

## Jahns and Tuttle (1963): Layered Pegmatite-Aplite Intrusives

David London (dlondon1@memphis.edu)

August 3, 2021

For most people who study pegmatites, the article by Jahns and Burnham (1969) was the touchstone of their model, which has prevailed in all thoughts about pegmatites and granites for over half a century. The real foundation of that model was laid by Bowen (1933), who speculated on the likely importance of resurgent boiling – the exsolution of an aqueous solution upon crystallization of a granitic melt – to the chemical transport and fractionation of constituents that form pegmatite “veins”. Jahns (1955) built upon Bowen’s ideas to develop his own applications of the concept (see essay #6 of this series) with reference to three of his own manuscripts that were cited as “*in preparation*”, but which were never published.

This essay examines Jahns and Tuttle (1963), a paper that presents analyses and a discussion of layered aplite-pegmatite dikes. Five new analyses and four previously published established that sodic aplites and potassic pegmatites were complementary portions of pegmatite-forming melts whose compositions plot close to the thermal minimum of the hydrous granite system. The paper carries a very brief statement about an experimental confirmation of what became subsequently known as the Jahns-Burnham model. Those experiments appear to be attributed to Jahns and Burnham (1963), another of Jahns’ citations to an unpublished manuscript. The experiments that profoundly shaped Jahns’ thinking, however, were conducted by Frank Tuttle and published in Tuttle and Bowen (1958).

### Overview

Following the comprehensive publication, *The Study of Pegmatites* (Jahns, 1955), the Jahns and Tuttle (1963) publication was Dick Jahns’ next major contribution. O.F. “Frank” Tuttle became Jahns’ colleague while Jahns was on sabbatical leave at Pennsylvania State University from the California Institute of Technology. Tuttle was an experimental geochemist who devised the early machines<sup>1</sup> and methods of achieving high fluid pressures at high temperatures, thereby enabling investigations of the effects of H<sub>2</sub>O on the silicate liquids derived from rock-forming systems under pressure. One might presume that Jahns and Tuttle (1963) would be largely a presentation of Tuttle’s experimental data. None is presented, at least not in the conventional way of scientific publication, and that brief discussion of experimental results is not attributed to Tuttle. The only new data in the paper were whole-rock analyses of five pegmatites in addition to a handful of line drawings and photos of pegmatitic and aplitic textures.

Jahns and Tuttle (1963) began by distinguishing occurrences of igneous rocks of granitic composition with the textures of aplite (very fine-grained granular texture) and pegmatite (variable but very coarse texture). Aplites occur without pegmatites and pegmatites without aplites. Aplites cut pegmatites and pegmatites cut aplites. Some dikes have pegmatitic margins and aplitic centers, or aplitic margins and pegmatitic centers. However, it was the layered structure of subhorizontal pegmatite dikes, such as those that Jahns encountered in southern California, that contain lower aplitic and upper pegmatitic parts that was the focus of this article, and which became the generalized model of all pegmatites for Jahns.

*“The following generalizations concerning individual pegmatite-aplite bodies have been drawn mainly from the writers’ studies of occurrences in New England, the southern Appalachian region, Minnesota, Missouri, Texas, the Black Hills region, the Rocky Mountain region from Montana to New Mexico, southern Nevada and western Arizona, and southern California and adjacent parts of Mexico.”* (Jahns and Tuttle, 1963, p. 81)

Jahns’ use of the plural form “*writers*” is notable. Tuttle was not a participant in the WWII field study of the pegmatite districts to which Jahns was referring. He was a lab man, an experimental and numerical geochemist. His bibliography contains no published works pertaining to pegmatites or even to field geology. Tuttle might have visited pegmatite-aplite dikes in San Diego County with Jahns, but nothing in his record hints at a field knowledge of pegmatites as broad and comprehensive as “*writers’ studies*” implies.

Cameron et al. (1949) scarcely noted aplites as any significant part of the geology of pegmatites in most of the districts cited by Jahns because paired pegmatite-aplite dikes are almost unknown in these districts (also confirmed from my own field studies). At one prominent occurrence of layered aplite and pegmatite, the Hale quarry, Portland, Connecticut, the aplite is along the hanging wall of the dike, and the pegmatite is on the footwall.

