

Fusion Relations in the System $\text{NaAlSi}_3\text{O}_8$ - $\text{CaAl}_2\text{Si}_2\text{O}_8$ - KAlSi_3O_8 - SiO_2 - H_2O and Generation of Granitic Magmas in the Sierra Nevada Batholith

ABSTRACT

Chemical analyses of 167 typical specimens indicate that about 95 percent of the intrusive rocks of the central Sierra Nevada contain more than 79 percent normative $\text{Ab} + \text{An} + \text{Or} + \text{Qz}$. If the composition of the lower continental crust is similar to or slightly more felsic than andesite, as seems likely, the system $\text{NaAlSi}_3\text{O}_8$ - $\text{CaAl}_2\text{Si}_2\text{O}_8$ - KAlSi_3O_8 - SiO_2 - H_2O provides an excellent chemical model for testing various schemes of fusion of the lower crust and crystallization of the resulting magmas. From consideration of this system in conjunction with field and petrographic data, we conclude that the intrusive rocks are best explained by repeated episodes of equilibrium fusion corresponding to magmatic sequences defined by field, petrologic, chemical, and geochronologic data. Fractional crystallization of the crystal-liquid mush generated by equilibrium fusion, coupled with periodic upward or lateral movement of the less crystallized central part of the magma, would produce the characteristic mafic to felsic sequence of intrusion; each mafic to felsic sequence corresponds to a separate equilibrium fusion event. In contrast, a close approach to fractional fusion of the lower crust is inadequate for obtaining most of the plutonic rocks, because rock compositions capable of being produced by this process do not match those observed. Normal amounts of conductive heat from the mantle and from radioactive decay in the crust may have been capable of causing fusion in the deepest parts of a thickened crust under the central part of the Sierra Nevada without the aid of a transient heat source from the mantle, but would have been inadequate where

the crust was thin in the western Sierra Nevada. However, upward transport of andesitic and basaltic magmas generated along a Mesozoic subduction zone dipping beneath the Sierra Nevada would have provided sufficient additional heat to make fusion of the lower crust unavoidable. This implies that a major portion of the present batholith must have been derived from the lower crust.

INTRODUCTION

The revolutionary new concepts of global tectonics have stimulated new interest in an old controversy, the origin of granitic batholiths. The principal Mesozoic batholiths are located around the margin of the Pacific Ocean (Bateman and Eaton, 1967) and their origin has been linked with the development of trenches and subduction zones marginal to continental masses (Hamilton, 1969a, 1969b; Dickinson, 1970).

However, the frequent association of granitic batholiths with subduction zones marginal to continents does not necessarily imply that batholithic rocks are derived by partial fusion of oceanic crust dragged down into the mantle. A notable feature of granitic batholiths is that they appear to be restricted exclusively to areas underlain by continental crust. If the source materials for batholiths were solely in the mantle or in subducted plates of oceanic crust, why are there no batholiths in the ocean basins where sialic crust is lacking? Where are the batholiths, or for that matter, silicic volcanic rocks in continental abundances, along the island arcs of the western Pacific? Gilluly (1971, p. 2387) has pointed out that in the western two-thirds of the Aleutian arc, where only oceanic crust is present, andesitic

volcanic rocks predominate, and only very small amounts of albite granite and rhyolite are present, whereas in the eastern one-third of the arc, where volcanics have penetrated sialic crust, stocks of quartz diorite and quartz monzonite are common.

As we will show later, the heat produced by repeated penetration of continental crust by andesitic and basaltic magma would unavoidably produce localized fusion of the lower crust. Thus, if a Mesozoic subduction zone existed beneath the Sierra Nevada batholith and was a source for andesitic and basaltic magmas, we believe that at least part of the source material for the granitic magmas must have come from the lower crust. Alternatively, it is possible that only small amounts of mixing would occur between a lower crust undergoing partial fusion and magmas rising through it from a subduction zone. This would produce the common association of andesitic volcanics with granitic batholiths, but the two rock types would have different source regions. A subduction zone dipping beneath the Sierra Nevada batholith would supplant an undefined convection cell called upon in previous publications to account for deformation that preceded and accompanied magma generation and to supply heat required to trigger magma generation in the crust (Bateman and Warhaftig, 1966, p. 123; Bateman and Eaton, 1967, p. 1414).

The concept of generating granitic magmas by partial fusion of crustal material was in part a reverse application of the extensive data collected by Bowen, Schairer, Tuttle, and many others, demonstrating that granitic magma could be produced by fractional crystallization. Presnall's (1969) analysis of partial fusion in various hypothetical and real systems showed, however, that fractional fusion is not the reverse of fractional crystallization, as has been commonly believed. The details of fusion of the lower crust to produce granitic magmas therefore need to be clarified. In this paper, we use the methods developed by Presnall (1969) to analyze partial fusion relations in the system $\text{NaAlSi}_3\text{O}_8\text{-CaAl}_2\text{Si}_2\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-SiO}_2\text{-H}_2\text{O}$ (hereafter referred to as *Ab-An-Or-Qz-H₂O*) and to predict the chemical trends that could be produced. Various schemes of fusion of the lower crust and crystallization of the derived magmas are then evaluated by comparing the theoretical trends

with the observed trends for rocks of the Sierra Nevada batholith.

CHEMICAL AND SPATIAL RELATIONS OF THE SIERRAN INTRUSIVE ROCKS

The chemical data used in this report are those used by Bateman and Dodge (1970), except for the addition of a few samples analyzed since their paper was published. Bateman and Dodge have assigned most of the granitic rocks in the central Sierra Nevada to eight provisional intrusive sequences. The geographic distribution of the best established sequences, going from west to east across the central part of the batholith, is western foothills rocks, Shaver sequence, John Muir sequence and Tuolumne Intrusive Series¹, Palisade Crest sequence, and White Mountains rocks (Fig. 1). The other less well defined sequences will not be discussed in this report.

Each sequence is composed of rocks which are believed to have been emplaced during the same intrusive epoch and which field, petrologic, and chemical data indicate are closely related. Most plutons assigned to a given sequence are spatially continuous with one another and form groups that are generally elongate in a northwesterly direction, parallel with the long axis of the batholith, although some plutons are widely scattered. Intrusive relations within the most firmly established sequences indicate that the oldest pluton within a sequence is generally the most mafic and that successively younger plutons are progressively more felsic.

In addition to the systematic compositional variations within each sequence, systematic chemical and mineralogical variations occur across the sequences. The most conspicuous variation is steplike increase of K_2O and of the K_2O index $[(\text{K}_2\text{O} \times 1,000)/(\text{SiO}_2 - 45)]$ eastward across the batholith as the different sequences are crossed (Bateman and Dodge,

¹ Since publication of the report by Bateman and Dodge (1970), the John Muir sequence has been found to consist of three successively emplaced sequences, each beginning with granodiorite and including similar felsic differentiates. The isotopic ages and the ranges and trends of composition of these sequences and of the Tuolumne Intrusive Series are almost identical. Because we wish to avoid proposing new sequence names here, we will continue to refer to all of these rocks as a single sequence.

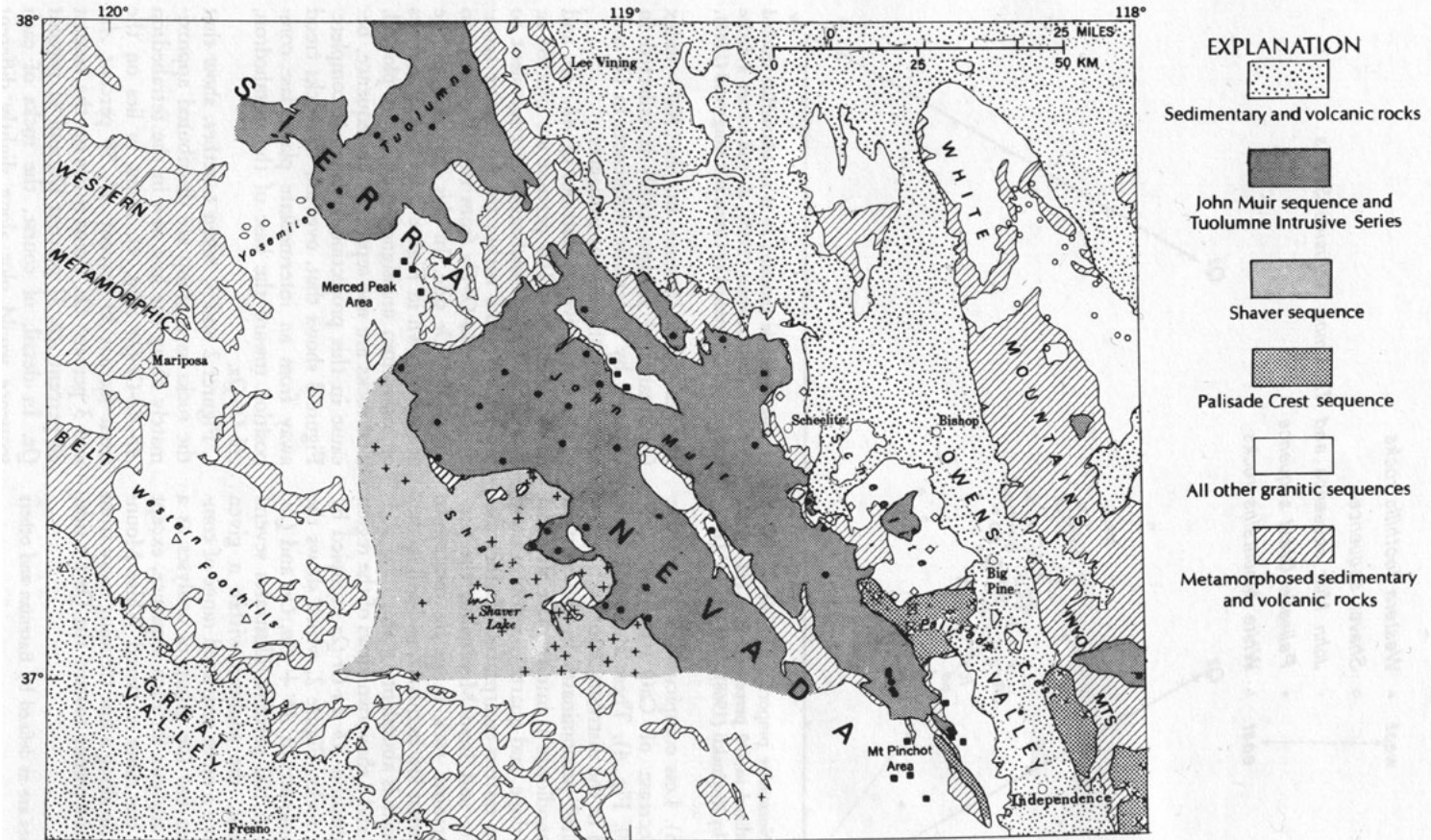


Figure 1. Geologic map showing locations of intrusive sequences and of chemically analyzed samples in central Sierra Nevada, White, and Inyo mountains.

