

THE GEOMETRICAL ANALYSIS OF PARTIAL FUSION*

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ABSTRACT. Equilibrium crystallization is the reverse of equilibrium fusion, but fractional crystallization and fractional fusion are distinctly different processes. During fractional crystallization, crystal paths show compositional breaks, but liquid paths do not. During fractional fusion, crystal paths are continuous, but liquid paths frequently have compositional breaks corresponding to temperature intervals during which addition of heat causes no melting. These compositional breaks result from a decrease in the number of components necessary to specify the compositions of the phases in the residual crystalline aggregate. Solidus fractionation lines define crystal paths followed during fractional fusion and can be used to deduce the corresponding liquid paths. Solidus fractionation lines may also be used to deduce crystal and liquid paths followed during equilibrium fusion. Examination of simple phase diagrams reveals that many compositions that melt to produce liquid at a peritectic or eutectic point or on a boundary line would yield the same or nearly the same liquid composition even though wide variations in the amount of melting are permitted. This type of melting is suggested as a possible explanation for the large volumes of chemically homogeneous tholeiitic magma extruded on the continents and along ocean ridges.

INTRODUCTION

Current hypotheses suggest that the crust, mantle, and core originated by fusion and segregation of an initially homogeneous cold Earth (Birch, 1965; Ringwood, 1960), and subsequent fusion of the crust and mantle throughout geologic time is thought to play a vital role in controlling the compositions of most of the igneous rocks now seen on the Earth's surface. Theories have been proposed suggesting that the compositions of granites (Winkler, 1967), andesites (Green and Ringwood, 1968), and various types of basalt (Kuno, 1959; Kushiro, 1968) are controlled primarily by fusion processes. Even if one subscribes to the classical concept of Bowen that fractional crystallization of basalt is responsible for the production of other igneous rock types, the composition of the basaltic parent must ultimately be controlled in large measure by fusion processes.

Through the writings of Schreinemakers (1905), Bowen (1914, 1915, 1941), and Bowen and Schairer (1933, 1935), the geometrical methods for deriving paths of crystallization on a phase diagram have been known for many years. Bowen (1928, p. 27, 31, 33, 43-44, 48) discussed fusion briefly and showed that it does not always yield the same sequence of liquids as are produced by crystallization, but despite this demonstration, one encounters statements in the current literature that fusion may be considered simply as the reverse of crystallization. In view of the importance of melting phenomena to petrogenetic theory and in view of the confusion that sometimes surrounds this subject, it seems useful to present the geometrical methods by which the process of fusion may be analyzed on a phase diagram. These methods are exactly analogous to those used by Schreinemakers and Bowen in their discussions of crystallization. Following the development of the geometrical methods, some

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aspects of the generation of basaltic magma will be discussed in the light of these methods.

Bowen (1941) distinguished two types of crystallization, *equilibrium crystallization* and *fractional crystallization*. In the former, crystals formed on removal of heat continually react and reequilibrate with the liquid. In the latter, the crystals are immediately isolated from the system as soon as they are formed and are thereby prevented from further reaction with the liquid. A precisely analogous distinction will be made here with respect to fusion. *Equilibrium fusion* will refer to the situation in which the liquid produced on heating continually reacts and reequilibrates with the crystalline residue. *Fractional fusion* will refer to the situation in which the liquid is immediately isolated from the system as soon as it is formed and is thereby prevented from further reaction with the crystalline residue.

The term fractional fusion is frequently used interchangeably with partial fusion to indicate melting of something less than the whole of a body of rock. This usage of fractional fusion is discarded here in favor of the above definition. *Partial fusion* will be retained as a term meaning fusion of some portion less than the whole. Thus, partial fusion could refer to equilibrium fusion, fractional fusion, or some process intermediate between these two extremes.

GEOMETRICAL METHODS

Complete solid immiscibility relationships.—In nature, all gradations between fractional and equilibrium fusion may be expected to occur, but it is convenient to start by examining the two extremes. Consider first a phase diagram with a ternary eutectic and with complete immiscibility of the solid phases (fig. 1). During equilibrium crystallization of composition x , the composition of the liquid will change along path $x-s-t$, here called the *liquid path*. Simultaneously, the aggregate composition of the precipitating crystals will change along the path $B-m-x$, called the *crystal path*. The term aggregate composition is used so as to emphasize the fact that the bulk composition of the precipitating crystals can, in general, consist of one phase or a mixture of several phases in varying proportions. During fractional crystallization, the liquid path in this special case is the same as for equilibrium crystallization, but the crystal path is discontinuous and consists of the point B , the line y_1-y_2 , and the point t . The lines y_1-s and y_2-t are tangents to the boundary line¹ $p-t$ at the points s and t respectively. This discontinuous nature of the crystal path is characteristic of layered intrusions formed by fractional crystallization (for example, see Wager, 1960, figs. 3, 4).

Equilibrium fusion of composition x results in precisely the reverse sequence of events as equilibrium crystallization. The liquid changes

¹ The term "boundary line" is used as defined by Levin, Robbins, and McMurdie (1964, p. 5). The familiar and equivalent term "boundary curve" is discarded so as to avoid, in a later part of the paper, the awkward necessity of referring to "curved boundary curves" and "straight boundary curves".

