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PERTHITES

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ABSTRACT

No one theory of the origin of perthitic feldspars is adequate because there are several processes capable of forming these intergrowths. There are processes obtaining under magmatic conditions which produce perthites by several kinds of exsolution. Other perthites are formed by deuteric solutions, others by pneumatolytic agents, still others by hydrothermal mineralization. There may be perthites formed by cold waters under vein conditions.

Andersen's suggestion that the anisotropic coefficient of contraction produces cooling and cleavage cracks which furnish both the orientation and the space for perthitic blebs is very plausible.

Vogt's 1926 thermal diagrams are discussed. His diagram showing a series of solid solutions with a minimum with inclined solubility curves, even though it does not show polymorphism, is as satisfactory as any.

A classification of perthities is offered in a temperature basis, using terms of Mäkinen and Andersen. The nomenclature of perthites is outlined with suggestions for a more specific terminology.

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INTRODUCTION

For the purpose of presenting the status of the origin of various perthites to my students in petrology, I summarized the ideas I have previously offered, together with the recent opinions of Mäkinen,[1] Vogt,[2] Andersen,[3] and Spencer.[4]

As this attempt apparently makes these problems easier to visualize, I have assumed that others would like to have it in available form, and therefore I am presenting it in this paper.

PERTHITES OF MANY ORIGINS

A study of the literature clearly shows that many perthites are secondary in origin; albitic blebs are believed to have been introduced from without[5] by later mineralization and replacement, Colony[6] even suggesting "injection perthite." There has been a decided trend of thought in this direction for some time. It is natural that some should favor lower temperatures and secondary processes for the formation of all perthites. There is, however, abundant evidence that some intergrown feldspars are high temperature phenomena. The term "secondary" is such an unsatisfactory one, that I shall try to get along without using it.

Andersen[7] recognizes a number of different textural characteristics of perthitic blebs, which I will discuss later, some of which he believes are due to exsolution.[8] As exsolution is a relatively high temperature phenomenon, I shall begin by discussing perthites of magmatic origin.

MAGMATIC PERTHITES

The most satisfactory way to grasp the process called exsolution is by the use of thermal diagrams. As a matter of fact, we do not

[1] Mäkinen, E., Über die Alkalifeldspate: *Geol. Fören. Förhandl.*, vol. **XXXIX,** 1917, pp. 121–184.

[2] Vogt, J. H. L., *Norsk. Videnskaps Akademi, Oslo. Mat. Naturivid,* No. **4,** 1926, pp. 87–101.

[3] Andersen, Olaf, The Genesis of Some Types of Feldspar from Granite Pegmatites: *Norsk. Geol. tidsskrift,* B. **X,** h. 1–2, 1928, pp. 116–205.

[4] Spencer, Edmondson, A Contribution to the Study of Moonstone from Ceylon and Other Areas and the Stability-Relations of the Alkali Feldspars: *Min. Mag.,* vol. **XXII,** 1930, pp. 291–365.

[5] Wenglein, O., *Aug. Diss.,* Kiel, **1903.** Warren, C. H., *Am. Acad. Arts & Sci.,* vol. **LI,** 1915, p. 143.

[6] Colony, R. J., The Final Consolidation Phenomena in the Crystallization of Igneous Rocks: *Jour. Geol.,* vol. **XXXI,** 1923, pp. 170–171.

[7] *Op. cit.*

[8] Alling, H. L., *Jour. Geol.,* vol. **XXIX,** 1921, p. 222. Especially the footnote.

possess an accurate one. There are many obstacles in getting what is much desired. However, there are many theoretical diagrams, nine of which I have reproduced in Fig. 1. I shall not attempt a thorough discussion of these as this has been done before, but will merely outline the opinions offered by Vogt and Spencer in their recent papers.

Vogt[9] believes that the potash-soda feldspars belong to type III (with a minimum[10]) or type V (with eutectic). However, in 1905[11] he drew the eutectic gap much too large as he himself states in 1926. Mäkinen[12] made the miscibility gap cover about 10 percent (by weight) which is "greatly exaggerated," meaning, if I have interpreted him correctly, that his conception of the diagram is a eutectiferous one closely approaching type III. With this clue, Vogt[13] offers diagrams, which I have copied as Fig. 1, E and F, showing in reality how type V, as he conceives it, closely resembles type III.

Ussing[14] and Beljankin[15] have objected to Vogt's original diagram as not quantitatively accurate. This comment applies with almost equal force to all the others as well.

Now it is significant that Vogt's early diagram with a wide miscibility (eutectic) gap was based upon granitic, and hence plutonic feldspars, which Mäkinen recognizes as having a broader compositional range than pegmatitic feldspars. I attempted to explain this difference in range through undercooling, a phenomen which Bowen,[16] in his discussion of the feldspar diagram, does not mention. Elsewhere he states that "a detailed study of the effects of viscosity and under-cooling . . . would be of some interest to the petrologist . . . Undercooling must be regarded as an unimportant

[9] Vogt, J. H. L., *Norsk Videnskaps Akademi, Oslo. Mat. Naturivid*, No. **4,** 1926, pp. 87–101.

[10] See Dittler, E., *Tscherm. Min. Petro. Mitt.*, vol. **XXIX** (1910), and **XXI** (1912), p. 513.

[11] Vogt, J. H L., *Tscherm. Min. Petro. Mitt.*, vol. **XXIV** (1905), pp. 437–543.

[12] Mäkinen, E., Über die Alkalifeldspäte: *Geol. Fören Förhandl.*, vol. **XXXIX,** 1917, pp. 121–184.

[13] Vogt, J. H. L., *Norsk Videnskaps Akademi, Oslo, I, Mat. Naturivid Klasse,* 1926, No. **4,** fig. 15, a and b, p. 88.

[14] Ussing, N. V., Geology of the Country around Julianehaab: *Meddelelser om Grönland,* **38,** 148, 1911.

[15] Beljankin, D., Ausscheidungsfolge der Feldspäthe in den Granitgesteinen: *Ann. Inst. Polytechn. Pierre le Grand à Petrograde,* **22,** 1914, pp. 259–277.

[16] Bowen, N. L., *Evolution of the Igneous Rocks,* Princeton, **1928,** pp. 227–231.

