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On Synneusis

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Abstract. Synnneusis is the process of drifting-together and mutual attachment of crystals suspended in a melt. This process is episodic, is most characteristic of the earlier stages of consolidation, and appears to be related to magmatic turbulence. Union of crystals in synneusis relation normally occurs on their broader faces in preferred orientations which coincide with positions of low interfacial energy. Quantitative studies of several common igneous minerals indicate that crystals of a single mineral characteristically show a strong affinity for synneusis and typically unite in parallel or twinned orientation. Some pairs of unlike minerals join readily in synneusis relation, but most appear to be antipathetic.

Synneusis structures have generally been overlooked or misinterpreted as epitaxial intergrowths, primary twins, irregular growth forms, or the random union of crystals which have grown into contact. These possibilities must be rejected where it can be shown that two or more distinct crystals are involved, that they were relatively large when they came in contact, and that they are oriented with prominent faces in common.

Synneusis is responsible for three major features of the magmatic fabric: (1) the small scale segregation of minerals; (2) the systematic mutual orientation of adjacent crystals in synneusis relation; and (3) the morphology of their common boundary. Because synneusis structures are restricted to igneous rocks and are widespread and easily recognized, they provide a definitive and ready criterion of magmatic origin.

Introduction

The term synneusis was introduced by VOGT (1921) to describe structures consisting of aggregates of a mineral formed by the "swimming-together" of crystals in a magma. Although it has not been widely adopted, the term is useful in drawing attention to the process of drifting-together and attachment of crystals during magmatic consolidation. This process is significant because it governs three cardinal elements of the magmatic fabric: 1. the mutual orientation of adjacent grains in synneusis relation; 2. the morphology of their common boundary; and 3. certain characteristic distribution patterns of the minerals. As synneusis textures dominate the fabric of many igneous rocks and are of simple origin, it is remarkable that they have been so generally overlooked and their genetic implications ignored. These structures imply the former presence of a liquid phase in which relatively free movement of crystals was possible and are therefore unequivocal textural evidence of magmatic origin.

VOGT's term is used here in a broadened sense to include all structures involving groups of crystals, whether of a single mineral, as in the original usage, or of different minerals, which have formed by the drifting together and attachment of crystals suspended in a melt. Used as a noun, synneusis refers to this process of attachment. Groups or clusters of crystals formed by this process may be said to exhibit *synneusis structure* (*Anlagerungsgefüge*) or to be in *synneusis relation. Synneusis twinning* is a common genetic type of secondary twinning which arises when crystals drift together and unite in twinned orientation. The synneusis structures include the glomero-porphyritic structures, but the term is broader in that the participating crystals need not be of phenocryst size. Other terms, both formal and informal, have been applied to the structures described here, especially with regard to synneusis twinning (e.g., the agglutination twinning of HARTMANN, 1956; and the combination twinning of ROSS, 1957). However, VOGT's earlier term with its simple etymology is to be preferred.

This paper is concerned with the morphological criteria for the recognition of synneusis and the role of this process in determining the magmatic fabric. Special emphasis is placed on the illustration of characteristic synneusis patterns in common minerals and mineral pairs for which the synneusis relation is well documented. Some speculations on the physical mechanism and possible causes of synneusis based on textural, experimental, and theoretical evidence are also presented.

Recognition of Synneusis Structures

As synneusis is a genetic term, it is imperative that these structures be distinguished from similar features with which they might be confused. Fortunately they show a diagnostic morphology determined by the geometry of the crystals and the mechanics of the synneusis process. Knowing these relations, rapid scanning of a thin section usually suffices to identify these structures.

Basically, synneusis involves a drifting-together of nearby crystals such that they become attached and adhere on their broader crystal faces. Where like minerals are involved, there is normally a strong tendency to join either in parallel or twin orientation; random attachment is rare. Though fewer data are available on mutual orientation of unlike minerals in synneusis relation, certain mineral pairs also show systematic relations.

In most cases, crystallization continues after synneusis, ultimately welding the crystals together into a tightly-knit unit. During this later growth, the initial planar surface of attachment is succeeded by a more irregular boundary arising from the interference of adjacent crystals as they compete for growing space. Crystals of a single mineral become intergrown after synneusis by the addition of zonal shells of uniform composition; these zonal overgrowths envelop the group as a whole, but change orientation in passing from crystal to crystal (Fig. 1).

The geometry of synneusis restricts the orientation of the contiguous crystals, imposing two conditions which are not simultaneously met by any relation likely to be confused with synneusis. these conditions are:

1. that two or more crystals are involved and were of relatively large size at the time of initial contact;
2. that a prominent crystal face in one individual is parallel to a prominent crystal face in the other.

The participation of more than one crystal is obvious were two different minerals are involved, but may be less evident when dealing with a single mineral, especially when the crystals are in parallel synneusis relation. In the latter case, two criteria may be of help. First, zoning may reveal composite crystal cores, thereby establishing the participation of two or more individuals. Second, the presence of more than one crystal may be indicated by the external morphology. The critical morphological feature is misfit — uneven alignment and disparity in size (and especially in length) of the individual crystals — giving rise to aggregates whose irregular

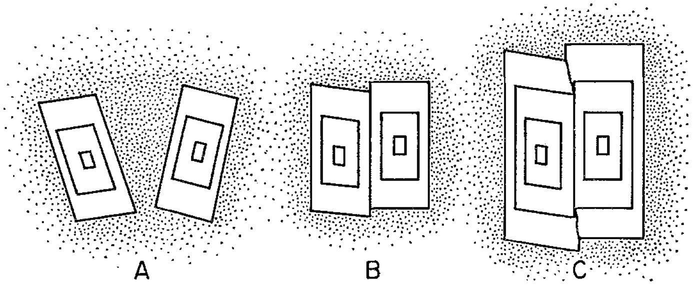

Fig. 1A—C. I Stages in development of synneusis aggregates. A Two isolated crystals. B Drifting together and union. C Post-synneusis overgrowth

blocky or polygonal outlines and re-entrant angles are inconsistent with the form of a single crystal.

The participation of two or more crystals is of critical significance in that it excludes the possibility that this is a single crystal showing growth twinning or a single irregularly developed crystal. The scant mention of synneusis in the literature leaves little doubt that these features have commonly been misinterpreted in one of these two ways. This misidentification is not difficult to understand, since formation of late zonal overgrowths may give the false impression that only a single crystal is involved. It is important, therefore, that the criteria of composite zoning and misfit be looked for in all doubtful cases.

During post-synneusis growth, there is a strong tendency for elimination of the initial misfit of crystals in parallel synneusis relation by preferential crystallization in steps and re-entrant angles (Figs. 2—4). In this way, external irregularities are ultimately lost and the group simulates a single crystal. Such a history can be demonstrated only if multiple zoned cores are present or if there is a slight departure from parallelism between the participating crystals. Parallel synneusis is a quantitatively important, if little appreciated, mechanism of crystal enlargement in magmatic rocks.

