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New observations on the formation of spilites and keratophyres of Glarus, Switzerland
(with special reference to material in the moraines of the Linth glacier)

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Abstract

The spilitic - keratophyric rocks of the moraines of the Linth glacier are in most respects identical to those found in the source area in the Canton of Glarus. As a contribution to the solution of the problem of their genesis, the following observations are reported and discussed:
(1) Of the albite generations, the phenocrysts display the highest An-content and a low structural state. The matrix albites have a lower An-content, but the highest structural state. Albites in amygdules, i.e. the latest generation, have the lowest An-content and the lowest structural state.
(2) The σ (sigma) angles measured on the (010)-pinacoid between the traces of the pericline composition plane and the cleavage (001) further confirm the primary nature of the phenocryst albites.
(3) A contact piece of basement granite frozen to spilite lava found in the moraines shows no alteration. And a pyroclastic layer between sediments ("Verrucano") and hematite spilites contains anorthoclase. Both observations likewise preclude any metasomatic origin for the rocks involved.

Zusammenfassung

Ein Vergleich der «Melaphyre» (Spilite bis Keratophyre) der Linth-Moräne von Glarus bis zum Rhein zeigt weitgehende Übereinstimmung in Gefüge und Zusammensetzung mit dem Anstehenden im Glarner Freiberg. Einige zusätzliche Beobachtungen tragen jedoch bei zum Problem der Spilitgenese in den Verrucanoschuppen der helvetischen Decken. Die massgeblichsten sind:
(1) Der Unterschied der Zusammensetzung zwischen Einsprenglingen und Grundmassealbiten sowie ihre Zustandsunterschiede ("high-low structural state").
(2) Ferner weisen Winkelmessungen (σ) am (010)-Pinakoid zwischen der Zusammensetzungsspur für Periklin und den (001)-Spaltflächen auf primär-magmatische Entstehung dieser Einsprenglinge hin.
(3) Ein Granitkontaktstück aus dem Grundgebirge mit fehlender Umwandlung und eine pyroklastische Lage mit Anorthoklas, zwischen Sedimentlagen und einem Hämatitspiliterguss, weisen zudem auch auf primären Ursprung hin und lassen eine metasomatische Deutung nicht zu.

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Introduction

Towards the end of extensive field work during the summers of 1945 to 1949, one of the present authors (G.C. Amstutz) started a comparison of volcanic moraine material with that collected during the outcrop mapping. A few of the moraine boulders displayed textures not observed in the outcrops. This contrast called for a thorough investigation of the types of lavas removed by erosion and carried down by glaciers - in order to obtain a more fundamental knowledge of the variability and properties of the Permian volcanism in the Verrucano.

Only two years ago this continuation of the work on the Glarus spilites could be initiated. The following is a summary of the first results obtained up to now.

The tectonic and lithologic position of the lavas investigated is amply treated in the monograph No. 5 of the Vulkaninstitut Friedländer (AMSTUTZ, 1954). The metamorphism which took place during the Alpine overthrusting is practically nil.

The field mapping of the junior author (G. Pfrang) also led to some valuable glaciological observations and these results will be published separately. The present paper will concentrate on observations pertinent to the still debated genetic questions of the albite rocks. The microscopic work (mostly performed with the U-stage) is largely the work of the first author, who owes thanks to the Chinese Ministry of Education for the two-years grant for a stay at the Mineralogic Institute of the University of Heidelberg for research on spilites.

General geology and petrology

On the basis of one of the author's previous works (AMSTUTZ, 1954, 1958, 1968, 1974; AMSTUTZ and PATWARDHAN 1974) a detailed study on the outcrops of spilitic rocks around Glarus area and the spilitic moraine material around Zürich is being carried out since 1979. The Glarus area (Eastern Swiss Alps) is considered by many petrologists as one of the ideal places to study the petrogenesis of spilitic rocks for two reasons:

1. The spilitic-keratophyre suite in this area occurs as subaerial extrusives or sill-like intrusives, associated with detrital sediments. The established epicontinental or even continental environment excludes the possibility of an interaction of the volcanic material with sea water.

2. The spilitic rocks in the Glarus area are unaffected or hardly affected by metamorphism. The essential mineral constituents remain fresh, the primary structures and textures well-preserved.

The spilitic moraine material found around Zürich originated from the Glarus lava flows and were carried down by the Linth Glacier in the last glacial ages. The study of the moraine material therefore serves as a supplement to the