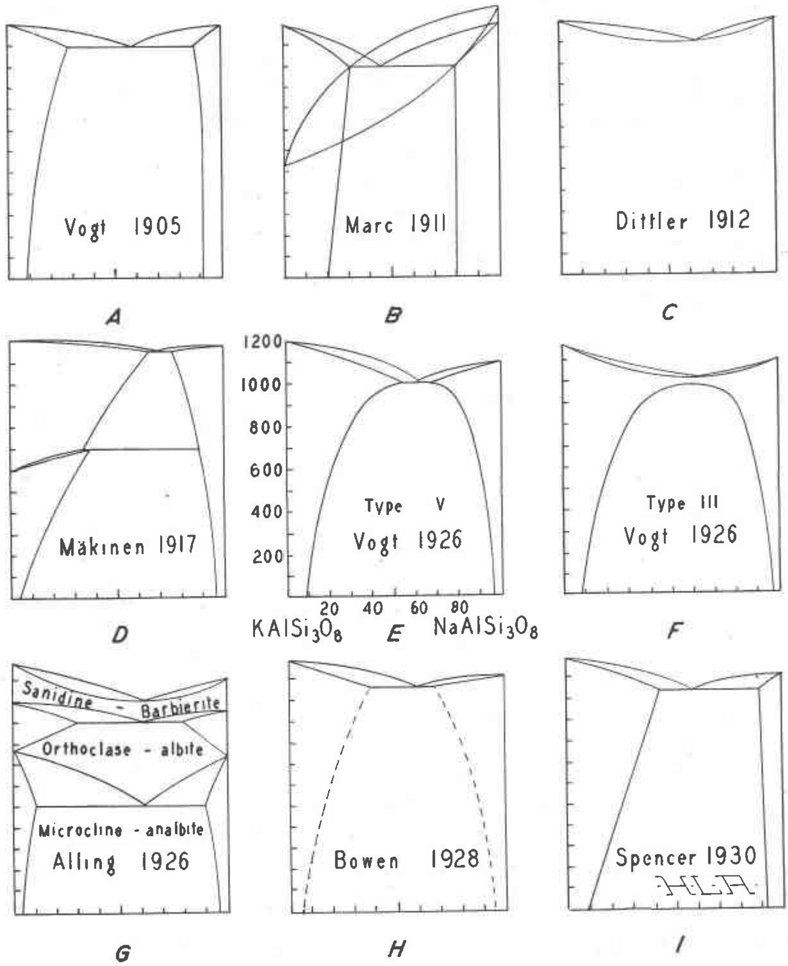

FIG. 1. A collection of thermal diagrams of the potash-soda feldspars showing the diversity of opinion. They have been drawn to the same scale.

A. Vogt, J. H. L., *Tscherm. Min. Petro. Mitt.*, vol. **XXIV**, 1905, p. 437.

B. Marc, Robert, Chemische Gleichgewischtslehre, **1911**, p. 102. The diagram was scaled off on the basis of 1200° C. for the incongruent melting point of potash feldspar and 0° C. for the base. Hence the temperature scale is only approximate.

C. Dittler, E., *Tscherm. Min. Petro. Mitt.*, vol. **XXXI**, 1912, p. 513.

D. Mäkinen, E., *Geol. Fören. Förhandl.*, vol. **XXXIX**, No. 2, 1917, pp. 121–184.

E. & F. Vogt, J. H. L., *Norsk. Videnskaps Akademi, Oslo, I Mat. Naturvid*, No. 4, pp. 88–91, 1926.

G. Alling, H. L., *Jour. Geol.*, vol. **XXXIV**, 1926, pp. 591–611. Suggested by data of Kôzu and Saiki.

H. Bowen, N. L., The Evolution of the Igneous Rocks, **1928**, p. 228. "As the relations are ordinarily assumed to be." I have added the solubility curves.

I. Spencer, Edmondson, *Min. Mag.*, vol. **XXII**, 1930, p. 327. Modification of Vogt's and Warren's diagram to explain the crypto- and microperthites, moonstones of Ceylon.

consideration . . . because . . . colossal masses of magma have been subjected to cooling at a rate which *precludes* undercooling."[17] (My italics.) In Fig. II, I have reproduced Spencer's diagram, which is Vogt's early one, modified to fit the moonstones of Ceylon. It seems unfortunate that Spencer did not use Vogt's 1926 diagram, type III, which in many ways, even though it does not show polymorphism, is as satisfactory as any offered up to the present.

The theory of simultaneous crystallization of blebs and host in forming perthites implies, although not necessarily, eutectic relations. It is perhaps natural to seek comparisons in the field of metallography. Metallic alloys unquestionably exhibit many textures that are due to simultaneous crystallization. Metallic intergrowths of this origin are usually not orientated in contrast to many perthites. Desch[18] contrasts metallic and silicate melts in respect to the dominance of eutectics. In alloys they are very important. They appear to be much less common in igneous rocks. He suggests the following differences:

Table I

Differences between:

	Metallic Alloys	Silicate Rocks
1.	Slightly associated	Highly associated
2.	Low viscosity	High viscosity
3.	Ease of diffusion	Diffusion very slow
4.	Undercool slightly	Undercool easily
5.	Many eutectics	More solid solutions
6.	Eutectic textures	Eutectic systems may not show textures
7.	Dominant eutectic textures	Some fine grained aggregates equivalent to eutectic textures

[17] Bowen, N. L., The Physical Chemistry of Igneous Rock Formation: *Trans. Faraday Soc.*, No. 60, vol. **XX**, 1925. The Reaction Principle, p. 478.

[18] Desch, C. H., The Theory of Crystallization in Rock Magmas: *Trans. Faraday Soc.*, No. 60, vol. **XX**, 1925, pp. 469–473.

These characteristics, outlined by a metallographer, and hence perhaps more significant, show how cautious the petrologist must be in judging origins of textures on mere appearances.

Eutectic Perthites

If perthites are due to eutectic relations it calls for type V which is the type of diagram nearly all of the investigators suggest. But if the relations are characterized by type III after Fig. 1-F, then such intergrowths are not eutectic.

If a parallel from metallic alloy eutectics is made, the lack of orientation of the blebs and spindles suggests that perthites are not eutectics because the latter are usually orientated. But there is this further difference between metallic and silicate alloys; many commercial metals possess cubical symmetry and hence their thermal expansion is the same in all directions. The thermal expansion of feldspars on the other hand, as their monoclinic and triclinic habit implies, differ along crystallographic axes. Internal strains in a cooling feldspathic crystal cause contraction cracks to develop, furnishing both a place and an orientation for eutectic melts.

It is conceivable, of course, that there are eutectic perthites. Intergrowths of quartz and feldspar in graphic granite and in myrmekite[19] have been interpreted as eutectic textures by some[20] and denied by others.[21] If eutectics why not perthite? I have not satisfied myself that there are true eutectic perthites.

Eutectoid Perthites

Let us investigate the possibility of eutectoid relations. Perhaps the term needs a word in explanation. Binary eutectics mark a change in solubility with falling temperature from a mutual liquid solution to a two phase system where the phases are solids with limited solubility towards each other. Similarly, binary eutectoids are produced from a mutual solid crystalline solution consisting of a single phase into a system composed of two solid phases.

