Cameron et al. (1949): Zones

David London (dlondon1@memphis.edu)
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The most important and lasting contribution of the monograph by Cameron et al. (1949) was the depiction of the principal structural units of pegmatites, recognizable by their combination of mineralogy and texture, as zones. The internal structure of pegmatites is not found in the more common igneous bodies, such as granites. Gene Cameron was familiar with layering that is prevalent in large, flat-lying gabbroic bodies. At that time, gabbroic layering was understood to result from the "*successive crops of crystals*" (words used by Cameron et al., 1949) that settled through largely molten magma to accumulate in layers on the bottoms of magma chambers. The zonal structure of pegmatites was wholly different. As Cameron et al. (1949) depict it, pegmatite zonation is a sequence of concentric shells that may be vertical in orientation, and hence not due to gravitational forces of accumulation. There are, however, distinctions to be made between the patterns of zonation in steeply dipping pegmatites compared to those whose attitude of emplacement is nearly horizontal (e.g., Norton, 1983).

Spatial Zonation within Pegmatite Bodies

Cameron et al. (1949) delineate zonal structure at two levels of classification. The first is by position:

(1) border zone, followed by
(2) wall zone, followed by
(3) intermediate zone, followed by
(4) core

Three zonal positions that make immediate intuitive sense are border (at the margin), core (at the center), and intermediate (in between margin and center). The term of wall zone is not intuitive, and Cameron et al. (1949) adopted it because it was "*a terminology that is firmly established within the domestic pegmatite mining industry*." (p. 20). It is likely that the wall zone was everything between the margin and the first intermediate zone, which is normally perthite-rich, and hence the first internal zone of economic value. In most pegmatite mining activity, the wall zone is gangue, and winds up on the dump pile. As Cameron et al. (1949) describe them, the border and wall zones surround pegmatite bodies more or less continuously, and conform in their uniform thickness to the overall shape of the body. The intermediate zones and core units are more irregular in their shape and distribution.

Border zone. Border zones (pp. 24-32) form a thin ("*rarely exceed 2 feet in thickness, and commonly less than 3 inches*" p. 24), continuous unit at the contact with host rocks. They are "*aplitic to fine-grained pegmatitic in texture*" (p. 24). Cameron et al. (1949) denote the border zone as principally "*feldspar, quartz, and muscovite*", but plagioclase plus quartz is the most prevalent assemblage, with or without muscovite. The mineralogy of the border zones can be the most complex of any unit in a common pegmatite. The accessory minerals "*may include any mineral present in the other parts of the pegmatite*" (p. 27). As an example, they cite the Harding pegmatite, New Mexico, whose border zone is said to consist of "*perthite, quartz, and muscovite, with minor beryl, columbite-tantalite, microlite, apatite, spessartine, and spodumene*"; albite is at least locally an appreciable component of that border zone. However, the most common accessories of the border zone are "*tourmaline, beryl, apatite and garnet*"; elsewhere, biotite, phosphates, and columbite-tantalite are mentioned as common constituents of the border zone and wall zones. Cameron et al. (1949) note that some border zones appear to possess the bulk composition of the entire pegmatite, and so can be regarded as chilled margins (p. 28). Chilled margins represent the sudden crystallization of the first injection of silicate liquid into much cooler host rocks. They make no mention of the fact that all border zones are, based on their location and textures, chilled margins, but that most do not reflect the bulk composition of the entire pegmatite.

Cameron et al. (1949) devote more discussion to the textures of border zones than to any of the other units. Despite their characterization as "*aplitic to fine-grained pegmatitic in texture*", minerals of the border zone are said to normally coarsen inward (p. 30), mineralogical layering is common, and the border zones of many pegmatites "*are characterized by orientation of the component minerals perpendicular or subperpendicular to the contact surfaces*." That anisotropic fabric, in which crystals develop with axes of elongation perpendicular to their substrate of growth, is referred to as comb structure (i.e., the relations of the teeth of a comb to the rib), stockscheider (widely used in Europe), and unidirectional solidification texture, or UST, a term that has come into common usage in the U.S., and will be used here. Cameron et al. (1949) illustrate a border zone as their Figure 19, a photograph and line drawing of the border zone from Atwood, New Hampshire. It contains a narrow border of aplitic pegmatite, followed inward by sharply coarser-grained crystals whose directions of elongation are perpendicular to the contact. The classification is theirs, but most workers would consider their Figure 19 as a combination of two zones: a fine-grained granular border, and a sharply coarser-grained wall zone with UST. The prominent UST of the outer zones, what Uebel (1977) termed as the pegmatite "*shell*", persists to the coarse, blocky texture of the first intermediate zones, Uebel's (1977) designation as "*core*". It is for this reason that the zone with prominent UST rightly belongs in the wall zone, not the border. Cameron et al. (1949) make reference to prominent UST in the border zone of the Case #1 pegmatite, which is illustrated below as Figure 1.