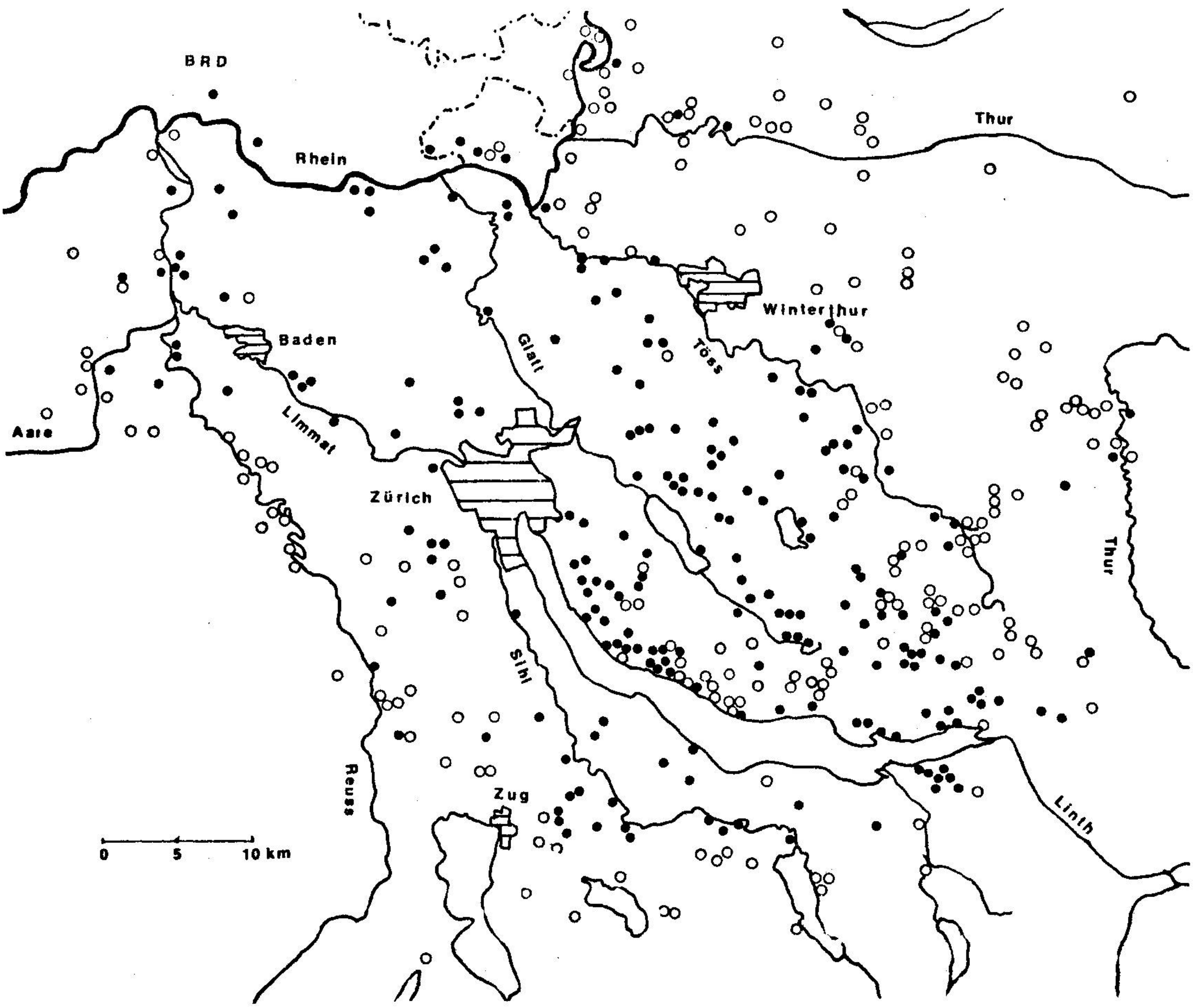

Fig. 1 Map showing the distribution of quarries and other outcrops of moraines sampled. Black dots with Glarus lava material, white without.

study of the Glarus spilites. This paper presents some results obtained from the moraine material, with an attempt to discuss the spilitic problem as a whole.

Since Brongniart introduced the term "spilite" in 1827, a great number of work has appeared in the literature concerning the age, the chemical and mineralogical composition, the fabric and the field occurrences of this rock type. But the problèm of the origin of spilites, primary versus secondary, remains as it was more than one century ago.

As the only typical feldspar in spilites, albite makes up more than 50% of the total rock volume.

However, the primary nature of this mineral has long been in dispute. We think it would be worthwhile to concentrate our attention on the origin of this problematic mineral, hoping that the results will help to clarify this controversial problem.

The petrogenetical problem of a spilitic flow is to a large extent solved if the primary or secondary nature of its albite can be confirmed. Our knowledge of the plagioclase as a whole and the modern techniques enable us to make accurate measurements of the optical properties, particularly the An-content, and structural state of any plagioclase in question. These properties, which reflect the physico-chemical condition at the time of their formation, make it possible to reconstruct their initial mode of occurrence. The data presented in this paper are mostly obtained from universal stage measurements, combined with microprobe analyses and x-ray powder diffraction techniques.

F. KARL (1954) and T.G. VALLANCE (1960) pointed out that «the replacement of originally high-temperature more calcic feldspar by albite shows no indication of an inversion first to a low-temperature analogue of the primary calcic feldspar; low-albite replaces directly the earlier high feldspar with no observable intermediate steps".

In the spilitic rocks found in the studied area, albite is the only feldspar present (with exception of rare occurrences of adularia in some veinlets and amygdules), no relicts of more calcic plagioclase have been detected. If the albites are of a secondary origin, as formed by pseudomorphic replacement of originally more calcic plagioclase, it would be justifiable to presume that both the phenocrysts and matrix albites, after such a thorough replacement, are equally affected and should have identical An-contents and the same low structural states. Inversely if they are primary, it would be reasonable to expect some differences in An-contents and structural states between the phenocrysts and matrix albites.

A. NOWAKOWSKI (1976) proposed a method to distinguish secondary albites from primary albites by means of the angle on the pericline twinnings. This method is also employed in our investigation.

All the data obtained in the present study favor a primary origin of the albites, and consequently a primary origin for these spilitic rocks.

Description of spilitic and keratophyric rocks

Spilitic and keratophyric rocks found in the moraines are essentially the same as those of the outcrops. They include spilites, albitites and quartz keratophyres. Rhyolitic ignimbrites are omitted in the discussion though they are occasionally found in the moraines and in the younger horizons of the outcrops. Since the mode of occurrence of the rocks involved is the main concern of this paper the nomenclature should not include the genetic aspect of the rocks. The names adapted here only refer to the respective chemical, mineralogical and fabric features.

