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Mechanics of pegmatite intrusion

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Abstract

The position, shape, orientation, and to some extent the size of pegmatite bodies are controlled by a complex interplay among pegmatite fluid pressures, rheologic state of the host rocks, lithostatic and directed stresses, pore-water pressures, strength and ductility anisotropies, and dilational directions. Pressures of pegmatite fluids must overcome confining normal stresses and, where applicable, tensile strengths at intrusive sites before intrusion takes place. In the upper crust, where brittle conditions prevail, lithostatic and directed-stress conditions combine with strength anisotropies—such as fractures, cleavage, schistosity, or bedding—to produce various preferred directions of minimum resistance to intrusion. Pegmatites encountering these conditions are tabular and have a preferred orientation normal to these directions. At lower levels in the crust, ductile hydrostatic conditions promote the intrusion of lensoid to irregular pegmatites. Changes in shapes and attitudes of pegmatites in the Winnipeg River and Yellowknife districts of Canada, in the Black Hills and Colorado of the United States, in Greenland and in Afghanistan all can be interpreted in terms of the theoretical models developed for the different combinations of these factors.

Introduction

This paper presents to mineralogists, petrologists, and explorationists a summary of the structural factors that interact to control the size, shape, orientation, and position of pegmatites. This summary is based on concepts that have been understood for some time in structural geology (Anderson, 1936, 1938; Roberts, 1970; Koide and Battacharji, 1975; Pollard, 1976, 1977; Muller and Pollard, 1977; Nakamura et al., 1977; Shaw, 1980), but that have not been fully acknowledged by workers concerned with the emplacement of pegmatites. The structural principles are presented in the context of the interaction between pressurized pegmatite fluids, stress conditions, and rock properties.

The variable form of pegmatites

Pegmatite bodies are characterized by a variety of sizes, shapes, orientations, and structural relationships to host rocks. They may occur as single tabular bodies, as multiple tabular bodies with a preferred orientation, or as multiple tabular bodies with a variety of orientations; in some cases the bodies are connected, in others, unconnected. They may be lenslike or podiform. They may occur as irregular bulbous masses, or they may be turnip shaped. They may have smooth curviplanar or extremely irregular contacts. Contacts are usually sharp. However, they may be gradational particularly when the pegmatite is in contact with its parent plutonic rock. The variability of these aspects of pegmatites has been discussed in the reviews by Jahns (1955) and Černý (1982a). Overall, the properties of the pegmatite bodies and their contact relationships to the host rock provide compelling evidence that most pegmatites were in a melt or fluid state during intrusion and that crystallization took place in situ (Černý, 1982a). One main thesis of the present paper is that the major form and orientation of this type of pegmatite is established during the intrusive phase, although multiple intrusive events or later deformational-metamorphic events may alter that form and orientation. The sequence of crystallization within a pegmatite body may be simple or extremely complex; in either case it does not appear to alter the overall physical characteristics of the body.

Factors controlling intrusion mechanics

Fluid pressure of the pegmatite melt

Pegmatite melts are characterized by hydrostatic pressure and will invade another rock only when the fluid pressure of the melt exceeds the ambient pressure condition within that rock. During intrusion, the fluid pressure of the pegmatite will adjust downward to the lower ambient level of pressure in the host rocks, and the intrusion will inflate the intrusive site volumetrically until pegmatite fluid pressure and the confining pressures are equalized.

There has been a tendency to presume that intrusive sites are extensional dilational openings that permit the intrusion of the pegmatite. Such an assumption is inconsistent with the state of stress in the crust which, with rare local exceptions, is compressive (Gay, 1980; Zobach and Zobach, 1980). Consequently, most pegmatites intrude as a result of their own fluid pressure's overcoming compressive stress conditions and in some cases the tensile strengths of the host rocks.

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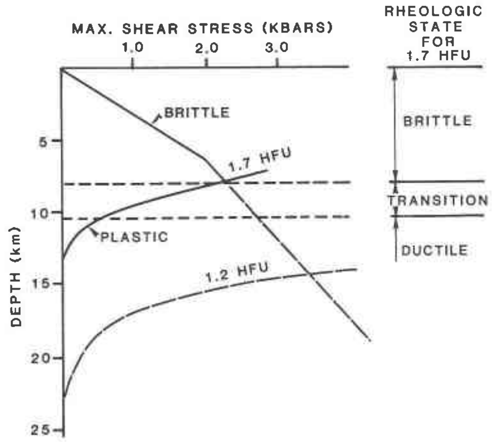

Fig. 1. Plot of maximum shear stress vs depth showing change in rheologic state from brittle to ductile (modified after Meissner and Strehlau, 1982). Curves are for a water-saturated quartz-rich rock, and the transition is marked for 1.7 heat flow units. Plastic-strength curve for lower heat flow (1.2 HFU) shows transition at greater depth.

