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Introduction

Pegmatites are usually thought of as late magmatic emanations from cooling batholithic masses; however, in recent years doubt has been cast on the intrusive nature of many of the larger granitic masses. The granite-gneiss massif used as an example in this discussion is the Kheis granitized geosyncline of South West Africa and the Union of South Africa. From the top downward it is a pile of metavolcanics, gray gneiss and three cyclothemes of metasediments. This complex was previously called the Namaqualand granite-gneiss batholith and thought to be intrusive. If massif is neither intrusive nor batholithic in nature, associated pegmatites cannot originate from its late magmatic products. In addition to the example of the Kheis System, phenomena of the Svionian in Fennoscandia, Hercynian in Corsica and Beltian in Idaho will be mentioned.

In exploring (6) for a mineralized area it can be seen that the theory of ore deposit genesis followed is of great importance. If an organization is instructed to look for cooling fractures about a hypothetical batholith, it would tend to restrict its search to a region about a broad outcropping of granite domes or "inselbergen" in South Africa; if it were instructed to work on metasedimentary theories, the workers would probably make traverses until they found likely members, and then follow these metasediments along strike.

The Composition of Pegmatites

The composition of pegmatites varies from extreme mafic to granitic; however, most are of granitic composition. Unusual gabbrodal and even charnockitic pegmatites are found in fissures through these same rock types. Basic pegmatites are decidedly subordinate in volume in contrast to "granitic" pegmatites. There must be a fundamental reason for such proportions. Granitic pegmatite is something of a misnomer as these coarse-grained bodies frequently contain rare metals such as Li, Be, Sr, K, U, Th, No, Ta, and U in quantities which are unheard of in granites and granite gneisses. Graphite, the thorium-rich hydrocarbon; thucholite, and bubbles in quartz crystals filled with liquid carbon dioxide are not uncommon in pegmatites. Possible sources of this carbon will be discussed in the last section. An abundance of water during the time of formation is indicated by: successive replacement of minerals, abundance of hydrous minerals, inclusions of water in bubbles and cavities which often contain particles describing Brownian motions. Kaolinization is probably due to release of water held in intergranular films or in "eutectic" mixtures with the silicates. The question of whether water associated with pegmatites is juvenile, or derived from metasediments which generate pegmatites under special structural and physical conditions, will be discussed in the last section.

The Association of Pegmatites With Schists

Certain metasediments are always closely associated with or host rocks to pegmatites. These are schists, hornblende gneisses, sillimanite-kyanite-corundum schists and gneisses, gneisses extremely rich in potash, and calcic gneisses which were once marls. Many of these metasediments are quite evidently former pelites, calcic-pelites, and precipitates. (34, 29, 16, 3) In the pre-Cambrian systems of the Rhodesias and in the Kheis System of South Africa one may give a rule—if there are no schists present there will be no pegmatites; and conversely where there are schists there are pegmatites. Schists and schistose suites often outcrop in belts stretching hundreds of miles along strike. Such metasediments represent deposition under varying conditions prevailing over great areas of the geosynclines. Usually schistose suites disappear only where covered by later metasediments or younger sedimentary systems. They tend to loop, forming ellipses and rings about gneissic and granulitic domes. It has been the custom to indicate these domes as intrusive plutons, or younger granites intruding old metasediments. This, however, is not the case; on close examination it has been found that many of these "plutons" represent highly folded metasediments originally of a more psammitic and psephetic nature than the schistose suites. Such gneisses often contain skialiths, agmatites, lines of agmatitic "xenoliths," ghost structures, and their fold axes are quite parallel with those in the surrounding schists. In general, schists of the Kheis, Svionian, Bulawayan, E. Greenland, Beltian, Nippon, and other such systems tend to be more markedly isoclinally folded, overfolded and ptygmatically folded than underlying and overlying granite gneisses. Their total thicknesses are also much less than that of the gneissic piles. In the Kheis System of Namaqualand, the position of the pegmatites with respect to the schistose suites is highly significant; they are universally found in and stratigraphically above major schistose suites; they are never found below unless they originate from a stratigraphically lower schistose suite.

It is worth mentioning that geological problems are much easier to work on in a desert where there is no vegetation whatever, where every crystal in every rock exposed is unobscured by lichens and clearly visible, and where up to 30 percent of the surface is bare rock.

