SUBDUCTION AND THE STRUCTURE
OF ANDESITIC VOLCANIC BELTS

WILLIAM S. FYFE* and ALEXANDER R. McBRINNEY**

ABSTRACT. Reactions between contrasting units of a descending lithospheric plate involve redistribution of water and other components and may have important thermal effects. Water released from a shallow zone of dehydration where amphibole, muscovite, talc, and serpentine break down will be relatively rich in sodium and other dissolved species and will hydrate overlying levels to produce uplifted belts that are characterized by sodium-rich metamorphic rocks. Potassium, retained together with the remaining water in phlogopite, is carried to greater depths. A second belt of structural upwarping overlies the outer part of the zone of phlogopite breakdown, but volcanism appears, commonly in a structural depression, where the rising fluid causes melting of the overlying lithosphere and mantle. There is a spatial correlation between principal zones of dehydration and the overlying structural elements of tectonically active continental margins and island arcs. There should also be a relation between the intensity of magmatism and the amount of water and potassium carried down with the descending plate.

INTRODUCTION

In the short time it has enjoyed wide-spread acceptance, the concept of subduction has proved to have remarkable utility as an explanation for a host of tectonic and magmatic phenomena. There are, nevertheless, certain basic aspects of the process that need further evaluation. One of the most important, in our view, is the mass balance of the system as a whole.

Seafloor-spreading and subduction involve a massive exchange of crustal and mantle material. Every one or two hundred million years something of the order of three-quarters of the Earth’s crust is thought to be rising from the mantle and then returning, along with a substantial volume of sediments of continental origin. And yet there seem to be no notable changes in the compositions and relative volumes of the continental crust, sea water, or oceanic basalts that would indicate that the process has gone through repeated cycles. If the accepted model is valid, the efficiency it demands is truly remarkable. It can allow for little permanent fractionation between the mantle and the continents, oceans, or atmosphere. Basalts continue to be erupted with no apparent systematic differences to distinguish them from oceanic basalts of Precambrian age. Sediments, only slightly less voluminous than the basalts, but derived mainly from the sialic continental crust, must be carried down without perceptibly diminishing the volume of the continents or altering the composition of basalts that subsequently appear at the ridges. If ocean crust is subducted at a rate equal to its production (about 4 × 10^9 g yr^-1), and if this crust carries with it about 5 percent water (2 × 10^15 g yr^-1) the entire ocean mass (1.4 × 10^24 g) would be subducted in 700 m.y. This mass of water would have been subducted and returned many times if seafloor spreading has been going on for much of geologic time.

These relations, if real, imply a high level of dynamic equilibrium, mainly in the subduction mechanism. A thorough appraisal of the process

* Department of Geology, University of Western Ontario, London, Ontario, Canada
** Center for Volcanology, University of Oregon, Eugene, Oregon, 97403

285
is clearly beyond our present capabilities; we can only point out some of the factors we think bear on the transfer of a few components of the system.

**Processes within a Descending Slab**

The oceanic lithosphere descending from the trenches beneath island arcs and continental margins is thought to consist of basaltic rocks covered by a blanket of sediments and passing downward into a much thicker layer of ultramafic rocks. The upper horizons, though of proportionately small volume, contain most of the crustal components, including those from continental sources, several weight percent of water, and large amounts of CO₂, S, and Cl that form the pore fluid and chemically bound constituents of minerals, such as clays, zeolites, and sulfides. These elements are fixed during ridge hydrothermal events (Spooner and Fyfe, 1973) and later diagenesis away from the ridges (Bass and others, 1973). Little is known about the underlying basalts. Some are relatively fresh, with only superficial submarine weathering; others are in advanced stages of hydrothermal alteration to chlorite, amphibole, zeolites, and clay. Even less is known about the ultramafic layer making up the major portion of the slab except that it is probably composed largely of olivine and serpentine.

Even though our knowledge of these rocks is incomplete, we can see that one of their dominant features is their heterogeneity. The individual units are out of equilibrium, both with each other and with the mantle into which they are being thrust, and as they descend, the changes that take place in and above the slab must tend to restore a chemical and thermal balance in response to increasing pressure and temperature. An important part of this process involves a redistribution of volatile and low-melting components.

