

## **Cameron et al. (1949): Origin of Pegmatite Units**

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I have already made a number of references to the underlying conclusions of Cameron et al. (1949) regarding the origins of pegmatites as deduced from their study of the lithologic units. These include zones, fracture fillings, and replacement bodies. Their discussion (p. 97-107) is short but insightful. They open with a general statement:

*“The wartime investigations have yielded much information on the origin of pegmatite units, and it seems desirable to analyze some of the data and to present whatever inferences are warranted...”*

*In considering the problem of origin, it must be constantly remembered that the fracture fillings and replacement bodies characteristically form structural patterns that are superimposed on the earlier zones. Pegmatite units therefore fall naturally into two major groups, one consisting of zones, the other fracture fillings and replacement bodies.”* (p. 97)

What follows is almost unique to the history of pegmatite study: the authors summarized the data they have acquired, and then assessed each of three existing models for goodness-of-fit. It is that latter assessment of multiple working hypotheses that makes this an exception among most other publications on the subject, wherein hypotheses are sometimes presented as facts with such conviction that the author seems to have been there to see them happen.

Their assessment of the origins of zones considered three working hypotheses:

- *“(1) Development by crystallization of pegmatitic magma in situ...”*
- *“(2) Development by deposition in an open system...”*
- *“(3) Development in two stages: (1) a magmatic or epimagmatic stage during which pegmatitic solutions were injected and crystallized to massive pegmatite (or aplite) in a restricted system, and (2) a hydrothermal (or pneumatolytic and hydrothermal stage) during which solutions passing through the pegmatite effected successive replacements in an open system.”* (p. 99)

A fourth hypothesis, conspicuous by its omission, is a wholly magmatic stage (1), followed by a hydrothermal stage (2) in which the aqueous solution is indigenous to the pegmatite and part of its closed system. However, it is important to remember that the publication came at a time when open-system metasomatism leading to “granitization” of other ordinary rock types was believed to be an important petrologic process, and before the experimental programs that subsequently established the limits of solubility of H<sub>2</sub>O in silicate liquid, which was C. Wayne Burnham’s principal contribution to the science. Much of the presentation by Cameron et al. (1949) was aimed at evaluating models proposed by specific authors, most notably by Schaller (1926), Landes (1933), and Uspensky (1943), in which external solutions were the source of replacement bodies, which included all of the coarsely-crystalline rare-element mineral zones. Up to the time of this publication, the various stages of evolution from magmatic to hydrothermal states were given names and subdivisions as if they were a continuum. Lindgren (1913, 1937), for one,

implied that the fluid medium from which crystallization ensued changed continuously in composition from granitic melt to hydrothermal solution, without a divisible state of separation into coexisting melt and vapor. References in Cameron et al. (1949) to the fluid medium as pegmatitic magma, melt, liquid, rest-liquid, and solution conveyed the ambiguities that existed at the time, and that persist today.

Cameron et al. (1949) applied the principals of fractional crystallization to the development of zones in pegmatites. They noted that the distributions of zones are such that they enclose a pegmatite body completely (border and wall), or else have distributions that are not reconcilable with an open system in which deposition occurs along the walls of a central fracture (model #2 above). Moreover,

*“...the fact that within a zone one mineral may be found to have replaced another does not seem especially significant. In a restricted system, reaction between crystals and rest-liquid might take place at any stage, and the textural relations produced might be indistinguishable from those produced by hydrothermal replacement in a open system.”* (p. 101)

In that, Cameron et al. (1949) were affirming Bowen’s (1928) concepts of fractional crystallization in two ways: a chemical reaction between early formed crystals and a more fractionated melt with which it is no longer in equilibrium, and peritectic reactions, which result when chemical fractionation or another change of state, such as cooling, lead to a new mineral assemblage that can precipitate directly from the melt, or by reaction of the melt with earlier-formed minerals (e.g., the succession of olivine by orthopyroxene as silica content increases with crystallization in mafic magmas).

For Cameron et al. (1949), one of the most compelling facts in support of a model of igneous crystal fractionation was the observed variation in the composition of plagioclase from margin to center of pegmatite bodies. Their Figure 76, depicted at Figure 1 here, shows a hypothetical concentrically zoned pegmatite and the generalized sequence of plagioclase compositions from margin to center. In most cases, these simply fall from anorthite content of  $An_{12}$  at the margin to  $An_{02}$  at the center.

