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PLUTONISM AND PLATE DYNAMICS: THE ORIGIN OF CIRCUM-PACIFIC BATHOLITHS

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ABSTRACT

Principal Mesozoic granitic batholiths are located around the Pacific Basin, implying their origin is tied to processes at consuming plate boundaries. Consensus among experimental petrologists is that partial melting of the lower crust is involved in their petrogenesis. In a normal crust of thickness 35 km, temperatures are not high enough to cause fusion in a water-deficient lower crust. Thermal calculations using a finite difference approximation to heat transfer equations indicate that localized melting will occur above a magma emplaced in crust preheated by volcanic activity. Implication is that magmas generated in the subduction zone or the overlying mantle wedge supply the heat necessary for crustal fusion.

Conditions for partial fusion are reached only in regions of high magma flux. This magma flux in island or continental margin arc complexes is related to the dynamics of plate descent, both with regard to the rate at which heat is supplied for the fusion process, and the rate at which magma is collected into bubbles of sufficient size to rise diapirically into the overlying mantle.

There are two critical rates of plate descent: the first is that rate necessary to bring the upper portion of the subduction zone to the basalt solidus; the second rate is defined as that which produces an intensity of magmatic activity sufficient to trigger melting in the overlying crust and the subsequent development of batholiths.

SOMMAIRE

Les principaux batholites granitiques mézoïques entourent le bassin du Pacifique, ce qui laisse supposer que leur origine est liée aux processus actifs impliquant deux plaques convergentes. La plupart de ceux qui étudient le problème expérimentalement sont d'accord qu'il y a fusion partielle de la croûte inférieure. Mais dans la croûte normale de 35 km d'épaisseur, les températures ne sont pas suffisamment élevées pour fondre la croûte inférieure déficitaire en eau. Les calculs des flux de chaleur laissent prévoir une zone de fusion localisée au-dessus d'un magma introduit dans la croûte chauffée par un volcanisme précoce. Les magmas formés dans la zone de subduction ou dans la portion du manteau au-dessus de cette zone seraient la source de chaleur nécessaire pour que la fusion soit possible dans la croûte. Cette fusion est envisagée seulement dans les régions d'un grand flux magmatique. Dans les arcs insulaires ou aux bordures continentales, ce flux dépend de la dynamique de la descente des plaques, en ce qui a trait aux taux de transfer de la chaleur nécessaire pour la fusion, et de collection du magma en bulles suffisamment grosses pour que l'ascension se fasse sous forme de diapirs dans le manteau supérieur. Deux taux critiques sont associés à la descente d'une plaque; le premier porte sur le temps nécessaire pour que la portion supérieure de la plaque en subduction soit chauffée à la température du solidus basaltique. Le second porte sur le temps requis pour qu'il y ait une venue magmatique assez considérable que la croûte inférieure soit amenée en fusion partielle. Le produit de cette fusion serait les magmas granitiques qui forment les batholites.

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INTRODUCTION

The plate tectonic theory has provided a framework for the production of granitic batholiths and it is now generally accepted that the origin of many batholiths must be intimately related to processes at consuming plate boundaries. Constraints on potential models for the origin of granitic batholiths have been established by studies in experimental petrology, isotope geochemistry, petrology, and geophysics. The purpose of this paper is to summarize the major features of Circum-Pacific batholiths, discuss a preferred model for their origin based on thermal requirements, and to thereby establish a relationship between the mechanisms of destructive plate margins and the origin of granitic plutonism in marginal continental crust.