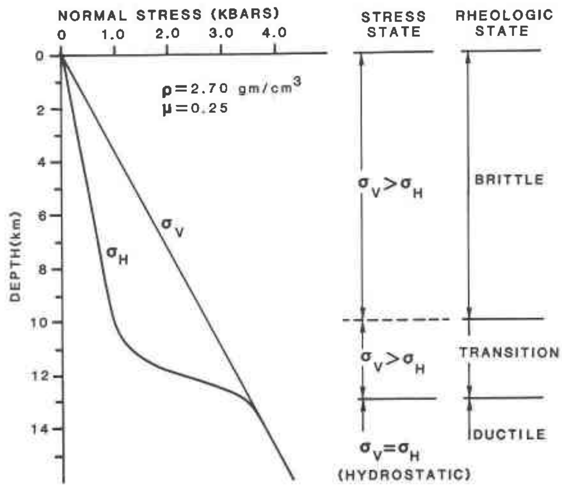

Fig. 2. Normal stress vs depth for the simple lithostatic case. σ_V = vertical normal stress, σ_H = horizontal normal stress, ρ = density of crust rocks, μ = Poisson's ratio. $\sigma_V > \sigma_H$ throughout the brittle domain and transition zone; $\sigma_V = \sigma_H$ in the ductile domain.

Rheologic state of host rocks at intrusive sites

At intrusive sites in the crust, the rheologic state is a function of rock composition, heat flow, lithostatic pressure, and pore pressure. All but the first of these parameters are sensitive to depth; consequently, rheologic state is sensitive to depth also.

At upper levels in the crust, the host rocks are in a brittle state and behave elastically to quasi-elastically. They withstand stress differences over long periods of time by deforming elastically; when failure occurs, it is usually by fracture. At deeper levels the character of strain in the host rocks is ductile. Stress differences cannot exist over long periods of time, and deformation takes the form of flow. The change from one state to the other is not sudden and takes place through a brittle-ductile transition zone at a level in the crust governed by lithostatic pressure, heat flow, strain rate, fluid pressures, and rock type (Sibson, 1977; Meissner and Strehlau, 1982). Figure 1 is an adaptation from the work of Meissner and Strehlau (1982) which shows this transition for a wet quartz-rich rock in the upper crust. The reaction of these host rocks to stress induced by pressurized pegmatite melts will be different at different depths; intrusion at upper levels will be accompanied by brittle host-rock behavior, whereas at lower levels, ductile response in the host rocks should be expected. In the transition zone, either type of response is possible, depending primarily on the dynamics of intrusion and the resulting strain rate in the host rock. In this environment, high strain rates promote brittle behavior, and low strain rates lead to ductile reactions in the host rocks. The same comments apply also to the ductile domain. Shaw et al. (1968) and Brace (1969) discussed brittle behavior in rheologic models of magmas where strain rates are high.

Lithostatic stress conditions at intrusive sites

The variation in the lithostatic stress with depth is shown in Figure 2. Although the lithostatic stresses act in all directions, for simplicity Figure 2 presents curves for only the vertical normal and horizontal normal lithostatic stresses (σ_V and σ_H, respectively). This treatment will be used in subsequent figures. In the brittle domain where quasi-elastic conditions prevail, lithostatic stresses have different magnitudes in the vertical and horizontal directions, such that $\sigma_H \approx \frac{1}{3}\sigma_V$ for any given depth (Means, 1976). The value of σ_H is the same in all directions; thus, the stress state in the brittle domain can be described as axially compressive about a vertical axis.

Within the ductile domain, the lithostatic stress becomes hydrostatic ($\sigma_H = \sigma_V$), because conditions are nonelastic. All compressive stresses are equal; consequently, curves showing the increase in σ_H and σ_V with depth, which diverge through the brittle domain, converge through the brittle-ductile transition, and achieve the same value in the ductile domain.

