PEGMATITES AND HYDROTHERMAL VEINS

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The recognition of hydrothermal mineralization in complex pegmatites has led me to speculate as to whether or not such a phase possibly connects pegmatites with ore-bearing hydrothermal veins. It has been appreciated for some time that both types of deposits are formed from residual magmatic liquids. Is the process of crystallization of a magma from the normal igneous rock stage through the pegmatite and hydrothermal phases continuous or discontinuous?

In seeking a possible solution of these problems I have drawn both upon my own field studies and upon those of others. The subsequent paragraphs review some of these observations, and the theories that have been built upon them. At the close I give what is to my mind the most logical explanation (at the present state of knowledge) of the connection between pegmatites and hydrothermal veins. This is admittedly pure speculation, but if it leads to additional thought and search in the field for pertinent evidence it will have served its purpose. More field studies are particularly needed in regions where the "roots" of ore-bearing veins are accessible.

Historical Review

The possible relationship between pegmatites and hydrothermal veins has been a subject of discussion for at least 35 years. Various comments made by different authorities during this period are quoted in chronological order in the following paragraphs.

An early contribution on this subject was made by Kemp (1901): "Pegmatites are a more or less pronounced pneumatolitic result of igneous intrusion. Pegmatites grade insensibly into quartz-veins. Quartz-veins not visibly associated with pegmatites are open to the same interpretation unless there is positive evidence to the contrary. On the other hand, pegmatites, although widely developed, are but rarely provided with metallic minerals in notable amounts, and the same is true of the quartz-veins visibly associated with them. But it is also true that many regions of great development of pegmatite-veins are devoid of ore-bearing veins, as, for instance, New England."

Spurr (1902–1903) two years later described the transition from a granite dike through a pegmatite to a quartz vein in southern California. "In a single dike he observed, within the length of not many yards, a complete transition from a fine-grained pegmatite to a typical quartz-vein." Similar observations were made in the Walker river range in northwestern Nevada. A few years later, Spurr (1907) published a theory of ore deposition from which the following appropriate paragraphs are quoted:

"To restate in a different form ideas already explained, it must be understood that after each epoch of crystallization in a rock magma, there remains residual from the crystallized-magma rock a more siliceous and aqueous magma, in which the proportion of water to silica becomes progressively greater, since an increasing amount of silica is deposited at successive stages, but very little water at any stage. Finally there results the highly siliceous and aqueous residual magma from which pegmatitic quartz veins have crystallized. With the progressive increase in silica and water, there is a corresponding increase of certain metals, a fact which is exposed by the final precipitation, in the pegmatites and pegmatitic quartz veins, of such rare metals as tin, molybdenum, tungsten, and gold, in considerable quantity (quite out of proportion to their relative amount in the earth's crust).

"I now submit further that there results from the consolidation of the pegmatites and the pegmatitic quartz veins, practically all the accumulated water in the magma; that with this water is associated a greatly accumulated (concentrated or magmatically differentiated) quantity of the highly mobile and solvent elements such as fluorine, boron, and chlorine, whose presence in granite and pegmatite magmas is shown by such granitic and pegmatitic minerals as tourmaline, mica, and apatite; that much silica is present; and that there are also present many valuable metals, constituting a large portion (in some instances by far the greater portion) of the whole amount contained in the original body of magma.

"I submit that from such a residual magma quartz veins of later origin than the quartz veins closely allied to pegmatites are deposited, and that in them valuable metallic minerals are deposited; that from these veins a further residue results, still fluid under such conditions, but subject to partial consolidation (or to phrase it differently, precipitation) at a later period, under different conditions, involving chiefly a lowering of temperature; and that many successive stages of precipitation follow. . . ."

Singewald (1912), after describing geologic relationships of tin deposits in the Black Hills, the Carolinas, and Bohemia, states: "These occurrences illustrate, therefore, a complete gradation from the tin vein type to cassiterite as a primary constituent in the consolidation of a molten magma." The latter refers to cassiterite in pegmatite.