MAJOR FEATURES OF CIRCUM-PACIFIC GRANITIC BATHOLITHS

The following list summarizes the major features generally associated with batholiths: (1)

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*Current address: Department of Geology, Indiana University — Purdue University, 925 West Michigan St., Indianapolis, Indiana 46202 elongate bodies, located parallel to destructive plate boundaries; (2) composite in nature, made up of a number of distinct and sometimes "nested" plutons; the Sierra Nevada batholith is typical, containing more than 200 separate plutons; (3) bulk composition is generally intermediate; the Southern California batholith is typical with more than 84% granodiorite-tonalite; (4) ubiquitously associated with a volcanic cover; in most cases, the volcanism predates the onset of plutonic activity; (5) volcanics are generally less rich in silica than the underlying plutonic rocks; (6) initial Sr 87/86 ratios are generally quite low, indicating relatively primitive rocks are involved in their petrogenesis; (7) the order of intrusion is generally gabbroic to granitic.

ORIGIN OF BATHOLITHS

Using the above observations, coupled with evidence from experimental petrology, several models for the origin of batholiths have been presented. Consensus among experimental petrologists now appears to be that partial melting of the lower crust is in part responsible for their origin. Tuttle & Bowen (1958) presented an anatectic model based on melting experiments in the water-saturated albite–potassium feldspar—water system. Winkler (1967) developed the anatectic model, relating it to the formation of migmatites and origin of granitic magmas. Piwinskii & Wyllie (1968) and Piwinskii (1968, 1973) gave further support to the crustal anatectic model by experimentally determining the phase equilibrium relationships for a series of igneous rocks from calc-alkaline batholiths under water-saturated conditions.

Brown & Fyfe (1970), Fyfe (1970, 1973) and Brown (1973) presented a model for crustal magma generation in water-deficient systems which contained water only in the hydrous minerals. In their model, granitic magmas were produced as a response to ultrametamorphism, with metamorphic rocks yielding a liquid fraction produced by the breakdown of muscovite, followed by a biotite fraction, and finally by an amphibole fraction. Presnall & Bateman (1973) compared fusion relations in the system $NaAlSi_3O_8$–$CaAl_2Si_2O_8$–H_2O with the granitic rock types in the Sierra Nevada Batholith and concluded that a major portion of the present batholith must have been derived from partial melting of the lower crust.

There are two major factors which must be considered with the crustal anatectic model. First there is the temperature required for melting of crustal material. The base of the crust is most likely to be water-deficient, implying that crustal fusion occurs with the breakdown of hydrous minerals in the manner suggested by Fyfe (1970). If biotite were the dominant hydrous mineral, melting would commence at about 800°C at a depth of 35 km. Lachenbruch (1968) estimated a temperature of only 250°C at the base of the crust in a portion of the Sierra Nevada region prior to initiation of plutonism. In a similar fashion, typical continental geotherms given by Blackwell (1971) and Smithson & Decker (1974) suggest temperatures at the base of the crust as substantially lower than those required for partial fusion (Fig. 1). Clearly, melting is not a steady-state process in the lower crust. When melting occurs it must be in response to unusual conditions, either thickening of the crust or the addition of transient heat sources from below.

A second problem with the crustal anatectic model is that assuming the solidus temperature is reached by a localized perturbation of the geothermal gradient, liquidus temperatures for typical calc–alkaline batholithic magmas are well over 1000°C, a temperature which is unreasonable in the continental crust. It has been suggested that the product of crustal anatexis is a crystal mush composed of crystals of biotite and hornblende with water-undersaturated granite liquid. Fyfe (1973), by comparing the rate of magma production with the rate of liquid segregation, concluded that a rather pure molten layer is likely to result. Thus, initial thermal considerations cast some doubt on the likelihood of producing intermediate composition magmas by fusion of the continental crust.

In order to more fully evaluate thermal constraints on batholith development, it is necessary to look at the peculiar geothermal conditions in island or continental margin arc complexes. The widespread occurrence of Mesozoic batholiths around the Pacific Basin strongly suggests that generation of batholiths is related to subduction zones and corresponding magmatic activity. The crust overlying an active subduction zone would be subject to repeated episodes of penetrative convection. The thermal structure of the crust would be altered, perhaps to the point of producing crustal melts.

