Spessartite and Pseudotachylyte intruded on the Thrusting-zone of the upper Jotun Eruptive Nappe near Nautgardstind, East-Jotunheimen.

By

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With 19 text-figures.

As a supplement to my paper treating pseudotachylytes on the thrusting zones SE of Jotunheimen (1953) I now give some preliminary results from investigation of samples collected in the summer 1954 near the summit of Nautgardstind (2257 m alt.).

The well known forms of this most important mountain in East-Jotunheimen, NW-part of quadrangle E30Ø, Sjodalen* appears on fig. 1, as they are recognizeable in most of the higland to the S and SE.

From the locality where the samples were collected and phot. fig. 2 was taken, namely 100 m lower and some hundred metres NNE of the summit, the configuration is more rugged. This is due to the great cirque extending to the north, with almost vertical walls 300 ms high in the south, the east and the west, forming a cul-de-sac 1 × 1½ kms. This is «Store Nautgarden», which means «the big enclosure for cattle». The summit is regarded as a former nunatak (Werenskiold 1945, p. 26) see fig. 3. The massive rock is broken into blocks, but these were not carried away by the glacier, as on the somewhat lower summits (below 2000 m alt.) in Jotunheimen.

The sample No. 92 shown in fig. 4 is however taken in situ rock from the narrow edge of the precipice (fig. 2), and so are the

* A synopsis of the results from the northern halves of this and the neighbouring quadrangle F30V, Vinstra, bearing on fundamental mountain problems is planned to come in Norsk Geol. Tidskr. Bd. 35, 1955.

Fig. 1. *Nautgardstind*, (2257 m) view towards the NW from Besstrand-Rundhø (1391) 9 kms distant. The river Russa occupies the valley; Store Hindnubben (2167 m) lies to the right. Authors photo.
Nautgardstind sett mot nord-vest fra Besstrand— Rundhø i avstand 9 km.

Fig. 2. Nautgardstind, view towards the SSW from the edge of the precipice 100 ms lower and about 250 ms from the summit. Layered mangerite (Hypersthene-monzonite) of Upper Jotun eruptive nappe — falling westward. Authors photo.
Toppen av Nautgardstind sett mot syd-sydvest fra kanten av Store Nautgarden ca. 100 m lavere i ca. 250 m avstand.

samples No. 91, the main, lightcoloured rock of Nautgardstind, and No. 93, a 20 cm dyke in this rock. Both are represented on fig. 4 by the light wall-rock and the dense grey, forkshaped dyke respectively.

The photomicropraph fig. 5 of No. 91 shows protoclastic bent plagioclase determinable as An_{32}, with mortar structure. Perthite-drops with higher refraction than the enclosing feldspar are visible in an adjacent, smaller fragment of supposed (not twinned) alkali feldspar. These were also observed in the larger, albite-twinned plagioclase-crystals (0,2—0,5 mm). The dominant rhombic pyroxene of about the same size has rounded (resorbed?) outlines, while the monoclinic, faint green-coloured diallage has sharper faces. Small prismatic apatite crystals show resorbed outlines. Some ore complete the picture. The wallrock in sample No. 92 is more fine-grained (photomicrograph fig. 11) than in No. 91. For comparison is added photomicrograph fig. 6 of sample No. 114, Hindnubbene 6 kms NE of Nautgardstind, 1500 m alt. This locality is discussed later. Fig. 6 shows a slightly more basic rock with An_{34} in a lot of bent plagioclase-crystals.

Analysis of No. 91, mainrock Nautgardstind 13/8—1954: By Miss Erna Christensen, N.G.U.chem lab. Nr. 337 Dec. 1954:

Sp.gr. 2,84 and H_2O-determination by Mr. R. Larssen.

SiO_2	55,84
TiO_2	0,96
Al_2O_3	16,93
Fe_2O_3	3,08
FeO	4,87
MnO	0,15
MgO	3,91
CaO	6,45
Na_2O	4,35
K_2O	2,92
H_2O —	0,07
H_2O +	0,18
CO_2	n.d
P_2O_5	0,41
	100,12

C. I. P. W. norm:

Ap.	Il.	Mt.	Or.	Ab.	An.	Di. Wo.	Di. Hy.	Hy	Q
0,8	1,2	3,0	17,0	39,0	17,7	5,0	5,0	10,6	0,6
5,0			73,7			10,0		10,6	0,6

19 % Or

81 % plag.: $Or_5Ab_{65}An_{30}$

Or_5 is assumed to be present in the plagioclase of this rock and in the other rocks calculated.

$$\frac{En}{Fs} = 2,1$$

Fig. 3. View towards the N from the edge of the precipice 250 ms NNE from the summit of Nautgardstind. Authors photo.

Utsikt nordover fra kanten av Store Nautgarden, ca. 100 m lavere enn toppen av Nautgardstind.

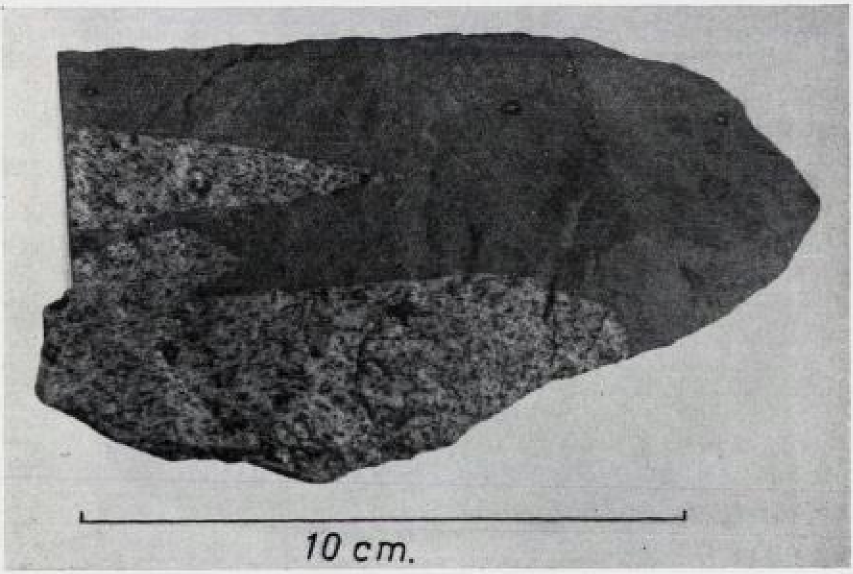


Fig. 4. *Sample No. 92.* From edge of precipice (2160 m), 100 ms lower and 250 ms NNE of the summit of Nautgardstind. Light wall rock mangerite (hypersthene-monzonite) mainrock of Nautgardstind. Dense, grey forkshaped dyke of pyroxene lamprophyre *(spessartite).* Thinsection No. 92 — photomicrograph fig. 11 was cut to the left. Sjøwall photo.