### **Compositions of Aplites and Pegmatites**

There are good reasons why few accurate analyses of pegmatites have been published. Exposures are rarely sufficient to fully encompass the spatial variations that are evident in zoned dikes. The coarse crystal size of pegmatites requires huge samples to be representative of some individual zones. By contrast, aplites are amenable to bulk analysis owing to their fine grain size and more uniform textures, whether massive or layered. Jahns and Tuttle (1963) contributed five new bulk analyses of pegmatites, and included four others reported previously by Orville (1960) and Simpson (1960). Jahns and Tuttle (1963) gave no details as to the methods used to calculate these bulk compositions, though Jahns (1953b)(see essay #5 of this series) expounded on procedures used at another time and place. The nine analyses in total were plotted on a normative quartz-albite-orthoclase diagram in three parts: a lower aplitic portion, an upper pegmatitic portion, and a weighted average of the two parts as a composite bulk composition (Figure 10 and table, pp. 88-89 of Jahns and Tuttle, 1963). Jahns and Tuttle (1963) stressed the close approximation of those composite compositions to that of H<sub>2</sub>O-saturated granitic liquid at its minimum or eutectic as determined by Tuttle and Bowen (1958). A few years later, Norton (1966) would publish a summary of normative chemical plots of 1,803 pegmatites from two districts in Colorado, the majority of which (to the 70<sup>th</sup> percentile) girdle the minimum composition of granite. These analyses were important: they established a granitic composition of pegmatites that was consistent with an igneous origin similar to that of granites. The key point for Jahns and Tuttle (1963), however, was that albitic footwall aplites and potassic hanging wall pegmatites in their data set were complementary portions of a granitic liquid that crystallized with highly disparate textures and in a systematic spatial relationship to one another.

Jahns and Tuttle (1963) distinguished aplites whose compositions are close to that of granite, and aplites whose compositions are markedly sodic:

*“The present writers regard all the aplitic rocks discussed in this paper as derivatives of magmas that were pegmatitic, i.e., that contained substantial amounts of dissolved water or other volatile constituents. However, quite different processes are thought to account for two contrasting types among these aplites:*