Younker & Vogel (1975) examined the alteration of the crustal thermal regime by penetrative convection. In regions of such magmatic activity, some of the magma diapirs reach the surface whereas others may be emplaced at various levels in the crust. In order to separate the two effects, two models were evaluated: the static model (Model I), and the dynamic model (Model II). The static model has as its essential feature the intrusion of a basaltic or andesitic magma de-

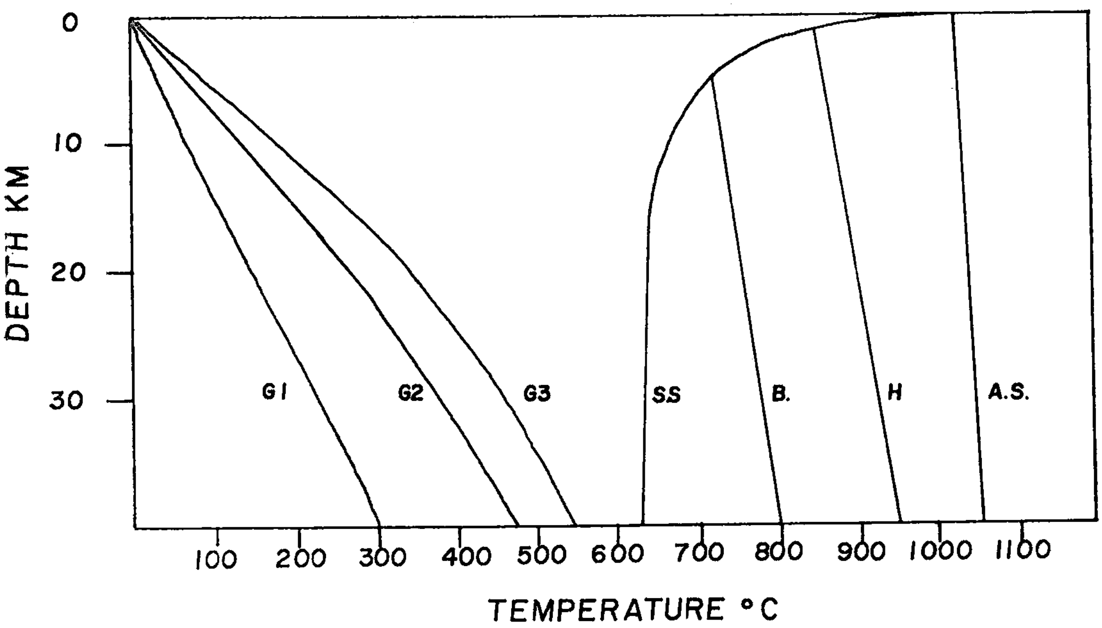

FIG. 1. Plot of range of geothermal gradients for regions which have not undergone penetrative convection, and conditions of melting for three types of melting. Gl — geothermal gradient for Sierra Nevada region taken from Blackwell (1971); G2 — geothermal gradient for predominantly metamorphic crust taken from Smithson & Decker (1974); G3 — geothermal gradient for eastern U.S. taken from Blackwell (1971); S.S. — H_2O–saturated solidus; B — melting associated with breakdown of biotite; H. — melting associated with breakdown of hornblende; A.S. — anhydrous solidus. Conditions of melting taken from Brown & Fyfe (1970).

rived from the upper mantle into crustal material and the subsequent cooling and crystallization at a given depth. The potential for producing crustal melts in the surrounding rock by this mechanism was evaluated. In Model II, the heat transferred to the surrounding crust by rapidly rising magma diapirs was calculated. The amount of preheating of the lower crust by volcanic activity was evaluated in this model.

