Cameron et al. (1949): Fracture-Fillings and Replacement Bodies

David London (dlondon1@memphis.edu)
October 20, 2020

Though Cameron et al. (1949) stressed the importance of zones as the principal structural units of pegmatites, they devoted considerable attention to fracture fillings and replacement bodies. Both features are cited as common in the pegmatite districts they studied. Like everything else about pegmatites, Cameron et al. (1949) noted that the distinctions among zones, fracture fillings, and replacement bodies are sometimes difficult to resolve. Fracture-fillings figured into their assessment of the role of replacement – meaning metasomatic recrystallization of pre-existing pegmatite – in the formation of the pegmatite zones. Fractures at some scale must exist to provide the conduits for the fluid that would be responsible for metasomatism. Metasomatism entails the removal, addition, or both of elemental constituents of a mineral or a mineral assemblage. These constituents must come from some place and go some place other than the locus of the replacement. They must, therefore, become soluble or locally insoluble in the fluid medium that is responsible for replacement. Following a lengthy assessment (*Origin of Pegmatite Units*, p. 97-107), Cameron et al. (1949) rejected metasomatic replacement as a means of generating the observed zones. This includes the rare-element enriched zones, which Landes (1933) deemed as replacements of common granitic pegmatite. In so rejecting a central role for metasomatism, Cameron et al. (1949) dismissed a hydrothermal origin for pegmatites, which was also a widely-held opinion dating from the 19th century.

Fracture Fillings

Cameron et al. (1949) opened the discussion of fracture fillings (pp. 70-83) with

"*Fracture fillings, formed by the simple filling of fractures in pegmatite, are similar in some respects to nonpegmatitic ore deposits that were formed along fractures.*" (p. 70)

This similarity is because "*Most common fracture fillings consist entirely of quartz.*" (p. 76) in pegmatites as well as in granite-hosted hydrothermal ore deposits. Throughout the discussion, however, Cameron et al. (1949) described fracture fillings whose mineralogy is far more complex than just quartz, and including monominerallic and multi-mineral aluminosilicate assemblages that occur elsewhere as zones in a pegmatite body.

Distribution. Line-drawn figures in this section portrayed the general or idealized distributions of fractures (p. 71 and 77) along with several maps of fracture fillings in specific pegmatite bodies. In the simplest cases, the fracture fillings consist of quartz in patterns that are radial to the dike center, form a stockwork from the dike center, or are parallel bodies transverse (discordant) to the principal zones of the pegmatite (Figure 1). As they depicted them, the radial and stockwork patterns of fractures originate within the pegmatite dikes. The transverse fractures are cross-cutting and hence might not have originated within the pegmatite body. Fracture fillings that correspond to the compositions of zones were shown as emanating from the core or inner intermediate zones of a pegmatite and propagating outward across earlier-formed units, and sometimes breaching the pegmatite body.

Figure 1. Illustrations of fractures in pegmatites adapted from Cameron et al. (1949)
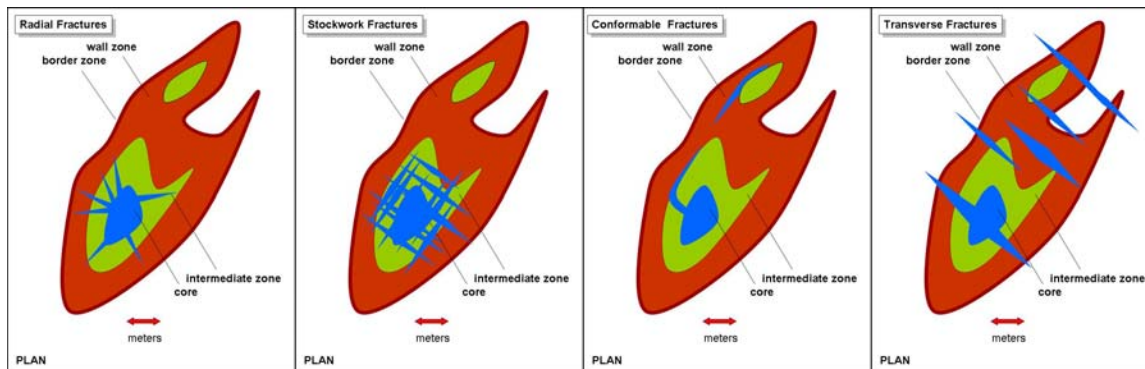
Composition. Cameron et al. (1949) did not formally classify fractures by their mineralogical types, as they did of zones, but their descriptions can be summarized as four different assemblages (types, as referred to below and by Duke et al., 1988): (1) pure quartz, (2) mostly quartz with minor quantities of aluminosilicate minerals such as feldspars, micas, tourmaline, etc., (3) mineral assemblages of any interior zones that are later than the zones the fractures cut, and (4) mineral assemblages of nearly monominerallic aluminosilicates such as albite or mica, many of which bear no obvious relation to the trace of fractures. Consequently, they regarded fracture fillings of types (1) and (2) as hydrothermal in origin, whereas the complex mineralogy of (3) is of the "*pegmatitic magma*" (p. 2) from which the primary zones form. They associated the fracture fillings of type (4) with replacement, whether by reaction of pre-existing pegmatite with aqueous solution or with later and more fractionated "*pegmatitic magma*".

