be used containing Sil in place of And:

$$10\ Or+33\ Cord+water=16\ Bi+18\ Sil+9\ Q$$

or

$$40\ Or+33\ Cord+water=42\ Ms+16\ Bi+16\ Q.$$

If we transform 14.9 parts of cordierite in our rock into biotite+andalusite, we obtain:

$$4.5\ Or+14.9\ Cord+water=7.2\ Bi+8.1\ Sil+4.1\ Q.$$

The kata norm of an andalusite-biotite-feldspar subfacies thus reads as follows:

Ru	Or	Plag	Bi	Sil(And)	Mt	Q
0.6	16.7	36.8	15.7	8.1	1.4	20.7

Usually the rocks of Saxony contain some muscovite and often some zoisite and thus already have the character of a meso facies. Accordingly, the Ms-equation must be calculated. In our case it contains the values:

$$18.1\ \text{Or}+14.9\ \text{Cord}+\text{water}=19.0\ \text{Ms}+7.2\ \text{Bi}+6.8\ \text{Q}.$$

The meso norm for the rock in question in a biotite-muscovite-feldspars subfacies is, therefore, given by the following expression:

Ru	Or	Plag	Ms	Bi	Mt	Q
0.6	3.1	36.8	19.0	15.7	1.4	23.4

These figures show that a muscovite-biotite-plagioclase gneiss could have the same composition. Actually andalusite or cordierite are rarely absent in the above-mentioned contact metamorphic rocks. This enables the particular conditions of metamorphism (or of the subfacies) to be circumscribed more precisely.

The problem of the formation of garnet (mostly almandine) in place of cordierite has been discussed by Willemse (1936) and Masson (1938), who in their Zürich dissertations made valuable contributions to this question. Very often slight chemical differences (c-content, mg-proportion) favour the formation of one or the other subfacies. General equations could be written in the following way:

$$8\ \text{Hy}+11\ \text{Cord}=16\ \text{Alm}+3\ \text{Q}.$$
$$8\ \text{Fe-Bi}+6\ \text{Sil}+1\ \text{Q}=7\ \text{Ms}+8\ \text{Alm}$$

Of course if the composition of the garnet is known, it must be used for the calculation.

For the formation of staurolite one of the following equations may obtain:

$$8\ \text{Alm}+15\ \text{Sil}+\text{water}=21\ \text{Staur}+2\ \text{Q}$$
$$8\ \text{Fe-Bi}+21\ \text{Sil}+\text{water}=7\ \text{Ms}+21\ \text{Staur}+1\ \text{Q}$$

or

$$11\ \text{Fe-Cord}+2\ \text{Hm}+\text{water}=7\ \text{Staur}+3\ \text{Mt}+3\ \text{Q}.$$

From the base we obtain directly

$$3\ \text{Hz}+3\ \text{Sil}+1\ \text{Q}+\text{water}=7\ \text{Staur}.$$

Calculations of a meso standard norm (with staurolite in subfacies) and an epi standard norm (with chloritoid) have been given by C. Burri and P. Niggli (1945), p. 614 and E. Niggli 1944, p. 238. Not until such calculations have been made and the formation of variants discussed, can the fundamental principles of metamorphic facies be properly grasped. For only with their help can the possible variations in mineral assemblage be established that can occur in connection with a given chemical composition.

By way of comparison the kata standard norm of the three hornfelses nos. 2, 3 and 4 (table 1) may be quoted as follows:

No.	Ru	Or	Ab	An	Cord	Fe Cord	Sil	Hy	Mt	Q
2	0.7	29.8	27.8	4.1	19.6	—	—	6.4	2.0	9.4
3	0.6	26.5	29.6	7.2	14.9	—	—	6.4	1.4	13.4
									Hm	
4	0.8	36.4	19.5	2.7	15.4	21.8	2.0		1.4	—

The fact that no. 2 contains andalusite and mica, while no. 3 contains cordierite, does not emerge immediately from the very similar kata standard norms. Differences in the physical conditions of the metamorphism must be the reason and undoubtedly the course of the reaction had an important influence (no. 2 is a nodular schist, no. 3 a uniformly recrystallized hornfels). The high Cord-value of 4 in conjunction with the lack of Q in the kata standard norm favoured the formation of mica beside cordierite in this rock. The chemical composition would under other physical conditions certainly have lead to a rock containing garnet or staurolite or chloritoid.

To build up a meso norm, we can first calculate magnesium biotite (Bi), iron biotite (Fe-Bi) and kyanite (Sil) of the ideal composition. Oligoclase is possible.