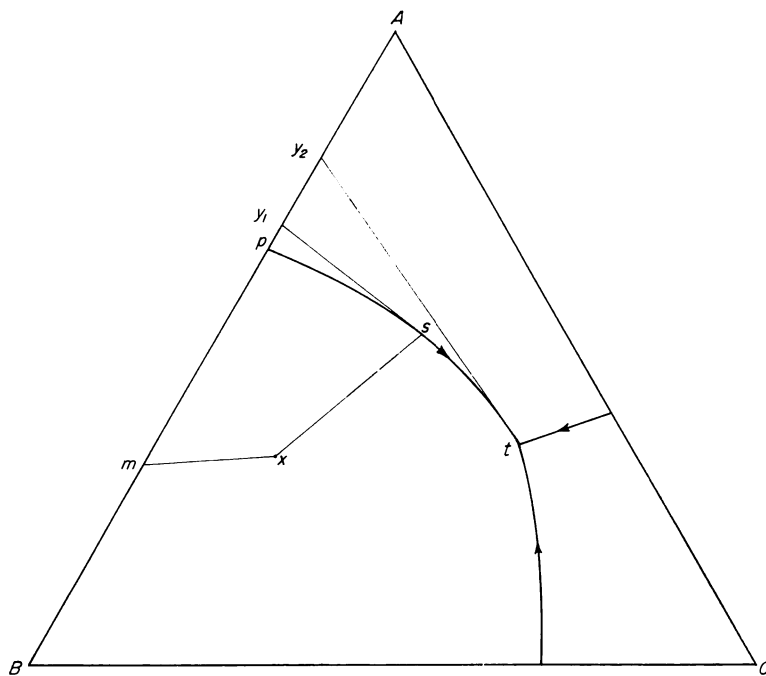


Fig. 1. Liquid and crystal paths for a ternary eutectic with no solid solution. Heavy lines are liquidus boundary lines with arrows indicating directions of decreasing temperature.

composition along the liquid path² t - s - x , and the aggregate composition of the crystals simultaneously changes along the crystal path x - m - B .

Fractional fusion of composition x produces quite a different result. As with equilibrium fusion, the first liquid produced is at the eutectic t . Removal of this liquid as it is formed drives the aggregate composition of the residual crystals directly away from t along the line x - m . Throughout this stage of melting, the temperature remains constant at that of the eutectic t . When the crystal path reaches point m , no further fusion takes place until the temperature rises to that of the binary eutectic p . This temperature interval during which heating occurs without the production of any liquid corresponds to a decrease from 3 to 2 in the number of components necessary to describe the phases present. Further addition of heat results in no increase in temperature while liquid p is produced and the aggregate composition of the residual crystals is driven from m to B . After the crystal path reaches B , there is an interval between the temperature of the eutectic p and the melting point of pure B when no fusion takes place. As before, the temperature interval without the production of liquid is the result of a decrease in the number of components necessary to specify the phases present. Upon reaching the

² The terms liquid path and crystal path will be used both for crystallization and for fusion processes.

melting temperature of pure B , a final liquid is produced of this composition. Thus, the liquid path is discontinuous and consists of three points t , p , and B , 35 percent of the original starting mixture being produced as liquid t , 31 percent as liquid p , and 34 percent as liquid B . In contrast, the crystal path $x-m-B$ has no compositional breaks.

In figure 1, any starting composition (except the one corresponding to the eutectic t) will have a similar fractional fusion history. The crystal path will always move directly away from t until it reaches a side of the triangle and then will move directly toward either A , B , or C . Figure 2 shows representative members of the family of lines that describe the crystal path during fractional fusion of any composition in the system; these lines, called *solidus fractionation lines*, are drawn on the solidus surface.

To summarize, equilibrium fusion produces precisely the same sequence of events as equilibrium crystallization, except in reverse order. On the other hand, fractional fusion and fractional crystallization yield distinctly different results. During fractional fusion, the liquid path is compositionally discontinuous; and the production of each liquid is separated by a temperature interval during which no fusion occurs, each temperature interval being the result of a decrease in the number of components necessary to specify the phases present. The crystal path is