Wall zone. Cameron et al. (1949) distinguish the border and wall zones (pp. 32-42) on the basis of grain size: "*In general the border zone of a pegmatite contains the same minerals as the wall zone, though the proportions commonly differ and the texture of the border zone is characteristically finer grained.*" (p. 28). There is no further mention of texture of the wall zone.

Figure 1a shows a sample from the contact of the Case #1 pegmatite, Portland, Connecticut. In this rare case, the pegmatite sample has separated cleanly from its host rock, a mafic gneiss. The contact surface is patterned with clusters of crystals whose crystal density varies from ~ 3 to 60 crystals per cm^2. Hexagonal beryl crystals (circled in red) dot the surface of the contact, signifying that their long axes are perpendicular to the contact. The boundary between border and wall zone is conspicuously defined by texture, where the wall zone exhibits strongly developed UST (Figure 1b). Just 4 cm away from the contact, the cross section of each crystal is > 1 cm^2. Beryl is absent. Those crystals of the border zone whose orientations enhanced their growth in the direction of the melt grew inward to create the wall zone. Many other crystals with unfavorable orientations in the border zone were immediately starved out.

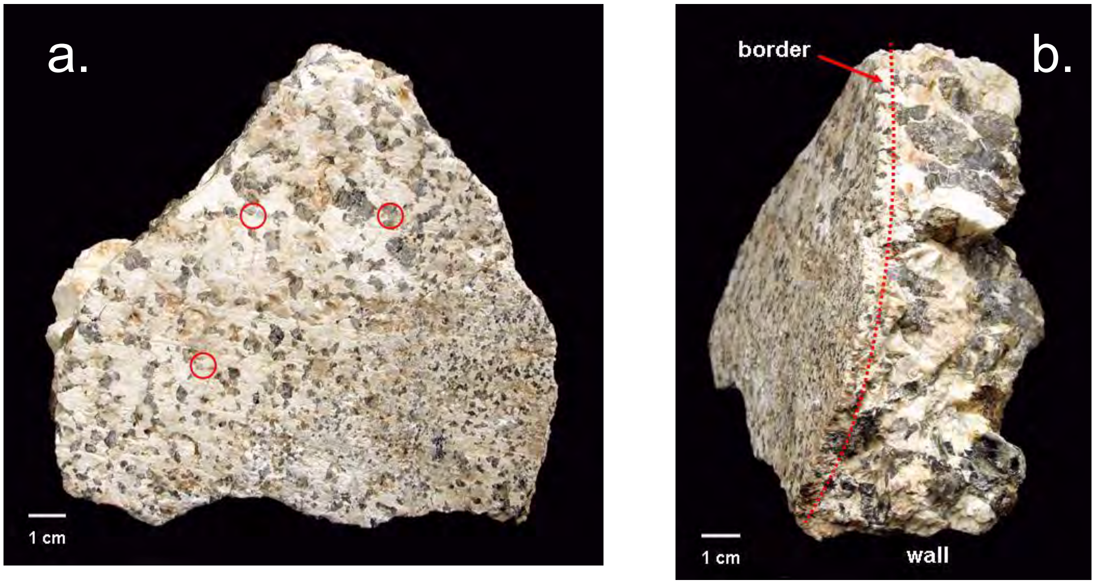

Figure 1, border and wall zone from the Case #1 pegmatite, Portland, Connecticut

Intermediate zone. Cameron et al. (1949) state "*The intermediate zones of a pegmatite include all zones between the wall zone and the cor*e" (p. 42), which leaves much to be imagined by the reader. They follow that statement with examples (p. 42-51) that are meant to convey the distributions of intermediate zones, but without any particular reference to distinguishing attributes.