Prøve nr. 92 fra kanten av Store Nautgarden 100 m lavere enn toppen av Nautgardstind. Lys hovedbergart gjennomset av tett, grå — upresset spessartit.

The composition is thus monzonitic and very near the «Mangerit, Übergangstypus zum Jotun-Norit, westlich des Bitihorns, Jotunheimen» Analysis I on request of V. M. Goldschmidt (1916, p. 40).

Our rock may likewise be termed mangerite, although the microperthite is less dominant, and is nearer the Jotun norite than Goldschmidts' mangerite.

How near our rock on the other side is related to the hypersthenesyenites of the Bergen-Jotun-kindred, appears from the two further analyses given below on p. 36. The mangerite may thus be regarded as belonging to *an intermediate gravimetrically differentiated layer in the magma-basin,* between the Jotun norite and the hypersthenesyenite. The analyses are carried out on samples collected in the Jotunheimen on a NE—SW line about 60 kms. apart. The reciprocal relationship between these two indicates as does the relationship between the analyses of No. 91 and of Goldschmidt's mangerite from West-Jotunheimen (op. cit.) — in a NNE —SSW line 30 kms apart — a wide extension of the primary layers and of the basin. As is well known the charnockitic (anorthositic) rocks characteristically form very large bodies (J. S. Shand, 1949, p. 279).

How far the layers in the summit of Nautgardstind, visible on fig. 2, falling from the E to the W, may safely be interpreted as the result of primary gravimetric differentiation, will require a series of samples for analyses — a useful task for climbers. The presumed layers seems roughly parallel to the westwards slope of the mountain (fig. 1). The semistiff nappe has during the thrusting towards SE developed concordance with the general configuration of the basement. As mentioned later (p. 29) this formed NW—SE running ridges and valleys.

The composition of this rock sample No. 127, analysis on p. 36 is thus as for a *hypersthenesyenite,* extraordinary rich in apatite and ore minerals. Megascopically and in thin-section the sample No. 127 shows however a picture quite different from the abyssic rock namely a dense, irongrey, tough rock with 3—4 mm black veinlets. Relics of flesh-coloured alkali feldspar and traces of pyrite are visible with the lens.

Photomicrographs of the thin-section (× 160, in plane polarized light and with crossed nicols respectively) are the figs. 7 and 8.

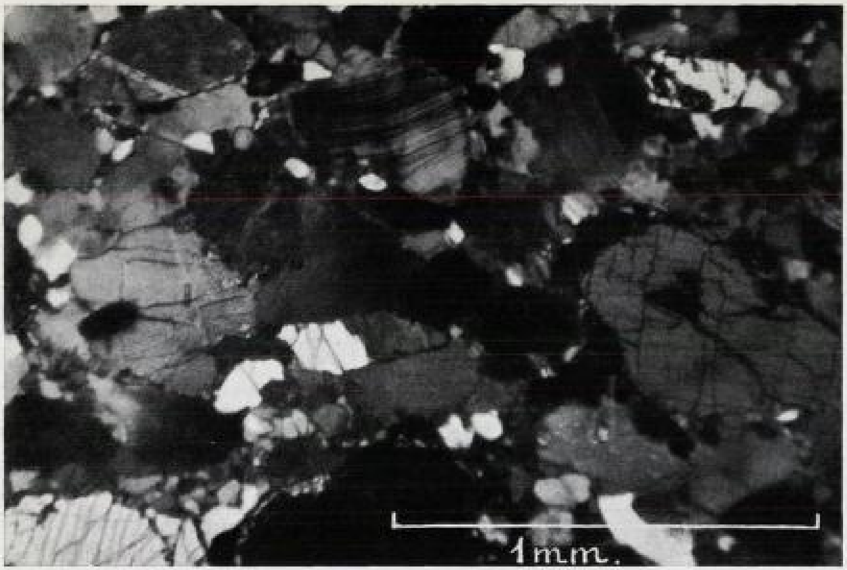


Fig. 5. Photomicrograph of sample *No. 91* (2160) mainrock of Nautgardstind (Mangerite) × 48, crossed nicols. Protoclastic bent plagioclase (An_{30}) Perthite, rhombic and monoclinic pyroxene. Authors photo.
Mikrofoto av hovedbergarten i Nautgardstind (prøve nr. 91). Protoklastisk struktur i plagioklas, An_{30} (× 48 + n).

Fig. 6. Photomicrograph of sample *No. 114* (1500 m) Jotun norite Slope from Hindnubbene 6 kms NE of Nautgardstind. Xenolith in lamprophyre, × 48, crossed nicols. Abundant bent plagioclase (An_{34}) Antiperthite, rhombic and monoclinic pyroxene. The locality is shown in fig. 13. Authors photo.
Mikrofoto av nr. 114 av xenolit i lamprofyr, hellingen av Hindrubbene 6 km NE for Nautgardstind — Jotun-norit med An_{34} i protoklastisk bøyde ploziokloskorn (× 48 + n).

Analysis of No. 127 E30Ø—1953, Mylonite, Valdresfly-veien (-highway), *Brurskardlia near Gjendesheim, Jotunheimen 19/8 1953* 1040 m alt., 5 kms SE of Nautgardstind by Brynjolf Bruun, N.G.U. chem. lab. No. 214, Dec. 1953.

Sp.gr. 2,76 and H_20-determination by R. Larssen.

$Si0_2$	58,43
$Ti0_2$	1,00
Al_20_3	17,17
Fe_20_3	5,22
Fe0	3,59
Mn0	0,08
Mg0	1,29
Ca0	2,52
Na_20	4,66
K_20	5,39
H_20 —	0,07
H_20 +	0,33
P_20_5	0,55
	100,30

C. I. P. W.norm:

Ap.	Il.	Mt.	Or.	Ab.	An.	Hy.	C.	Q
1,1	1,6	5,4	32,0	42,0	9,0	4,0	0,5	4,4
	8,1			83,0		4,0	0,5	4,4

36% Or

64 % plag. Or_5 Ab_{78} An $_{17}$

$$\frac{En}{Fs} = 9$$

Analysis of sample of hypersthene-syenite, collected by Th. Kjerulf on Suletind (1781 m alt.) Filefjell, quadrangle D31Ø — West-Jotunheimen, 60 kms from No. 127, carried out by O. Røer on the request of *V. M. Goldschmidt* (1916, p. 43).

Sp.gr. 2,703, determined by Endre Berner.