Among these mineralogical variants:

"Quartz is by far the most abundant and widespread mineral in fracture fillings. Cleavlelandite, sugary albite, perthite or microcline, muscovite, and lepidolite are locally abundant, and accessory constituents comprise virtually all accessory species that occur in pegmatites."

Their implication was that the constituents that form fracture fillings, and the fluid from which they precipitate, are mostly indigenous to pegmatites, not of external origin.

Replacement Bodies

The discussion of replacement bodies (p. 83-97) opened with a lengthy consideration of the criteria that might be used to ascertain a primary assemblage (deposited in the space of the fluid medium from which minerals grow, which would include primary zones and fracture fillings) from a replacement assemblage (deposited in the space previously occupied by other minerals). Among the processes that Cameron et al. (1949) considered, they noted that crystal pseudomorphism, in which the outlines of the pre-existing crystal remain, or crystallographically oriented relicts of the pre-existing crystal remain, is a clear indication of replacement. That interpretation is less obvious than it seems. For example, Waldemar Schaller and Kenneth Landes – both eminent petrologists of their time – thought that the intergrowth of quartz and K-feldspar that constitutes graphic granite formed via the selective replacement of feldspar by quartz (Schaller, 1926; Landes, 1933).

In addition to pseudomorphism and cross-cutting relationships, Cameron et al. (1949) dwelled on the ages of mineral assemblages as measured by the radiometric age determinations of minerals in different assemblages. Radiometric age determinations were still quite novel at the time, and some of the first minerals to be dated by radiometric means came from pegmatites (e.g., Boltwood, 1907; Holmes, 1913). Cameron et al. (1949) rightly concluded that the accuracy of age determinations was insufficient to constrain the likely differences in time between primary and replacement assemblages, as both were part of the pegmatite-forming process. They did not speculate on the time interval over which pegmatites might crystallize, other than to concur with prior authors that most replacement features of pegmatites likely occurred during the hydrothermal stage, meaning deposited from aqueous solutions after the main stage of igneous crystallization.

Cameron et al. (1949) cited and illustrated several examples of what they regard as clear evidence of replacement involving coarsely crystalline minerals – of a size comparable to the minerals of the primary zones – and for which there is no evident structural control, such as the traces of fracture surfaces. Many of these examples are attributed to R.H. Jahns. One such illustration is their Figure 64 (p. 86), taken from work by Jahns, of radial spherical aggregates of coarse platy albite (cleavelandite habit) in similarly coarse-grained perthite-quartz pegmatite. The cleavelandite aggregates radiate from minute grains of columbite and monazite at their centers. The authors, presumably Jahns, regarded the perthite-quartz pegmatite as primary, and the cleavelandite aggregates as a replacement assemblage.

Discussion

As a mostly descriptive work, Cameron et al. (1949) did not delve into the mechanisms by which fracture fillings and replacement bodies might arise. These features did not figure prominently in the final portion of the publication, which mostly addressed the origin of zones. As is evident from the beginning, Cameron et al. (1949) regarded zones as the principal and magmatic structural units of pegmatites. All else was secondary in nature. Yet the occurrence of fracture fillings and replacement bodies must inevitably fit within the pegmatite paradigm in a way that is consistent with all pertinent scientific knowledge. My comments below aim to frame these problems more than to provide the answers.

