

On the variolitic structure.

By

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Abstract.

The article presents detailed descriptions of the variolitic structure in selected minor intrusions and lavas. The evidence indicates that the varioles formed by liquid segregation rather than by spherulitic crystallization.

Introduction.

The commonly accepted opinion on the origin of varioles is reflected in modern petrographic textbooks which traditionally state that the variolitic structure of basic igneous rocks is equivalent to the spherulitic structure of silicious lavas and intrusions, which are presumably formed by rapid crystallization in a viscous magma or by devitrification of glass around scattered nuclei. The spheroidal shape of varioles by this hypothesis is thus accounted for by the crystallization of one mineral from numerous centers with equal velocity in all directions. A number of observations presented below are, however, inconsistent with this view.

Petrographic literature of this century conveys the impression that varioles are a structural curiosity. This is probably not so. Studies of minor intrusions and lavas from Norway have shown that in certain rocks this structure exists almost invariably. Certain types of lamprophyres and spilitic pillow lavas are particularly prone to a variolitic development. The variolitic structures of some Norwegian rocks, one monchiquite, a few vogesites, and a glassy augitite lava, are described below. The Norwegian pillow lavas are altered and not suitable for detailed treatment.

Minor intrusions.

a) *Monchiquite dyke, Hamar*

The dyke is exposed in a limestone quarry at Furuberget about 3 km north of Hamar. The dyke is obviously connected with the Permian volcanism of the Oslo region and has intruded into a Middle Ordovician limestone. It has a thickness of 1 m, dips vertically, and strikes N 30° E.

The dyke is multiple, Fig. 1. The first intrusion (no. 1) developed two planes of weakness near the contacts (Tyrrell 1926, p. 32) which acted as channels for the next injection (no. 2), thus consisting of two members. Injection no. 3 is a leucocratic albite-rich rock (albitite) which intruded along the western contact of the monchiquite and the limestone.

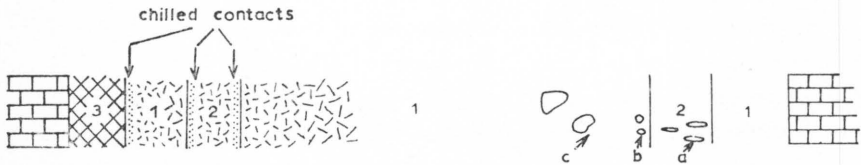


Fig. 1. Section through the multiple dyke at Furuberget. Successive injections of monchiquite, 1-2. Hornblende albitite, 3. Lenticular ocelli with long axis normal to the walls, a. Globular ocelli, b. White, irregular amagdaloidal spots, c.

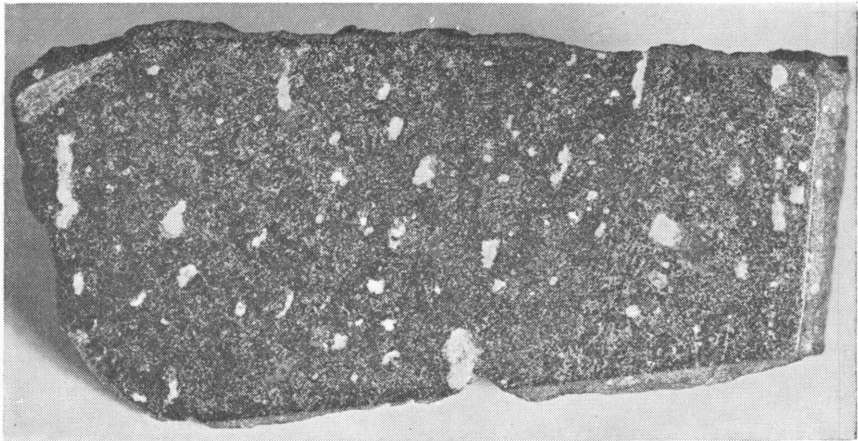


Fig. 2. Variolitic monchiquite, central member of intrusion 1. The specimen is polished and etched with HCl. - Natural Size.

All the dykes are variolitic. In the central member of intrusion no. 1, the variolitic structure is not easily noticeable, but it may be demonstrated with large thin sections (without coverglass) or with large polished specimens, Fig. 2.