Figure 2, then, presents the stress or pressure conditions inhibiting intrusion by pressurized pegmatite melts for the simple lithostatic case. In the brittle domain and in the transition zone, the direction of least resistance to intrusion is horizontal. In the ductile domain, the lithostatic stresses are equal in all directions; consequently, there is no preferred orientation of least resistance.

The presence of subsurface fluids in pores, fractures, and other openings in the brittle domain alters the lithostatic stress conditions because of hydrostatic pore-fluid pressure. The lithostatic compressive normal stresses in the rocks are reduced by the same amount as the pore-fluid pressure in all directions at a given depth.

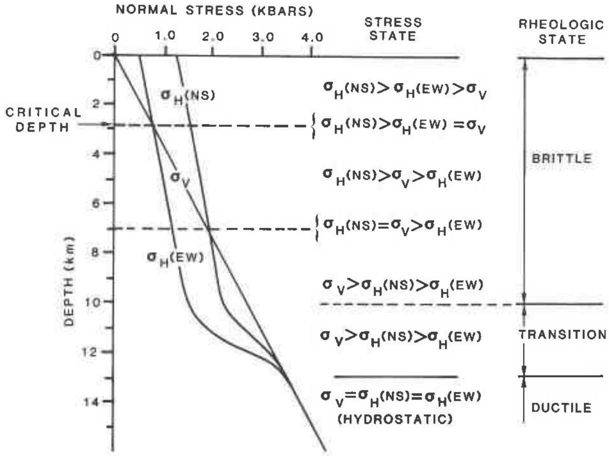

Fig. 3. Normal stress vs depth for lithostatic conditions plus directed horizontal stresses. Values of horizontal stresses are north-south = 1.25 kbar, east-west = 0.5 kbar. σ_H(NS) = normal stress in a north-south direction, σ_H(EW) = normal stress in an east-west direction, σ_V = vertical normal stress. Critical depth is the depth at which there is a change in the orientation of the minimum normal stress.

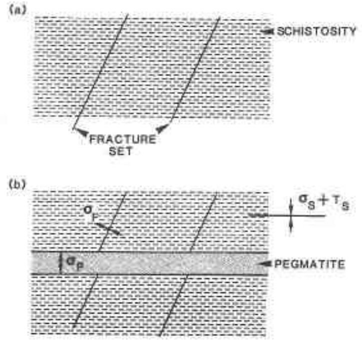

Fig. 4. (a) Pre-intrusive strength anisotropies. (b) σ_F = normal stress across fracture; σ_S = normal stress across schistosity; T_S = tensile strength across schistosity, fractures have no tensile strength; σ_P = pegmatite fluid pressure. Pegmatites intrude along the schistosity if $\sigma_P > \sigma_S + T_S$ and if $\sigma_P < \sigma_F$.

Directed-stress conditions

In some pegmatite emplacement, the host rocks may be subjected to some directed tectonic loading. Under these conditions, the lithostatic stress conditions represented in Figure 2 are modified by directed stresses. Figure 3 shows the results of adding horizontally directed tectonic compressive stresses to the lithostatic stresses uniformly throughout the brittle domain, such that the greater compressive tectonic stress is north-south and the lesser is east-west. This addition leads to stress conditions in the upper crust that are much more complicated than those demonstrated for the simple lithostatic case (Means, 1976, p. 116).

The most important condition expressed in Figure 3 is the orientation of the minimum stress with depth. In the upper levels of the brittle domain, the minimum normal stress is vertical; below the "critical" depth, the minimum normal stress is horizontal, directed east-west. At the critical depth, the minimum normal stresses are equal in the vertical and the east-west horizontal directions, and as well in all other directions in an east-west vertical plane. No preferred orientation of minimum normal stress occurs in the ductile domain. As will be shown in subsequent sections, these variations in minimum stress orientation profoundly influence the orientation of intruding pegmatites.

Effect of anisotropies

In massive, solid, isotropically strong rocks in the brittle domain, pressurized pegmatite fluids must overcome the tensional strength of the host rock, as well as the compressive normal stress acting on the incipient fracture plane, before a fracture will develop and before intrusion and dilation of the fracture will take place. This process is known as hydraulic fracturing. If the rocks contain no tensile-strength anisotropy, the only factor controlling the fracture orientation during hydraulic fracturing is the direction of the minimum stress within the rock due to lithostatic loading and directed stress.