Sources of fractures. The crystallization of a silicate liquid of granitic composition, in the absence of H_2O, results in a reduction of volume of ~ 5-10%, depending on the initial temperature of the melt. If the solidified portion of a pegmatite body contracted by that amount, fractures might open in a radial or stockwork pattern emanating outward from the center to margin, or transverse to the long axis of the pegmatite body, as do cooling joints in thin basalt flows and shallow dikes. Melt that remains in the central portions of a dike could migrate outward. This is hypothetical, as it is a hypothetical treatment by Cameron et al. (1949), and it does not consider the likelihood of larger-scale deformation of solid portions of crystallized pegmatite as a means of opening fractured conduits. However, Duke et al. (1988) speculated that the volume reduction upon crystallization of granite might have created conduits for fracture fillings by pegmatitic bodies in the Calamity Peak pluton, SD.

The crystallization of hydrous granitic melt will also generate open space, which might take the form of open fractures. In a model calculation (p. 201 of London, 2008), a granitic liquid that is just saturated in H_2O (6.6 wt% H_2O) at 200 MPa and 700°C will generate an increased volume of 21%, of which 24% is void space occupied by the aqueous solution that exsolves along with the anhydrous mineral assemblage of quartz and feldspars. Figure 2 shows a fully crystalline experiment in which a melt derived from the Macusani obsidian was initially saturated at ~ 9 wt% H_2O. The resultant void space occupies ~ 25% of the total volume of the product.
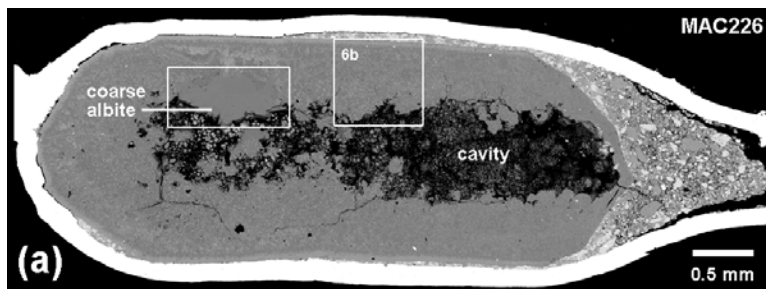

Figure 2. Detail from London and Morgan (2017), showing the miarolitic cavity at the center of a fully crystallized pegmatitic sample. Granular material at the right end is crushed amphibolite.

Fracture-controlled, cross-cutting relationships of igneous pegmatitic units are well documented for the portions of pegmatite systems that are close to their source pluton. In the layered aplite-pegmatite system of Calamity Peak, Duke et al. (1988) detailed aplite cutting pegmatite, pegmatite cutting aplite, and abrupt truncations of one against the other on a meter scale. Duke et al. (1988) also described four types of fracture-fillings, all of which are variants of the composition and texture of granite, aplite, and pegmatite. I have observed similar cross-cutting features in the pegmatites that emanate from granites at Spruce Pine, NC, and Middletown, CT.

Type (3) fracture fillings. At the face of it, the case of fractures filled with "*pegmatitic magma*" is the least problematic of the various situations. As noted by Cameron et al. (1949), these are difficult to recognize because of their mineralogical similarity to the pegmatite zones they cut. However, they are the easiest of the fracture fillings to account for by a geologic process that is consistent with the Cameron et al. (1949) model, wherein a pegmatite-forming melt crystallizes from the margins to center. These fracture fillings represent the escape of late-stage melt across and along fractures that develop in outer solidified zones.