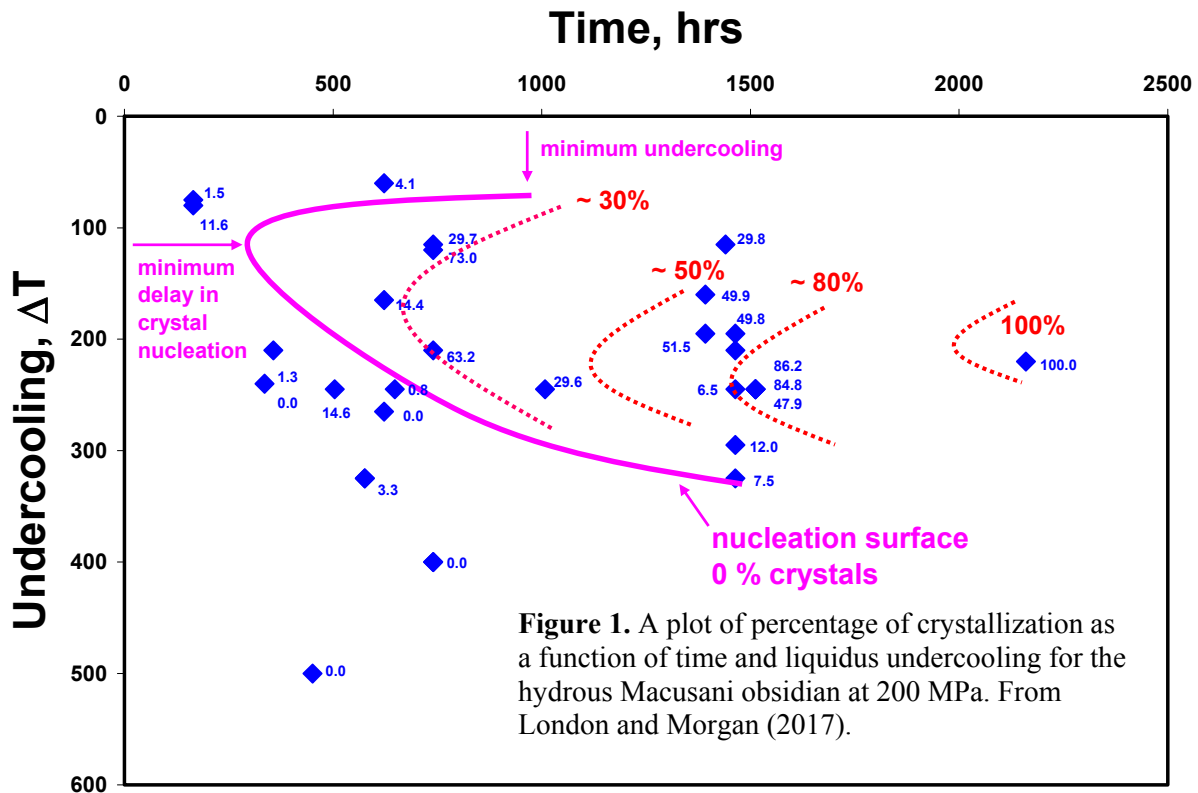
- 1. Normal aplites, with compositions near the "granite minimum," that occur as separate bodies containing little or no pegmatite and that also form distinct masses within some bodies of pegmatite.*
- 2. Sodic aplites that form separate bodies containing abundant megacrysts or pegmatite and that also occur as segregated masses within many bodies of pegmatite. Gradations between these types of aplite and among these modes of occurrence are common, and they probably reflect combinations of the processes outlined below. It is suggested that the normal aplites were formed from magmas, including rest-magmas in pegmatite systems, that incurred substantial losses of dissolved volatiles through reduction in confining pressure. This is thought to have occurred either during or after emplacement, as argued by Emmons (1940, pp. 5-8). Prior to any loss of volatiles, the liquidus temperatures of such pegmatitic magmas would be relatively low, say in the range 600°-680° C., at moderate to high confining pressures. If a magma in this temperature range were to lose volatiles through a drop in confining pressure, its liquidus temperature would rise in quick response and crystallization in flood necessarily would follow, regardless of any change in viscosity. The aplite thus formed would be a quenched rock, but in this instance the result of a "pressure quench." The sodic aplites, together with their complementary pegmatites or perthite megacrysts, constitute bodies whose bulk composition trends toward correspondence with the thermal valley of petrogeny's residua system. These rocks evidently were developed by processes of segregation, and their genesis can be explained in terms of the model proposed by Jahns and Burnham (1963) for the crystallization of granitic pegmatites. According to this model, segregation of major alkalies can occur in significant degree if a pegmatitic magma becomes saturated with volatile constituents, i.e., if both silicate melt and vapor are present in the system. Experimental evidence indicates that potassium is extracted from the liquid by a vapor in preference to [sic] sodium, and that potassium and other constituents can travel rapidly through the vapor in response to a temperature gradient. If the composition of the magma were at or near the thermal minimum for the confining pressure imposed upon it, preferential loss of the potassium feldspar component would promote crystallization of albite-rich rock from the melt, probably in the form of an aplite. Potash feldspar could crystallize from the vapor, either in the immediate vicinity or elsewhere in the system.” (p. 89-90)*

### **Normal Aplites**

Students of geology are taught that the crystal sizes of igneous rocks are functions of the rate of cooling of their melts: fast cooling promotes fine-grained rocks, slow cooling leads to coarsely crystalline textures. This relationship holds to an extent, but it is not inviolate. There is no simple relationship between the rate of cooling and the numbers of crystals that form in response to cooling (Swanson, 1977, Fenn, 1977). Consider two igneous rocks of equal volume and identical mineralogy and composition, one fine-grained and the other coarse. The sizes of their crystals are different, but the crystal sizes are determined by the numbers of crystals that nucleate in the volume. The more crystals that nucleate and compete for space and for the liquid components from which they grow, the smaller each crystal can grow. Thus, it is the number of crystals that nucleate per unit volume of melt that determines the sizes of individual crystals, not the other

