

Jahns and Burnham (1969) Experimental Studies of Pegmatite Genesis: I. A Model for the Derivation and Crystallization of Granitic Pegmatites. *Economic Geology and the Bulletin of the Society of Economic Geologists*, 64, 843-864.

David London

September 17, 2021

Introduction

When academic professionals review manuscripts for publication today, one of the questions that editors ask is whether the title is accurately representative of the material in the manuscript? A reviewer, therefore, might have expected the manuscript that was submitted as Jahns and Burnham (1969) to present experimental evidence that confirms a model. From the inception of the publication of experimental petrology, such a manuscript would normally contain a table of the chemical compositions of all constituents used, a table that summarized each experiment by label, composition, pressure, temperature, duration, and abbreviated results, and some form of depiction of those results. Before the 1980s, some authors included transmitted-light photomicrographs of run products. Since the 1980s, backscattered electron images have been the standard means of portraying the texture, spatial organization, and compositional aspects of experimental products.

In Jahns and Burnham (1969), Jahns' model¹ for the derivation and crystallization of granitic pegmatites was discussed in detail. However, the experimental basis for the model was not. No previously unpublished experimental works by these authors other than abstracts were presented in this article except by way of a few brief remarks with no substantiation. Most of the experimental data that were cited came from other published sources. Experimental results of Jahns and Burnham were mostly in the form of abstracts at professional meetings. These included a summary² in which the liquidus and solidus temperatures of granite, and similar compositions derived from crystalline samples of two pegmatites, were obtained by the melting of crystalline compositions (Jahns and Burnham, 1958). Other experiments in which the solubility of H₂O in granitic melts and the compositional aspects of coexisting aqueous solution and silicate liquid were measured were also cited as abstracts (Burnham and Jahns, 1958, 1961). These and other previously published experimental data were employed to model the evolving concentration of H₂O in granitic melts, presumably using a Rayleigh-type fractionation model, though none was actually described. That application of those experimental results led to the point of separation of an aqueous solution from initially H₂O-undersaturated silicate melt, which Jahns and Burnham (1969) took to be the starting point for the formation of pegmatites. No experiments pertinent to pegmatites themselves were presented, nor was there discussion of the "failed experiments" of Tuttle and Bowen (1958) that Jahns claimed to be so important to his understanding (see essay #8 of this series). The Jahns and Burnham (1969) publication would normally be the place where all of the experiments cited in their previously published abstracts at professional meetings would finally be fully presented and discussed. They are not. The appropriate answer to the editorial question posed above, therefore, would be "NO."

The title of this paper continued a trend in Jahns' work to cite articles as numbered parts of a series. The "Genesis of Pegmatites" series of articles contained five numbered citations in his lists of references, only the first two of which were ever published (see essay #6 of this series). A later title cited as Jahns and Burnham (1963), the first of a numbered series on experimental

applications to pegmatites, did not exist (see essay #8 of this series). This article by Jahns and Burnham (1969) was apparently that article in preparation that was cited in Jahns and Tuttle (1963). Jahns and Burnham (1969) alluded to another paper of this experimental series that would be forthcoming, but never was:

“A more detailed discussion of these and other features of crystallization from the aqueous phase in pegmatite systems will appear in a future paper of this series.” (p. 858)

Jahns and Burnham (1969) was constructed in a manner similar to Jahns’ previous publications. Jahns’ visual concept of the pegmatite-forming process was presented in several places in the manuscript. Key topics, such as the viscosity of pegmatite-forming melts and the nature of thermal gradients in pegmatite dikes were mentioned multiple times, but they were not developed as separate sections of the manuscript. Though Jahns and Burnham (1969) opened with a list of eight essential features of pegmatites that a model must account for, only the first of these was discussed explicitly by them.

This essay opens with the sequential stages of the Jahns-Burnham model as presented by these authors. After that, the main points of the Jahns-Burnham model are considered under appropriate headings. Finally, in the absence of published experiments by Jahns and Burnham, I have added illustrations studies of experimental petrology that bear upon the genesis of pegmatites.

The Essential Features of Pegmatites

Jahns and Burnham (1969, p. 844-845) opened with a series of statements that were meant to convey the key attributes of pegmatites that a model must account for. The numerical list of topics followed, more or less, a sequence of formation in the internal evolution of pegmatite bodies, beginning with border zones (1) and ending with replacement and corrosion of prior crystals (7 and 8). Jahns’ (1982) final article opened the same way, though the list of essential features was different with a greater emphasis on the miarolitic stage.

“1. Relatively fine-grained border zones with compositions markedly different from the bulk compositions of the respective pegmatite bodies.”

“2. Major discrepancies between the compositions of many zones and other interior segregations (especially quartz cores) and the compositions that would be expected for these rock units if they had formed in sequence within an essentially closed system whose liquid phase was yielding solid material only.”

“3. Profound segregation, commonly involving crystals of giant size, in pegmatites formed from silicate melts with relatively high viscosities.”

“4. Marked asymmetry of zonal structure, with arrangement and compositional trends consistently related to the gravitational field.”

“5. Penecontemporaneous pegmatite and aplite indigenous to the same igneous body, as well as pegmatite minerals differing enormously in grain size from other contemporary minerals in the same body.”

“6. Widespread mineral replacement, not readily ascribable to simple reaction between crystals and silicate liquid, that generally show a definite sequence of development.”

“7. Temporal overlap, within the same body, in formation of zones or other segregations and formation of replacement bodies.”

“8. Evidence for vigorous corrosion and replacement of quartz, potash feldspar, and other minerals simultaneously with crystallization of the same minerals at other points within the same pegmatite body.”

Outline of the Model (p. 845-849)

“The model is based primarily on extensive field and laboratory studies of natural pegmatites, but it also embodies some modifications and additions deriving from results of experimental investigations beginning in 1957 (cf. Jahns, 1955, p. 1084-1099; Jahns, 1956; Jahns and Burnham, 1961). It is by no means complete or in its final form, despite a decade of our testing it in the field and in the laboratory.” (p. 845)

So began the exposition of the model and the experimental evidence for it. Here, the authors cited one article that predated 1957 and which contained no experimental studies of its own (Jahns, 1955), and two abstracts on the melting relations of pegmatitic bulk compositions (one prior to 1957). Other experimental studies figured into the text elsewhere, but by implication they were not directly relevant to the specifics of the model of pegmatites as presented.

The “*Outline of the Model*” of Jahns and Burnham (1969) started with the derivation of granitic melts from their sources, and the ensuing changes in the concentrations of H₂O in melt that would attend the crystallization of those melts. They considered plutonic masses of granitic magmas as the ultimate sources of pegmatites. Here, as in Jahns (1955), Jahns and Burnham (1969) acknowledged that some pegmatites might arise from metamorphic processes, but they regarded that process as a sideline to the main sources of pegmatites. They considered partial melts of granitic composition that initially contained from 0.2 to 2 weight percent H₂O. Though not mentioned, these values were derived from Burnham’s experiments and calculations of partial melting in likely crustal sources, where hornblende and muscovite were the low and high-concentration sources, respectively, of H₂O. With these and other intermediate initial values, their Figures 2 and 3 depicted the increase in the concentration of H₂O in melt as functions of the fraction of crystallization that ensued. The figures appeared in the form of Rayleigh fractionation trends, though no specific methods of their calculation were presented. As a limiting case, they assumed that the crystallizing assemblage was anhydrous, consisting solely of quartz and feldspar. For their model, the important experimental constraint came from the measurements of the limits of solubility of H₂O in granitic melts as functions of pressure and temperature. Those limits were known from early experiments by Goranson (1931), and later work by Burnham and Jahns (1958, 1962). The purpose of that exercise was to estimate the extent of crystallization of an anhydrous granitic mineral assemblage that was necessary to bring any remaining melt to saturation in H₂O. In their model, the pegmatitic stage ensued from the granitic stage with the exsolution of an aqueous solution from H₂O-saturated melt via crystallization, or what has been referred to as resurgent boiling of the melt.

The “*Outline of the Model*” continued to a vision of the pegmatitic stage of crystallization with the separation of an aqueous solution from H₂O-saturated melt:

“The aqueous phase initially separates on a submicroscopic scale and then progressively assumes the form and role of an interstitial fluid. It also collects into larger masses that are first recognized as tiny bubbles, either uniformly or patchily distributed throughout the liquid. Partitioning of other volatiles and of relatively non-volatile constituents between the two fluid phases occurs immediately upon their separation, and increases in scope as more and more aqueous fluid is formed in response to continued crystallization within the system. Diffusion of materials along temperature-induced concentration gradients can take place much more rapidly in the aqueous phase than in the relatively viscous melt, the rates differing by as much as eight to ten orders of magnitude.” (p. 848)

Derivation of Pegmatitic Magma (p. 849-853)

The fraction of melt remaining after reaching that point of saturation in H₂O was regarded as the portion of melt that could form pegmatite: a hypothesis of Jahns (1955), a statement of fact in Jahns and Tuttle (1963), and again here:

“Appearance of the aqueous phase can be regarded as the most decisive step in the genesis of pegmatites, as it marks the beginning of fundamental changes in texture and the distribution of the crystallizing materials.” (p.862)

The authors noted that the granitic textures of the outer zones of pegmatites could result from the extraction of pegmatite-forming melts from their source granites prior to achieving H₂O saturation of those melts. This hypothesis points to an important corollary of the Jahns-Burnham model – that the ordinary textures of granitic plutons arise only from magmas that have not achieved saturation in H₂O and that have not exsolved an aqueous solution from their melts:

“Crystallization from granitic magma that is not saturated with water is thought to yield rocks with normal phaneritic texture rather than with textures usually identified as pegmatitic. These rocks commonly are coarse grained, and either granitoid or inequigranular. Taken alone, they ordinarily are given names such as granite, quartz monzonite, and granodiorite.” (p.853)

Later, Burnham (1979) would present a model for the evolution of base-metal mineralized porphyries of granite, granodiorite, and quartz monzonite that entailed the saturation of melt in H₂O and the separation of an aqueous solution early in the consolidation of the magmatic bodies. In that model, the aqueous solution produced quartz veins in the crystalline carapace within and around the magma body, but not pegmatites. It was not noted then or later that the model stood in direct conflict with this conclusion of Jahns and Burnham (1969) as to the causative role of aqueous solutions and the formation of pegmatites.