At the Harding mine near Dixon, NM, the exposed hanging wall contact locally contains a border unit consisting of coarsely crystalline (to 10 cm) crystals of beige to blue apatite and white anhedral beryl in a groundmass of albite and lepidolite and accessory columbite, and little or no associated quartz (Figure 3). Abundant samples in the dump indicate that this was a more voluminous unit than it appears today. Wallrock alteration adjacent to this unit produced abundant bityite – a Li-Be brittle mica of the margarite group – with coarse (to 10 cm) spessartine garnet and recrystallized muscovite, followed outwardly by biotite (Figure 3). It is not the typical border unit here or elsewhere, and wallrock alteration rich in Li and Be is not found adjacent to the common border zones elsewhere. Mineralogically, the unit most resembles the late-stage albite-lepidolite-apatite-beryl assemblage that fills the interstices of large spodumene crystals in the core of the pegmatite (Figure 4 left). To that extent, the assemblage belongs to zone [9] of Norton (1986)(see essay #2 on Zones), the last primary assemblage, and hence it is possibly a silicate-phosphate liquid that migrated along a fracture to and along the pegmatite contact.
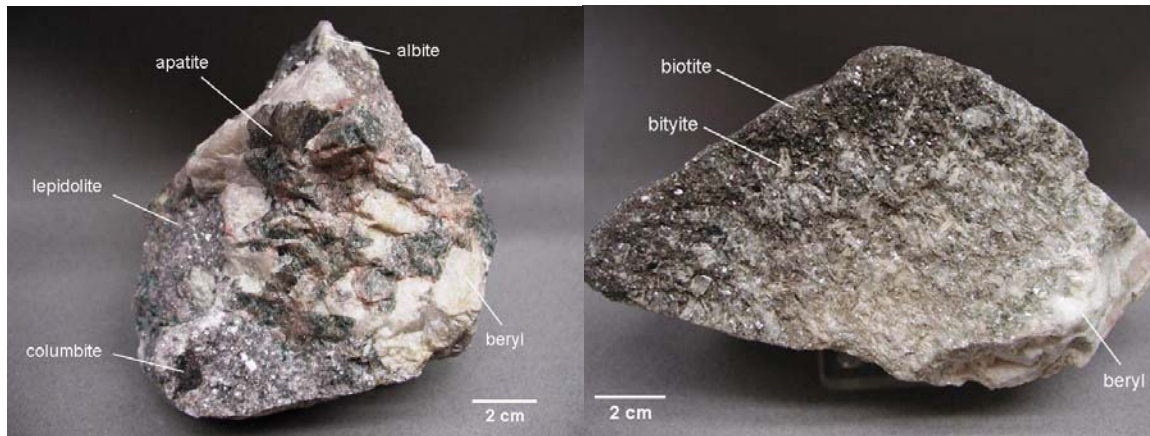
Figure 3. (left) A sample of the mineralogically complex border zone at the Harding mine, NM. (right) A sample of the altered host rock adjacent to the assemblage at left.

Geologic cross sections constructed from drill core data at the Tanco mine, Manitoba, reveal very large masses of pollucite that lie close to the pegmatite margin along the hanging wall at center and near the footwall of the southeastern portion of the dike (Stilling et al., 2006). Large bodies of quartz and of lepidolite-albite aplite lie nearby. As the latest and most fractionated units in the pegmatite, these would be expected to lie at center of the thickest portions of the body. Their location at or close to contacts with the host metagabbro suggests but does not confirm that they are fracture fillings of latest-stage melt that migrated from the center of the dike, where pollucite and lepidolite-albite aplite also occur.

Type (1) and (2) fracture fillings. Cameron et al. (1949) offered numerous specific examples (p. 73) of quartz-filled fractures (type 1) that emanate from within pegmatites. The implied source of the fracture-filling assemblage is the core zone itself. They are explicit in some cases, as for example:

"The Big Boulder pegmatite, Laramie County, Colo., contains a quartz fracture filling 35 feet long and 2 to 4 feet wide. It is a projection from the quartz core or from the perthite-quartz intermediate zone, and extends northward across the quartz-albite-perthite-muscovite wall zone into the mica-schist country rock."(p. 73)

In turn, that implies that the medium from which the core formed was a fluid capable of migrating along fractures. A liquid composed of pure silica is not stable at the temperatures of pegmatite-forming melts. The temperature at which quartz melts in the presence of H_2O exceeds 1100°C (Tuttle and Bowen, 1958).