The monchiquites are dark, almost black rocks with visible hornblende needles and white ocelli and amygdales. Analcime icositetrahedra are seen with a hand lens in the central member of no. 1. Brown hornblende (40 ± 5 % by volume) and abundant magnetite are set in a groundmass of analcime, chlorite, and some calcite. Accessories are clinopyroxene, apatite, sphene, alkali feldspar, and pyrite. The mafic minerals are evenly distributed throughout the rock and the globular structure is due to the concentration of analcime in spherical units. The groundmass (groundmass and matrix in the following text always refer to the mass in which the varioles and other globular structures occur) is very rich in chlorite, and sometimes large fields of serpentine – evidently pseudomorphs after olivine – may be present. The varioles are not sharply bounded, but their outlines are somewhat better defined near the margins of the injections. The diameter increases away from the contacts, ranging from 1–7 mm. The hornblende occurs in up to 4 or 5 mm long needles and has usually no definite orientation in relation to the globules. Sometimes there is a slight tangential arrangement in the vicinity of the globules, but more often the hornblende projects from the chloritic matrix into the globules without any change in the optical properties.

According to a partial chemical analysis ($\text{TiO}_2=3.99$, $\text{FeO}=9.33$, $\text{Fe}_2\text{O}_3=2.70$, $\text{MgO}=11.32$, $\text{CaO}=11.28$) the composition of the hornblende is kaersutitic. The rather low content of TiO_2 does not, according to Wilkinson (1961), exclude this hornblende from the family of kaersutites.

Next to kaersutite, analcime is the most abundant mineral. The main part of the analcime occurs within the varioles as small subhedral crystals, or as a structureless mass. Another mode of occurrence is together



Fig. 3. Various globular ocelli consisting of analcime and calcite.
The ocelli are about 2 mm in diameter.

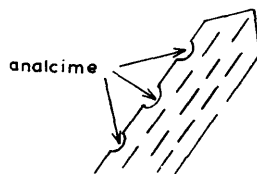


Fig. 4. Subangular analcime crystals idiomorphic against hornblende.

Table 1. *Chemical analyses of the hornblende monchiquite of Furuberget.*

	1	2	3	4	Molecular norm
SiO ₂	39.64				Or 6.6
TiO ₂	4.04				Ab 15.5
Al ₂ O ₃	12.88				An 16.5
Fe ₂ O ₃	6.31				Ne 10.8
FeO	7.80				Di 19.9
MnO	0.08				Ol 13.9
MgO	9.20				Mt 6.9
CaO	10.20				Il 5.8
Na ₂ O	3.63	3.10	3.98	8.56	Ap 1.5
K ₂ O	1.08	1.11	1.58	0.18	Cc 2.6
H ₂ O+	3.28				
P ₂ O ₅	0.70				
CO ₂	1.02				
FeS ₂	0.24				
	100.10				

1. W. C. Brøgger's analysis (1933 b) of the monchiquite.
2. Intrusion no. 1, central member. Analyst R. Stokland.
3. » 2, most westerly member. »
4. » 3, albitite. »

with calcite, feldspar, and biotite as a mineral filling of ocelli and amygdalae, Fig. 3. The texture produced by growth interference between kaersutite and clear subhedral analcime, Fig. 4, compares closely with similar textures in so-called leucite monchiquites of Bohemia. The leucite of these monchiquites seems, however, to be analcime – primary or pseudomorphs after leucite. There is no indication of a secondary origin for the analcime of the Furuberget monchiquite. The analcime of the groundmass is cloudy, partly birefringent, and somewhat altered. The analcime of the ocelli and the amygdalae is clouded but usually has a fringe of slightly birefringent and clear analcime that according to analyses contains less potassium than the cloudy analcime.

The Furuberget dyke was mentioned briefly by Brøgger (1933 a) and he also presented an analysis of the monchiquite (1933 b), given in Table 1.

b) Vogesites of Southern Norway

The lamprophyres from the south coast of Norway have been described by the author (1959). A typical variolitic vogesite from the island Songvaar between Kristiansand and Mandal is chosen for description below. The dyke is vertical, 25–30 cm in width and variolitic throughout. The varioles are not visible to the naked eye in the tachylitic selvage, their diameter being 0.05 mm or less. These globules probably consist of glass, but display strain birefringence. The varioles increase rapidly in size and 4–5 mm from the contacts the diameter may be over 2 mm. They are observed in various stages of coalescence and are separated by a matrix rich in chlorite. In a zone on both sides, 3–7 cm from the contacts, the varioles (4–5 mm in diameter) are close-packed, leaving a