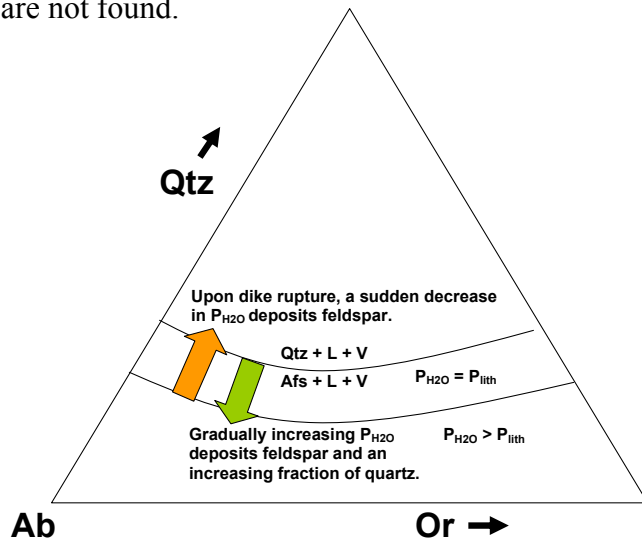
way around. Objectively, the two rocks reveal different crystal sizes as a result of the numbers of crystals, but say nothing about the conditions of crystallization.

Figure 1 is a time-temperature plot of the first appearance and volumetric abundance of crystals in experiments in which a hydrous melt formed from the Macusani obsidian was cooled below its liquidus temperature (a value of zero on the axis of undercooling). The region above the magenta curve (zero percentage of crystallization), labeled “minimum undercooling”, is the amount of undercooling necessary to initiate crystallization. Above that curve, no crystallization will occur no matter the rate of cooling nor the length of time in that state, as the magenta curve becomes asymptotic to time. The area beneath the magenta curve is a field in which no crystallization occurred, despite the fact of rapid and appreciable undercooling, because of the high viscosity of the melt and its transformation to glass at these low temperatures. Consequently, there would be no crystallization if the liquid was held at a temperature close to its liquidus with very slow cooling, and no immediate crystallization of the melt when cooled very rapidly by hundreds of degrees below its liquidus. In between those two extremes, crystals would nucleate and grow.



To make the point further, some of the examples cited by Jahns (1955) and Jahns and Tuttle (1963) and illustrated in Chapter 8 of London (2008) show pegmatites in which exceedingly large megacrysts of K-feldspar-quartz intergrowths formed a crystallization front with an interstitial matrix of granitic to aplitic rock dominated by albite plus quartz. These minerals crystallized simultaneously, under the same regime of cooling, with radically different numbers of crystals of each mineral per unit volume.

Jahns and Tuttle (1963) envisioned that a sudden drop in H<sub>2</sub>O pressure on the melt that was crystallizing a granitic assemblage would cause that melt to be highly undercooled and to precipitate a fine-grained rock of granitic composition, what they refer to a normal aplites. There are two problems with Jahns' hypothesis of a "pressure quench". One, at elevated pressures corresponding to the depths of pegmatite formation (6-9 km, 2 to 3 kilobars), the surrounding rocks can sustain ~ 50 to 100 bars of overpressure by an aqueous solution before they rupture and release that overpressure (Candela and Blevin, 1995). From the work of Tuttle and Bowen (1958), a change of pressure upward by 50 to 100 bars corresponds to a shift of the liquidus (crystallization) temperature of only ~ 5°C, which is not enough to induce any change in the crystallization response of the melt. Two, the sudden loss of H<sub>2</sub>O pressure would not yield a rock of uniformly granitic composition; rather, it would produce a rock composed almost solely of feldspar. Figure 2, from London (2008) and constructed with data from Tuttle and Bowen (1958), illustrates why this is so. As H<sub>2</sub>O fluid pressure increases with crystallization, the composition of the crystalline assemblage gradually changes to become richer in quartz as the liquid composition is enriched in feldspar-forming components (in the direction of the green arrow). With a sudden drop in H<sub>2</sub>O fluid pressure, the melt is undercooled in the field of feldspar, and feldspar only crystallizes until an equilibrium that includes quartz is once again attained (orange arrow). The aplitic rocks so formed, therefore, should be composed almost solely of plagioclase and K-feldspar in their proportion in the melt. Aplites of such composition are not found.