There has been an equilibrium diagram of the potash-soda feldspar system published that shows eutectoid relations.[22] Such a dia-

[19] Sederholm, J. J., *Bull. de la Comm. Geol. de Findlande*, No. 48, **1916.**

[20] Harker, Alfred, The Natural History of Igneous Rocks, **1909,** pp. 270–272.

[21] Schaller, W. T., The Genesis of Lithium Pegmatites: *Am. Jour. Sci.*, (V) **1925,** pp. 269–279.

[22] Alling, H. L., *Jour. Geol.*, vol. **XXXIV,** 1926, p. 602, fig. 2; p. 607, fig. 5,

gram, by the nature of the case, is hypothetical. Such devices to explain perthites presuppose polymorphism of either one or both of the end members of the system under discussion. Polymorphism of orthoclase and albite is a working theory not proved nor universally acceptable.[23] Nevertheless, if granted, then eutectoid perthites are not only possible but probable. The orientation of the blebs, controlled by cooling and cleavage cracks, seems highly plausible. I am inclined to believe that many actual specimens of perthite which I have seen are perhaps better explained as eutectoid textures rather than eutectic intergrowths. Such specimens are not pegmatitic feldspars. And it is well to insist, for the sake of rigorous thinking, that different perthites in different petrological "habitats" presumably have different origins.

Exsolution Perthites Due to Polymorphism

Again polymorphism is assumed. The inversion point marks a decrease in solubility of one solid solution for another. Such a condition is pictured by Warren,[24] and Harker.[25] Such a conception is, I believe, a reasonable one and may account for some perthites. However, this theory of exsolution due to polymorphism should be distinguished from other theories involving exsolution. See Fig. 1-G.

Exsolution Perthites Due to Inclined Solubility Curves

The usual concept conveyed by the term exsolution is that process of crystal separation by decrease in solubility with falling temperature, as is indicated by inclined solubility curves in a thermal diagram. Such a theory is dependent upon phase rule diagrams but is independent of polymorphism. Hence if potash feldspar is monomorphic, as it may be, then some perthites are due to separation because of decrease in solubility with falling temperature. This is a process I have suggested for many feldspars[26] but not for all. In this respect Megathlin[27] is mistaken in thinking I would assign all pegmatitic perthites to exsolution when he says: "This relation-

[23] Vogt, J. H. L., *Norsk. Videnskaps Akademi, Oslo, I. Mat. Naturivid,* No. **4,** 1926, p. 13.

[24] Warren, C. H., *Am. Acad. Arts & Sci.*, vol. **L1,** 1915.

[25] Harker, Alfred, The Natural History of Igneous Rocks, **1909,** p. 256.

[26] Alling, H. L., *Jour. Geol.*, vol. **XXIX,** 1921, p. 222. Especially the footnote.

[27] Megathlin, G. R., The Pegmatite Dikes of the Gilsum Area, N.H.: *Econ. Geol.*, vol. **XXIV,** 1929.

ship has been claimed by Alling[28] to be due to exsolution and not to replacement." Megathlin refers to my early paper.[29] There he will find I am discussing the theory of exsolution with the aid of Warren's[30] diagram and applying it to the feldspar described by Smyth[31] as occurring in a *plutonic* igneous rock and not to a pegmatite. Megathlin will find in a subsequent paper[32] a definite reference to "secondary changes taking place following primary deposition." Here hydrothermal replacement would be cataloged.

It would be well for us to remember that the choice of theories of the genesis of perthite depends upon the geologic "habitate" of the feldspars in question, for I am confident that different processes are responsible for different perthites. To distinguish between these different perthites is often a difficult task.

The Orientation of Blebs

The perthite from its "type" locality[33] was described as follows: "the albite plates are polysynthetically twinned and parallel or approximately parallel to the *a*-axis."[34] Other directions for albitic plates in intergrown feldspar from Perth, Ontario, Canada, are parallel to the (110) face. Since then many other orientations have been noted.

All feldspars have good cleavage-planes, one parallel to (001) and another parallel to (010). Other cleavages are known but less common. Andersen[35] suggests that the maximum expansion, and hence contraction, in alkali feldspars[36] lies in the plane of symmetry

[28] *Op. cit.*

[29] Alling, H. L., *Jour. Geol.*, vol. **XXIX**, p. 222, 1921.

[30] Warren, Charles H., *Proc. Am. Acad. Arts & Sci.*, vol. **LI** (1915), pp. 125–154.

[31] Smyth, C. H., Jr., *Trans. New York Acad. Sci.*, vol. **XII** (1893), p. 204.

[32] Alling, H. L., *Jour. Geol.*, vol. **XXXIV** (1926), p. 593.

[33] Thomsen, **1832,** Shep. Min. (1) 232, "Interlamination of Orthoclase and Albite. First considered a variety of orthoclase."

[34] Rogers, A. F., Observations on the Feldspars: *Jour. Geol.*, vol. **XXI,** 1913, p. 203.

[35] Andersen, Olaf, The Genesis of Some Types of Feldspar from Granite Pegmatites: *Norsk Geologisk tidsskrift*, B. **X,** h. 1–2, 1928, pp. 116–205. See Review by H. L. Alling, *Am. Mineral.*, **14,** 1929, pp. 241–242.

[36] See Schmann, J., Über die Mikroclin und Perthitstructur der Kalifeldspathe und Abhängigkeit von äu Beren. z. Th. mechanischen Einflüssen: *Jahresber. Schles. Ges. Vaterl. Cultur*, vol. **63,** 92–100 and vol. **64,** 119, 1886.

Fizeau, H., Über die Ausdehnung starrer Körper: *Pogg. Ann.*, vol. **135,** 383–390, 1868.

Beckenkamp, J., Über die Ausdehnung monosymmetrischer und assymmetrischer Krystalle durch die Wärme: *Zeit. Kryst.*, **5,** 452–461, 1881.

(assuming these feldspars to be monoclinic), at an angle of 18–20° to (001) and the direction of minimum expansion (and contraction) is usually along the *b*-axis (010). The curves of Kôzu and Saiki[37] show, as earlier investigators have established, that the maximum expansion (and contraction) parallel to (001) is very considerably greater than in other directions. But it must not be inferred that stresses of cooling in natural rocks is sufficiently rapid to exceed the internal strain to produce abundant fractures. The bulk of even extrusive flows is so great, the cooling of a lava is slow,[38] and hence if the cracks are formed they occur in spite of the very gradual fall of temperature. It can, however, be suggested that a more rapid rate of the loss of heat occurs in dikes and pegmatites; the large size crystals of the latter being due to volatile constituents.