A comment on the distinction of primary (growth) twins from synneusis twins is appropriate here. Although growth twins, like synneusis twins, typically show re-entrant angles, they differ in the presence of only one crystal, in the superior fit of the twin individuals, and they are mostly simple contact twins (Fig. 5A). Since many of these primary twins are nucleisupersaturation twins (BUERGER, 1945), initiated in small seed crystals, the twin units are commonly symmetrical and of uniform width. Simple concentric zoning indicates the presence of a single crystal. A further distinction between these genetic types of twins lies in the nature of the composition surface. Growth twins either have planar composition surfaces or relatively regular surfaces nearly parallel to the ideal orientation, though they may be broken intermittently by step-like interruptions. In most synneusis twins, by contrast, the composition surface is composite, consisting of a planar inner segment and an irregular outer boundary (Fig. 5B) (cf. CHUDOBA and FRECHEN, 1941; KÖHLER and RAAZ, 1947). The explanation is simple, as already noted. Synneusis twinning arises through union of two crystals on a crystal face or a combination of faces. The composition surface is thus the planar surface of initial

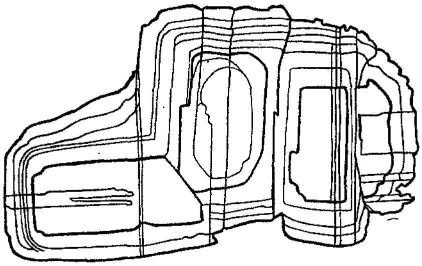

Fig. 2. Schistose metadacite porphyry, Snake Range, Nevada Four zoned plagioclase crystals in synneusis relation, all approximately normal to *a*. The three grains on the left are crystallographically parallel. Note the tendency for the large reentrant angle between them to be eliminated by rapid growth. Width 1.2 mm

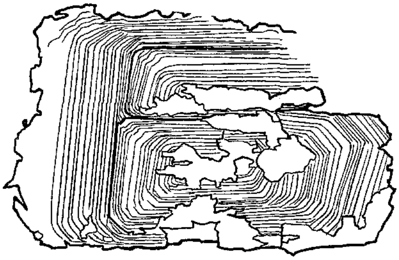

Fig. 3. Quartz monzonite, St. Cloud, Minnesota (010) sections of two plagioclase grains in parallel synneusis relation. The irregular unpatterned inclusions are patchy zoning. The slight initial misfit between the two crystals has been entirely eliminated by infilling of the reentrant. Width 4.1 mm

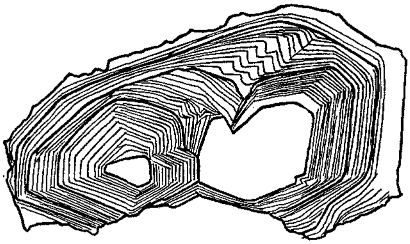

Fig. 4. Granodiorite, Caulfeild Pluton, near Vancouver, B. C. Two plagioclase grains cut parallel to (010) in parallel synneusis relation. Reentrant angle entirely eliminated by post-synneusis overgrowth. Width 2.4 mm

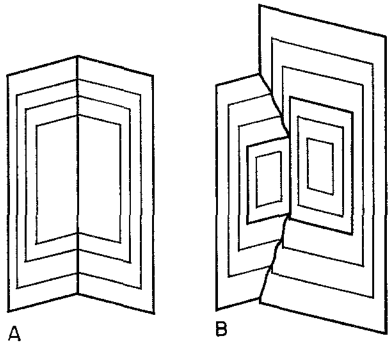

Fig. 5A and B. A. A generalized sketch of a typical growth twin. Note the uniform size and fit of the individuals. B. Generalized sketch of a synneusis twin. Note the misfit in size and arrangement of the twin individuals, the zoning indicating participation of two crystals, and the composite nature of the composition surface

attachment. During continued crystallization after synneusis, the two individuals become intergrown as penetration twins. This occurs necessarily whenever misfit or unequal length brings together two faces with unequal growth rates at the interface of growth. During subsequent growth the boundary between the two crystals tends to be extended in the direction of enlargement of the most rapidly growing face; but, unless further development of the more slowly growing face is suppressed entirely, this direction cannot exactly coincide with that of the initial plane of

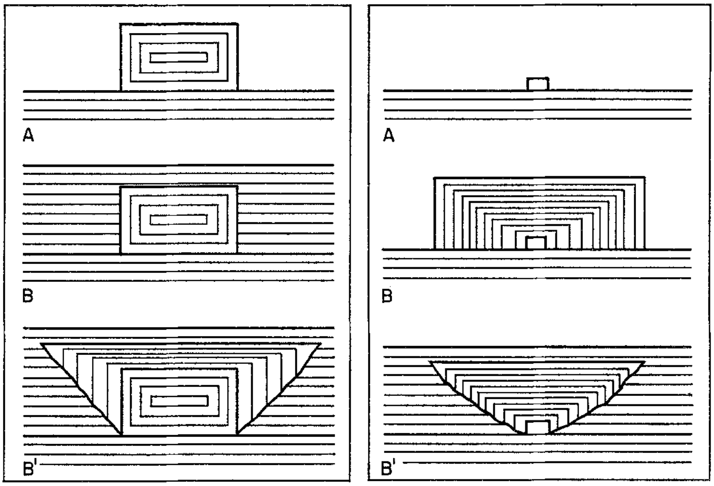

Fig. 6. Left Column. *A* Synneusis of a small crystal on the surface of a much larger host crystal. *B* Rapid growth of the larger host crystal engulfing the smaller one which does not grow or grows very slowly. *B'* Growth of both crystals, the host crystal more rapidly, incorporating the smaller one which is assymetrically developed. Note that at least the inner portion of the smaller crystal is fully and symmetrically developed in the case of synneusis. Right Column. *A* Nucleation of a small crystal in epitaxial relation on the surface of a larger crystal. *B* The seed crystal grows, while the host does not, developing assymetrically. *B'* Both crystals grow, but the host grows more rapidly ultimately incorporating the smaller assymetrically developed crystal. Note that in epitaxis the smaller crystal develops assymetrically from the beginning, as shown by zoning

attachment. Thus, with continued crystallization, the contact becomes irregular, deviating systematically from the ideal composition plane in response to the changing growth rates of the two adjacent surfaces competing for space.

This variation in the morphology of the composition surface is inconsistent with the hypothesis of primary twinning. It is to be emphasized that this same composite boundary morphology is developed in all crystals in synneusis relationship which have experienced further growth, not just in twinned crystals or, indeed, in crystals of the same mineral. Unfortunately this criterion cannot always be applied in thin section studies for the reason that synneusis commonly occurs when the crystals are still relatively small. In subsequent intergrowth irregular boundaries develop over most of the contact area of the crystals. Consequently, only infrequent sections will be so oriented as to pass directly through the surface of initial attachment and reveal the characteristic straight segment.

Where unlike crystals are involved the possibility of an epitaxial relation, arising from oriented nucleation of one crystal on the surface of another of a different mineral, must be considered. Although synneusis and epitaxis are closely related processes, they differ in that epitaxis involves nucleation of small crystals on the surface of a larger one. In synneusis, by contrast, the crystals have nucleated independently and are of relatively large size at the time of initial attachment. Accordingly, epitaxis can be ruled out where the crystals can be shown (by their external form or concentric zoning) to have been relatively large when they first came in contact (Fig. 6).