"*Intermediate zones may be either continuous shells within the wall zone; hoods that cap cores or inner intermediate zones; inverted troughs around the lower part of the core; series of disconnected lenses symmetrically arranged inside the wall zone; or single lenses either on one side or at the ends of the pegmatite.*" (p. 44)

Regarding the occurrence of intermediate zones, they state that "*Many pegmatites contain only border zone and core, or border zone, wall zone, and core. Many have none, others only a single intermediate zone, whereas others have as many as five or even more.*" Even when intermediate zones are present, they normally consist of the same minerals as the border and wall zones: "*In the lithium-free pegmatites, the intermediate zones are rarely more than three in number and they are generally composed of perthite or combinations of plagioclase, quartz, perthite, muscovite, and biotite.*" (p. 48) These are important and necessary statements for those who have not seen large numbers of pegmatite bodies. They convey the fact that the vast majority of pegmatites lack the rare minerals for which pegmatites have acquired such a following among mineral collectors and mineral scientists, and that have come to be defining features of pegmatite classification (e.g., Černý and Ercit, 2005). These common pegmatites, as I have called them (London, 2008), are close to the composition of granites (Norton, 1966), which is a subject for another essay.

Other than noting the large size of (some, but not necessarily all) minerals in the intermediate zones, Cameron et al. (1949) disperse comments about texture in the descriptions of units from specific pegmatites. They mention graphic granite (a skeletal intergrowth of quartz and feldspar), elongate ribbons of micas, perthite euhedra, and spheroidal masses of radial cleavelandite (a habit of albite) in this context. They do not emphasize the more equant, massive textures of the intermediate zones as dominated by blocky perthitic microcline, or what Soviet petrologists termed "*block*" pegmatite as a mappable zone (e.g., Vlasov, 1961). Cameron et al. (1949) do note that quartz, which generally appears as dispersed mineral grains in the border and wall zones, becomes more organized as interstitial fillings to other coarse-grained crystals and occurs as separate masses in the intermediate zones.

Core zone. Like the prior zones, the designation of a pegmatite's core (pp. 51-59) is based solely on its position within the zoning sequence, "*at or near the center of a pegmatite body*" (p. 20), yet "*symmetrically located with respect to the sides of the body, but asymmetrically located with respect to the crests and keels of plunging bodies*." (p. 51) That latter phrase is related to the vertical displacement of cores in steeply dipping pegmatites. Cameron et al. (1949) generally portray the cores as displaced roofward in such pegmatites, but only if the pegmatites expand (thicken) toward the top. Otherwise, wherever a pegmatite dike is thinned, the core unit disappears. As an example of keelward displacement, they include a geologic map (Figure 29, p. 38) of the Strickland-Cramer pegmatite, Connecticut, in which the inner intermediate zone (plagioclase-quartz pegmatite) and core (quartz) are displaced toward the bottom (*keel*) of the pegmatite, and are overlain by a thick outer intermediate zone containing abundant graphic granite. The cores of most pegmatites are pure massive quartz.

The Spatial and Textural Relations of Zones

Illustrations of Figures 6, 7, and 12 in Cameron et al. (1949) are summary generalizations about the relationships of the positions of intermediate zones and cores to thickness – lateral or vertical – across a pegmatite body whose thickness varies. The distribution of intermediate and core zones conforms not so much to shape as to thickness of a pegmatite body; they are restricted to the thickest portion of a pegmatite of variable width (Figure 2).