Elsewhere, Jahns and Burnham (1969) speculated that the border zones of pegmatites, with their comparatively fine-grained and granitoid textures, might arise from a wholly different process than cooling:

“Selective losses of material to the country rock also might account for the anomalous composition of fine-grained border zones in many pegmatite bodies. Although it is tempting to view these selvages as typical chilled margins, they generally are much more sodic or silicic than the entire pegmatite bodies they enclose. It seems more likely that they represent

crystallization from pegmatite magmas that were losing materials selectively to the wall rock via a coexisting aqueous phase.” (p. 858)

This hypothesis stems from the compositions of border zones, which are rich in the most calcic plagioclase found in any given pegmatite body, along with quartz, micas, garnet, tourmaline, beryl, apatite, columbite, and other lesser minerals. Cameron et al. (1949) (see essay #4 of this series) observed that the anorthite content of plagioclase declined from the margins inward, and they took this trend to reflect the fractional crystallization of a granitic melt from the margins to center. Subsequent work has reaffirmed the trend of decreasing anorthite content of plagioclase, which falls rapidly from $\sim \text{An}_{15}$ to $\text{An}_{0.5}$ within centimeters from the contact (London et al., 2019). On the basis of thermometry and texture, the border zones are indeed chilled margins (London et al., 2019), and their non-granitic compositions arise from the initial response of the pegmatite-forming melt to abrupt undercooling at the contact with host rocks (London and Morgan, 2017). In the vast majority of cases, the border zones of pegmatites are flanked by unaltered host rocks (London, 2008), most of which would have recorded an influx of potassium in the formation of new micas if the hypothesis offered by Jahns and Burnham (1969) was correct.

Throughout this section, the crystallization of granitic melt was modeled as a response to cooling, which entails the migration of melt from its source into cooler hosts, or else extremely slow cooling of melt *in situ* at the rate of regional uplift. The temperatures of crystallization were pegged to the liquidus and solidus intervals of the granite system at saturation in H_2O , which were taken from the experimental investigations of Tuttle and Bowen (1958) and Luth et al. (1963) at a pressure of 5,000 bars (~ 15 kilometers depth). In that case, there could be no migration of melt upward because such migration would necessarily proceed through cooler host rocks, and liquidus undercooling would occur. Jahns was well aware that pegmatite-forming melts extend for kilometers upward and outward from their source granites, and hence they would span a gradient in pressure and a sharp gradient in temperature as imposed by their host rocks. In his first solo publication on pegmatites, Jahns (1953) did not explain his prescient suggestion that pegmatite-forming melts must crystallize rapidly, but he might have deduced this from the mineral textures and from the occurrence of pegmatite bodies as thin dikes far from their inferred granitic source (commonly not exposed). He might also have also envisioned that rapid crystallization was necessary because thin granitic dikes could not remain hot for long in their final place of emplacement far from their original magmatic source.

Effects of Viscosity on Ionic Diffusion

Jahns and Burnham (1969) were correct in characterizing the bulk of the pegmatite-forming melt at “*relatively viscous*”, in contrast to the interference of low viscosity melts by Cameron et al. (1949) and Jahns (1953). They cited Burnham (unpublished) as having measured the viscosities of granitic liquids:

“Their relative magnitudes have been under investigation by Burnham during recent years, and values between 10^6 and 10^7 poises [= 10^5 to 10^6 Pascal-seconds] have been obtained for viscosities of water-rich granitic melts at and near their liquidus temperatures and under a corresponding pressure range of 1,000 to 7,500 bars.” (p. 853)

The high viscosity of such melts was perceived as a barrier to the rapid transport of ionic constituents to growing crystal surfaces:

“Diffusion of materials along temperature-induced concentration gradients can take place much more rapidly in the aqueous phase than in the relatively viscous melt, the rates differing by as much as eight to ten orders of magnitude.” (p. 848)

No sources of data are cited for the numerical magnitudes or their differences. I have searched exhaustively for experimental measurements of the diffusion of ions through aqueous solutions at elevated pressures and temperatures, and I have found but one reference that applies, sort of, to this environment (Ildefonse et al., 1979). Without citations, it is impossible to know what Jahns and Burnham (1969) were using as sources of diffusion data for either type of fluid, but almost all of the experimental measurements of ionic diffusion in melts have come long since this article was published. Among them are works by Acosta-Vigil et al. (2017), who demonstrated that the far-field diffusion of sodium and potassium through granitic liquid is essentially instantaneous in response to crystallization, and especially in response to gradients in other ions with which the alkalis tend to associate in the melt. The flow of alkali ions in melt has been likened to a positive ionic current (Morgan et al., 2008).

London (2009) determined the rate at which a boron- and fluorine-rich alkaline melt that was undersaturated in silica achieved equilibrium with a seeded crystal of quartz. The result was that the *effective* diffusion of silicon – that is, the rate at which the gradient in its concentration was brought to saturation throughout the melt – was 10^7 times faster than in hydrous granitic melt at the same conditions. The flux of silica – referring to the apparent mass transferred per unit volume of fluid – was 10^7 times that of a corresponding volume of aqueous solution at the same conditions. The diffusion of silicon away from the dissolving quartz crystal was faster than in experiments with hydrous granitic melt (Figure 1a), but the means by which the gradient in the concentration of silicon was erased so quickly was by the rapid diffusion of all of the other constituents of melt toward the dissolving quartz crystal over the entire length and volume of the column of melt.

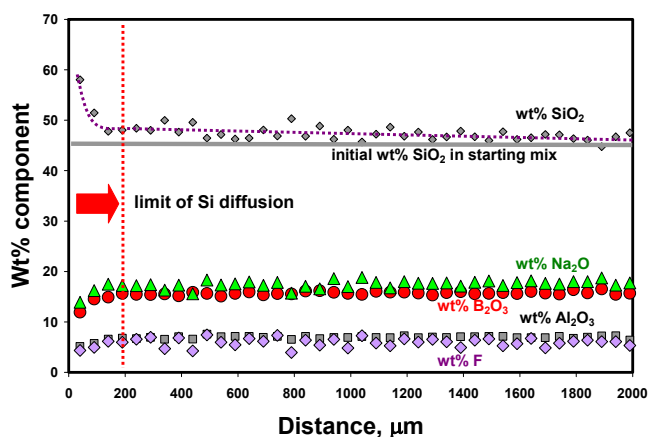


Figure 1a. Diffusion profiles after 1 hour in melt of the composition CGBF (see Table 4 of London, 2009, for the composition). An interface between quartz and melt is located at distance 0 (zero). Note that the concentration of silica is elevated over the entire length of the melt column after just one hour. From London (2009).

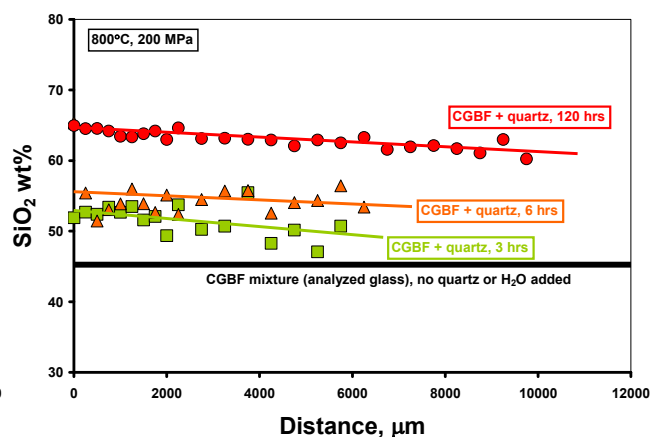


Figure 1b. Silica concentrations in melt of the composition CGBF as functions of time at 800°C, 200 MPa. An interface between quartz and melt is located at distance 0 (zero). The quartz saturation value is ~ 65 wt%SiO₂. From London (2009).

By the migration of other components toward the dissolving quartz crystal, the concentration of what was left – silicon – rose in all parts of the melt volume (Figure 1b). These results indicate that ionic diffusion can be extremely rapid, even in viscous melts, and that the mass of ionic constituents that are transferred through the fluid medium is many orders of magnitude greater in melts than in corresponding volumes of aqueous solution.

Jahns appears to have long recognized that the problem of making crystals of giant dimensions hinged upon the transport of ionic constituents to growing crystal surfaces, and that those rates are determined primarily by the viscosities of the melts. His original hypothesis (Jahns, 1953) that pegmatite-forming melts must possess low viscosities hints at his awareness that the migration of ions through pegmatite-forming melts must be rapid on the timeframes of cooling and crystallization within dikes, which he also characterized as “*very rapid crystallization*”. (Jahns, 1953, p. 590).

Burnham’s (1964) initial findings of high viscosities of hydrous granitic liquids reinforced Jahns’ contention that the mass transport of ions through melt would be too sluggish to foster the rapid growth of giant crystals. Burnham did not, however, do the experiments to validate that hunch. The recognition of far-field chemical diffusion does not negate the potential role of an aqueous solution, but it demonstrates that ionic diffusion through silicate melts can be exceedingly rapid for the alkalis, and that the diffusion of some components can quickly erase gradients in others, such as silicon, that diffuse slowly. The diffusion gradients created by far-field effects are independent of length: the gradients are established over the entire width of a melt column, or the distance between crystals or between dike margins (London, 2009, 2014b, 2018; London et al., 2012; Acosta-Vigil et al., 2017).

