

## Petrological aspects of the correlation between potash content of orogenic magmas and earthquake depth

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**SUMMARY.** The petrological interpretation of the variation of  $K_2O$  content with depth to the Benioff zone in orogenic magmas is complicated by several factors: (1) Magmas may not be true primary liquids but have undergone differentiation.  $K_2O$  contents, at a specific  $SiO_2$  level, will depend upon the  $SiO_2$  content of the parental magma and the nature of the crystallizing phases more than on original  $K_2O$  content. (2) The depth to the Benioff zone may not give a true reflection of the depth of melting. Magmas may not be derived from the uppermost layer of subducted oceanic crust but rather the overlying upper mantle. Earthquakes may not occur in the uppermost layer of the subducted plate, but in its colder, central parts. Hence, earthquake depth may not be related to the source of the magma. (3) It is difficult to envisage how the temporal increase in  $K_2O$  may occur in certain areas (*e.g.* Aleutian I., Fiji) if it is primarily controlled by the depth to the Benioff zone.

There may be some correlation between  $K_2O$  content of magmas and earthquake depth, but its cause is difficult to determine. None of the existing explanations is entirely satisfactory, and it is suggested that varying degrees of fractional crystallization may play an important role in controlling  $K_2O$  contents.

THE existence of systematic chemical variations in magma compositions across orogenic zones has been known for a long time. Sugimura (1968) provided an excellent review of the development of ideas and observations on this zonation. The work and interpretation of Kuno (1959) on the spatial distribution of pigeonitic, high-alumina basaltic, and alkaline volcanism and their relation to calc-alkaline magmas in Japan provided the fundamental model on which much subsequent work in orogenic belts has been based. One chemical parameter that shows a variation across orogenic belts is the  $K_2O$  content. Dickinson and Hatherton (1967) suggested a correlation between the  $K_2O$  content and the depth to the underlying Benioff zone ( $= h$ ), which could be used to determine the position of volcanic rocks, both modern and ancient, within a tectonic region. The reliability of the correlation has been questioned (Nielson and Stoiber, 1973) and has required modification to a scheme whereby the different types of orogenic volcanic belts have distinct  $K-h$  correlation patterns (Dickinson, 1975).

This kind of systematic chemical variation is not unique to orogenic belts. McBirney (1967, fig. 5) suggested that there was a correlation between the horizontal distance from a mid-ocean ridge and the degree of alkalinity of volcanism.

### *Previous models*

Several possible explanations have been presented to explain why the  $K_2O$  content apparently increases with the distance to the Benioff zone.

*Increase in  $K_2O$  content of the mantle with increasing depth.* This would appear to be the simplest model for explaining the  $K-h$  correlation. However, implicit in this model are the assumptions that phase relations remain identical over the depth range considered and that the degree of melting is constant. There is no other evidence for variations in  $K_2O$  content of the mantle and this has been rejected by most workers (Dickinson and Hatherton, 1967; Best, 1975).

*$K_D$  between liquid and solid changes with depth.* Dickinson (1968) suggested that if the partition coefficient ( $K_2O$  of solid/ $K_2O$  of liquid) decreased with increasing pressure, higher  $K_2O$

contents in magmas would be anticipated at greater depth (all other parameters remaining constant). Dickinson did not state to which minerals this hypothesis applied. Olivine and pyroxene are essentially free of  $K_2O$ . Hence,  $K_D$  must be extremely small (e.g. Delong, 1974) even at very low pressure. Thus a significant decrease in  $K_D$  for these phases with increasing pressure is not possible. The only plausible mantle phase that could have a significant  $K_D$  is phlogopite. If this phase were present in sufficient quantity at depth, its behaviour could produce the desired effect. Bravo and O'Hara (1975) demonstrated that the liquid in equilibrium with phlogopite and mantle minerals at 15 kb (= 1500 mPa) contains 1%  $K_2O$ , while at 30 kb it is over 3%.  $K_D$ , therefore, changes in the right direction to support Dickinson's (1968) hypothesis. However, while the synthetic liquid composition at 15 kb has similarities with andesites, at higher pressure it does not (Bravo and O'Hara, 1975). At pressures greater than 20 kb it is unlikely that any melting process in the mantle could produce a quartz-normative liquid (Kushiro, 1972; Nicholls and Ringwood, 1972; 1973). Some fractionation process would be required to produce andesite from these high-pressure primary magmas, which would cause changes in the original  $K_2O$  content of the magma.