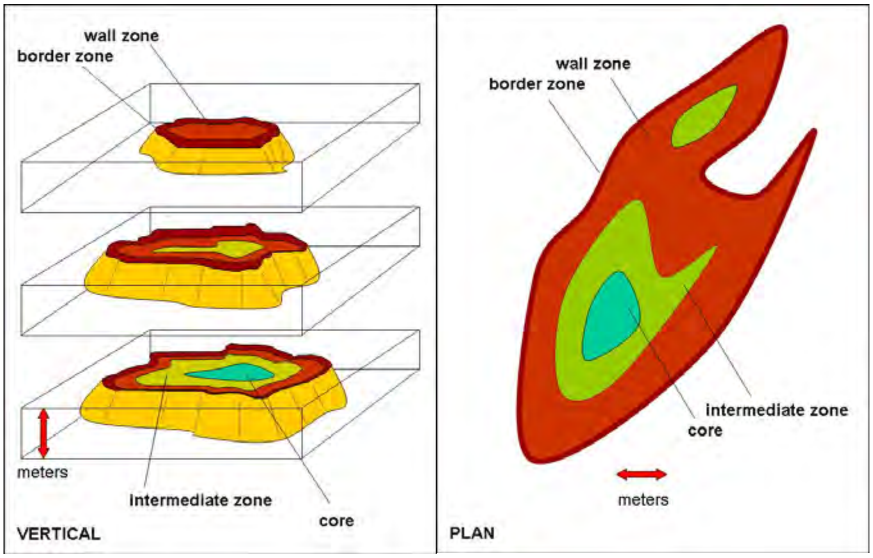

Figure 2

Figure 2 redrafted from Figures 6, 7, and 12 (pp. 18, 19, 23) in Cameron et al. (1949), represents the position of a core unit in a pegmatite whose overall plunge is steep but which narrows or thins upward (vertical), or of variable thickness in horizontal cross section (plan). As they portray it, the core and intermediate zones of a pegmatite disappear as the pegmatite body thins upward or narrows at its ends. I redrafted their Figure 12 but inverted it in Figure 3-17 of my book (London, 2008), with the intent of showing the difficulty of recognizing the true core unit in any two-dimensional plane. In hindsight, I missed the real significance of their Figure 12.

The border and wall zone of a thin dike segment are one and the same as their expression in a thick segment of the same body, which includes additional intermediate zones and core units. Figure 3 is an excellent photographic example of such a case. In the thin portion of the dike, the border and wall zone with a very thin quartz core constitute 100% of the rock; the thicker portion contains a sharply coarser intermediate zone that includes muscovite and tourmaline.

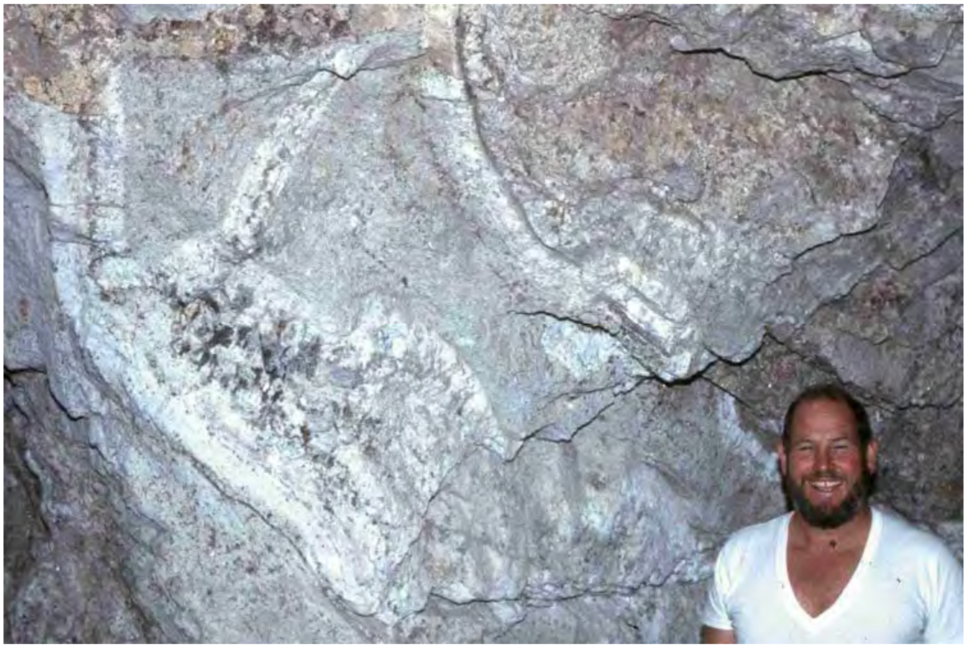

Figure 3. miner Bob Dawson next to an outcrop of pegmatite in granite at the Pala Chief mine, Pala, California

What is significant, therefore, about the disappearance of inner units, either upward or downward, or as a pegmatite body thins or bifurcates, is this:

(1) the narrow conduits that the thin dike segments represent are sealed by crystallization long before the melt within larger pools solidifies. This relationship is implicit in the summary statement of Cameron et al. (1949), wherein they describe the consolidation of pegmatites as "*crops of crystals deposited as successive layers upon the walls of the chamber enclosing a body of pegmatitic liquid …*" It is partly for this reason that Cameron et al. (1949) viewed pegmatites as melts that, once emplaced, crystallize in isolation as essentially closed systems (p. 101).