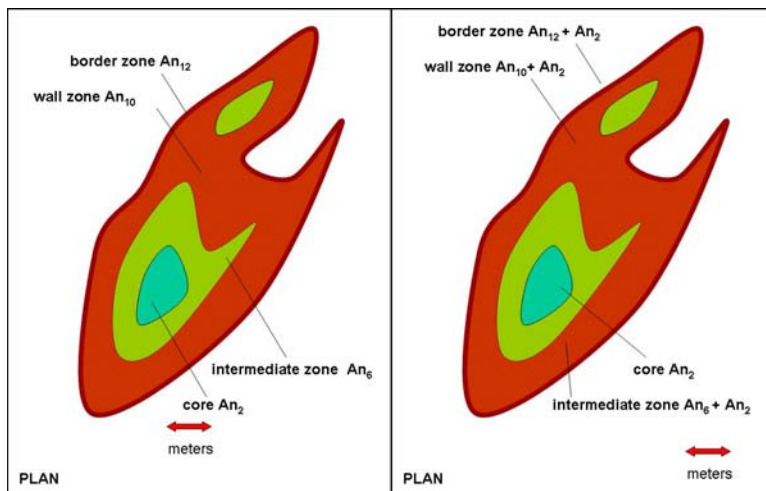
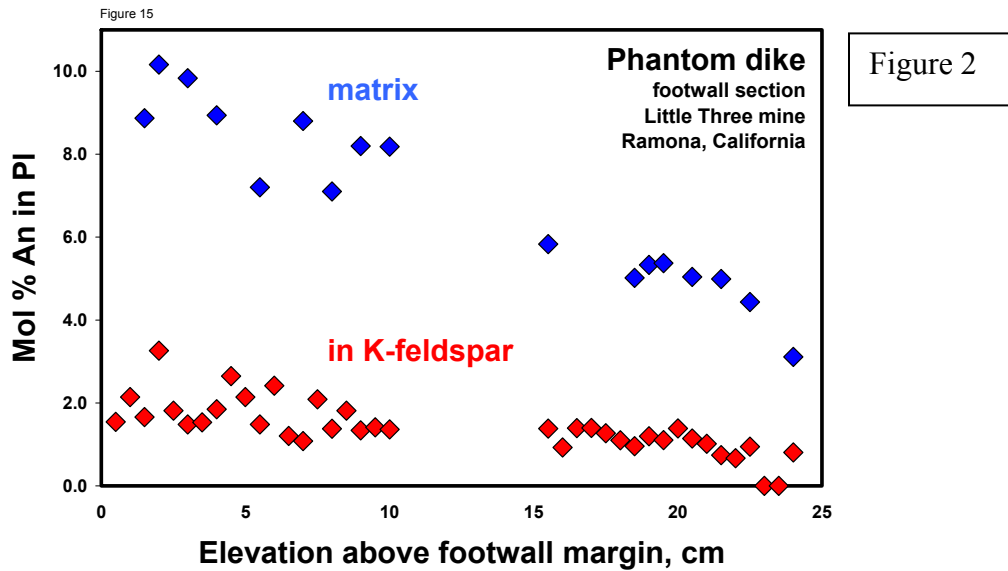


Figure 1

They attribute the change in plagioclase composition to cooling upon the liquidus surface of plagioclase, which becomes less anorthitic with decreasing temperature (p. 101-102). By implication, they infer that the temperature of crystallization falls from margin to center of dikes. This is a misconception that others have made: intrusive bodies cool from the outside in, such that thermal gradients increase, not decrease, from margin to center. This fact will be developed later in discussing some of Jahns' ideas, but the case is made in part here: Chapter 16 of London (2008).

Cameron et al. (1949) refer to other pegmatites (p. 99) in which two compositions of plagioclase coexist, one more anorthitic than the other (Figure 1 right). Figure 2 is a plot of plagioclase compositions from the Phantom dike, Little Three mine, Ramona, CA, from margin to center (London et al. 2020). Two associations of plagioclase were noted: primary crystals included within K-feldspar (non-perthitic orthoclase at margin to perthitic microcline near dike center), and primary plagioclase in the groundmass between the gigantic K-feldspar crystals. Their anorthite contents are different, and both decrease from margin to center.



However, the temperatures of corresponding pairs of primary feldspars – a single average K-feldspar composition compared to coexisting (at same elevation within dike) plagioclase of the matrix and included within K-feldspar crystals, gave nearly identical temperatures and temperature profiles (Figure 3), each grouping with a small standard deviation of 21°C. As recorded by the feldspars, the changes in their composition reflect Bowen's (1928) notion of fractional crystallization, but their crystallization was isothermal and not in response to cooling.