Now Andersen[39] assures us that "the direction perpendicular to the axis of maximum expansion coincides with one of the prominent directions of orientation of perthite intergrowths." He furthermore discusses the effect of strains set up not only within feldspar grains by cooling but by being enmeshed with adjacent crystalline masses of quartz in granitic pegmatites, the different behavior of quartz in the matter of coefficient of cubical expansion. The work of Sosman,[40] and Kôzu and Saiki[41] show that the transformation point of $\alpha \rightarrow \beta$ quartz is marked by various directions. Below 575°C. (at one atmospheric pressure) quartz expands in a similar fashion to that experienced by feldspar, but above that temperature the curve flattens out and actually drops showing, on heating, a contraction. Because of the strong adhesion between quartz andfeld-

Offret, A., De la variation, sous l'influence de la chaleur, du indicies de refraction de quelques especes minerales, dans l'etendue du spectre visible: *Bull. Soc. Franc. Min.*, **13,** 614–644, 1890.

Kôzu, S., and Saiki, S., The Thermal Expansion of Alkali Feldspars: *Sci. Rept Tôhoku Imp. Univ.*, Ser. III, vol. II, pp. 203–238, 1925.

Kopp, H., *Liebig's Ann.*, Suppl. 3, 289, **1859.**

Pfaff, F., *Pogg. Ann.*, **107,** 148, 1859.

Von Fedorov, E. S., *Zeitsch. Kryst.*, **28,** 486, 1897.

Joly, J., *Trans. Roy. Soc.*, Dublin, (2) 6, 283, **1897**; 41, 250, **1887.**

[37] *Op. cit.*

[38] See N. L. Bowen, Diffusion in Silicate Melts: *Jour. Geol.*, vol. **XXI,** 308, 1921.

[39] *Op. cit.*, p. 131.

[40] Sosman, R. B., The Properties of Silica: Chem. Cat. Co., N. Y., **1927,** pp. 360–415.

[41] Kôzu, S., and Saiki, S., *Sci. Rept. Tôhoku Imp. Univ.*, Ser. III, **1925,** vol. 2, pp. 203–238.

spar in acid igneous rocks, this peculiarity of quartz, Andersen argues, would stress the feldspar beyond its elastic limit. Now the strength of feldspar is likewise a vector function. I have not at hand any quantitative data but suppose that the planes of cleavage and parting are planes of weakness. As above noted, cleavage is very distinct parallel to the (001)-face and less so parallel to the (010)-face. Parting is often parallel to the (100)-face and sometimes is parallel to a hemi-orthodome and inclined a little to the orthopinacoid.

TABLE II
CLEAVAGES IN POTASH FELDSPAR AND ORIENTATION OF PERTHITIC BLEBS

Face	Face	Cleavage	Expansion	Parting	Blebs
a	(100)		Max. +18–20° from (100)	‖ to (100)	"normal" ‖ or nearly ‖ to (100). Perth, Ont.
b	(010)	‖ to (010) imperfect	Minimum ‖ to (010)		+6.5–6.5° to (010)
c	(001) Basal Pinacoid	‖ to (001) perfect	Mean 6°–8° from (001) ⊥ to (010)		‖ to (001) nearly ⊥ to (010)
m	(110) Prism	‖ to (110) and (1$\bar{1}$0) separation			‖ to (110) "Peculiar"
x and *y*	(110) and (201) Hemiorthodomes			‖ to a hemi-orthodome and inclined to the orthopinacoid	
Δ	(13.0.$\bar{2}$) (320)				‖ to (13.0.$\bar{2}$)[42] (320)[42]

On consulting Table II, giving data compiled from various sources, the reader will note that while there is some relation between the direction of expansions and planes of perthitic blebs, there are enough inconsistancies to weaken the suggestion that

[42] Spencer, Edmondson, *Min. Mag.*, vol. **XXII, 1930**, p. 362.

there is always a direct relation between them. How important this failure is I am unable to judge. But investigation along this line is worthy of continued effort.

Orientation of Blebs where Polymorphism and Eutectoid Relations are Assumed

Andersen[43] shows the thermal expansions of potash and soda feldspars, constructed on data by Kôzu and Saiki[44] for the *a*-, *b*-, and ⊥(001), as smooth curves, which are almost linear. I have pointed out[45] that there are small irregularities or cusps in the curves of these Japanese investigators which Anderson did not seem to recognize. Turning to Kôzu and Saiki's own data,[46] there are critical points, some of which are based upon optical behavior and others upon volumetric changes These data point to cusps in potash rich feldspars at 900°–950°C. and 650°–700°C. Furthermore at 500° perthitic blebs are reported to dissolve on heating and exsolve on cooling.[47] These points may well be due to allotropic (polymorphous) changes, where the relations between the solid phases are eutectoid ones.

If this is granted for the purpose of discussion, we may ask, in what way should Andersen's arguments regarding the origin of cleavage cracks by cooling in these anisotropic materials be altered, when modifications are assumed as occurring with falling temperature? It may be that directions of such cracks may be quite different depending upon the initial temperature from which these feldspars were cooled. We do not have sufficient information to be assured that the maximum and minimum directions are the same order of magnitude for each modification. It is possible that some of the directions taken by perthitic blebs, which are seemingly not explained by Andersen's proposal, can thus be satisfactorily understood.

The rate of cooling, more especially a differential rate, with a slow decrease in temperature followed by a rapid fall, seems to me

[43] Andersen, Olaf, The Genesis of Some Types of Feldspar from Granite Pegmatites: *Norsk. Geologisk tidsskrift*, B. **X**, h. 1–2, 1928, p. 132, fig. 7.

[44] Kôzu, S., and Saiki, S., *Sci. Rept. Tôhoku Imp. Univ., Ser. III*, vol. **II**, No. 3, pp. 203–238, 1925.

[45] Alling, H. L., *Am. Min.*, vol. **14**, No. 6, 1929, pp. 241–242.

[46] *Op. cit.*, p. 235, Table XX.

[47] Alling, H. L., The Potash-Soda Feldspars: *Jour. Geol.*, vol. **XXXIV**, 1926, p. 602.

important if polymorphism is assumed. If the coefficients of expansion (and consequently contraction) differ from modification to modification, it is conceivable that certain cleavage planes in "unusual" directions can be thus produced. In feldspathic systems, possessing eutectoid relations, the different solid phases in transition (inversion) if they possess different solubilities, two phases would undoubtedly separate and occupy these cleavage planes. This process is one of exsolution by virtue of polymorphism and eutectoid relations. I believe we should distinguish perthites not solely on the basis of (1) simultaneous crystallization, (2) exsolution and (3) hydrothermal replacement. This is commonly done but it ignores much that is germaine to the problems here. Exsolution can take place by (1) inclined solubility curves, (2) polymorphous transformations, (3) by eutectoid relations and (4) various combinations of the above. Exsolution, therefore, is a general term without a very concise meaning. When possible it seems desirable to be more specific. The nomenclature of the perthitic feldspars is discussed and tabulated later on.