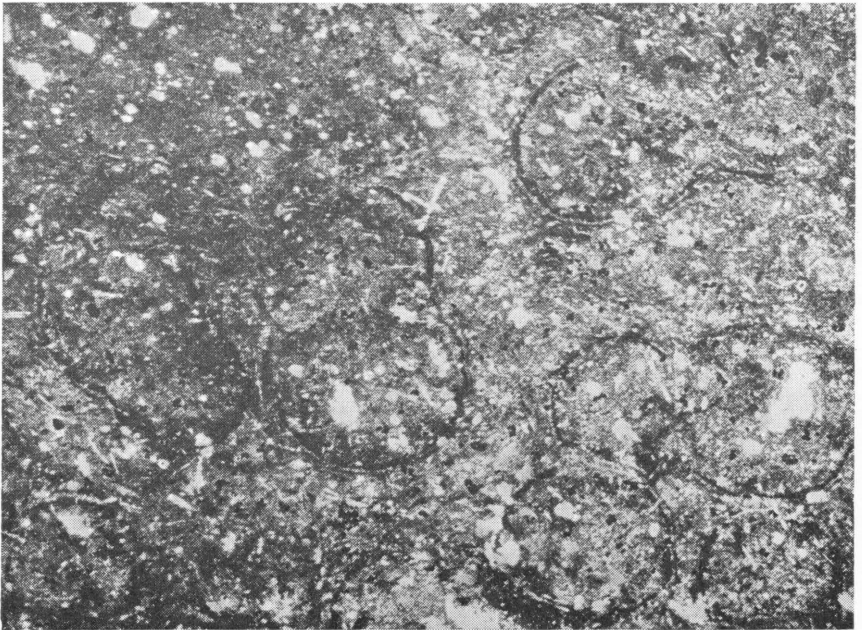


Fig. 5 a. Photomicrographs of varioles. $\times 11$.
Vogesite from Skarvøy off Kristiansand.

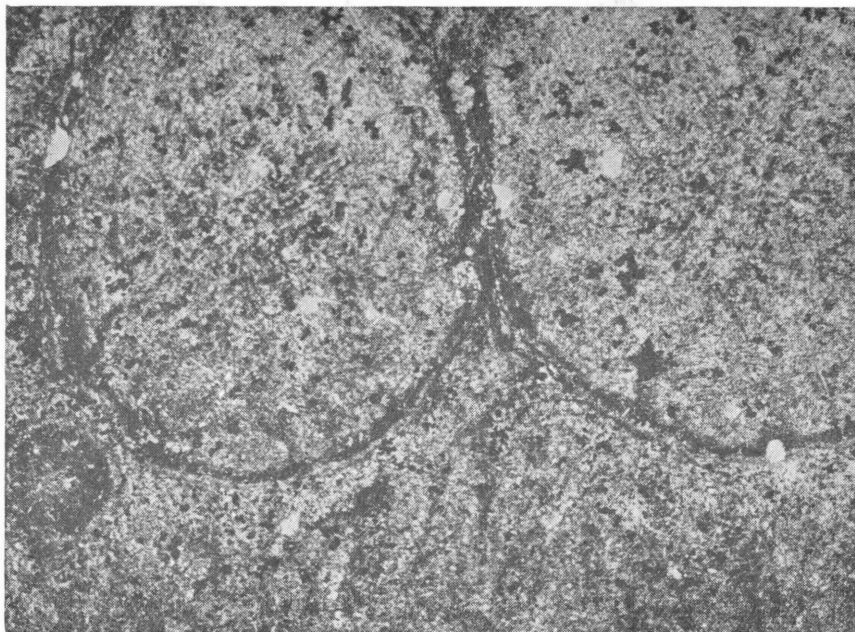


Fig 5 b. Vogesite from Nesodden in the Oslofjord. The boundaries are sharp and marked by a dark rim.

groundmass which amounts to less than the theoretical 27 %. This is due to distortion of the globules and the presence of globules of various sizes. Small ocelli of feldspar are commonly found within the varioles in the closely packed zones. In the central part of the intrusion the varioles (5–7 mm in diameter) are further apart.

Most vogesite dykes in this area are multiple. In no case, however, have variolitic structures been observed in the internal chilled contact zones.