Such conditions are not even approached in more humid areas of the earth. In an area several hundred miles square it is to be expected that sedimentary conditions will vary; even if general conditions are similar through an entire section of a sedimentary trough, local shallows and basins are to be expected. This is reflected by the thickness, mineralogy, composition, relic sedimentary features, and structure of schistose and other metasedimentary suites studied by the writer in South Africa, Scandinavia and Greenland. This is also reflected by the composition of the pegmatites of each local basinal area.

Metasedimentary Gneisses and Granulites

Pegmatite-bearing schistose suites are associated with masses of granite-gneiss and granulite; pegmatites, however, are practically unknown in areas of anatectic granite or rhyolites. Granite gneisses and granulites also form belts hundreds of miles long. They represent ultrametamorphosed sediments of the Kheis System lying stratigraphically below the schistose suites, tending to resist weathering and to form protruding domes, which structurally are almost always anticlinal. Agmatites are common in these granitic-gneisses, representing minor schist bands which have been assimilated. In the Kheis System the frequently hypothesized intrusion of schists into such gneissic piles seems improbable. The writer has mapped, mined through and drilled through single schist members which maintain their thicknesses for distances of up to 60 miles from their outcroppings. In many cases he has been able to follow stratigraphically higher and lower granitic-gneisses for some scores or even hundreds of miles into areas where the same members showed ripple marks, graded bedding, rhythmic bedding, cross bedding, sedimentary zircons, tourmalines, and outlines of pebble, etc. Intercalated schistose members usually grade into marls. Lit-par-lit injection of pegmatites between schists is often mentioned, but is this a necessary or even logical theory? Imagine a thin aqueous fluid forcing its way through a schist band only two feet thick (to take one example in Namaqualand) and to do this over lateral distances of up to 200 miles. Could not these "lit-par-lit" pegmatites be venites and arterites generated locally from ingredients which were always present in the "schists"? Is this not much more logical? Marked development of pegmatites is much more typical of gneissic piles in ageosynclinal environment than it a geanticlinal environment like that of the Pyrenees, Aara Massif, Himalayas, or Rocky Mountain-Andes Chain. If pegmatites originate from rest liquors of cooling granitic masses one would expect to find a great many in asthenolithic bodies of the Andes; yet, the Andes are remarkably poor in pegmatites. In the Rocky Mountains of America, pegmatites are most abundant in old Pre-Cambrian Systems such as the Beltian, which have little to do with the Rocky Mountain orogeny. This section may be concluded by saying: pegmatites and pegmatite-bearing schists are associated with granite-gneiss massifs, but only those of a geosynclinal, and metasedimentary nature. (1, 10) (33)

A Structural Sequence of Pegmatites

The internal structure of pegmatites has been discussed at length by researchers who worked in various pegmatized regions of the United States during and immediately after World War II. (7) Not much attention has been given to the external structure of pegmatites. The writer finds that pegmatites of the Kheis System of South Africa fall into an almost idealized structural sequence; pegmatites in other regions seem to do the same. The internal structures and compositions of pegmatites in the Kheis and probably elsewhere are directly related to their external structures, attitudes, distance above source beds, and supply of materials from the source beds. Five ideal types are listed below:

A. *Concordant pegmatites:* These are sheet-like, clot-like, or irregular, and found in their source beds. (concordant)

B. *Dominantly concordant with a slight tendency to penetrate stratigraphically higher metasediments:* These bodies include pegmatized masses, rolls and humps of gneiss which have been pegmatized, and sheets of pegmatite metasomatically altering stratigraphically higher beds. In such bodies, the discordance is always quite obviously the result of metasomatism. (concordant and penetration)

C. *Sheets with fins:* The lower, sheet-like part, tending toward the horizontal, and the concordant part of these pegmatites tend to lie in the source bed; while the discordant "shark's fin" cuts through stratigraphically higher metasediments and tends to the vertical. (concordant and discordant)

D. *Footed-dikes:* The foot represents a pedicle, resting in the source metasediment; the main body of the pegmatite tends toward the vertical in rocks which did not contribute matter to the forming pegmatite. Horizontal sections through such pegmatites often show a tendency toward circularity as one moves upward, and away from the source metasediments; though this is by no means a rule. (almost completely discordant)

E. *Pegmatitic diapirs, dikes, lenses:* Such bodies are completely discordant, have no readily observed connection to the source beds, and tend to stand vertical. (discordant)

Note: If several source beds were stratigraphically close to one another it can be seen that a complex body would form; however, source beds tend to appear at the tops of cyclothemes, while pegmatites rarely penetrate from one cyclotheme through to the former pelitic and precipitated members of the stratigraphically higher cyclotheme. For practical purposes, and quite literally, the formerly pelitic metasedimentary suite of one cyclotheme may be considered as a single horizon.