Melting in the crust was envisaged to be a response to a period of penetrative convection in a region overlying a subduction zone. Results of the study supported a lower crustal origin for the batholith magma. In the dynamic model, the amount of heat lost by each gram of magma during ascent was estimated by comparing the heat content at eruption with the heat content when it penetrated the lower crust. Combination of this estimate with estimates of magma flux made it possible to evaluate heat generation per unit time due to penetrative convection. Assuming temperature-constant thermophysical properties, perturbation of the thermal structure of the lower crust by periods of volcanic activity similar in duration and intensity to that observed in Japan was calculated. Such activity was found to result in 100°C of crustal heating.

In the static model, a one-dimensional variable property finite difference approximation to the heat transport equations was used to investigate melting in the lower crust. Results indicated that a significant amount of crustal melt could be produced by the emplacement of a mantle-derived magma into this region. The amount and extent of melting is a function of the original temperature of the crust, size of the magma body, latent heat of fusion of the crust, and the temperature of the intruding magma. For a basaltic magma superheated 200°C with a liquidus temperature of 1200°C, solidus temperature of 1100°C, intruding into crustal rocks at 500°C, with latent heat of fusion equal to 50 cal/gm, the melting front advanced a distance equal to one pluton halfwidth into the country rock with 70% partial melting at the contact. The temperature profile across the magma chamber into the country rock at a time 40,000 years after emplacement is illustrated in Figure 2. It can be seen that significant amounts of crustal melt coexist with differentiating basaltic magma, and hybridization can produce compositions similar to those observed in calc–alkaline batholiths.

RELATIONSHIPS BETWEEN PLATE DYNAMICS AND BATHOLITHIC ACTIVITY

It has been established that although melting is not a steady-state phenomenon in the crust, mantle-derived magmas can provide the heat necessary to make it a viable process for batholith genesis. The observed association between batholiths and destructive plate margins suggests that upward transport of andesitic and basaltic magmas along subduction zones may produce environments where crustal melting phenomena are localized.

The model of crustal magma production proposed here is one which calls for localized melting around the margins of intrusions of mantle-derived magma. The amount of melt is critically dependent on the temperature of the lower crust prior to intrusion. This temperature is in turn functionally related to the amount of magma which has "passed through" the region. The probability of melting in the lower crust is therefore unquestionably related to the total volume of mantle magma which penetrates the crust.

With frictional heating as the main source of heat for melting along a subduction zone, it is to be expected that a relationship exists between rate of plate descent and volume of magma production (Fitton 1971). This relationship, once established, would make it possible to relate batholithic activity to the dynamics of plate movement.

Different rates of motion will produce different shear-strain heating effects. If it is assumed that melting in the subduction zone is at an invariant point, vast amounts of magma can potentially be generated which are uniform in composition (Presnall 1969). Differences in heating due to shear effects will then be reflected by different amounts of magma produced.

To illustrate, let us assume melting in the subduction zone takes place in a rather narrow zone of 10 km. This assumption is supported in both observation and theory. Wyss (1973) showed that the thickness of the deep seismic zone in Tonga was about 11 km. Minear & Toksoz (1970) showed that the low conductivity of the mantle, coupled with the temperature dependence of viscosity, produced a narrow band of high deformation rates. McKenzie (1967) has shown that most of the movement in subduction zones occurs as creep, with only a small percentage being radiated as elastic waves. Most of the stress energy is therefore dissipated as frictional heat within this narrow zone. It is within this zone that melting should take place.

The picture of melting envisaged is that whenever slip rate is high enough, melting takes place on the slip zone. With invariant–point melting, the temperature is buffered at the basalt solidus. After this temperature is reached, all additional frictional heating goes into the production of more melt.