DEUTERIC PERTHITES

The crystallization of an igneous rock is brought about by the solidification of a magma. It is a change in phase; liquid to solid. Such a complicated system does not suddenly become solid on fall-

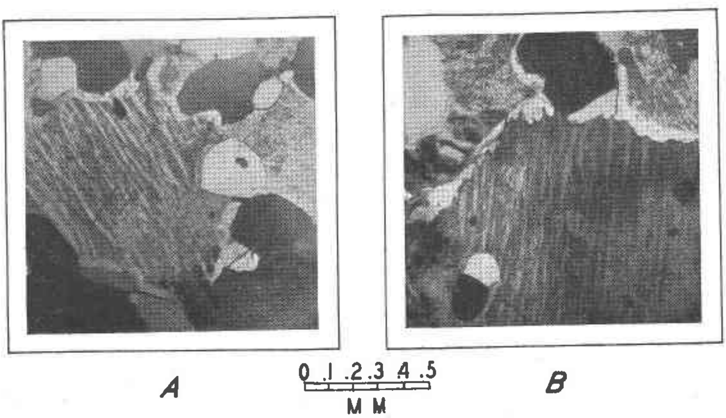

PLATE I.

Photomicrographs of deuteric perthite, from Fort Ann, N.Y. Slide (C101) kindly loaned by R. J. Colony, illustrating his "injection perthite." Polarized light. Original magnification x66.

ing temperature, but for a considerable time consists of both crystals and liquid. It is during this "mushy" stage when under mountain-building stresses that protoclastic structures are developed. This liquid may be squeezed away from the solid crystals and be replaced by others of the same or different composition. These liquids are potentially capable of entering cleavage and cooling cracks or freezing on the margins of previously solidified crystals producing intergrowths.

Such blebs are the result of introduction from without the crystal *but not from without the system.* Many important changes in rocks are the result of late stage crystallization activity where it is perfectly conceivable that such introduced and replacing solutions were normally part of the crystallizing magma. Such processes are magmatic and not hydrothermal, yet the blebs were introduced. To such phenomena the term deuteric can well be applied.[48]

I am using the term deuteric for those late stage magmatic changes within a *closed* system. The plutonic rocks of the Adirondack Precambrian furnish adequate examples of deuteric feldspars. Colony[49] has photographed perthites from Fort Ann, New York, clearly showing a core of perthite coated by introduced feldspar which is apprently replacing certain blebs of the main crystal. He calls this "a sort of 'injection perthite' " and refers to the rock as a "deuterized granite." Through his kindness I have examined his slides and reproduce in Plate I photographs of my own. The evidence is quite clear that late stage activity is responsible for the blebs near the surface of the crystals. To my mind it is also clear that the perthite of the core is not deuteric in origin but due to exsolution, in all probability due to inclined solubility curves. Hence this is a perthite of double origin, exsolution and deuteric.

Other illustrations from the Adirondacks are shown in Plate III.

HYDROTHERMAL PERTHITES

The nomenclature of the physical chemist is applicable here and serves a very useful purpose. The term *closed system* clearly distinguishes those systems where there has been nothing added during the period of crystallization on one hand, from those referred to as

[48] Sederholm, J J , *Bull. de la Comm. Geol. de Findlande,* No. **48,** 1916.
Colony, R. I., *Jour. Geol.,* vol. **XXXI,** 1923, pp. 170–171.
Gillson, J. L., *Jour. Geol.,* vol. **XXXVI,** 1928, pp. 149–153.
Osborne, F. F., *Econ. Geol.,* vol. **XXIV,** 1929, pp. 335–336.
[49] Colony, R. J., *Jour. Geol.,* vol. **XXXI,** 1923, pp. 170–171, fig. **1.**

open system where material from the outside has been introduced on the other. So far we have discussed those perthites which are closed systems. In dealing with hydrothermal action we pass to those systems which are open. Such introduced solutions can fill cleavage and cooling cracks and on freezing produce intergrowths. Furthermore, such solutions may replace in whole or in part a feldspathic original and hence replacement perthites are produced.

Economic geologists, who are students of metalliferous deposits, have of recent years emphasized replacement as the cause of many intergrowths, particularly of sulphide minerals and frequently refer to them as possessing a "pseudo-eutectic texture." Lindgren[50] has recently expressed his opinion with references to the literature and illustrates his paper with beautiful photomicrographs showing intergrowths of tennantite, $Cu_6As_2S_6$, and stromeyerite, $(Cu,Ag)_2S$, sphalerite and galena, sphalerite and chalcopyrite. I could give many other references such as to Whitehead,[51] Rogers,[52] etc., but these will suffice to make my point: intergrowths in rocks and ores which exhibit perthitic or eutectic textures are by no means the product of the same process. The problem is fundamentally a psychological one. Metallographers observe true eutectic textures in metallic alloys definitely the result of simultaneous solidification of a melt. Then all eutectic textures are eutectics? Certainly not! The economic geologist, studying polished specimens of ore minerals under the reflecting microscope, finds "pseudo-eutectic" textures. Are *all* such textures due to replacement? In all honesty he must reply "no," but conscientiously he holds that certain ones, or the great majority of them even, are due to replacement. Why this difference in conclusions between the metallographers on one hand and the economic geologists on the other? Because essentially one is dealing with closed systems and the other with open systems. The former are systems whose fluidity is due to heat; the latter due to a solvent.

The petrologist studies phenomena covering both ranges. Perthites occur in plutonic, hypabyssal and volcanic rocks and in many secondary products derived thereform. I therefore insist that perthites must have many origins. There are perthites and perthites.

What conclusions are reached when a student of ore deposits

[50] Lindgren, Waldemar, *Econ. Geol.*, vol. **XXV**, 1930, pp. 1–13.

[51] Whitehead, W. L., *Econ. Geol.*, vol. **XI**, 1916, pp. 1–13.

[52] Rogers, A. F., *Econ. Geol.*, vol. **XI**, 1916, pp. 582–593.

studies perthite from a pegmatite knob? Hydrothermal replacement, of course.[53] And it may be in whole or in part. When a petrographer investigates the evolution of plutonic rocks and finds perthite, and concludes that exsolution would account for it, are we surprised at his opinion? Not at all.