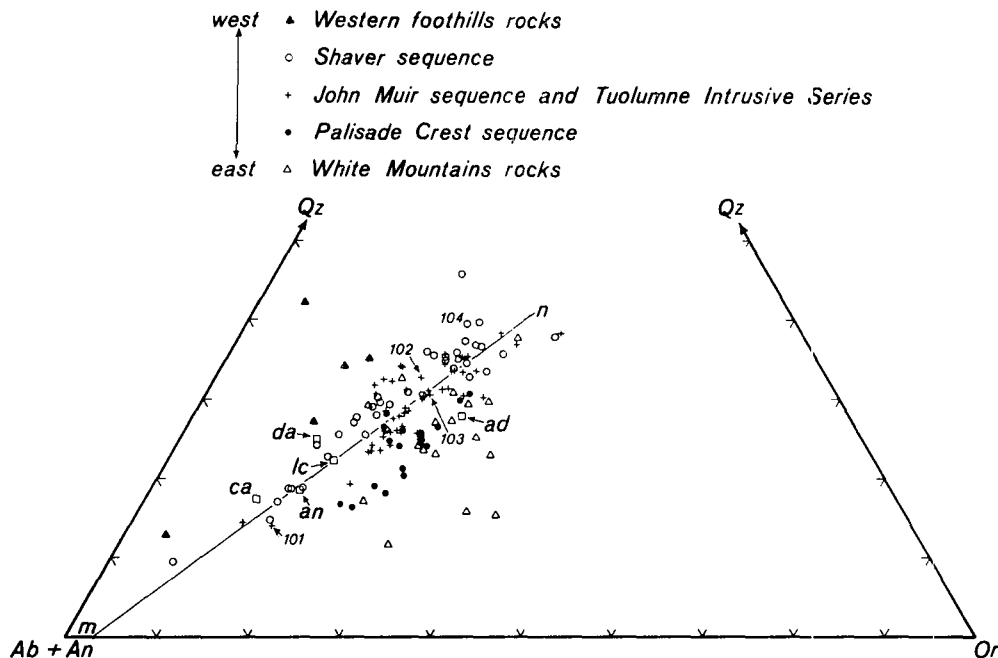


Figure 2. Normative proportions of $Ab + An$, Or and Qz normalized to 100 percent. Points 101-104 are rocks studied by Piwinski (1968), ca is Chayes' (1969)

average Cenozoic andesite, ad is an adamellite studied by Green and Lambert (1965), da and an are a dacite and an andesite studied by Green and Ringwood (1968).

1970, Fig. 6). Less conspicuous is progressive eastward decrease of CaO (Bateman and Dodge, 1970, Fig. 4). These chemical trends are reflected in the distribution of rock types: quartz diorite² predominates in the western foothills, granodiorite at intermediate altitudes on the west slope, and quartz monzonite along the crest and eastern escarpment. Farther east in the White and Inyo Mountains, the predominant granitic rock is quartz monzonite that is somewhat low in quartz, and still farther east, monzonite is abundant.

Figures 2 and 3 show two views of the region of the tetrahedron $Ab-An-Or-Qz$ occupied by the granitic rocks. Figure 2, which shows the normative amounts of $Ab + An$, Or , and Qz , normalized to 100 percent, illustrates several features. First, the analyses within a given sequence have a more restricted range of composition than has the group of analyses as a whole. The analyses for each sequence, except perhaps for the more scattered White Mountains rocks, lie along a line trending away from the $Ab + An$ corner toward the $Qz-Or$ side.

The eastward increase in the K_2O index (Bateman and Dodge, 1970) is reflected in Figure 2 by systematic differences in Or content among the various sequences.

The normative proportions of Ab , An , and Or normalized to 100 percent are plotted in Figure 3. This normalization is equivalent to projecting points within the normative tetrahedron $Ab-An-Or-Qz$ from the Qz apex onto the $Ab-An-Or$ side. In this diagram, all the analyses shown in Figure 2 as well as analyses of rocks from unassigned plutons are plotted. The rocks are not separated by sequence, because in this projection, overlap is complete. Figure 3 shows that, over-all, the rocks trend away from an intermediate plagioclase composition toward the base of the tetrahedron, $Ab-Or-Qz$.

Figures 2 and 3, taken together, show that the rocks as a group are distributed approximately along the line $m-n$ in the tetrahedron $Ab-An-Or-Qz$ (Fig. 4). Point m lies on the front face at 39 percent Ab , 58 percent An , and 3 percent Or . Point n lies on the base at 28 percent Ab , 31 percent Or , and 41 percent Qz . In detail, of course, the rocks of each sequence would plot along slightly different

² Rock names are as defined by Bateman and others (1963, Fig. 2).

lines, each of which would intersect the base and front face at slightly different points. Reflecting the eastward increase of potassium across the batholith, lines for successively eastward sequences would plot increasingly farther from the *Ab-An-Qz* face and closer to the *Ab-An-Or* face.

APPLICABILITY OF THE SYSTEM *Ab-An-Or-Qz-H₂O* TO SIERRAN INTRUSIVE ROCKS

Bulk Chemistry of the Batholith and Lower Crustal Source Region

Of fundamental importance to the conclusions reached in this paper is the assumption that, for the Sierran intrusive rocks, crystal-liquid equilibria in the source region and in the magmas derived from it can be closely modeled by the system *Ab-An-Or-Qz-H₂O*. One method of evaluating this assumption is

to consider what proportion of the rock compositions are omitted by considering only normative *Ab*, *An*, *Or*, and *Qz*. Consider first the derived magmas as represented by the presently exposed rocks of the batholith. Only four of 167 analyses (2 percent) of typical rocks contain less than 79 percent normative *Ab + An + Or + Qz*, and the average for all rocks is 90 percent. Mafic and ultramafic rocks are not included among those analyzed, but their areal extent in the central, most thoroughly studied, part of the batholith represents less than about 3 percent of the exposed plutonic rocks. Thus, if we take the available analyses as representative of the exposed felsic rocks, approximately 95 percent of the exposed plutonic rocks in the central Sierra Nevada batholith contain normative *Ab + An + Or + Qz* in excess of 79 percent. The system *Ab-An-Or-Qz-H₂O* is thus a very good ap-

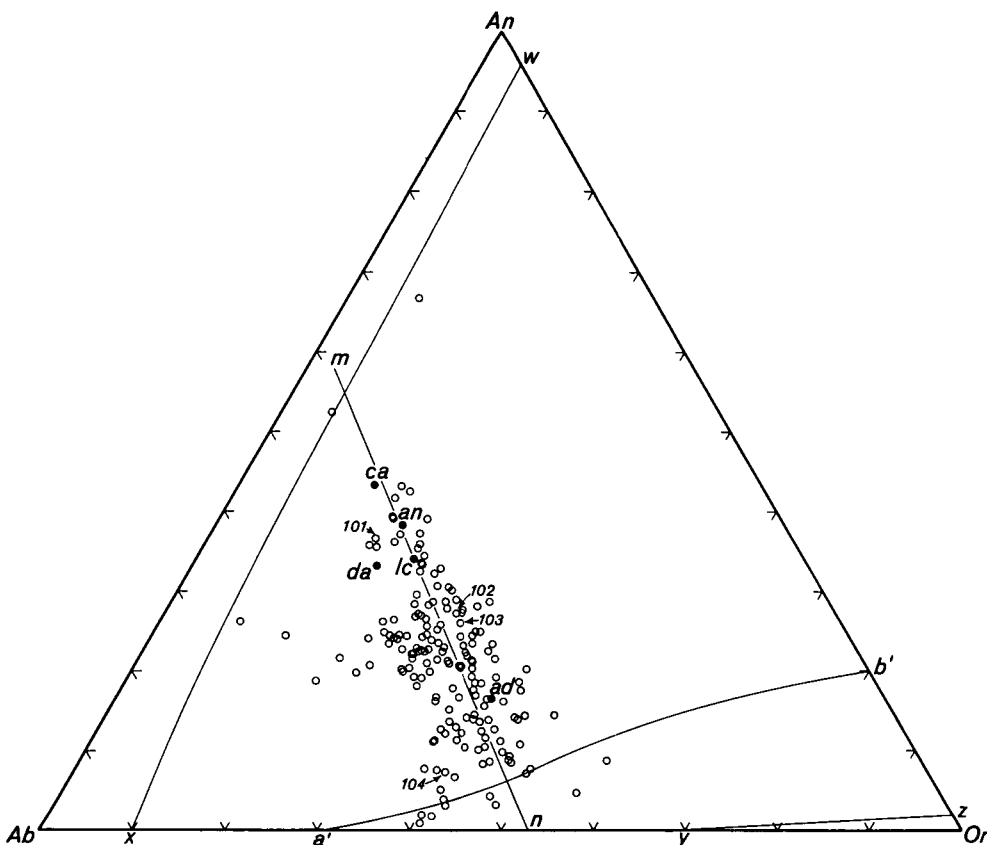


Figure 3. Normative proportions of *Ab*, *An*, and *Or* normalized to 100 percent. Labeled points are the same as in Figure 2.

proximation of the exposed rocks and doubtless also of the magmas from which they crystallized.