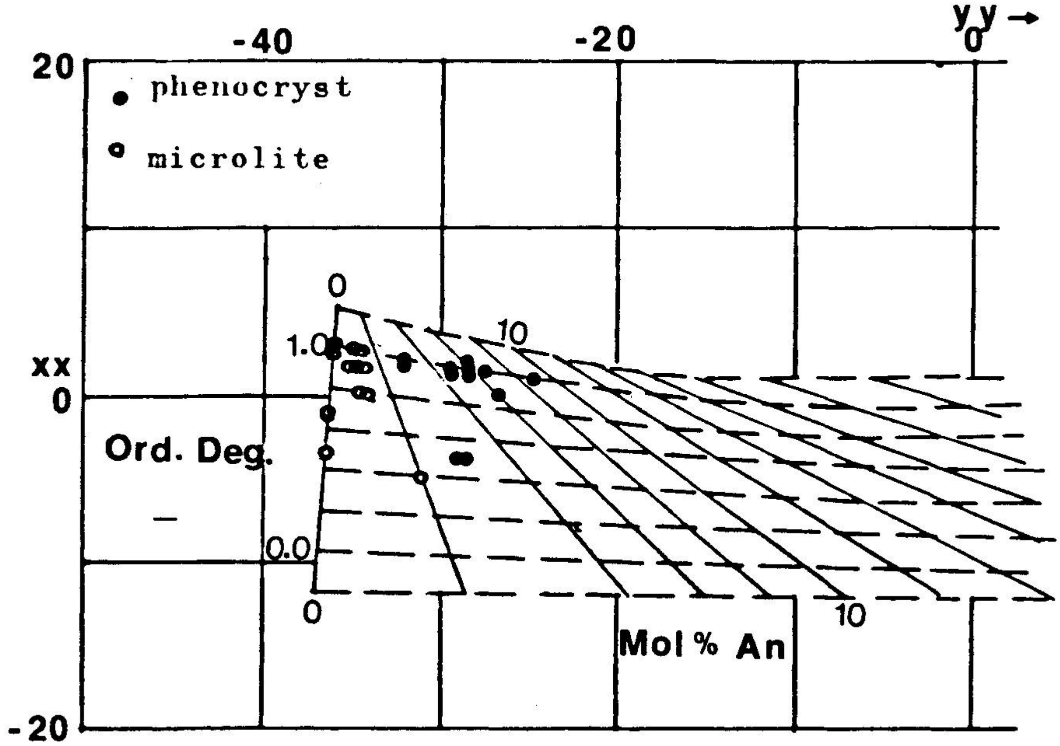

Fig. 2 The σ angle variation of rhombic section (RS) and of pericline composition plane (PCP) with An-content and structural state of plagioclase series (after A. NOWAKOWSKI, 1976).
O. D. - curves showing variation of σ - RS of highly ordered (O) and disordered (D) plagioclases.
P - curve showing variation of σ - RS in plutonic plagioclases.
V - curve presenting variation of σ - PCP in structurally intermediate plagioclase.

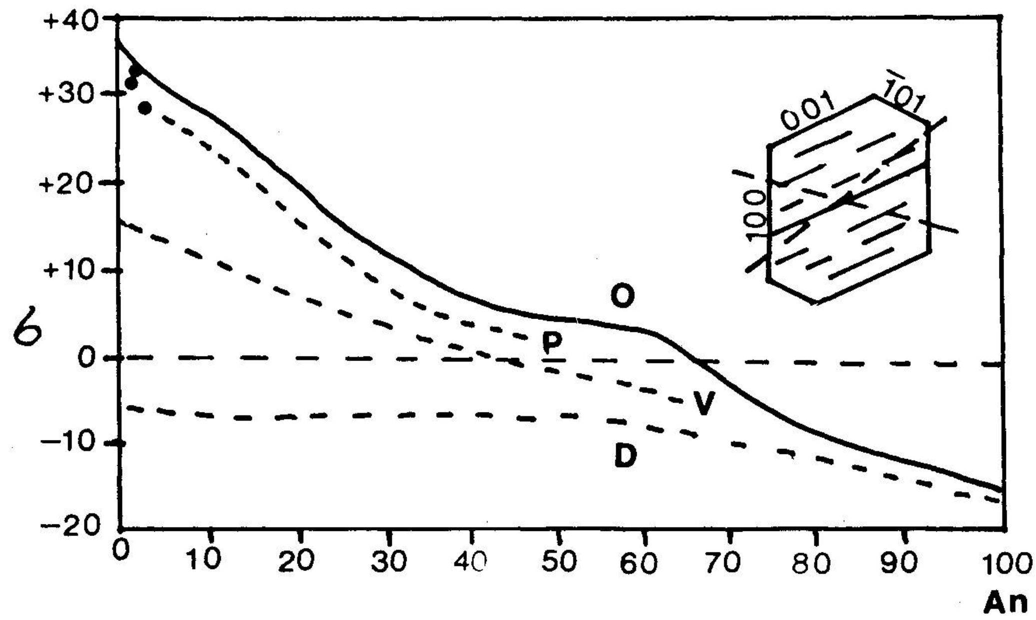

Fig. 2a An-contents and ordering degrees of phenocryst and matrix albites (diagram after K. URONO, 1963).

Hematite spilites and chlorite spilites

The rocks designated here as spilites are basaltic in composition with albite as one of the main constituents and colour index normally ranging from 30 to 50. They are fine-grained amygdaloidal to massive, usually non-schistose purplish red or grayish green in colour. Two or more generations of albites can usually be distinguished. Albite phenocrysts and albites in the matrix form idiomorphic prismatic and usually inclusion-free crystals, well-developed fluidal texture is ubiquitous, albite crystals are often bent and show undulatory extinction and tattered ends (Fig. 3 and 4).

Two main types of spilites can be distinguished, namely the hematite-spilites and the chlorite-spilites, depending on which mafic constituent predominates, gradation between the two are often observed. Other minerals frequently occuring in spilites are diopsidic augite (Ny = 1.685 ± 0.005. $2V_Z$ = 48°–59°), pseudomorphs of olivines (?), calcite and epidotes, accessory minerals are sphene, leucoxene, mica and very rarely zircon.

Amygdules are filled with chlorite, pure albite, quartz, calcite, epidote and sometimes sphene. In some rare cases, amygdules are rimmed with crystals of adularia.

In two specimens, hematite-spilites are seen in direct contact with a leucocratic granite, the fluidal texture and the prismatic crystals of albites of the former are oriented parallel to the contact, the plagioclase and microcline in granite are fresh and show no trace of albitization (Fig. 5).