**Figure 2.** A schematic illustration of the effect of increasing and suddenly decreasing H<sub>2</sub>O fluid pressure on the crystallization of granitic liquid. The tail of the green arrow corresponds to a state in which quartz and feldspars crystallized from a liquid that is (over)saturated in H<sub>2</sub>O at lithostatic (rock) pressure. The point of the green arrow shows the liquid composition at higher H<sub>2</sub>O pressure. With sudden loss of H<sub>2</sub>O pressure, the quartz-feldspar phase boundary (black curve) shifts back to its original location with the precipitation of feldspars only.



**Figure 3.** Surface exposure of the San Diego pegmatite, Mesa Grande district, San Diego County, California. The scale bar at center is in centimeters and inches.

## Sodic Aplites

The key dictate of the Jahns model relates to the complementary compositions of albite-rich aplite in the footwall portion of the body and upper pegmatitic units rich in potassic feldspar, as portrayed in the Himalaya mine, Mesa Grande, California (Figure 4 of Jahns and Tuttle, 1963). In the same pegmatite dike exposed elsewhere (San Diego mine property, down dip from the Himalaya mine) a layered footwall aplite of unknown composition except for its well defined bands of feldspar and quartz is overlain by megacrystic K-feldspar, and the hanging wall zone is plagioclase-quartz-tourmaline with little else (Figure 3). Such is the nature of pegmatites that their zonation can vary substantially along their strike as well as across it.

In many of the thin subhorizontal dikes that Jahns studied in southern California, the aplitic portion lies well above the footwall contact. An intervening wall zone rich in K-feldspar lies beneath the aplitic section (see dike sections in Chapters 8 and 17 of London, 2008). The same relations hold for the Tanco pegmatite, Manitoba, where gigantic crystals of K-feldspar and skeletal quartz crystals with albitic matrix grew up from the footwall over ~ 5-10 meters, and are overlain inward by layered sodic aplite followed upward by coarse pegmatite (Figure 4).



**Figure 4.** Two views of the footwall portion of the Tanco pegmatite, Manitoba. Left: branching gigantic crystals of K-feldspar point upward from the footwall contact of the dike, along with gigantic skeletal crystals of quartz with fine-grained albite matrix. Layered aplite lies at the top. FOV is ~ 5 meters across. Right: the top of a giant skeletal quartz crystal is truncated by an overlying drape of sodic layered aplite. A white fringe of Cs-beryl separates the aplite from an overlying quartz core pod. FOV is ~ 4 meters across.

The relationships illustrated by Jahns and Tuttle (1963), therefore, are selective among a wider range of variations in the zonal assembly of composite aplite-pegmatite bodies. The passage cited on p. 90 contains this phrase in reference to the paired sodic aplite – potassic pegmatite:

*‘...and their genesis can be explained in terms of the model proposed by Jahns and Burnham (1963) for the crystallization of granitic pegmatites.’*

The word “*proposed*” is past-tense, meaning that the ideas and their presentation have been published as Jahns and Burnham (1963). Yet, the citation to Jahns and Burnham (1963) is this:

*“Jahns, R.H. and Burnham, C.W. (1963) Experimental studies of pegmatite genesis. I. A model for the crystallization of granitic pegmatites (in preparation).”*

This would be the fourth time that Jahns cited evidence in articles as if they were published when in fact they were not. Jahns (1955) cited three fictitious publications on multiple occasions to imply that the opinions he was expressing were grounded in facts that would soon be published. Jahns’ use of unpublished manuscripts as citations in a list of references is unprecedented to my knowledge, and not in keeping with editorial expectations of the time (see the discussion in essay #6 of this series).