*Varying degrees of melting.* It is likely that  $K_2O$  will be strongly partitioned into the liquid during melting; and  $K_2O$ -bearing phases, such as phlogopite and sanidine, will disappear very close to the solidus. Hence, with higher degrees of melting the  $K_2O$  content of the liquid will be diluted. If smaller degrees of partial melting were produced at higher pressure the  $K-h$  correlation might be explicable. However,  $dT/dP$  for hydrous peridotite is almost zero (Kushiro *et al.*, 1968; Green, 1972). This will probably be less than the geothermal gradient. Hence, provided melting under hydrous conditions is considered, as seems likely, to explain the properties of the low-velocity zone (Anderson, 1970) these gradients suggest that the degree of melting may increase with increasing depth. This is the reverse of that required to explain the variation in  $K_2O$ .

Green *et al.* (1967) envisaged the generation of magmas from diapirs initiated near the subduction zone. Depending on the distance up which they migrated, variable degrees of melting would be produced. However, diapirs from a deeper source would have the chance of greater upward movement with subsequent greater degree of melting and lower  $K_2O$  content; again producing the reverse of the desired effect.

*Breakdown of hydrous phases.* The extent to which hydration of oceanic crust occurs is unknown. However, assuming some water is subducted the formation of hornblende in the oceanic crust seems plausible. Conditions for the breakdown of hornblende in subduction zones have been located from experimental data (Lambert and Wyllie, 1968; Nishikawa *et al.*, 1971; Holloway and Ford, 1975) with a maximum at 30 to 35 kb. With its breakdown to pyroxene and garnet some  $K_2O$  as well as  $H_2O$  may escape into the overlying mantle. Phlogopite or sanidine may form during this process and may be carried to greater depth before breakdown or melting of these minerals to release  $K_2O$  from the subduction slab. These dehydration reactions may provide the driving force in orogenic magmatism as advocated by Fyfe and McBirney (1975). However, release of  $K_2O$  should occur at fairly discrete depths and hence produce distinct peaks rather than a systematic variation across tectonic belts.

*Sanidine eclogite buffer.* Marsh and Carmichael (1974) determined the stability of sanidine eclogite and liquid from the thermodynamic data and concluded that with increasing pressure the liquid should become enriched in  $K_2O$ . This may be perfectly plausible at the beginning of melting of oceanic crust. Green and Ringwood (1968) showed that 30 to 50% melting of oceanic crust was required to produce andesitic liquids. It remains to be demonstrated whether, at such a high degree of melting, sanidine would still be a stable phase, but it seems unlikely from published data on melting of tholeiitic material (e.g. Green and Ringwood, 1968). The

high-alumina quartz tholeiite used by Green and Ringwood (1968) contained 0.6 %  $K_2O$ , which is higher than that for oceanic tholeiite (Engel *et al.*, 1965), although it may be lower than for the altered material subducted, and yet they did not report sanidine from any of the anhydrous runs above or below the solidus. If sanidine is no longer in equilibrium with liquid, this mineral will not be able to buffer the  $K_2O$  content of the liquid.

*Scavenging of incompatible elements.* Best (1975) suggested that the incompatible elements may become enriched in the liquid by a zone-refining or wall-rock equilibration type of reaction. In view of the data presented by Jamieson and Clarke (1970) and Cox and Jamieson (1974) supporting a process of continued wall rock equilibration with magma, Best's hypothesis seems possible. The longer path-length of magmas from deeper sources would permit higher  $K_2O$  content to build up.

*Crustal contamination.* Somewhat similar to the previous model is the hypothesis of contamination of magma by crustal material. Dickinson (1975) has compiled isotope data ( $^{87}Sr/^{86}Sr$ ) that suggest that orogenic magmas are not, in general, significantly richer in radiogenic Sr than ocean-floor tholeiites, and hence this process is unlikely to have played a major role in determining magma composition.