Mineralogically the vogesites differ from the monchiquites mainly in having anorthoclase instead of analcime. The varioles consist of anorthoclase, kaersutite, and magnetite with small amounts of sphene, apatite and chlorite. The groundmass is very poor in feldspar, and chlorite is the most abundant mineral followed by kaersutite and magnetite. Small phenocrysts of kaersutite occur in the tachylitic selvage, indicating that this mineral precipitated from the magma first. Occasionally kaersutite needles cross the boundaries of the varioles. The sharpness of these boundaries varies, but is usually well defined and marked by a dark rim

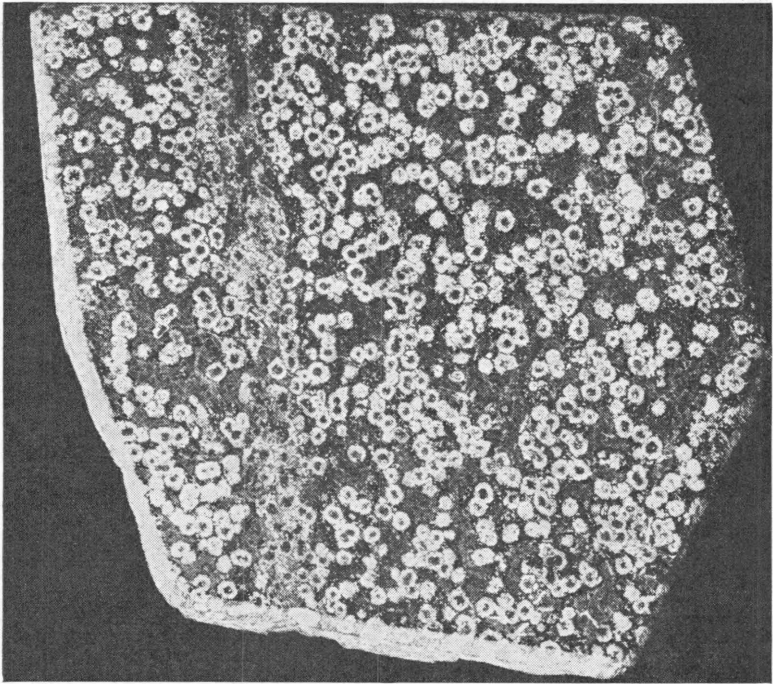


Fig. 6. Variolitic vogesite, Zwingenberg, Odenwald in Germany. A very pronounced concentric structure is superposed on a radiate structure produced by fibrous feldspar. The center consists of red alkali feldspar. Surrounding the center is a thin zone rich in calcite which in turn is enveloped by alkali feldspar less pigmented than the central feldspar. The specimen is polished and etched carefully with HCl. Slightly enlarged.

near the contacts, Fig. 5. Magnetite is not present in this rim, and the cause of the dark colour is not known.

Very similar variolitic vogesites were seen by the author in a stone quarry at Zwingenberg in Odenwald, Germany, Fig. 6.

A variolite collected by J. H. L. Vogt in 1904 at Søndre Spro, Nesodden near Oslo was found in the collections of the Geological Survey of Norway. This dyke, evidently of Permian age, cuts a Pre-Cambrian microcline granite. The composition is vogesitic. The hornblende is brown and similar to kaersutite near the contacts, but light green and actinolitic a small distance away. Because epidote also gradually appears in the chloritic matrix, the vogesite of the central part of the dyke resembles a low grade spilite. The globules have a rim of a dark substance, and a thin zone of calcite separates the varioles from the chlorite of the groundmass. Contiguous globules are of various sizes, Fig. 7.

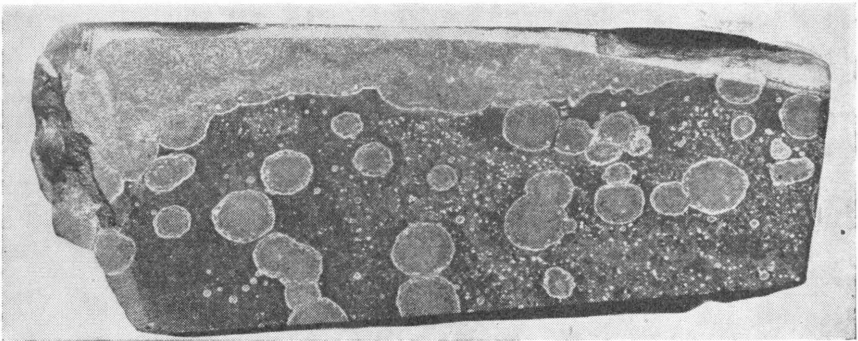
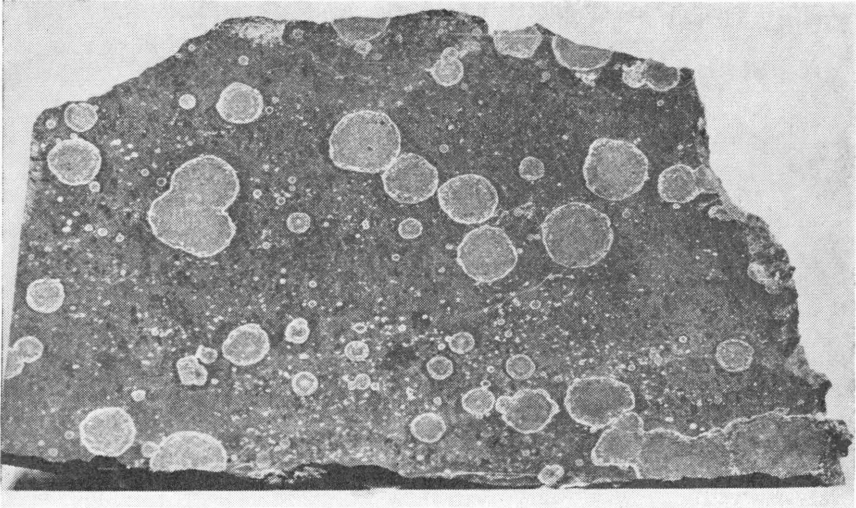