Spurr (1923) in his book on ore-magmas goes into considerable detail in regard to the relationship between pegmatites and ore veins. He states that "In all these dikes, pegmatite, quartz (feldspar), and quartz, the quartz is of a characteristically easily recognized type—coarsely crystalline, blue-white. It is identical in appearance with the quartz of the deeper-seated gold-quartz veins, as those of the Appalachians and California; . . . ." Farther on he states: "Closely allied to the pegmatites, however, are the pegmatitic quartz veins, in which the segregations of metallic minerals are often considerable and are valuable commercially. These are pegmatites with practically all the non-metallic minerals withdrawn save quartz. They characteristically occur in the vicinity of true pegmatites and show by transition their intimate connection with and derivation from these. They may and often do contain feldspar and other non-metallic pegmatitic minerals, but only in small quantities and as accessory minerals. They evidently represent, in short, a more highly differentiated, more strictly residual pegmatitic magma from which most of the principal granitic constituents save quartz have been separated.

"Closely allied to these metalliferous quartz veins of close pegmatitic affiliation are similar quartz veins not so closely associated with pegmatites and carrying scattered free gold, auriferous pyrite, and other sulphides."

Elsewhere in his monograph he notes that at Silver Peak alaskite pegmatite is "transitional into the gold-quartz veins, and primary free gold was found in this pegmatite."

Niggli (1929) evidently believes that mineral formation is a continuous process from the magmatic stage, which produces igneous rocks, through the pegmatite and pneumatolytic stage to the hydrothermal stage. He refers to the pegmatite and pneumatolytic stage as forming the connecting link between the stage of silicate melts and the aqueous solutions characteristic in the hydrothermal stage. He describes this process as follows: "The residual solutions continuously change in composition, and the melt gradually assumes the character of a pegmatitic, pneumatolytic, and finally hydrothermal solution while progressively decreasing in quantity. If it should be a fact that ore deposits are formed from the residual solutions derived from igneous rock consolidation, these deposits must be regarded as *magmatic formations* no less than the igneous rocks themselves.

"*Magmatic solutions in all their stages, showing a normal and complete sequence of mineral products, are only to be expected under conditions of moderate depth. Below such a medium level the last stages fall out, their contents being 'crowded' into the pegmatitic-pneumatolytic stage. In more superficial levels a similar 'crowding' takes place under hydrothermal conditions; the pneumatolytic stages are missing.*"

Farther on, Niggli refers to deposits containing pyrite, tourmaline and quartz as representing the transition to hydrothermal deposits.

A compilation of quartz veins or dikes of igneous origin has been published by Tolman (1931). He excludes quartz veins that contain metallic ore deposits, but does mention auriferous quartz veins in Victoria, Australia, which are believed to be of pegmatitic origin because of the presence in varying amounts of feldspar, muscovite and tourmaline.

Holmov (1931) after describing the succession of vein formation, which starts with a pegmatite period, in the Duldurga tungsten deposit of Siberia, states: "The gradations from the pegmatite dikes to the quartz veins, the coarse-grained structure of the interlocking wolframite-quartz veins of drusy structure with a simultaneous formation of wolframite and quartz, point to the magmatic nature of the quartz veins presenting the extreme members among the diaschistic rocks of the granite magma. The siliceous magmatic solutions reopened the pegmatite dikes and, in their turn, were again reopened by later siliceous magmatic solutions."

Loughlin and Behre (1933), although admitting the possibility that a few ore minerals may be deposited by pegmatitic solutions, believe that in most instances the ore minerals are later than the pegmatites and come from a deeper source.

"It is sufficient here to recall that in some pegmatites primary crystallization was followed by fracturing and by the introduction of new material which effected replacement of the original minerals by such later minerals as tourmaline, garnet, and cassiterite. Some of these minerals are characteristic of contact-metamorphic and hydrothermal deposits in both siliceous and carbonate rocks, and appear to be the most direct link that connects the after-effects of igneous intrusion with ore deposits; but the likelihood of a distinct interval between the deposition of these minerals and the introduction of sulphides from a deeper source has already been emphasized.