$Si0_2$	61,93
$Ti0_2$	0,78
Al_20_3	17,41
Fe_20_3	1,16
Fe0	3,74
Mn0	0,18
Mg0	0,73
Ca0	2,14
Ba0	0,21
Na_20	5,07
K_20	6,16
P_20_5	0,32
$C0_2$	0,08
H_20 — 105°	0,08
H_20 + 105°	0,37
S	0,02
	100,38

C. I. P. W.norm:

						Di			
Ap.	Il.	Mt.	Or.	Ab.	An.	Wo.	Hy.	Hy.	Q
0,8	1,2	1,2	36,0	45,5	6,4	0,8	0,8	5,2	2,1
	3,2			87,9		1,6		5,2	2,1
							6,8		

37½ % Or

62½ % plag: Or_5 Ab_{83} An_{12}

Considering that Ba0 goes into Or, one should probably quote:

62 % plag: Or_5 Ab_{84} An_{11}.

$$\frac{En}{Fs} = \frac{1}{2}$$

They show the black veinlet with much hornblende (plagioclase—hornblende lamprophyre—spessartite?) and the adjacent dense, but somewhat coarser mylonitic wallrock with abundant microlites and some feldspar-relics with many perthite-drops evidently of much higher refraction. They probably consist of more An-rich plagioclase, similar to those in No. 91 — fig. 5, and in No. 93 and No. 92 (figs. 9—10—11) but appearing more abundant in No. 127. The development of the rocks represented by the samples No. 91—92—93 on one side and the sample No. 127 on the other seems, as will be demonstrated below, due to closely related processes during the tectonization. —

The second analysis or p. 36 is quoted from V. M. Goldschmidt (1916, p. 43) whose description of the rock I am not able to improve upon. On p. 44 l.c. Goldschmidt has the following mineral calculation for the rock, in fairly good accordance with the C. I. P. W.norm, though I have reckoned BaO in $An_{6,4}$. In realty the Celsian goes into Or:

Apat.	Ilm.	Magn.	Ort.	Alb.	An.	Cels.	Diops.	Hyp.	Qtz.	Pyr.	Calc.
0,78	1,48	1,68	36,49	43,09	6,03	0,58	1,5—2,0	5,5	2,38	0,04	0,19
	3,94			86,19			7,34				

The 3 analyses hitherto quoted seemingly represent layers of slightly increasing acidity, supposing that no considerable quantities of alkalies have migrated from the mylonitizated layer represented by sample No. 127. In the vicinity of the locality (S. Brurskard-knapp, see Dietrichson 1950, p. 115), where the alkalirich layers during the thrusting came in contact with phyllites or other H_2O rich schists, (The flysch of the Valdressparagmite) the production of «ichor» on the thrusting zones is manifested in some «pegmatite»-dykes and veins.

The layers represented by sample No. 127 and the sample of hypersthene-syenite from Suletind, evidently belong primarily to higher layers in the upper Jotun eruptive nappe than our layer in Nautgardstind (No. 91), and they were thrusted forward in the SE direction. The present distance between the «frontier» of the layers of Nautgardstind (No. 91) and the frontier of the layers represented by No. 127 in 1040 m alt. (Gjendesheim) is 5 kms. Similarly of the hypersthene-syenite in Suletind (1781 m alt.) may be estimated to about the same distance.

The advancement of the nappes is naturally much dependent on the configuration of the basement and its mechanical and chemical character. The mineral composition changes with P, T variations, but very important for the metamorphism on the thrust-zones is the extent to which the primarily «dry» charnockitic (V. M. Goldschmidt 1922, p. 9) Jotun eruptive nappes were exposed to H_2O — influence (cfr. I. Th. Rosenqvist 1952, p. 91). This was obviously abundant where the thrust-plane developed on a sedimentary, schistose basement, and great masses of anorthosite-norite were transformed into «saussurite-gabbros». The newly formed OH-bearing minerals controlled the further the movement serving as lubrication medium.

The *upper* Jotun eruptive nappe in the foreland met with a rugged relief of NW-SE running ridges, remnants of the lower, anorthositic layers of the *lower* Jotun eruptive nappe. Between the ridges the advancing upper nappe contacted sedimentary layers, *first* of the flysch (the Valdressparagmite) deposited during the very long period of erosion (cfr. T. Strand 1941, p. 274, and 1951, p. 27) following and contemporanous with the overfolding from NE towards SW (Dietrichson 1950, p. 140, map fig. 1), and 1953, p. 66). The regonial, general character of these movements (lateral compression) was quite recently pointed out by Th. Vogt (1954, A, B, C). *Secondly*, farther towards SE in the foreland the upper Jotun eruptive nappe also contacted parts of the Cambro-Ordovician sedimentary basement. A host of varied metamorphic, tectonized rocks were produced on the outer parts of the thrust-zones. Through the ages geologists have tried to force these rocks to tell: «Ihre lange Geschichte von besseren Tagen». (Friedrich Becke). The key to the inner part of our mountainchain and the problem seems however to be represented by the rock described in the following section.

The grey, dense dykerock of Nautgardstind.

The intrusion of this rock seems evidently to be due to the same movements as is the mylonitization of No. 127 near Gjendesheim, with its black veinlets, apparently similar to No. 93, cfr. the photomicrographs figs. 7 & 8.

First shall be considered the analysis of No. 93 (p. 40):

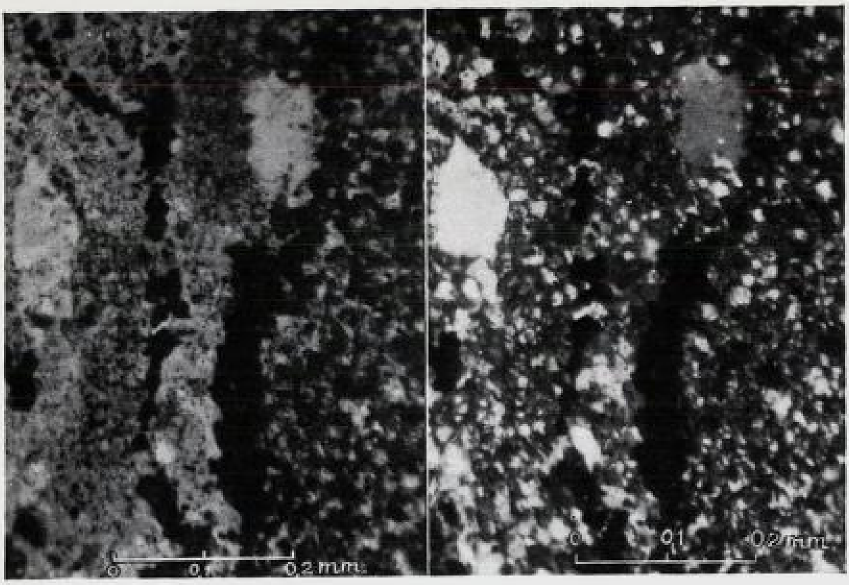


Fig. 7. Photomicrograph of sample *No. 127* (1040 m). Hypersthene-syenite-mylonite, Valdresfly highway near Gjendesheim. × 160, planepolarized light. light. Wallrock with feldspar relics to the left. Notice perthite drops, An-rich with high refraction. Black: magnetite. To the right hornblende-rich black veinlet (spessartite?). Authors photo.