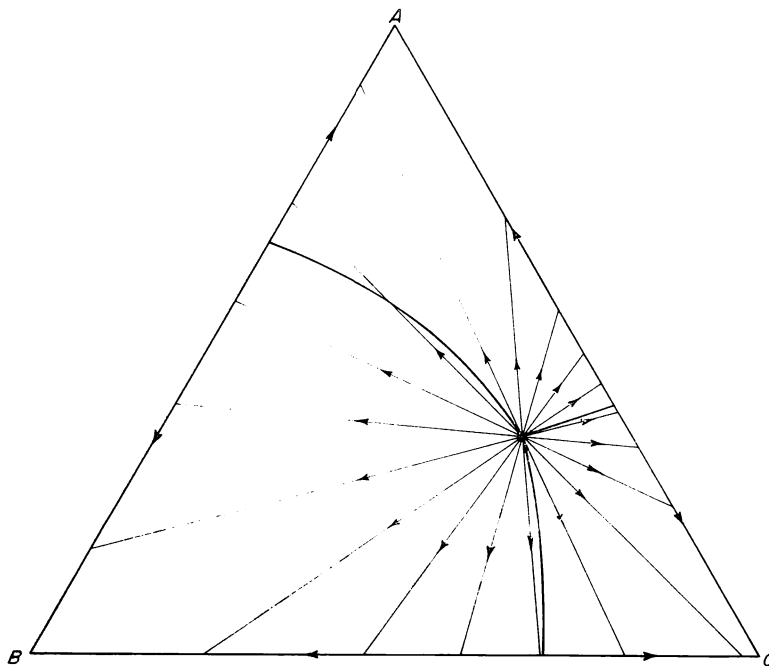


Fig. 2. Solidus fractionation lines for the system illustrated in figure 1. Arrows on fractionation lines indicate directions of change in the aggregate composition of residual crystals during fractional fusion.

compositionally continuous. During fractional crystallization, the liquid path is compositionally continuous and shows only one point of overlap (t) with the liquid path produced by fractional fusion; the crystal path is compositionally discontinuous and contains one point of overlap (B) with the crystal path produced by fractional fusion.

Solid solution relationships with straight boundary lines.—Now consider a ternary system (fig. 3) with one component (A) showing complete solid immiscibility with the other two components, and with these other two components (B, C) showing complete solid solution with each other. Assume further that the solidus and liquidus curves of the system B - C show a continuous decrease in temperature toward B . Such a system is diopside-albite-anorthite (Bowen, 1915). Figure 3 is drawn nearly identically to the system diopside-albite-anorthite, except the liquidus boundary line m - n has been drawn perfectly straight rather than curved, as it actually exists. It is now known (Kushiro and Schairer, 1963) that the system forsterite-diopside-anorthite cannot be rigorously described using these three components, but this need not concern us here since figure 3 is only an idealized representation.

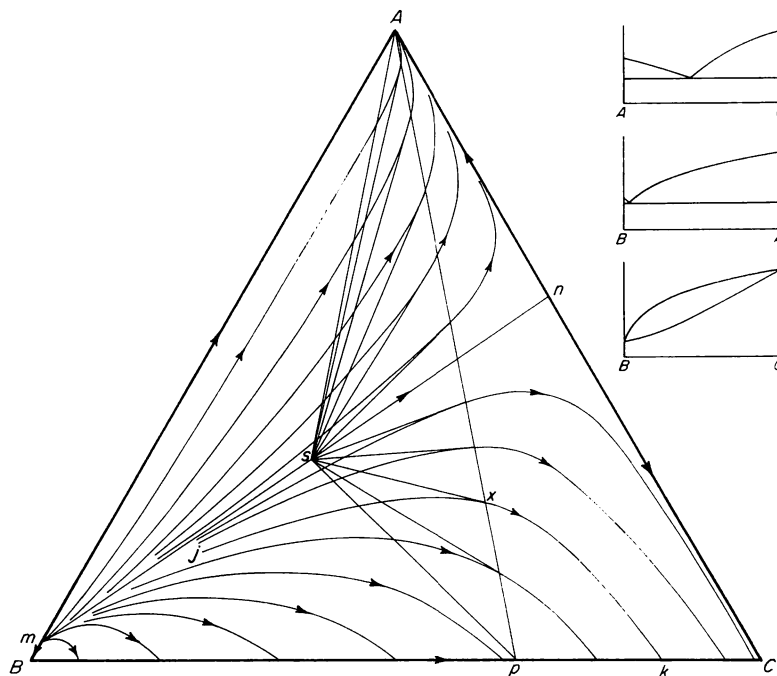


Fig. 3. Solidus fractionation lines for a system showing complete solid solution between B and C and complete solid immiscibility between A and B and between A and C . The straight fractionation line m - n coincides with a liquidus boundary line that decreases in temperature toward m . Arrows are used as in figure 2. The three bounding binary systems are shown in the upper right corner.

Crystallization behavior in a system of this type has already been treated (Bowen, 1915) and need not be repeated.

In deriving paths of fusion, it is necessary first to picture the shape of the solidus surface. In the previous example (figs. 1 and 2), this was a trivial matter since the solidus surface (exclusive of the bounding binary systems) consisted merely of an isothermal plane. Where solid solution exists, as in figure 3, the solidus surface is a sloping, generally curved, surface. In figure 3, the solidus surface slopes to the left, and isotherms on this surface consist of a family of straight lines, all passing through the apex A and intersecting the base $B-C$. For example, all mixtures on the solidus isotherm $A-p$ will start melting at the same temperature, and the composition of the first liquid to form will be s . For any starting composition on the line $A-p$, say x , subtraction of an infinitesimal amount of liquid s during fractional fusion will drive the aggregate composition of the residual crystals directly away from s ; the line $s-x$ is thus tangent to the crystal path at x . Repetition of this construction over the entire diagram yields a family of solidus fractionation lines, one of which is $j-x-k$. These curved lines are drawn so as to be always tangent to lines such as $s-x$ at x . Given the solidus fractionation line through any aggregate crystalline composition (x), the composition (s) of the liquid in equilibrium with that aggregate crystalline composition is defined by the intersection of the tangent to the solidus fractionation line at x and the appropriate liquidus boundary line ($m-n$). A solidus fractionation line, then, describes the crystal path followed during perfect fractional fusion. The lines called fractionation curves by Bowen (1941) will be referred