Fig. 7. Variolitic vogesite, Nesodden. 133 globules are counted in the upper specimen. The range in size is 0.2–7.5 mm with a frequency maximum at 0.7–0.8 mm. The white rim is calcite. Coalescing on a large scale forms a continuous zone in the lower specimen. Slightly enlarged.

Lavas.

a) Pillow lavas

It is well known that pillow lavas commonly are variolitic. Such lavas in the Norwegian Caledonides were first described in detail by Bugge (1910). In the pillows different zones may be recognized by variation in packing density, size and composition of the contained varioles. These zones correspond to the zonal variations in the vogesite dyke previously

described. Epidote replaces the feldspar ocelli of the vogesitic varioles, and is often seen as an epidotized yellowish band near the pillow margins.

b) Glassy lavas

At Falkenstein near Horten Professor O. Holtedahl found in 1942 a variolitic lava at the base of the Permian lava series. Specimens of the variolite were later described by Barth (1945). The author visited the locality in the autumn of 1962 but found only loose boulders of a variolitic rock apparently fallen down from the lava cliffs and therefore probably represent a younger member of this lava series. This variolite differs from Holtedahl's specimens in being very rich in glass which, according to Barth, does not seem to be present in the variolite studied by him.

The glass is light to dark brown, sometimes almost opaque. It contains small granules of titaniferous magnetite and abundant rod-shaped or dendritic crystallites. The glass of the varioles is dark brown and slightly anisotropic ($n=1.560$). The glass in the groundmass is light brown and nearly isotropic ($n=1.560-1.565$). The glass is magnetic, being more magnetic in the varioles than in the groundmass. Small and commonly euhedral crystals of colourless clinopyroxene (length 0.1–0.2 mm, $\gamma = 1.718 \pm 0.003$, $\alpha = 1.700 \pm 0.003$) are embedded in the glass. A few pyroxene phenocrysts also occur. Chlorite is present as a constituent of both varioles and groundmass, and together with calcite in amygdales. Glass is most abundant in the varioles, and pyroxene and chlorite seem to be enriched in the groundmass. The glass has been subjected to secondary crystallization as shown by the presence of crystallites. The dark colour of the glass in the varioles, considering its magnetic character, suggests a concentration of Fe_2O_3 .

Green amygdales of chlorite or serpentine are sometimes abundant. This lava is a variolitic augeite.

Summary

The facts which seem to be of critical importance both in regard to a definition of the structure and from a genetic point of view, is given in summary form below.

Varioles are essentially spherical. Contiguous varioles are often of different sizes, but the average size increases towards the interior of the intrusion. The mode of packing, the «density», is related to the distance

from the contact. Varioles may coalesce with such results as twin, triple, or quadruple globules etc., or the formation of continuous bands. There are usually sharply bounded globules near the contacts, but their outline gradually becomes more diffuse towards the center of the intrusion. The globules may eventually merge indistinguishably with the groundmass. Radial as well as concentric structures are common. Varioles and groundmass contain the same minerals but in different proportions. Olivine, as serpentine pseudomorphs with the outline of olivine crystals, may be an exception having been seen in the matrix only. The compositional relations are always the same: the varioles are feldspathic or rich in analcime, the groundmass contains abundant chlorite. No reversal of this relation has ever been observed. Glass is the main constituent of varioles and groundmass in some lavas.

Discussion.

Globules in mica lamprophyres – “Kugelminetten” and “Kugelkersantite” of Rosenbusch – may sometimes produce a variolite-like structure. The globules consist mainly of feldspar with a skin of mica, and are almost identical to a structure common in many lamprophyres, now usually called ocelli.