Mikrofoto av prøve nr. 127. Hypersthen-syenit-mylonit (til venstre) med sort, tett åre av hornblenderik bergart, som antas å ha samme opprinnelse som spessartiten i Nautsgardstind. Bemerk pertit-dråper i mylonitten (× 160 ∦ lys).

Fig. 8. Photomicrograph, same as fig. 7. × 160, but crossed nicols. Authors photo.

Mikrofoto — samme som fig. 7 + n. Opak. magnetitrand langs grensen.

Trøger (1935) quotes for No. 318 (p. 140). Spessartite as the theoretical example of hornblende-plagioclase-lamprophyre:

ca.	45 plagioclase An_{25-45}	Our rock has norm:	52,2 An_{41}
»	40 hornblende	—»—	37,6 Hy+ Di
	± diopside		
»	10 orthoclase	—»—	4,5 Or
	± quartz	—»—	1,2 Q
»	5 ore, apatite	—»—	4,5Ap+Il+Mt.

Analysis of No. 93, dyke-rock Nautgardstind 13/8, 1954 by Miss Erna Christensen, N. G. U. chem. lab. No. 338, Des. 1954. *Sp.gr. 2,97* and H_2O-determination by R. Larssen:

SiO_2	53,66
TiO_2	1,29
Al_2O_3	14,38
Fe_2O_3	2,30
FeO	7,49
MnO	0,13
MgO	8,08
CaO	7,94
Na_2O	3,40
K_2O	0,81
H_2O —	0,15
H_2O +	0,28
CO_2	n.d.
P_2O_5	0,26
	100,17

C. I. P. W. norm:

						Di			
Ap.	Il.	Mt.	Or.	Ab.	An.	Wo.	Hy.	Hy.	Q.
0,3	1,8	2,4	4,5	30,5	21,7	6,8	6,8	24,0	1,2
4,5			56,7			13,6		24,0	1,2
						37,6			

1,5 % Or

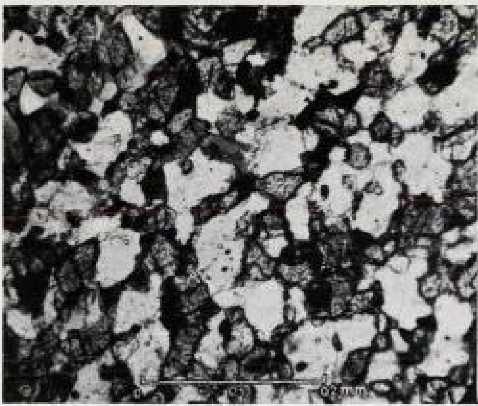
98,5 % plag: $Or_5\ Ab_{56}\ An_{39}$

$$\frac{En}{Fs} = 2{,}7$$

Our rock may thus be termed pyroxene-plagioclase-lamprophyre in accordance with the augite-plag.-lamprophyre mentioned by Trøger as *Spessartite.*)*

Presenting the photomicrographs fig. 9 and fig. 10 of sample No. 93 (× 160 respectively planepolarized light and crossed nicols) it should be pointed out: That the small pyroxenes (0,02—0,05 mm) are mainly rhombic. Scattered grains (0,1—0,2 mm) uppermost in the figs. consist of altered hypersthene rimmed with some biotite, are obviously relics. The interstices are filled mainly with clear, unaltered plagioclase, a few albite *and* pericline (?) twinned grains (fig. 10) are also visible. Spherical nuclei 0,01—0,005 mm are visible in the plagioclase-grains. The light ones are supposed to consist of considerably more An-rich plagioclase than the enclosing grains. They have much higher refraction than the latter. The — in the photomicrograph — black nuclei display the typical interference colours of the diopsidic pyroxenes in the Bergen—Jotun-rocks.— Microperthites of two types are well known as a typical feature of the andesinebearing Bergen—Jotun-rocks (Goldschmidt 1916, Taf. III, fig. 5 & 6 p. 48, see also p. 36) also antiperthites. The «drop-

*) The analysis of No. 93 is further almost identical with the spessartite-analysis of R. A. Daly (1933 p. 28).



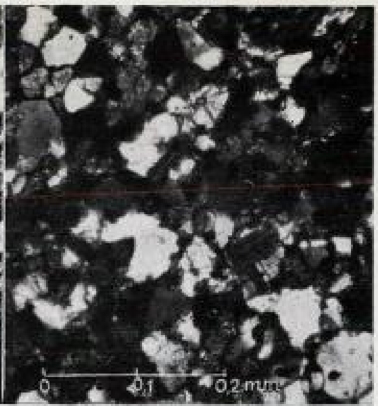


Fig. 9. Photomicrograph of sample *No. 93, Spessartite*, 20 cm dyke in mangerite (No. 91) Nautgardstind. × 160, Planepolarized light.

Altered hypersthene, 0,2 mm, uppermost. Pyroxenegrains 0,02—0,05 mm hypersthene dominant. Plagioclase, (An_{39}) and some orthoclase filling the interstices. Droplets of more limerich plagioclase and of diopsidic pyroxene 0,01—0,005 mm embedded in the plagioclase. Ore grains 0,01 mm evenly distributed. Authors photo.

Mikrofoto av prøve nr. 93 — 20 cm bred spessartit-gang i Nautgardstinds hovedbergart. Større korn (0,2 mm) av omvandlet hypersthen øverst.

Friske, mindre korn av rombisk og (oven) monoklin pyroxen. Grunnmasse: plagioklas An_{39} med dråper av sterkere lysbrytende, antagelig mer kalkrik plagioklas, samt også dråper av diopsidisk podyxen (+ 160 — lys).

Fig. 10 Same as fig. 9, × 160 but crossed nicols. Attention is drawn to the albite- and pericline (?) twinned plagioclasegrain to the right and somewhat lower than centre of photomicrograph. It may be identified on fig. 9, embedding droplets of more limerich plagioclase as well as of diopsidic pyroxene. Authors photo.

Samme som fig. 9 men + n. Bemerk det tvillingstripete plagioklaskorn, med altbitlameller og antagelig periklinlameller. Kornet kan identifiseres på fig. 9, med dråper av mer kalkrik plagioklas og diopsidisk pyroxen.