#### *Fractionation effect*

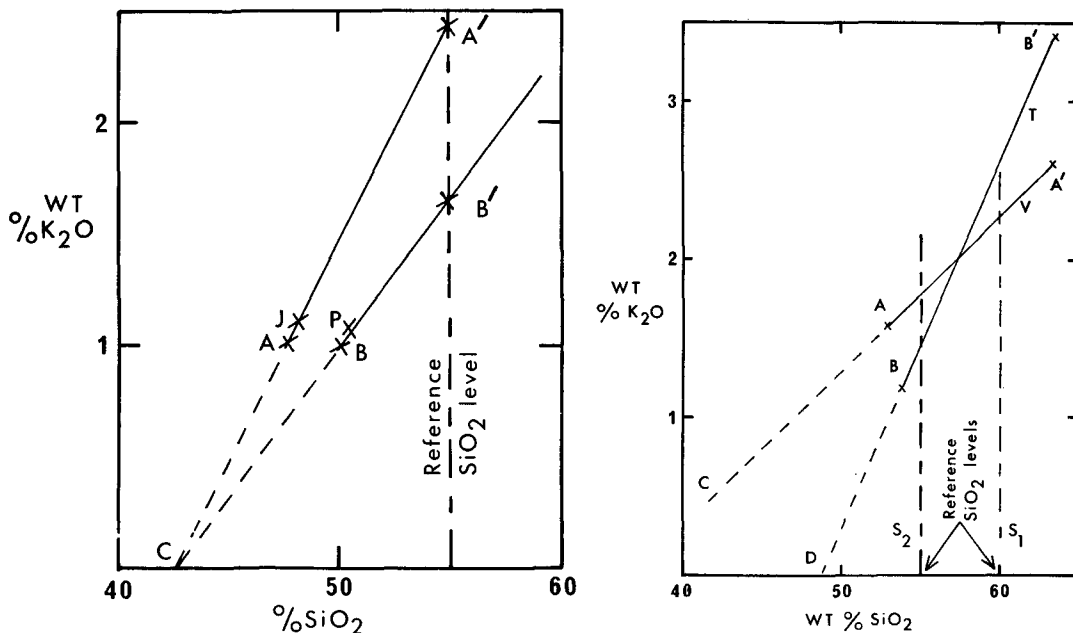
Implicit in the first five models discussed above is the assumption that the erupted magma is a true primary melt. The correlation between  $K_2O$  and depth has been attempted at various  $SiO_2$  values. Dickinson and Hatherton (1967) used reference levels of 55 % and 60 %  $SiO_2$ , while Dickinson (1975) used a value of 57.5 %  $SiO_2$ . It would seem unlikely that magmas with these different  $SiO_2$  values could all be true primary magmas.

One of the main factors that may affect the  $K_2O$  content of a magma at any particular  $SiO_2$  level is fractionation. Nearly all orogenic volcanic suites show a linear chemical variation, which may satisfactorily be interpreted as the effect of fractional crystallization. The fact that basalt is subordinate to andesite in calc-alkaline suites has frequently been used to support the hypothesis that andesite is the primary magma. It may equally be argued that this relationship is excellent evidence for a fractionation hypothesis. That some basalt is erupted demonstrates that there was some material more basic than andesite present in the sub-volcanic region. The large volumes of andesite could indicate that fractionation has been extremely effective in allowing only a small volume of the parental composition (basalt) to erupt as the composition rapidly differentiated to the more evolved members of the series. Kuno (1968) came to a similar conclusion using his differentiation index (SI), stating (p. 674): 'This maximum frequency of eruption of the middle stage magmas (andesites) is interpreted as being caused by a balance between the decreasing amount of successive magmas produced by fractionation in magma reservoirs and the increasing tendency of the successive magmas to erupt at the surface because of gradual concentration of volatile substances. . . .'

In order to interpret the variation in  $K_2O$  across orogenic belts it may, therefore, be necessary first of all to remove the effect of fractionation from the  $K_2O$  values so that the  $K_2O$  values of the parental magmas, rather than of evolved magmas, may be compared with each other and with the depth to the subduction zone.