The extent to which the system *Ab-An-Or-Qz-H₂O* approximates the composition of the source region is less certain. Seismic velocities within the crust are quite variable from one region to another (Steinhart and Meyer, 1961), and this must be due at least in part to differences in chemistry. It is especially difficult to estimate the prebatolithic chemistry of the lower crust beneath the Sierra

Nevada, because it is no longer present in its original form. Nevertheless, it is still possible to place some approximate limits on the composition of the source region based on general arguments.

Ringwood and Green (1966a, p. 412-414; 1966b) have argued convincingly against the traditional view that the composition of the lower crust in stable shield areas is gabbroic. These authors also argue for a relatively dry lower crust in most areas, and at pressures and temperatures representative of the lower crust,

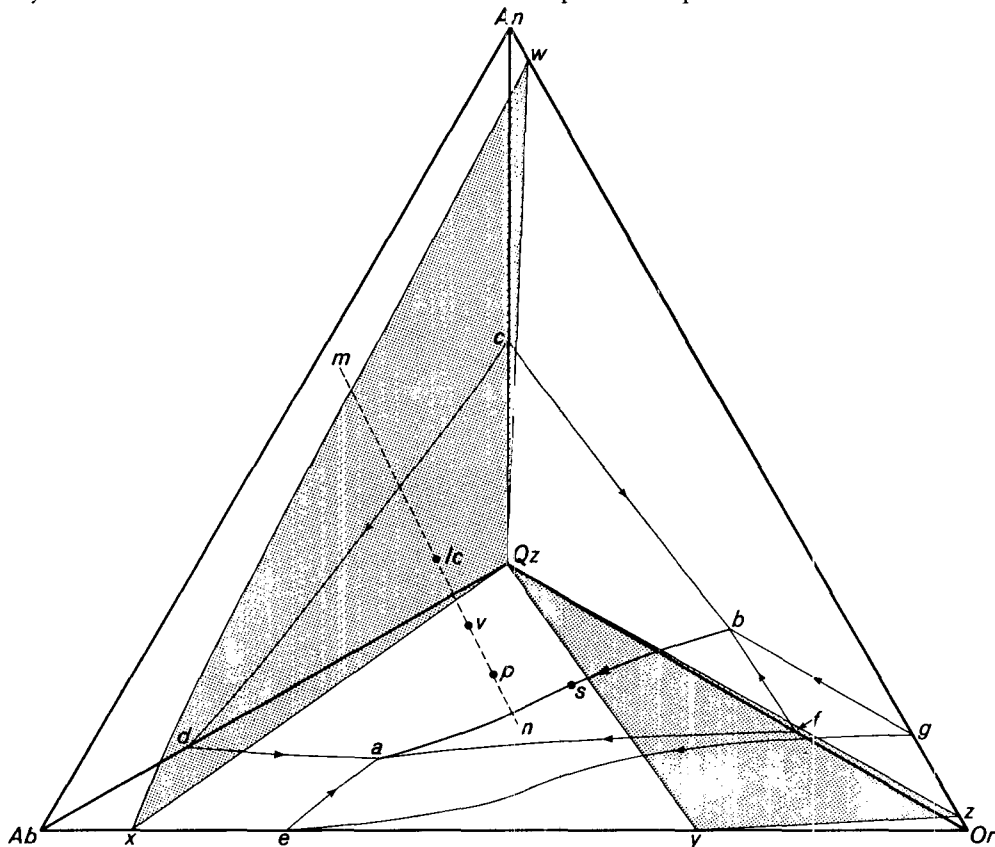


Figure 4. Vapor-saturated equilibrium diagram for the system $\text{NaAlSi}_3\text{O}_8$ (*Ab*)- $\text{CaAl}_2\text{Si}_2\text{O}_8$ (*An*)- KAlSi_3O_8 (*Or*)- SiO_2 (*Qz*)- H_2O at 5 kb shown with the *Qz* apex in the rear (wt percent). Phase relations are projected from H_2O . Lines with arrows are liquidus univariant lines with temperatures decreasing in the directions of the arrows. Shaded surfaces separate solidus volumes within the tetrahedron. The dashed line *m-n* (also shown in Figs. 2 and 3) shows the approximate trend of rock compositions in the Sierra Nevada, with *m* lying on the front face and *n* on the base. Point *lc* (also shown

in Figs. 2 and 3) is a hypothetical composition of the lower crust. At point *p*, the line *m-n* pierces the surface *a-b-c-d*. See text for explanation of other points. Compiled from data by Yoder and others (1957), Luth and others (1964), Yoder (1968), Stewart (1967) and Morse (1970). Polymorphism of SiO_2 and solid solution of SiO_2 in feldspars (Kim and Burley, 1971) are neglected. Liquidus boundary lines on the face *Or-An-Qz* and the position of the line *a-b* are inferred from the data of James and Hamilton (1969) at 1 kb.

a relatively dry gabbroic composition would consist of eclogite or garnet granulite and would have a density and seismic P-wave velocity much greater than is observed in most areas. Following Green and Lambert (1965), Ringwood and Green favored a composition intermediate between basalt and granite. On petrologic grounds, den Tex (1965) has also favored a lower crust of intermediate composition. This conclusion applies for stable parts of the crust and probably is valid for the continental lower crust that existed under the Sierra Nevada region prior to magma generation. Thus, we will assume that the pre-batholithic lower crust under the Sierra Nevada was more felsic than gabbro.

Of the common rock types, andesite would have the most mafic composition capable of satisfying typical lower crustal densities and seismic velocities under relatively dry conditions. Taking Chayes' (1969) average composition of Cenozoic andesite as representative (point *ca* in Figs. 2 and 3), the lower crust would consist of 79 percent normative $Ab + An + Or + Qz$. Green and Lambert (1965) carried out high pressure experiments on an adamellite composition containing 92 percent normative $Ab + An + Or + Qz$ (point *ad* in Figs. 2 and 3) and concluded that it would be too felsic to satisfy observed densities and seismic P-wave velocities. A likely average composition for the lower crust is intermediate between andamellite and andesite, probably toward the mafic end of the Sierra Nevada trend near the andesite composition. Such a composition is plotted as *lc* in Figures 2, 3, and 4 and contains 80 to 85 percent normative $Ab + An + Or + Qz$. Thus, we consider the system $Ab-An-Or-Qz-H_2O$ to be nearly as close an approximation of the lower crustal source region as of the magmas derived from it. Point *lc* will be used as a starting composition for discussion of partial fusion relations, but none of our conclusions are dependent on the exact location of *lc*.

Just as line *m-n* applies to Sierran rocks as a whole, so also does point *lc* apply to the source region. Because potassium increases eastward across the batholith, points equivalent to *lc* for the individual sequences would plot farther from the $Ab-An-Qz$ face and closer to the $Ab-An-Or$ face, the more easterly the sequence. This systematic geographic shift in the composition of the source material for magma

generation is certainly one of the more significant inferences that can be made. If Dickinson's (1970, p. 841-844) proposal that the amount of potassium in granitic rock sequences reflects the depth of magma generation along a subduction zone can be rejected for reasons summarized earlier, at least two possible explanations remain: (1) lower crustal source material was progressively richer in potassium eastward, possibly because it is progressively older and has undergone increasing numbers of cycles of magmatism and metamorphism, (2) the source material consisted of mixtures of potassium-rich crustal material and potassium-poor mantle material, and the ratio of crustal to mantle material increased eastward.

If a Mesozoic subduction zone existed beneath the Sierra Nevada, magmas rising from this zone would be expected to penetrate the crust along the axis of the Sierra Nevada. These magmas may have acted primarily to supply heat with only minor mixing into the lower crustal source region. Initial Sr^{87}/Sr^{86} ratios for the granitic rocks that are intermediate between those of mantle and old crustal material (0.703 to 0.708) (Hurley and others, 1965; Kistler and others, 1971) could then be explained by fusion of geosynclinal sedimentary rocks containing large amounts of mantle-derived volcanic material erupted at an earlier time, as suggested by Hurley and others (1965). Alternatively, it is possible that some of the magmas rising from the subduction zone were trapped in the lower crust and became part of the source material for the batholith. This would also explain the intermediate initial Sr^{87}/Sr^{86} ratios of the batholithic rocks. By analogy with currently active volcanism associated with subduction zones, the major magma type added to the lower crust would be andesite. Thus, the major-element chemistry of the lower crustal source region for the batholith would not be altered greatly, and our conclusion regarding the applicability of the system $Ab-An-Or-Qz$ would not change.