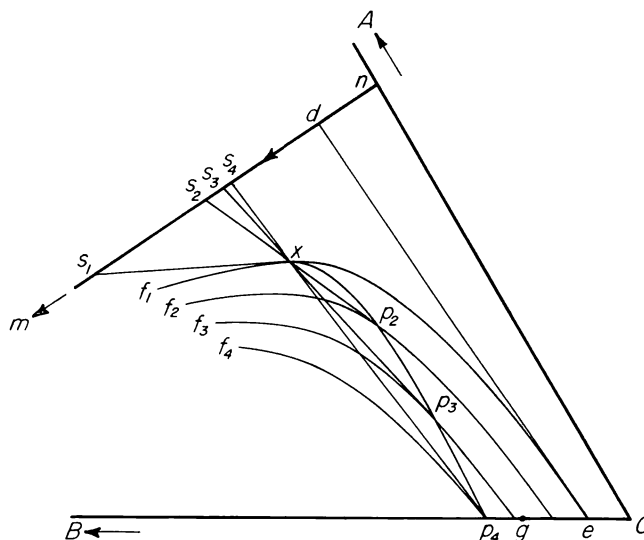


Fig. 4. Derivation of liquid and crystal paths during equilibrium and fractional fusion. The arrow on the liquidus boundary line $m-n$ indicates the direction of decreasing temperature.

to here as *liquidus fractionation lines*; they are drawn on the liquidus surface and describe the liquid path followed during perfect fractional crystallization.

In deriving crystal and liquid paths followed during equilibrium fusion, one may use familiar methods for determining the equilibrium crystallization history and recall that equilibrium fusion yields precisely the reverse sequence of events. On the other hand, it is more convenient and instructive to derive certain parts of the equilibrium fusion history directly from the solidus fractionation lines. Figure 4 illustrates the method. From the starting composition x lying on the solidus fractionation line f_1 , tangents to the fractionation lines f_2 , f_3 , and f_4 are drawn at p_2 , p_3 , and p_4 . The crystal path, $x-p_2-p_3-p_4$, is the locus of all such points of tangency. At each stage of fusion, the starting composition must lie on the join between the composition of the liquid and the aggregate composition of the crystals. Thus, as the crystal path moves from x through p_2 and p_3 to p_4 , the liquid path moves from s_1 through s_2 and s_3 to s_4 .

The solidus fractionation lines define only the aggregate composition of crystals in equilibrium with liquids on the boundary line $m-n$. In order to complete the melting of composition x at temperatures above s_4 , the liquid path must leave the boundary line $m-n$ and travel along a curved line (not shown) to x as the crystal path moves a short distance toward C from p_4 . Therefore, this part of the equilibrium fusion history cannot be deduced from the solidus fractionation lines; it is necessary to use the liquidus fractionation lines (see Bowen, 1941, for a discussion on their use).

On the other hand, an understanding of the complete course of fractional fusion of composition x does not require the use of liquidus fractionation lines, for the only liquids produced lie either on the boundary line $m-n$ or on the base of the triangle $B-C$. That is, the liquid path is discontinuous and consists of the lines s_1-d and $g-C$; s_1-x and $d-e$ are tangents at x and e to the solidus fractionation line f_1 . The point g marks the composition of the first liquid produced on melting the crystal-line solid solution e and is determined from a knowledge of the binary system $B-C$; it cannot be determined from either the solidus or liquidus fractionation lines. The crystal path during fractional fusion of x is the continuous path $x-e-C$.

Again, as in the case of the previous example of a system with a ternary eutectic, the crystal path during fractional fusion is compositionally continuous, and the liquid path is discontinuous with a temperature gap at the discontinuity during which no fusion occurs. As before, this gap is the result of a reduction (from 3 to 2) in the number of components necessary to specify the phases present in the residuum.

In figure 3, the sense of curvature is the same for all fractionation lines on one side of the liquidus boundary line $m-n$. The explanation for this is evident from the geometry shown in figure 5. Here $A-p$ is the base of a three-phase triangle whose apex on the liquidus boundary line