The complications that may arise due to fractionation may be conveniently discussed by reference to different chemical models. Suppose two parental magmas have different  $SiO_2$  contents but comparable  $K_2O$  levels: What inferences could be made about the  $K-h$  correlation based on  $K_2O$  contents at a fixed  $SiO_2$  value? This situation is indicated in fig. 1, where A and B represent the parental magmas. Let us suppose that the chemical variation in both

suites is the result of crystallization of the same phases, having the bulk composition C. The two trends are indicated as A-A' and B-B'. At the arbitrary reference SiO<sub>2</sub> value the K<sub>2</sub>O contents of magmas from the two suites would be different because the degree of fractionation is not the same. Hence, applying the K-h correlation the interpretation would be that the depth to the subduction zone under suite A was greater than under suite B.



FIGS. 1 and 2: FIG. 1 (left). K<sub>2</sub>O-SiO<sub>2</sub> plot to show the effect of differentiation on K<sub>2</sub>O of two magmas with identical K<sub>2</sub>O but different SiO<sub>2</sub> contents. J—parent to alkali olivine basalt series in Japan (Kuno, 1967). P—parent to high-K series in Papua (Gill, 1970). Solid lines are liquid evolution paths; dashed line indicates extract composition. FIG. 2 (right). Example of effect of differentiation of different crystalline extract compositions on magma series. T—Mt. Trafalgar; V—Mt. Victory differentiation trends from Jakes and Smith (1970). Solid lines are liquid evolution paths; dashed lines project back to hypothetical extract compositions.

To determine the parental magma of a suite is an extremely subjective matter. It is also a matter of personal prejudice whether or not one regards that parental magma as the primary melt produced during melting of some source rock. The terms parental magma and primary melt are used here as defined by Carmichael *et al.* (1974). While the least siliceous aphyric lavas may give a reasonable estimate of the parental magma composition, unless a very large number of samples have been analysed, one cannot be sure that the parental magma of a suite has been sampled.

One could cite, as an example of the effect mentioned in fig. 1, the high K<sub>2</sub>O rocks of Eastern Papua (Gill, 1970; Jakes and Smith, 1970). The most basic lava analysed contains 50.5 % SiO<sub>2</sub> and 1.07 % K<sub>2</sub>O (Gill, 1970; Fig. 8). For Japan, Kuno (1967) suggested the parental magma of the alkaline series contains 48.1 % SiO<sub>2</sub> and 1.13 % K<sub>2</sub>O. If these were used as the two examples in fig. 1 that fractionated the same phases, the K<sub>2</sub>O contents at 55 % SiO<sub>2</sub> (or whatever reference concentration one chose) would be significantly different. From the K-h correlation one might conclude that the Japanese samples were derived from greater depth, while from seismic data the Benioff zones are probably at comparable depths (Sugimura, 1968; Gill, 1970).

An example of the varying degree of differentiation undergone by the different suites may be taken from the data of Hatherton (1969). In his Fig. 12 he shows that the MgO values of various magma suites at 60 % SiO<sub>2</sub> decreases systematically with inferred increase in depth to the Benioff zone. MgO values decrease with increasing differentiation. Hence, it may be that the suites overlying progressively deeper parts of the Benioff zone have undergone a greater proportion of fractionation to reach the reference SiO<sub>2</sub> level. As K<sub>2</sub>O increases with fractionation this extremely good negative correlation between K<sub>2</sub>O and MgO suggests that fractionation may play a major role in determining K<sub>2</sub>O contents of erupted magmas.

As an alternative geometrical complication of K-*h* correlation, consider the case where two parental magmas have the same SiO<sub>2</sub> contents, but different K<sub>2</sub>O levels and suppose they crystallize different phases. The situation is shown in fig. 2 where parental magmas A and B crystallize phases with compositions C and D respectively. The resultant differentiation trends are A-A' and B-B' and they may cross each other. Depending on what SiO<sub>2</sub> content is chosen as the reference, it would be possible to infer that either suite A or B had the higher K<sub>2</sub>O content. Hence if S<sub>1</sub> were the reference level, K<sub>2</sub>O contents would imply that the distance to the Benioff zone were greater under suite B than A; while at S<sub>2</sub> exactly the reverse situation would be indicated.