Phase Relations

In the Sierra Nevada, a relatively dry magmatic environment is indicated by a scarcity of pegmatites and miarolitic cavities and lack of evidence for hydrothermal solutions passing through the surrounding metamorphic rocks. On the other hand, the existence of some water in the granitic rocks is indicated by the

presence of biotite and hornblende. Thus, water-undersaturated phase relations in the system $Ab-An-Or-Qz-H_2O$ are probably most relevant to fusion and crystallization processes that have taken place.

The pressure range of interest varies somewhat. Bateman and Eaton (1967) found a maximum crustal thickness in the central Sierra Nevada of about 55 km; thus, fusion of the lower crust could have taken place at pressures up to about 16 kb (Bullen, 1963, p. 235). If significant erosion has occurred, pressures at the base of the crust could have been even higher, perhaps 18 or 19 kb. However, crystallization of the resulting magmas presently visible at the surface would have occurred at somewhat lower pressures, perhaps in the range 1 to 5 kb.

It would be desirable to know the phase relations in the system $Ab-An-Or-Qz-H_2O$ at varying water contents and over the complete range of pressure up to 19 kb. Such detailed knowledge is not at hand, but sufficient data are available for an understanding of many features of the equilibrium relations. The most complete data are at 5 kb under water-saturated conditions (Fig. 4).³ The liquidus consists of three primary phase volumes, one for quartz ($d-a-f-b-c-Qz$), one for plagioclase ($a-e-g-b-c-d-Ab-An$), and one for K-feldspar ($g-e-a-b-f-Or$). These three primary phase volumes intersect along the quaternary univariant line $a-b$, along which quartz, K-feldspar, and plagioclase are in equilibrium with liquid. The tetrahedron is filled by three solidus volumes, one for plagioclase + quartz ($w-x-Ab-An-Qz$), one for plagioclase + K-feldspar + quartz ($w-x-y-z-Qz$), and one for K-feldspar + quartz ($y-z-Or-Qz$).⁴ At solidus temperatures, compositions in the plagioclase + quartz volume are in equilibrium with liquids on the surface $a-b-c-d$, compositions in the plagioclase + K-feldspar + quartz volume are in equilibrium with liquids along the line $a-b$, and compositions in the K-feldspar + quartz volume are in equilibrium with liquids on the surface $a-b-f$.

³ In this diagram, the constant presence of a separate vapor phase will be assumed and will not be referred to repeatedly. It will also be assumed, as an approximation, that the vapor is pure water.

⁴ The solidus volumes are designated according to the crystalline phases in equilibrium with liquid at solidus temperatures.

The water-saturated phase diagram at 5 kb will be used as a basis for all the subsequent discussion of fusion and crystallization. Differences in pressure and water content cause changes in the phase relations, but many of the changes do not significantly affect our interpretations. For example, at pressures below 3.6 kb under water-saturated conditions and at all pressures within the crust under anhydrous conditions, the line $a-b$ does not extend completely to the base of the tetrahedron because of complete solid solution between albite and K-feldspar (Schairer, 1950; Tuttle and Bowen, 1958; Luth and others, 1964; Luth, 1969). This change is very important to an understanding of granites that plot near the base, but it is of little consequence here, because most rocks in the Sierra Nevada plot well away from the base and within the solidus volume quartz + plagioclase + K-feldspar. Thus, the final liquid obtained by equilibrium crystallization of most Sierran rocks must lie on the line $a-b$. Also, first liquids derived by fusion of compositions in the central part of the tetrahedron would lie on the line $a-b$. We will also ignore the fact that K-feldspar melts incongruently below 2.6 kb under water-saturated conditions (Scarfe and others, 1966) and at all pressures up to 19 kb under anhydrous conditions (Lindsley, 1966).

A final change that will be ignored is the incongruent melting of anorthite to corundum + liquid, which occurs at high pressures beginning at 9 kb under anhydrous conditions (Lindsley, 1968) and some pressure less than 10 kb under water-saturated conditions (Boettcher, 1970). Also, Boettcher (1972, written commun.) has found that plagioclase containing as little as 20 mole percent anorthite melts incongruently at 10 kb to corundum + liquid under water-saturated conditions. However, it is probable that water-saturated liquids at lower temperatures within the tetrahedron $Ab-An-Or-Qz$ are still in equilibrium with plagioclase of intermediate composition without complications involving corundum. Also, interpolation of the anhydrous results of Lindsley (1968) indicates that at 19 kb, the approximate upper limit of pressure to be expected in the crust, the system $Ab-An$ remains binary for plagioclase containing up to 60 mole percent An , with no complications involving corundum. At lower temperatures, liquids within the tetrahedron would be in equilibrium with plagioclase of even greater

An content without the presence of corundum. The absence of corundum in the rocks is a further indication that the incongruent melting of plagioclase can be neglected.

Under water-saturated conditions, boundary lines *d-a*, *e-a*, and *f-a* exist at high pressures up to 17 kb (Merrill and others, 1970), but their exact positions are not known above 10 kb. However, the general form of the phase diagram for *Ab-Or-Qz* is the same from 5 to 10 kb (Luth and others, 1964) and probably remains the same up to 17 kb. For water-saturated conditions above 17 kb, the disappearance of point *a* and the appearance of jadeite would critically change the form of the diagram. Under anhydrous conditions, the eutectics between albite and quartz (point *d*) and between K-feldspar and quartz (point *f*) exist at pressures up to and beyond 19 kb (Bell and Roseboom, 1969; Luth, 1969). Under both water-saturated and anhydrous conditions, the primary phase volume of quartz expands with increasing pressure (Luth and others, 1964; Luth, 1969). The position of point *b* is known only at 1 kb under water-saturated conditions (James and Hamilton, 1969), but its exact location is not critical to our discussion.

In summary, the available data indicate that Figure 4 can be used for semiquantitative discussions of fusion and crystallization of granitic compositions under dry and water-undersaturated conditions throughout the crust (up to 19 kb). At pressures below 17 kb, the diagram probably is also a good approximation of water-saturated conditions, but there is a possibility that the incongruent melting of plagioclase would cause complications. Above 17 kb, Figure 4 would not apply to water-saturated conditions. However, for Sierran rocks, these are not serious problems because of the field evidence for dominantly water-undersaturated conditions. In using this diagram at varying water contents and pressures, two features must be kept in mind: (1) the size of the quartz primary phase volume increases with pressure, and (2) liquidus temperatures increase with pressure and decrease with increasing water content.

One might still argue that the small amounts of other components in the rocks could invalidate application of the system *Ab-An-Or-Qz-H₂O* to fusion and crystallization behavior of granitic compositions. Data bearing on this matter have been published by Piwinski and

Wyllie (1968, 1970) and Piwinski (1968) who carried out melting experiments on granitic rocks, including four from the Sierra Nevada batholith. They found that the results agreed well with what would be predicted from a knowledge of the system *Ab-An-Or-Qz-H₂O* (Piwinski and Wyllie, 1968, p. 225).

Piwinski's (1968) melting experiments were conducted on four granitic rocks from the Sierra Nevada batholith under water-saturated conditions and at pressures from 1 to 3 kb. The normative compositions of these four rocks are indicated in Figures 2 and 3 by the numbers given them by Piwinski (101, 102, 103, 104). If Piwinski's results are extrapolated to 5 kb so as to correspond to the pressure of Figure 4, the solidus temperature and the temperatures of appearance of plagioclase, quartz, and K-feldspar can be predicted for each of the rocks generally within 15 to 20 degrees, which is only about twice the experimental uncertainty in the data of Piwinski. It is also possible to predict correctly from the phase diagram the approximate proportions of crystals and liquid at various temperatures as well as the highly siliceous compositions of liquids produced just above the solidus temperature of each rock. Finally, it is important to note that the predicted crystallization behavior of plagioclase, quartz, and K-feldspar holds true despite the presence of small amounts of mafic phases in the rocks.

The above discussion of predicted and observed behavior applies only to moderate pressures and water-saturated conditions. Some limited data are also available for comparisons under other conditions. Green and Ringwood (1968) carried out high-pressure melting experiments on synthetic mixtures of dacitic and andesitic composition (points *da* and *an*, respectively, in Figs. 2 and 3) under anhydrous conditions. They found that the minor mafic phases are garnet and clinopyroxene at 18 kb and clinopyroxene alone at lesser pressures. Plagioclase and quartz remain as the major crystalline phases, and their order of appearance during crystallization corresponds to what would be expected from the system *Ab-An-Or-Qz*. That is, plagioclase is the primary phase in both compositions at low and moderate pressures and has a long interval of crystallization before the appearance of quartz. At 18 kb, quartz becomes the primary phase for the dacite and appears shortly after plagioclase in the andesite. This would be expected because

the quartz primary phase volume increases in size with increased pressure and because dacite is richer in normative quartz than is andesite. Green (1972) studied the crystallization behavior of a natural andesite with 2 percent water by weight. At pressures below about 18 kb, he found that plagioclase crystallizes before quartz, indicating that the presence of small amounts of water does not alter the anhydrous sequence of crystallization of these phases.

Thus, available data on compositions corresponding to actual rocks indicate that the major features of crystal-liquid equilibria in granitic compositions can be predicted from the system *Ab-An-Or-Qz-H₂O*. Even though this system cannot be considered adequately known, present knowledge of the general relations is sufficient for making useful and instructive comparisons with the observed compositional trends in the Sierra Nevada. Consideration of the mafic phases must, of necessity, be neglected, but for a lower crust similar to andesite, these would be present only in minor amounts, and we have just shown that they do not greatly alter the crystallization behavior of plagioclase, quartz, and K-feldspar.