Many illustrations are available which can be called into court as evidence for the introductions of feldspar materials from without. Many pegmatitic microclines show irregular patches of plagioclase apparently without orientation of any kind. These are common and called "secondary."[54]

BLEBS INFLUENCED BY INCLUSIONS IN ADIRONDACK PERTHITES

Microscopic studies of Adirondack syenite-granites show inclusions of quartz and soda-bearing pyroxenes in perthites. It is at once seen that there are two generations of blebs in these perthites. one set is in the form of round or elliptical rods which Andersen calls "string" perthite, which is an early development and is assigned both by Andersen and myself to exsolution. The other set

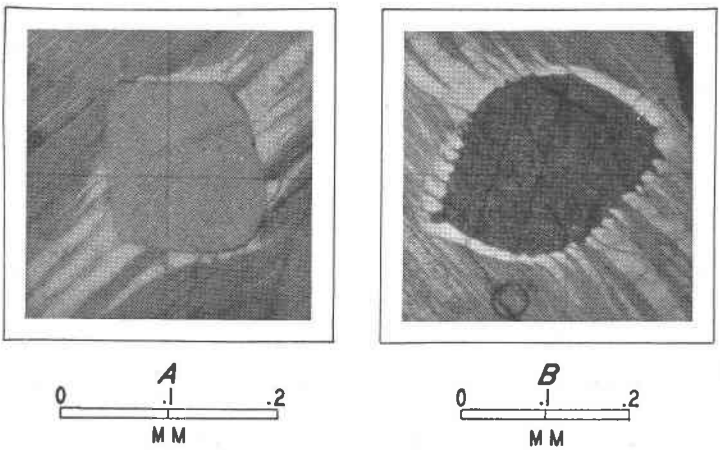

Plate II.

Photomicrographs of composite perthite influenced by inclusions. Syenite-granite, Ausable Forks, Ausable quadrangle, Adirondack Mountains. Polarized light. Slide 1087c.

A. Inclusion of quartz. Original magnification x285.

B. Inclusion of aegirite-augite. Original magnification x224.

[53] See Megathlin, G. R., The Pegmatite Dikes of the Gilsum Area, N.H.: *Econ. Geol.*, vol. **XXIV,** 1929.

[54] Harker, Alfred, The Natural History of Igneous Rocks, **1909,** p. 259.

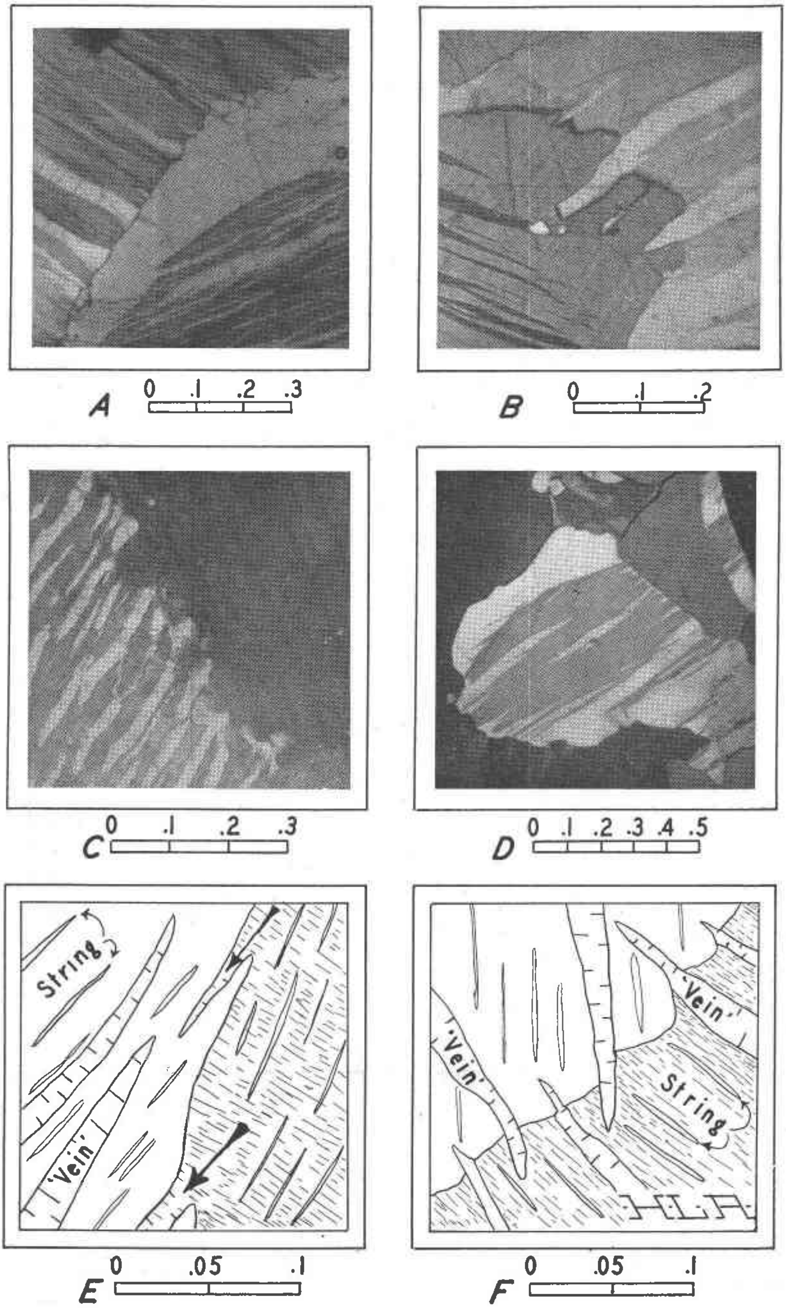
A
0 .1 .2 .3
B
0 .1 .2
C
0 .1 .2 .3
D
0 .1 .2 .3 .4 .5
String
'Vein'
E
0 .05 .1
'Vein'
'Vein'
String
H.L.A.
F
0 .05 .1

PLATE III

Photomicrographs and drawings of various composite perthites from the Adirondacks.

A. String and "vein" penetrating perthite in syenite-granite (quartz nordmarkite), Ausable Forks, N.Y. Polarized light. Original magnification x118. Slide 1087c.

B. String and "vein" penetrating perthite in syenite-granite (quartz nordmarkite), Ausable Forks, N.Y. Polarized light. Original magnification x160. Slide 61.

C. Composite perthite in granite, three-quarter mile south southwest of Little River, Canton Quadrangle. Polarized light. Original magnification x143. Slide 1948.

D. Deuteric perthite in syenite-granite (quartz nordmarkite) Ausable Forks, N.Y. Polarized light. Original magnification x80. Slide 61′.

E. Camera lucida drawing of composite penetrating perthite in syenite-granite (quartz nordmarkite), Ausable Forks, N.Y. Original magnification x 450. Slide 1087c. The arrows point to penetrating blebs.

F. Composite camera lucida drawing of composite interpenetrating perthite in syenite-granite from several slides from Ausable Forks and the Saranac Lake Quadrangle. Original magnification x 400.

consists of albite-rich blebs much more irregular in shape and in orientation which are later in development. These masses appear to be identical to, or very similar to what Andersen calls "vein" perthite.

The position of the "vein" type of bleb is greatly modified by the presence of these inclusions as can readily be seen from Plate II. The "vein" albite-rich feldspar appears to have been pushed aside by the inclusions. This feldspar is more or less completely coating the margins of the inclusions and yet it is strongly influenced by the cooling cracks and roughly parallel to the directions taken by the exsolution "string" type of blebs.