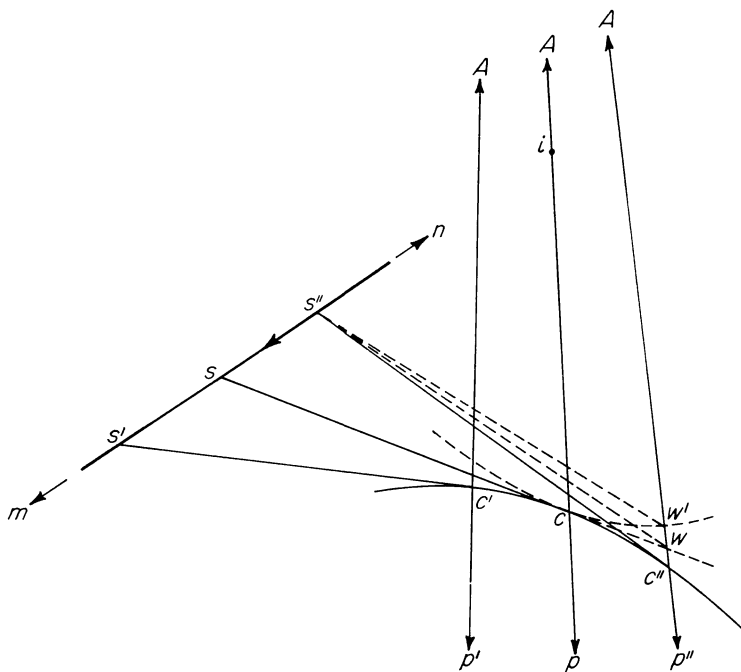


Fig. 5. Schematic portion of figure 3 illustrating curvature of solidus fractionation line $c'-c-c''$.

$m-n$ is s . Similarly, $A-p'-s'$ and $A-p''-s''$ are three-phase triangles at arbitrary distances to the left and right of $A-p-s$. The point i is the intersection of the base of the three-phase triangle $A-p-s$ with the tangent to the liquidus boundary line at s . In this case, the boundary line $m-n$ is straight, so i is also the intersection of the base of the three-phase triangle with the boundary line. Let c be any point on the line $A-p$ below i . Then $s-c$ is the tangent to the solidus fractionation line passing through c . We now inquire if the fractionation line passing through c is straight, concave upward, or concave downward. It cannot be straight or concave upward, for then it would intersect the base of the three-phase triangle $A-p''-s''$ at w or w' . In these two cases, it is geometrically impossible for the lines $s''-w$ or $s''-w'$ to be tangent to the fractionation line, as they are required to be by definition. The same arguments apply for the three-phase triangle $A-p'-s'$. The only alternative is for the fractionation line $c'-c-c''$ to be concave downward at c . By the same logic, if we had chosen any point on $A-p$ above i , the fractionation line passing through that point would have to be concave upward. Point i marks the change in curvature along the line $A-p$, the fractionation line passing through i having no curvature at i . In this special case, it possesses no curvature anywhere along its length and is coincident with the boundary line $m-n$.

Solid solution relationships with curved boundary lines.—Taking now the case of a boundary line $m-n$ that is curved, the same construc-

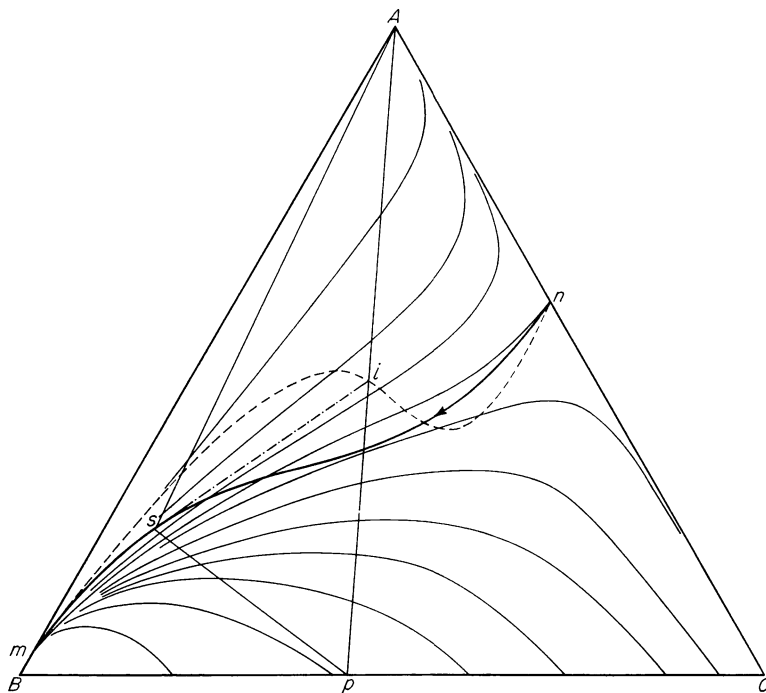


Fig. 6. Solidus fractionation lines for the case of a curved boundary line with an inflection point.

tion used in figure 5 applies, since a straight line can be made to approximate the curvature at s to any desired accuracy simply by choosing arbitrarily small distances $s'-s$ and $s-s''$. The point i remains as the intersection of the base of the three-phase triangle $A-p$ and the tangent to the boundary line at s , but i no longer lies on the boundary line. As before, i is the point at which fractionation lines crossing $A-p$ change their sense of curvature, and a fractionation line passing through i has no curvature at i . In this case, it has curvature elsewhere, and i marks the location of an inflection point.