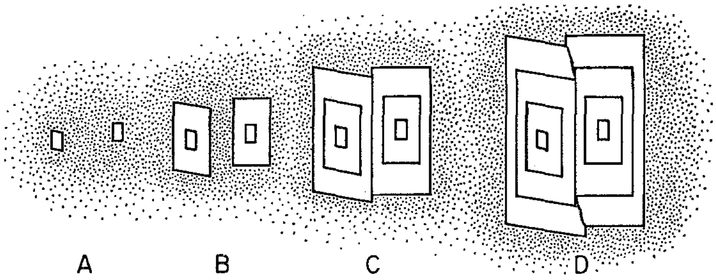

Fig. 7. A Two small separate crystal nuclei develop with mutually parallel crystal faces, B These crystals grow. C Come in contact. D After union develop a common overgrowth

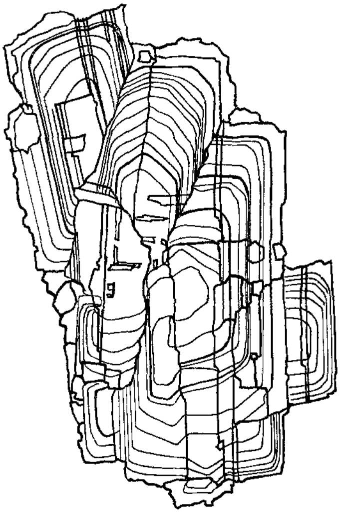

Fig. 8. Granodiorite, Squire Creek Pluton, Washington. Complex synneusis group of plagioclase crystals cut normal to (010). Most crystals are in Carlsbad or albite-Carlsbad twin relation. This group shows extensive post-synneusis overgrowth. Width 3.3 mm

Synneusis structures must also fulfill the condition that the participating crystals have a prominent face parallel to a contiguous prominent face in the adjacent individual. This reflects the fact that the crystals become permanently attached only when two broad faces are in contact. It is true, of course, that such parallelism would also arise where two neighboring, but not contiguous crystals oriented with two faces parallel were ultimately to grow into contact (Fig. 7). It is inconceivable, however, that more than a very small fraction of the crystals in a rock should chance to have such an initial mutal orientation, and in most rocks observation shows that if this critical parallelism is present at all it is exhibited by a large number of crystals. Moreover, the crystals are characteristically involved in complex synneusis groupings of many individuals which show not only a two-dimensional, but a systematic three-dimensional orientation (e.g., Fig. 8). These features are clearly incompatible with growth from scattered randomly oriented nuclei. In the igneous rocks to which these structures are restricted synneusis is the only possible mode of origin.

Parallelism of crystal faces is commonly evident in thin section where it can be recognized by the presence of zoning, external crystal faces, cleavage, twinning, or some combination of these.

In summary, synneusis is demonstrated where it can be shown that more than one crystal is involved, that these crystals were of relatively large size at the time of attachment, and that there is a parallelism of prominent crystal faces between adjacent grains. Simple inspection of a thin section oridnarily serves to establish these relations. Demonstration of the synneusis relation is easy where zoning is prominent, as with most igneous plagioclases, and in porphyritic and in many hypidiomorphic rocks where groups of phenocrysts show euhedral or subhedral outlines. Synneusis, however, is usually obscure in anhedral material, unless zoned.

Illustrations of Synneusis

Introduction. Although no systematic study of synneusis has been made, even for a single mineral, there is a large body of data dealing with isolated examples and special aspects of the problem. This section attempts to illustrate something of the range and variety of these structures with examples drawn from the literature and with some newer observations. Emphasis is placed on plagioclase, not because synneusis is more characteristic of this mineral than of others but because synneusis has been most generally recognized and intensively studied in zoned material from this important mineral group. Several other common minerals and mineral pairs for which data are available are treated more briefly and some tentative petrogenetic implications are drawn from specific examples of synneusis.

Plagioclase Synneusis. Judging from the frequency with which they are figured in the literature, plagioclase crystals in synneusis relationship, especially in volcanic rocks, have intrigued petrographers since the first introduction of the petrographic microscope. Examples in recent petrography texts include HARKER (1964, p. 167, 168), WILLIAMS, TURNER, and GILBERT (1954, p. 96), and MOORHOUSE (1959, p. 168, 189, 190). Few workers, however, appear to have considered the origin of these features. VIOLA (1902) was among the first to recognize their significance, noting examples of attachment on (010) in both Carlsbad and random orientation in certain volcanic rocks, though he did not describe the distinctive morphological characteristics of these structures. It remained for KÖHLER and RAAZ (1947) to point out the significance of disparity in size and differences in zoning between two individuals and the composite nature of the composition surface of certain twinned feldspars as evidence of synneusis.

ROSS's study (1957) of synneusis twinning in the plagioclases of some volcanic and plutonic igneous rocks from British Columbia is a major advance in that it employs a quantitative approach and considers the genetic implications of the process. ROSS emphasizes three important characteristics of the synneusis structures: their composite nature demonstrated by concentric zoning of the individual crystals involved; the common presence of zonal overgrowths enveloping the synneusis group as a whole; and, the irregular outlines of the crystal aggregates. ROSS's findings may be summarized as follows; all the plagioclases in synneusis relation were found to be in twin orientation; a predominance of these crystals are united on (010); the common twin laws are albite-Carlsbad, Carlsbad, and Ala in order of decreasing abundance. Indepent observations in literature (KÖHLER and RAAZ, 1947; KRAUS, 1962) confirm the importance of these three laws in synneusis twinning. They are not, however, the only common relations. Synneusis on

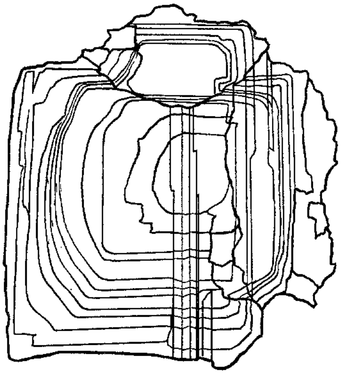

Fig. 9

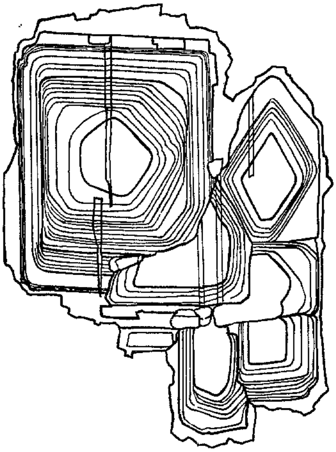

Fig. 10

Fig. 9. Granodiorite, Squire Creek Pluton, Washington. The large plagioclase grain is an *a*-normal section in Baveno synneusis relation with the upper grain (also *a*-normal) and in Carlsbad relation with the grain on the right. Width 2.4 mm

Fig. 10. Granodiorite, Squire Creek Pluton, Washington. Synneusis cluster of plagioclase grains mostly in *a*-normal orientation. The large crystal is in Baveno relation to the contiguous grains; these are all in parallel orientation, except the lower grain which is in Carlsbad relation with the grain to its right. Width 2.1 mm

other twin laws—notably albite, Baveno, and Manebach—is conspicuous in many rocks. Moreover, parallel synneusis is an exceptionally common relation. Finally, synneusis in random orientation, though rare, has been reported.