(2) In the concept of fractional crystallization as described by Bowen (1928), the composition of the melt changes as successive fractions of crystals are removed from contact with the melt in response to cooling. In that model, however, the compositions of crystals and of melt are determined by the fraction of melt that has crystallized, but not the volume. Hence, large and small bodies of the same melt composition should end having produced the same minerals in the same proportion. This result is inherent, too, in the widely used model of Rayleigh fractionation, which tracks the concentration of an element in fluid (melt or aqueous solution) as a certain fraction of minerals crystallize.

These relationships do not strictly hold where crystallization commences as a solidification front from the walls inward of a magma body of variable thickness. Figure 4 (from Figure 17-8 of London, 2008) illustrates a solidification front in a cross section of pegmatite from Ramona, California. Several growth surfaces (red dotted lines) are delineated by bands of fine-grained tourmaline that were deposited at the solidification front. They are what are referred to as phantoms within crystals of graphic quartz-K-feldspar intergrowth (graphic granite).

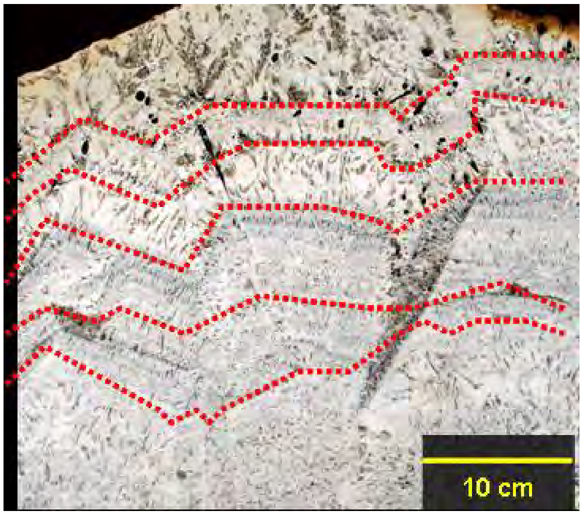

Figure 4. Lower wall zone and lower intermediate zone of the Phantom dike, Ramona, California

Fracture-filled hydrothermal veins, such as common quartz veins, solidify in the same way. Once the two sides merge, the conduit is sealed off. Hydrothermal veins, however, are open systems that result from the flow of aqueous solution through the fracture. The deposition of minerals along the fracture is dictated by the composition of the nutrient solution all along the open path of the vein. In the view of Cameron et al. (1949), pegmatites are closed systems: once emplaced, the pegmatite-forming melt experiences little chemical interaction with the environment around it (p. 101).

It is for these reasons that the thickest portions of a pegmatite body of variable thickness contain the more evolved mineral assemblages, including intermediate zones and cores, which are absent in the thinnest portions of the same dikes, as Cameron et al. (1949) have portrayed it. As a model for this fractional crystallization, the process referred to as zone refining is a more accurate depiction than is the process that entails Rayleigh fractionation (see pp. 262-266 in London, 2008, and Figure 22 of London, 2016). This conclusion does not negate the more general observations that pegmatites become more chemically evolved with increasing distance from source. (e.g., Vlasov, 1961; Trueman and Černý, 1982; Černý and Lenton, 1995). It does, however, challenge the hypothesis of buoyancy-driven gravitational separation that would always make the upper portions of a pegmatite body more chemically evolved (e.g., Jahns, 1982). In detail, size matters in the distribution of internal zones.

Unlike the classification of Cameron et al. (1949), Uebel's (1977) scheme for the internal structural units of pegmatites is based entirely on texture. Uebel (1977) referred to two spatial units – the pegmatite shell and the pegmatite core, with minor subdivisions within each. The shell included all zones – border, wall, and potentially outer intermediate zones – that possess unidirectional solidification texture, mineralogical layering parallel to the contacts, and the skeletal habits of quartz and K-feldspar. The core comprises all interior units that possess extremely coarse, blocky, idiomorphic, and more randomly oriented crystals of the principal minerals as encased in massive interstitial quartz. Like Cameron et al. (1949), Uebel (1977) restricted the core unit to the central and thickest portion of a pegmatite of variable thickness, and to the keelward thicker portions of pegmatites that thin upward. His Figures 2 and 3 are virtually identical to Figure 12 of Cameron et al. (1949).