### **The Jahns-Burnham Experimental Model**

*“Experimental evidence indicates that potassium is extracted from the liquid by a vapor in preference to to [sic] sodium, and that potassium and other constituents can travel rapidly through the vapor in response to a temperature gradient.”*(Jahns and Tuttle, 1963, p. 90)

This is first the statement of experimental evidence that supported the Jahns-Burnham model. It references no source. Regarding the utility of experimental investigations to his understanding of pegmatites, Jahns conveyed his opinion to me in a conversation at a professional meeting in 1979 in San Diego, California. Jahns said:

*“All I ever learned about pegmatites from experiments was from experiments that failed.”*

He went on to describe some experiments in which the normally sealed capsules had leaked, and their constituents were redistributed along the length of the water-pressurized reaction vessel spanning a gradient of several hundred degrees along its length. When I first published this personal communication, in London (2005), reviewers and editors took me to task about the inappropriateness of this comment, as if my personal communication was demeaning to Jahns, who was no longer alive to defend himself. It was published because it was true, and because I convinced skeptics that Jahns meant for me to make it known. As Jahns explained it to me, the “*failed experiments*” were highly useful and significant to his understanding of the pegmatite-forming process.

Jahns’ personal comment next appeared in my book, *Pegmatites* (2008). Robert Martin, as editor of my manuscript and as a former PhD student of Jahns, pointed out to me that the “*failed experiments*” to which Jahns referred were actually performed by Tuttle, and they are described in Tuttle and Bowen (1958, p. 89-91). This revelation might explain why Tuttle was a co-author on Jahns and Tuttle (1963): it was his experimental work that was cited on pages 89-90 of their article, not work by C. Wayne Burnham. It leaves unexplained (1) why the experiments appear to be attributed to Jahns and Burnham (1963), not Tuttle and Bowen (1958); (2) why such important the experiments were not discussed in more detail in this paper; (3) why Tuttle was not explicitly included in the Jahns-Burnham (1963) pegmatite model.

Burnham's role in the development of an experimental model for pegmatites remained unclear, at least to this point of his collaboration with Jahns. He published an important experimental study with Jahns (Burnham and Jahns, 1962), in which the solubility of H<sub>2</sub>O in albitic melt was calibrated, and which revealed a wide miscibility gap in the compositions of coexisting aqueous solution and hydrous melt (meaning, the coexisting fluids possess widely disparate compositions). The work provided further credence to Jahns' proposal (actually, Bowen's (1933) proposal, see essay #6 of this series) that resurgent boiling might be the underlying process in the internal differentiation of pegmatites. David Vaughan, one of Burnham's graduate students, conducted melting experiments on two pegmatitic crystalline compositions – that of Spruce Pine, North Carolina, and the Harding pegmatite, Dixon, New Mexico – that appeared in his unpublished Master's thesis (1963), and in various other subsequent publications by Burnham and others. The experimental results first appeared in an abstract by Jahns and Burnham (1957). Another Burnham student, Attila Kilinc (1969), performed melting experiments for his PhD; some of these unpublished experiments revealed that K is not preferentially partitioned over Na into an aqueous solution that is equilibrated with granitic melt, as Jahns' deduced from the "failed experiments." In their definitive statement of the Jahns-Burnham model, Burnham and Nekvasil (1986) cited the investigations by Vaughan (1963) and by Kilinc (1969), but they were the only ones coming from Burnham's laboratory that were directly associated with the study of pegmatites.

Wyllie (1963) published the only visual representation of an experiment that was credited to Jahns and Burnham (Figure 5). The photo in Wyllie (1963) shows a texturally and spatially zoned experimental result of glass plus crystals. Of that photo, Wyllie (1963) stated:

*"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."*



**Figure 5.** From Wyllie (1963). The experimental product is described as 1/2 inch across its narrow dimension.

Wyllie (1963) ascribed the textural heterogeneity of the charge to a thermal gradient across the narrow dimension of the capsule, but such a gradient was not possible. By the experimental methods that were in use then, which employed helically wound furnace elements surrounding a cylindrical furnace core tube, thermal gradients might occur along the length of capsules, but not across their narrow dimension. Also, if Burnham had conducted such an experiment, he would



not have tolerated a thermal gradient in his equipment, as he was steadfastly seeking an equilibrium state in his experiments. In an email to me dated 17 February 2008, in which I requested Wyllie's permission to use the photo of the experiment, Peter replied:

