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**BATHOLITHS and
EXPERIMENTS in the 1970s**

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**LEON T. SILVER  
70 th BIRTHDAY SYMPOSIUM  
AND CELEBRATION**

RELATION OF PHASE EQUILIBRIA STUDIES  
ON TONALITE-TRONDHJEMITE-H<sub>2</sub>O  
TO THE ORIGIN OF CORDILLERAN BATHOLITHS.

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RELATION OF PHASE EQUILIBRIA STUDIES  
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The title of the paper I offered was less prosaic than the one assigned. My proposed paper was entitled: "**A Field Trip with Lee Silver through the Coast Range Batholith of British Columbia**", and what I present will at least begin by following that field trip, while tackling the assigned title. During the 1970s, Lee Silver was a regular participant in a series of Field Trips in the "**Circum-Pacific Granite (or Cordillera, or Batholith) Project**" under the aegis of IGCP (I think). Groups of petrologists led by distinguished granite experts visited and compared batholiths in countries which included Japan, Korea, Malaysia (I think), Australia, Chile, and probably others. When **the group came to Canada in the mid-70s, within reach of my budget**, I joined them from my Chicago home in the flat country in order to receive a first-hand, first-class tour of the extensive vertical exposures of the granitic rocks which had been sweating away in my pressure vessels under the tender care of many associates. The active "granite" coworkers of that period included **A. J. Piwinski, A. L. Boettcher, J. K. Robertson, I. B. Lambert, W.-L. Huang, C. R. Stern, and S. Maaløe**. Most of the results I will outline below derive from the more recent work of **A. D. Johnston, M. R. Carroll, S. van der Laan, B. S. White, D. Sykes, and M. B. Wolf**.

A buoyant continental crust is generated when lithosphere is percolated and pierced by granitoid magmas, and successive tectonic events and continental evolution are associated with successive granitic generations, e.g. archaic grey gneisses, calc-alkaline rocks of convergent plate boundaries, and red alkaline granites of anorogenic regions. The most dramatic examples of plutonic intrusions of granitic rocks are in Cordilleran batholiths, where possible source rocks for the parent magmas of the granites are within the subducted oceanic crust, in the overlying mantle wedge, or in the base of the continental crust.

Discussions on the outcrops in the Coast Range Field Trip were often argumentative. I remember repeated discussions between **Lee Silver, Wally Pitcher, Paul Bateman**, and many others about the distinctions among tonalite, granodiorite, and trondhjemite, with reference, deference and denial of Streckeisen's IUGS-approved 1967 classification scheme for the igneous rocks. **Paul Bateman and I** discussed whether or not the variable concentration of alkali feldspar could be used as a guide to the distribution of interstitial granite melt within a crystal mush. Batholiths are granitic, and large alkali feldspar phenocrysts are beautiful, but one striking feature of the Coast Range Batholith and others in western USA is the abundance of tonalite - the abundance of quartz, and the paucity of alkali feldspar. Our experiments had made it clear that even with lots of H<sub>2</sub>O, tonalites were high temperature liquids (although magmas of liquid + crystals could exist at lower temperatures), and at that time this fact was still news to some of the participants. The solidus for granite-H<sub>2</sub>O on metamorphic facies diagrams is the lower limit for the formation of migmatites, but more relevant for calibration of magmatic processes and tectonic environments is the liquidus of granitoid magmas.

**Linc Hollister**, one of our expert guides, showed us through his best rock displays in the rain, and explained to us how the tonalites had been formed by partial melting, right there - in the quarry - and then the whole mass had been intruded upwards as a tonalite pluton. He showed us migmatites with leucocratic veins termed tonalite, rocks shot through with massive tonalite dikes, and many smaller cross-cutting dikes and veins. Those rocks certainly indicated the importance of crack formation and dike injection even in the early, deep stages of pluton and batholith formation. The fact that the normative feldspar components of a rock analysis project into the tonalite field on a feldspar diagram does not necessarily make that rock equivalent to a real tonalite, containing a fair percentage of mafic minerals. The leucocratic tonalite-like veins may have temperatures of 800°C or so, as determined by Hollister and his coworkers, but real tonalite masses even with high H<sub>2</sub>O contents must reach temperatures of at least 900°C, probably more than 950°C if they are to become liquid magmas.