Vlasov (1961) observed that the distal pegmatites contain all of the outer zones of that comprise the common pegmatites, but with the addition of successively more and mineralogically complex intermediate zones with distance from source. Cameron et al. (1949) made no reference to the distribution of the complex rare-element pegmatites by location within a pegmatite district. Vlasov's (1961) depiction, that the most evolved pegmatites with the most intermediate zones lie farthest from their apparent source, has been borne out by subsequent studies. For example, Figure 5 (from London, 2016 and Redden et al., 1982) shows the locations of the six largest rare-element pegmatites of the Black Hills, South Dakota, as cited in Cameron et al. (1949), in relation to the Harney Peak granite source (pink) and the distribution of pegmatite bodies per square mile. All of the principal Li-rich pegmatites lie near the edge of the pegmatite field, close to the zero density contour.

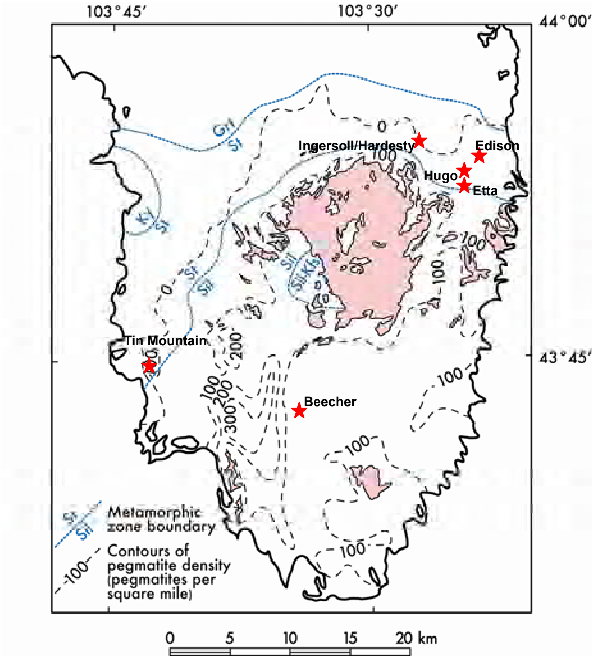

Figure 5. Pegmatite density contour map (pegmatite bodies per square mile) in the Black Hills district, South Dakota (redrafted from Redden et al., 1982), Metamorphic zones and isograd reactions are shown in blue. Six of the largest Li-rich pegmatites in the district are plotted as red stars.

Mineralogical Zonation within Pegmatite Bodies

The second level of classification of zones by Cameron et al. (1949) is according to mineral assemblage. Recognizing that, "*on the whole the sequences of mineral assemblages in the various pegmatites show a remarkable approach to uniformity*" (p. 60), Cameron et al. (1949) established a sequence of 11 zonal assemblages in pegmatites. They are:

(1) Plagioclase – quartz – muscovite
(2) Plagioclase – quartz
(3) Quartz – plagioclase – perthite ± muscovite ± biotite
(4) Perthite – quartz
(5) Perthite – quartz–plagioclase – amblygonite – spodumene
(6) Plagioclase – quartz – spodumene
(7) Quartz – spodumene
(8) Lepidolite – plagioclase – quartz
(9) Quartz – microcline
(10) Microcline – plagioclase – lithia-micas – quartz
(11) Quartz

Except for the inner intermediate zones of the lithium-rich pegmatites, the diversity of mineral assemblages among all of the zones is low: only the proportions of minerals change. These consist principally of plagioclase, K-feldspar, and quartz with lesser muscovite, biotite, and accessory minerals. Consequently, from their Tables 2-5, this sequence of mineral zones appears in the majority (> 50%) of the pegmatites that were mapped in detail, by district:

Southeastern states:
(1) Plagioclase – quartz – muscovite
(2) Plagioclase – quartz
(3) Quartz – plagioclase – perthite ± muscovite ± biotite
(4) Perthite – quartz
(11) Quartz

New England:
(1) Plagioclase – quartz – muscovite
(3) Quartz – plagioclase – perthite ± muscovite ± biotite
(4) Perthite – quartz
(11) Quartz

Petaca, New Mexico
(4) Perthite – quartz
(11) Quartz

Black Hills, South Dakota
(1) Plagioclase – quartz – muscovite
(3) Quartz – plagioclase – perthite ± muscovite ± biotite

Beyond zone (3), no single zone occurs in half or more of the pegmatites, and quartz corse were documented in only four out of twenty bodies. Most of the inner units were combinations of zones

(5) Perthite – quartz–plagioclase – amblygonite – spodumene
(6) Plagioclase – quartz – spodumene
(7) Quartz – spodumene in eight out of the twenty pegmatites.