The sizes of individual crystals, however, are determined by the number of crystals per unit volume (see essay #8 of this series, and London, 2008), not the rates at which they grow. The sizes of crystals are indeterminate: they grow until they can no longer attract nutrient ions to their surfaces, or until they are limited by impingement against other crystals. As long as some ionic diffusion of nutrients can occur, crystals continue to grow to fill the space of their nutrient solution. The rate of growth is less important as long as it is sustainable. For practical purposes, that state ends when a melt transforms to glass, which so limits the migration of ions that crystallization, if it ensues at all, is exceedingly fine-grained. Conductive cooling models predict that thin dikes will reach their glass-forming temperatures in a matter of weeks or months. This is the constraint, which Jahns may or may not have realized, that puts the crystallization interval of pegmatite-forming melts on a short timeframe. If correct, it requires that crystallization ensues rapidly, and hence that ions migrate rapidly to sustain the growth of crystals.

Buoyant Ascent of Aqueous Solution from Melt

The issue of the viscosity of the pegmatite-forming melt as a barrier to mass transfer arises in various parts of this article, but no more so than in what became the underlying mechanism of Jahns (1982; Jahns and Tuttle, 1963), which relied on the buoyancy-driven separation of aqueous solution from silicate melt to explain the spatial segregation of zonal assemblages. Here, Jahns and Burnham (1969) speculated on the role of buoyancy in the upward separation of aqueous solution from melt:

“Under favorable conditions, among which sufficient time is important, the aqueous fluid also can migrate upward through the denser liquid and become concentrated in structurally high parts of the consolidating pegmatite body.” (p. 853)

The 4th essential attribute of pegmatites described (above) by Jahns and Burnham (1969) is that pegmatite zones are *“related to the gravitational field”*, implying a fundamental importance of density contrasts between fluids to the transfer of mass from one part of a pegmatite body to another. *“Sufficient time”* is the other variable over which mass transfer might occur. At several places in the manuscript, Jahns and Burnham (1969) observed that the solubility of melt components in the aqueous solution is low, and that the viscosity of melt is relatively high. *“Sufficient time”*, therefore, alludes to the limits of mass transfer as imposed by the composition of the aqueous solution and its rate of ascent through silicate melt. The calculated shear viscosity of hydrous granitic melts at 450°-500°C, the upper limit of temperatures based on feldspar thermometry (e.g., London et al., 2019), is $\sim 10^8$ Pascal-seconds. That viscosity is equivalent to asphaltic pitch at 25°C, which is sufficiently viscous that it shatters with the blow of a hammer (see <https://smp.uq.edu.au/pitch-drop-experiment>). A bubble of aqueous solution 1 millimeter in diameter would ascend through the melt at a rate of ~ 0.3 millimeters per year (London, 2008). That rate of ascent is far too slow for the buoyant separation of aqueous solution from melt if the thermal histories of pegmatite-forming melts are correctly understood. Water, as hydrogen ions, would actually diffuse much more rapidly through the granitic melt (millimeters per day: London, 2009) than bubbles of water could ascend. Bubbles, however, occupy volume, and the volume of aqueous solution that is created by the crystallization of an H₂O-saturated granitic melt at moderate crustal pressures is ~ 25 percent of the total volume, left as void space in the form of miarolitic cavities (London, 2008; London and Morgan, 2017). Miarolitic cavities of macroscopic size, however, are prevalent in only in a minute fraction (much less than 1 percent) of known pegmatites, and the miarolitic space found is usually less than 5 % of the total volume of pegmatite except in rare cases. The rarity of miarolitic cavities and the slow rate at which aqueous bubbles might migrate through melt hearken back to Bowen’s (1928) observation:

“...deep bodies have sent dikes into surrounding rocks at all stages of their careers and these dikes are often, at least at their margins, aphanitic or glassy. They have thus crystallized so rapidly that if the liquid were vesicular the aphanite would be vesicular as well. Yet vesicular dikes or dike selvages are exceedingly rare and are apparently always found in association with flows which indicate for them a shallow depth... It is very much to be doubted, therefore, that any process which involves vesiculation can be the principal or even an important process in igneous differentiation. But even on the supposition that vesiculation is a common condition in deep-seated magma and that for some reason its evidence is concealed from us, the quantitative adequacy of the process is seriously in doubt.” (p. 294)

Mass Transfer of Constituents

Jahns and Burnham (1969) restated their picture of the process, similar to that in the *“Outline of the Model”*:

“Once a cooling granitic melt has become saturated with water, a free aqueous phase likely would begin to separate as scattered units of submicroscopic size, doubtless unevenly distributed through the melt if thermal or compositional inhomogeneities were present. This phase probably

would accumulate as thin films along crystal-melt interfaces in the manner suggested by Neumann (1948, p. 82). With continued separation in response to falling temperature, it could assume the form of an interstitial fluid intimately distributed within the liquid-crystal aggregate, thereby effectively interconnecting various parts of the system on a growing scale. Owing to marked differences in the physical properties of melt and aqueous fluid, collection of the less viscous phase in the form of discrete bubbles also would be expected, and these bubbles would increase in number and size with time. They also might join with one another to form still larger bubbles and masses of irregular shape, with relationships to the melt akin to those described by Greig (1927, p. 21-25) for two immiscible liquids. With a density considerably less than that of the silicate melt, the aqueous phase also could migrate slowly upward through the crystal-bearing liquid, both as a flowing interstitial fluid and as rising bubbles. Given sufficient time relative to the viscosity effects of the host liquid, it thus could become preferentially collected in the upper parts of the system. The two fluid phases would differ drastically from each other in composition, even though all constituents of the system could be present in both. Contributions of materials from the silicate melt to the aqueous phase might be viewed in terms of respective partial pressures and volatilities of these materials (e.g., Bowen, 1933, p. 119-124) or, more realistically, in terms of their respective solubilities in the two contrasting fluids (e.g., Smith, 1948; Yoder et al., 1957). Owing to limited solubilities of the relatively non-volatile constituents, the aqueous phase would be very dilute unless the pressure were in a geologically high or moderately high range, but actual concentrations at any one point in the system by no means would determine the role of this phase in effecting transfer of such constituents; differences in concentrations from part of the system to another can be quite another matter.” (p. 856)

“Considerable transfer of relatively non-volatile materials could be accomplished by large quantities of moving dilute fluid, or, much more likely in pegmatite systems, by diffusion of these materials through the fluid in response to compositional gradients. Grossly systematic thermal gradients are to be expected in cooling igneous bodies, and in pegmatite-forming systems they would be responsible for compositional gradients in the aqueous phase, if, for example, the concentrations of dissolved constituents in this phase were to vary with temperature or the rates of diffusion were significantly different for different constituents... It thus seems reasonable to regard the aqueous phase that separates from a cooling and crystallizing pegmatite magma as a powerful scouring agent and transporting medium, for it can, in effect, extract portions of various constituents from the much more viscous melt and it can serve as an avenue for ready movement of these constituents from one part of the system to another. Moreover, both the partitioning of materials between the two fluid phases and their movement through the aqueous fluid can be considerably different for different constituents.” (p. 856)

In this iteration, the model hinged upon the interconnected nature of an aqueous solution, not the buoyant ascent of bubbles, and upon thermal gradients to drive the mass transfer of ions to different temperature domains in which different assemblages of minerals become stable:

“Marked segregation on the scale of individual crystal groups is extended to larger and larger domains with increasing general migration of the nourishing constituents through the aqueous phase to some preferred part of the system prior to precipitation. Thus a more extended transfer of potassium relative to sodium through this phase, in response to a general temperature

gradient, can account for gross segregation of muscovite and perthite in the outer parts of numerous pegmatite bodies.” (p. 857)

In review of Jahns and Tuttle (1963), essay #8 of this series, I discussed some “*failed experiments*” that were highly significant to Jahns’ model. I noted that in those experiments, which were published by Tuttle and Bowen (1958), the separation of an albite-rich domain from an assemblage rich in quartz and “*an orthoclase component*” was in response to the thermal gradient imposed in those experiments. Jahns and Tuttle (1963) misinterpreted or misrepresented those results, such that the aqueous solution became the principal cause of the segregation of mineral assemblages, not the thermal gradients. Thus, Jahns and Burnham’s (1969) depiction of the aqueous solution as a “*powerful scouring agent*” is in reference to the transfer of potassium and silica to the cool end of an experimental vessel. This, and its consequent changes to the composition of melt in the footwall portion of pegmatites, were the underlying principles behind the model for paired pegmatite-aplite dikes (Jahns and Tuttle, 1963), which became Jahns’ (1982) generalized model for pegmatites. However, prior to the publication of Jahns and Tuttle (1963), Burnham and Jahns (1961) had already performed experiments that pertained to the fractionation of alkalis between melt and aqueous solution, and their results appeared in an abstract as:

“Certain aspects of the model for pegmatite crystallization proposed by Jahns and Burnham have been tested by experimentally determining the composition of the aqueous fluid in coexistence with natural pegmatites and synthetic granite mixtures in the P_{H_2O} - T range 2,000-10,000 bars and 550°-800 °C... The amount of material dissolved in the aqueous fluid ranges from 1.0 weight per cent at 2000 bars and 550 °C... Throughout this P - T range, the ratios of Na_2O and Li_2O to all anhydrous constituents are generally higher in the aqueous phase than in the coexisting, condensed phases, and the corresponding ratios for both K_2O and Al_2O_3 are lower.”