In other locations, **Hutch Hutchison** showed us compelling examples of great tadpoles of granite bubbles rising through the crust. **Cliff Hopson** has graphically illustrated the whole sequence from migmatite root to bulbous tonalite magmatic pluton at shallower levels. **E-an Zen** was mapping the distribution of epidote in batholiths, and he led the discussion at those plutons bearing primary epidote with the claim that the epidote indicated great depths of crystallization. At that time, I think that there were no experimental results on granites with epidote, but **A.D. Johnson and I** (1988) confirmed that epidote does occur within the crystallization interval of a trondhjemite, but only at pressures greater than 12kb (deeper than 45 km).

**Linc Hollister** more recently joined **E-an Zen** in promoting the Al-content of hornblendes as a working geobarometer for granitoid rocks. There have been several experimental calibrations with somewhat divergent results. **Lawford Anderson**, a hornblende geobarometer champion, has recently put together a clarification involving a family of curves showing the effect of pressure and temperature, and hornblende may yet become a panacea for a limited range of rock compositions - but there are a lot of variables involved, and rather few controls.

**Wally Pitcher had seen the paper by Maaløe and Wyllie** which showed how granitic magmas with different water contents would precipitate minerals in different sequences, a paper which then went on to suggest that determination of the sequence of crystallization of natural granites would help to define the water content of the magmas: **Pitcher said**: "Do you fellows know how difficult it is to be sure of the sequence of crystallization in a granite with the petrographic microscope?" *Squelch!* But we had found half a dozen papers where the authors appeared to be confident of the crystallization sequence, and application of our calibrated granite-H<sub>2</sub>O section suggested that it was unlikely that the H<sub>2</sub>O content of large granitic magma bodies exceeded about 1.5 weight per cent. These magmas are H<sub>2</sub>O-undersaturated through most of their histories (if they evolve CO<sub>2</sub>, then some H<sub>2</sub>O is carried off as well, but magma H<sub>2</sub>O contents are little affected), but uprise and crystallization produces H<sub>2</sub>O-saturation around margins and in the upper regions, and H<sub>2</sub>O-saturated rhyolitic and dacitic magmas with phenocrysts can be erupted from these regions.

In all of the granitoid rocks we studied with H<sub>2</sub>O, we had found that hornblende was precipitated at a higher temperature than biotite. **Dave**

**Wones** did not believe that this experimental observation was maintained in all natural granitic magmas. He cited rocks where he was convinced that biotite was precipitated before hornblende - I think that these were all alkaline granites. From our results with calcalkaline rocks, there was no doubt about the sequence hornblende first, biotite second with high water contents, but we could not exclude a reversal of phase boundaries at very low H<sub>2</sub>O contents.

Some **Japanese geochemists**, and others, claimed that some granites were primary magmas from mantle peridotite. I maintained then, and I believe now, that the available evidence indicates strongly that normal granite cannot be derived by direct partial melting of peridotite. The liquidus surface of granite-H<sub>2</sub>O is dominated by primary quartz or coesite, and no additional mineral is precipitated through a significant temperature interval at mantle pressures. Such liquids could never have been in equilibrium with peridotite at mantle pressures. But what about tonalites? Geochemical arguments have been adduced to support claims that some tonalites are primary magmas from metasomatised mantle peridotite. Experiments have confirmed that melting peridotite with H<sub>2</sub>O under some conditions does yield magmas with SiO<sub>2</sub> content approaching that of tonalites, but the minerals on the liquidus surface of tonalite-H<sub>2</sub>O do not include assemblages corresponding to residual minerals in a hypothetical source peridotite.

A two-stage process involving separation of basalt from peridotite, with remelting of basalt or amphibolite within a short geological time interval, appears to satisfy the geochemical data without the claim of primary-from-mantle-peridotite. There are very close field and petrological relationships between basalt/amphibolite and the granitoid rocks, granite, trondhjemite and tonalite.

