Ague and Brandon's reply follows after this discussion, which is included for completeness.

Regional tilt of the Mount Stuart batholith, Washington, determined using aluminum-in-hornblende barometry: Implications for northward translation of Baja British Columbia: Discussion and Reply

Discussion

J. Lawford Anderson* *Department of Earth Sciences, University of Southern California, Los Angeles, California 90089-0740*

INTRODUCTION

Ague and Brandon (1996) attempted to use Al-in-hornblende barometry to assess tilt of the Mount Stuart batholith. Although this might work in principle, there are substantial problems with their analysis that negate their conclusions. Anderson and Smith (1995) reformulated the barometer to take into account the effects of temperature using the experimental calibrations of Johnson and Rutherford (1989) and Schmidt (1992). Ague and Brandon (1996) ignored the effects of temperature by obtaining emplacement temperature estimates for only 10 of 46 samples. Temperature estimates for those 10 samples ranged from 616 to 695 °C. From that, they concluded that their entire sample set represented crystallization conditions with an average temperature of ~650 °C and then calculated their pressures using the isothermal calibration of Schmidt (1992). Hence, pressure estimates for these 10 samples were not corrected for temperature and the remaining 36 of their pressure estimates lack any form of temperature control. Thus, all of their pressure (and therefore depth) estimates are not reliable.

The notion that granitic or tonalitic magmas have an isothermal solidus is unreasonable, particularly at pressures less than 4 kbar. Ague and Brandon's uncorrected pressures range from 0.8 to 4.8 kbar. At these pressures, the water-saturated tonalite solidus ranges, with decreasing pressure, from 660 to 780 °C (Wyllie, 1988), a temperature range that will have a significant effect on the aluminum content in hornblende causing uncorrected pressures to be inaccurate by as much as 1.3 to 1.9 kbar (Anderson and Smith, 1995). As reviewed by Anderson (1996), granitic magmas also need not crystallize on a water-saturated solidus, and actual temperatures may be considerably higher, due to fluid undersaturation, mixed volatiles, or crystal accumulation, or lower, due to the presence of fluorine or boron.

Ague and Brandon (1996) stated that they are interested in the relative precision of their pressure determination and not absolute accuracy. However, by not correcting for temperature variations, not only are their results inaccurate, they are also imprecise.

HORNBLENDE-PLAGIOCLASE THERMOBAROMETRY

To estimate temperature for their 10 samples, Ague and Brandon (1996) used the hornblende-plagioclase thermometer calibrations of Holland and Blundy (1994). Unfortunately, they have also incorrectly applied these calibrations by using a 13-cation method of hornblende normalization. Cosca et al. (1991) documented that the 13-cation method yields reliable estimates of Fe^{3+}, Fe^{2+}, and site occupancies. However, Holland and Blundy (1994) have used in their calibrations a normalization scheme that can yield very different estimates of these parameters. Because it is imbedded in their calibrations, it is the normalization scheme that must be used. Using a different amphibole normalization scheme can lead to serious miscalculation of temperatures with this thermometer (Anderson, 1996).

I have recalculated temperature and pressure for the 10 samples for which Ague and Brandon provided plagioclase and amphibole data. Results, depicted in Figure 1, offer another reason why the conclusions of Ague and Brandon (1996) are fundamentally flawed. Most of the pressure-temperature (*P-T*) estimates are subsolidus. The Al-in-hornblende barometer has been calibrated for a granitic mineral assemblage in equilibrium with melt. If the mineral compositions do not reflect solidus or hypersolidus equilibration, then the barometer can not be expected to yield accurate pressures. It has not been calibrated for subsolidus mineral assemblages.

The hornblende-plagioclase thermometer is more robust than others that can be applied to granitic rocks and is not easily reset during cooling. Anderson (1996) reported hornblende-plagioclase temperature estimates for 16 plutons, and all of the estimates were at solidus or hypersolidus temperatures. None yielded subsolidus results as seen here, and the thermometer calibrated by Holland and Blundy (1994) yielded results comparable to those derived from other thermometers. Thus, there is some indication that these low temperatures for the Mount Stuart batholith are indicative of extensive retrogressive event. Ague and Brandon (1996) recognized the occurrence of intragrain subsolidus amphibole compositions and attempted to avoid using such data. Unfortunately, they did not recognize the full extent of subsolidus reequilibration within the batholith.