This is certainly one of Burnham’s most consequential experimental contributions to the model: an aqueous solution dissolves negligible quantities of melt solutes at moderate pressures, and the aqueous fluid extracts sodium from the melt over potassium, leaving that melt and its crystalline products richer in potassium. This is the opposite of the explanation given by Jahns and Tuttle (1963) and fostered again here in Jahns and Burnham (1969). Burnham and Nekvasil (1986) subsequently acknowledged that the ratio of potassium to sodium in an aqueous solution is approximately the same as in a coexisting granitic melt. Like Burnham and Jahns (1961), other sources of the data (presented in London, 2008) reported a slight enrichment of sodium over potassium in the aqueous solution. If this was Jahns’ model¹, then Burnham bought into it knowing that this fundamental precept of the model was invalidated by his experimental results.

*“Given sufficient time in the appropriate thermal range, local equilibration of crystals and the two fluids involves significant exchanges of materials and promotes the enlargement of crystals whose initial growth came directly from the melt. **Such progressive coarsening of crystal aggregates derived from silicate liquid in the presence of an aqueous phase has been observed by us in numerous experiments.**” (p. 859) [emphasis added in **bold**]*

This one sentence is the sole statement of experiments in which an aqueous solution fostered the growth of large crystals. There is no attribution, no presentation of data, and no explanation of how the conclusion was drawn from the results. A photo shown by Wyllie (1963), which was ascribed to Jahns (see essay #8), is likely one of these experiments. Wyllie (1963) attributed the separation of textural domains in that experiment to an impossible thermal gradient in the capsule (see essay #8). He might have been inferring the results of Tuttle's failed experiments that redistributed melt components in a thermal gradient.

Thermal Gradients

Jahns and Burnham (1969) made seven references to thermal gradients as a driving force for mass transfer, e.g.:

“Temperature-dependent compositional variations have been determined experimentally for feldspar-bearing natural and synthetic systems (e.g., Burnham and Tuttle, 1960; Burnham and Jahns, 1961; Orville, 1963), and the reality of material transport in an aqueous fluid coexisting with silicate glass, with feldspars, or with feldspars plus silicate melt has been shown in numerous experiments... (e.g.,... Tuttle and Bowen, 1958, p. 90-91).” (p. 856)

They noted the efficacy of thermal gradients to drive mass transport in experimental simulations, including the important work of Orville (1963) on the thermally-driven segregation of alkali feldspars, and they cited Tuttle and Bowen (1958) (see essay #8 of this series) but without discussion.

“Grossly systematic thermal gradients are to be expected in cooling igneous bodies,” (p. 856)

They were not explicit about the symmetry of those thermal gradients, but their reference to cooling igneous bodies conveyed an understanding that they cool from the outside inward. That would mean the pegmatite-forming dikes cool initially along both margins toward the center, as has been shown by numerical simulations (e.g., Chakoumakos and Lumpkin, 1991; London, 2008), creating “*grossly symmetrical thermal gradients*” from both sides of a dike. In reference to the “*failed experiments*” of Tuttle and Bowen (1958), and Orville's (1963) study of alkali feldspars, such thermal gradients, therefore, would foster the transport of potassium to the cooler margins of the pegmatite bodies, leaving the hotter centers enriched in albite. In steeply dipping pegmatite bodies, the zonation of feldspars is precisely the opposite (Cameron et al., 1949). In shallowly dipping layered pegmatites, the zonation of feldspars is asymmetric with respect to a thermal gradient that would be symmetrically cooler along both margins³. These conclusions might explain why Jahns (1982) diminished the role of thermal gradients and finally relied instead on the buoyancy-driven separation of aqueous solution from melt to create the vertical asymmetry of the feldspar assemblages.

The Jahns-Burnham Model (p. 856-862)

“The large crystals that characterize pegmatites are thought to have grown mainly through nourishment, via the aqueous phase, of relatively few nuclei with materials supplied from the magma, while much smaller crystals were developing directly from the silicate liquid. Although separation of constituents between the two fluids never is complete or even nearly so, a strong

tendency nonetheless exists for preferential development of common potash-bearing minerals via the aqueous phase and soda-bearing minerals from the melt during most stages in which both kinds of minerals are being formed. Quartz, in contrast, evidently can be formed simultaneously and in abundance from both fluids. Crystallization of lithium-bearing minerals, in systems containing substantial amounts of this element, appears to occur mainly from the aqueous phase, in general with formation of quartz and following the major crystallization of feldspars.” (p. 856)

“Appearance of the aqueous phase can be regarded as the most decisive step in the genesis of pegmatites, as it marks the beginning of fundamental changes in texture and distribution of the crystallizing materials. Coarse mineral aggregates with characteristically pegmatitic texture now are formed, and pronounced segregation of constituents within the system is now effective over a wide range of scales. Rock bodies with aplitic texture or with combinations of pegmatitic and aplitic textures also can be developed during this stage.” (p. 862)

The Jahns-Burnham model was a detailed visual image of a pegmatite-forming process. It rested upon five scientific hypotheses:

- (1) The point at which an aqueous solution exsolves from granitic melt marks the transition from granitic to pegmatitic textures.
- (2) As a corollary, granitic rocks that possess ordinary plutonic textures reflect their crystallization from a melt that is undersaturated with respect to an aqueous solution.
- (3) An aqueous solution that coexists intimately with a granitic liquid can accomplish the mass transfer of melt constituents that a melt cannot achieve.
- (4) An aqueous solution fosters the growth of a few large crystals, whereas crystals that precipitate directly from melt are finer-grained.
- (5) Vertical asymmetry of zones, where these exist, arise from the selective removal of potassium (or other constituents) from melt, and its transport upward through the buoyant ascent of water bubbles, or else in response to thermal gradients that might exist.

Jahns' approach to the matter was to convey in words the way he envisioned the interactions between silicate melt and aqueous solution and the consequences of crystallization from one or the other fluid. The question arises, where in Jahns' papers (1955; Jahns and Tuttle, 1963; Jahns and Burnham, 1969; Jahns, 1982) did he present field or experimental evidence, or refer to published works, that turned these five hypotheses into facts? Other than several abstracts, two of which pertained specifically to the liquidus relations of pegmatite compositions, Jahns and Burnham reported no other experimental results that pertained directly to Jahns' model except through comments such as the ones cited in this article, and in Jahns and Tuttle (1963).

Experiments as Simulations of Natural Processes

The most difficult aspect of using experimentation of the sort shown by Wyllie (1963) (see Figure 5 in essay #8 of this series) is to constrain the many variables such that the results can be unequivocally interpreted. In my opinion, that level of knowledge of cause and effect is never, ever, achieved in experiments. All one sees is the end result, not the means by which it was attained nor the sequence of events within the capsule, in all but a few contemporary experimental configurations. Wyllie's (1963) comment about the experiment that he attributed to Jahns is revealing:

“Jahns & Burnham (1958) embarked on an experimental programme, using natural samples in the presence of water under pressure, aimed at answering some of the controversial questions related to the origins and crystallization of pegmatites. This programme, which soon achieved spectacular success, is a fine example of how natural rock samples may yield useful experimental data despite the fact that the system is too complex to be treated theoretically in terms of the phase rule.”

In layman’s terms, Wyllie acknowledged that the scientific basis for understanding such experiments was inadequate, but that the results could be interpreted from intuition. It was Wyllie’s intuition that led him to attribute the experimental result to a thermal gradient in the capsule. That was not a fact that was derived or derivable from the experiment itself. Jahns (1982) took the same approach.

The pitfalls of petrologic experiments are many – especially those that attempt to simulate natural phenomena – and most geochemists fall into them blindly. I could cite numerous shortcomings, but one of my own illustrates the point. Since the beginning of Bowen’s experimental petrology in the 1920s, experimentalists have used finely milled and mixed powders of mineral, rock, glass, and other reagents in their experiments. The rationale was that fine homogeneous powders would react more quickly, and equilibrium (Bowen’s goal) would be achieved more quickly. In early work with the Macusani obsidian (London et al., 1989), I employed such powdered samples to study how a hydrous melt of that composition would crystallize in response to cooling (Figure 2a). Later, a student working on the granite system conducted similar experiments with powdered glass, but at my suggestion he also conducted some work with solid cores of the same glass. Replicate experiments with powder versus solid core consistently produced disparate results. As a result, I conducted a new set of experiments with the Macusani obsidian using solid glass cores (London and Morgan, 2017), and again, the results were fundamentally different from those with powder (Figures 2b,c). For example, starting with powder, the dry obsidian crystallized completely in hours, and crystallization ensued in undercooled melts that contained less than 4.5 wt% H₂O. With more than 4.5 wt% added water, the melts failed to crystallize at any combination of time and temperature. In the solid core experiments, the dry obsidian cores failed to crystallize at any conditions, but the more water that was added to the glass (including a pre-hydration step), the more crystallization ensued. Powder experiments, even those that crystallized extensively, failed to nucleate abundant water bubbles within the glass; the glasses sometimes contained a few vesicles that were formed by air that was trapped upon melting (Figure 2a). In these experiments, the crystallization occurred in clusters along the margin, with melt in contact with the surface of the precious metal tubing. In the solid core experiments, incipient crystallization formed a continuous border around the core, and numerous vapor bubbles were trapped along the growth front (Figure 2b). The solidification front in the solid-core experiments may have prevented the diffusion of H₂O out of the melt, and so fostered the nucleation of bubbles. For the powder results, H₂O may have diffused readily out of the melt into the space where it was in contact with the container tubing. However, that is a hypothesis, not a known fact.