"The transition of pegmatites into massive quartz veins, even where there is no subsequent development of these later pegmatitic minerals, has led some to maintain that there is a continuous transition through these veins into metalliferous veins; but, if any such transitions have been proved, they are extremely rare. The usual structural relations where metalliferous deposits of appreciable size are closely associated with pegmatites show that the metalliferous minerals, especially the sulphides, were introduced at a distinctly later stage than the pegmatitic quartz by solutions derived from a deeper source than that of the local pegmatites. Small amounts of certain ore minerals may admittedly be the end products of the solutions that formed the pegmatite or the late pegmatitic minerals noted above; but their very scarcity, although according with the general sequence of mineral deposition, lends further support to the suggestion that ore-forming solutions in large quantity are derived from a deep source that was developed by further differentiation after the pegmatitic and contact-metamorphic stages."

The Loughlin-Behre hypothesis, however, does not preclude the possibility that the hydrothermal veins may come from much deeper pegmatites.

Emmons (1933) divides pegmatites into two groups, one of which he considers to be closely related to the hydrothermal veins. "With regard to the distribution of pegmatites it is practicable to consider two groups: (1) those that are composed of feldspar, quartz and mica with subordinate metallic minerals, and (2) those of feldspar, quartz, and mica without workable amounts of metallic ores. The first group is formed chiefly in the fractured hood and in the roof region near the batholith. Pegmatites do not form so far above the base of the roof as do metalliferous veins and, as already stated, those that contain metals in important amounts do not extend far below the roof of the batholith or into the part below the hood. The dead line for such pegmatites is probably two or three miles from the contact between the top of the hood and the base of the roof. For the second group of quartz-feldspar-mica pegmatites no dead line can be established. They may be found in essentially all deeply eroded batholiths, even in those that are most deeply eroded. They lie far below the dead line for metalliferous pegmatites and for mineral veins and presumably form at all stages of cooling. All pegmatites that carry important amounts of metals and those mineral deposits that have quartz-feldspar gangue, like the gold lodes of Silver Peak and Passagem, certain tin lodes of Malay Peninsula and the copper lodes of Moonta, are in the roof and hood regions of batholiths. These deposits have strong pegmatitic affiliations although many of them are more closely allied to veins of the deep zone—the hypothermal deposits of Lindgren's classification." In the next paragraph Emmons states that the formation of fractures "continues after the main stage of the deposition of pegmatites with metals, for the pegmatites generally are older than the normal metalliferous veins. Such veins cut pegmatites."

Weed (1933) definitely connects the hydrothermal veins with pegmatites. "As the molten granitic magma is the mother of pegmatite, so the latter gives birth to the highly gaseous fluids which form quartz veins, and most of our primary ore deposits. The great majority of pegmatites are however as barren of ore minerals as most granites." Farther on he states ". . . it is certain that the strictly igneous period ends in the pegmatite stage and the Volatile or Hydrothermal period begins. There is no sharp line between the ores of one period and the other, since the pegmatites connect them . . . ."

Ross (1933) is one of those recognizing a hydrothermal phase in pegmatites. In regard to a possible relationship between pegmatites and ore veins he states: "It is generally believed by petrologists that aplite-forming and pegmatite-forming materials result from the expulsion of residual magma during the late stage of crystallization when alkalic feldspar and quartz are known to be forming in the parent magma. Quartz is also a late mineral, and during the stage of its formation the expulsion of residual material may be a source of the quartz veins and dikes, but quartz forms over so wide a range of conditions that this is probably not the only source of quartz-forming material." A closer relationship is implied by the same writer (1934) in a later article. "Many pegmatites have been modified and new minerals introduced by post-magmatic hydrothermal replacements. Most of these minerals are of a type that show no obvious relation to ore deposits, but the biotite, tourmaline, garnet, other ferro-magnesian minerals, and the sulphides that belong to the later hydrothermal stages of certain pegmatites, are probably derived from the parent magma by the same processes as similar minerals of ore-bearing veins, and indicate a relationship between the hydrothermal processes in pegmatites and ore veins."