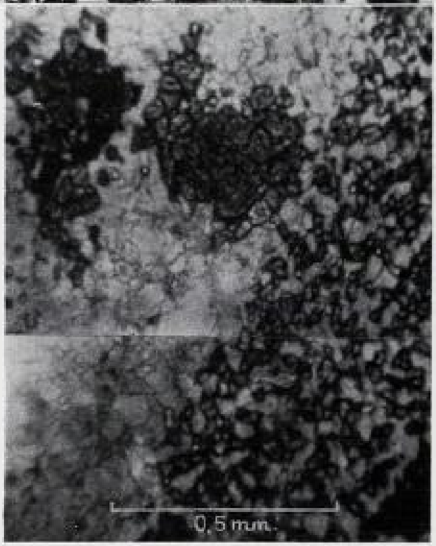


Fig. 11. Photomicrograph of sample *No. 92*, × 80, Planopolarized light. To the right spessartite with droplets of limerich plagioclase embedded in the feldsparinterstices. To the left borderzone with the mangerite, with two larger hypersthenegrains and feldspars mainly squeezed from the spessartite with some droplets (one between the larger hypersthenes) of lime-rich plagioclase. Authors photo.

Mikrofoto av prøve No. 92 som er vist i fig. 4. Spessartite til høyre, grensesonen mot hovedbergarten til venstre. — Den består tilsynelatende av utpresset plagioklas tilsvarende fyllmassen i spessartiten (× 80 ∓ lys).

perthites», (Taf. III, fig. 5) may now be interpreted as due to exsolution (Bowen and Tuttle, 1950 p. 582) of high- and lowtemperature-plagioclases below about 700°C, decreasing displayed when An>An_{40}. In our spessartite the drops occur on a small but visible scale. Ore grains, size about 0,01 mm, are evenly distributed in the rock.

In fig. 11 is presented a photomicrograph of sample No. 92 (shown in fig. 4, where the slide is cut to the left) exhibiting the border between the mangerite and the spessartite. (× 80, plane-polarized light). The grain-size of the feldspar in the «mangerite» (0,1—0,2 mm) is considerable smaller than in sample No. 91 (fig. 5). Anorthite-rich drops (0,01—0,02 mm) are visible in the «mangerite» and in the spessartite. The hypersthene grains in this *border zone* have, however, the common grain-size of the mangerite proper (fig. 5) 0,2—0,5 mm and they are here not so altered as in the spessartite proper (fig. 9 & 10), possibly indicating that the home of the bigger hypersthenegrains is the mangerite or related lower layers of Jotun-norite. Thus the light rock to the left in fig. 11 consists mainly of feldspar material squeezed out identical with the feldspar filling the interstices in the spessartite (to the right in fig. 11). This rock displays the same appearance and grain-size with the small, rounded (corroded) pyroxene grains (0,02—0,05 mm) as in the figs. 9 & 10.

The common definition for lamprophyres is as follows (Rosenbusch, 1907, p. 653):

«Ich adoptiere die Gümbel'sche Bezeichnung Lamprophyr für eine vorwiegend dem gefalteten Gebirge angehörigen Gangesteinsformation die bei wechselnder, teils den verschiedenen Syenit — teils den Diorit-, Essexit- und Theralit-typen entsprechender, teils hiervon abweichender mineralogischer Zusammensetzung durch makroskopisch feinkörnige dichte, oder porphyrische Struktur, durch im frischen Zustande graue bis schwarze Farbe und grosse Neigung zur Verwitterung unter reichlicher Entwicklung von Karbonaten charakterisiert ist.»

CO_2 is not named by Tröger in his example on Spessartite-composition quoted above, but in one of the 3 analyses in the tables of Washington (1917, p. 1048) is quoted 0,84 % CO_2 (from A. N. Winchell, Min. Res. Oregon p. 141, 1914). N. L. Bowen 1928, p. 258) gives the general characters of «Lamprophyres and related Rocks» and mentions (l.c.) the conclusion of Niggli and Beger

(1923) «that these rocks are to be accounted for by the local accumulation of early crystals, which have then remelted or redissolved and given a liquid of lamprophyric composition».

And now we are approaching the aim of this preliminary paper: *to point out the close relation between the somewhat «illdefined group of lamprophyres»* (Bowen l.c. p. 258) *and the likewise hitherto illdefined group of mylonites including the pseudotachylytes* (that is the Cryptomylonites and the Hyalomylonites in the term of Scott and Drever (1953)) *and further to emphasize these two rock-groups' importance,* the first as the base, which during the advancement of the nappe gradually assimilated, than frettet and embedded substances from the adjacent complexes. The resulting mylonites served as a lubrication medium for the semistiff, eruptive nappe (here the upper, layered Jotun nappe). Not forgetting the gradually development one could possibly distinguish between:

1. The upwards transportation of the nappe lubricated by the relatively pure, hot, lamprophyric melt.

2. The forwards slipping on a gently dipping basement lubricated by mylonites of varied composition.

3. The foreland advancement where the movements were facilitated by saussuritization mainly due to the excess of H_2O furnished from the sedimentary basement in a way already outlined above (p. 29).

A characteristic feature of the lamprophyres seems to be their capacity of incorporating different material from the wallrocks they penetrated. The CO_2 named as characteristic in the definition of Rosenbusch and stated to occur in the spessartite from the Coast Range (Oregon) both quoted above, may probably originate from sedimentary layers. The hypersthene relic grains in our spessartite and the source of the recrystallized smaller pyroxene grains in it are probably from the Jotun norite and mangerite layers penetrated. The origin of the «glorified form of pseudotachylyte» the enstatite-granophyre of the Vredefort Region (Hall and Molengraaff 1925, p. 112), or — as this much discussed rock is termed by Willemse (1938, p. 117) — *the basic granophyre,* according to the latter is explained by «an original alkali lamprophyric magma which has assimilated mainly quartzite and granite» (from old sedimentary layers and old Vredefort granite forming the circular boss, heaved 14,000 metres upwards through the sedimentary covering. (Hall and Molengraaff 1925, p. 153)). I return to the basic granophyre below, more explicit quoting Willemse's conclusions.

Another region most interesting for correlation with the Jotunheimen is *The Outer Hebrides* (Jehu and Craig 1923—25—26). Similar rocks — also lamprophyres (1923, p. 636) intersect the extensive mylonite zones.

The spessartite dykes of Nautgardstind (No. 92—93) obviously represent apophysis only *from much greater masses of the same rock which now occur about 6 km NE of Nautgardstind.* The direction of the south Norwegian Caledonian mountain range — the front of movement from the NW — is about SW—NE.

The locality at 1500 m alt. investigated by the writer in 1954 is on the slope at the foot of Hindnubbene a range of summits continuing from Nautgardstind towards the NE. They are distinguished over the vaste levelled area of Hindflyen. This is about 3 kms. broad gently rising from 1440 to 1700 m alt. from NE towards SW (fig. 12). It is covered with talus and outwashed moraines, fig. 12 in the foreground showing a 40—50 m deep valley cut by a river through the front of the moraine running SW—NE. This high level, like several other «flyer» (norw.) in the Jotunheim Region, is supposed to be due to erosion along the thrusting plane, where fine-grained, broken mylonites and related rocks are exposed.