Burri (1963) in a review of the literature has shown that plagioclase Baveno twins of the *Banat* type—those characterized by an irregular composition surface, prominent reentrant angles, and by cross-, T-, or L-shapes in sections cut normal to the *a*-axis—are synneusis twins formed by the union of two crystals, (010) on (001), with their *a*-axes parallel. This common twin type (Figs. 9, 10) differs strikingly in morphology from that which we normally associate with the Baveno law (i.e., the squarish outline and the familiar diagonal composition plane in sections normal to *a*). Baveno twins of the latter type are much less common in plagioclase than the first and are clearly growth twins.

In my experience, albite synneusis twinning is quite common, though it has rarely been mentioned in the literature (Ross, 1957). Manebach synneusis twins occur in the plagioclase of some granitic rocks, although they appear to be less abundant than primary Manebach twins.

Although synneusis commonly involves union of the crystals in twin orientation, deviations of as much as several degrees from ideal orientation as well as rare cases of random synneusis have been recorded (Viola, 1903; Köhler and Raaz, 1947; Kraus, 1962). Slight departures from ideal twin relations are a possible source of internal scatter of universal stage data (see Vogel, 1964). Such scatter is petrogenetically significant—and as pointed out by Kraus is itself supporting evidence for synneusis—but may lead to confusion or errors in determination of composition. Further inconsistencies arise where plagioclase crystals of differing

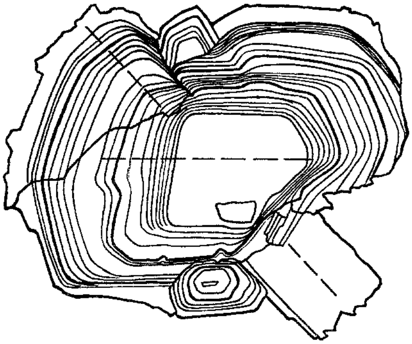

Fig. 11

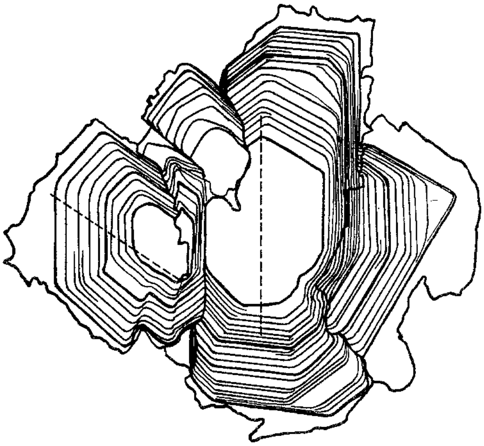

Fig. 12

Fig. 11. Granodiorite, Squire Creek Pluton, Washington. Synneusis complex of several plagioclase grains cut parallel to (010) and very close to the composition surface. Synneusis in parallel relation and on the Carlsbad twin law (dashed lines showing the traces of (001) make an angle of 52° in two large Carlsbad twin individuals.) Width 3.0 mm

Fig. 12. Granodiorite, Caulfeild Pluton, near Vancouver, B. C. Large plagioclase grains in Carlsbad synneusis relation—dashed line is the trace of (001). Two smaller grains are seated in parallel synneusis relation on the larger ones. (010) section of all grains. Width 3.4 mm

composition have joined by synneusis. Clearly the origin of the scatter and the validity of composition determinations cannot be properly evaluated unless care is taken to establish whether a synneusis relation is involved. The anomalies sometimes encountered in plagioclase determinations by the "Carlsbad-albite" method are probably in large part the result of imperfect twinning (or even widely deviant orientation) arising from synneusis on (010). In two special cases Carlsbad orientation (or albite-Carlsbad orientation) can be checked rapidly without recourse to the universal stage. In sections normal to (010) where one Carlsbad individual is cut normal to the *a*-crystallographic axis (e.g., Fig. 9), one need only compare the compositions determined independently by extinction angle measurements using the *a*-normal and "Carlsbad-albite" methods (taking care to use an outer zone common to both crystals); if the results agree, the individuals are in, or near ideal orientation. Synneusis Carlsbad and albite-Carlsbad twins cut parallel or subparallel to (010) near the surface of attachment consist of two individuals usually in an X- or V-shape (Figs. 11—12); when these are in ideal twin relation, the angle between the basal cleavages, as well as any (001) zones or crystal faces present, will be very close to 52° (Turner, 1951).

A final synneusis relation, probably the most common one in plagioclase, is orientation in parallel or near parallel position (Figs. 2—4, 13, 21—22). It is remarkable that these structures are mentioned but rarely in the literature, though widely illustrated there. This oversight largely reflects the misidentification of synneusis groups as single crystals. One need not look far, however, to find striking examples of plagioclases in parallel orientation showing the multiply zoned cores and irregular external form distinctive of synneusis. In my experience,

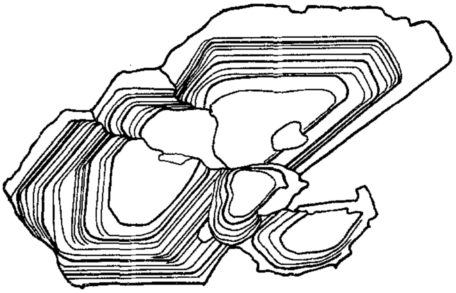

Fig. 13. Granodiorite, Squire Creek Pluton, Washington. (010) section of five plagioclase grains in parallel synneusis relation. Width 3.1 mm

parallel synneusis is prominent in all magmatic rocks in which plagioclase synneusis is conspicuous and it is not unusual to encounter groups of crystals with 3, 4, 5, or more individuals all in identical orientation. Parallel synneusis groupings on virtually all prominent crystal faces appear to be common in the plagioclases.

The available data indicate that the most common synneusis orientations in plagioclase are parallel, albite-Carlsbad, Carlsbad, and Ala. These orientation laws reflect preferential attachment on (010), normally the most broadly developed face in igneous plagioclase. Widespread, though generally less frequent synneusis relations of plagioclase include the albite, Baveno, and Manebach twin laws.