Fig. 3 Hematite spilite. Lath-shaped albites embedded in matrix with fine dispersion of hematite. Albite crystals often bent and oriented in fluidal texture. (lenght of base line, L = 3.27 mm, without analyser)

Fig. 4 Chlorite spilite. Euhedral albites with intersertal chlorite and opaques. (L = 3.27 mm, without analyser)

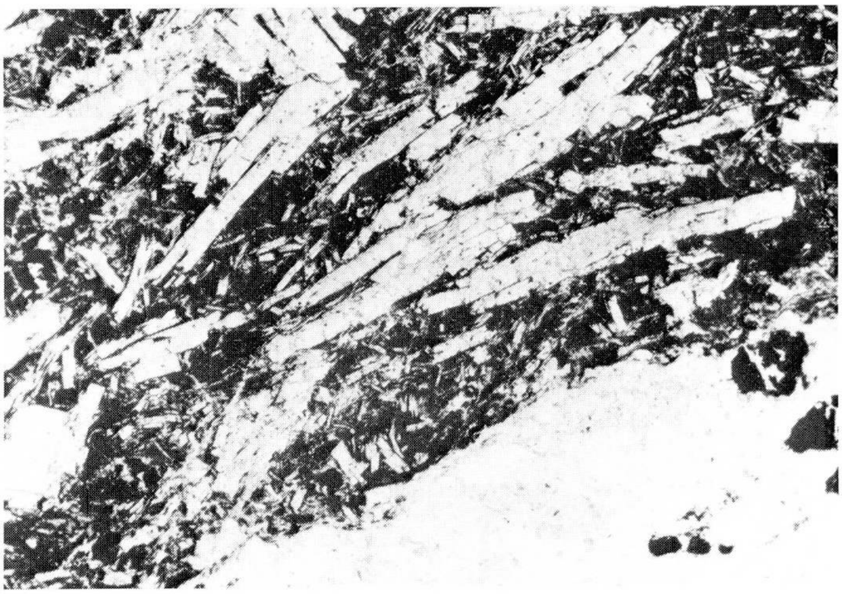

Fig. 5 Intrusive contact of hematite spilite and leucocratic granite (lower right). Albites in spilite oriented parallel to the contact, granite remains fresh and unaltered.
(L = 3.27 mm, without analyser)

Albitites (albite rich spilites)

This is a fine-grained rock variety intimately associated with spilites, it has albites as the only main constituent, other minerals as found in spilites are also present, but only in minor amounts (Fig. 6). Albitites and normal spilites have nearly the same structural and textural features, with the former rock type being

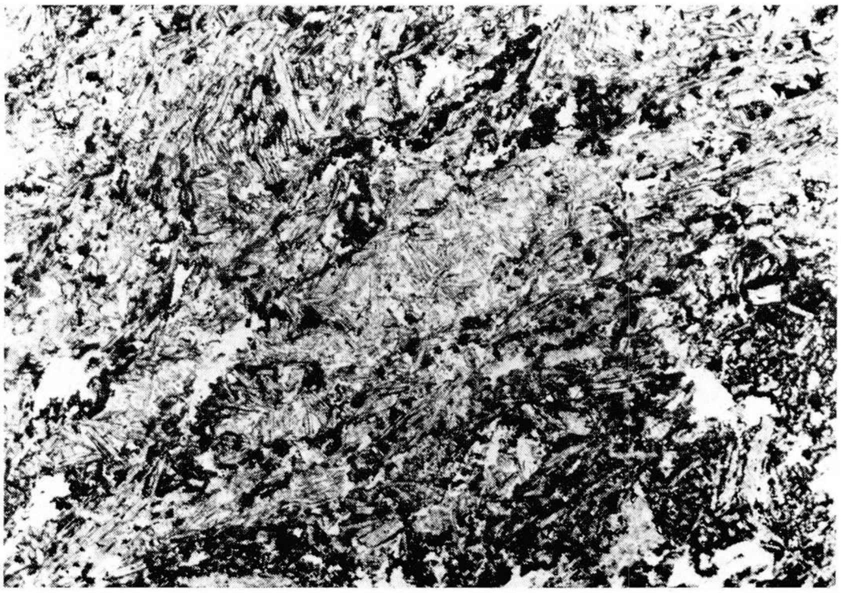

Fig. 6 Albitite. Albites and hematites in intersertal texture.
(L = 3.27 mm, without analyser)

more uniform in grain size. Gradation between the two and blebs or veinlets of one type in the other are frequently observed (Fig. 9). Liquid immiscibility of iron-rich and iron-poor phases in the magma probably accounts for this phenomenon.

An albitite with two distinct generations of albites is found in the moraines as well as in the outcrops. The first generation albites form clean tabular crystals with well-developed twinnings. The second generation has irregular out-

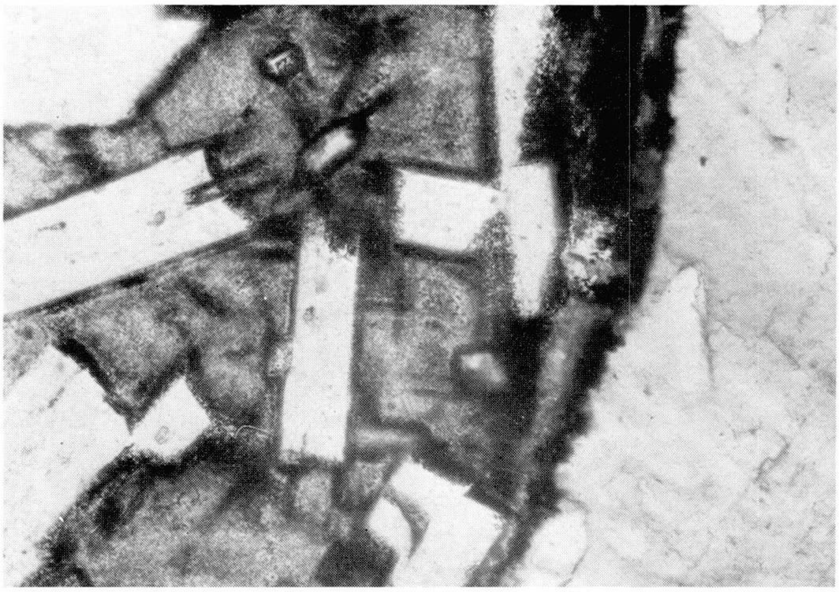

Fig. 7 1st generation albite forms euhedral tabular crystals, the interspaces are filled by 2nd generation anhedral albites.
L = 1.30 mm, without analyser)