*“Dear David:*

*I'm delighted that you're bringing out a book on pegmatites, and delighted that you can "save" Dick Jahn's [sic] experiment... Pete”*

Jahns (1982) cited this critical experiment as well, though he did not take credit for it. His interpretation of the textural domains in that experiment was that the fine-grained portion of the charge crystallized from melt, but the coarsely crystalline portion embedded in glass crystallized from aqueous vapor. No vapor space is evident in the photo of the experiment. It is almost certain that neither Wyllie (1963) nor Jahns (1982) correctly identified the cause of the textures.

Finally, there is this excerpt from a memorial to Jahns by Lauren Wright (1985):

*“... Dick could periodically escape to Wayne Burnham's laboratory and with him test experimentally Dick's previously conceived model for pegmatite genesis.”*

If Jahns and Burnham did not conduct or oversee any additional experiments on pegmatites, such as the one shown by Wyllie (1963), they certainly left people with the impression that they had.

There is one important phrase from Jahns and Tuttle (1963) in the cited text (p. 89-90) that carried over into the paper by Jahns and Burnham (1969), but not Jahns' (1982) final exposition of the model<sup>2</sup>. It is in reference to *“a temperature gradient.”* As described by Tuttle and Bowen (1958), leaks in a platinum capsule allowed the granitic constituents of their charge to escape to the aqueous fluid that was the pressure medium in the vessel. In the end, the platinum capsule contained mostly albite, and at the cooler end of the vessel, abundant quartz and *“an orthoclase component”* were deposited. These are the *“failed experiments”* that Jahns referred to in his conversation with me. In the same year, Phil Orville (1963) published what amounted to a replication of these experiments in a more controlled fashion with alkali feldspars, and he too reported that the feldspars segregated along a temperature gradient of as little as 25°C: albite to the hot end, K-feldspar to the cold end. Jahns used Tuttle's results to imply that the aqueous solution preferentially leached potassium and silica from the melt, leaving it albite-rich, which was Jahns' cause of quench to form the sodic aplites. That, however, was a misrepresentation or misinterpretation of the results. The process is a reversible equilibrium having to do with the thermal stability of the feldspars, as Orville (1963) and others (Lagache and Weisbrod, 1977) have shown. It was the temperature gradient, not the nature of the transport medium, that led to the fractionation of the feldspars.

### **The Jahns-Burnham-(Tuttle) Model**

Jahns and Tuttle (1963) concluded with this statement:

*“Role of water vapor. Water vapor is essential for the formation of granite pegmatites and aplites, and perhaps the most important function is to provide a low viscosity fluid for the growth of large crystals. It is also important in lowering the liquidus temperature of the magma, thereby*

*permitting two alkali feldspars to crystallize side by side. Liquidus lowering also permits certain hydrous phases which are unknown as phenocrysts of rhyolites (such as muscovite) to appear at liquidus temperatures. Water vapor serves to recrystallize early-formed minerals and act as an agent for metasomatic reactions. An essential function of water vapor in the genesis of aplites is to provide a mechanism for quenching by relief of pressure. This is probably the only way that rapid quenching can be induced in deep seated rocks.*

*Thus we have four important functions of the water vapor in the genesis of pegmatites and aplites: 1) lowering of the liquidus temperature by solution in the liquid, 2) providing a low viscosity medium for transport of material, 3) promoting recrystallization and metasomatic replacement of early-formed crystals, and 4) affording a mechanism for quenching by relief of pressure.” (p. 91)*

This is the complete statement of the Jahns-Burnham model, though Burnham was not an author. Personal comments to me, however, provided the threads to this conclusion: the experiments that constituted the experimental confirmation of the Jahns-Burnham model were the same “*failed experiments*” that Jahns mentioned to me. They were conducted by Tuttle and published in Tuttle and Bowen (1958).