The locality was previously mentioned when comparing photomicrograph fig. 6 of sample No. 114 with fig. 5, which exhibits the main rock of Nautgardstind. Fig. 13 shows the small outcrop (at 1500 m alt.) surrounded by talus. Sample No. 114 was taken from the light rock to the right of the outcrop, which has vertical border against the dark, dense, cracked rock, representing the main rock along the slope and in the 1616 m summit. No. 114 is a *Jotun norite* with An_{34} (opt.determ.) in the plagioclase, closely related to the mainrock No. 91 of Nautgardstind, termed *mangerite* by the writer, who wishes to keep the classical investigations of V. M Goldschmidt of the Bergen—Jotun-rocks fresh in mind. No. 114 represents probably a big *xenolith*, taken by the lamprophyre, the dense dark rock to the left in fig. 13, for not far from the big xenolith was taken sample No. 116 from a smaller, light xenolith enclosed into the lamprophyre and intersected by a 2 cm. dyke of the latter. Fig. 14 is a photomicrograph (× 80, planepolarized light) showing the light rock, proving to be a mangerite, to the left.

Fig. 12. View towards the N to Hindnubbene (Stornubben, 2167 m to the left, 1616 m summit to the right) Highlevel Hindflyen 1440—1700 m alt., cut by river Stor-Hinde in the foreground. Authors photo.

Utsikt nordover mot Hindrubbene — fra kanten av Hindflyen i ca 1450 m o h. — Morenemassene gjennomskåret av Stor-Hinde.

Fig. 13. Outcrop of lamprophyre (spessartite) with xenolith of Jotun-norite (right) — shown in ph.micr. fig. 6 — and smaller xenolith of typical Jotun-perthite-bearing mangerite by hammer to the left. The mangerite is shown in ph.micr. fig. 14.

Blotning av lamprofyr med xenolit av Jotunnorit (fig. 6) til høyre og av mangerit (fig. 14) ved hammeren — til venstre. Hellingen av Hindnubbene i 1500 m o h med talus og morenemasser.

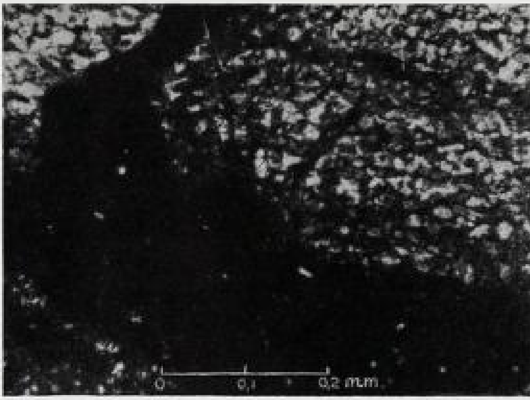


Fig. 15. Photomicrograph of sample No. 115. Planepolarized light × 160. Locality shown in fig. 13. Pseudotachlyte-veinlets in lamprophyre (spessartite).

Authors photo.

Mikrofoto av prøve nr. 115. Pseudotachyletårer i lamprofyr fra lokalitet vist i fig. 13. (× 160 ∦ lys.)

Fig. 16. Photomicrograph of sample No. 115. Same as fig. 15 but crossed nicols.

Authors photo.

Samme som fig 15 men + n.

Fig. 14. Photomicrograph sample No. 116. × 80. Planepolarized light. Mangerite xenolith (left) in lamprophyre (right). Locality shown in fig. 13. — 1500 m alt. at the foot of Hindnubbene. Authors photo.

Mikrofoto av prøve nr. 116. Mangerit xenolit i lamprofyr fra blotningen i hellingen av Hindrubbene vist i fig 13. Lamprofyr til høyre i foto (× 80 ∦ lys).

Here the typical micro-perthites of the lath-type (see Goldschmidt 1916 Taf. III fig. 6, p. 48) the «*Jotun-perthites*» are beautifully developed. C. F. Kolderup (1903) who first described the mangerite (after Manger near Bergen), emphasized this microperthite as criterion for the rock. According to verbal communication with P. Michot, who has recently studied the anorthositic region of Egersund (Norway, Publications 1939 and later) this perthite-type is supposed to be restricted to the katazone. Similar microperthites were stated by the author in 1949 to occur near the summit of Ruven (1400 m alt.) a mountain about 80 km. NE of Egersund in in the great pre Cambrian basement of south-western Norway. How far the origin of this characteristic mineral is due to exsolution analogous to the formation of the «drop-perthites» but restricted to deeper levels is a question of considerable interest. This type of microperthites is common in the quartzites and other clastic rocks of early Cambrian age in the uncovered sedimentary basement to the SE of Jotunheimen. When more completely investigated, it may be used for identifying the primary eruptive layers as well as relative age of the sedimentary layers — and vise versa. (Dietrichson 1950 pp. 89—91, and photomicrographs from several new localities to be published in the near future).

To the right in fig. 14 the dense lamprophyre (grain-size about 0,01 mm) is shown.

Characteristic for the presumed primary lamprophyric, basic granophyre in the Vredefort region are the highly fretted xenoliths of quartzite and granite derived from the wallrocks. (Hall and Molengraaff 1925, p. 59). As I am going to point out in detail in the paper announced above, colossal-breccias are common along the thrust-zone of the upper Jotun-eruptive nappe. The finegrained mylonites represent the other extreme of the breccation developed during the progress of the thrusting. While the solid fractions were partly remelted and incorporated in the lamprophyric base, the whole stressed mass served as a lubrication medium for the slowly cooling, advancing nappes.

It is suggested that we, in the deeply eroded region of the Norwegian Caledonides, have the chance of demonstrating this process, one of supreme importance for mountain-movements in general. —

Then turning to *the pseudotachylytes* I present the photomicrographs fig. 15 and fig. 16 (× 160 respectively planepolarized light and crossed nicols) of sample No. 115: Lamprophyre as in fig. 14 from the same locality, is intruded by black, anastomosing veinlets of pseudotachylyte, commonly 0,5—1 mm thick. Similar veinlets are visible in most of the samples of fine-grained rocks, stated under my somewhat exciting ascent up the SW slope of Hindnubb (1616 m alt.), which is shown in fig. 12 and fig. 17. The latter was taken from the locality fig. 13. As may be made out of fig. 17, the talus at the foot of the peak consists of small material, as is the loose material on the slope: It is small and sharpedged, almost like glass, slipping on the rock, lubricated by melting-water from small glacier remnants above. It may be mentioned, that due to the retreat of the glaciers in Jotunheimen, this rock is probably uncovered for the first time for man — and for the geologist.

For a more minute investigation of the Hindnubb 1616 m — especially the xenoliths and their border zone and also leucokratic dykes appearing in the lamprophyre — it will be necessary to camp at the foot of the peaks, though a certain risk of wandering oxen in the Veo valley.