Cameron et al. (1949) regarded the quartz-filled veins in pegmatites as hydrothermal in origin, but they did not explicitly describe the medium from which quartz cores form, except by way of relating all of the pegmatitic zones to crystallization from "*pegmatitic magma*". In discussing fracture-fillings, they used the phrase "*pegmatite solutions*"(p. 76). The contrast with "*pegmatitic magma*" seems intentional. Jahns (1982) and Burnham (Burnham and Nekvasil,

1986) openly disagreed on the means by which quartz cores formed, and neither of them advanced much more than a one-line hypothesis to explained them. Burnham and Nekvasil (1986) stated that quartz cores must be hydrothermal in origin, and the products of "*vigorous convection*" within a pegmatite body. Jahns (1982) regarded the quartz cores as igneous, and discounted the likelihood of convection in thin pegmatite dikes. Viewed in this context, quartz-filled fractures that emanate from quartz cores in pegmatites are a problem.

Burnham (1979) proposed a model for the generation of the hydrothermal base-metal deposits in which an aqueous solution separates early in the crystallization of a granitic magma body, but quartz veins, not pegmatite dikes, are precipitated in the fractures in the overlying rock, including the outer portions of the same granitic mass as the source of the solutions. The divergence of this model from that of Jahns and Burnham (1969) has not been previously noted or discussed. However, the quartz veins of typical hydrothermal ore deposits are thought to form from an exceedingly large volume of aqueous solution. Using data on quartz solubility from Fournier et al. (1982), a liter (1000 cc) of aqueous solution containing a few weight percent of salt and CO_2 at pegmatite-forming pressures and temperatures can deposit less than 1 cc of quartz if all of the silica is precipitated (London, 1992). In the quartz vein system of Panasquiera, Portugal, Polya (1988) calculated that the volume of fluid to vein precipitate must have been close to 10,000:1. That aqueous solution is circulated through fractures by long-lived convection that is driven by the heat of the large granitic masses at depth. Pegmatites possess no such thermal mass to sustain long-lived convection.

An assemblage of quartz with minor perthite (fracture type 2) is even more problematic. It is not in itself an igneous liquid composition any more than pure quartz is at pegmatite-forming conditions. Moreover, the solubility of feldspar in the same saline and carbonic aqueous solution is more than an order of magnitude lower than that of quartz (Anderson and Burnham, 1983), due to the exceedingly low solubility of aluminum in saline aqueous solutions. It is for this reason that the hydrothermal veins in granite-sourced mineral deposits are almost entirely quartz, and lack abundant feldspar.

Type (4) fracture fillings. The foregoing discussion highlights the problem of a hydrothermal origin for feldspars, which constitute approximately two-thirds of pegmatites. Feldspars of hydrothermal origin certainly do exist, as for example K-feldspar of adularia habit in what are known as Alpine-type fissures of Austria. Feldspars of pegmatites recrystallize from their original disordered states of sanidine or orthoclase to microcline perthite, and hydrothermal veins of potassic feldspar also form in the hydrothermal ore deposits mentioned above. These are regarded as replacement reactions, meaning that something is replaced by something else, and so fall under the heading of replacement bodies below. In these latter cases, however, the crystallization that takes place conserves aluminum, meaning that the reactions do not involve the transport of aluminum in or out of the system. The knowledge that aluminum is nearly immobile in typical hydrothermal solutions has guided metamorphic petrologists to balance mineral reactions by conserving aluminum on both sides of the chemical equation for most of the history of the discipline. Consequently, it is not uncommon that feldspars might crystallize from aqueous solutions by replacement of a pre-existing aluminous mineral, but it is unexpected that feldspars would be the dominant components of open fracture fillings, which would require the transport of substantial aluminum.

6

As specific examples of feldspar-rich fracture fillings, Cameron et al. (1949) cited these occurrences (p. 70):

"Excellent examples are the cleavelandite-beryl veinlets in massive quartz at the Harding mine, Taos County, N. Mex., and the branching aggregates of quartz, albite, and "wedge-A" muscovite in many pegmatites of the Crabtree area, Mitchell and Yancey Counties, N.C."