Ocelli may be defined as spherical or ellipsoidal aggregates consisting of alkali feldspar and analcime, with minor biotite, hornblende, and pyroxene (Knopf 1936).

Detailed descriptions of ocelli usually include one or more of the following features. 1. Calcite and/or chlorite comprise the central part. 2. Hornblende, pyroxene, biotite, or feldspar surround the ocelli tangentially or project into them. 3. The feldspar radiates from excentric or multiple points. 4. The feldspar laths are curved. 5. Sphene abounds. In some lamprophyres the center of many ocelli is occupied by a crystal of sphene. 6. Epidote, prehnite, quartz, apatite, or pyrite may be present. 7. The grain-size is coarser within the ocelli than outside. 8. The ocelli increase in size towards the center of the dyke until they gradually fade out. 9. The ocelli coalesce and form irregular rounded patches. See also Fig. 8.

Thus the ocelli are leucocratic, globular units of the lamprophyres, the most important minerals of which are analcime or feldspar. Monomineralic analcime ocelli are fairly common, but the feldspar is always associated with chlorite, biotite, hornblende, or calcite. It appears that

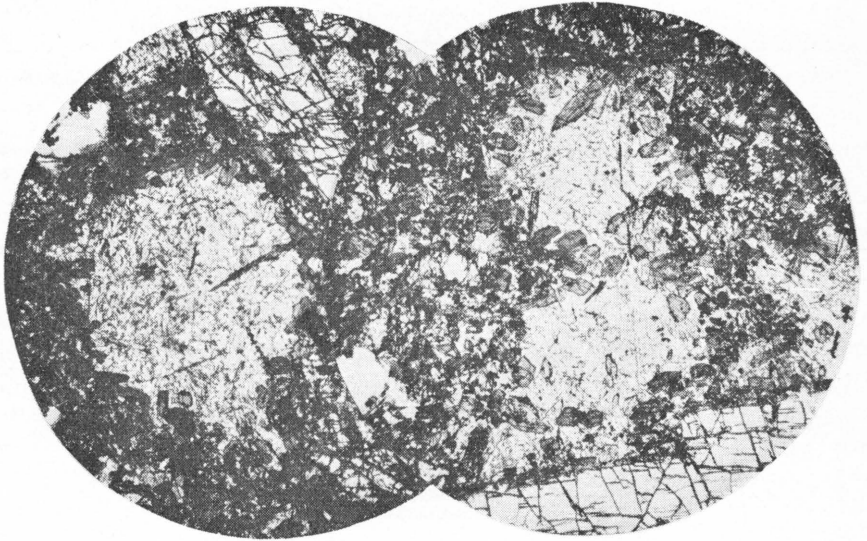


Fig. 8. Ocellar vogesite, Fen. X 22. Left: long needle-like sphenel in the ocellus. Right: hornblende included in the outer sphere of the ocellus.

water or the ionic groups $(OH)^-$ or $(CO_3)^{--}$ are important parts of the structure.

Exceptions to the rule that ocelli are globular are sometimes found. A subangular outline may give the ocelli a close resemblance to the white eyes of many tinguaite, so-called pseudoleucite. The possibility therefore exists that ocelli are pseudomorphs after some cubic alkali aluminosilicate. On the other hand, ocelli may grade into normal amygdales and most petrologists in dealing with this matter dismiss the ocelli as infilled vesicles. The preceding summary shows the great similarity of ocellar structure to variolitic structure. The ocelli are, however, more leucocratic and usually not so sharply bounded. They are also younger than the varioles and formed after crystallization had proceeded for some time, but before the minerals around the globules were no longer able to rearrange themselves. Ocelli and varioles are common in lamprophyres and therefore frequently occur together. It is necessary that any suggested hypothesis accounts for both structures.

Ocelli and varioles resemble in some ways the spheroidal bodies in stony meteorites, so-called chondrules. Merrill (1930) probably first called attention to the similarity between the globules of a "Kugelgrünstein", obviously a variolite, and the chondrules. The mineralogical com-

position of chondrules usually sets them apart from varioles, yet feldspar chondrules, closely resembling some ocelli-like globules of terrestrial rocks, occur. The mineral responsible for the radiating structure of such chondrules usually radiate from one or more points at or near the periphery in contrast to the centric or slightly excentric disposition in varioles. Ringwood (1959, 1961) has argued in favour of a spherulitic origin of such chondrules, but remarks in a note added during proof-reading of the last paper, that an unpublished work by dr. Fredriksson has convinced him that most chondrules originated as liquid drops rather than by spherulitic crystallization. Such drops may have been formed by disruption of an chondritic magma as a fiery rain (Sorby 1877) or by cavitation and fragmentation of the magma due to loss of volatiles (Ringwood 1961).