Many rocks that host pegmatites are characterized by tensile-strength anisotropies such as pre-existing fractures, cleavage, schistosity, and layering. In the case of fractures, there is no tensile strength to be overcome by fluid pressures. In the case of cleavage, schistosity, and layering contacts, these planar features have tensile strengths across them that are usually considerably lower than other directions in the rock. As planes of weakness, these features play a part in controlling the orientation of pegmatite intrusions; however, they cannot be considered in isolation. Variations in tensile strength must be considered in combination with lithostatic and directed stresses. Pegmatites will intrude sites where the pegmatite fluid pressure overcomes the lowest combined effects of normal stress and tensile strength (Fig. 4).

In the ductile domain, ductility anisotropies, rather than tensile-strength anisotropies, may control the intrusion of pegmatites. These anisotropies may be produced by mineral alignment or by compositional changes. Consequently, pegmatite intrusion in the ductile domain may follow a foliation or gneissosity, or may be confined to a more ductile layer.

The influence of anisotropies in the transition zone is dependent on strain rate. At high strain rates, brittle behavior is promoted, and the anisotropies are of tensile-strength character. In contrast, low strain rates produce ductile behavior, so that anisotropies due to changes in ductility are of the greatest importance.

Dilational directions

Dilational directions during intrusion of pegmatites within the brittle zone may be simple or complex (Fig. 5). In rocks where a single fracture orientation is present and the fractures serve as sites for pegmatite intrusion, the dilation will be normal to the fracture walls (Fig. 5b).

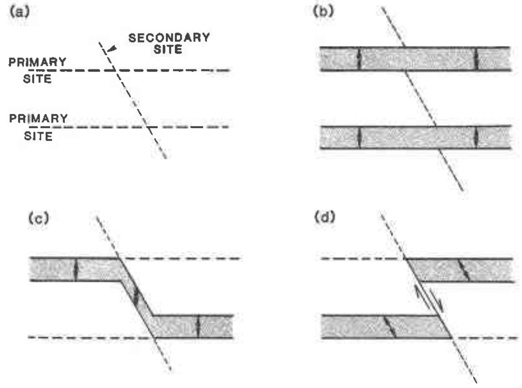

Fig. 5. Dilational directions across primary and secondary sites. (a) Primary sites are those controlling intrusions. Secondary sites are other strength anisotropies that may cause offsets of primary sites. (b) Simple dilation of primary sites perpendicular to the sites. (c) Dilation perpendicular to the primary sites. Secondary site shows oblique dilation. (d) Oblique dilation of primary site influenced by the orientation of the secondary site at the offset. Secondary site shows slip displacement but not dilation.

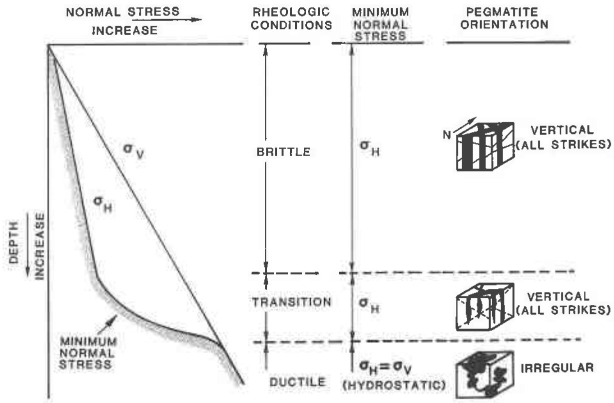

Fig. 6. Variation in normal stresses, rheologic conditions, and pegmatite orientations with depth, for simple lithostatic conditions. Values of minimum normal stress are shown at any given depth by the shaded curve.

In volumes of rock where a fracture system is made up of a set of primary fractures offset by a secondary set, oblique dilation can take place on the secondary fracture set as a result of dilation normal to the primary fracture set (Fig. 5c). Alternatively, the dilation on offset primary fractures can be oblique, controlled by the orientation of the offsetting fracture (Fig. 5d).

Most dilation observed on pegmatites is apparent dilation only, because the exposure surface is rarely in an orientation containing the true dilation. True net dilation, expressed as a length and an orientation, can be determined only when two formerly juxtaposed points on the opposite walls of the pegmatite can be identified.

In the ductile domain, the stress conditions approach a hydrostatic state, so that dilation of the intrusive site by the pressurized pegmatite may form lensoid, turnip-shaped, or balloon-like forms when strain rates are low. Under these circumstances, dilational directions and amounts will be highly variable from place to place. Higher strain rates may lead to quasi-brittle phenomena and dilational movements, similar to those in the brittle domain.