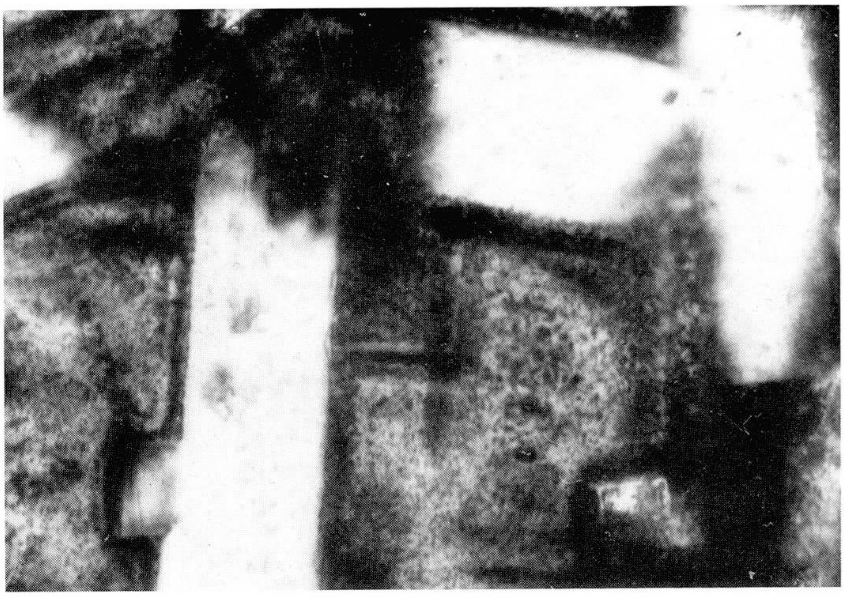

Fig. 8 Same as Fig. 7 under higher magnification, showing the hematite inclusions in 2^{nd} generation albite mostly concentrated along the margins. (L = 0.50 mm, without analyser)

lines filling the interspaces of the first generation crystals and usually exhibits no twinnings. The second generation albites are always choked with hematite dust; these tiny inclusions are mostly concentrated along the margins, parallel to the crystal edges of the first generation albites (Fig. 7 and 8).

Quartz keratophyres and keratophyres

These are rock types on which petrographers also disagree regarding the definition, as in the case of spilites. In this paper we designate the quartz keratophyre as a "leucocratic sodic felsic quartz-albite-phyric or albite-phyric volcanic rock" and keratophyre as a "leucocratic sodic intermediate albite-phyric volcanic rock" as proposed by L.J.G. SCHERMERHORN (1973).

This type of rocks is usually massive, light grey in colour, texturally porphyritic or glomerophyric with felsitic matrix. The phenocrysts are albite and quartz (only albite in keratophyre). Albite phenocrysts are tubular, while quartz phenocrysts if present, are usually rounded due to corrosion. Chlorites and micas often occur in minor amount in the matrix, other accessory minerals are sphene, leucoxene, apatite, zircon and opaque minerals (Fig. 13 and 14).

Pyroclastic rocks

It is worthwhile to point out that two thin layers of pyroclastic rocks were found interlayering with hematite-spilite on the outcrops in the Glarus area (in both, the Central Freiberg and the Gulderstock area). One of which is a scoria-

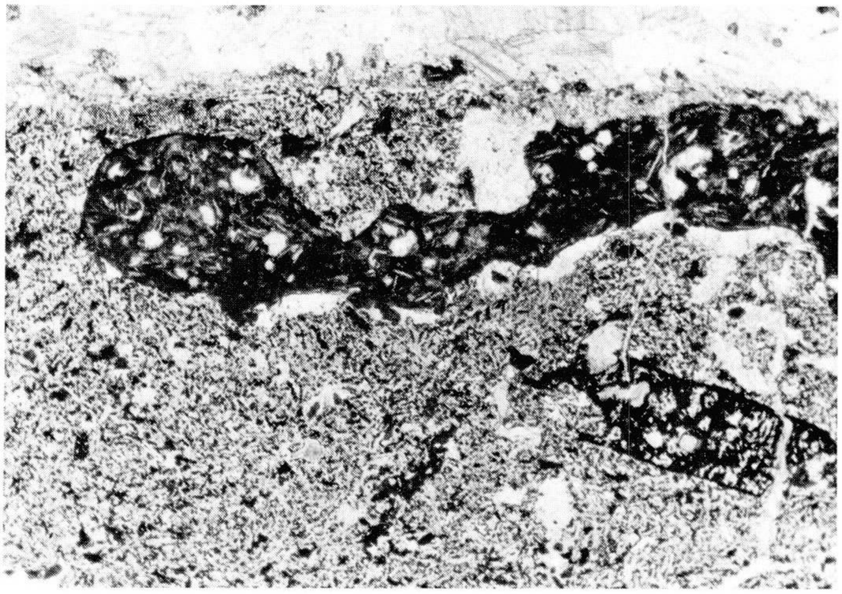

Fig. 9 Schlieren and veinlets of hematite spilite in albitite.
(L = 3.27 mm, without analyser)