Mesofacies of the Hornfelses

No.	Ru	Or	Ab	An	Ms	Bi	Fe-Bi	Sil	Mt	Q
2	0.7	0.5	27.8	4.1	25.2	10.3	7.8	—	2.0	21.6
3	0.6	3.2	29.6	7.2	18.9	7.7	8.0	—	1.4	23.4
4	0.8	—	19.75	2.7	36.4	7.6	8.8	6.75	2.0	15.2

Instead of Fe-Bi we often find garnet or staurolite. A garnet subfacies (almandine) of No. 4 gives:

No.	Ru	Ab	An	Ms	Bi	Alm	Sil	Mt	Q
4	0.8	19.75	2.7	44.1	7.6	8.8	0.15	2.0	14.1

Staurolite is calculated in the next subfacies:

No.	Ru	Ab	An	Ms	Bi	Fe-Bi	Staur	Sil	Mt	Q
4	0.8	19.75	2.7	38.65	7.6	6.2	6.75	—	2.0	15.55

Of course garnet and staurolite are in reality not free of magnesium and instead of oligoclase there may be albite (a part of the sodium is also in the muscovite) and zoisite+epidote. If the minerals are analyzed, the calculation of an equivalent mode is easy. But in connection with our problem the best way to elucidate the connection between kata- and meso-alumosilicate rocks is the calculation of a kata standard norm from some well known meso rocks of the Swiss Alps.

TABLE 5. SOME METAMORPHIC ROCKS OF THE SWISS ALPS

No. lit. 11	si	al	fm	c	alk	k	mg	ti	
IV 448	430	46	24	3	27	.63	.83	1.2	Biotite gneiss, M. Cauri, Ticino
IV 404	314	40	30.5	2.5	27	.58	.46	2.7	Two-mica-gneiss, Binnental, Valais
IV 447	305	37	39	2	22	.53	.89	2	Mica-gneiss (kyanite, sillimanite), M. Cauri, Ticino
II 305	170	38	40	5	17	.55	.50	4.2	Sericite-chlorite-albite gneiss, Maderanertal, Uri
IV 461	337	37.5	36.5	9	17	.47	.44	6.4	Biotite gneiss (garnet, sillimanite), S. Roveredo, Ticino
IV 460	223	39.5	41	3.5	16	.66	.39	3.8	Muscovite-chlorite-schist, S. Iorio, Ticino
III 172	196	44	38	3.5	14.5	.78	.48	3.1	Kyanite-two-mica-schist, Frodalera, Ticino
IV 145	300	48.5	34	5	12.5	.50	.43	4.2	Garnet-two-mica-schist (kyanite), Frodalera, Ticino
IV 221	148	53.5	34	4	8.5	.76	.29	3.9	Garnet-two-mica-schist (staurolite, kyanite) P. Molare, Ticino
IV 146	86	42	49.5	5	3.5	.27	.15	1.6	Staurolite-mica-schist (garnet, kyanite), P. Molare, Ticino
III 174	168	57	26.5	4	12.5	.42	.25	4.9	Staurolite-sericite-schist, Aquacalda, Ticino
IV 149	91	59.5	27.5	1.5	11.5	.64	.18	2.5	Staurolite-schist (kyanite), Pizzo Molare, Ticino

Table 5 gives the molecular values, the rock name, the percentages and number in lit. 11. In lit. 11 the analyses are given in weight %.

The kata standard norm is calculated in Table 6. In some cases the

TABLE 6. THE KATA STANDARD NORM OF THE ROCKS OF TABLE 5

	Or	Ab	An	Cord	Fe-Cord	Hy	En	Sil	Mt Hm	Ru	Q	Not satu-rated −Q
IV 448	28.7	16.3	2.5	14.3	—	.9	1.3	—	.2	.2	35.6	—
III 404	32.4	23.3	2.8	11.7	—	2.8	1.5	—	2.0	.6	22.9	—
IV 447	25.3	22.5	2.2	15.2	—	1.5	9.2	—	.1	.4	23.6	—
II 305	27.3	23.7	7.7	27.2	—	8.3	2.0	—	2.1	1.3	10.4	—
IV 461	16.2	18.2	9.2	12.7	—	7.1	1.7	—	.6	1.3	33.0	—
IV 460	27.2	14.0	4.7	22.6	6.6	4.7	—	—	3.1	1.0	16.1	—
III 172	31.5	9.5	4.7	27.9	7.0	—	—	2.7	4.3*	.9	11.5	—
IV 145	14.0	13.5	5.2	17.2	12.5	—	—	3.8	1.9*	.9	31.0	—
IV 221	20.5	6.5	6.7	17.1	28.1	—	—	14.3	2.7*	1.2	2.9	—
IV 146	4.3	11.3	10.5	17.1	61.4	—	—	1.4	5.7*	.8	—	−12.5
III 174	15.3	20.8	6.0	10.8	7.0	—	—	25.8	4.5*	1.4	8.4	—
IV 147	28.0	16.0	2.8	10.3	12.3	—	—	40.5	6.2*	1.0	—	−17.1

SiO_2-content was too low to form the normal standard minerals; in these cases the deficit of Q is given, instead of the calculated amount of olivine or spinels.

The first group of 7 analyses (without much Fe-cordierite or sillimanite in the kata standard norm) corresponds to rocks with only subordinate quantities of special minerals. If the content of Fe-cordierite and sillimanite is a little higher, garnet (almandine) is more easily formed in the mesofacies (the next 2 analyses). Higher content of Fe-cordierite and (or) sillimanite is found in the last 3 analyses which correspond to meso rocks rich in staurolite.

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