They regarded giant bladed crystals of biotite as fracture fillings in quartz in pegmatites of North Carolina and New England (p. 76). In the ensuing discussion (p. 76-83), Cameron et al. (1949) offered up many examples of "*polymineralic fracture fillings*", some of which possess the same mineralogy as do the pegmatite zones. When those fracture fillings are conformable to the boundaries between zones, the situation becomes "*indecipherably confused*" (p. 73).

Cameron et al. (1949) associated the quartz-rich fracture fillings with a hydrothermal solution, but they did not extend that analogy to the "*polymineralic fracture fillings*", except perhaps in one case. At the Buckhorn pegmatite, Larimer County, CO, two pegmatitic zones containing quartz, cleavelandite, perthite, and spodumene form what they construed as a fracture filling that was deposited from "*pegmatite solutions*".

Replacement bodies. Cameron et al. (1949) noted that at the time of their work, the literature on pegmatites was already replete with examples of what other workers recognized as replacement phenomena in pegmatites. In their discussion (p. 83-97), they again referred to "*solutions*" (p. 84), both indigenous to a pegmatite or originating outside of it, as the medium that promotes replacement. Their usage of the term "*replacement body*" pertains to the state when the body undergoing replacement is entirely crystalline; hence, they affiliated the state of system with the "*intermediate- to low-temperature hydrothermal stage*" (p. 85), same as for fracture fillings.

They noted that fracture fillings may evolve into replacement bodies as solutions react with the mineral or rock adjacent to the fracture. As an entirely subsolidus (post-magmatic) process, replacement must be fracture-controlled, even if it is at the scale of crystal boundaries or of cleavages within crystals. However, the traces of fractures are not present in many of the examples they cited, which contrasts with the fracture-controlled replacement that is associated with the hydrothermal ore deposits and their abundant quartz veins.

One excellent example of replacement that is not obviously fracture controlled can be seen in outcrops at the Harding mine, NM. The mine is accessible by permission from the University of New Mexico; a mandatory release form can be found at

https://eps.unm.edu/research/harding/index.html

The site contains a walking tour with descriptions of features along the way. Jahns and Ewing (1976) mapped the pegmatite, and depicted two "*core variants*". One consists of decimeter-scale fresh white laths of spodumene that are euhedral (Figure 4). Albite of cleavelandite habit forms a UST perpendicular to the surfaces of the spodumene, and interstices between spodumene crystals are filled with albite, lepidolite, white beryl, blue apatite, and small fresh crystals of locally

bluish (amazonite) K-feldspar. Microlite (nominally $Ca_2Ta_2O_7$) is a common accessory, and this unit is the principal ore of Ta in the pegmatite. Quartz is mostly absent. The unit is a good representation of Norton's (1986) zone [9], the last to form in lithium-rich pegmatite bodies and in experiments with comparable compositions. It is well exposed along the eastern end of the main cut. To the west, this unit grades into a body of fine-grained lepidolite that contains oriented and ovoid relics of microcline and spodumene. Microlite is a common accessory mineral, and quartz is rare. This is named the "spotted rock" zone for the occurrence of isolated relics of spodumene and microcline (Figure 4). From the spotted rock zone, station 5 on the walking tour, and path leads westward uphill to stop 3. Along the way, a gigantic microcline crystal exhibits a gradient in its replacement. Close to the spotted rock zone, the microcline is massive, lavender in color from fine-grained lepidolite, and it has mostly lost its cleavage. Islands of fresh vitreous white K-feldspar appear as a second generation within the original crystal. Moving westward, the pink coloration of lepidolite fades, the cleavage and beige color of the original feldspar becomes apparent, and the original microcline is free of replacement along its western edge.
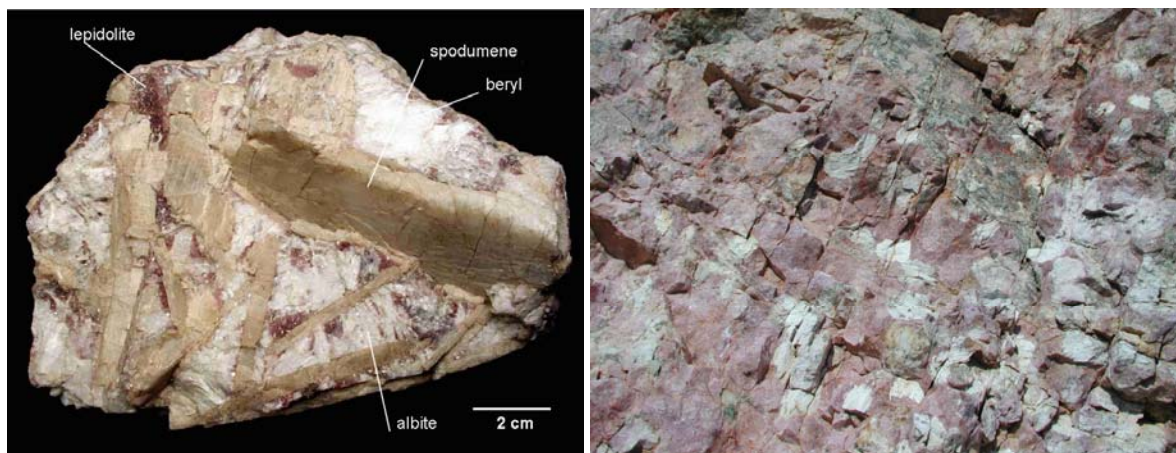