The pore fluid that is expelled during early stages of compression may rise into the overlying rocks, but part of it must react with anhydrous minerals of the adjacent basaltic and ultramafic layers of the slab to form amphiboles, micas, chlorite, talc, and serpentine. At low temperatures and high pressures, water is an excellent solvent. As it is redistributed between units of strongly contrasting composition and metamorphic grade, it will facilitate metasomatic exchanges and reactions within the slabs that tend to reduce the steep chemical and thermal gradients and form new mineral assemblages of progressively higher metamorphic grade.

Reactions such as those shown diagrammatically in figure 1 must dominate the upper layers of the slab. The early reactions in this series are exothermic by about 10 kcal/H₂O mol and will contribute to the heating of the descending rocks. Whether or not the quantities of water involved are large enough for this to be an important effect is hard to say, but the tendency will be to cause the reactions to proceed at shallower levels than would be predicted from temperature estimates that ignore this added heat.
Fig. 1. As the heterogeneous units of a descending slab are heated and compressed, they can be expected to undergo a series of metamorphic changes and reactions that tend to reduce compositional and thermal gradients. The relations shown schematically here indicate the order and direction of some of the principal reactions. Ultramafic rocks are shown on only one side but will be both above and below the other two units.

With continued descent, levels will be reached where some of the hydrous minerals become unstable. Part of the water they release may be expelled upward, but much of it will be redistributed within the descending slab. Owing to the fact that the interior of the slab is cooler and of differing composition, the liberated components will diffuse down temperature and chemical potential gradients to lower levels where the same or new hydrous minerals are still stable.

An effective barrier to upward diffusion may develop along the upper surface of the slab. Much depends on the nature and position of the shear surface forming the upper boundary; it need not necessarily follow the original top of the oceanic lithosphere. Ultramafic rocks in the hanging-wall wedge consist largely of olivine (part of which may be serpen-tinized at shallow levels), and they are likely to have less shear strength than consolidated sedimentary or basaltic units; they could well take up most of the differential movement, just as they are commonly observed to do in Alpine ultramafic bodies. Water moving into such a layer will encounter rocks whose permeability is diminished by the volumetric increase that accompanies hydration, and the resulting high vapor pressure would gas-lubricate the shear zone and stabilize its position.

The transfer of water from the sedimentary and basaltic layers to the ultramafic rocks between which they are sandwiched entails migration of other components as well. At temperatures and pressures where muscovite breaks down (about 600°C and 30 kb or 100 km) the solubility of silica and alkalies is exceptionally high. Supercritical water carries more than 10 percent silica, and the solubility of alkalies may be even higher. Hence, the metasomatic addition of these components to the ultramafic layers will convert part of the serpentine and peridotite to phlogopite-bearing pyroxenites. These same solutions may account for some of the spectacular metasomatic effects seen in blueschist rocks (Fyfe and Zardini, 1967).
Experimental studies (summarized by Wyllie, 1973) provide data from which one can estimate the depth to which specific minerals may persist. While these depths depend to some extent on the temperature distribution one assumes, most currently accepted conditions require that talc, serpentine, muscovite, and hornblende disappear within a relatively shallow and restricted depth range, whereas phlogopite persists beyond this zone to greater depths.

If the temperature distributions calculated by Griggs (1972) and by Toksoz, Minear, and Julian (1971) are compared to the stability limits determined experimentally, it is seen that all hydrous minerals except phlogopite will be gone by the time the slab reaches a depth of about 150 km. These calculations have not taken into account the thermal effects of dehydration. In contrast to the exothermic nature of reactions that involve redistribution of water, dehydration reactions are strongly endothermic, and their principal effect is to buffer the temperature of the rocks and extend the dehydration interval to greater depths. The amount of heat absorbed for each weight percent of water released is of the order of 30 cal/g of rock — enough to extend the stability range about 30 km, or, if estimates of as much as 3 percent are realistic, almost 100 km down the dip of the slab. On the other hand, if part of this water is incorporated into phlogopite, the endothermic effect is reduced accordingly.

The amount of water carried to greater depths is largely a function of the amount of potassium in the rocks. Each molecule of water incorporated into phlogopite requires a corresponding atom of potassium, and the greater the amount of potassium, the more water that will be retained below the main zone of shallow dehydration. Thus, dehydration occurs in two main zones, a shallow one where amphibole, muscovite, talc, and serpentine become unstable and a deeper one where phlogopite breaks down, and the proportion of water released in the two zones is largely related to the potassium content of the system.