AMPHIBOLE COMPOSITIONAL VARIATIONS

Ague and Brandon (1996) further concluded that compositional variations for amphiboles within the Mount Stuart batholith were consistent with the pressure-sensitive Tschermak

*e-mail: anderson@usc.edu

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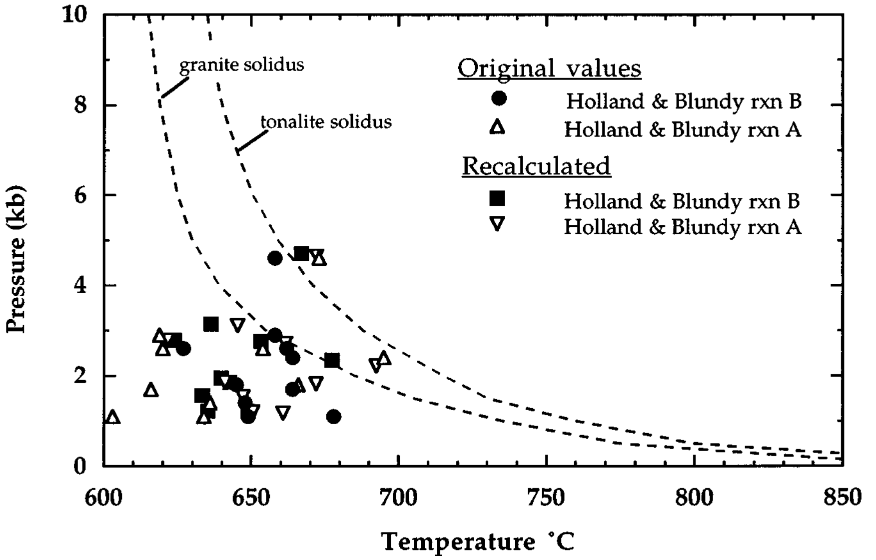

Figure 1. Estimates of pressure and temperature for the Mount Stuart batholith using the data of Ague and Brandon (1996). Included are (1) their original determinations, which used a 13-cation normalization for amphibole and the Schmidt (1992) calibration of the Al-in-hornblende barometer, and (2) recalculated estimates using the Holland and Blundy (1994) normalization scheme and the Anderson and Smith (1995) reformulation of the same barometer. Temperatures are based on two calibrations of the hornblende-plagioclase thermometer of Holland and Blundy (1994).

exchange, but they ignored findings by Anderson and Smith (1995) that edenite exchange is also important in amphiboles in this batholith. The edenite exchange is considered to be largely temperature sensitive and this exchange forms the basis of one of the two hornblende-plagioclase thermometer calibrations of Holland and Blundy (1994). At low (subsolidus) temperatures, the edenite exchange causes originally magmatic hornblendes to lose both Al^{iv} and Al^{vi} and become actinolitic. Pressures calculated from such retrograded amphiboles will be erroneously low; hence, the low pressures they have determined for the southern end of the batholith (0.8–1.5 kbar) are not real. Thus it follows that the shallow depths calculated for the southern half of the batholith and their estimate of tilt are also not valid.

VARIATIONS IN APPARENT PRESSURE

That the Mount Stuart batholith exhibits systematic variations in apparent Al-in-hornblende pressure is not discounted. Ague and Brandon (1996) observed a northwest to southeast decline in apparent pressure. Paterson et al. (1994) and Anderson and Smith (1995) also observed systematic variations. Their expanded data set showed an apparent domal pattern of observed apparent pressures with lower apparent pressures were found along the perimeter of the batholith. However, Paterson et al. (1994) and Anderson and Smith (1995) concluded that the pressure pattern was not real and largely an artifact of temperature control. They questioned the reliability of observed low pressures ($P < 2$ kbar), because at six of nine localities in the contact aureole, calculated metamorphic pressures differed and were much higher. They also pointed out that the Al-in-hornblende pressures below 2 kbar are outside of the calibration range of the barometer.