Figure 4. (left) A sample of the core unit at the Harding mine, NM. (right) The spotted rock zone.

The spotted rock zone and its extension into adjacent microcline are as good as any example of replacement in pegmatites. What is more equivocal is its relation to the other core variant, which is entirely fresh and lacking in replacement texture. The walking tour describes other features of the pegmatite that are attributed to replacement, including the replacement of quartz by albite of cleavelandite habit.

In the lithium-rich pegmatites of the White Picacho district, AZ, replacement is evident in the form of pseudomorphism of single crystals of the lithium minerals spodumene, montebrasite, elbaite, and lithiophilite, and in narrow bands of fine-grained mica that emanate from the cores of pegmatites to the surrounding hosts, where intense metasomatism produced tourmaline plus quartz in the place of the mafic schist (London, 1979; London and Burt, 1982). London and Burt (1982) proposed that the driving force for replacement might have arisen as an aqueous solution that equilibrated with one zonal mineral assemblage migrated into another different assemblage with which it was not in equilibrium. London and Burt (1982) identified that the initial stage of

hydrothermal replacement entailed the replacement of Li by Na and Ca, which they characterized as a reaction with an aqueous solution of alkaline character. This was followed by the wholesale removal of alkalis, which led to the formation of the fine-grained micas, in a solution that they deemed acidic. In all cases involving spodumene, montebrasite, and elbaite, however, aluminum was conserved in the host minerals. The replacement reactions involved only those alkali and alkaline earth ions, together with H^+, that are normally soluble in saline aqueous solutions.

In several instances, Cameron et al. (1949) cited radial crystal growth from a point, or parallel crystal growth perpendicular to a surface, as evidence of replacement. This might seem odd, because most of the mineral fabric of zones possesses unidirectional solidification texture (UST), in which crystals have grown with directions of elongation perpendicular to their substrate. Though Cameron et al. (1949) scarcely mentioned textures, they could not have been ignorant of or indifferent to the UST that is so prominent in pegmatites. I surmise that their conclusion – that pegmatites crystallize sequentially from margin to center – was influenced by the texture of UST. What is different about the UST of zones and the UST of what they identify as replacement bodies is this: the primary pegmatitic zones are "*polymineralic*" and hence more or less granitic and therefore plausibly igneous in composition, whereas the replacement bodies are essentially monominerallic. Throughout the history of the study of pegmatites, continuing to the present day, most geoscientists have not been able to grasp a mechanism by which monominerallic assemblages could be precipitated from igneous melts of eutectic composition, or as in the case of pegmatites, as monominerallic layers or masses of the more uncommon minerals, such as beryl or tourmaline. Quartz cores pose the ultimate challenge to an igneous model, which will be taken up again in a later essay. However, it is important to remember that replacement entails material transport in and out of a rock body via an aqueous solution, and that fluid and its solute load must come from and go somewhere. The replacement reactions must take place in response to chemical or energy gradients that drive the reactions to occur. If cleavelandite in UST replaced quartz at the Harding mine, then a chemical gradient must have existed that made albite more stable, and quartz in that volume less stable than the quartz around it. The volume of quartz undergoing replacement must have been dissolved, and much of that silica must have been transported out of the reaction site into massive quartz, where the system was already saturated in silica. Aluminum must have been transported in to the reaction site and selectively deposited there, not elsewhere along the fluid migration path.