An excellent example of this may be taken from the data of Jakes and Smith (1970). They analysed lavas from Mount Trafalgar and Mount Victory in Eastern Papua and presented a K<sub>2</sub>O-SiO<sub>2</sub> variation diagram from which fig. 2 is taken. Mount Trafalgar is a recently extinct volcano while Mount Victory is still active. If one took 55 % SiO<sub>2</sub> as the reference composition it would be inferred from fig. 2 that Mount Victory had a higher K<sub>2</sub>O content and hence that the depth to the subduction zone, *h*, might be increasing with time. However, if 60 % SiO<sub>2</sub> were chosen as the reference exactly the reverse inference would be obtained. Geographically these two volcanoes are so close together that one or both of these inferences must be invalid and one must therefore question the reliability of choosing arbitrary SiO<sub>2</sub> values for the K-*h* correlation.

Kuno (1968) cited an example in which he believed that two divergent suites were produced from the same parental magma by fractionation of different phases. In fig. 3a are plotted the average composition of the pigeonitic and hypersthentic series determined by Kuno (1968; Tables 3 and 4). From this graph it would seem that no single parental magma could give rise to the two series, although two very similar parental magmas could be envisaged (P' and P''). However, the second half of Kuno's hypothesis seems justifiable, that these magmas fractionated different phases to produce the observed trends. The exact mineralogy of these extract compositions, somewhere in the region of E' and E'', is not important here. That they are different is all that matters in this discussion. The nature of plausible crystallizing minerals has been reviewed by Cawthorn and O'Hara (1976).

The variation in K<sub>2</sub>O values at different SiO<sub>2</sub> levels is only very minor in the above example. However, Kuno (1968) referred to another example where differences are much more significant. Holmes (1916) analysed samples from an alkaline and a hypersthentic suite of rocks that appear to be intimately associated. Kuno (1968) suggested that fractionation of different phases from a common parental composition may be responsible for the diversity of the trends plotted in fig. 3b. Inspection of this diagram suggests that there may not be a common parent to both series but that fractionation of the same phases from both series might have occurred. Perhaps instead of Kuno's (1968) interpretation, a model analogous to that discussed for fig. 1 might apply. However, the conclusion that may be drawn from the data is that distinctly different K<sub>2</sub>O contents at specific SiO<sub>2</sub> levels may be deduced for suites that (according to Holmes) are spatially and temporally inseparable. The use of the K-*h* correlation model for these suites

would demand the simultaneous existence of two different depths to a Benioff zone (or zones) at the same place. The author feels this is a rather unlikely situation.

The complications that could arise during fractionation due to the existence of different parental magmas having different  $K_2O$  and  $SiO_2$  content and crystallizing different phases would make interpretation of the  $K-h$  correlation model extremely difficult.