Since the observations of Gorai (1951) it has been increasingly recognized that twin laws in plagioclase other than albite and pericline are largely restricted to igneous rocks. Two different explanations could account for this. It is possible that the twins characteristic of magmatic plagioclase have formed as growth twins favored by special conditions, such as rapid and euhedral growth (Vance, 1961), realized principally in magmatic environments. This view is endorsed by Seifert (1964). The alternative is that most of the twin laws peculiar to igneous plagioclase reflect formation by synneusis. Synneusis twins, of course, are necessarily restricted to igneous rocks, as they may form only in a medium sufficiently fluid to permit extensive differential movement of crystals (Ross, 1957). It would be an oversimplification, however, to assume an either-or approach to this question, for there are many clear examples of both synneusis twinning and growth twinning in igneous rocks. The problem, rather, is the relative importance of these two types. Obviously, careful quantitative studies of plagioclase twinning from the genetic standpoint will be needed before a final answer can be given. My own experience, however, —supported by the observations of Ross, Kraus, and others— indicates that many, if not most, Carlsbad (including albite-Carlsbad) twins in magmatic plagioclase are synneusis twins and that synneusis on a number of other twin laws is common also. Synneusis thus appears to be a major factor in the twin frequency patterns recognized by Gorai; indeed, his illustrations of typical twins in igneous plagioclase show striking synneusis morphology, If this conclusion is correct, it is worth noting that determination and plotting of twin types and their frequency, as in the procedure of Gorai, serves no essential purpose in establishing the origin of a rock. Magmatic origin can be demonstrated by direct reference to the synneusis relation itself. With zoned plagioclase, inspection is normally sufficient to reveal whether synneusis structures are present. Relict synneusis structures in plagioclase commonly survive even medium- and

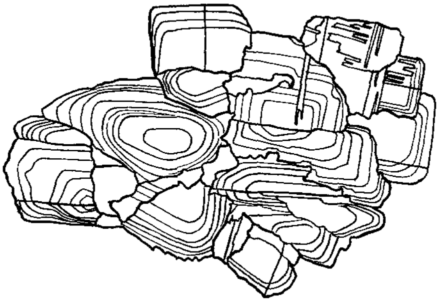

Fig. 14. Schistose metadacite porphyry, Snake Range, Nevada Complex synneusis grouping of many individual plagioclase crystals. Igneous zonal features have largely survived, despite appreciable recrystallization and incipient development of schistosity in the matrix. Width 3.9 mm

high-grade metamorphism and are a diagnostic criterion of the magmatic parentage of certain orthogneises and meta-volcanic rocks (Figs. 2, 14).

Synneusis of Potassium Feldspar. Synneusis in K-feldspar has received much less attention than that of plagioclase—probably because of greater difficulty of recognition, related to the common absence of conspicuous zoning and to the frequent restriction of synneusis to simple groups of two individuals in twinned or parallel orientation. Although no systematic study of synneusis has been made for this mineral group, the frequency with which glomero-porphyritic aggregates have been noted in the literature shows the synneusis relation to be common. Examination of phenocrysts weathered out of porphyritic rocks further indicates that parallel groupings and intergrowths are abundant. The fundamental problem of K-feldspar synneusis, however, lies not in these obvious features, but in the origin of twinning, and especially of Carlsbad twinning. Where zoning is absent, differentiation between primary and synneusis twinning must depend largely on morphological evidence, especially on external form and the nature of the composition surface. Fortunately, the study of Carlsbad twinning by Tertsch (1936) provides the data for a provisional interpretation. Tertsch subdivided Carlsbad twins in K-feldspar into two types on the basis of morphology:

1. contact twins of equal size characterized by a planar composition surface, the crystals show prominent development of 101—these twins are typical of pegmatites and veins;
2. penetration twins characterized by abundant and complex re-entrant angles, by a composite composition surface which is planar and parallel to (010) in the center of the twin, but is irregular and deviates systematically from (010) in its outer portions, the crystals exhibit well developed $\bar{2}01$ faces—this morphology characterizes the K-feldspar of many porphyries and granites and, interestingly, is consistently developed in twins from the Carlsbad granite.

Twin types (1) and (2) correspond respectively to primary and synneusis twins. Fig. 15 shows a typical Carlsbad twin with synneusis morphology. If Tertsch's observations are generally valid for porphyries and magmatic granites it would seem that may Carlsbad twins in these rocks have formed by synneusis. This conclusion is supported by Drugman's (1938) description of thousands of twinned K-feldspar crystals weathered out of a porphyritic granite from Goodsprings, Nevada. Many of these twins—including Carlsbad and less common laws and complex combinations of several laws—are penetration forms with irregular external morphology which are difficult to reconcile with a primary origin.

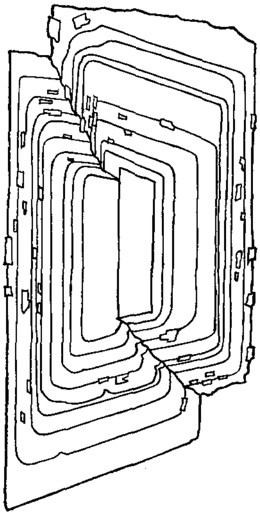

Fig. 15. Trepča, Yugoslavia. Carlsbad synneusis twin in sanidine section normal to (010). The included grains are small plagioclase crystals which show a synneusis relation with crystal faces of the host. Length 3.3 cm

Ingerson's (1952) statistical study of twins and related intergrowths in sanidine from a Texas sill supplies some interesting evidence consistent with origin by synneusis. Though the frequency relations differ somewhat according to position in the sill (the first figure refers to the upper contact the second to the center), Ingerson found that single crystals predominate (73.4—83.0%), followed by parallel intergrowths (9.5—8.6%), Carlsbad twins (8.5—3.3%), and Manebach twins (6.9—7.4%). His key observation is that the parallel growths and twins are significantly larger (typically 10—30% by weight) than the single crystals. This relation is readily understood if the parallel growths and twins formed by union of two or more already developed crystals. The magnitude of the average size difference suggests, moreover, that synneusis occurred at an early stage when the crystals were still relatively small. Had the twins formed as growth twins, there would be no such marked and systematic size difference between twinned and untwinned grains, while if the twins had formed by synneusis after termination of crystal growth, the twins should average twice the size of the single crystals.

The data cited indicate that parallel synneusis and synneusis twinning, notably on the Carlsbad law is widespread in the K-feldspar of some porphyries and magmatic granites. Primary Carlsbad twinning appears to be common in other porphyries and granites, however. Further investigation of the nature of the composition surface using sections cut through the center of individual crystals will be required to gain an accurate idea of the relative frequency of primary and synneusis twins in K-feldspar.

Synneusis in Quartz. The clearest evidence for synneusis of quartz is based on the textures of the quartz porphyries. The typical glomero-porphyritic habit of high quartz (Figs. 16 and 17), commonly involving 3—10 individuals which was noted as early as 1888 (McMahon), has since been confirmed by many petrographers (Laemmlein, 1930, Vance and Gilreath, 1967) and clearly establishes the importance of synneusis in these rocks. Statistical studies of many thousands of quartz crystals weathered from porphyries (Drugman, 1928; Laemmlein, 1930,

Fig. 16

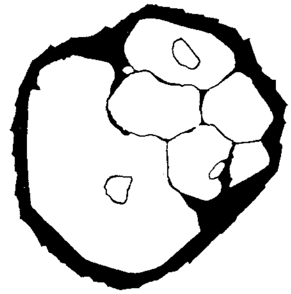

Fig. 17

Fig. 16. Rhyodacite porphyry dikerock, Monte Capanne, Elba. Complex glomero-porphyritic group of quartz crystals. Many contiguous individuals in parallel synneusis relation. Post-synneusis corrosion and incipient disaggregation. Width 5.1 mm

Fig. 17. Rhyodacite porphyry dikerock, Monte Capanne, Elba. Close-knit synneusis cluster of quartz crystals. Some corrosion along grain boundaries. Width 7.3 mm

1940) have shown that a high proportion are not simple single crystals, but are parallel intergrowths and twins consisting of two or more individual crystals. Complex interpenetrating forms are characteristic while simple and regular contact pairs are subordinate. The crystals are united on the rhombohedral faces $10\bar{1}1$ in the parallel intergrowths and the Esterel twins (Frondel, 1962), the two most common orientations. From these relations and from evidence provided by zoning, Laemmlein (1930, 1940) concluded that these crystal groups had formed by oriented attachment of already formed dipyramidal high quartz crystals on their rhombohedral faces. He also recognized that the irregular surface of intergrowth between the crystals was the result of continued growth after synneusis.