Norman L. Bowen brought great insight to igneous petrology when others of his time thought that granites formed by metasomatic replacement reactions between solid rock and aqueous solutions. Bowen's (1928) contention, that *" ... to many petrologists a volatile component is exactly like a Maxwell demon; it does just what one may wish it to do."* (p. 282), has been cited repeatedly by those who emphasize the importance of aqueous solutions in explaining phenomena that lie outside of the understanding or expectation that produces ordinary rocks such as granite, which is something of an irony for Bowen's original lament. Phenomena that lie outside of the expectations of igneous magmas include many of the mineralogical and textural features found in pegmatites. These have driven models that make an aqueous solution essential to the formation of these rocks, and they have spurred reliance on replacement processes to account for many of the features of pegmatites. However, Cameron et al. (1949) saw it differently. Despite their occasional ambiguity between "*pegmatitic magma*" and "*pegmatite solutions*", they came down clearly on the side of an essentially igneous origin for the internal

structures of pegmatites, presumably including their quartz cores, and they relegated hydrothermal phenomena to a short subsection of *"Origin of Other Units."* (p. 105-106).

REFERENCES

Anderson, G.M. and Burnham, C.W. (1983) Feldspar solubility and the transport of aluminum under metamorphic conditions. *American Journal of Science*, **283-A**, 283-297.

Boltwood, B.B. (1907) On the ultimate disintegration products of the radio-active elements. Part II. The disintegration products of uranium. *American Journal of Science*, **23**, 77-88

Bowen, N.L. (1928) The evolution of the igneous rocks. Princeton University Press, 332 p.

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 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.

Duke, E.F., Redden, J.A., and Papike, J.J. (1988) Calamity Peak layered granite-pegmatite complex, Black Hills, South Dakota. 1. Structure and emplacement. *Geological Society of America Bulletin*, **100**, 825-840.

Fournier, R.O., Rosenbauer, R.J., and Bischoff, J.L. (1982) The solubility of quartz in aqueous sodium chloride solution at 350 degrees C and 180 to 500 bars. *Geochimica et Cosmochimica Acta*, **46**, 1975-1978.

Holmes, A. (1913) The age of the earth. Harper & Brothers, London, 196 p

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., 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.

Jahns, R.H. and Ewing, R.C. (1977) The Harding Mine, Taos County, New Mexico. *Mineralogical Record*, **8**, 115-126.

Landes, K.K. (1933) Origin and classification of pegmatites. *American Mineralogist*, **l8**, 33-56 and 95-103.

London, D. (1979) Occurrence and alteration of lithium minerals, White Picacho pegmatites, Arizona. Unpublished M.S. thesis, Arizona State University, Tempe, Arizona, 131 p.

London, D. (1992) The application of experimental petrology to the genesis and crystallization of granitic pegmatites. Granitic Pegmatites (R.F. Martin and P. Černý, eds.) *Canadian Mineralogist*, **30**, 499-540.

London, D. (2008) Pegmatites. *Canadian Mineralogist Special Publication* **10**, 347 p.

London, D. and Burt, D.M. (1982) Alteration of spodumene, montebrasite, and lithiophilite in pegmatites of the White Picacho district, Arizona. *American Mineralogist*, **67**, 97-113.

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. (1983) Sequence of mineral assemblages in differentiated granitic pegmatites. *Economic Geology*, **78**, 854-874.

Polya, D.A. (1988) Efficiency of hydrothermal ore formation and the Panasqueira W-Cu(Ag)-Sn vein deposit. *Nature*, **333**, 838-841.

Schaller, W. T. (1926) Mineral replacements in pegmatites. *American Mineralogist*, **12**, 59-63.

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 $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O. *Geological Society of America Memoir*, **74**, 153 p.