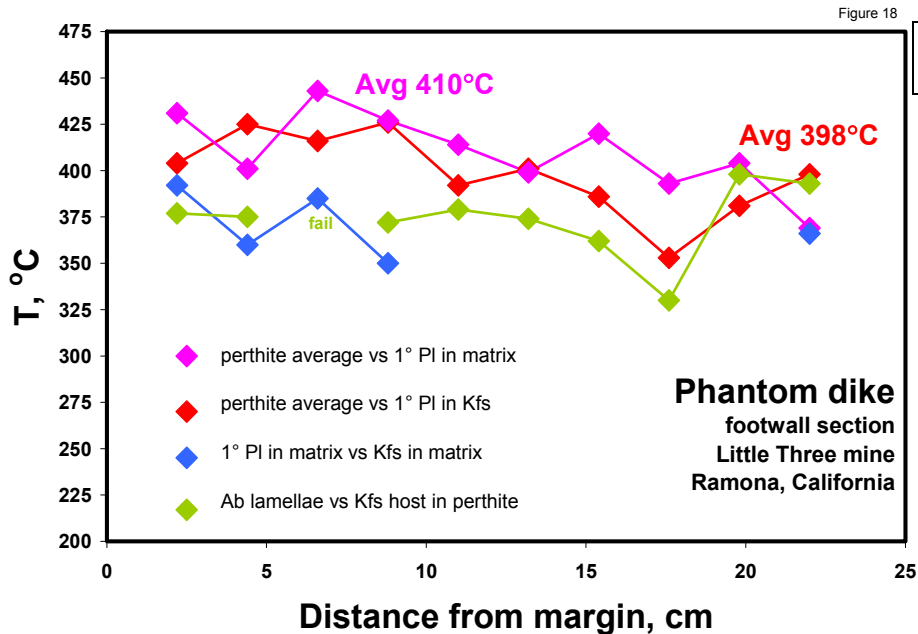


Figure 3

**Conclusion.** “For these reasons, the writers feel obliged to adopt, as a working hypothesis, the concept that zones have developed from the walls inward, essentially by fractional crystallization and incomplete reaction in a restricted system.” (p. 104).

In support of an igneous origin for the zones of pegmatites, Cameron et al. (1949) point out that the sequence of zones and their mineral assemblages is consistent among all of the districts studied (p. 103). They attribute that consistency to the magmas from which pegmatites are derived. No where do Cameron et al. (1949) explicitly link pegmatites to large granite bodies, though they refer to the compositions of pegmatites as granitic in several places. By contrast, they anticipate that the sources of hydrothermal fluids that might produce pegmatites along open fracture systems should be so varied that a uniform sequence of zones would not be expected.

They describe a “restricted system” for pegmatites as “a system closed to the extent that nothing is added to it from the source of the liquid from the time of original injection to the end of zone development, but open to the extent that some material may escape during crystallization, and reaction between the pegmatite and its walls may take place.” (p. 99)

Buried in this statement, and interspersed throughout the text, are references to *liquids* and *fluids* and *solutions* as the media from which pegmatites crystallize. Along with their conclusion that pegmatites form from successive crops of crystals deposited on the walls of the chamber, Cameron et al. (1949) conveyed, for the first time, that pegmatite-forming melts are initially crystal-free liquids. This is an important and overlooked conclusion, one that is surprising in light of current representations of large igneous bodies as crystal mushes. The generation of crystal-free liquids from mushes is much debated in the literature of large-volume silicic magma chambers (e.g., Hildreth and Wilson, 2007), and for which satisfactory explanations have not been advanced. Pegmatites develop in the roof zones of such silicic magma bodies and emanate

outward. The magma that occupies the volume of melt in the pluton that becomes the pegmatite carapace and dike system is entirely liquid.

However, the primary objective of the wartime study was to learn enough about pegmatites to predict and locate their economic commodities; hence, the focus was on internal structures and their position, composition, and uniformity among pegmatites as a whole and pegmatites of a mining district. They observed that mining in the known districts was tied to surface discoveries of minable pegmatite, and that those deposits known from surface exposures were already in decline at the time of the study. Their contribution, therefore, was a comprehensive system of resource evaluation that could be applied generally to all deposits, and they illustrated close similarities of zoning among pegmatites of a given district. They advised:

*“The pegmatite that is lean or barren at the surface may contain minable portions below. The clues to these portions can only be detected by applying a broad knowledge of pegmatite structure and mineral distribution, and by careful study and correlation of internal structures and lithologic sequences in the various pegmatites within a given district.”* (p. 107)

Among the participants in this wartime study, only a few continued their careers in pegmatite studies (e.g., Dick Jahns, Jim Norton, Abe Heinrich, Tom Kesler). Jahns, however, took the lead in pegmatite studies and distinguished himself as the authority on the subject. Some of Jahns’ few early publications are discussed in the next essay.

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