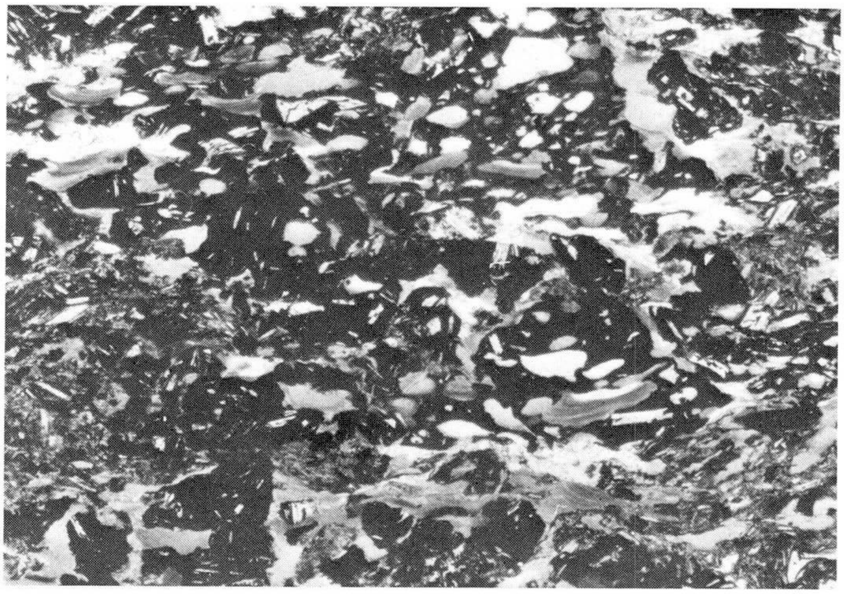

Fig. 10 Spilitic tuff. Composed mainly of hematite, crystallites of albite and devitrified glass shards.
(L = 3.27 mm, without analyser)

ceous spilitic tuff with devitrified glass shards. The essential constituents are hematite, albite, and quartz (minute grains filling vesicles, Fig. 10). The other layer of pyroclastic rock is a tuff of intermediate to acidic composition with crystal fragments of anorthoclase and quartz embedded in a matrix of devitrified glass shards and dust of hematite. Anorthoclase fragments show well developed cross-hatched twinnings (Fig. 11 and 12).

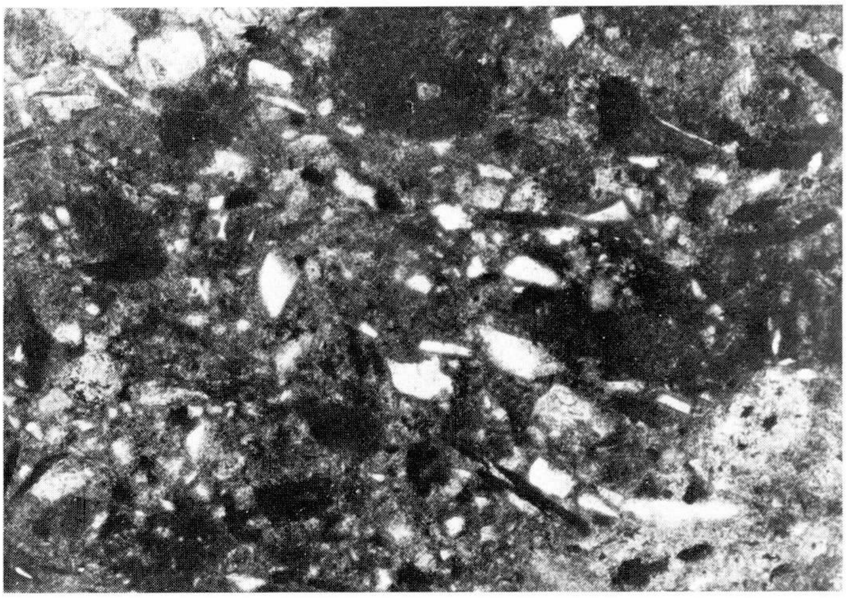

Fig. 11 Tuff. Crystal fragments of quartz, anorthoclase, decomposed mafic minerals and devitrified glass shards embedded in dusts of hematite and felsitic minerals. (L = 3.27 mm, without analyser)

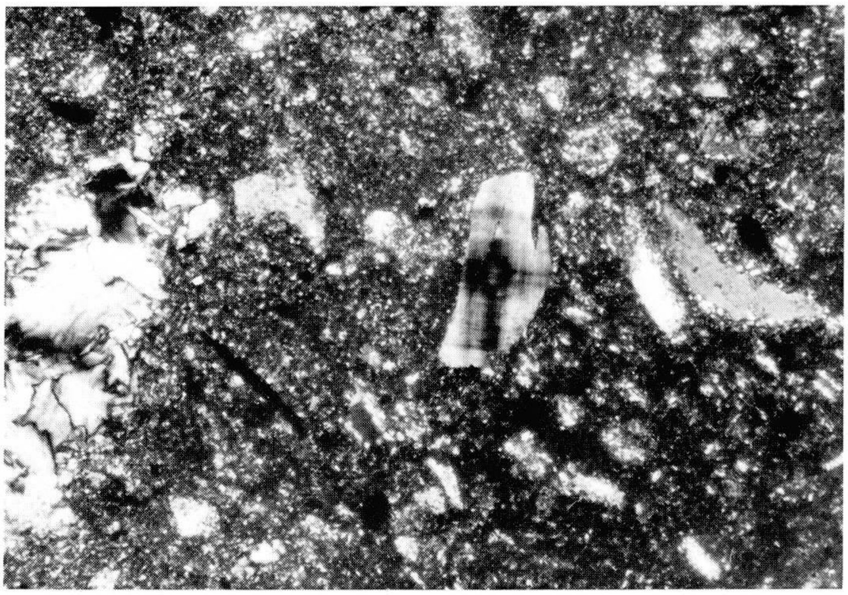

Fig. 12 Same as Fig. 11 under higher magnification, showing cross-hatched twinnings in anorthoclase fragments. (L = 1.30 mm, with analyser)

Other spilitic rocks

Another type of spilitic rocks were found in the moraines, which closely resembles the rocks described by VUAGNAT (1946) from the Hörnli of Arosa. These must have come down with the Rhein-Glacier and will be described later. These rocks desplay a distinct arborescent texture typical for "Arosa spilites" from the Hörnli area, whereas such textures are conspicuously absent in the Glarus spilites.