FUSION AND CRYSTALLIZATION RELATIONS IN THE SYSTEM *Ab-An-Or-Qz-H₂O* APPLIED TO THE SIERRA NEVADA ROCKS

We will now evaluate various schemes of producing the Sierra Nevada intrusives by partial fusion of the lower crust with and without subsequent fractional crystallization of the derived magmas. First, we will consider the consequences of assuming the process operating in the source region closely approached fractional fusion, that is, a continuous extraction of small increments of completely liquid magma. Second, we will discuss equilibrium fusion, whereby the melt remains in equilibrium with the residual crystals at the site of melting until it is intruded upward. Equilibrium fusion may be thought of as a single melting episode and fractional fusion as an infinite number of infinitely small equilibrium fusions. Perfect fractional fusion could never be attained in nature, but it is geologically reasonable to think of an approach to this type of process in terms of a large number of separate extractions of magma from the same source region. Perfect equilibrium fusion would be approached as the number of separate extractions of magma

decreased to one. Finally we will consider processes transitional between fractional and equilibrium fusion. These processes will be evaluated as they apply to a single mafic to felsic sequence of intrusions such as, for example, the Tuolumne intrusive series.

Fractional Fusion

A completely rigorous discussion of fusion paths is not possible because data are not available on the exact compositions of feldspars in equilibrium with liquids within the tetrahedron *Ab-An-Or-Qz*. Seck (1971) determined the positions of solidus tie lines between coexisting plagioclase and K-feldspar at 650°C and pressures up to 10 kb and found that the tie lines are positioned in the diagram *Ab-Or-An* in a similar manner at all pressures. In our discussion of fusion relations, Seck's data are used as a guide together with reasonable estimates of the compositions of liquids on the line *a-b* (Fig. 4) that are in equilibrium with these feldspars. Accordingly, the fusion relations derived from these estimates are only approximate, but the general features discussed should remain valid when more data become available. A knowledge of the schematic relations is sufficient for the conclusions reached here.

Within each of the solidus volumes (Fig. 4) will be a set of solidus fractionation lines⁶ describing crystal paths followed during perfect fractional fusion (Presnall, 1969). A feature that greatly facilitates an understanding of the solidus fractionation lines is the presence of quartz in all of the solidus volumes. That is, the initial liquid produced by fusion of any composition within the tetrahedron *Ab-An-Or-Qz* (Fig. 4) will be in equilibrium with quartz. Because quartz shows no solid solution, it is possible to project the quartz-saturated equilibrium relations from the *Qz* apex of the tetrahedron onto the front face, *Ab-An-Or*, and treat the resulting diagram as if it were ternary (Fig. 5). (In the discussion of Figure 5 that follows, the constant presence of quartz and vapor will be assumed and will not be referred to repeatedly.) The line *a'-b'* is the projection of the liquidus univariant line *a-b* (Fig. 4), and it separates the quartz-saturated primary phase field of plagioclase (*a-b-c-d* in Fig. 4)

⁶ In mathematical texts, a line is considered to be straight. However, we intend for the term "fractionation line" to include both straight and curved types.

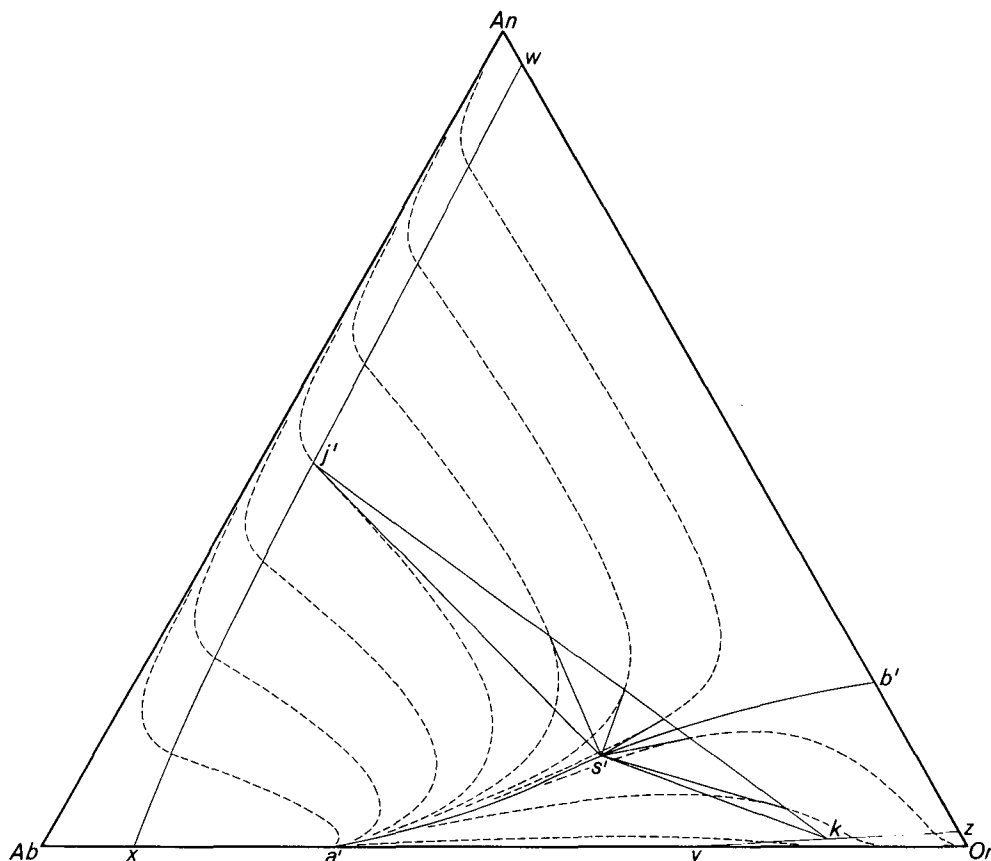


Figure 5. Qz -saturated phase relations in Figure 4 projected from Qz onto the face $Ab-An-Or$. Dashed lines are solidus fractionation lines.

from that of orthoclase ($a-b-f$ in Fig. 4). The three projected solidus fields in Figure 5 are $w-x-Ab-An$ (plagioclase), $w-x-y-z$ (plagioclase + K-feldspar), and $y-z-Or$ (K-feldspar). The solidus and liquidus fields on this diagram have the same general appearance as those for the ternary system $Ab-An-Or$, except that the phase boundaries are slightly shifted.

Projected solidus fractionation lines within the area $w-x-y-z$ (Fig. 5) are derived by drawing three-phase triangles (such as $s'-j'-k$) showing the equilibrium coexistence of plagioclase, K-feldspar, and liquid. Solidus isotherms in the area $w-x-y-z$ are coincident with tie lines such as $j'-k$, which connect coexisting compositions of plagioclase and K-feldspar. Heating of any composition along the line $j'-k$ would yield the same initial liquid (s') at a single temperature. The solidus fractionation lines are drawn so as to be tangent, along the base ($j'-k$) of the three-

phase triangle, to lines radiating from the liquid apex s' (Presnall, 1969, p. 1183).

Fusion of compositions within the solidus field of plagioclase ($w-x-Ab-An$) would yield initial liquids within the primary phase field of plagioclase ($a'-b'-An-Ab$). Similarly, fusion of compositions within the solidus field of K-feldspar ($y-z-Or$) would yield initial liquids within the primary phase field of K-feldspar ($a'-b'-Or$). The exact shapes of the solidus fractionation lines in these solidus fields would have to be obtained from experimentally determined tie lines, but the general form of the fractionation lines would be as shown.

Figure 6 shows how solidus fractionation lines and solidus isotherms within the tetrahedron $Ab-An-Or-Qz$ are related to their projected representations in Figure 5. The solidus isotherm $j'-k-Qz$ in Figure 6 projects as the solidus isotherm $j'-k$ in Figure 5. All mixtures

lying on the plane $j'-k-Qz$ melt at the same temperature to produce the same initial liquid s . The plane $j'-k-Qz$ is representative of a family of isothermal planes that sweeps across the solidus volume $w-z-y-z-Qz$, and heating of mixtures on these other planes would yield initial liquids at other points on the line $a-b$. The temperatures of these isothermal planes decrease downward toward the base $Ab-Or-Qz$.

The curved line $a'-j'-An$ in Figure 6 is the same as the identically labeled line in Figure 5; and the ruled surface $a'-j'-An-Qz$ (Fig. 6) represents a family of solidus fractionation lines within the tetrahedron, all of which project as the same line $a'-j'-An$ in Figure 5. One member of this family is the dashed line $a-j-t$. Fractional fusion of a starting composition on the line $a-j$ produces a crystal path that moves along the dashed line toward j . Simultaneously, liquids are produced along the line

$a-b$. At j , all the K-feldspar is used up and the crystal path leaves the plagioclase + K-feldspar + quartz solidus volume and enters the plagioclase + quartz solidus volume. Further heating produces liquids on the surface $a-b-c-d$ as the crystal path moves along the dashed line toward t lying on the front face of the tetrahedron. Fractional fusion beyond this point yields liquids on the front face of the tetrahedron, $Ab-An-Or$, and the relations would have to be described using the ternary system $Ab-An-Or$. Quartz would no longer be present and therefore Figure 5 would no longer apply.

Other members of the family of fractionation lines lying on the surface $a'-j'-An-Qz$ (such as $a-r$ in Fig. 6) would intersect the front face $Ab-An-Or$ at various points along the line $a'-j'-An$. Still others would curve into the Qz apex.