I suggest that the differential rates of contractions of the host feldspar and the inclusions have produced strains along the contact, producing channelways for the solutions that were responsible for the "vein" type of feldspar, and yet I feel that this phenomenon is not hydrothermal but deuteric in origin.

PENETRATING PERTHITES

Slides of Adirondack granitic rocks from many localities show that the contacts between perthite grains are decidedly undulatory by large irregular blebs of one grain penetrating another. Plate III illustrates this phenomenon. In certain slides there is a mutual penetration and hence albitic blebs interpenetrate each other. The penetrating blebs have the appearance of the "vein" type of Andersen. They certainly belong to a second generation[55] of blebs. Andersen's "vein" type is found in pegmatites. This type of bleb he regards as due to "circulating solutions derived from the same pegmatite magma from which the initial crystallization of the feldspar took place.[56] I believe I am correct in interpreting this statement to mean a closed system and hence I believe these "vein" blebs are deuteric. However, Andersen's "interlocking perthite" as seen in his beatiful photomicrographs[57] does not have the appearance of the type I have in the Adirondack plutonic rocks, and hence the theory of simultaneous crystallization is thought not to apply to these.

THE CLASSIFICATION OF PERTHITES

I have been maintaining for some years now, that there is no single origin for perthite. Rather that there are many possible causes of these intergrown feldspars. Recent publications have emphasized this growing opinion. Andersen, after carefully studying, listing, and photographing many textural relations exhibited by pegmatitic perthites, states that there is "conclusive evidence for the assertion that the perthites have been formed as a result of *several* (my italics) processes."[58]

He proceeds to recognize a number of textural types to which he assigns appropriate origins, as follows:

(1) *String Type of Perthitic Bleb.* These are relatively long round or elliptical rods of soda-rich feldspar in a potash-rich host. They usually lie parallel to (010). This type, Andersen believes, is due to "exsolution in the solid state at an early stage in the evolution of the feldspar."[59]

(2) *Film Type of Perthitic Bleb.* These soda-rich feldspar blebs occur as thin films perpendicular to (010), and at an angle of about 73° to (001), and are larger than the string type. Andersen assigns this to "exsolution but probably at a later stage (lower temperature) than string perthite."[60]

(3) *"Vein" Type of Perthitic Bleb.* These are very common in pegmatites and relatively large in size, rather irregular in shape,

[55] Alling, H. L., *Jour. Geol.*, vol. **XXXIV**, 1926, p. 610.
[56] Andersen, Olaf, *Norsk. Geologisk tidsskrift*, B. **X**, h. 1–2, 1928, p. 150.
[57] *Op. cit.*, Pl. VII, 2A, 2B, and 3.
[58] Andersen, Olaf, *Norsk. Geologisk tidsskrift*, B. **X**. h. 1–2, 1928, p. 163.
[59] *Op. cit.*, p. 149.
[60] *Op. cit.*, p. 150.

though usually lens shaped. Generally they are roughly parallel to the (100) face but are noted as running through the host feldspar without much relation to crystallographic directions. These Andersen considers due to solutions derived from the pegmatitic magma filling contraction cracks. My experience with feldspars, with this type of bleb in pegmatites, leaves me in doubt whether they are deuteric or hydrothermal in origin. I don't know whether my experience has been too limited or too extensive to allow me to reach a decision. I am willing at the present time to suggest that "vein" perthite in pegmatites is the result of lower temperature conditions than is the case of similar blebs in perthites in plutonic rocks. Hence pegmatitic "vein" blebs may be on the boundary between deuteric and hydrothermal, while plutonic "vein" blebs are deuteric.

(4) *Patch Type of Perthitic Bleb.* By this term Andersen recognizes a transitional type: "vein" type grading into "pure" albite. The patches of albite are noticeable elongated in the direction of the *b*-axis. He states that this type of perthite is commonly supposed to be the product of replacement. Here I would suggest that the "pure" albite represents still lower temperatures.

It may be that the term "pure albite" is perhaps a little misleading, in that its composition may not be one hundred percent $NaAlSi_3O_8$. I suppose what Andersen desires to convey is that it appears to be homogeneous and is not a two phase system.

In Fig. 2. I have attempted a classification based upon a thermal scale, ranging from high (magmatic) temperatures to low temperatures. I recognize closed and open systems[61] and the difficulty of always clearly distinguishing them. Many readers may not accept the terms used in column 3, questioning with Ross[62] the wisdom of employing the word "magmatic" as too inclusive. Likewise "deuteric" is none too definite in meaning. "Pneumatolytic," implying gas-controlled processes, has been so attenuated that it has "lost all definite meaning"[63] and so on. Nevertheless, they have proved useful in class and may be here as well.

Andersen's terms are used in column 4. The only change I have made was in the placing of quotation marks around the term "vein" as applied to a type of perthitic bleb, as the word is likely to be confused with low temperature vein conditions as is used in column 3.

[61] See Schaller, W. T., *Am. Min.*, vol. **XII**, 1927, p. 59.

[62] Ross, C. S., *Econ. Geol.*, vol. **XXIII**, 1928, p. 867.