It is *a priori* possible that the glassy and the holocrystalline varioles are of different nature. This is not supported, however, by the analyses presented in Table 2, which show that the distribution of the major elements between varioles and groundmass is very similar independent of the degree of crystallinity. The varioles are enriched in Si and alkalis, but contain less Mg, Fe, Ti, and Mn than the groundmass. This consanguinity of the varioles which are crystalline throughout and the glassy ones is important, as the latter may point to the origin of the former.

With regard to the glassy varioles, the possibility that they formed by crystallization phenomena is of course ruled out. They indicate, on the contrary, that varioles represent drops of molten matter which solidified suddenly.

All crystalline varioles are polymineralic, and it is difficult to see how such globules could have been formed by spherulitic crystallization. Spherulitic crystallization is favoured by rapid cooling in a viscous magma, but the magma which solidified to form the variolites must have been rather fluid as testified by the basic composition and the high water content. Moreover, a radiate structure is apparently lacking in some variolites. The writer believes that the radiate structure is secondary to the globular structure and a consequence of the spheroidal shape and the chemical composition of the globules. These were more viscous than the variolitic magma and more liable to spherulitic crystallization. The fact that the variolitic structure is usually seen at the contacts of the intrusions and in lavas naturally suggested to the earliest writers (a list of references may be found in Rosenbusch 1908) that sudden chilling was a prerequisite for their development. The finding of varioles in the Furuberget dyke which are on the verge of merging with the groundmass

Table 2. *Spectrographic and chemical analyses of varioles and matrix in three variolites.*

	Songvaar ¹		Nesodden ²		Falkensten ²	
	Varioles	Matrix	Varioles	Matrix	Varioles	Matrix
SiO ₂	46.48	38.58				
TiO ₂	5.46	5.84	2.7	3.2	3.1	5.8
Al ₂ O ₃	13.48	11.05	14.0	13.0	14.0	14.5
Fe ₂ O ₃	4.49	7.34	11.0	14.5	10.5	23.0
FeO	5.83	7.76				
MnO	0.27	0.22	0.17	0.24	0.11	0.37
MgO	6.39	11.75	3.9	5.7	3.8	12.0
CaO	6.50	5.58	6.0	6.9	3.7	7.6
Na ₂ O	3.03	0.62	3.3	0.3	1.3	0
K ₂ O	2.83	1.81	4.3	4.3	10.0	2.0
H ₂ O	2.99	5.91				
H ₂ O	0.84	2.80				
P ₂ O ₅	0.60	0.68				
CO ₂	0.90	0.21				
Loss on ignition			2.95	8.78	5.20	7.81
	100.09	100.15				

¹ Chemical analyses. Analyst R. Stokland.

² Spectrographic analyses. Analyst M. Ødegård.

shows, however, that the effect of quenching is rather to preserve the structure. The general absence of varioles in the central parts of variolitic dykes is due to their disappearance by slow cooling under conditions of phase equilibria.

Some varioles may have got their crystalline structure by the devitrification of glassy ones, but there are reasons to believe that most varioles in minor intrusions crystallized directly from a liquid. This is borne out by the structural relationships between the mineral constituents of the varioles. For example the structure drawn in Fig. 4 could not possibly have been developed by secondary crystallization, neither could the ocelli nor the amygdales that often are seen in varioles.

The old hypothesis of Gumbel (1876) that varioles are xenolithic fragments transformed and rounded by a prolonged period of suspension in the magma, has in recent years been revived by Holmes (1936). The relationship of the varioles to the contacts, however, shows that they are authigenic constituents of the magma; they originated in place as pro-

ducts of magmatic segregation. This precludes the xenolithic hypothesis, and Chierci's suggestion that varioles are metamorphosed garnets has only historical interest.

These hypotheses were challenged by Loewinson-Lessing (1935). He proposed that the globules and the groundmass of a variolite of Yalguba in Karelia (described by himself in 1885) represent two immiscible parts of the magma – a magmatic emulsion. Later Vaugnat (1946) seriously considered this possibility concerning the varioles of Swiss spilites. Drever (1960) described the globular structure of a picritic intrusion on Greenland and claimed that this was “the most unambiguous natural evidence hitherto recorded of silicate immiscibility”. Drever does not, however, mention the similarity of these globules to the variolitic structure to which his statement probably more correctly applies.