The hornblende-plagioclase temperature estimates of Paterson et al. (1994) and Anderson and Smith (1995) were based on the Blundy and Holland (1990) calibration, which was superseded by that of Holland and Blundy (1994). Recalculation of their data using temperatures obtained with the Holland and Blundy (1994) calibrations forms a similar *P-T* array, except that the sample set includes a larger number of samples preserving magmatic conditions (Fig. 2). All of the low pressures, whether from just the southeast margin (Ague and Brandon, 1996) or elsewhere in the batholith (Paterson et al., 1994; Anderson and Smith, 1995), coincide with subsolidus temperatures. Although Brandon and Ague (1996) argued that they had confirmed their igneous pressures with two metamorphic pressure estimates taken from the contact aureole, they did not obtain rigorous confirmation for observed low pressures.

PROPAGATION OF ERROR THROUGH THE Al-IN-HORNBLENDE BAROMETER

The idea of using igneous barometry to assess batholithic tilt remains possible, but is extremely problematic. At its current state of development, the Al-in-hornblende barometer remains unso-

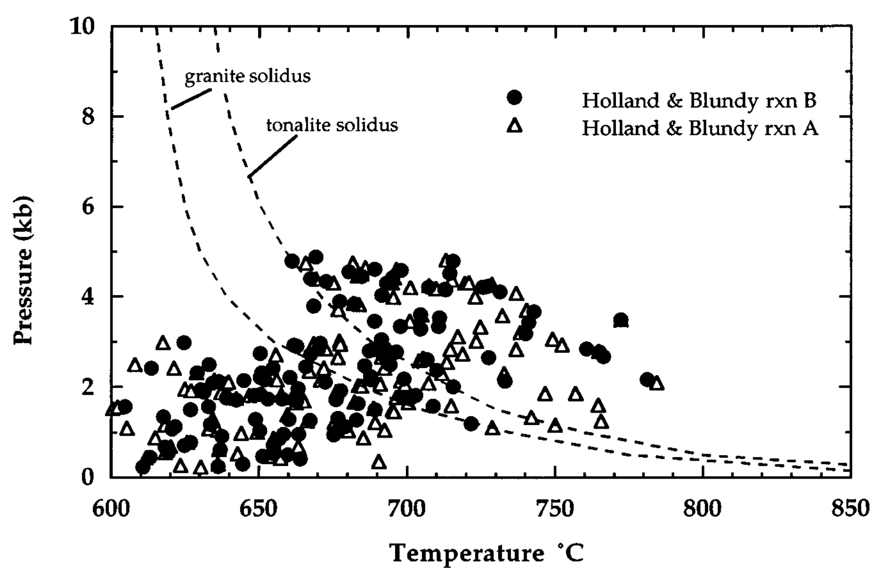

Figure 2. Estimates of pressure (Anderson and Smith, 1995) and temperature (Holland and Blundy, 1994) for the Mount Stuart batholith using the data of Paterson et al. (1994) and Anderson and Smith (1995).

phisticated (see discussion in Anderson, 1996). The complete barometric reaction has not been calibrated and, until revised by Anderson and Smith (1995), lacked rigorous temperature control. The barometer has strong temperature dependence, a fundamental attribute of all barometers. Hence, pressures derived from a barometer without concern for temperature are fundamentally suspect. Ague and Brandon (1996) ignored the influence of temperature and have derived an estimate of tilt based on pressure differences of only 1.5 kbar. The Al-in-hornblende barometer lacks this sensitivity, particularly when used below its range of calibration (P < 2.5 kbar), as done in this study. Had Ague and Brandon (1996) fully propagated error through their calculations, they would have also observed that their estimate of tilt was questionable on this basis alone. Anderson and Smith (1995) showed that uncertainties in its experimental calibration coupled with ±50 °C uncertainty in temperature and 1% analytical uncertainty contribute to an overall uncertainty of ±1.5 kbar.

CONCLUSION

There are insufficient grounds in the Ague and Brandon (1996) data set to support their conclusion, based on barometric data, that the batholith is tilted. Apparent pressure variations are not real but rather result from variable magmatic to post-emplacement thermal conditions preserved within the batholith. Ague and Brandon (1996) did not rigorously study the effect of temperature on their pressure determinations. If they had evaluated temperature, they would have found that over half of their data set yielded false pressures because they came from retrograded samples. The retrogression of igneous hornblende is on a vector toward actinolite, a low-Al end member that carries no pressure information. Ignoring this, Ague and Brandon (1996) have derived conclusions from a database that not only ranges from magmatic to subsolidus, but also one that is nonsynchronous.