Metasedimentary Sequences in Granitized Geosynclines

Granite masses or massifs of great size, for example the Beltian in Idaho, Svionian of Norway, Sweden and Finland, or Kheis of South Africa, are by no means homogeneous masses. The above named distinctly show sedimentary attitudes on a regional scale; and in the case of the Kheis the belts of sedimentary attitude may be divided into cyclothemes. A typical cyclotheme is the stratigraphically lowest of the Kheis Geosynclinal System, the Springbok, tabulated below:

	Metasediment		Former Sediment
Uppermost	calcic-granulite	50′	limestone or precipitates
	schists	100′	pelites
	quartzite-silexites	200′	cherts and psammites
	granulite	1000′	psammites
Lowermost	gneiss	2000′	psephites

Pegmatites are most frequently associated with schistose and calcareous members of the cyclothemes; and furthermore, are more abundant in and above the schistose-calcareous members of stratigraphically higher cyclothemes. This is because these upper "pelitic-precipitate" suites are thickest in the upper cycles. While in contrast, granulites and gneisses tend to make up less and less in proportion of successively higher cyclothemes. There is also some tendency in stratigraphically higher cycles for pegmatites to be somewhat more abundant toward but not at the axis of the geosynclinal fold.

Pegmatites of the Kheis fall into groups which may be dominantly potash, feldspar, plagioclase feldspar, or quartz and otherwise characterized by Li, Sr, Be, Ta-Cb, W-Fe, W-Ca, Be, Th, Al mineralization. Pegmatites of the three major cyclothemes distinguished in the Kheis System have the following general characteristics:

Characteristic Silicates	Size of Pegmatites	Economic Minerals
Cycle 3. Potash feldspar Stratigraphically highest	Enormous with potential for large Li mines	Li, Be, Ta-Co, Al, Sr
Cycle 2. Plagioclase feldspar and quartz	Medium sized, several major tungsten mines	W-Fe, U, some Al
Cycle 1. Quartz Stratigraphically Lowest	Small	W-Ca, Sn

The Sequence of Metasedimentary Suites in a Granitized Geosyncline

The three cycles or cyclothemes are not the only metasediments of the Kheis System. Stratigraphically above them there is a system of

Gray Gneisses which represent transformed pelites, calci-lutites, pyroclastics, precipitates, occasional basic extrusives and occasional psammites. Above the Gray Gneisses lie metavolcanics. Practically all of these are basic, though occasionally remnants of acidic or rhyolitic extrusives are found. Outcrops of Gray Gneiss and metavolcanics are found only toward the center of the syncline; they are in most cases intensely isoclinally folded; occasionally they are intruded by ultrabasics which appear as late, narrow, post folding dykes. A table showing a complete section through the geosyncline is given below. Note that thicknesses of the cyclothemic metasediments were taken at least 100 miles from the center of the syncline (which lies close to the course of the Orange River), while thicknesses of the Gray gneiss and metavolcanics were taken close to the center of the syncline.

	Metasedimentary Suite	AP. Thicknesses	Former Sediments (Stratigraphically Highest Given First)
Uppermost	Metavolcanics	500′	spilites, pyroclastics, rhyolites, large basic flows
	Gray Gneiss Suite	2000′	pelites, calcilutites, pyroclastics, precipitates, psammites, basic extrusives
	Cyclotheme 3	2000′	Ca-granulite, schists, quartzite, granulite, gneiss
	Cyclotheme 2	2250′	Ca-granulite, schists, quartzite, granulite, gneiss
Lowermost	Cyclotheme 1	2000′	Ca-granulite, schists quartzite, granulite, gneiss

Rock Types and Structures Associated With Pegmatites

Pegmatites are associated with schists. A number of other rock types, petrological structures, metasomatic features, and ore deposits are closely associated with these same schists or the stratigraphically higher calcic granulites:

Orbicular bodies are abundant in Namaqualand. They are restricted stratigraphically to calcic granulites and schists, structurally to positions on the north flanks of discordant anticlines distorting the granulites and schists, and physically to rock volumes of the granulite facies which have neither undergone anataxis or marked diapthoresis (12, 13, 15, 19, 24, 28, 38).