Landes (1934), after describing a quartz vein which contains beryl and molybdenite, concludes that "the relationship between beryl and pegmatite is so close that one is justified in assuming that beryl-containing deposits have been formed by pegmatitic solutions. The quartz-molybdenite-beryl vein of Chaffee County, Colorado, which occurs in a region of granite and pegmatite intrusion, is thought to have been deposited by hydrothermal solutions escaping from a deeper solidifying pegmatite. If these conclusions are correct, quartz veins containing beryl may be looked upon as a link connecting pegmatites with normal quartz veins."

A somewhat similar conclusion in regard to quartz veins containing feldspar has been reached by Anderson (1935): "Much has been written of the association in some districts of gold with pegmatites, but the nature and frequency of this association have not been as fully understood as they should be—probably because this pegmatitic phase is often so limited in extent as to pass unrecognized. Yet, in my experience, it is one of the most frequent and most positive signals of the impending death of a quartz vein.

"Study of a great many outcrops in areas where erosion has largely destroyed the horizons in which the gold-bearing quartz veins were formed shows that at and near the top limit of the dike with which they were associated there was a tendency to the local segregation of its component minerals, the feldspar crystallizing separately, often in large pegmatitic crystals, the quartz as irregular quartz veinlets without continuity or persistence. Usually, the range of travel of the feldspar was small, as, once separated from the quartz, it quickly cooled to the temperature of crystallization. Often the gray or white feldspar is not recognized as such, being thought to be simply a different character of quartz. Thereafter the quartz continued upward alone, with its burden of metallic minerals. If the nature of the invaded rocks and the physical condition of the fracturing permitted, it very quickly assumed a definite course and formed a typical quartz vein."

Palache (1935) in describing paragenesis at Franklin, New Jersey, was unable to draw a sharp boundary between minerals formed by pneumatolytic processes in pegmatite contact zones and those deposited by hydrothermal solutions:

"There is no sharp delimitation between the pneumatolytic veins and those of the next or hydrothermal group. Some species of minerals are found in both, but in the hydrothermal group there is less evidence of replacement in the walls, the veins being in general clearly fissure veins.

"The mineralogy of the hydrothermal veins is scarcely less complex than that of the pneumatolytic veins. Many of the minerals, however, were obviously formed at lower temperatures than the pneumatolytic minerals and either farther from the pegmatitic intrusions or during later fissuring."

Lindgren (1936) apparently believes that a continuous process connects the formation of igneous rocks with hydrothermal vein formation. "In intrusive bodies the residual magma is an aqueo-igneous melt of SiO_2, K_2O, Al_2O_3, Na_2O, which is in condition to produce pegmatite. Finally, there takes place by fractional crystallization a separation between the silicates and the volatiles. The pressure increases and the volatile extract, still of acid reaction, may escape and is now in condition to attack any minerals it may encounter. 'It is probable these acid solutions are the principal agents of contact metamorphism, of vein formation, of replacement and metasomatism in general.' "

In summary, most of these writers believe that deposition by hydrothermal solutions is continuous with pegmatite formation. A few cite field observations in support of their conclusions. But almost all admit that with few exceptions ore minerals are noticeably scarce in pegmatites. This subject will be covered more fully in the following section.

Ore Minerals Occurring in Pegmatites

Many references are given in the literature to occurrences of metals in pegmatites, but most such occurrences are non-commercial. An outstanding exception is tin which is mined in pegmatites at a number of localities. Lesser exceptions are tungsten, molybdenum, and some of the relatively unimportant rare metals. These last are not included in the following discussion.

I believe that where metallic minerals do occur in pegmatites they have precipitated from hydrothermal solutions that are formed during and by the crystallization of the pegmatite magma. The evolution of this concept has been given elsewhere (Landes, 1933).