Fig. 13 Keratophyre. Phenocrysts of albite showing normal twinning, embedded in a felsitic matrix. Inclusion zoning is also seen.
(L = 3.27 mm, with analyser)

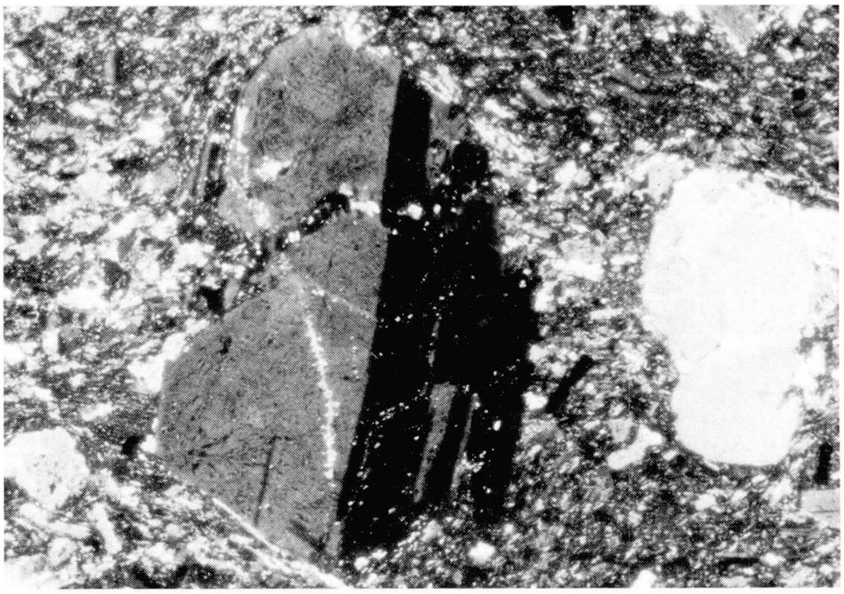

Fig. 14 Quartz keratophyre. Phenocrysts of albite and corroded quartz embedded in a felsitic matrix.
(L = 3.27 mm, with analyser)

The characteristics of the albites

Three generations of albites were recognized in most of the samples investigated. The first generation is represented by the phenocryst albites. These are either clean or contain inclusions of chlorite and/or opaque dusts. In some thin sections weak normal zonation or zoned inclusions were observed in the phenocrysts (Fig. 13), but compositional variations between outer and inner zones of

Fig. 15 Albite phenocryst in hematite spilite showing Baveno twinning.
(L = 1.30 mm, with analyser)

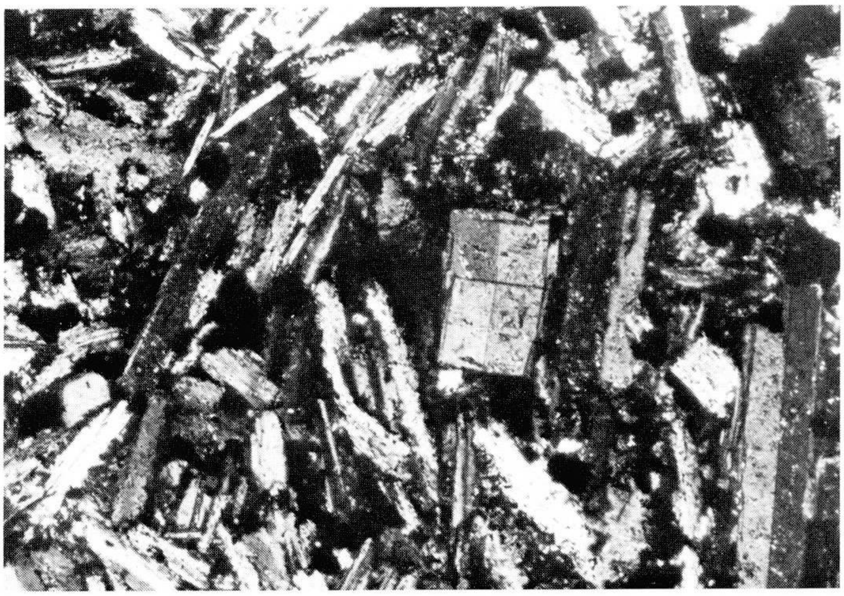

Fig. 16 Albite phenocryst in hematite spilite showing combination of Albite and Ala-A twinning laws.
(L = 1.30 mm, with analyser)

the crystal were indetectable. Complex and rare twinning laws on the phenocrysts is another marked feature. In addition to albite, Carlsbad, Roc Tourné, other twinning laws as Manebach, baveno, pericline, Ala-A and complex twinnings such as Manebach-Ala, Manebach-acline etc. are frequently observed. The second generation of albites are those which constitute the major part of the matrix. In spilites and in most of the albitites, this generation of albites form euhedral microlites of prismatic shape, while in quartz keratohyres (kerato-

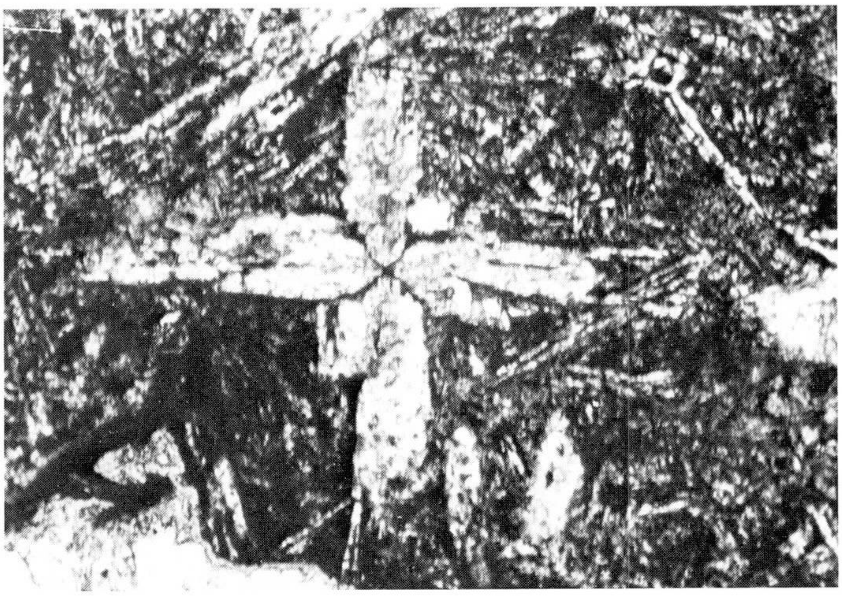

Fig. 17 Albite phenocryst in albitite showing «Banater intergrowth» (Baveno twinning).
(L = 1.30 mm, with analyser)

phyres) and in some varieties of albitites, they possess no crystal outline. Albite, Carlsbad and Roc Tourné are the only twinning laws observed, the lamellae are often very fine. Tiny inclusions of chlorite flakes sometimes occur.