[63] *Op. cit.*

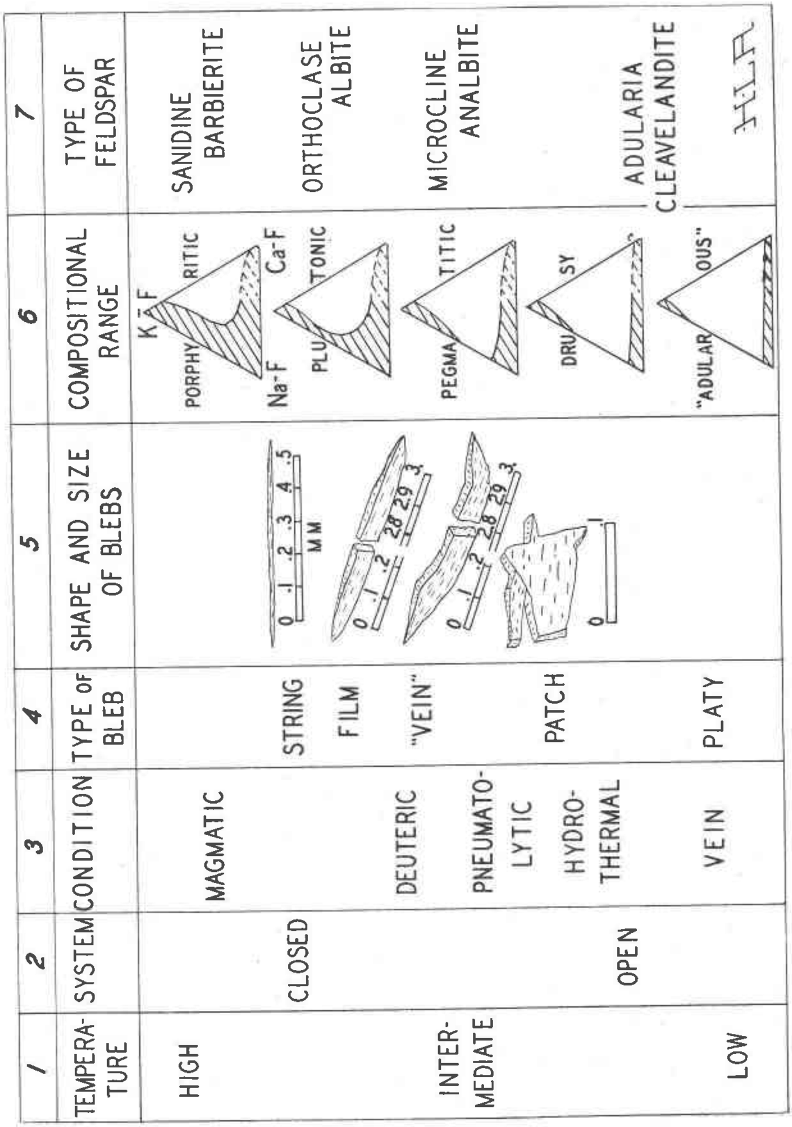

FIG. 2. A Classification Chart of Various Perthites. Compiled from a number of sources.

Column 2. The terms are those used by Schaller.[a]

[a] Schaller, W. T., *Am. Min.*, vol. **XII,** 1927, p. 59.

Column 3. The terms are useful even though not without objections.[b]

[b] Ross, C. S., *Econ. Geol.*, vol. **XXIII,** 1928, p. 867.

Column 4, gives the names used by Andersen.[c]

[c] Andersen, Olaf, *Norsk. Geologisk tidsskrift*, B. **X,** h. 1-2, 1928, p. 163.

Column 5 shows conventionalized drawings of size and shape of perthitic blebs, the data taken from Andersen.

Column 6. The composition ranges were taken from diagrams of Mäkinen.[d]

[d] Mäkinen, E., *Geol. Fören. Förhandl.*, vol. **XXXIX,** 1917, pp. 121–184.

Column 7. The names I have used as modified from Winchell[e] and Andersen.

[e] Winchell, A. N., *Jour. Geol.*, vol. **XXXIII,** 1925, p. 719. Elements of Optical Mineralogy, Part II, Wiley and Sons, 1929, pp. 316–7.

Alling, H. L., *Jour. Geol.*, vol. **XXXIV,** 1926, p. 593.

The sizes and shapes of the blebs have been conventionalized as the variety in these is seemingly unlimited and I desired to simplify the diagram as much as possible.

The compositional ranges and terms are patterned after Mäkinen's diagrams.[64] Normal feldspars are confined to the lined areas, compositions consisting of a single phase. According to the diagrams, homogeneous anorthoclasic feldspars are possible in porphyritic and plutonic feldspars but not in lower temperature diagrams. The term "adularious" is an adjective coined from adularia. Here I depart from Winchell[65] and regard adularia as hydrothermal in origin or as a product of vein formation. Tolman[66] has discussed the presence of feldspars in quartz dikes and concludes that "under . . . low temperatures are formed the purest feldspars: adularia, with little Ab[67] (+An), and plagioclase with no K-feldspar. They constitute the feldspars normally found in veins." Also that "perthite is not an orthodox vein forming mineral."[68] It can be observed that the white areas in Mäkinen's diagrams, denoting two phase conditions, increase with falling temperatures. To place "adularia" where "orthoclase" is printed, as Winchell has done, interrupts the nicety of the scheme.

[64] Mäkinen, E., *Geol. Fören. Förhandl.*, vol. **XXXIX,** 1917, pp. 121–184.

[65] Winchell, A. N., *Jour. Geol.*, vol. **XXXIII,** 1925, p. 719. Elements of Optical Mineralogy, Pt. II, Wiley and Sons, 1929, pp. 316–317.

See Alling, H. L., *Jour. Geol.*, vol. **XXXIV,** 1926, p. 593.

[66] Tolman, Carl, *Am. Min.*, vol. **XVI,** 1931, p. 296.

[67] Na-Feld. would be noncommittal regarding the exact modification co-existing with adularia.

[68] *Op. cit.*, p. 297.

In the last column I have shown the names I have used for trimorphous modifications of both components. The placing of cleavelandite with adularia was, I admit, an inspiration, but it may be subject to criticism.

Horizontal lines have not been drawn across the chart. I do not wish to lose sight of the gradational, transitional characters intended in spite of the apparent definiteness of the diagram.

TABLE III
TERMINOLOGY OF THE PERTHITES

Process	Name
Eutectic. Simultaneous crystallization.	1. Eutectic Perthite. (Are there any?)
Loss in solubility by change in modification. Sanidine-barbierite to orthoclase-albite. That is, from gamma feldspars to beta.	2. Gamma→beta Perthite.
Eutectoid on change in modification. Sanidine-barbierite to orthoclase-albite. That is, from gamma feldspars to beta.	3. Gamma→beta Perthoid[69]
Loss in solubility in change in modification. Orthoclase-albite to microcline-analbite. That is, from beta feldspars to alpha.	4. Beta→alpha perthite.
Eutectoid on change in modification. From orthoclase-albite to microcline-analbite. That is, from beta feldspars to alpha.	5. Beta→alpha perthoid[69]
Loss in solubility due to inclined solubility lines.	6. Exsolution perthite.
Deuteric, closed system	7. Deuteric perthite.
Pneumatolytic	8. Pneumatolytic perthite.
Hydrothermal	9. Hydrothermal perthite
Replacement	10. Replacement perthite
Composite	11. Composite perthite

[69] Alling, H. L., *Jour. Geol.*, vol. **XXIX**, 1921, p. 224. "There would be a gain for clearness if . . . 'perthoid' [could be used] to refer to intergrowths of potash-soda feldspars due to [certain types of] exsolution."

THE TERMINOLOGY OF PERTHITES

It would simplify matters if the term "perthite" should be limited to a textural meaning. Then generic terms could be used in connection with, or hyphenated to, it. With this as a basis I have drawn up Table III, in the hope that it may assist others. If the nomenclature is too ponderous, as it may be, I believe that the ideas there implied are of value nevertheless.

It is believed that the processes listed above overlap and consequently many perthites are composite in order. I have seen perthites where the string type of blebs were probably due to those processes numbered 2 and 3, while the film type of blebs represent those numbered 4, 5, and 6, and also "vein" blebs produced from those numbered 7 and 8. These would be listed as composite perthites.