Synneusis of quartz is more difficult to establish in plutonic rocks where the effects of superimposed deformation and recrystallization combined with the absence of zoning, and the common absence of crystal form may obscure or obliterate the critical morphological evidence. Analogy with the porphyritic rocks would suggest, however, that the synneusis relation should be common in those granitic rocks in which quartz was among the early minerals to begin to crystallize. The clustering of subhedral dipyramids of high quartz noted in certain granodiorites and quartz monzonites confirms this expectation. The composite nature of these aggregates can sometimes be recognized by the presence of a thin layer or film of potassium feldspar between the quartz individuals (Figs. 18 and 19). The relation is directly analogous to that in many porphyries where a film of groundmass separates the individual gains making up the glomero-porphyritic groups (Balogh, 1913).

Synneusis of Plagioclase with Potassium Feldspar. Large crystals of potassium feldspar containing small oriented laths of plagioclase characterize many porphyritic granitic and related volcanic rocks (Figs. 15 and 20). As this structure has been considered at length in an excellent review by Frasl (1954), only a brief summary of its more significant features need be given here. The included plagioclase consists of plates or laths, tabular parallel to (010) which commonly show delicate concentric oscillatory zoning. In volcanic rocks the included plagioclase tends to be euhedral, but in plutonic rocks its form may be somewhat irregular

Fig. 18. Granodiorite, Chilliwack Batholith, Mineral Mountain, Washington. Complex quartz synneusis aggregate. Many adjacent grains in parallel or twin relation. Embayed quartz grains separated by orthoclase (black). Width 6.0 mm

Fig. 19. Granodiorite, Sunday Pluton, Washington Quartz synneusis patterns. Corroded aspect of quartz grains emphasized by surrounding orthoclase. Width 9.1 mm

Fig. 20. Carlsbad-twinned sanidine crystal from porphyry dike, Rogers Pass Montana. Section cut through center normal to c. Irregular outlines due to attrition in grinding. Concentric zones of small oriented plagioclase (unpatterned) and biotite (black) inlcusions in the sanidine host. Note that plagioclase synneusis occurred both on 110 and 010 while biotite is largely restricted to the prismatic faces. Diameter of crystal 1.2 cm

owing to replacement or albitic overgrowth related to incipient post-magmatic recrystallization. A majority of the inclusions is oriented with (010) parallel to prominent crystal faces or zones of the K-feldspar host, notably (010), (001), (110), $(1\bar{1}0)$, $(\bar{2}01)$. Biotite plates when present, likewise, tend to show parallelism of the base with the faces of the host. Commonly the inclusions occur in one or more concentric zones within the K-feldspar. Some typical patterns are seen in Figs. 15 and 20. Detailed studies of the mutual orientation of host and inclusions (Maucher, 1943; Kraus, 1962) indicate that, in addition to the obvious 2-dimensional orientation, a 3-dimensional orientation is commonly present also. Parallelism or near parallelism of the *c*-axes of the two feldspars when (010) of the plagioclase is parallel to (010), (110), or $(1\bar{1}0)$ of the host is an especially typical relation. Orientation with (010) of plagioclase on (001) and $(\bar{2}01)$ of the host likewise show certain statistical regularities.

As interpreted by Maucher and by Frasl the systematic orientation of inclusions and host implies the following history:

1. movement of plagioclase crystals suspended in a melt into contact with the larger K-feldspar crystals so that their broad faces are parallel;
2. rotation of the small plagioclase crystals toward certain stable positions determined by the lattice of the host, and attachment of the crystals;
3. incorporation of the plagioclase within the more rapidly growing K-feldspar host.

This mutual orientation cannot be explained in terms of epitaxis (that is growth of the plagioclase from oriented crystals nucleated on the surface of the host) because the symmetrically developed concentric zoning of the plagioclase inclusions shows that they were essentially full-grown when they became attached to the K-feldspar. These structures can only have formed in a fluid medium present in sufficient amount to permit free differential movement of crystals over distances at least as great as the maximum dimensions of the included minerals. Such mobility demonstrates the former presence of a melt phase and is consistent only with a magmatic environment. This interpretation is supported by Hibbard's study (1965) which shows that successive crops of plagioclase crystals included in concentric zones within the K-feldspar are increasingly sodic from the core to the rim of the host crystal (in keeping with the sequence of fractional crystallization).

Several recent workers (Cannon, 1964; Smithson, 1965), finding these same textures in augen-gneisses, have advocated their formation by growth in the solid state. Such an origin, however, cannot be reconciled with the evidence for rotation of the plagioclase inclusions implied by the parallelism of crystal faces of the included plagioclase with those of the host K-feldspar and with the systematic three-dimensional preferred orientation of host and guest. It would seem more reasonable to regard these gneisses as orthogneisses and the large K-feldspar crystals as relict phenocrysts.

K-feldspar phenocrysts with oriented plagioclase inclusions are among the most spectacular and useful of the common synneusis structures. Since they are commonly visible in hand specimen; they afford a field criterion of magmatic origin. As demonstrated by Frasl, these structures commonly survive metamorphism and provide compelling evidence for the magmatic parentage of certain augen-gneisses.

Synneusis of Minor Accessory Minerals with Biotite and Hornblende. Petrographers have long recognized the striking preferential association of minor accessory minerals such as apatite, zircon, and magnetite with biotite and hornblende in many igneous rocks. The validity of this observation has received decisive confirmation from recent statistical studies which show apatite and zircon to be concentrated in biotite and hornblende in amounts varying characteristically from 1.5 to 10 times that of a purely random distribution within the fabric (MOORHOUSE, 1956; LARSEN and POLDERVAART, 1957; KRAUS, 1962, 1963). The included crystals of accessory minerals characteristically tend to be oriented with their long dimension parallel to crystal faces of the host, and a 3-dimensional orientation is commonly present as well (KRAUS).

These relations are fully consistent with SCHERMERHORN's interpretation (1958) that the accessory minerals crystallized early and, moving about in the melt, became preferentially attached to the surfaces of the mafic early main constituents and eventually incorporated within them. Preferential synneusis thus appears to be a major factor in the distribution of the early accessory minerals within the fabric. It is of interest to note that early synneusis and incorporation of an accessory mineral in larger crystals of another mineral reduces the number of crystals of the accessory available for synneusis at a later time. Accordingly, the sequence of crystallization may strongly influence the quantitative relations of the included accessories with respect to the various host minerals.