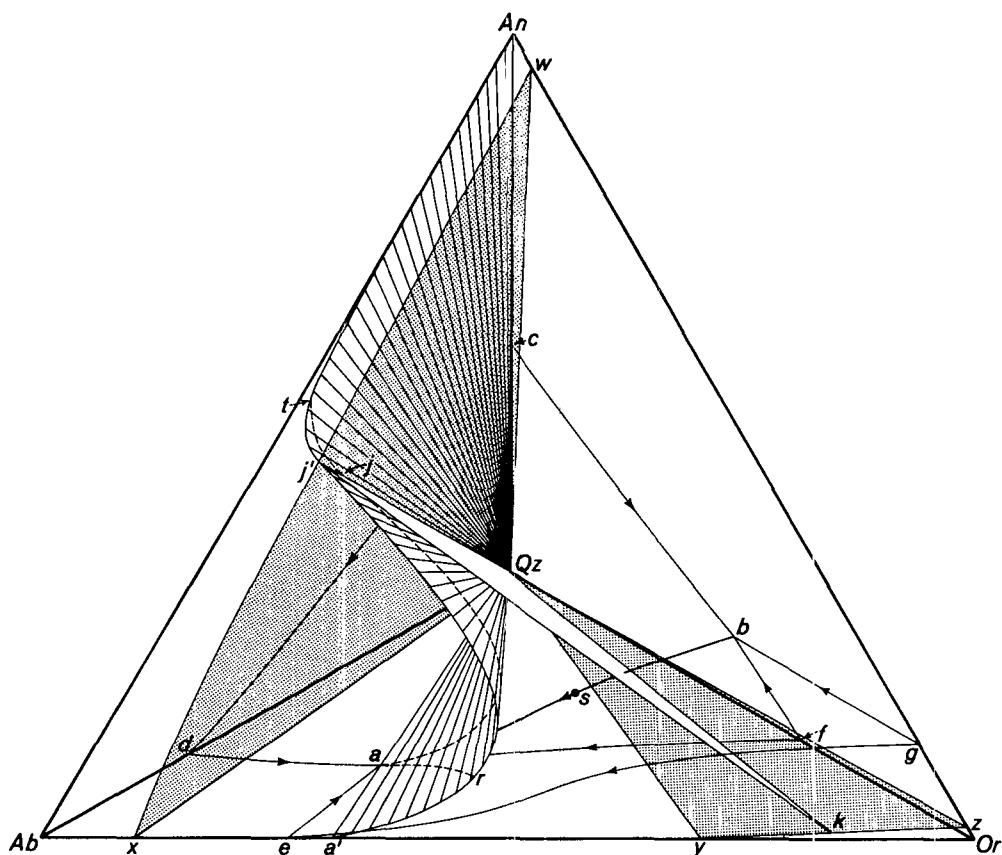


Figure 6. The system $Ab-An-Or-Qz-H_2O$ as in Figure 4 with the addition of a solidus isothermal plane

($j'-k-Qz$) and a ruled surface containing a family of solidus fractionation lines.

Figure 5 can be used to describe fusion relations only as long as the crystal path remains within the tetrahedron $Ab-An-Or-Qz$. This criterion coincides with the previously mentioned criterion that the diagram is valid only for equilibria in which quartz is present. Fractional fusion of any composition within the tetrahedron produces a crystal path that starts along one of the projected solidus fractionation lines in Figure 5, and the distance it travels along this line depends on the starting composition (for example, compare the two crystal paths $a-r$ and $a-j-t$ in Fig. 6).

In general, fractional fusion of any composition within the solidus volume of plagioclase + K-feldspar + quartz ($w-x-y-z-Qz$ in Fig. 6) yields initial liquids on the line $a-b$. Removal of these liquids from the mass that is melting drives the crystal path toward one of three surfaces that bound this solidus volume, either the surface $w-x-Qz$, the front face $w-x-y-z$, or the surface $y-z-Qz$. The two other surfaces that bound this volume, $x-y-Qz$ and $w-z-Qz$, are never intersected by solidus fractionation lines. For those crystal paths that intersect the surfaces $w-x-Qz$ or $y-z-Qz$, further fractional fusion drives crystal paths toward either the Qz apex or one of two areas on the front face ($w-x-Ab-An$ and $y-z-Or$). During this stage of fusion, the liquid path leaves the line $a-b$ and moves, without a temperature break, along one of the surfaces $a-b-c-d$ or $a-b-f$. That is, liquids are produced that are in equilibrium with either quartz and plagioclase or quartz and K-feldspar. Liquids within the tetrahedron and in equilibrium only with plagioclase and K-feldspar (that is, liquids on the surface $a-b-g-e$) are never generated during fractional fusion. After the crystal path reaches either the Qz apex or the front face $Ab-An-Or$, there is a temperature interval during which further addition of heat would produce no new liquids. After this interval, continued heating would produce either pure Qz liquid or liquids on the front face $Ab-An-Or$. Thus, an important feature of fractional fusion is that the only liquids that can be obtained within the tetrahedron lie on the quartz-saturation surface $a-f-b-c-d$. Also, it is important to realize that this holds regardless of the position of the starting composition within the tetrahedron.

From the earlier discussion, it will be recalled that some of the granitic rocks plot near the quartz-saturation surface but that most plot well within the primary phase volume of

plagioclase and that the trend lies at a high angle to the quartz-saturation surface. At high pressures, the primary-phase volume of quartz would expand and cut across a more central part of the Sierra Nevada trend, but this trend would still lie at a high angle to the quartz-saturation surface. Thus, a process closely approaching fractional fusion of the lower crust is incapable of producing the observed Sierra Nevada trend. As long as the composition of the source region can be closely approximated by some point within the system $Ab-An-Or-Qz$, this conclusion holds regardless of the specific composition chosen.

The sequence of intrusion in the Sierra Nevada as well as in many other batholiths is from mafic to felsic, and it is frequently argued that such batholiths could not be produced by fractional fusion because this would produce the reverse sequence of intrusion. Implicit in this argument is the erroneous assumption that fractional fusion may be thought of as the reverse of fractional crystallization. The argument does not apply for a close approach to fractional fusion because the observed rock compositions simply do not correspond to those expected by this process. The mafic to felsic sequence of intrusion is, however, important in considering processes intermediate between fractional and equilibrium fusion, as will be shown below.

In this analysis of fractional fusion, we have ignored the effects of water; varying amounts of water strongly affect liquidus temperatures but do not alter the positions of phase boundaries enough to change any of our conclusions. Also, we have ignored the effects of retention of residual crystals from the source region as well as fractional crystallization of the derived magmas because perfect fractional fusion, by definition, is the extraction of clean liquids in infinitesimally small amounts. If significant amounts of residual crystals are retained, and the magmas are extracted from the source in steps large enough for later fractional crystallization to be effective, the process is intermediate between fractional and equilibrium fusion. This is discussed below.

Equilibrium Fusion

Let us now consider chemical trends that could be produced by equilibrium fusion, that is, a single extraction of magma for each sequence. Until the magma starts moving upward, the liquid fraction will be assumed to

remain in equilibrium with any residual crystals at the site of melting. Because the rocks of each sequence cover a wide range of compositions, the possibility of equilibrium fusion without subsequent fractional crystallization of the derived magma can be dismissed immediately. All schemes of equilibrium fusion must incorporate some mechanism for differentiating the derived magma. We will consider the production of completely liquid magmas by equilibrium fusion and also the possibility that some or all of the residual crystals were carried along with the escaping magma.

Production of Completely Liquid Magma.

Consider first equilibrium fusion of the crust (as approximated by lc in Fig. 4) at about 10 kb (36 km) or less. At these pressures, the quartz-saturation surface cuts across the felsic end of the Sierra Nevada trend, and fusion of any amount up to approximately 50 percent of the crust would produce a liquid on the quartz-saturation surface. Separation and upward intrusion of this liquid with subsequent fractional crystallization would produce a series of liquids and crystal accumulates lying near the quartz-saturation surface. Therefore, this mechanism fails to produce the Sierra Nevada trend.

However, if equilibrium fusion proceeded beyond about 50 percent, the liquid composition would move out into the plagioclase primary phase volume toward lc , for example, to the general vicinity of v . If this liquid were then separated from the source region, intruded upward, and fractionally crystallized, precipitation of plagioclase of intermediate composition (near m) would drive the liquid path toward the vicinity of p on the quartz-saturation surface, thus producing the felsic part of the Sierra Nevada trend. Rocks more mafic than the starting liquid could be produced as crystal accumulates of plagioclase plus interstitial liquid; these also would fall along the Sierra Nevada trend. The closeness of point m , the high-temperature end of line $m-n$, to the $Ab-An$ edge of the tetrahedron supports the view that the precipitation and removal of plagioclase was the dominant control in the production of the Sierra Nevada trend. Each of the Sierra Nevada sequences would grade transitionally from plagioclase-rich crystal accumulates toward the mafic end to plagioclase-poor fractionated liquids toward the felsic end.

At higher pressures deeper in the crust, the quartz-saturation surface expands and cuts

across a more central part of the Sierra Nevada trend. The position of the high pressure equivalent of line $a-b$ (Fig. 1) is not known, but barring an extreme and unlikely shift of a to a position close to the $An-Qz$ edge, $a-b$ would be approximately as shown but closer to the front face $Ab-An-Or$ and in front of the Sierra Nevada trend. For small amounts of fusion, the liquid would lie on the high pressure equivalent of $a-b$ and therefore in front of the Sierra Nevada trend. However, more extensive fusion could produce a liquid on the boundary surface between the plagioclase and quartz primary phase volumes and in an intermediate position on the Sierra Nevada trend. If such a liquid were separated from the source region and intruded upward, it would lie within the primary-phase volume of plagioclase because of shrinkage of the quartz primary-phase volume with decreasing pressure. Fractional crystallization with precipitation of plagioclase of intermediate composition would then produce the mafic and felsic parts of the Sierra Nevada trend as described in the preceding paragraph.

Production of Partially Liquid Magma.