Small anorthositic, noritic and charnockitic bodies are stratigraphically restricted to schists and calcic granulites though they may form somewhat discordant bodies above their source beds; they are physically restricted to rock volumes which were altered under physical conditions of the granulite facies. The writer wishes to emphasize that these bodies are small—less than one quarter of a mile in lateral extent. This is in order to distinguish these basic bodies from larger ones such as the Adirondack anorthosites, etc., which might have quite a different origin (17).

Schistose belts rich in aluminous minerals such as sillimanite, kyanite, corundum, mullite and deposits of the same are typically associated with pegmatitic belts or areas. If one accepts the metasomatic-metasedimentary origin of pegmatites, as outlined in the preceding paragraphs, it is obvious why such aluminous belts should be associated with pegmatites. The pegmatites would originate from such formerly pelitic beds; and the most marked pegmatite development would be associated with the most extensively developed sediments—metasediments of this nature. Furthermore, the thickest beds of the aluminum-bearing sediments would logically be expected in the stratigraphically highest metasedimentary suites, exactly as is found in the Kheis System.

Agmatites are commonly associated with pegmatitic belts; however, they are not always in the vicinity of the pegmatites. The writer believes that there is both a physiochemical and stratigraphic reason for the association of marked agmatite development with pegmatites. First, the agmatites do not seem to develop in amphibolites; or, defining the rocks physically, in the amphibolite facies. Temperatures seem to be too low. Secondly, agmatites form preferentially in basic sediments or metasediments, such as marls, basic extruive, pyroclastics which would form Gray gneisses under extreme metamorphic conditions. When Gray gneisses are subjected to physical conditions of the granulite facies, agmatites form. It can be seen that agmatites would tend to form near pegmatites, as the source metasediments of both would tend to have been formed in close association during periods of slow sedimentation. Agmatites would tend to be more common in the stratigraphically highest members of a geosynclinal sequence (18, 35).

Physical conditions influencing the formation of granitic pegmatites in the Kheis System: The pegmatites were found closely associated with rocks of the granulite, and amphibolite facies. Few were found in rocks which seem to the writer to have been under physical conditions of the granulite facies for excessive lengths of time; it seemed also that pegmatites in this environment had been partially or wholly destroyed by having their ingredients driven away.

A supply of water seems essential to the formation of pegmatites. The writer believes that it acts as an intergranular flux through which complex and simple ions, the pegmatizing medium, can move in and out of a rock volume. Water associated with the pegmatizing process has been classified as "juvenile," water new to the surface of the earth, water being contributed from the depths of the earth to its atmosphere and oceans for the first time. However, such theories of juvenile water are scarcely necessary if one accepts a metasomatic-metasedimentary theory of pegmatic genesis. It is obvious that pelitic sediments would contain a great amount of water:

(a) intergranular water, which would tend to be driven quickly from psammites and less quickly from pelites during diagenesis; (b) water held by capillary forces, which would tend to be more abundant in finer-grained sediments and would be driven from the pelites with less ease than intergranular water; (c) water of crystallization, which would be the last to move. It is quite probable that water of crystallization, rather than being driven away from the pelitic rock volumes during initial heating toward the granulite facies, would tend to become more and more miscible with the initially finely divided silicates (clays) as they approached an anatectic or magmatic condition. It is probable that much of this water of crystallization would be driven from the pelitic volumes only upon their cooling. Notice that this would be quite in keeping with the classical theory of a late aqueous fluid given off by cooling granitic body. (It would be most interesting to see calculations of the affinity or holding power of clays and phyllosilicates for water versus rising temperatures and the miscibility and holding power of liquid magmas for water.) The writer believes that water associated with pegmatization in the Kheis System is derived from the same sediments that the other pegmatizing substance comes from.