Barometric reactions are invariably dependent on other intensive parameters, particularly temperature. To calculate pressure without knowledge of the effects of temperature and other variables is an imperfect exercise that predictably can lead to false interpretations.

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Reply

Jay J. Ague*
Mark T. Brandon
Department of Geology and Geophysics, Yale University, P.O. Box 208109, New Haven, Connecticut 06520-8109

INTRODUCTION

We (Ague and Brandon, 1996) used the aluminum-in-hornblende (AH) barometer to estimate the regional tilt of the Mount Stuart batholith, Washington, and to correct previously published paleomagnetic data for tilting effects. As we see it, Anderson (1997) raised two main issues in his discussion of our paper: (1) conditions of equilibration for the AH barometer mineral assemblage and (2) propagation of errors for estimates of regional tilt. These issues remain controversial, in part because the governing reaction(s) for the AH barometer are incompletely understood and also because of a misunderstanding, perhaps widespread, of our statistical methods. We went to considerable lengths to address all of these issues in our paper, but welcome the opportunity here to clarify our conclusions.

ALUMINUM-IN-HORNBLENDE BAROMETRY—KEY FACTS

The AH barometer is based on the empirically and experimentally observed positive correlation between the total aluminum (Al^T) content of hornblende and equilibration pressure (P) for granitic rocks of appropriate bulk composition. All calibration studies of the barometer have suggested that in order for the barometer to be most effective, hornblende should coexist with quartz, K-feldspar, biotite, plagioclase, sphene, and Fe-Ti oxides. The Al^T-P relations for all empirical and experimental AH barometer calibrations are illustrated in Figure 1. This figure shows that the strong positive correlation between Al^T and P is beyond question. Moreover, the maximum total difference in P between all of the calibrations is only about 1.5 kbar. None of Anderson's arguments negate these important facts—there is a strong and well-defined corre-

*e-mail: ague@milne.geology.yale.edu

lation between Al^T and P.

As emphasized by many workers (e.g., Spear, 1981; Hammarstrom and Zen, 1986; Schmidt, 1992; Anderson and Smith, 1995), it is also true that the Al^T of hornblende is a function of equilibration temperature (T). For example, at a given pressure and bulk composition, a hornblende that equilibrates at a high temperature will be enriched in Al^T relative to a lower temperature hornblende. The high Al^T of the higher temperature hornblende results from temperature-sensitive substitutions such as the edenite substitution. We appreciate the impact of T variations on P estimates (cf. Anderson and Smith, 1995), but point out that the calibration curves of Figure 1 incorporate large T effects yet still agree to within about 1.5 kbar of each other.

CONDITIONS OF EQUILIBRATION

The P-T estimates of Ague and Brandon (1996) suggest that the AH barometer mineral assemblage equilibrated under subsolidus conditions throughout much of the Mount Stuart batholith. Anderson asserted that the AH barometer must equilibrate in the presence of melt, and therefore questions our P estimates. The solidus temperatures of low-pressure (~1–2 kbar) magmas are significantly higher than the temperatures of most AH barometer calibrations (such as the calibration of Schmidt, 1992, used by Ague and Brandon, 1992). Therefore, if the AH barometer assemblage equilibrates at the solidus in a low-pressure system, one would expect that the Al^T of the hornblendes would be artificially high and produce spuriously high pressure estimates. Nonetheless, many studies have found that demonstrably low-pressure intrusions that contain the AH barometer assemblage yield reasonable pressure estimates. For example, the original AH barometer calibration of Hammarstrom and Zen (1986) contained many plutons that intruded at pressures in the 1 kbar range. Ague and Brimhall (1988) found that shallow-level plutons that intruded their own volcanic cover in the Ritter Range of the Sierra Nevada batholith gave reasonable pressure estimates on the order of 1–2 kbar. The AH barometer also provides reasonable pressure estimates for the Yerington batholith (data of Dilles, 1987), which crystallized in the 1–2 kbar range.

How can this apparent discrepancy be resolved? We argue that the pressure-sensitive Al substitutions are probably controlled by solid-solid reactions much like other reactions used for barometry. One possibility is the reaction proposed by Hollister et al. (1987):

2 quartz + 2 anorthite + biotite =
tschermakite + orthoclase.

Ague (1997) discusses the reaction tremolite + phlogopite + 2 anorthite + 2 albite = 2 pargasite + 6 quartz + K-feldspar.