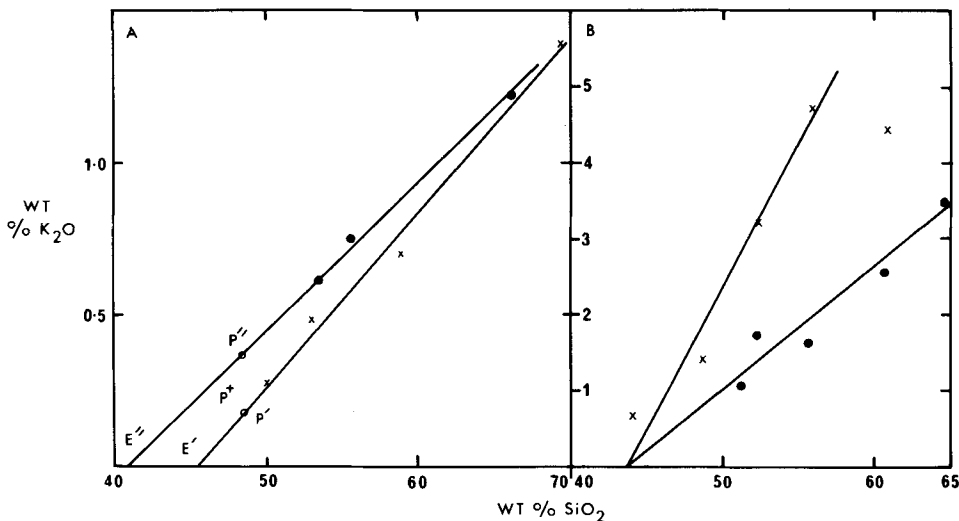


FIG. 3A (left). Differentiation trends of the pigeonitic series (crosses) and hypersthentic series (solid dots) from Japan (Kuno, 1968). P is parental magma to both series from Kuno (1950); P' and P'' indicate more probable parental magma compositions based on a linear differentiation model with different phases crystallizing. 3B (right). Differentiation trends for alkalic (crosses) and hypersthentic series (solid dots) from Holmes (1916) indicating a common extract composition.

#### *Variation in $K_2O$ with time*

The potassium variation recognized by Dickinson and Hatherton (1967) was essentially a spatial relationship. Subsequently, it has been demonstrated that  $K_2O$  also increases with time within a given area (Jakes and White, 1969). In terms of the  $K-h$  correlation hypothesis, this would imply that the distance to the Benioff zone from a specific point on the surface increased with time. This could be created by three different processes as shown schematically in fig. 4.

Fig. 4a depicts a situation where the dip of the subduction zone gradually increases with time, the position of the trench-arc relation remaining stationary. If this were the likely mechanism the oldest arcs would be expected to have the steepest slopes of the subduction zone. Such a trend would be difficult to demonstrate as there is no independent mechanism for determining the orientation of subduction zones in the past. Some tholeiitic to calc-alkalic regions have a very steep dip to the Benioff zone; for example, Tonga (Sykes, 1966) and Bougainville (Jakes and White, 1969). Hence, it would seem unlikely that more alkalic compositions could be erupted here by increasing the dip.

A second model involves the shifting of the trench relative to the arc, but not changing the angle of the subduction zone. One way this could occur is shown in fig. 4b and involves the locking of a subducted plate, breaking of the oceanic crust and the generation of a new subduction zone. The new subduction zone would be at a greater depth than the older one by an amount depending on the thickness of the old plate and the angle of subduction. Assuming the

oceanic plates are approximately 70 km thick and taking a dip of 30°, the increased distance from Benioff zone to surface would be 100 km (fig. 4b). Hence, if a tholeiitic magma were initially erupted, with the new orientation the depth to subduction zone would be increased from 100 km to 200 km and shoshonitic or alkaline magmatism would be anticipated. This change is far more drastic than documented for the Aleutian Islands and Indonesia (Jakes and White, 1970; Gill, 1970). Hence, unless the new subducted material intrudes into the old plate rather than underneath it, as shown in fig. 4b, this mechanism would not produce the observed variation.