Intrusion of Pressurized Pegmatites into Host Rocks

Each factor discussed in the preceding sections may play some part in the intrusion of a given pegmatite. The way in which the factors combine to yield different sizes, shapes, orientations, and positions of intrusions is illustrated in the following three hypothetical cases. In each case the fluid pressure of the pegmatites is sufficiently high to overcome minimum normal-stress conditions and tensile strengths (where applicable) at intrusive sites, so that pegmatite emplacement takes place. Lithostatic stresses are assumed to include pore-fluid pressures and to follow a simple linear increase with depth. Where applicable, directed stresses are presumed to be horizontal with the maximum directed stress in a north-south direction. Real geologic conditions would be much more complex; however, these simplified assumptions serve to illustrate the way in which the structural factors play their respective roles.

Case A. Simple lithostatic stress

In this case (Fig. 6), the host rock is characterized by fractures with random orientations, lithostatic stress conditions prevail in the brittle domain such that $\sigma_V > \sigma_H$, and all horizontal stresses are equal. There is no directed stress. The minimum normal stress that has to be overcome by pressurized pegmatite fluids in the brittle domain and throughout the brittle-ductile transition is horizontal (in all directions). Consequently, pegmatite melts will intrude only into vertical fractures, produce dilation of these fractures, and yield tabular vertical pegmatite bodies with no preferred strike orientation.

Although horizontal and dipping fractures are also present, they are held closed by normal stresses in excess of the pegmatite pressure, which has been lowered to values approaching σ_H. Some thin septa of pegmatite may find their way into openings along nonvertical fractures; however, no primary dilation will occur. Secondary dilation may be possible on nonvertical fractures where they transfer the dilation from one vertical fracture to another.

In the ductile domain, the pattern of intrusion changes dramatically. Ductility precludes fractures; other ductility anisotrophies are considered to be absent, and hydrostatic normal stresses prevail ($\sigma_H = \sigma_V$). The resulting intrusions are bulbous, irregular, or disharmonic without preferred orientations. High strain rates in the ductile domain could yield fractures without any preferred orientation.

The conditions specified in this case yield two distinct styles of pegmatite intrusions, one characterizing the brittle domain and the other characterizing the ductile domain. In the transition zone, one style gradually changes to the other.

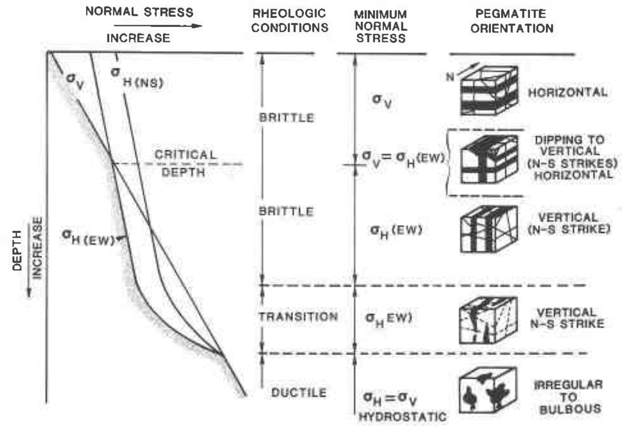

Fig. 7. Variations in normal stresses, rheologic conditions, and pegmatite orientations with depth, for conditions of lithostatic stress plus directed horizontal stress. Maximum directed stress is north-south. Values of minimum normal stress are shown at any given depth by the shaded curve.

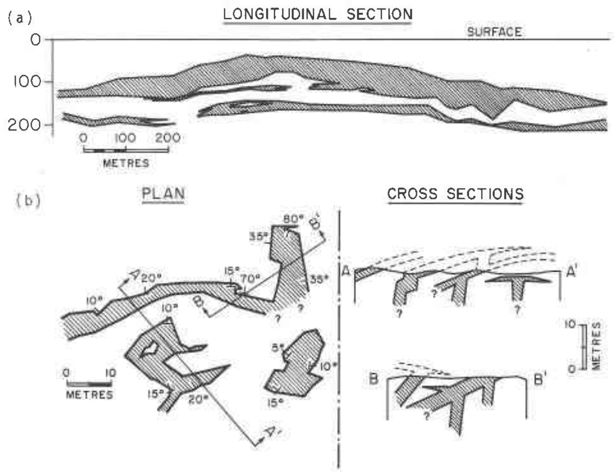

Fig. 9. (a) Tanco pegmatite of the Winnipeg River pegmatite district. Schistosity in host rocks is steeply dipping and approximately parallel to the longitudinal section. (b) Rush Lake pegmatites of the Winnipeg River pegmatite district.