The third generation albites are euhedral to anhedral crystals together with other minerals filling amygdules. The crystals are always free from inclusions. Albite twinning law predominates, while Roc Tourné has also been observed. The twin lamellae are much broader than those of the second generation.

All three generations of albites were separately measured on the universal stage. The An-contents and structural states were obtained by plotting the re-

Table I An-contents, ordering degree and optical properties of phenocryst and matrix albites (note that albitites are differentiation products of normal spilites - compare AMSTUTZ, 1974, p. 1-5).

No. of samples	rock types	phenocrysts			microlites		
		An (mol. %)	ord. deg.	$2V_z°$	An (mol. %)	ord. deg.	$2V_z°$
913	spilite	6	1	82	1	0.9	92
250	spilite	6.5	1	87	1	0.8	93
834	spilite	3	1	86	1	0.8	91
847	spilite	5	1	85	0	0.7	96
898	spilite	3	0.5	110	2	0.4	113
823	albitite	3	0.5	115	0	0.5	116
X	albitite	5	1	86	1	1	—
4	albitite	6	1	79	0	1	82
11	albitite	3	1	86	1	0.9	96
322	albitite	9	1	90	1	1	85
726	albitite	6	1	86	0	1	83
885	keratophyre	6	0.9	93	1	0.9	82.5

sults on SLEMMONS (1962) and K. URUNO'S (1963) curves, optic angles were directly measured from the universal stage. Some refractive indices of albite phenocrysts were measured with immersion oil method also to serve as a check-up (Table I). The third generation albites are nearly pure albites with low structural state, and is omitted from the table for simplicity.

The results listed in Table I show distinctive differences in the An-contents and degrees of (Al, Si) ordering between phenocrysts and matrix albites. The An-contents of phenocrysts range from 3 to 9, where in the matrix albites, they range from 0 to 2. The structural states of phenocrysts are low, while that of the matrix albites are low to low-intermediate. Two exceptions are noteworthy: both the phenocrysts and matrix albites of samples 868 and 823 correspond to intermediate to high-intermediate structural states. This feature suggests that it is very unlikely for the albites here to have undergone metamorphism, nor were they formed by alteration. The differences mentioned above indicate that the phenocrysts and matrix albite have followed a crystallization trend of normal extrusive rocks.

A method has been proposed by A. NOWAKOWSKI (1976) for the determination of the primary plagioclase composition. His method is based on the position of the relict pericline composition plane in albite, taking into account the (Al, Si)-ordering state in plagioclase of volcanic and plutonic rocks.

The pericline composition plane (PCP) in plagioclase is an irrational plane of [010] zone, the position of which depends on the An-content, the σ angle is used to characterize this position. An originally more calcic plagioclase will retain its original σ angle after being replaced by albite. Hence the primary nature of an albite in question can be checked the other way round, that is, when the PCP coincides with the position of the theoretical rhombic section (RS). According to the studies of NOWAKOWSKI, albites with σ_{PCP} values rangig from 29° to 37°, which are close to the theoretically established σ_{RS} angle in the ordered albite, are primary.

Three albite phenocrysts with measurable σ angles were examined. The σ values observed range from 29° to 33,5°, (Fig. 3). All three crystals are highly ordered. They fell well within the albite field on the curve for plutonic plagioclase (Fig. 2). This result further enhanced the primary nature of the albites.

Conclusions

From the above investigation the following conclusions can be reached:

1. The spilitic-keratophyric rock types found in the moraines around Zürich are in most respects similar to those found in the Glarus outcrops. Apparently they were originally part of the Glarus lava flows. (The "Arosa spilites" are not considered here.)

2. Three generations of albites were observed in the spilitic-keratophyric rocks. The phenocrysts, i.e., the first generation, have the highest An-content and a low structural state. The matrix albites, i.e., the second generation, have lower An-content but the highest structural state; the amygdule-filling albites, i.e., the third generation, have the lowest An-content and the lowest structural state. These differences imply that at least the first two generations of albites must have been crystallized earlier under a relatively stable condition, as in the case of an ordinary extrusive rock.

3. The σ angles measured on the (010)-pinacoid between the traces of the pericline composition plane and the cleavage (001) further confirmed the primary nature of the phenocryst albites.

4. A granite intruded by hematite-spilite without showing signs of alteration indicates lack of albitization in spilites.

5. The existence of an anorthoclase-containing pyroclastic layer between Verrucano and hematite spilite implies a primary origin of both, the pyroclastic rock and the hematite spilite.

6. The relation between hematite-spilites and albitites is an interesting feature, which suggests that liquid immiscibility of a "feldspar-rich" phase and a "hematite-rich" phase might have played a significant role in the formation of these rocks. As pointed out also from many other spilite provinces by AMSTUTZ (1974), albitites within spilites are merely one type of differentiation products.

7. Similar conclusions, although on the basis of somewhat different approaches, were reached by other workers, e.g. BENSON (1915), BESKOW (1929), DEWEY and FLETT (1911), LEHMANN (1941), NIGGLI, P. (1952), NIGGLI, E. (1941), SUNDIUS (1930), ZAVARITSKY (1960).

In the spilitic province of the Glarus area a "unique set of causes" did exist for the spilitic rocks since all the evidences favor a primary origin.

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