The pseudotachylyte exposed in the basic lamprophyre is opaque, the light inclusions excepted. (fig. 15 & 16). The pseudotachylytes on the thrusting zones SE of Jotunheimen commonly display grey and brown colours and are semitransparent in plane-polarized light. I therefore have added two photomicrographs of a thin section prepared for C. Bugge from sample collected by him and kept by N.G.U. That is the thin section He XII No. 5 named «Grønsten, 1581 m høyden N f. Sandåni, Hemsedal» (West-Jotunheimen) described by C. Bugge (1939, p. 46) with the radial microlite aggregates (figs. 18 & 19). The almost identical appearance of a photomicrograph of pseudotachylyte from The Outer Hebrides (Jehu and Craig, Vol. 53, Pl. III, fig. 6; and further of S. J. Shands' pseudotachylyte Type 3, 1916, p. 206, Pl. XIX, fig. 4) is here pointed out. The white veinlet, transparent in plane-polarized light (fig. 18) — black — isotropic under crossed nicols (fig. 19) intersecting the microlite-aggregates, seems to have escaped Bugge's attention, as well as the colourless, glassy rims, bordering inclusions in his thin sections from Hemsedal. Similar glassy rims are demonstrated by Scott and Drever (1953 Pl. V, fig. 2) and by Doris L. Reynolds (1954, p. 596 and Pl. 2 A, p. 597, see later). One can thus hardly deny the original glassy character of the microlites — and of the veinlet in figs. 18 & 19.

I have before (1953, pp. 60—68) pointed out the Hemsedal region as an extensive area, where tectonically remelted rocks are developed on a great scale. We now must add the Nautgardstind region, and likewise an intermediate area belonging to the thrust zone of the upper Jotun eruptive nappe. It is like Nautgardstind situated in quadrangle E30Ø (Sjodalen) to the N of the great Vinstervann (lake), where K. O. Bjørlykke (1905, p. 478) reported brecciated

Fig. 17. View of 1616 m.-Hindnubb towards the NE from the locality shown in fig. 13. (1.500 m. alt.) Authors photo.

Utsikt mot NØ mot 1616 m-Hindnubb — lengst mot nordost av disse, Veodalen i bakgrunnen til høyre. Fra lokalitet i 1500 m o h., vist i fig. 13.

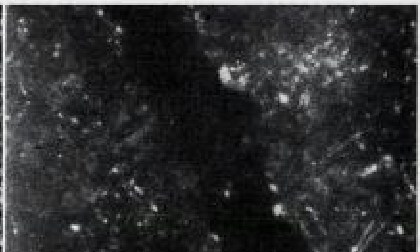


Fig. 18. Photomicrograph. Planepolarized light × 160. Sample collected C. Bugge (1939 p. 46). «Greenstone 1581 m. summit N. of Sandåni, Hemsedal,» West Jotunhemen. Aggregate of radiating laths of plagioclase, intersected by transparent pseudotachylyte-veinlet. Authors photo.

Microfoto av C. Bugges tynnslip 1581 m topp N for Sandåni, Hemsedal (1939). Pseydotachylit-åre av gjennomsiktig glass i radialstillede plagioklas mikrolitter (× 160, ╪ lys).

Fig. 19. Same as fig. 18, but crossed nicols. Authors photo.

Samme som fig. 18, men + n. Viser pseudolachylit-årenes isotrope karakter.

and mylonitic rocks in Malmkollen and in Kvernhø (1682 m alt.). From the latter locality he collected samples in 1898, and much later V. M. Goldschmidt noticed «glassy diabase» in a thin section (Dietrichson 1953, p. 59).

It may thus be emphasized, that the pseudotachylytes and related mylonites and probably lamprophyres are abundantly displayed in the Jotunheim region. Though running a certain risk as a heretic, I support Erich Kaiser (1927) in considering these rocks as most important for our magmatic as well as for our tectonic conceptions (quoted Dietrichson 1953, p. 64).

In a recent publication Doris L. Reynolds (1954) has attempted a new explanation of the origin of pseudotachylytes and related rocks in the Vredefort region. These rocks occasioned Kaisers expression mentioned above. R. A. Daly (1953, p. 249) wrote of «the rise of the almost incredible, magma-invaded Vredefortdome».

In a most exhausting and penetrating petrographical treatment of the much discussed basic granophyre in the Vredefort region, Willemse (1938, p. 117) among his conclusions states:

«The basic granophyre cannot be regarded as a normal differentiation product of the magma with which it may possibly be connected. An explanation is outlined by which this rocktype is referred to an original alkali-lamprophyre magma which has assimilated mainly quartzite and granite. The special conditions favouring the formation of this abnormal and yet comparatively homogenous rock are fully in accordance with the complicated tectonic history of the region.

Its close relation to the pseudotachylytes is also taken into consideration».

As to the pseudotachylytes of the Vredefort region Willemse also concludes:

«The result of röntgen-ray analyses of the pseudotachylytes do not bear out the supposition that the rock has originated through fusion.»

And further:

«It is suggested that the pseudotachylyte did not arise through solidification from a melt, but where coarsely crystallised through recrystallisation in the solid state. Otherwise in the ultramicroscopic varieties it may only represent very finely pulverised rock material».

This interpretation of «the most puzzling of rocks» (A. Holmes, 1916, p. 221) seems to have been adopted by petrologists in Tertiary and in older mountain ranges as well. When judging from the röntgen-ray analyses, one must have in mind that the presence of inclusions of all dimensions in a submicroscopic base is a well known, invariable feature of the pseudotachylytes.

Scott and Drever (1953) and the writer (1953) have now contemporaneously and independently described similar rocks formed by fusion on thrusts in the Himalayas and in the Jotunheimen respectively, and offered explanations partly along the same lines i.e. as to glass originated from biotite.

As mentioned above, Doris L. Reynolds (1954, p. 596) advocates that «the partial fusion of the bytownite may be taken as a minimum temperature of about 1355°C,» which is about the same the writer found probable for the solidus temperature of a similar plagioclase found in a remelted anorthosite-norite on the thrusting zones SE of Jotunheimen, namely 1330°C. (Dietrichson 1953, p. 57).

The aim of Doris L. Reynolds' paper (1954) is however to launch a brand new explanation bearing on the problem of intrusive granites, and here the basic granophyre of the Vredefort region is used as one of the most convincing pieces of evidence.

Gaseous outbreaks are supposed to «fluidizate» the fine-grained material (like the ignimbrites in the Valley of Ten Thousand Smokes) which were then blasted into cracks and fractures there forming for example the basic granophyre dykes («a width of 30 m not being rare», Hall and Molengraaff 1925, p. 56) and the related pseudotachylyte veins (down to microscopical veinlets).