The ore mineral of tin, cassiterite, has been found in pegmatites in many parts of the world. Ahlfeld (1936) describes such occurrences in Bolivia, Artemiev (1930) notes the presence of cassiterite in commercial quantities in lithium pegmatites in Siberia, Davison (1930) classifies some of the Cornwall tin deposits as pegmatite, Dunn (1907) has found tin in pegmatites in Victoria, Krusch (1928) reports a similar occurrence in western Spain, and Scott (1932) mentions cassiterite in pegmatites in a district in the Belgian Congo. A few of the many other authors who have found cassiterite in pegmatites include Ferguson and Bateman (1912), Graton (1906), Hess (1933), Singewald (1912), Anderson (1928) and Faribault (1908). Many tin-bearing pegmatites are described by Jones (1925) in his monograph on the tin deposits of the world.

Another metal commonly found in pegmatites is tungsten. This element occurs both with tin and separately. Deposits in Bolivia are described by Ahlfeld (1932), in western Spain by Krusch (1928), and at various localities by Rastall (1918). Hess (1933) describes the occurrence of wolframite and other ore minerals in pegmatites.

Magnetite is abundant in some pegmatites, especially in the New Jersey highlands as described by Bayley (1910) and Palache (1935). Other localities are mentioned by Buddington (1933). Gold has been recorded from a few localities. Occurrences in Utah have been described by Butler (1920), in Nevada by Spurr (1923), in Brazil by Kemp (1901) and Derby (1911), in Victoria by Tolman (1931), and in Dartmoor, England, by Brammall and Harwood (1924). Even platinum has been found in pegmatites in South Africa, as mentioned by Vogt (1930) and Tyler and Santmyers (1931).

Only one sulphide ore mineral, molybdenite, is found in pegmatites with any consistency. Thomson (1918) describes a number of Canadian occurrences. Among other authors who have mentioned molybdenite in pegmatite are Ahlfeld (1936), Buddington (1933), Rastall (1918), Spurr (1923), Landes (1934), and Warren and Palache (1911). Miscellaneous sulphides, such as pyrite, arsenopyrite, bornite, and chalcopyrite, have been described in pegmatites by Buddington (1933), in Southwest Africa by Niggli (1929), in British Columbia by Kemp (1901), in Washington state by McLaughlin (1919), and in California by Graton (1909). Palache (1935) records galena and sphalerite in the Franklin, New Jersey, pegmatites and over a dozen sulphides, arsenides, and native metals among the pneumatolytic products in the pegmatite contact zones.

Conclusions

Tin, tungsten, and molybdenum.—The important metals which may occur in commercial amounts in pegmatites are practically confined to tin, tungsten, and molybdenum. Considerable field evidence has been amassed that the pegmatite occurrences of these metals imperceptibly merge with typical hydrothermal veins. The source magmas for the ores of tin, tungsten, and molybdenum are very acidic (Hulin, 1929–30). *Granitic magmas produce pegmatites and these in turn produce hydrothermal solutions which may precipitate ores of tin, tungsten, and molybdenum both in the pegmatite and in veins in the country rock, adjacent to and for indefinite distances above the pegmatite.*

Other metals.—Most ore minerals, such as gold and sulphides, are derived from less acidic magmas (those that crystallize into granodiorite, monzonite, diorite, and varieties of these rocks). These minerals are not found in pegmatites in commercial quantities. One reason for this is that known pegmatites are very scarce in rocks of this type, much more so than is justified by the lesser area of outcrop (compared with granite) of intermediate rocks, including granodiorite. Is this because most of these rocks have not yet been eroded to the level of abundant pegmatites? Or is it because the intermediate magmas for some reason pass through but a very subordinate pegmatite phase before entering the hydrothermal phase?[1] The previously quoted remarks of Anderson (1935) lend support to this theory, for he found the "mother pegmatite" of gold to be so insignificant as to possibly escape recognition in many cases. *Intermediate magmas during their crystallization sequence pass through a minor pegmatite phase before entering the hydrothermal phase. During the latter gold, sulphides, and similar ore minerals are deposited in whatever pegmatites are present, but mainly in hydrothermal veins in the overlying rocks.*

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[1] In my experience pegmatites are large and abundant only where they are offshoots of potash rich rocks (granite and syenite).

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