The endothermic effect of phlogopite breakdown is even stronger than that of the first zone, because it probably entails melting of a part of the descending lithosphere. In figure 2 we have shown in simplified form the stability ranges of the principal components as they are now known from experimental data. The stability limit of amphibole in the presence of garnet is poorly known, so the curve CDE is uncertain. The thermal gradient is also poorly known, but we have indicated the range of recent estimates by a shaded zone; the actual gradient is probably closer to X-Y, and amphibolite probably breaks down well before the melting curve of basaltic compositions is reached (Nicholls and Ringwood, 1973). If we are correct in deducing that phlogopite breaks down above the melting temperature of the basaltic and sedimentary layer in the presence of water vapor, the release of water will result in melting and an even stronger endothermic effect (about 100 cal/g of melt). Because of this enhanced effect, the buffering caused by phlogopite dehy-
Fig. 2. Some important stability fields and reactions in a descending slab: H-G-F, melting of water-saturated basalt; A-B-C-E, melting or reaction of basaltic amphibolite; G-C, the basalt-eclogite transition; I-K stability limit of phlogopite; I-J, approximate partial melting curve of phlogopite-pyroxenite. The shaded area represents the possible P-T regime in the descending slab.

drivation may be important, even though the quantity of water released is small.

It should be stressed that our knowledge of the nature and stability of mineral hydrates at pressures appropriate to subduction zones is inadequate, and there may be other important phases in addition to those we have just considered. For example, members of the hydrogarnet family are not uncommon in leached submarine metamorphic rocks, and hydrogarnet-type phases could trap water in eclogite rocks. Further, there is little real knowledge of temperature changes that would follow from the long-term operation of a descending slab. The thermal structure must change with time as the overlying mantle is cooled. These and other unknown factors make it difficult to predict the thermal distribution and depths of dehydration except by the crudest estimates.

PROCESSES IN THE HANGING WALL WEDGE

Having considered the processes of equilibration and dehydration within the descending lithosphere, we turn now to the attendant effects that should be expected in the overlying rocks. Certain general conditions will prevail over both the dehydration zones. Any fluid released by dehydration and rising through the overlying mantle will encounter first
hotter than cooler rocks and tend to be re-incorporated into hydrous minerals at a shallower horizon, the depth of which will decrease with time as increasing thicknesses above the slab become saturated with stable hydrous phases. Water released at considerable depths may move by generating hydraulic fractures and shear zones as is observed in deep crustal metamorphism. Depending on the permeability and other physical properties of the rocks and fluid, the process may be either steady or episodic.

Not only water but other elements it carries in solution will be introduced into the overlying horizons. The composition of the rising fluid will depend on which components are retained or expelled from a portion of the descending slab that is undergoing metamorphic reactions in response to its rising temperature and pressure. Hydration of mantle rocks is an exothermic process with a positive change of volume. It should cause an increase in surface heat flow and a volumetric expansion reflected in structural uplift.

Looking first at the region directly overlying the first dehydration zone, we have already noted that the temperatures in this section are probably too low for significant amounts of melting to occur, either in the slab or in the overlying rocks. Water escaping from this interval will carry important quantities of silica and alkalies and halide-mobilized metals like copper and gold, but, because potassium is retained in the slab in the form of phlogopite and the solubility of silica increases less rapidly with pressure than that of the alkalies, sodium will be an important and possibly the dominant component of the rising fluid. This seems compatible with the sodium metasomatism that is so characteristic of glaucophane-jadeite assemblages of outer metamorphic belts found in linear uplifted blocks forming the coast ranges adjacent to inferred ancient subduction zones. The same belts are being uplifted today to form outer non-volcanic arcs and coast ranges adjacent to active trenches.

Fluids rising from the second dehydration zone where phlogopite breaks down should be similar to those released earlier but more potassic, and if they are deep enough, they almost certainly will be associated with melting and will not form a free vapor phase. Most calc-alkaline volcanic belts stand upon or immediately behind a second uplifted belt. The abrupt appearance of volcanism along this well-defined "volcanic front" must somehow reflect relations in the underlying rocks that result in the generation of magma that succeeds in reaching the surface.