A pegmatite is a localized structure—both a local physical (thermodynamic) and localized structural environment acted to concentrate matter originally dispersed through a source bed. A second hydrous front may overtake the rock volume on cooling of a rock mass. In some cases this results in accelerated retrograde metamorphism or diapthoresis. This might alter rocks of the granulite facies to those of the amphibolite facies, or even kaolinize the mass. The writer would like to mention without too much discussion what might be called "The Principle of Interdependent Fronts": The movement of elements through a rock body is accelerated by the presence of water as H_2O, intergranular films, or disassociated water molecules. When a hydrous front outruns a complex of silicates which are relatively unstable under current PVT conditions, movement of ions is greatly diminished. Movement does however continue and at this stage the influences of unstable ions upon each other is accentuated. Every element does seem to have its own velocity; but when several move through the same volume they may either accelerate or retard each other—hence, interdependent fronts.

In concluding the section on physical conditions associated with pegmatization, it is suggested that replacement rather than crystal differentiation seems to be a universal feature in all pegmatites the writer has seen. No one has ever seen a pegmatite magma. The ability of such a hypothetical magma to accomplish lit-par-lit injection through a schist six inches thick over distances of up to 200 miles seems as improbable to the writer as phlogiston. Why shouldn't these small lit-par-lit bodies be simple venites and arterites?

Granitized Geosynclines With Large Pegmatized Areas

There are several examples of pegmatitic provinces similar to the Kheis. Svionian of Fennoscandia shows lower red and white gneisses and granites (Stockholm Granite). These lie stratigraphically below and on occasion intrude a Gray Gneiss Suite (Uppsala Granite). In turn Uppsala granite is overlain by metavolcanics and metasediments which were formerly pelites. The association of pegmatites, orbicules, basic bodies, etc., is similar to that in the Kheis System. The Beltian System of Idaho shows similar features respecting pegmatites, aluminous rocks, orbicules, gray-gneisses and white granite gneisses. Similar features are found in the Black Hills, North Carolina, the Pala District of California and Prieska la Corne District of Canada.

Suggestions for Searching for Pegmatized Areas

When a metasomatic theory of pegmatite genesis is accepted for a region, it is suggested that the following criteria and methods be used in searching for areas which are pegmatized: (2, 9, 11)

1. Search in rocks of the amphibolite, epidote-amphibolite, and granulite facies.
2. Search in granitized geosynclinal provinces.
3. Search about and stratigraphically above schistose metasediments which were originally pelitic.
4. Search in areas where high temperature aluminous minerals such as sillimanite, kyanite, corundum and mullite are abundant. Lower temperature minerals such as staurolite, etc., are not often associated with economic pegmatites.
5. Search in areas where belts or isolated orbicular bodies are found and where agmatites and small noritic or charnockitic bodies are extensively developed. The pegmatites should not be in the immediate vicinity of these rock types but are often in their neighborhood.
6. If sedimentary conditions in the former pelites (schists) can be determined, further evidence as to what type of pegmatitic province might be in an immediate area will be indicated. Fresh or slightly salty water suggests Al and K-rich pegmatites, reducing conditions with marked development of hydrolyzate-organic systems will suggest Na, U, Th, Ta-Cb, thucholite rich pegmatites; quiescent shallow, salty environments suggest later W-Ca, W-Fe and siliceous pegmatites (36) (8, 14, 25, 27).

Granite pegmatites tend not to be found in provinces under the following conditions:

1. Where large noritic or anorthositic bodies (which the writer imagines as originating from transformation of volcanic-calcareous piles) are present.

2. In metavolcanic suites except where fed from below (in which case the writer has observed veins carrying wolframite and ferberite mineralization, altering to a vein carrying scheelite in the calcareous volcanic suite).

3. In massive, fresh, granite-gneisses, granulite, rapakivis, or massive asthenolithic harpolithic laccolithic or other such intrusive bodies.

4. With ultrabasics, oceanites, dolerites and plateau basalts.

Summary and Conclusion

A theory of pegmatite genesis from pelitic sediments has been presented with illustrations from the Kheis Geosynclinal System of Southwest Africa and the Union of South Africa given as typical examples. It is suggested that the theory is applicable to most of the major pegmatitic regions of the United States. The metasedimentary sequence in the Kheis System is tabulated together with sedimentary antecedents. This is not theory as the members were traced along strike from rocks of the granulite facies to sediments of the epidote-amphibolite and even green schist facies. It is shown that pegmatites that are associated with pelitic members found in the upper parts of each of the three cyclothemes comprising the System and that they are most abundant in the upper cycles. In the last two sections criteria are outlined by which pegmatized areas should be searched for by parties instructed to work with a metasomatic theory of pegmatite origin. (4, 5, 20, 21, 22, 23, 26, 30, 31, 32, 37)

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