There is no a priori reason why the compositions of phases in these types of reactions must equilibrate at the water-saturated solidus of a magma in the presence of melt. Like most reactions, diffusion-controlled compositional modification may take place over a range of temperatures down to some nominal “blocking” temperature. In reality, the final temperature of equilibration depends on several key factors, including the coexisting mineral assemblage, grain size, and cooling rate. Thus, in order to estimate pressures effectively, it becomes critical to use samples that contain the AH buffer assemblage and that equilibrated near the temperatures of barometer calibration. The results for samples that represent the entire range of K-feldspar–bearing intrusions throughout the batholith presented in Figure 9 of Ague and Brandon (1996) show that our sample suite probably equilibrated at average temperatures of around 650 °C. Anderson (1997) argued that these temperature estimates should be recalculated using a different structural formula normalization scheme, but his results (his Fig. 1) do not differ significantly from ours. Our samples seem to have equilibrated at temperatures near those of the AH barometer calibration of Schmidt (1992). We conclude that the hornblendes attained their compositions under P-T conditions just below the solidus.

Anderson asserted that the AH barometer has not been calibrated in low-pressure systems, but this is untrue. The empirical calibration of Hammarstrom and Zen (1986) included many ~1 kbar intrusions. Their calibration is virtually identical to the experimental one of Schmidt (1992). The agreement between the two calibrations is strong evidence that Hammarstrom and Zen’s data were not contaminated by high-temperature Al substitutions, and that the AH barometer can be used successfully in low-pressure settings. In fact, the success of the AH barometer under these conditions appears to us to be an important attribute, not a flaw.

Anderson argued that the low pressures obtained by Ague and Brandon (1996) for the southern part of the batholith are an artifact of edenite exchange under retrograde conditions. This argument cannot be sustained because increases in the Al content of hornblende in our data set are controlled by pressure-sensitive Tschermak-type substitutions (Ague and Brandon, 1996, Fig. 8). The Al systematics of our hornblendes are identical to those obtained by Schmidt (1992) in his experimental calibration of the AH barometer (see Fig. 8 in Ague and Brandon, 1996). Moreover, we were careful to avoid samples that showed evidence of very low temperature retrograde alteration and chloritization (Ague and Brandon, 1996, Fig. 5).

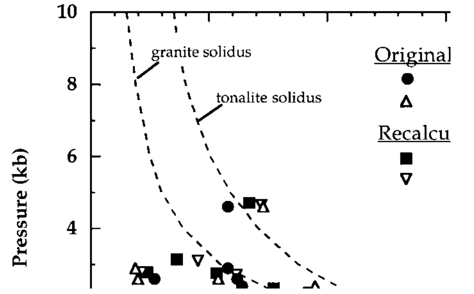

Figure 1. Empirical and experimental calibrations for the aluminum-in-hornblende barometer. HZ86—Hammarstrom and Zen (1986); H87—Hollister et al. (1987); JR89—Johnson and Rutherford (1989); TE—Thomas and Ernst (1990); S92—Schmidt (1992). Al^T—total aluminum content of hornblende (atoms per 23 oxygens); P—pressure.

It is critical to emphasize that our data set is very different from Anderson’s. Unlike our sample suite, the bulk of Anderson’s data set is made up of relatively mafic tonalites and quartz diorites that lack K-feldspar and sphene. Thus, although Anderson failed to mention it, most of his samples fall outside the bulk compositional range for which the AH barometer was calibrated. As a consequence, it is difficult for us to interpret the P-T results presented in his Figure 2. The samples yielding hypersolidus temperatures may retain a high-temperature signature because diffusive equilibration in assemblages lacking phases like K-feldspar may stop at a different time (and temperature) than the AH assemblage.

PROPAGATION OF ERROR

As discussed in depth by Ague and Brandon (1996), systematic errors in P estimates across a batholith will produce systematic errors in tilt reconstructions. Anderson’s arguments, however, seem to be focused on random, rather than systematic, errors. In an effort to resolve any lingering misunderstandings, we restate more simply the basic statistical reasoning here.