There is abundant experimental evidence that calc-alkaline igneous rocks owe their distinctive compositional character to melting at elevated water pressure (see Boettcher, 1973, for an excellent summary of recent work). Moreover, the problem of generating large volumes of magma in a region where the mantle is being cooled by descending lithosphere becomes less of an obstacle if one can assume that melting is induced by the fluxing effect of water and other components produced by dehydration of the descending slab (McBirney, 1969).
The authors of two recent papers (Wyllie, 1973; Nicholls and Ringwood, 1973) have questioned whether important amounts of water can be produced by the breakdown of hydrous minerals that reach depths great enough to be below the active volcanic belts. Recognizing that phlogopite is the only important hydrous mineral that could contribute water to melting at those depths, Wyllie concluded that the amount of water carried by this mineral would be insignificant, because he considered the interior of the descending slab to be depleted in both water and potassium. We have pointed out, however, that redistribution of these components during earlier stages of descent almost certainly occurs and surmounts this problem. The total amount of potassium in the slab is difficult to estimate, but spilites and other products of ocean-floor metamorphism commonly contain about 1 percent K₂O (Hyndman, 1972), more than enough to stabilize the necessary amount of phlogopite.

There still remains the question of where the bulk of the calc-alkaline magmas are generated. It seems inescapable that the sialic fraction of the descending slab must eventually return to the continental crust. And yet, there is little geochemical evidence that magmas reaching the surface were produced by melting of older crustal material. On the contrary, the trace-element and isotopic compositions of calc-alkaline rocks indicate that the magmas were derived, at least in part, from mantle sources (Lewis, 1970; Jakes and Gill, 1970; Hedge and Lewis, 1971; Ewart and Bryan, 1973).

The only way we can reconcile these two divergent lines of reasoning is by concluding that melting is induced by a fluid phase so rich in water, alkalies, silica, and other components that it is almost a melt. The

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**Fig. 3.** Principal structural elements of island arcs and continental margins.
mass of these introduced components need only be of the order of a few percent of the resulting magma; in such proportions the contribution of recycled crustal material will be swamped by the larger mantle-derived fraction.

**SPATIAL RELATIONS**

In view of the uncertainties in our knowledge of most of the processes going on at depth, it would be useful if we could relate them more precisely to visible manifestations at the surface. Several of the structural features we have mentioned are common to almost all tectonically active continental margins and island arcs. The relation between subduction, trenches, Benioff zones, and well-aligned chains of andesitic volcanoes is frequently cited. No less regular, however, are the prominent belts of uplift and subsidence that form coast ranges and central valleys between the trenches and volcanic fronts (fig. 3). Typical profiles that illustrate these features on continental margins are shown in figure 4. A similar

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**Fig. 4.** Generalized structure sections across the Cascade system of central Oregon (above) and northern and southern Central America.
arrangement of outer non-volcanic arcs or submerged basement ridges has been recognized in many island arcs.

In figure 5 we have reproduced Wyllie's (1973) graphical depiction of the stability ranges of various hydrous minerals according to experimental data and the temperature distributions calculated by Toksoz, Minear, and Julian (1971) and by Griggs (1972). Over the same diagram, we have indicated the positions of coast ranges and outer arcs as well as the second, inner belts of uplifted rocks and the volcanic fronts of a number of continental margins and island arcs.

There seems to be a crude correspondence between uplifted belts and those intervals in the underlying subduction zone where hydrous minerals break down. Coast ranges and outer arcs tend to overlie the first dehydration zone, central valleys the zone of phlogopite stability, and second uplifts and volcanic chains the second dehydration zone due to the breakdown of phlogopite. It is to be expected that the exact positions of these linear elements will vary from province to province depending on the inclination of the descending plate, the rate and continuity of subduction, and other factors. Thus, they offer a means of predicting the positions of the two dehydration zones in an individual system.

At the volcanic front, the sense of vertical displacement is commonly reversed, especially in very active chains. The resulting depression may be inconspicuous, because the volume of volcanic material poured into it nearly keeps pace with subsidence. A simple explanation for these relations would be that the subsidence is caused by removal and upward transfer of magma from a source below the volcanic axis.