Some Further Observations and Implications

Synneusis and the Distribution of Minerals in the Magmatic Fabric. In the examples just considered it was found that synneusis determines certain basic intergrain relations—notably mutual orientation (including twinning) and the nature of grain boundaries—in the magmatic fabric. Synneusis, however, is a selective process and implies a further and equally fundamental relation, the small-scale segregation of various individual minerals or groups of minerals within the overall fabric. Inspection of most porphyritic rocks reveals marked preferential clustering of phenocrysts into glomero-porphyritic aggregates. In order to define more precisely the selective character of synneusis, VANCE and GILREATH (1967) made a quantitative study of a varied group of porphyritic rocks each containing two or three phenocryst minerals. The modal amounts of the phenocrysts and the length of the contacts between all the phenocrysts of each mineral and mineral pair were determined by point-counting traverses. In each porphyritic rock a ratio was obtained for each mineral and mineral pair by dividing the percentage of the total contact area of mineral A occupied by mineral B by the modal amount of mineral B (phenocrysts recalculated to 100%). A ratio close to one indicates that the tendency for synneusis corresponds broadly to statistical probability and that synneusis is not selective. Ratios significantly greater than one indicate preferential synneusis, while values significantly less than one indicate antipathy toward synneusis. This study, supplemented by qualitative examination of synneusis structures in many other igneous rocks, supports the following generalizations:

1. for most minerals individual crystals of the same mineral species show a moderate to strong tendency for synneusis;

2. different pairs of unlike minerals show quite different synneusis tendencies; most pairs show moderate to strong antipathy, but some show a preference—specific pairs, however, commonly exhibit systematic behavior (e.g. plagioclase and K-feldspar characteristically show a distinct tendency for preferential synneusis, while quartz and plagioclase are strongly antipathetic).

Synneusis and Magmatic Paragenesis. In the plutonic igneous rocks the mineral distribution patterns occasioned by preferential synneusis have a critical bearing on the interpretation of the sequence of crystallization. This can be illustrated by a comparison of the textures of the porphyritic dacites with those of the equivalent plutonic rocks, the granodiorites and quartz diorites. A characteristic feature of many dacites is the preferential clustering of plagioclase with plagioclase and quartz with quartz in glomero-porphyritic aggregates, groupings of the two minerals being distinctly subordinate. Analogous structures are developed in many igneous granodiorites and quartz diorites. In these plutonic rocks the plagioclases are prominently grouped together in synneusis relation as may be seen from their zoning and morphology. The quartz is typically confined to an interstitial position and rarely penetrates far into the plagioclase grains. The morphology of the quartz commonly indicates a clustering of grains in synneusis aggregates (Fig. 18 and 19). In one interpretation the interstitial position of quartz and its absence as inclusions in the plagioclase are taken as evidence that it crystallized largely, or entirely at a very late stage. Such a history, however, is incompatible not only with the simultaneous early formation of quartz and feldspar in the equivalent quartz porphyries, but with the results of experimental crystallization of granitic liquids (TUTTLE and BOWEN, 1958).

Once the characteristic antipathetic behavior of quartz and plagioclase is recognized a more acceptable interpretation presents itself. Plagioclase and quartz may have crystallized together over a large part of the interval of consolidation. The absence of quartz inclusions in the plagioclase reflects the same antipathy toward synneusis which is so conspicuous in the porphyritic dacites. These two minerals simply never came into permanent contact until the final stages of crystallization when the unwanted contacts could no longer be avoided. The interstitial habit of quartz thus reflects its small amount and its aversion to synneusis with plagioclase, not simply late crystallization.

Many workers have remarked on the difficulty of evaluating magmatic paragenesis by the traditional textural criteria. Once the prevalence of synneusis textures in igneous rocks is recognized the reason for this difficulty becomes understandable. The selective and episodic character of this process necessarily precludes development of host-inclusion relationships which would fully record the crystallization sequence of all the minerals over the entire span of consolidation.

Disaggregation of Glomero-Porphyritic Groups. The boundaries between grains in synneusis relation are surfaces of weaker bonding than crystallographic planes within single grains, particularly so where initial attachment of the grains took place in orientations differing slightly from the stable parallel or twin orientations and atomic match across the boundary is not ideal. As a consequence, these boundaries are potential surfaces of mechanical separation. Such separation leading to disaggregation of synneusis groups is probably common, especially in porphyritic hypabyssal and volcanic rocks. LAEMMLEIN (1930) showed this mechanism to be responsible for the typical assymetrically developed quartz phenocrysts of many porphyries which had been previously attributed to "one-sided corrosion". Disaggregation is probably also widespread in other types of synneusis groups, such as plagioclase. This may be the origin of many assymetric crystals which have been interpreted as broken single crystals. Such crystals, however, never were complete, but owe their assymetrical development to post-synneusis growth in competition with adjacent grains.

Disaggregation may result from mechanical forces, such as explosive volcanism or stresses related to pressure-decrease during rise of magma in the crust, but perhaps more commonly involves "ungluing" of glomeroporphyritic groups by preferential resorption along grain boundaries.

Experimental Synneusis. Structures directly analogous to synneusis have been produced experimentally. In 1896 GAUBERT recognized the mechanism here termed synneusis twinning. He found that crystals of lead nitrate grew untwinned when allowed to develop undisturbed from an aqueous solution, but developed as groups of crystals twinned on the spinel law or intergrown in parallel orientation when shaken periodically and allowed to settle together on the bottom of the container during the crystallization process. He was able to observe directly that these twinned and parallel structures are the result of oriented attachment of separate crystals on their octahedral faces.

VIOLA (1902) carried out several experiments on artificial synneusis of plagioclase crystals suspended in heavy liquids. He noted that if the liquid is shaken and allowed to slowly come to rest, the crystals tend to drift together and adhere on their broadest faces, typically in such a way that their longest dimensions are parallel.

SCHASKOLSY and SCHUBNIKOW (1933) carried out a series of experiments patterned after those of GAUBERT and VIOLA from which they were able to statistically evaluate the preferred orientation of small potash alum crystals which became attached to larger ones. Approximately 80% of the resultant groupings involved attachment of the crystals on the octahedron (the most prominent face), the prevalent relations being parallel or near parallel orientation and, somewhat less frequently, twinning on the spinel law.

These experiments all duplicate the two most characteristic features of synneusis in igneous rocks, the strong affinity for union of like crystals and their prevalent attachment in parallel or twinned orientation. Further studies along these lines should help resolve the problem of the ultimate nature of the forces responsible for synneusis.