Norton (1983) made an important revision to Cameron et al. (1949) with regard to zonation in lithium-rich pegmatites. He combined units (8) and (10) of Cameron et al. (1949) and placed them last [9] in the sequence:

[8] Quartz
[9] Lepidolite or lithian mica – plagioclase – quartz – microcline

As such, the lepidolite-albite bodies follow massive quartz, yet the assemblage of zone [9] does not lie within, i.e. contained by, the massive quartz bodies. Assemblage [9] typically lies adjacent to a massive quartz body, which is why Cameron et al. (1949) placed the lithium-rich zone (8) in the position of an intermediate zone, or what they term a "*core margin*" zone (p. 21). Evidence to corroborate Norton's (1983) proposed sequence, in which a quartz-poor lepidolite-albite unit succeeds pure quartz, came from an experiment with a suitable analogue to a lithium-rich pegmatite, as Figure 6, an x-ray map of Si, from London and Morgan (2019) shows:

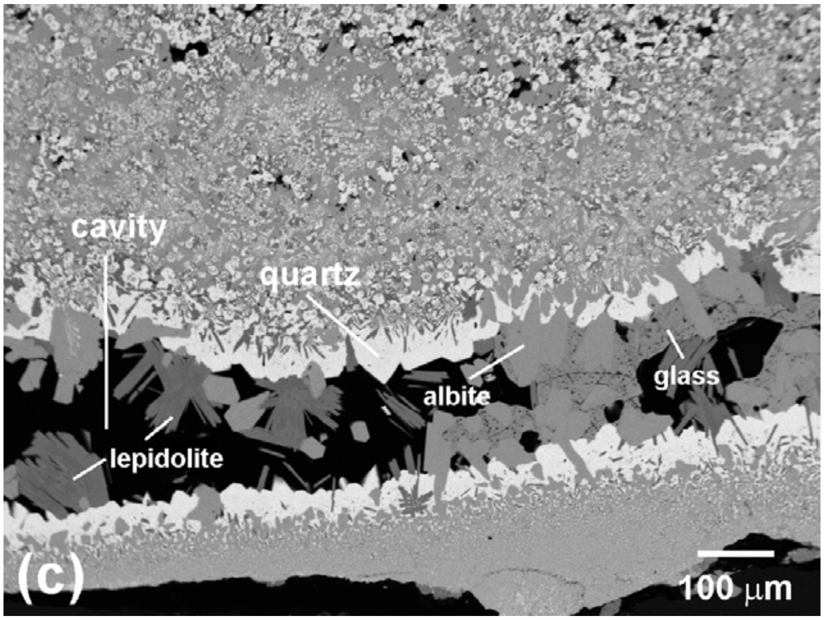

Figure 6

Cameron et al. (1949) did not correlated the positional sequence of zones with the mineralogical sequence of zones. The first plagioclase-rich mineralogical zone of each district can be regarded as the border and wall zones of the pegmatites, as Cameron et al. (1949) note the mineralogical similarity of both zones. The last unit can be regarded as the core, which as they note is pure massive quartz in the vast majority of pegmatites. Those units in between, mostly of perthite-rich zone (5), are intermediate zones.

The Petaca district stands out as lacking in plagioclase, if correctly mapped by Jahns (1946). Those pegmatites belong to a chemically distinct family that Černý (1991) characterized as NYF, for niobium-yttrium-fluorine, and whose tectonic environment and sources are thought to be wholly different from the more common pegmatites, Černý's LCT (lithium-cesium-tantalum) family, to which the other major districts reported by Cameron et al. (1949) belong. Otherwise, in the common pegmatites of the LCT lineage, the most abundant minerals in successive zones are: plagioclase first, followed by K-feldspar, followed by quartz. These are the principal minerals of granite, in which they occur in nearly equal proportions, and which are thought to crystallize simultaneously in their proportionate abundance (Tuttle and Bowen, 1958). The conclusion of Cameron et al. (1949) – that these minerals crystallize sequentially rather than simultaneously in pegmatites – violated the principles of equilibrium crystallization of a crystal-melt system at its minimum or eutectic, the composition of melt at the lowest temperature in equilibrium with crystals (Bowen, 1928; Tuttle and Bowen, 1958). That contradiction was the crux of what became the Jahns-Burnham model.

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