On the same diagrams we have added the liquidus of andesitic melts in the presence of free (excess) water vapor. This line is so high in both models that if it were the controlling factor for magma generation, melting would begin far to the seaward side of the volcanic front. This inconsistency, together with the fact that most calc-alkaline magmas erupting at the surface have only a percent or so of water — much of which may be meteoric — indicates either that melting proceeds almost to the dry liquidus or that other components in the fluid expelled during dehydration contribute to the flux-melting of the mantle. We have indicated the liquidus curves of andesitic melts with more realistic water contents of 2 percent on the same diagrams and find that the volcanic front is quite close to this boundary, especially for the model calculated by Toksoz, Minear, and Julian (1971). The relationship cannot be considered valid, however, until more is known about melting in the presence of silica-saturated fluids.

There are certainly other factors involved in the subduction process besides those we have discussed. We have said little about temporal or volumetric relations. Several of the processes are obviously irreversible ones that cannot continue indefinitely without lateral or vertical migrations. Similarly, volcanism and structural deformation are commonly episodic rather than steady and prolonged, and there seem to have been periods of subduction without these surficial manifestations, just as there
Fig. 5. Relationship of the stability limits of the principal hydrous minerals to structural features of several orogenic volcanic belts. Thermal regimes are taken from Toksoz, Minear, and Julian (1971) (left) and Griggs (1972) (right), and breakdown zones are from Wyllie, 1973. The temperature gradient above the upper part of the descending slab is probably too high in the calculation by Toksoz, Minear, and Julian, but this error is offset, at least in part, by the exothermic nature of the hydration process, which did not enter the original calculations (see text).
are places where the reverse seems to be true. We have ignored several mechanical factors, such as subduction rates, effects of heat transfer on the physical properties of the mantle and crust, and other potentially important relations that undoubtedly play important roles in the process.

**SUMMARY AND CONCLUSIONS**

Considerations of the stability relations of minerals making up the principal units of a subducted oceanic plate permit a correlation of the major dehydration zones with conspicuous structural and volcanic features of the overlying orogenic belt. Although quantitative factors are uncertain, a general relation, depicted schematically in figure 6, can be deduced as follows:

1. Reactions between the sedimentary, basaltic, and ultramafic layers involve transfer of water, alkalis, silica, and other components down thermal and chemical potential gradients to form new stable mineral assemblages. The initial reactions in this series are exothermic and will tend to raise the temperature of the slab.

2. The plane of shearing corresponding to the top of the plate may be displaced upward into more easily deformed ultramafic rocks, so that a slice of mantle may cap the sedimentary unit. Such a layer will absorb and serve as a carrier for some of the components, such as silica and potassium, driven out of the underlying units undergoing dehydration.

3. Most hydrous minerals will break down as they pass through a relatively shallow zone before melting conditions are reached. The fluids released in this interval will be richer in sodium than in potassium, because the latter is retained as newly formed phlogopite that is stable to greater depths. Such sodium-rich hydrous fluids rising to shallower levels account for metasomatic glaucophane and jadeite-bearing rocks of outer metamorphic belts.

4. The volumetric expansion accompanying hydration of the mantle over a zone of dehydration in the subducted plate is a logical cause of uplifted coast ranges and outer basement ridges of non-volcanic arcs. The total volumetric increase is a measure of the mass input of sialic material during subduction.

5. The dehydration process is strongly endothermic and will tend to prolong the stability interval of hydrous phases to greater depths. The endothermic character is even stronger where release of water induces melting.

6. The beginning of breakdown of phlogopite occurs beyond the interval of stability below central valleys and closer to the volcanic front. In most systems it causes a second belt of uplifted rocks. Beyond a line marked by the volcanic front, temperatures are high enough for the release of water to cause solution or melting of a sialic fraction from the associated rocks in the slab. Rise of the resulting fluid into the overlying mantle wedge leads to further melting of a much larger quantity of mag-
ma, the geochemical character of which is dominated by mantle-derived components.

7. The rate of magma generation must be a direct function of the amount of phlogopite and in turn the amount of potassium originally in sediments and alkali-rich basalts of the descending slab.

8. The fact that most of the foregoing processes are irreversible requires that repeated episodes of structural deformation and magmatism be associated with changes in the rate or locus of subduction.

References