Of the two methods, the one that used solid starting material more closely resembles the natural world (it is not a powder with entrapped air bubbles), and that is the method that, for now, should

be used. What it means is that all the work that was conducted with powdered starting material as a simulation of a natural process is farther from Nature, and mostly reflects the conditions imposed by the experimentalist.

After more than 270 experiments that attempted to crystallize the hydrous granite composition, I concluded that we had not produced results that were wholly intrinsic to the composition of the melt. By that, I mean that the products were a result of the experimental methods used, and as such, they were more anthropogenic than natural. For this reason, I have not published these results.

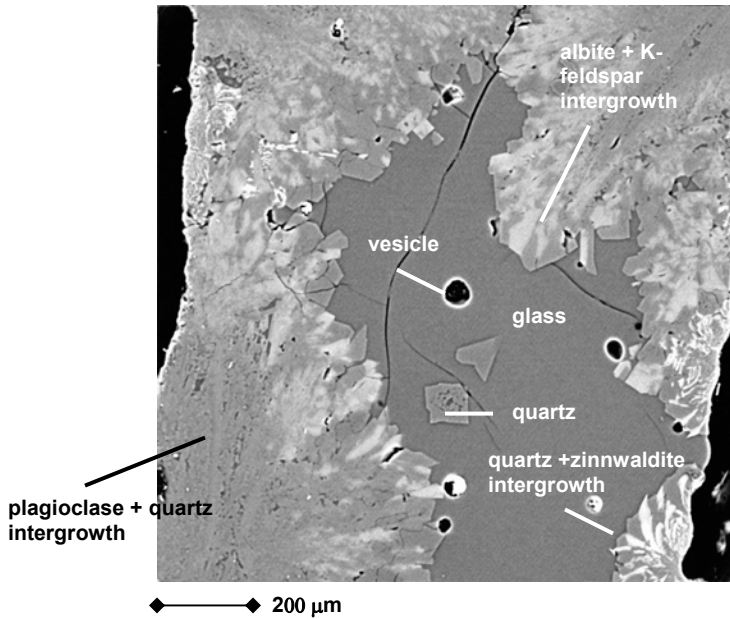


Figure 2a. Experiment MAC61 started with powder and 2.9 wt% H₂O, preheated to 800°C, run at 600°C for 336 hrs. The fine-grained crystalline margins contain trapped bits of glass. The main mass of glass contains a few vapor bubbles. From London et al. (1989).

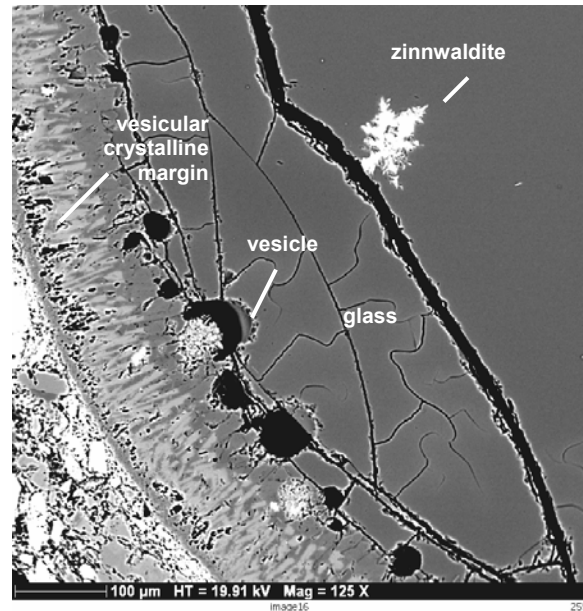


Figure 2b. Experiment MAC216 started with solid glass core and 9.8 wt% H₂O, preheated to 850°C, run at 500°C for 622 hrs. The fine-grained crystalline margins are vesicular; those vesicles represent aqueous solution. Aqueous bubbles formed in glass along the crystallization front. From London and Morgan (2017).

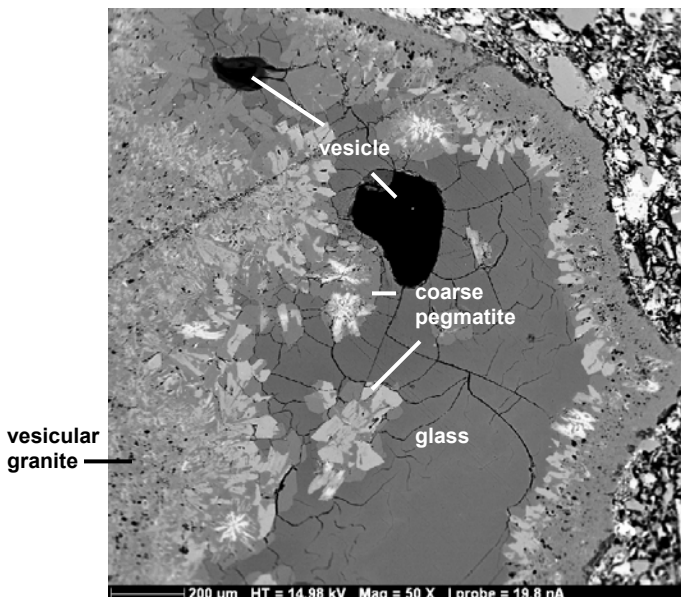


Figure 2c. Experiment MAC230 started with solid glass core and 5.4 wt% H₂O, preheated to 750°C, run at 500°C for 1512 hrs. The fine-grained crystalline margins and central portion of the charge are vesicular due to the exsolution of H₂O and its trapping as vesicles, but in this case those vesicles represent aqueous solution. Coarse crystallization along the margins of a melt pool produced coarsely crystalline minerals. Typical of most experiments, the large vapor bubbles in glass are not in contact with crystals. From London and Morgan (2017).

I contend that Jahns (1982) could not have uniquely associated the different textures in such an experiment to the selective effects of crystallization from melt (fine-grained) or from aqueous solution (coarse-grained, in glass), even if he had conducted that experiment. From the final result, he could not have known at what point in the crystallization of the charge that an aqueous solution formed, if it did form, when crystallization first commenced, and where. Yet, Jahns (1982) stated the explanation – supporting evidence for his model – as fact. Wyllie (1963) inferred an impossible thermal gradient in the experiment but presented it as fact. Jahns (1982) referred to such an experiment as singular, and it might have been the photograph published by Wyllie (1963). Here, in Jahns and Burnham (1969), they refer to “*observed by us in numerous experiments.*” (p. 859).

In the hundreds of undercooled experiments conducted in my laboratory, we have observed crystallization from aqueous solution and simultaneous crystallization from melt in a few cases. In general, the crystals formed from vapor are no larger in size than the last-formed crystals in the melt, and commonly much smaller in size. A backscattered image of a portion of experiment MAC230 (Figure 2c) is typical of the results. The initial crystallization from an undercooled melt produced fine-grained assemblages with an abundance of vesicles. This stage of crystallization was H₂O-saturated (it conforms to Bowen’s (1928) expectation that viscous silicate melts that crystallize rapidly will trap water as vesicles, as is characteristic of shallow-seated granites that are commonly designated as the A-types). In MAC230, the continued crystallization from the melt led to the coarsening of crystals as fluxes (boron and fluorine in particular) increased. The melt might have been saturated in H₂O at that stage, but the largest crystals grew in contact with melt, and not from an aqueous solution.

Spatially Heterogeneous Mineral Assemblages from a Homogeneous Magma

In reference to the segregation of minerals in pegmatites, Jahns and Burnham (1969) proposed a model in which the process of segregation was essentially, meaning necessarily, conveyed through an aqueous solution in response to gravitational or thermal gradients. As applied by Jahns and Tuttle (1963), that segregation resulted in paired sodic aplite along lower portions of pegmatites and K-feldspar rich pegmatite along the upper portions of a body, which was ascribed to the separation and buoyant ascent of aqueous bubbles through the pegmatite-forming melt. Jahns and Burnham (1969) made numerous but more general references to the selective transport of specific constituents to various parts of a pegmatite, citing thermal gradients as the driving force, but they did not develop either idea (selective transport, thermal gradients) further.

In London (2008), I proposed that the spatial zonation of mineral assemblages hinges more on where crystallization commences than on any relationship to the gravitational field, as Jahns and Burnham suggested. For example, approximately half of the layered pegmatites I have seen in San Diego County, California, have more K-feldspar along the footwall portion than along the hanging wall contact (see Chapter 8 of London, 2008). I have cited the upside-down zonation of the Hale pegmatite in Connecticut, and similar cases of aplitic zones along the hanging wall portion are described from the Wodgina-Marble Bar districts in Western Australia. Albite aplites in the Tanco pegmatite, Manitoba, occur along the footwall portion of the dike, but they also form floating and folded rafts of material that appear to have fallen from above, coming to rest on a substrate and contained within massive quartz (see Figure 7-4 of London, 2008).

It has only dawned on me recently that Uebel's (1977) depiction of a pegmatite in Africa conveyed the meaning that the development of zones is largely controlled by the thickness of a pegmatite body. Within a single pegmatite dike, the thicker the body, the more zones it possesses, and these are more fractionated than in the thinner segments of the dike, even if these thinner segments lie structurally above the bulge. Cameron et al. (1949) illustrated this relationship as a fundamental feature of zoned pegmatites. The ramifications of this observation are discussed elsewhere (e.g., London, 2014b, 2018), but what it means for the Jahns-Burnham model is that the zones of coarse potassic feldspar are not necessarily the apical zones in a pegmatite body. If present, they and the more fractionated assemblages are, however, located in the thickest portions of a body.

Černý and Lenton (1995) described the progressive fractionation along the length of a single subhorizontal pegmatite dike. They observed that by virtue of the dike's orientation, gravitational separation of a buoyant aqueous solution could have played no role.