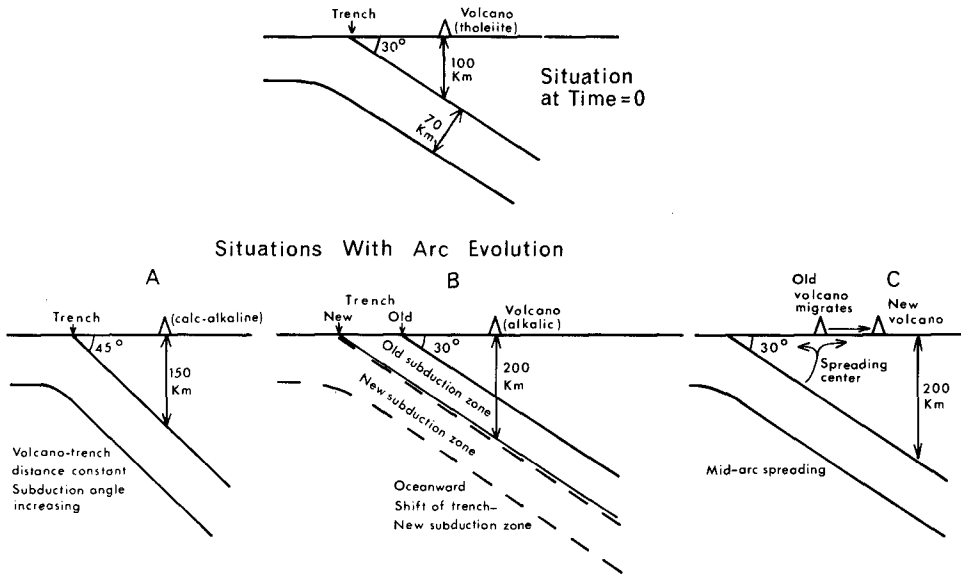


FIG. 4. Models to explain increasing depth to subduction zone during evolution of volcanic sequence causing increase in  $K_2O$  content of magmas with time. See text for explanation.

A third possibility could be termed ‘mid-arc spreading’ and is indicated on fig. 4c. In view of the immense volumes of batholiths exposed in the western Americas, it is tempting to suggest that some lateral expansion may occur to permit intrusion of these vast complexes. The main objection to this process is that the necessary volume of new crust is not always apparent. For example, in Tonga, the three stages of magmatism documented by Gill (1970) would require an increase in depth to the Benioff zone from 75 to 175 km. Assuming an angle of 45° for the subduction zone in this region (Sykes, 1966), this would imply an extension of 100 km in the continental crust to the south-east of Tonga for which there is no evidence.

Best’s (1975) zone-refining model fitted the  $K-h$  correlation applied to the spatial variation in volcanic magmas. Can it be applied to the temporal relation? If we assume that the position of the Benioff zone does not shift appreciably with time (as discussed above) then suggesting that younger magmas may tap  $K_2O$  from a greater length of material cannot be considered. In fact, if the same material is being repeatedly processed one might even expect a decrease in  $K_2O$  contents with time, not an increase.

In conclusion, it is rather difficult to see how the  $K-h$  correlation model of Dickinson (1975) can be applied to the temporal variation observed in some orogenic areas (Jakes and White, 1969).

Orogenic magmas may be derived from mantle overlying the Benioff zone. If this is the case, then it might seem surprising that magmas become enriched in  $K_2O$  with time rather than

depleted. The difference in minor element chemistry between tholeiitic and alkalic magmas has generally been attributed to varying degrees of melting (Gast, 1968) or varying degrees of fractionation (O'Hara, 1968) or a combination of the two effects. In an island arc environment there seems to be no reason why the degree of fractionation should increase with time to explain increasing  $K_2O$  contents, unless a thickening crust has greater resistance to penetration by magmas and hence causes a greater period of fractionation prior to final eruption. However, the degree of melting might well decrease with time if cold oceanic crust is constantly being introduced into the mantle. Small changes in temperature close to the beginning of melting may have a significant effect on the content of minor elements in magmas, which would increase in amount as the degree of melting decreased due to falling temperatures. This is different from the varying degree of melting mentioned earlier as this situation is envisaged as taking place at constant depth.

One consequence of decreasing degrees of melting for younger volcanics is that the actual volume of magma erupted ought to decrease as the magma becomes more potassic (if the degree of fractionation is the same for each suite). This has been demonstrated for the spatial relations between tholeiitic to alkalic lavas in Japan by Sugimura (1968), but there are no volumetric data available for an area that shows the same transition with time.

#### *Significance of $h$ values*

The depth of the Benioff zone gives the depth to the plane where earthquakes are commonest. The data of Billington and Isacks (1975) showed that this plane can be located only as a zone at least 35 km thick (due either to experimental error or a real effect). As volcanoes usually occur in regions where the distance to the Benioff zone is between 80 and 180 km (Dickinson, 1975) there is a very significant relative error on all these measurements. However, far more serious than this is the assumption that the magma is derived from material within the earthquake zone. One of the preferred models for the origin of calc-alkaline magmatism is that it is derived from the mantle overlying the subduction zone (Kushiro, 1972; Boettcher, 1973; Fyfe and McBirney, 1975). Hence, the site of magma generation and the position of earthquake foci may be different. If there were some constant relation between the earthquake zone and the site of melting in the mantle the  $K-h$  correlation might still be valid, although  $h$  values would be somewhat lower.