Some Theoretical Aspects of Synneusis. Synneusis typically involves preferred orientation of the participating crystals in certain systematic patterns. It can be shown that these orientations meet the requirement that one or more atom rows common to the two structures are coincident. As permanent attachment normally occurs only in these orientations, they are evidently the most stable ones possible. Conversely, it may be supposed that the antipathy of certain mineral pairs toward synneusis reflects the absence of lattice rows with similar parameters on the prominently developed crystal faces. The common mutual orientations in synneusis correspond to positions of minimum or near minimum interfacial energy. Especially significant is the fact that parallel orientation is the most common relation among like crystals. Crystal accretion by parallel synneusis has much the same physico-chemical significance as simple crystal growth, though on a different scale. As in crystal growth, addition of new units to the structure in parallel position produces the configuration of lowest free energy and greatest stability. Addition of new units in twin position is only slightly less stable energetically, but addition in random orientation is unstable (see BUERGER, 1945).

The marked aversion of certain mineral pairs toward synneusis demonstrates that reduction of the total surface energy by decrease in surface area is probably only a minor factor in synneusis. It is evident from the observation that certain synneusis combinations do not occur, in spite of the lower surface energy which would accrue, that other, stronger forces must be involved.

From the purely mechanical standpoint there are two different ways in which preferred orientation may have come about during synneusis. These possibilities are briefly considered here, for they relate directly to the problem of the nature of the forces responsible for synneusis. Most workers who have considered the mechanism of synneusis favor the interpretation that the crystals first came together with two broad faces parallel and subsequently rotated into one of the preferred mutual orientations (hypothesis I). The theoretical basis for this view has been developed by FRONDEL (1940). For two crystals lying in contact there is only one orientation of minimum interfacial energy. This orientation is the most stable mutual coincidence of the crystals. If a freely suspended crystal is brought randomly on a plane crystalline surface it will tend to rotate toward this position under its original impetus. As the impetus decreases a point will be reached at which the kinetic energy is insufficient to push the crystal over some position of relatively high interfacial energy. These factors will lead to a statistical preference for orientations, near, but not necessarily coincident with, the most favored position. Secondary maxima will be associated with any slightly less-favored orientations that may exist.

An alternative hypothesis is that the crystals joined initially in the preferred position. This second hypothesis has two variations. The first (hypothesis IIa) is that the crystals approach each other in a random manner and that only those crystals which meet fortuitously in or near the proper orientation will adhere permanently. The second possibility (hypothesis IIb) is that most initial contacts occur in a preferred position and are permanent. This would imply the existence of some long range force to cause mutual attraction of the crystals and to orient them before contact.

A choice between these several possibilities must await direct observation of synneusis in controlled experiments. Hypothesis I, however, appears to be the most immediately attractive. Hypothesis IIa would imply a great many transitory encounters between crystals for every instance of permanent attachment. It seems improbable that purely random encounters would give rise to the high proportion of crystals in synneusis relation actually observed. Hypothesis IIb is difficult to evaluate, given the problematical nature of the "force of attraction" which would be required. The possible existence of some long range force capable

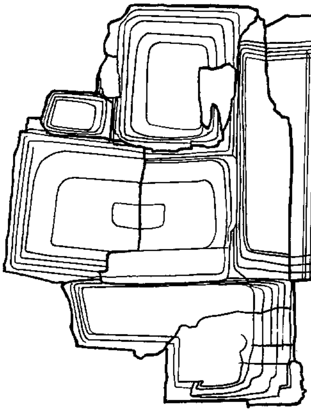

Fig. 21

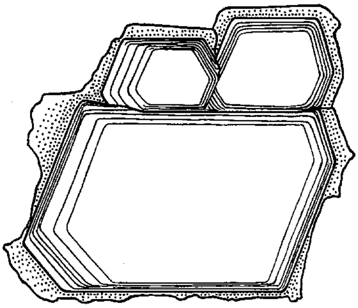

Fig. 22

Fig. 21. Granodiorite, Squire Creek Pluton, Washington Group of plagioclase crystals, mostly normal to *a*, in parallel synneusis relation. Minor post-synneusis overgrowth. Note the tight nesting of later-arrived crystals in preexisting reentrants. Width 1.3 mm

Fig. 22. Granodiorite, Methow Washington. Three plagioclase crystals cut parallel to (010) in parallel synneusis relation. Note the snug fit of the two smaller crystals seated on (001) of the larger crystal. Width 1.4 mm

of both attracting and orienting the crystals cannot, however, be dismissed a priori, in fact one line of petrographic evidence lends strong support to this hypothesis. It is commonly observed that not all like crystals in synneusis relation show the misfit in alignment that might be expected in hypothesis I. In K-feldspars showing synneusis Carlsbad twins, for instance, the individual crystals are commonly united in a remarkably symmetrical and balanced manner so that their centers of gravity are as close as possible and that there is a maximum overlap on surface of initial contact. Moreover, in complex synneusis groups of three or more plagioclase crystals, the crystals which became attached latest, are commonly fitted-in like building blocks so as to snuggly occupy a reentrant between earlier-united crystals (Figs. 21 and 22). The abundance of such synneusis groupings seems inconsistent with purely random encounters. In order to accommodate these relations, hypothesis I would have to be modified to include a major component of translation within the plane of contact as well as the requisite rotation normal to it. Initial impetus, however, lacks the vectorial properties implied by such translation and interfacial forces would seem too weak to produce it. On the other hand the activity of a long range force, possibly electrostatic, is fully consistent with the observed synneusis relations.

It is probable that magmatic turbulence is a major factor in the differential movement of crystals in synneusis. Turbulence would have to be active enough to bring about many contacts between crystals, yet not so vigorous as to overcome the cohesive forces between the crystals and separate them. As a highly turbulent magma comes slowly to rest there will presumably be some stage at which these factors are balanced so as to favor synneusis. If this interpretation is correct, each episode of synneusis reflects a single phase of active movement within the magma related to processes such as emplacement, injection of a new magma pulse into the magma reservoir, vigorous convection, etc. In some rocks, notably certain layered gabbros, gravity has been the principal agent of differential movement of crystals leading to synneusis. Planar interfaces between otherwise anhedral grains in such gabbros have been described by Brown (1956) and Brothers (1964) and interpreted as the result of union of crystals during settling prior to intercumulus overgrowth. A study of the fabric produced by crystal sedimentation from the standpoint of the synneusis concept ought to reveal interesting parallels with those produced experimentally.

Textural evidence suggests that synneusis is an episodic process. In many rocks it seems to have been largely restricted to the earlier stages of consolidation, as is indicated by extensive post-synneusis intergrowth or overgrowth of the participating crystals. Synneusis in the earlier stages of consolidation would be favored by the high ratio of melt to crystals, permitting relatively free differential movement. Progressively increasing viscosity would also tend to restrict the activity of synneusis later in the interval of crystallization. Two or more episodes of synneusis can be established in some rocks. Early glomero-porphyritic groups which have become intergrown may be joined by microlites in synneusis relation at a later stage (e.g. Ross, 1957). Recurrent synneusis is demonstrated in still other rocks by large K-feldspar crystals showing repeated zonal concentrations of oriented plagioclase or biotite inclusions.

Crystal habit may also influence synneusis patterns, for observation shows that the most frequent synneusis combinations involve union on the best developed crystal faces. Variation in the synneusis patterns of a single mineral or mineral pair in different rocks can probably be explained largely in terms of differences in crystal habit and in the timing of periods of magmatic turbulence with respect to the crystallization sequence.

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