## **References**

- Bowen, N.L. (1933) The broader story of igneous differentiation, briefly told. In *Ore Deposits of the Western States* (A.W Finch, ed.). *American Institute of Mining and Metallurgical Engineering*, University of Wisconsin – Madison (USA), 106-128.
- 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).
- Burnham, C.W. and Nekvasil, H. (1986) Equilibrium properties of granite pegmatite magmas. *American Mineralogist*, **71**, 239-263.
- 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.
- Candela, P.A., and Blevin, P.L. (1995) Do some miarolitic granites preserve evidence of magmatic primary volatile phase permeability? *Economic Geology*, **90**, 2310-2316.
- Fenn, P.M. (1977) The nucleation and growth of alkali feldspars from hydrous melts. *Canadian Mineralogist*, **15**, 135-161.
- Holloway, J.R. and Wood, B.J. (1988) *Simulating the Earth, experimental geochemistry*. Unwin Hyman, Boston, Massachusetts, United States, 196 p.
- Jahns, R.H. (1955) The study of pegmatites. *Economic Geology, 50<sup>th</sup> 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) *Bulletin of the Geological Society of America*, **69**, 1592-1593.
- Jahns, R.H. and Burnham, C.W. (1969) Experimental studies of pegmatite genesis: I. A model for the derivation and crystallization of granitic pegmatites. *Economic Geology*, **64**, 843-864.
- Kilinc, I.A. (1969) Experimental metamorphism and anatexis of shales and graywackes. Unpublished Ph.D. thesis, Pennsylvania State University, 191 p.
- Lagache, M., and Weisbrod, A. (1977) The system: two alkali feldspars KCl-NaCl-H<sub>2</sub>O at moderate to high temperatures and low pressures. *Contributions to Mineralogy and Petrology*, **62**, 77-101.
- London, D. (2005) Granitic pegmatites: an assessment of current concepts and directions for the future. *Lithos*, **80**, 281-303.
- London, D. (2008) Pegmatites. *Canadian Mineralogist Special Publication* **10**, 347 p.
- 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.
- Norton, J.J. (1966) Ternary diagrams of the quartz-feldspar content of pegmatites in Colorado. *U.S. Geological Survey Bulletin*, **1241**, D1-D16.
- Orville, P.M. (1960) Petrology of several pegmatites in the Keystone district, Black Hills, South Dakota. *Geological Society of America Bulletin*, **71**, 1467-1490.
- Orville, P.M. (1963) Alkali ion exchange between vapor and feldspar phases. *American Journal of Science*, **261**, 201-237.
- Simpson, D.R (1960) Geology of pegmatites of the Ramona pegmatites, San Diego County, California. Ph.D. thesis, California Institute of Technology, 197 p.
- Swanson, S.E. (1977) Relation of nucleation and crystal-growth to the development of granitic textures. *American Mineralogist*, **62**, 966-978.
- Tuttle, O.F. and Bowen, N.L. (1958) Origin of granite in the light of experimental studies in the system NaAlSi<sub>3</sub>O<sub>8</sub>-KAlSi<sub>3</sub>O<sub>8</sub>-SiO<sub>2</sub>-H<sub>2</sub>O. *Geological Society of America Memoir*, **74**, 153 p.

Vaughan, D.E.W. (1963) The crystallization ranges of the Spruce Pine and Harding pegmatites. Unpublished M.S. thesis, Pennsylvania State University.

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**

<sup>1</sup> The “Tuttle-type bomb” is more widely known as a cold-seal reactor, in which the high-pressure “cold” seal is made outside of the furnace; see Holloway and Wood (1988).

<sup>2</sup> In a lengthy conversation with me at a pegmatite symposium in Winnipeg, Canada, in 1982, Jahns affirmed his belief in his model, but he cited numerous ways in which he thought others had misconstrued it. One, he said, was the misconception that pegmatitic textures arise when minerals crystallize from aqueous “vapor.” He said he never meant to imply that, he meant that the silicate melt is the ultimate source of the crystal-forming components. However, he went on to convey his notion that a vapor film surrounds crystals that grow to pegmatitic dimensions, as the melt components dissolve into and through that vapor film. He was, therefore, envisioning a boundary layer of liquid (aqueous) that separated crystals from the melt.