As no rise in temperature due to reaction of the gasses as in volcanic outbreaks or reactions as by pneumatolytic deposits seems expected, they obviously must have originated from exceedingly hot and extended reservoirs. The theory as a whole may be taken as a remarkable example of modern, transformistic science and is hardly consistent with the features of the mylonites and related rocks on the thrust-planes of, for example the Jotunheimen, as I hope appears from the evidence in this paper.

Oslo, January 1955.

Sammendrag:

Spesartit og pseudotachylit fra øvre Jotuneruptivdekkes bevegelses-sone i Øst-Jotunheimen.

Under den programmessige kartlegning for N.G.U. sommeren 1954 på NW-delen av gradteig E30Ø Sjodalen, samlet jeg prøver på Nautgardstind og Hindnubbene. En upresset gang (fig. 4) var så interessant at jeg fikk utført komplett analyse av denne (nr. 93) og hovedbergarten i Nautgardstind (nr. 91). Videre publiseres analyse av mylonit fra ny fjellskjæring på Valdresflyveien (nr. 127 fra 1953) som har hypersthen-syenitsammensetning. Den sammenholdes med Goldschmidts (1916) analyse av tilsvarende bergart fra Suletind, likesom hele fremstillingen bygger på Goldschmidts grunnleggende undersøkelser særlig av de av Bergen-Jotunstammens bergarter som er representert i dette område, og som vi nå henfører til det øvre Jotuneruptiv-dekke. Ytterligere belyser vel 6 feltfotos og 12 mikrofotos forholdene bedre enn beskrivelser i denne preliminære meddelelse. Gangene i Nautgardstind antas å være perifere apofyser fra større masser som nå er representert i hellingen av Hindnubbene mot Hindflyen og i 1616 m Hindnubben lengst i NE, nærmest Veodalen. Her trenges mer detaljerte undersøkelser. At forf. kom over så representative lokaliteter skyldes sammentreffende heldige omstendigheter: snedekning og uvær er det alminnelige i denne høyden, talus og morenemasser dekker også det faste fjell vidt og bredt. De mest motstandsdyktige bergartene står i toppene og i de få blotningene.

Den tette gangbergart er lamprofyr, nærmere betegnet *spessartit.* Den tilhører Bergen-Jotunstammen. At den er intrudert som smeltemasse under det øvre Jotuneruptivdekkes bevegelse er tydelig, likeså at denne smeltemasse har assimilert dettes dypbergarter og fører større og mindre bruddstykker og xenolitter av disse. Om den i sin helhet representerer deler av dette, oppsmeltet under bevegelsen, eller om den vesentligste del er primære smeltemasser tilført fra magmabassenget kan det ikke tas standpunkt til, men at disse har vært «overopphetet» (ca. 1500°C?) er sannsynlig, samtidig som hele eruptivdekket har holdt en temperatur på kanskje ca. 600°C som sank langsomt sammenlignet med lamprofyrmassenes temperatur. Gjennomvevningen med pseudotachylitganger og årer kan som jeg tidligere har fremholdt forklares ved et temmelig sterkt opphetet miljø. Det fremholdes at lamprofyrmassene har virket som smøremiddel under eruptivdekkets oppskyvning, at de dannet basis for mylonitmasser som hadde den samme funksjon under dettes glidning nedover et underlag med liten gradient, men at mylonitmassene snart og etterhvert forandret sammensetning utover i forlandet, avhengig av P—T forholdene og foreliggende substans i bevegelsesplanet. H_2O tilførslen spiller en dominerende rolle.

Lagdelingen i det øvre Jotuneruptivdekke indikeres temmelig tydelig ved de fremlagte analyser og tynnslip, fra hypersthen-syenit øverst gjennom den monzonitiske mangerit i Nautgardstind og den typiske mangerit og Jotun-norit representert i xenolitter i lamprofyr, samt direkte ved lagningen i Nautgardstinds nordvegg, hvor der ville være ønskelig å få tatt en prøveserie. Fallet av lagningen i Nautgardstind forklares ved at dekket har beveget seg i halvstiv tilstand på et underlag med NW—SE løpende rygger og mellomliggende daler, det nevnes kort at dette relieff skyldes overfoldningen fra NE mot SW, som tidligere fremholdt av forf., samt at dette viktige forhold for forståelsen av vår fjellkjedes tektonik nå fremholdes av Th. Vogt som et regionalt, generelt trekk i den kaledonske fjellkjede fra Norge til de Britiske Øer.

Tynnslipene viser den protoklasiske struktur av dekket ved bøyde plagioklaskrystaller, tilsynelatende mer utbredt i de mer basiske, lavere lag enn i de høyereliggende. Videre viser de begynnende dråpeperthit-dannelser, som antas å skyldes avblanding under avkjølingen av plagioklasenes høy- og lavtemperaturmodifikasjoner. Ved detaljert bearbeidelse kan der ventes nytt lys over temperaturforholdene ved spessartittens intrusjon. Spindelpertittene — de vanlige «Jotunpertitter» berøres også, med antydning om at de skyldes analoge prosesser under høyere trykk — deres betydning som «anorganisk ledefossil» i klastiske bergarter nevnes.

Korreleringen mellem Vredefortfeltets basiske granofyr og spessartitten, begge ledsaget av pseudotachylit dokumenteres. Det påvises at vi i pseudotachylittene ifl. nyere undersøkelser her og fra andre fjellkjeder har med virkelig glassdannelse og nykrystallisasjon fra oppsmeltede masser å gjøre. Der tas avstand fra Doris L. Reynolds «fluidiserings»-teori på grunnlag av de fremlagte data i Nautgardstind-området.

Acknowledgement.

The provisional character of many of the results in this paper and my preceding paper in N.G.U.'s yearbook, treating the Pseudo-tachylyte SE of the Jotunheimen, is not only due to a wish to rush into print.

Rather is it in harmony with the unsettled nature of our times when the author's prospects for further work in the central parts of our mountain-chain are in jeopardy.

For the past three eyars I should like to thank S. Føyn, Director of the Norwegian Geological Survey for fair treatment.

I am also much obliged to Dr. T. Strand, also of the Norwegian Geological Survey, for almost daily collaboration during the preparation of collections from our area of common interest in the Caledonides of Northern Gudbrandsdalen. If his friendly advice has been considered unduly conservative in the author's mind, it has only served as a stimulans to further effort.

P. Padget M. Sc. corrected the English of the manuscript in the same careful way as in the Summary of my preceding paper (N.G.U. No. 184, 1953). During the work he also pointed out certain sections requiring a more explicit treatment. The author wishes to express his sincere thanks for his helpfulness.

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Abbreviations: N.G.U.: Norges geologiske undersøkelses skrifter.
N.G.T.: Norsk Geologisk Tidsskrift.

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