Let us now consider the consequences of assuming that separation of melt from crystals at the source region is imperfect. All variations in the efficiency of separation will be allowed including the extreme possibility of no separation, that is, upward intrusion of the entire crystal-liquid mush.

At pressures of about 10 kb or less, liquid h (Fig. 7) would be the initial liquid formed on equilibrium fusion of our assumed lower crustal composition lc , and this liquid would be in equilibrium with plagioclase q , K-feldspar u , and quartz. The average composition of the three crystalline phases, projected from Qz , lies at lc , because only an infinitesimal amount of liquid would have been formed. By comparison with Figure 3, it will be noted that the liquid composition h lies near the felsic end of the Sierra Nevada trend. More extensive equilibrium fusion of lc would result in the complete melting of K-feldspar. Thus, when the liquid composition reaches s' (Fig. 7), the average composition of the crystals is at j' and consists of quartz and plagioclase, and K-feldspar is completely dissolved. Again, the liquid composition s' lies near the felsic end of the Sierra Nevada trend and has changed very little from the initial liquid h . If the rising liquid s' carried some or all of the crystals j'

with it, the resulting magma would lie on the line $lc-s'$.

More extensive equilibrium fusion would cause the liquid path to leave the line $a-b$ (Fig. 4) and move a short distance along the boundary surface $a-b-c-d$. Finally, it would leave this surface and move through the plagioclase primary phase volume along a slightly curved path to lc , where fusion would be complete. During these later stages of fusion, the liquid composition would continue to lie either near the felsic end of the Sierra Nevada trend, or for very large amounts of fusion, upward along this trend toward lc . The average composition of the crystals would be located initially near the mafic end of the Sierra Nevada trend and, with more extensive fusion, would migrate to a position close to an extension of the Sierra Nevada trend (point m on Fig. 4). Throughout equilibrium fusion, plagioclase of intermediate composition would be the predominant residual phase. For the starting composition described here, it would be joined by smaller amounts of quartz at intermediate stages of fusion, and quartz and K-feldspar at early stages of fusion.

Thus, regardless of the degree of melting or the proportion of crystals carried along with the rising liquid fraction, the average composition of the crystal-liquid mush would lie approximately along the Sierra Nevada trend with a composition at least as felsic as the starting composition lc . If fusion were extensive enough to drive the liquid composition into

the plagioclase primary-phase volume, the Sierra Nevada trend could be duplicated by low-pressure fractional crystallization and precipitation of plagioclase of intermediate composition. As in our previous discussion of a completely liquid starting magma, the Sierra Nevada trend would grade transitionally from crystal accumulation near the mafic end to fractionated liquids near the felsic end.

At higher pressures up to 19 kb, small amounts of fusion would yield liquids along the high-pressure equivalent of $a-b$ (Fig. 4) in front of the Sierra Nevada trend, but incorporation of some or most of the crystal fraction with the escaping liquid would move the bulk composition of the rising magma close to lc to a position where subsequent low-pressure fractional crystallization could produce the Sierra Nevada trend. More extensive equilibrium fusion at the source would also move the liquid composition closer to lc . The escaping liquid would then not need to retain as much of the crystal fraction in order to obtain a bulk composition capable of producing the Sierra Nevada trend by fractional crystallization.

Thus, according to the phase diagram, equilibrium fusion of the lower crust is capable of producing the Sierra Nevada trends under all conditions of separation of liquid from crystals: (1) complete separation of liquid from residual crystals, (2) retention of some crystals in the rising magma, and (3) upward movement of the entire crystal-liquid mass.

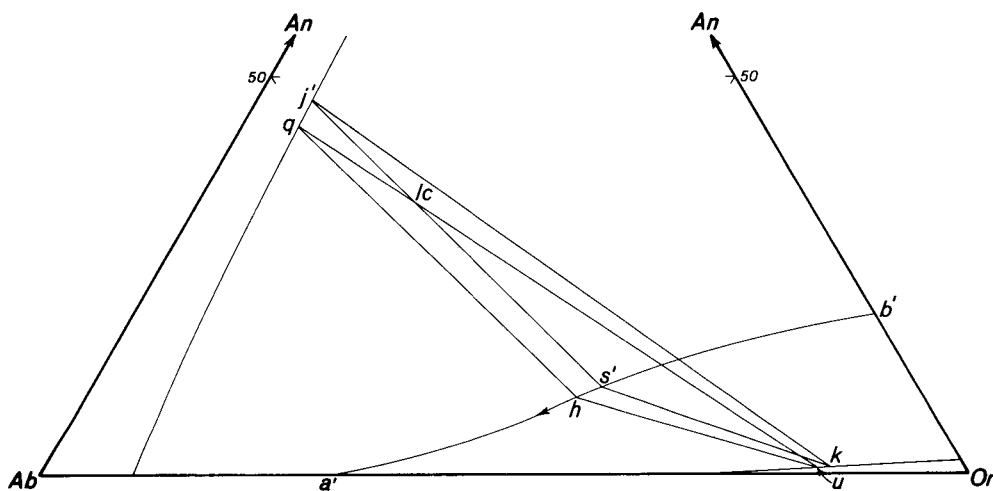


Figure 7. Qz -saturated phase relations as in Figure 5 with solidus fractionation lines omitted.

Phase relations in the system *Ab-An-Or-Qz-H₂O*, taken alone, are entirely compatible with all these possibilities.

Processes Intermediate between Fractional and Equilibrium Fusion

Consider now a process intermediate between fractional and equilibrium fusion. This can be thought of as several equilibrium fusion events from the same source region. All of the previous discussion of equilibrium fusion would apply for each event except the composition of the source material would change in a stepwise fashion after each extraction of magma.

If completely liquid magmas were episodically separated from the source region by an intermediate process, it would be possible to obtain magma compositions departing from the quartz saturation surface and lying along the Sierra Nevada trend, as pointed out in the previous discussion of equilibrium fusion. With increasing temperature in the source region, the successive magmas would become increasingly mafic, and the sequence of intrusion at the site of emplacement would be from felsic to mafic. This is contrary to field relations, which show that within the best studied sequences, younger intrusives are progressively more felsic. The observed order of intrusion would require periodic extraction of magma from a source region that was steadily decreasing in temperature. It seems highly artificial to suppose that magmas were always separated from the source region during cooling and never during heating. Also, complete or nearly complete fusion of the lower crust would be required in order to produce completely liquid magmas near the mafic end of the Sierra Nevada trend. In the absence of other compelling reasons, we believe the very high temperatures required to produce complete melting are unlikely. Also, field evidence discussed below in the section on retention of residual crystals from the source region suggests that complete melting did not occur. For these reasons, we believe a single mafic to felsic intrusive sequence could not have formed from completely liquid magmas produced by a process transitional between fractional and equilibrium fusion.

Turning now to partially liquid magmas, it will be recalled from our previous discussion of equilibrium fusion that magma compositions along the Sierra Nevada trend could also be produced in this way. Consider first fusion at about 10 kb or less. The predominant residual

phase would be plagioclase of an intermediate composition in the vicinity of *m* (Fig. 4); thus, the residual crystalline fraction would lie toward the mafic end of the Sierra Nevada trend. The liquid fraction would lie toward the felsic end of the Sierra Nevada trend. Therefore, depending on the proportion of residual crystals retained in the magma, the bulk composition of each successive magma could lie either toward the felsic or mafic end of the Sierra Nevada trend, and there is no reason to expect the characteristically observed mafic to felsic sequence of intrusion.

Relations at higher pressures up to 19 kb are less certain because of lack of data, but some general arguments can still be made. Assuming a lower crustal composition at *lc* and assuming as before that the high-pressure equivalent of line *a-b* lies in front of the Sierra Nevada trend, liquids produced along this line would be in equilibrium with crystal residues much richer in *Qz* than at lower pressures. Thus, variations in the proportions of crystals carried along by each successive magma would cause some of these magmas to be high in *Qz* and low in *Or*, whereas others would be low in *Qz* and high in *Or*. Such a trend of variation would lie at a high angle to the observed trend; therefore, this mechanism is unsatisfactory. More extensive fusion would yield liquid and crystal fractions lying closer to the Sierra Nevada trend but the objections in the preceding paragraph would apply.

Thus, a field association involving a well-established mafic to felsic sequence of intrusion is not satisfactorily explained by a series of equilibrium fusion events from a single lower crustal source region. Such an association is best explained by a single equilibrium fusion event with subsequent fractional crystallization of the derived magma higher in the crust, as discussed in the preceding section. Processes transitional between fractional and equilibrium fusion may have occurred in the Sierra Nevada but not within a sequence having a mafic-to-felsic order of intrusion.

ROCK SEQUENCES

The task of finding what body of rock constitutes a single equilibrium fusion event is a matter to be resolved by field, petrologic, and chemical study of the rocks. Such studies lead us to equate each intrusive sequence with a single equilibrium fusion event. The simplest kind of sequence is a concentrically zoned pluton in which relatively mafic rock in the

margins grades inward without discontinuities to more felsic rock in the core. Such a compositional pattern requires that crystals accrete inward from the margins and that with crystallization the liquid phase be displaced continuously inward. Convection would assure a continuous supply of crystals to the outer part of the magma but probably is not required for the formation of a zoned pluton, because only crystals can accrete and the melt must be displaced inward. Many zoned plutons are present in the Sierra Nevada—for example, the Cartridge pluton (Moore, 1963, p. 62 and Fig. 25; Bateman and others, 1963, p. D30–D33 and Fig. 16), the Mount Givens granodiorite and the granodiorite of Lake Edison (Bateman and Lockwood, 1970), and the Bald Rock batholith (Compton, 1955). Most of these plutons have been intruded locally by felsic rocks that are thought to represent abrupt upward movements of liquid magma into more completely crystallized magma or rock.