Case B. Lithostatic plus directed horizontal stress

In this case (Fig. 7), the host rock is characterized by fractures with random orientations. The lithostatic stress is modified by horizontal tectonic compressive stresses. The major tectonic stress is north-south and the lesser is east-west. Under these conditions the stress field in the brittle domain undergoes several changes with depth. Near the surface, the minimum normal-stress direction is vertical, so that only horizontal fractures will serve as sites for pegmatites. At the depth marked as "critical" on Figure 7, the minimum normal stress is the same in the vertical and in the horizontal east-west directions ($\sigma_V = \sigma_H(EW)$). At this level, vertical and dipping fractures, which strike north-south, and horizontal fractures all have the same minimum normal stress acting across them; consequently, they should all serve as equal sites for pegmatite emplacement.

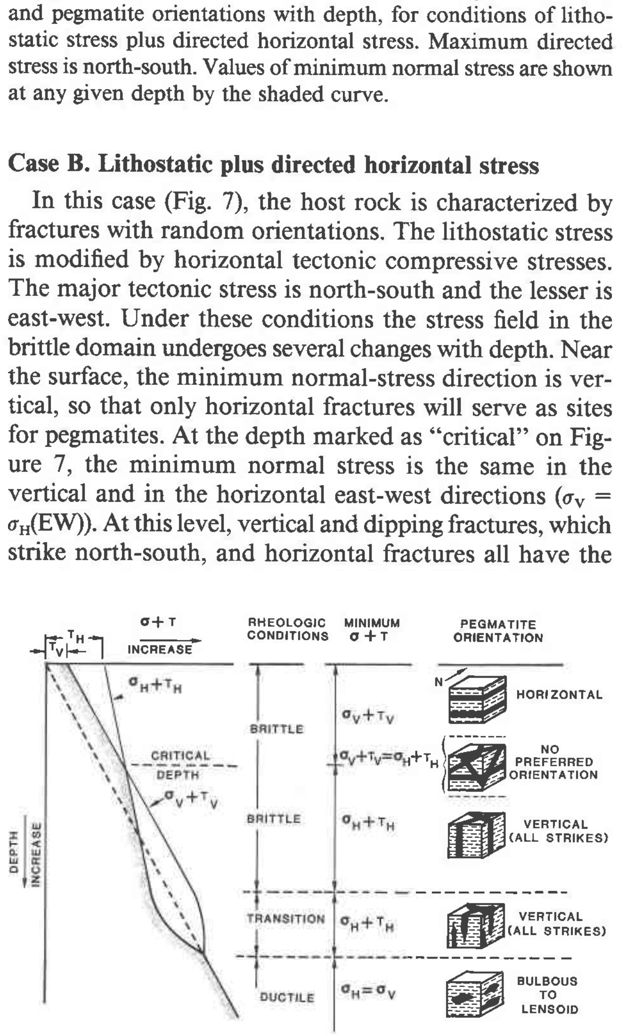

Fig. 8. Variations in normal stress plus tensile strength, rheologic conditions, and pegmatite orientations with depth, for simple lithostatic conditions with a strength anisotropy. T_H = horizontal tensile strength. Tensile strength in all other orientations other than vertical is assumed to be equal to T_H. T_V = vertical tensile strength. $T_V < T_H$. Values of minimum normal stress plus tensile strength are shown by the shaded curve.

Below the critical depth, the minimum normal stress is horizontal east-west, so that only north-south vertical fractures will dilate in response to highly pressurized pegmatite fluids. This condition persists into the transition zone.

In the ductile domain, the host rocks are assumed to be isotropically ductile, and the normal stresses are hydrostatic so that the intrusion of pegmatites will be irregular and nonsystematic for low strain rates. For high strain rates, brittle fracturing without preferred orientation may take place, followed by dilation.

In this case there are four distinct patterns of pegmatite intrusions representing four distinct levels in the upper crust: the upper brittle domain, the critical depth, the lower brittle domain and transition zone, and the ductile domain.