In the experiments with solid cores of Macusani obsidian (London and Morgan, 2017), most experiments contained amphibolite added to one end, both ends, and surrounding the glass core. The intent was two-fold: one, to create a more natural contact with the melt (other than the precious metal tubing), and two, use the amphibolite as a trigger to initiate crystallization. Figure 3 is representative of the experiments in which amphibolite was added just to one end.

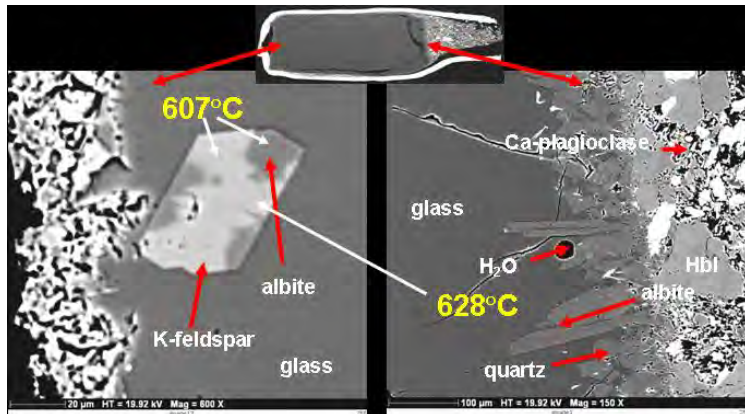
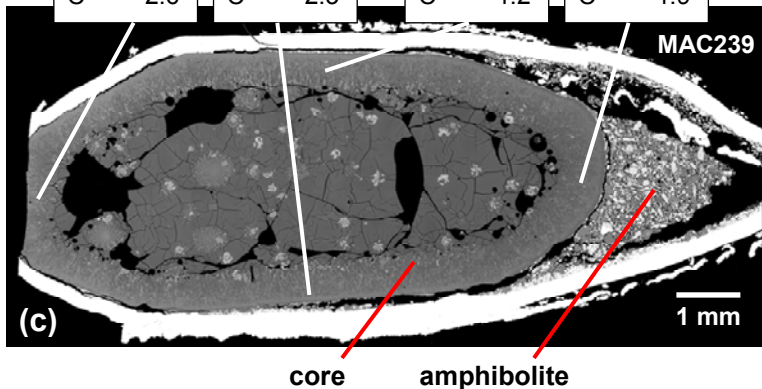


Figure 3a. Experiment MAC215 started with solid glass core and 10.1 wt% H₂O, preheated to 850°C, run at 600°C for 622 hrs. Traces of plagioclase crystallized against the amphibolite. A few crystals of zoned K-feldspar crystallized at the opposite end. Temperatures from feldspar thermometry are close to the equilibrium values. From London and Morgan (2017).

Qtz	24.6	Qtz	26.6	Qtz	21.6	Qtz	30.3
Or	36.3	Or	29.0	Or	30.1	Or	8.8
Ab	34.3	Ab	40.9	Ab	46.2	Ab	52.0
An	0.0	An	0.0	An	0.0	An	7.3
Hy	1.8	Hy	1.3	Hy	0.9	Hy	1.3
C	2.6	C	2.3	C	1.2	C	1.9

Figure 3b. Experiment MAC239 started with solid glass core and 9.8 wt% H₂O, preheated to 750°C, run at 550°C for 1440 hrs. The normative mineral compositions of the crystalline margins are indicated. At the end with amphibolite (right), the margin was rich in plagioclase of moderate anorthite content and quartz. Toward the opposite end, the anorthite content fell to zero, and the proportion of normative K-feldspar increased. From London and Morgan (2017).



In Figure 3a, crystallization had just commenced. A thin layer of plagioclase formed along the edge with amphibolite. K-feldspar crystallized simultaneously at the opposite end. The compositions of the two feldspars were close to their equilibrium values, as the temperatures reconstructed from their compositions closely approached the actual temperature of the experiments. Other nuances of this relationship are discussed in London and Morgan (2017). In Figure 3b, more advanced crystallization formed a complete crystallization front that surrounded the entire melt body, as do the outer zones of pegmatites. London and Morgan (2017) found that the finest-grained border consists of plagioclase plus quartz, which evolves into a K-feldspar richer inner zone. However, overall, the crystallization at one end in contact with amphibolite was dominated by plagioclase plus quartz. The anorthite content of the plagioclase fell off to zero away from this end. Experiments with no added amphibolite possessed the same high initial anorthite content of first-formed plagioclase (London et al., 1989). Therefore, the calcium content of the plagioclase was derived from the melt, and not due to contamination from the amphibolite. From the amphibolite end, the normative content of K-feldspar increased as plagioclase and quartz fell (Figure 3b). The experiments of Figure 3, therefore, generated complementary domains of plagioclase plus quartz adjacent to amphibolite and of K-feldspar at opposite end of the melt column, possibly analogous to opposite sides of a pegmatite dike, solely by the diffusion of alkalis through the melt, with no thermal gradient and no gravitational gradient. Both glasses were saturated in H₂O from the start, but vesiculation, when it occurred, was restricted to isolated bubbles along the crystallization front.

Figure 4 of MAC221 (5.0 wt% H₂O added) illustrates several pertinent features. In this experiment, which went no higher than 550°C, the glass core retained its original shape. That means that at that temperature, the core was sufficiently viscous as to be considered at least as a semi-solid. The composition of the Macusani obsidian is as rich in Li, B, P, and F as any pegmatite-forming melt is likely to be; its composition is close to that of the Tanco pegmatite (Stilling et al., 2006). Yet, whereas such high concentrations of fluxes may substantially reduce viscosity at high temperatures (e.g., Bartells et al., 2011), that effect diminishes rapidly at lower temperatures in the pegmatite-forming range. The chemical diffusion illustrated in Figure 3 above, therefore, occurred in a highly viscous, semi-solid medium. That viscous state of melt would likely apply to natural pegmatites as well, especially those that are less enriched in fluxes than the Macusani obsidian. Second, despite its high initial H₂O content and extensive crystallization, the melt did not vesiculate. Minute vesicles are present in the very fine-grained, crystalline interior portion of the charge, but not in the late-stage, coarsely crystalline domains in contact with the melt. Third, crystallization commenced along the borders inward and in the center outward. This pattern of crystallization, which occurred in multiple experiments, is an

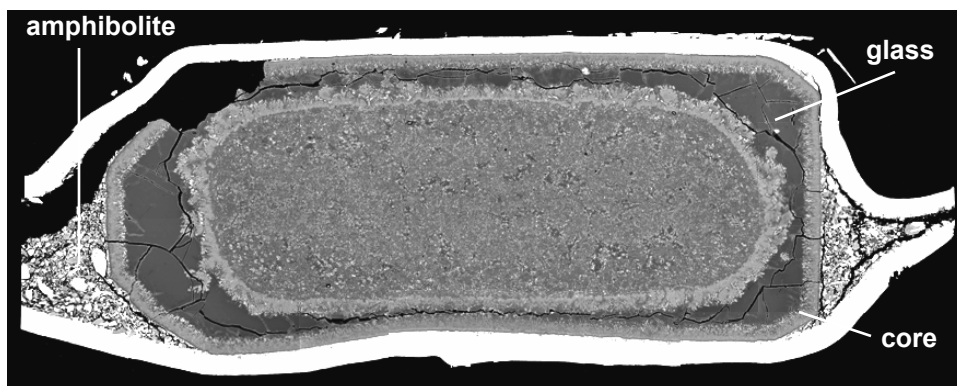


Figure 4. Backscattered electron image of experiment MAC 221, 5.0 wt% H₂O added, run to 550°C 740 hrs. From London and Morgan (2017).

1 mm

example of what I called the anthropogenic effect, the distinct result of the experimental configuration. In these examples, there is no temperature gradient across the entire melt volume. Experiments such as MAC215 indicated that crystallization began along the margins of the core. London and Morgan (2017) noted that crystallization produced a marked increase in the boron and H₂O content of the glass along the crystallization front (see Figure 10 of London and Morgan, 2017). Boron is a well known glass-forming flux, which has the effect of suppressing crystallization. Melt at the center of the core, at the same temperature, was not enriched in boron. London and Morgan (2017) proposed, therefore, that crystallization commenced simultaneously in the center and along the margins until the accumulation of fluxes like boron stalled the crystallization, leaving a moat of melt. Bear in mind that the distribution of boron in the resultant glass is known, but its contribution on the overall distribution of crystals and melt is a hypothesis.

In most of the solid-core experiments that initially contained > 5 wt% H₂O, the portions that crystallized immediately at the border, and in the central domains, were exceedingly fine-grained and vesicular. In the central crystalline domains, the assemblage was also sharply zoned (Figure 5). The central crystalline mass was dominated by plagioclase plus quartz. Potassic feldspar formed a fringe around the last pools of melt, which were almost filled with vermicular (wormy) quartz and minor topaz. The nearly pure quartz pods could be thought to resemble the quartz cores of pegmatites, similar overall to those pegmatites that form isolated segregations in granite. They have the appearance of having formed last, following the fringe of K-feldspar that rimmed the melt pools and projects into them. Bear in mind that this is a hypothesis, not a known fact.