The complete set of solidus fractionation lines for the case of a curved boundary line is shown in figure 6. Here, the boundary line $m-s-n$ is not only curved but shows an inflection point. This is the situation as it actually exists for the system diopside-albite-anorthite (Bowen, 1915), although the curvature in figure 6 has been exaggerated for clarity. The dashed line is the locus of inflection points on fractionation lines, any point i on this line being given by the intersection of the base $A-p$ of a three-phase triangle and the tangent $s-i$ to the liquidus boundary line at the apex s of the three-phase triangle. It follows from the construction of figure 5 that all fractionation lines intersecting the base $A-p$ of a three-phase triangle will be concave upward between A and i and concave downward between i and p .

Fusion relationships in the system MgO-iron oxide-SiO₂.— Having considered fusion relationships for liquids produced at ternary invariant points (figs. 1 and 2) and along univariant lines (figs. 3-6), now consider a more complex system that displays both these situations in combination. Such a system is MgO-iron oxide-SiO₂ in equilibrium with CO₂ (fig. 7). As explained in a previous paper (Presnall, 1966, p. 755-757) figure 7 may be treated as a ternary system for purposes of deducing crystal and liquid paths.

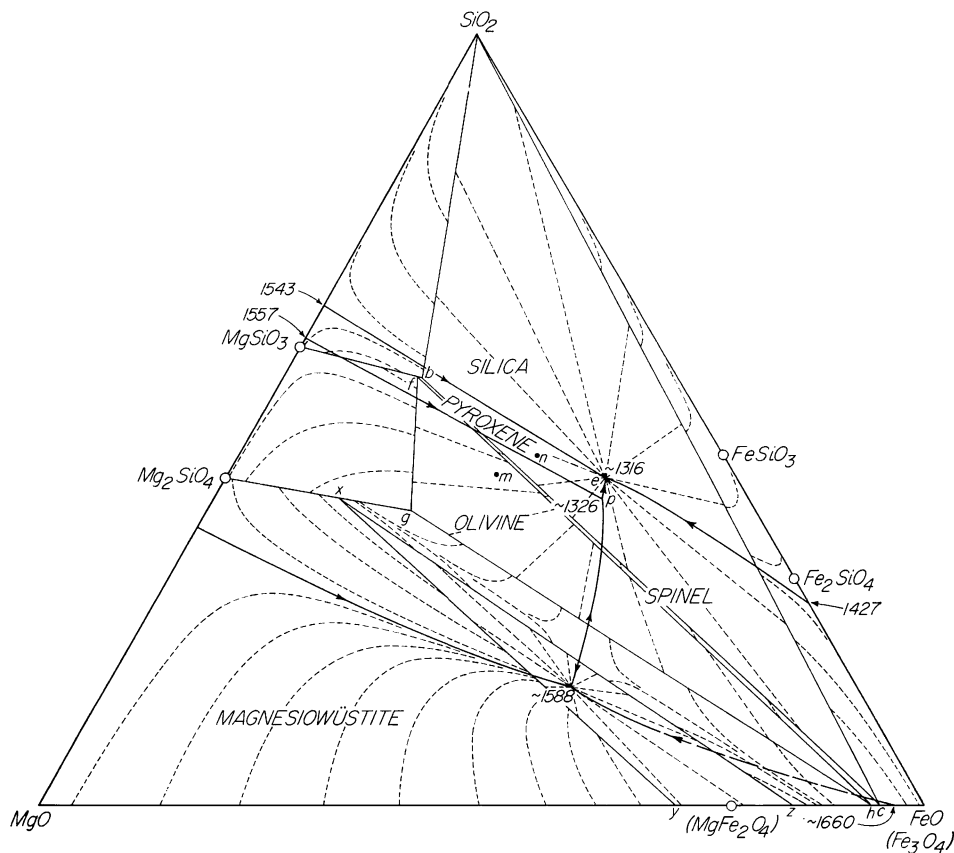


Fig. 7. The system MgO-iron oxide-SiO₂ (wt percent) at the oxygen fugacity produced by the equilibrium decomposition of pure CO₂, interpolated from diagrams and data by Muan and Osborn (1956), Phillips, Sōmiya, and Muan (1961), and Speidel and Osborn (1967). All iron oxide is calculated as FeO. Compounds in parentheses have been projected onto the join MgO-FeO from the oxygen apex of the triangle Mg-Fe-O. Heavy lines with arrows indicating directions of decreasing temperatures are liquidus boundary lines. Light solid lines show compositions of phases in equilibrium at solidus temperatures. Light dashed lines are solidus fractionation lines. Due to lack of data, these lines, where curved, are only schematically correct. Compositions of olivine, spinel, and magnesio-wüstite in equilibrium at points x, y, and z are inferred.

The solidus surface of figure 7 consists of a combination of three triangular isothermal planes (the triangles SiO_2 - b - c , f - g - h , and x - y - z) and six sloping, curved surfaces (such as Mg_2SiO_4 - $MgSiO_3$ - f - g and x - g - h - z), each isothermal plane being associated with a liquidus invariant point, and each sloping, curved surface being associated with a univariant liquidus boundary line. In addition, there are temperature discontinuities on the solidus surface along the lines Mg_2SiO_4 - g , $MgSiO_3$ - b , and the three bounding binary systems. The temperature of each isothermal plane is that of its corresponding liquidus invariant point, and the temperature variations on the sloping surfaces are those of their corresponding liquidus univariant lines. Isotherms on the sloping curved surfaces are straight lines coincident with tie-lines (not shown). On each of the three isothermal planes, solidus fractionation lines radiate directly away from the appropriate liquidus invariant point just as in figure 2; solidus fractionation lines on the sloping surfaces are curved lines derived as in figure 3.