Tomkeieff (1952) advocates that analcime ocelli, first described as “circular areas of analcime” by Evans (1901), originated as an immiscible liquid phase. The present writer suggested that feldspar ocelli might be similarly explained (1959). Studies of metasomatism in British pillow lavas led Nicholls (1958) to the conclusion that the amygdales of these spilites formed by segregation of a second liquid enriched in Mg, Fe, and H₂O. This idea was not new, however, having already been offered for consideration by Tomkeieff (1926, 1942). Incidentally it may be noted that the chlorite amygdales represent an interesting compositional reversal as compared to variolites in which an iron-rich chlorite is the main constituent of the matrix.

If the extrusive variolites were not formed by shattering of the magma by explosive volcanism or by the action of surface water on the lava flow, then the existence of glassy varioles in a glassy groundmass is in best agreement with the hypothesis of Loewinson-Lessing. Indeed it is hard to explain the different composition of varioles and groundmass by any other known process. The rarity of glassy variolites is no argument against liquid immiscibility, as we have seen that varioles have an inherent tendency to crystallize, and to become distorted or wholly disappear during solidification.

Many arguments in favour of an origin by liquid immiscibility of the Greenland globules were brought forward by Drever in the paper cited above. It seems unnecessary to repeat them here, but a few comments may be appropriate. Drever found evidence of liquid immiscibility in the roundness of the globules and the manner in which they coalesce. Referring to Greig (1928) he demonstrated that multiple globules show

exactly the transitional forms such globules should have if they once were liquid. This is due to the fact that when two liquid drops meet, the surface tension tends to combine them into a larger spherical globule. Compound varioles may also assume the shapes predicted by Greig, but more often they preserve their individuality until a late stage of coalescence, Fig. 7. High viscosity may have prevented the varioles from fusing together immediately. A glance at the same picture shows the wide range in size of varioles lying together. This feature may be expected if the globules formed as immiscible drops in the magmatic phase. Drever pointed out that crystals which occur jointly in globules and matrix have the same chemical composition, a condition demanded by the theory of phase equilibria in conjugate liquids. The optical continuity of the kaersutite which sometimes crosses the borders of the varioles is likewise in accordance with this theory.

The tendency of Norwegian lamprophyres to exhibit variolitic structures contrasts with the absence of varioles in the associated diabase dykes. It is also an interesting fact that lamprophyres and spilites have features in common other than the varioles. The mineralogical problem of spilites, the absence of an An-rich plagioclase in spite of the high Ca content of the rock, is inherent in some lamprophyres, i. e. the vogesites in which an alkali feldspar has formed rather than plagioclase. Both rock types are rich in H_2O and CO_2 and consequently often amygdaloidal or carbonatized. The low potash content of the Furuberget albitite recalls the association of pillow lavas with soda keratophyres. It is probably not fortuitous that variolitic rocks are rich in volatiles and usually in alkalies (Na). Certainly water must play an important part in producing the variolitic structure. Water distributes itself between varioles and groundmass with marked affinity for the latter which also is the more basic. However meagre the experimental evidence of liquid immiscibility (Steinar 1960), the work of Tuttle and Friedman (1948) indicates that water in a silicate melt enlarges the immiscibility field.

The contrasting content of Na in the globules and the matrix is probably a typical feature of variolitic rocks. Remarkable is the extreme enrichment of K in the Nesodden varioles which in this respect resemble the feldspar ocelli (Carstens 1961). In one case only has the author found structures in a genuine potash lamprophyre which may be variolitic. Variolitic rocks therefore are sodic rather than potassic and it appears likely that Na has an effect similar to water.

Varioles in the strict sense of the word are confined to the basic rocks.

Globular structures indicative of liquid immiscibility according to some recent literature, also occur in acid rocks. V. I. Lebedinskij and Mo Ke-Min (1958) arrived at the conclusion that the spherulitic structures of the perlitic lavas of Kalgan in Mongolia suggest unmixing in a rhyolitic magma. In the presence of contrasted glasses of New Zealand ignimbrites Steiner (op. cit.) found evidence of liquid immiscibility. (Steiner's hypothesis has been rejected by Fitch (1962) mainly on field evidence). It is probable that the enigmatic globular structures of the cristobalite trachytes of Jan Mayen (Carstens 1961) also have this origin. Limited liquid immiscibility in tektites is indicated by the presence of lechatelierite (Cassidy and Segnit 1955).

Thus basic and acid rocks alike bear witness of immiscibility phenomena in magmas at a temperature near that of crystallization. The evidence here presented further indicates that the composition of the residual liquid of basic magmas may lie within a second immiscibility gap.

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