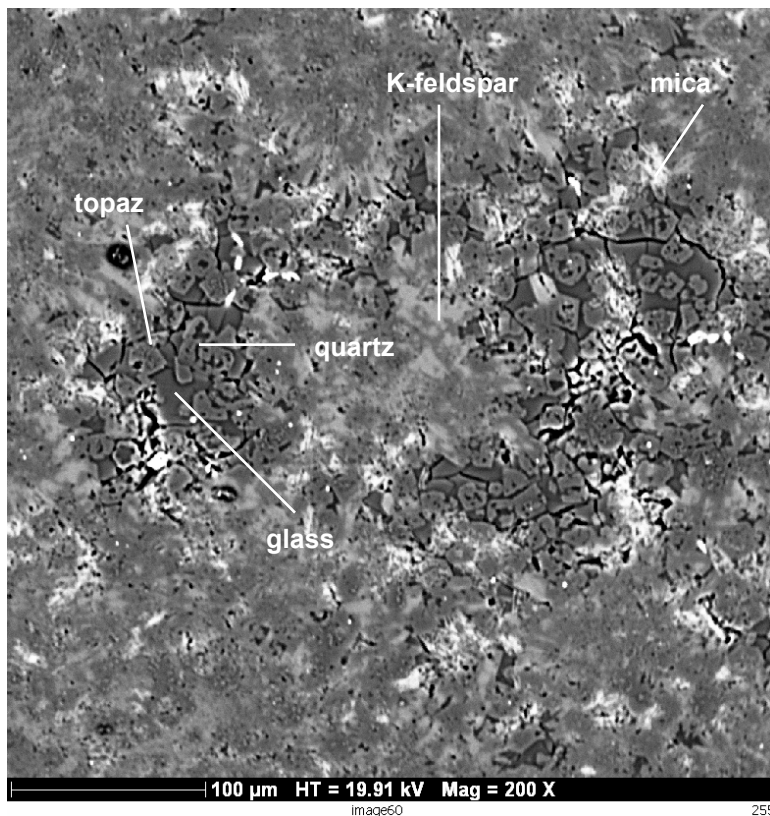


Figure 5. Backscattered electron image of experiment MAC 221, 5.0 wt% H₂O added, run to 550°C 740 hrs. From London and Morgan (2017).

Figure 6 shows a portion of experiment PEG46 (1.4 wt% H₂O, 575°C, 578 hr), one of the first with solid cores of the Macusani obsidian. Like MAC221, this experiment produced a crystalline border terminated by a fringe of inwardly directed K-feldspar in graphic intergrowth with quartz, and an exceedingly fine-grained, vesicular central crystalline domain with the same quartz-rich aggregates in the melt pools of MAC221. This experiment, however, produced an abundance of petalite, which was not found in any experiments with higher initial concentrations of added water. The petalite crystals formed a fringe along the edge of the central crystalline domain, together with graphic K-feldspar-quartz intergrowth. A notable feature of this experiment is that petalite formed an almost monomineralic aggregate along the crystallization front (with minor mica), bordered on each side by the graphic feldspar-quartz intergrowth. Here, then, is an example of what geochemists might call self-organization of a mineral assemblage from an otherwise homogeneous melt: the simultaneous crystallization of a petalite (mica) domain and a feldspar-quartz domain formed a mineral assemblage, but in spatially segregated regions, akin to pegmatite zones. Figures 3, 4, 5, and 6 illustrate examples of the spatial segregation of minerals, some of them monomineralic, that have no relationship to an aqueous solution. Many more examples using the Macusani obsidian, powdered and solid core, produced segregated mineral domains (e.g., see London et al., 1989, London and Morgan, 2017), but one more experiment warrants mention.

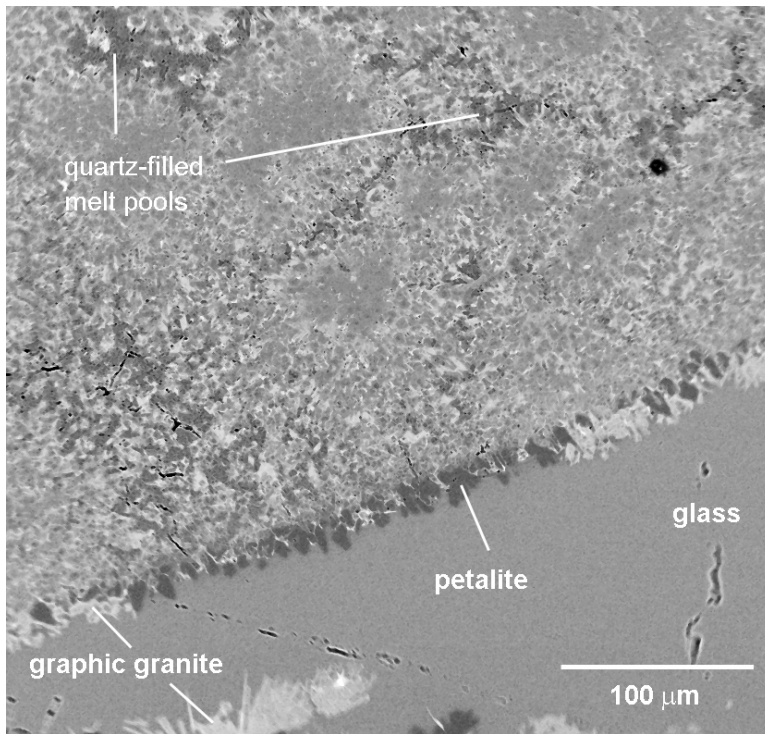


Figure 6. Backscattered electron image of PEG46 (1.4 wt% H₂O, 575°C, 578 hrs. From London and Morgan (2017).

Experiment PEG16 consisted of haplogranite glass powder ($Ab_{38.23}Or_{28.72}Qtz_{33.04}Crn_{0.01}$) with 3 wt% B₂O₃ glass and no water added other than adsorbed moisture (London, 1999). The experiment was conducted at 450°C and 200 MPa. Most of the experimental product consisted of a graphic intergrowth of feldspar and quartz (Figure 7). In the absence of calcium, K-feldspar is the first-formed feldspar (London and Morgan, 2017). In this experiment, a graphic intergrowth

of K-feldspar plus quartz formed radial aggregates from the margins. The normative quartz content of this intergrowth was below that of the bulk composition (as in the Little Three pegmatite, California: see London et al., 2012). The next inward zone was a texturally similar intergrowth with the same deficit of quartz, but with the proportions of K-feldspar and albite perfectly reversed. A third zone consisted of albite-dominant feldspar only, and that was followed inward by central masses of pure quartz. Another portion of the same experiment contained a finer-grained segment with alternating layers dominated by albite and by quartz, which resembled a layered aplite. Insofar as a single experiment could record the textures and mineralogical/chemical zonation that resemble a zoned pegmatite body, PEG16 was it. Whether or not that parallelism is valid, PEG16 demonstrated that many of the textural attributes of pegmatites (except miarolitic cavities), the oscillations of mineral compositions between zones (see Cameron et al., 1949), fine-grained layered oscillations that resemble line-rock, and pure quartz cores could be produced in a single experiment solely by the crystallization of melt in the absence of an aqueous solution.

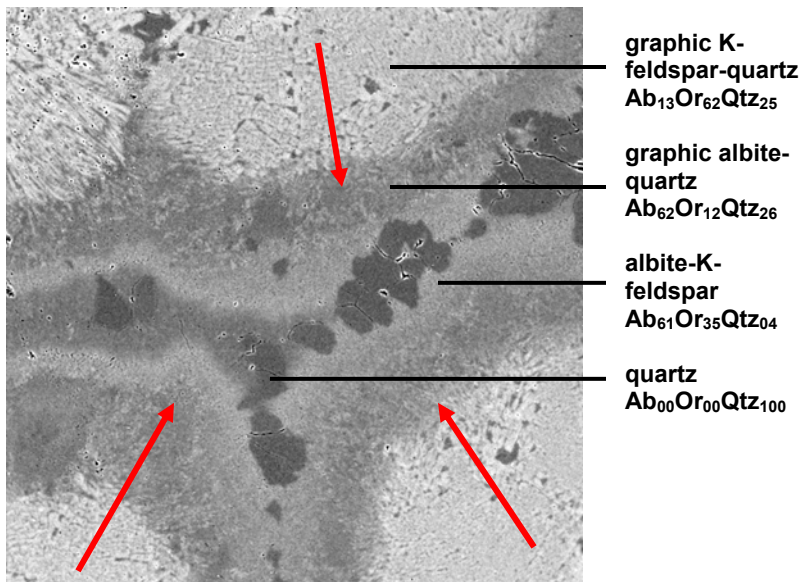
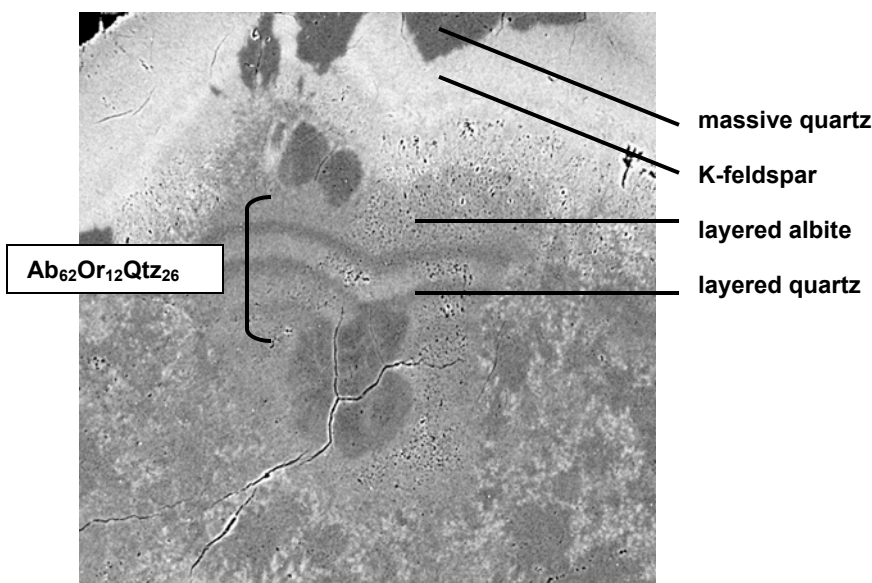


Figure 7. Backscattered electron images of experiment PEG-16, which consisted of haplogranite glass powder with 3 wt% B₂O₃ glass and no water added other than adsorbed moisture. The experiment was conducted at 450°C and 200 MPa. The red arrows show the direction of crystallization inward from margins to center. The compositions of individual zones are represented as their normative mineral proportions in terms of the weight percentages of albite (Ab), K-feldspar (Or), and quartz (Qtz).