As an illustration of equilibrium fusion, consider composition v (fig. 8). The first liquid formed on heating lies at the peritectic p and remains at p as the crystal path moves from v to r_1 ; the addition of heat during this stage does not increase the temperature. Just as the crystal path reaches r_1 , 28 percent of the total mass is present as liquid p . The crystal path is extended past r_1 by dropping tangents from v to the dashed solidus fractionation lines at r_2 , r_3 , and r_4 ; since the starting composition must always lie on the tie-line between the liquid composition and the aggregate composition of the crystals, the liquid path moves from p through n_1 and n_2 to n_3 . With further heating, the liquid path moves along a curved line (not shown) from n_3 to v as the crystal path moves a short distance toward e from r_4 .

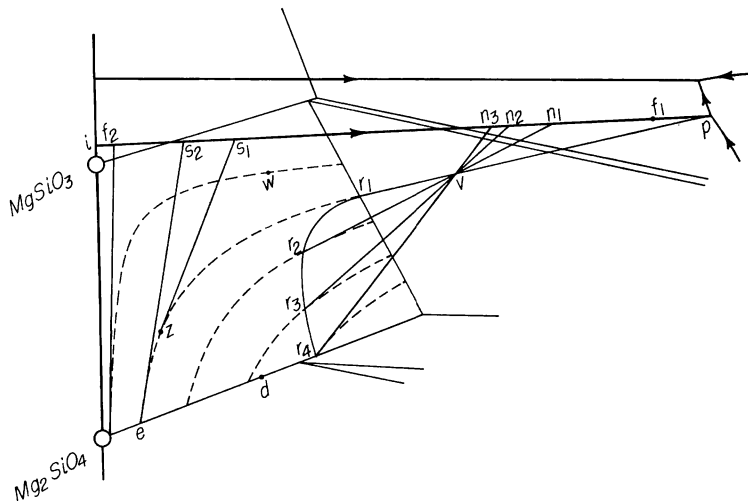


Fig. 8. Enlarged portion of figure 7 to show crystal and liquid paths.

During the initial stages of fractional fusion of composition v , the crystal and liquid paths are the same as for equilibrium fusion; that is, the crystal path moves from v to r_1 as liquid is produced at p . Further heating causes the crystal path to follow along the solidus fractionation line r_1 - z - e as the liquid path moves from p to s_2 along the boundary line p - i . When the liquid path reaches s_2 , the temperature is approximately 1530°C, and further addition of heat produces no more liquid until the temperature reaches about 1840°C. At this temperature liquid d is produced, and with continued heating the crystal and liquid paths both move along the olivine join to pure Mg_2SiO_4 , where fusion is complete at 1890°C, the melting point of Mg_2SiO_4 .

GEOLOGICAL APPLICATIONS

In the above discussion, only the two extremes of fractional and equilibrium fusion have been considered, but it is not intended to imply that partial fusion in the Earth's crust and mantle may be represented only by one or the other of the extremes. All gradations between equilibrium and fractional fusion probably occur.

As more data become available on systems at high pressures, the geometrical methods outlined above should become increasingly useful in gaining a better understanding of magmatic processes in the mantle and lower crust. As an illustration of the use of these methods, some aspects of the generation of tholeiitic³ magmas will now be considered.

Tholeiitic magmas.—Tholeiitic lavas associated in time and extruded within a given geographic region or environment frequently are erupted in great volume and are found to be very uniform in chemical composition. For example, Waters (1962, p. 162) noted that the Yakima basalt on the Columbia Plateau probably exceeds a volume of 30,000 cubic miles. He noted further that (p. 162) "The most striking feature of the Yakima tholeiitic magma was its surprising uniformity in composition when we consider the great volume of lava that was extruded. . . . In many measured sections, 2000 or more feet thick, there is no appreciable difference in the flows from top to bottom, and the same uniformity holds with respect to samples collected from widely spaced areas in the lava field." Later in the same paper, he noted in regard to the high-alumina basalt of the Oregon plateaus that (p. 164) "The undifferentiated high-alumina basalt . . . shows great uniformity in petrographic and chemical character, [and] is present in enormous volume. . . ."