Anderson asserted that because the variability of an individual pressure determination is ~1.5 kbar, we cannot resolve regional tilts. An absolutely essential point that we made in our paper and that must be repeated here is that the variability of an individual depth determination cannot be taken as an indicator of the precision of the overall tilt estimate. Our estimate of average tilt is much more precise because it is based on all of the depth determinations across the full area of the batholith (see Taylor, 1982). A simple example of the basic principles involved in our argument is the confidence interval for the univariant mean. Consider a hypothetical Gaussian data set containing 50 data points ($N = 50$) with a mean of 1 and a sample standard deviation (σ) of 1. The variation among these single observations is commonly represented by $\pm 2\ \sigma$ (=2 for our example); $\pm 2\ \sigma$ contains ~95% of the distribution around the mean. The distribution can also be used to estimate the mean. For a Gaussian distribution, the precision of the estimated mean is given by the standard error (or more formally by the standard deviation of the means); the standard error, σ_{SE}, is defined by $\sigma_{SE} = \sigma/\sqrt{N}$. The variation of estimated means has a ~95% confidence interval estimated $\pm 2\sigma_{SE}$, which for our example is 0.28. Thus the 95% confidence interval for the mean is about 2.0/0.28 = 7.1 times smaller than the 95% variation expected for a single determination (N = 1). The statistical reasoning for a fit to a planar tilt surface is similar, but is slightly more complicated because it involves the spatial distribution of samples as well as *N*. The critical features of the bootstrap-based statistical methods used by Ague and Brandon (1996) are that (1) no assumptions about Gaussian distributions are required and (2) random variations in temperature and other factors discussed by Anderson are included automatically in the analysis by means of bootstrap resampling procedures (cf. Efron and Tibshirani, 1993).

Anderson's strong criticism of our overall uncertainty estimates for AH pressure determinations is unfounded. Our estimate for the relative precision of a single AH barometer pressure determination (±95% confidence) is about ±1 kbar (about ±3.2 km in depth; Ague and Brandon, 1996, p. 481). Anderson calculated an overall uncertainty that is a little larger—about ±1.5 kbar. It is important to point out that although Anderson characterized the AH barometer as being "unsophisticated," overall uncertainties of ±1–1.5 kbar (for a single pressure determination) are comparable to those obtained for other accepted barometers. It is clear that uncertainties associated with AH barometry *P* estimates remain incompletely understood and, as a result, no one, including Anderson, is in a position to make sweeping, unequivocal statements about the success or failure of AH barometry. On the basis of available evidence, we maintain that the barometer is sufficiently precise for our application, namely, determining regional gradients in equilibration *P* across tilted batholiths.

DISCUSSION

Independent geologic evidence is consistent with our estimate of regional tilt. For example, five additional pressure estimates for the contact aureole published by other workers (see Fig. 7 in Ague and Brandon, 1996) also support our tilt estimate. Our pressure estimates are all consistent with the growth of andalusite in the contact aureole. Furthermore, some units of the Ingalls ophiolite in the southwestern part of the batholith, far removed from the thermal aureole of the batholith, contain very low grade, prehnite-bearing mineral assemblages (Miller, 1985). This suggests that the shallowest parts of the batholith are exposed at its southern end, consistent with our barometry results. Moreover, as one moves from north-northwest to south-southeast across the batholith, one moves in an up-section direction from metamorphic rocks of the Chiwaukum Schist through the Ingalls ophiolite, into the unconformably overlying sedimentary rocks of the Swauk Formation. These relations suggest that the Mount Stuart area currently dips gently in a south-southwesterly direction, and are consistent with our AH barometry results.

It is also important not to lose sight of the basic conclusions reached in our paper. One of the major tilt models proposed previously for the Mount Stuart batholith (Butler et al., 1989) was that the pressure of intrusion, at the present level of exposure, increased from 1–2 kbar in the southwest to 6–7 kbar in the northeast. Our results demonstrate that this scenario is untenable—the batholith appears to be characterized by a very gentle decrease in equilibration pressures to the southeast.

Our disagreements notwithstanding, we thank Anderson for this opportunity to discuss further the application of the AH barometer to the problem of the tilt of the Mount Stuart batholith. We hope that our discussion and reply exchange stimulates new experimental and theoretical studies aimed at determining the barometer reaction, determining kinetic rates of cation exchange, and refining thermodynamic data and activity models for hornblende. These efforts will be important because accurate and precise emplacement pressure estimates from granitic rocks provide invaluable constraints on tectonic processes.

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