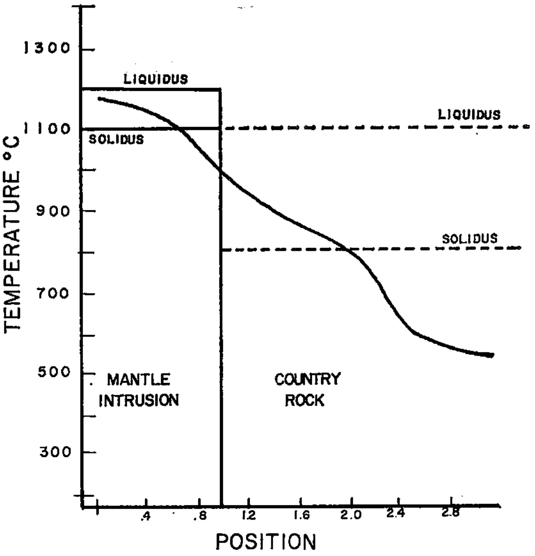

FIG. 2. Plot of temperature versus position for magma of half-width 1 km and initial temperature 1400°C intruding country rock with initial temperature of 500°C. Curve represents temperature profile 40,000 years after intrusion. Area under curve compared with area between solidus and liquidus for both mantle intrusion and country rock represents the percent melt. Position refers to the position ratio with a value of 0 corresponding to the center of the mantle intrusion and a value of 1 corresponding to the contact.

If we assume the system behaves like a Newtonian fluid, the rate of heat production is given by the following equation (Uyeda & Jessop 1970):

$$\bar{w} = \eta \frac{v^2}{a}$$

where η is viscosity, v is velocity of descent, and a is thickness of zone. From this we can see that rate of heat production, and therefore rate of magma production, is critically related to the viscosity, velocity of plate descent, and thickness of deformation zone.

While the above equation expresses the theoretical relationship between rates of plate descent and rate of shear-strain heating, accurate estimates of shear-strain heating in a slab are difficult. In order to use the equation, the temperature dependence of viscosity, and the functional relationship between rate of descent and thickness of the shear zone would have to be known. To circumvent these problems, Toksoz *et al.* (1971) heuristically determined values of shear-strain heating required to produce melting for rates of descent of 8 cm/yr and 1 cm/yr. The values are 15.3 x 10^{-12} cal/cm^3–sec and 3.29 x 10^{-12} cal/cm^3–sec, and we will use them to get an estimate of the relationship between amount of melt produced and velocity of plate descent. Both of these values are at least two orders of magnitude higher than any of the other heating effects in the shear zone, and would therefore be the primary source of heat for the melting process.

It is probable that the values used for heat production are much too high through the melting interval. Because of the dependence of shear-strain heating on viscosity, and dependence of viscosity on the amount of melt present, shear-strain heating should dramatically decrease with the onset of melting. Shaw (1969) demonstrated that viscosity of solid melt systems varies from 10^{21} poise for the unmelted to 10^1 poise for the completely molten basalt. Shear-strain heating should drop by a similar proportion. In the shear zone, frictional heating should therefore become negligible after small amounts of melting (>10%). Shaw demonstrated that for relatively small amounts of melt fraction (<5%), the viscosity remains relatively constant. Therefore, it is reasonable to assume that the value of shear-strain heating will also remain relatively constant through small amounts of melting.

Frictional heating will occur in the top few km of the descending slab. The temperature in this zone is raised to the basalt solidus at depths ranging from 100 to 150 km (Turcotte & Schubert 1973). The exact depth is dependent on the rate of descent. The temperature is buffered at the basalt solidus, and any subsequent heat available is consumed in the melting process. After small amounts of partial melting (<5%), shear-strain heating would be reduced by several orders of magnitude, and little additional melt is produced. Following Weertman's (1972) analysis of bubble coalescence in the shear zones, the magma bubbles will coalesce into fewer bubbles which are of sufficient size to rise buoyantly into the overlying mantle and crust. Following removal of the melt, the viscosity of the system is again raised to the level where significant shear-strain heating occurs and the process repeats itself.

In order to assess the effect of variable rates of plate descent on this process, we can look at the length of time required to produce a given amount of melt under the two rates of plate descent discussed by Toksoz *et al.* (1971). With a plate descent of 8 cm/year, 5% melt in the shear zone would be achieved in approximately 1150 years. With a plate descent of 1 cm/year, this same amount of melt would be produced in 4600 years.