Even if magma were generated along the upper surface of the Benioff zone its relation to  $h$  may be questioned. Earthquakes may not, in general, occur along the contact plane between subducted plate and overlying mantle. Engdahl (1971) and Mitronovas *et al.* (1969) showed that intermediate and deep-focus earthquakes tend to occur in the cold centre of the subducted slab. Hence, if  $h$  is determined from seismic evidence, its relation to the upper surface of the plate, where melting may occur, is unknown. For example, if a plate is 70 km thick and is descending at  $45^\circ$ , an earthquake 30 km down in the slab would be 45 km vertically below the upper surface of the slab (fig. 5). Thus it seems that the seismically determined value of  $h$  may bear very little resemblance to the depth at which melting actually occurs.

#### *Conclusions*

$K_2O$  contents of orogenic volcanic suites do increase with distance to the Benioff zone, although the original linear correlation of Dickinson and Hatherton (1967) has been modified by Dickinson (1975). Both these authors in all their publications suggest that this correlation may be due either to the chemical characteristics (notably  $K_2O$ ) of a suite reflecting the partial melting process at depth, or to variations in the nature of the eruption path (differentiation,



contamination, etc.) between source and volcano. Nearly all the models that have been proposed to explain the correlation have assumed the former situation—that the  $K_2O$  content reflects that of the primary magma. The  $K_2O$  content for this correlation has been interpolated at various  $SiO_2$  levels—55, 57.5, and 60 %  $SiO_2$ . It is unlikely that these can all be primary magmas and it seems that some degree of fractionation must be invoked to produce these  $SiO_2$  values.

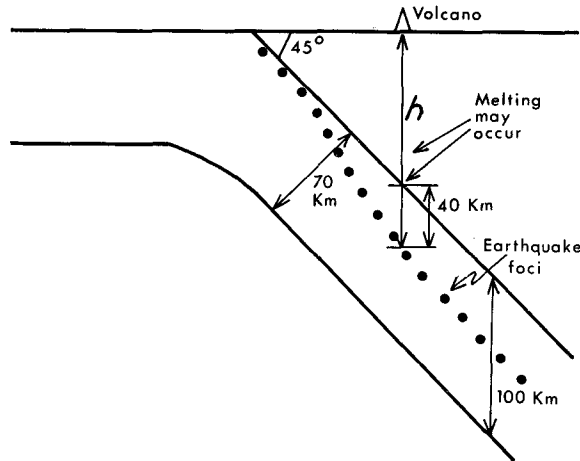


FIG. 5. Location of earthquake foci within the subduction zone in relation to possible different magma sources in the subducted plate or overlying mantle.

The alternative hypothesis—that of fractional crystallization—has been investigated by means of various theoretical  $K_2O$ - $SiO_2$  variation diagrams. A natural example analogous to each theoretical model has been documented. It is suggested that the  $K_2O$  content of a magma at a particular  $SiO_2$  level may be more greatly influenced by the  $SiO_2$  content of the parental magma and the nature of the crystallizing phases than the original  $K_2O$  content.

The value of  $h$ —the depth to the earthquake zone—may not indicate the depth of melting. Magmas may originate in the overlying mantle rather than the upper surface of the subducted slab and hence the depth of melting may be considerably less than that predicted from the value of  $h$ . The exact location of the earthquake foci may not coincide with the upper surface of the subducted slab along its entire length, but may occur *within* the slab. Hence, even if magmas were generated from the upper portion of the subducted oceanic crust the correlation with  $h$  is questionable.

The  $K_2O$  content of magmas also appears to increase with time in certain regions (e.g. Aleutians, Fiji). It is difficult to interpret this change in terms of a plate tectonic model whereby the depth to the earthquake zone is continually increasing. An alternative solution may be that the mantle is progressively chilled by the addition of cold subducted crust and that the degree of melting of the mantle consequently decreases, producing more potassic liquids.

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