Similar observations have been made on the Karroo dolerites and associated Stormberg basalts. The Stormberg lavas extend over an area of 10,000 square miles with a maximum thickness of 4500 feet and Du Toit (1920, p. 3) noted that the dolerites are intruded over an area of at least 220,000 square miles. Walker and Poldervaart (1949) compared the average compositions of the undifferentiated dolerites, the chilled

³ This term will refer to basalts whose normative composition in the tetrahedron nepheline-olivine-clinopyroxene-quartz lies to the SiO_2 -rich side of the plane olivine-clinopyroxene-plagioclase (Yoder and Tilley, 1962, fig. 2).

margins of the dolerites, and the basalts and stated that (p. 672-673) "The three averages show remarkable agreement [and] . . . the average chemical compositions of the chief types of dolerite are grouped quite closely around the grand average." Crystal fractionation is characteristic of these rocks, but those dolerites that are differentiated apparently arrived at their present locations in an essentially undifferentiated state. Walker and Poldervaart (p. 673) noted that ". . . the proportion of phenocrysts in the marginal basalts attains a maximum of 15 percent in the type Perdekloof sill but is generally much lower; the average is only 6.7. Crystallization cannot, therefore, have been far advanced when the Karroo dolerite magma was emplaced."

A third classic example is the Deccan province of western India. The volume of Deccan basaltic lava is apparently comparable to that of the Yakima basalt, and Sukheswala and Poldervaart (1958, p. 1492) were ". . . especially impressed by the lack of compositional variation in the bulk of the basaltic rocks." Washington (1922, p. 773) also remarked on the chemical uniformity of these basalts.

In the oceans, even greater volumes of apparently chemically uniform tholeiitic basalt have been erupted along oceanic ridges. Engel, Engel, and Havens (1965, p. 723) have remarked on ". . . the general uniformity in composition of the oceanic tholeiites from widely separated parts of two oceans." If the findings of Engel, Engel, and Havens are upheld by more extensive sampling, then large areas of the ocean floors are covered with basalt of a very uniform composition.

In view of the factors potentially capable of producing chemical diversity, it is perhaps surprising that uniformity is ever preserved. O'Hara (1965) has argued that the compositions of basalts produced at the surface of the Earth are controlled by continuous fractional crystallization as the magmas rise, and he has described how a variety of basaltic magma types may be derived depending on the rate of ascent and extent of fractionation at various pressures. In continental areas, varying degrees of assimilation of crustal material would also be expected to contribute to chemical diversity. Finally, the compositions of primary magmas may be expected to differ at the site of generation depending on the depth of origin (Kushiro, 1968). Some or all of these factors may be responsible for the chemical diversity observed in many volcanic provinces, but their relevance to the vast outpourings of chemically homogeneous tholeiitic magma on the continents and possibly along oceanic ridges must be minimal.

Yoder and Tilley (1962, p. 519) suggested a mechanism for obtaining a single liquid composition from heating of a wide variety of mantle compositions. They pointed out the existence of only two eutectics in the system K_2O - MgO - Al_2O_3 - SiO_2 , and that a wide variety of compositions in this system would melt to produce initial liquids at only these two invariant points. They suggested that the mantle melts similarly to compositions in this system, but that chemical inhomogeneities in the

mantle are sufficiently restricted that only a single liquid composition would be obtained at a given pressure.

To illustrate this relationship, imagine for the moment that the composition of the mantle can be represented rigorously by figure 7, and that this diagram applies for the pressure at the site of magma generation. If we imagine further that the composition of the mantle is inhomogeneous but always lies within the triangle SiO_2 - b - c , the first liquid produced on heating any part of this mantle will be at the eutectic e .

This line of reasoning can be carried further. Suppose the mantle composition lies at n . Not only does the first liquid produced lie at the eutectic e , but any arbitrary amount up to 42 percent of the total mass may be melted without changing the composition of the liquid produced. This relationship applies to both equilibrium and fractional fusion and to any composition within the triangle SiO_2 - b - c , but of course the maximum amount that may be melted without changing the composition of the melt depends on the position of the original starting composition.

In order to produce large volumes of liquid of a uniform composition from an inhomogeneous mantle, there is no requirement that this liquid be of a eutectic composition. For example, consider a mixture within the triangle f - g - h (fig. 7) such as m . For this composition, the first liquid produced on heating lies at the peritectic p , and as in the previous example, a very large amount (up to 44 percent) of the total mass could be fused without altering the composition of the liquid.

But suppose the mantle melts to produce an initial liquid along a univariant line rather than at an invariant point. Such would be the case for composition w (fig. 8). The first liquid produced on heating, given by the tangent relationship described earlier, is f_1 . If liquids are continually extracted as they are formed (fractional fusion), a complete range of compositions from f_1 to f_2 could be obtained. During a one-stage process of equilibrium fusion followed by extraction of the liquid, a similar, though slightly more restricted, range of possible liquid compositions could be produced, and the liquid composition obtained would depend on the proportion of the total mass that was fused. Here, then, is quite a different situation than was observed earlier for melting at an invariant point. No longer is it possible to produce large amounts of liquid of identical composition without regard for the exact composition of the starting mixture or the amount fused.

However, mixture w was chosen deliberately so as to produce a wide range of possible liquids. Other compositions, such as z , would also produce a first melt along the olivine-pyroxene boundary line, but only a very restricted range of liquids could be derived. During fractional fusion of composition z , any proportion up to about 33 percent of the total mass could be melted, yet the range of possible liquids would vary only between s_1 and s_2 . The range of liquid compositions that would be obtained during equilibrium fusion would be slightly less than for fractional fusion.

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