In a similar manner, efficiency of magma collection is also related to rate of plate descent. Weertman (1972) established the following relationship for bubble coalescence in a shear zone:

$$\frac{c}{c_0} = \exp \frac{(-4\,v\epsilon)}{\pi}$$

where c is concentration of bubbles, c_0 is initial concentration of bubbles, v is volume % magma, and ϵ is shear strain. Low values of the ratio indicate severe coalescence of bubbles whereas higher values reflect less coalescence. The rate of magma collection is then directly related to volume of melt produced and total shear strain. In the slip zone the total shear strain is given by $\epsilon = \int_0^T \dot{\epsilon}\, dT$ where T is time, ϵ shear strain and $\dot{\epsilon}$ is shear strain rate. For the slip zone, $\dot{\epsilon} = \frac{du}{dy}$; u is velocity ($u = -\,U_s\, e^{-y/H}\; y \leq H$); y is distance from top of slip zone; H is thickness of shear zone: and U_s the slab velocity (Minear & Toksoz 1970). For a volume element in a 10 km-wide slip zone, degree of magma coalescence is approximately twice as high for a rate of descent of 8 cm/yr as compared to 1 cm/yr.

Therefore, it is concluded that rate of plate descent controls both the rate at which melting occurs and the rate at which the melt collects into bodies of sufficient size to rise independent of the solid residue. Magma flux in island arc or continental margins is correspondingly related to the dynamics of plate motion. In the analysis it has been assumed that melting occurs in the top layers of the subduction plate. The same type of analysis would hold if the melting occurred in a shear zone in the overlying mantle wedge.

We might then define two critical rates of plate descent. The first is a threshold value, necessary in order for shear-strain heating to raise the temperature of a portion of the subduction zone to the basalt solidus. The second critical rate of plate descent might be defined as that rate producing an intensity of magmatic activity sufficient to trigger crustal melting and the subsequent development of batholiths. More detailed analysis of the production and collection of magmas in the subduction zone will be necessary before realistic estimates can be made of these critical rates.

SUMMARY

The following sequence summarizes the model of batholith genesis established above.

(1) Initiatiton of subduction beneath continental margin.
(2) Temperature at the base of crust is too low for partial melting.
(3) As plate descends, a prime source of heat is friction.
(4) At a depth of roughly 150 km, the basalt solidus is reached and melting begins in the top 10 km of the subducting plate.
(5) Rate at which melting takes place and the rate at which the melt collects are related to rates of plate descent.
(6) Low rates of descent will produce a low magma flux and little perturbation of the overlying crustal thermal regime.
(7) If the rate of descent is high enough, the increased magma flux will serve to preheat the lower crust — perhaps as much as 100°C.
(8) After a period of volcanic activity, the emplacement of a mantle-derived or subduction zone-derived melt (basalt or andesite) in the lower crust will cause localized melting in the region directly overlying the magma.
(9) Mantle-derived basaltic or andesitic melt coexists in close proximity to incipient crustal melt.
(10) Strong convection in the magma chamber will serve to mechanically mix the two melts producing a hybridized liquid of intermediate composition.
(11) Hybridized liquids rise and are emplaced beneath the volcanic cover forming plutons of intermediate composition.
(12) Undifferentiated melts from the mantle and unmixed crustal melt rise to produce the spectrum of rock types observed in batholiths.

The model proposed here is consistent with the major characteristics of Circum-Pacific batholiths. It offers explanations for the order of emplacement of plutons, relatively primitive initial Sr 87/86 ratios, intermediate composition of the majority of batholithic rocks, the high liquidus temperature of batholithic rocks, age relationships between plutonic and volcanic activity, and the attainment of temperatures required for production of partial crustal melts. More detailed analysis of specific subduction zones should result in better estimates of the relationship between the rate of plate descent and the production of batholiths.

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