A more complex sequence is shown by the Tuolumne Intrusive Series in which successively younger and more felsic plutons in sharp contact with one another lie in concentric arrangement within older and more mafic plutons. Here, the marginal accretion of crystals inward has been repeatedly interrupted by upward movements of the less crystallized core magma.

Still more complicated sequences result when the core magma breaks through the outer more completely crystalline carapace of a crystallizing pluton and intrudes the country rocks. An apparently excellent example of a sequence in which the map pattern seems clearly to show that core magma repeatedly broke through the outer margins of a crystallizing body is the White Creek batholith of southeastern British Columbia (Reesor, 1958). In some sequences, separation of core magma has been so complete that outcrop patterns fail to show the kind of relation so evident in the White Creek batholith. In such sequences, the successively emplaced members are related to one another by means of field, mineralogic, petrologic, chemical, and geochronologic criteria.

RETENTION OF RESIDUAL CRYSTALS FROM THE SOURCE REGION

Earlier we showed that the phase relations are compatible with the separation of either completely or partially liquid magmas from the lower crust. However, several other lines

of evidence can be cited in support of the view that substantial amounts of crystalline material were retained in the parent magmas as they rose from their source regions in the lower crust to their sites of emplacement. Three general considerations are that substantially lower temperatures are required to produce a partial melt than a complete melt, buoyancy is not likely to allow a mobile partial melt to lie quietly until it becomes a complete melt, and the high viscosity of water-undersaturated granitic melts would inhibit complete separation of liquid from crystals.

Turning to the rocks themselves, many of the earliest plutons of magmatic sequences are crowded with mafic inclusions and vaguely defined dark clots composed of anhedral biotite, hornblende, plagioclase, magnetite, and sphene. Some mafic inclusions have been shown to have been derived from nearby wall and roof rocks, but such a source does not adequately explain mafic inclusions distributed across mile after mile of outcrop, especially where country rocks of suitable composition for the formation of the inclusions are lacking (Bateman and others, 1963, p. D17–D18). The most likely source for most mafic inclusions and the accompanying smaller less well defined clots is in refractory material that remained after partial fusion and was remade as it was carried upward as part of the magma. The presence of discrete euhedral crystals of hornblende and biotite, which clearly formed as new crystals in the magma, contrasts with the anhedral biotite and hornblende in the clots and suggests that the clots had a different origin.

Still another line of argument in favor of crystalline material having been carried upward as part of the magma is found in the compositional patterns of the plagioclase crystals. Many plagioclase crystals have mottled cores of intermediate composition, which are encased in rims that are increasingly more sodic outward but that exhibit both compositional discontinuities and oscillations. The cores of some crystals have been corroded; in a few, the innermost part of the rim immediately adjacent to the core is even more calcic than the core. A reasonable explanation for both the corrosion of the cores and the subsequent deposition of more calcic plagioclase adjacent to the core is that temperatures of crystallization decreased as a result of the rise of a partially liquid magma undersaturated in water into a region of lower pressure (Vance, 1962, p. 644–645).

HEAT SOURCES TO TRIGGER FUSION OF THE LOWER CRUST

In order to test fully an origin for the Sierra Nevada batholith by partial fusion of the lower crust, it is necessary to compare the temperatures required by this process with temperatures likely to have been available. Lachenbruch (1968) calculated hypothetical maximum geotherms in the Sierra Nevada under two assumptions: (1) the mantle heat flow was the same as at present, and (2) heat sources were uniformly redistributed throughout the crust prior to magma formation. In the western foothills (locality SJ of Lachenbruch, 1968, Fig. 7), seismic data indicate that the crust is 31 km thick (Bateman and Eaton, 1967) and uniform redistribution of heat sources would yield a calculated temperature at the base of the crust of only 250°C prior to magma generation. Taking the seismic data literally, Lachenbruch concluded that melting of significant parts of the lower crust at locality SJ would require either (1) a transient heat source from the mantle or (2) massive erosion on the order of 20 km. This amount of erosion would permit a former crustal thickness of about 50 km at the time of magma generation and temperatures high enough for melting in the lower crust. Even greater erosion (30 km) would be required immediately to the west at his locality ST.

Assuming that erosion has removed 20 to 30 km of crustal rock and that the geotherm was close to Lachenbruch's reference model prior to magma generation, the former pressure of the rocks presently exposed at the surface would be 5.5 kb at locality SJ and 8.3 kb at locality ST. This pressure range is in excess of that indicated by the metamorphic assemblages. The metamorphic rocks of the western foothills are mostly in the greenschist facies of regional metamorphism; near plutonic rocks, however, they are in the hornblende-hornfels or even pyroxene-hornfels facies of contact metamorphism. These facies indicate moderate to low pressures during metamorphism. The widespread occurrence of andalusite, the presence of sillimanite adjacent to plutonic rocks, and the absence of kyanite indicate pressures less than 3.8 kb using the data of Holdaway (1971) or less than 5.5 kb using the data of Richardson and others (1969). Thus, 20 to 30 km of erosion could not have

occurred (see also Kerrick, 1970, p. 2934), and seemingly we are left with Lachenbruch's alternative that melting in the lower crust beneath the western foothills could have occurred only with the assistance of some transient heat source from the mantle.

An obvious source of additional transient heat which fits into current concepts of global tectonics, is upward transport of magmas originating from a subduction zone. By analogy with currently active subduction zones such as the Aleutian arc, the dominant magma type would be andesite (Coats, 1962). Data from several different island arcs (Hamilton and Gale, 1968; Oxburgh and Turcotte, 1970; Stoiber and Carr, 1971) indicate that the depth to the Benioff zone beneath active volcanoes is consistently between 100 and 200 km. Taking 150 km (48 kb) as average and extrapolating the data of either Green and Ringwood (1968) or Green (1972), the temperature required to produce an anhydrous andesite liquid at this depth would be about 1,550°C. The presence of, say, 1 percent water in the andesite liquid would reduce the required temperature to about 1,500°C (Green, 1972). This temperature is compatible with the range of temperatures calculated for the upper surface of a descending slab of lithosphere at a depth of 150 km (Oxburgh and Turcotte, 1970; Toksöz and others, 1971; Griggs, 1972). If the andesitic magma moved rapidly upward under approximately adiabatic conditions, it would pass through the lower crust at about 1,400° to 1,450°C, and it would be in a superheated condition because of falling liquidus temperatures with decreasing pressure. Less rapid upward movement would allow further cooling of the magma because of transfer of its superheat to the intruded rocks, but in order to remain in a predominantly liquid condition when it arrived in the lower crust at, for example, 15 kb, its temperature could not fall below about 1,150° to 1,200°C (Green, 1972). Thus, the subduction-zone model for the generation of andesite implies that rocks in the lower crust came in contact with magma at a minimum temperature of about 1,150°C and a maximum of about 1,450°C.

Some might argue in favor of water-saturated andesite magmas, which could exist at much lower temperatures. However, only limited amounts of upward intrusion are possible for a water-saturated magma. The solidus curve

under this condition has a negative value for dP/dT at crustal pressures (Tuttle and Bowen, 1958), and the magma would crystallize on reduction of pressure and never reach the surface.

Temperatures of 1,150° to 1,450°C are higher than those required for fusion of the lower crust, even under completely anhydrous conditions. Assuming a lower crustal composition close to andesite, the data of Green (1972) indicate an anhydrous solidus temperature of 1,100° to 1,150°C at 15 kb. Because of the presence of biotite and hornblende in the Sierran granitic rocks, a completely anhydrous lower crust is unreasonable. Solidus temperatures for andesite with small amounts of water are not yet available, but Green (1972) indicates that for andesite containing 2 percent H_2O , the solidus at 15 kb is less than 900°C. Thus, it is clear that semicontinuous eruptions over a period of time along a linear belt of andesitic volcanism would eventually heat the lower crust enough for partial fusion. In fact, there would appear to be no way to avoid local fusion of the lower crust, particularly because some of the magmas passing through the crust would be of basaltic composition and even hotter than the andesitic magmas.

It is interesting to note that the heat-flow calculations of Roy and others (1972) give a temperature of about 1,030°C at 50 km (15 kb) in the Basin and Range province, a region of extensive Cenozoic volcanism. Using a range of possible heat-flow parameters, Lachenbruch (1970, Fig. 5) has calculated even greater temperatures at this depth in the Basin and Range province. These calculations are for a somewhat different tectonic setting than the Sierra Nevada, but nevertheless, they reinforce our conclusion that active volcanism in the Sierra Nevada would produce temperatures in the lower crust high enough for extensive fusion.

The quantities of heat that would have to be transferred from the andesitic magma to the lower crust are not excessive. As a rough calculation, assume that the lower crust is already near its solidus temperature prior to the intrusion of andesite from the mantle. In order to raise the temperature of one unit mass of lower crustal material by 100°C and also melt 50 percent of its mass, about two unit masses of completely liquid andesitic magma would be required to fall in temperature by 100°C. If,

in addition to falling in temperature by 100°C, 50 percent of the andesitic magma crystallizes, only one unit mass would be required. Mixing of the partially fused crust with the partially crystallized andesite would result in two unit masses of magma containing 50 percent crystals that would be ready to move upward and form an intrusive sequence.

Thus, we conclude that if the subduction-zone model with accompanying andesitic volcanism is accepted, fusion of the lower crust along the belt of volcanic activity would have been inevitable, and there would appear to be no escape from the conclusion that a major component of the Sierra Nevada batholith was once lower crustal material.

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