H<sub>2</sub>O-undersaturated liquidus surfaces have been determined to 20 kb for five rocks with different SiO<sub>2</sub> contents: granite, trondhjemite, and tonalites. The surfaces are mapped in terms of liquidus minerals, providing information about the residual minerals required in source rocks (amphibolites, metasediments) if the magmas were primary. Tracking the liquidus boundary for [garnet + amphibole] relates tonalites and trondhjemites to the potential amphibolite sources. The liquidus results correlated with experimental results on the melting of amphibolite provide specific limits for the generation of the granitoid rocks as a f(P,T,H<sub>2</sub>O). Calibration of conditions for the generation of parent granitoid magmas and conditions of their emplacement facilitate selection among various tectonic models.

It is commonly proposed that tonalites, trondhjemites and granites were derived by partial melting of amphibolite, or the high pressure equivalent, hornblende-eclogite. Five 1991 experimental studies on the solidus for dehydration-melting of amphibolites yield somewhat divergent results. **Wyllie & Wolf** (1993) explained these in the context of a new phase diagram showing the vapor-absent solidus for closed-system simple

amphibolite (Hb + Pl) in two parts, the beginnings of multivariant reactions (1) a near-vertical curve (steep positive  $dP/dT$ ) where augite is formed, and (2) a near-horizontal curve BC at higher pressures ( $< 10$  kb; shallow positive  $dP/dT$ ) where garnet is formed (this curve and the associated solidus backbend to lower temperatures and pressures were previously unacknowledged). There is a wide, pressure-sensitive reaction interval for amphibole. The solidus curves shift with bulk composition. The field for liquid generation with garnet- amphibolite residues extends to much lower temperatures and pressures compared with the other recent experimental results. This feature has significance for REE and other trace element concentrations in partial melts from amphibolite.

The liquidus surfaces for  $H_2O$ -undersaturated granitoid magmas can be mapped with contours for %  $H_2O$  and field boundaries separating fields of primary minerals. From such diagrams, one can read the depths, temperatures and  $H_2O$  contents of primary magmas that left specific residual minerals in the source rocks. We have determined liquidus surfaces and field boundaries for four granitoid magmas (tonalite, trondhjemite, granite) with different  $SiO_2$  contents. The field boundaries for amphibole and garnet in tonalites and trondhjemite occur in similar positions, but the granite has neither mineral on its liquidus.

Conclusions from the forward (amphibolite) and reverse (granitoid magmas) experimental approaches include: (1) If granitoids leave residual amphibole, this requires moderate temperatures (800-1000°C) but  $H_2O$  contents (about 10-15%) which are higher than those in melts produced from dry amphibolite. (2) Residual garnet requires depths greater than -50 km, temperatures higher than -1,000°C and lower  $H_2O$  than for residual amphibole; greater depths and temperatures are required for magmas with lesser  $H_2O$  contents. (3) The limited area for coexisting garnet and amphibole on the liquidus (with relatively high  $H_2O$  contents) – contrasting with the large, relatively low-temperature PT area for amphibolite where the residual minerals coexist with  $H_2O$ -undersaturated liquid – suggests that although experimental liquids from amphibolites plot in the fields for trondhjemite and tonalite in feldspar classification diagrams, they do not necessarily have the compositions of the real rocks; they appear to need additional dissolved mafic mineral components to correspond to the natural magmas.

The concept of primary magmas for the granitic magmas is an oversimplification, but the equilibrium phase relationships provide the framework for unravelling the complications of multiple melting and fractionation episodes. Experimental data are consistent with proposals that trondhjemites may be derived from secondary partial melting of tonalites which were derived by melting of amphibolite or eclogite. Further refinement of the experimental field maps for melting amphibolites and crystallizing granitoid magmas will place tighter constraints on the conditions of generation and emplacement of the magmas in terms of depth, temperature and  $H_2O$  contents, yielding insights into the tectonic conditions for the formation, uprise and emplacement of granitic rock in batholiths.

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