These images illustrate what Jahns might have observed in “*numerous experiments*”, though the advent of backscattered electron imaging made those results more discernable. It appears questionable whether Jahns actually conducted experiments, or rather relied on others to convey the results to him. The directness of that contact matters. The experimentalist is the chef who envisions the dish, chooses the ingredients, and executes all the steps of technique to prepare it; the diner only knows the dish as it is brought to him in its final form.

In the absence of the voluminous knowledge that Jahns must have collected – some of it experimental from Tuttle and from Burnham – it is not possible to state whether the Jahns-Burnham model might be correct in its main conclusion, which is that an aqueous solution represents an essential feature of the pegmatite-forming process. For the most part, except for the rare presence of miarolitic cavities, the evidence that could affirm the presence of an aqueous solution is lacking (London, 2008). Jahns and Burnham (1969) presented experimental evidence that initially H₂O-undersaturated granitic melts should achieve saturation in an aqueous solution at some point in their crystallization. However, it can be said that Jahns did not provide the evidence that might have confirmed his pegmatite model beyond that point, and especially its validation through experiments. Jahns and Burnham (1969) should have been the publication in which that experimental evidence was presented in detail.

Jahns was, however, the first geoscientist to treat pegmatites as a whole system, which is the disciplinary field of petrology. By taking a holistic view of pegmatites, the model he constructed appeared to be internally consistent and comprehensive. It is the unifying effect of his ideas, right or wrong, that made his model so appealing for so many years.

References

- Acosta-Vigil, A., London, D., Morgan VI, G.B., Cesare, B., Buick, I., Hermann, J., and Bartoli, O. (2017) Primary crustal melt compositions: insights into the controls, mechanisms and timing of generation from kinetics experiments and melt inclusions. *Lithos*, **286**, 454–479.
- Bartels, A., Vetere, F., Holtz, F., Behrens, H., and Linnen, R.L. (2011) Viscosity of flux-rich pegmatitic melts. *Contributions to Mineralogy and Petrology*, **162**, 51–60.
- Bowen, N.L. (1928) The evolution of the igneous rocks. Princeton University Press, Princeton, NJ, 334 p.
- Burnham, C. W. (1964) Viscosity of a water-rich pegmatite melt at high pressures. (abstr) *Geological Society of America Special Paper*, **76**, 26.
- Burnham, C.W (1979) Magmas and hydrothermal fluids. In *Geochemistry of hydrothermal ore deposits*, 2nd ed. (Barnes, H.L, ed.). John Wiley and Sons, New York, 71-136.
- Burnham, C.W. and Jahns, R.H. (1958) The solubility of water in granitic magmas, (Part 1) of Experimental studies of pegmatite genesis. (abstr) *Geological Society of America Bulletin*, **69**, 1544-1545.

- Burnham, C. W., and Jahns, R. H. (1961) Experimental studies of pegmatite genesis: the composition of pegmatite fluids. (abstr) *Geological Society of America Special Paper*, **68**, 143-144.
- Burnham, C.W. and Jahns, R.H. (1962) A method for determining the solubility of water in silicate melts. *American Journal of Science*, **260**, 721-745.
- Cameron, E.N., Jahns, R.H., McNair, A.H., and Page, L.R. (1949) Internal structure of granitic pegmatites. *Economic Geology Monograph*, **2**, 115 p.
- Černý, P. and Lenton, P.G. (1995) The Buck and Pegli lithium deposits, southeastern Manitoba: the problem of updip fractionation in subhorizontal pegmatite sheets. *Economic Geology*, **90**, 658–675.
- Chakoumakos, B.C., Lumpkin, G.R. (1990) Pressure-temperature constraints on the crystallization of the Harding pegmatite, Taos County, New Mexico. *Canadian Mineralogist*, **28**, 287-298.
- Goranson, R.W. (1931) The solubility of water in granite magmas. *American Journal of Science*, **22**, 481-502.
- Ildefonse, J.P., Jambon, A., Carron, J.P., Delbove, F., and Gabis, V. (1979) La diffusion chimique dans les solutions hydrothermales et dans les verres et magmas silicatés. *Mémoires de la Société géologique de France*, **53**, 81-85.
- Jahns, R.H. (1955) The study of pegmatites. *Economic Geology, 50th Anniversary Volume*, 1025-1130.
- Jahns, R.H. (1982) Internal evolution of pegmatite bodies. In: Černý, P. (Ed.) *Granitic Pegmatites in Science and Industry. Mineralogical Association of Canada Short Course Handbook*, **8**, 293-327.
- Jahns, R.H. and Burnham, C.W. (1957) Preliminary results from melting and crystallization of Harding New Mexico pegmatite. (abstr.) *Geological Society of America Bulletin*, **68**, 1751-1752.
- Jahns, R.H. and Burnham, C.W. (1958) Melting and crystallization of granite and pegmatite, (Part 2) of experimental studies of pegmatite genesis. (abstr) *Geological Society of America Bulletin*, **69**, 1592-1593.
- Jahns, R.H. and Tuttle, O.F. (1963) Layered pegmatite-aplite intrusives. *Mineralogical Society of America Special Paper*, **1**, 78-92.
- London, D. (1999) Melt boundary layers and the growth of pegmatitic textures. (abstr.) *Canadian Mineralogist*, **37**, 826-827.
- London, D. (2008) Pegmatites. *Canadian Mineralogist Special Publication* **10**, 347 p.

- London, D. (2009) The origin of primary textures in granitic pegmatites. *Canadian Mineralogist*, **47**, 697-724.
- London, D. (2014a) Subsolidus isothermal fractional crystallization. *American Mineralogist*, **99**, 543-546.
- London, D. (2014) A petrologic assessment of internal zonation in granitic pegmatites. *Lithos*, **184-187**, 74-104.
- London, D. (2018b) Ore-forming processes within granitic pegmatites. *Ore Geology Reviews*, **101**, 349-383
- London, D., Hunt, L.E., Schwing, C.R., and Guttery, B.M. (2019) Feldspar thermometry in pegmatites: truth and consequences. *Contributions to Mineralogy and Petrology*, **175**, <https://doi.org/10.1007/s00410-019-1617-z>.
- London, D. and Morgan, G.B. VI (2017) Experimental crystallization of the Macusani obsidian, with applications to lithium-rich granitic pegmatites. *Journal of Petrology*, **58**, 1005–1030.
- London, D., Morgan, G.B. VI, and Acosta-Vigil, A. (2012) Experimental simulations of anatexis and assimilation involving metapelite and granitic melt. *Lithos*, **153**, 292–307.
- London, D., Morgan, G.B., VI, and Hervig, R.L. (1989) Vapor-undersaturated experiments in the system macusanite-H₂O at 200 MPa, and the internal differentiation of granitic pegmatites. *Contributions to Mineralogy and Petrology*, **102**, 1-17.
- Luth, W.C., Jahns, R.H., and Tuttle, O.F. (1964) The granite system at pressures of 4 to 10 kilobars. *Journal of Geophysical Research*, **69**, 759-773
- Morgan, G.B. VI, Acosta-Vigil, A., and London, D. (2008) Diffusive equilibration between hydrous metaluminous-peraluminous liquid couples at 200 MPa (H₂O), and alkali transport in granitic liquids. *Contributions to Mineralogy and Petrology*, **155**, 257-269.
- Orville, P.M. (1963) Alkali ion exchange between vapor and feldspar phases. *American Journal of Science*, **261**, 201-237.
- Stilling, A., Černý, P., and Vanstone, P.J. (2006) The Tanco pegmatite at Bernic Lake, Manitoba. XVI. Zonal and bulk compositions and their petrogenetic significance. *Canadian Mineralogist*, **44**, 599-623.
- Tuttle, O.F. and Bowen, N.L. (1958) Origin of granite in the light of experimental studies in the system NaAlSi₃O₈-KAlSi₃O₈-SiO₂-H₂O. *Geological Society of America Memoir*, **74**, 153 p.
- Uebel, P.-J. (1977) Internal structure of pegmatites, its origin and nomenclature. *Neues Jahrbuch für Mineralogie Abhandlungen*, **131**, 83–113.

Wright, L.A. (1985) Memorial to Richard H. Jahns, 1915-1983. *Memorials, Geological Society of America*, **15**, 1-10.

Wyllie, P.J. (1963) Applications of high pressure studies to the earth sciences. In *High Pressure Physics and Chemistry* (Bradley, R.S., ed.), Academic Press, New York, 2, 1-89.

Footnotes

¹ In a memorial to Dick Jahns, Wright (1985) wrote: “... *Dick could periodically escape to Wayne Burnham’s laboratory and with him test experimentally Dick’s previously conceived model for pegmatite genesis.*”

² In the abstract, the authors noted that sanidine transformed to perthite (albite-K-feldspar intergrowth) in as little as three days at the conditions of the experiments. This rate is many orders of magnitude faster than estimates from other sources, but it is in line with contemporary cooling models for pegmatites.

³ The sequential and spatial crystallization of the feldspars, the trends of decreasing anorthite content of albite inward from margin to center, and the precipitation of increasing amounts of quartz inward have been explained as the result of undercooling of the pegmatite-forming melt (London, 2014a,b).