Case C. Simple lithostatic stress with a strength anisotropy

In this example (Fig. 8), simple lithostatic stress conditions are present and no directed stress exists. No fractures are present; however, the brittle domain is characterized by a horizontal schistosity with low tensile strength. Tensile strengths in all other directions are presumed to be greater, and all have the same value. Pegmatitic melts must overcome both tensile strength and lithostatic stress for intrusion to occur. Consequently, Figure 8 is a plot of normal stress plus tensile strength against depth. Curves for only vertical and horizontal directions are plotted.

Figure 8 illustrates that at shallow levels the minimum combined normal stress plus tensile strength is vertical; consequently, hydraulically generated fractures develop along the horizontal schistosity, and pegmatites intrude these features. At the critical depth where the curves for the horizontal and vertical conditions intersect, the combined effects of normal stress and tensile strength are the same in the vertical (T_V) and in all horizontal (T_H) directions ($\sigma_V + T_V = \sigma_H + T_H$), so that theoretically, fractures due to pegmatite fluid pressures may propagate in any direction without preferred orientations.

Below the critical depth, the minimum combined normal stress and tensile strengths are in any direction in the horizontal plane. If pegmatite fluid pressures exceed these minimum values, vertical fractures filled with pegmatites will result, cutting across the schistosity.

In the ductile domain, hydrostatic normal stresses prevail, and ductility anisotropies such as gneissosity may occur. Pressurized pegmatite melts invading such an environment with slow strain rates would be expected to produce lenticular pegmatite bodies enveloped by the gneissosity.

Although much more complicated scenarios may exist, their discussion does not improve the understanding of the basic principles that have been illustrated. The shape, orientation, and position of pegmatites give important clues as to the relative depths of emplacement, and to the lithostatic and directed-stress conditions at the intrusive sites at the time of emplacement.

Discussion of the applicability of models

Only a few papers provide sufficient data on the structural setting of pegmatites with which to assess the applicability of the principles discussed here. Few areas show exposures over a range of crustal depths, so that changes in orientation and shape are rarely observed. Nevertheless, the following pegmatite districts and families illustrate these structural controls quite well.

In the Winnipeg River pegmatite district, Brisbin and Trueman (1982) have recognized variations in the preferred orientation and dilational direction of pegmatite dikes. These variations have been interpreted by these authors as representing pegmatite emplacement at different depths in the brittle domain of the crust under the influence of both lithostatic and directed stress. The Tanco and Lower Tanco pegmatites of the Winnipeg River district represent highly fractionated pegmatites, enriched in Be, Ta, Li, and Cs (Černý, 1982b; Ferreira, 1984), that occur as two sheets with almost horizontal orientations (Fig. 9a). The bodies have sharp contacts and show evidence of vertical dilation during emplacement. Although the host rocks had a steeply dipping schistosity, at the time of emplacement this strength anisotropy had little control on the orientation of the intrusion. These properties indicate the presence of a directed horizontal stress at the time of emplacement, and intrusion above the critical depth, conditions similar to those shown in Figure 7. Furthermore, the generation of fractures across an existing strength anistropy suggests that hydraulic fracturing accompanied the intrusion.

The Rush Lake pegmatites of the Winnipeg River district (Fig. 9b) consist of interconnected tabular bodies with a variety of orientations. They have sharp contacts and dilational directions are variable. The host metasedimentary rocks show evidence of prepegmatite fracturing having a variety of orientations. At the time of pegmatite emplacement, the normal stresses across the fractures were all of similar magnitude; consequently, all fractures dilated. These conditions indicate emplacement at a critical depth (Fig. 7) where lithostatic and directed horizontal stresses combine to produce normal stresses of similar magnitude in all directions.

The Osis Lake pegmatitic granites of the Winnipeg River pegmatite district have been described by Černý and Brisbin (1982). These bodies intruded a host rock with a complex pre-existing fracture pattern. However, the intrusions developed only within vertical fractures with a preferred strike. The ambient stress condition required in the host rocks to lead to the observed preferential dilation is consistent with emplacement below the critical depth (Fig. 7).

Changes in orientation with depth have also been described for the late aplogranite-granite pegmatite dikes of the Qǒrqut granite complex of southwest Greenland (Brown et al., 1981). Although these authors did not deal with the significance of the changing orientations, the pegmatites appear to be consistent with the conditions above, at, and below a critical depth as portrayed in Figure 7. In the Hindu Kush region of Afghanistan, Rossovskiy and Chmyrev (1976) and Rossovskiy and Konovalenko (1978) have described areal variations in the preferred orientation of tabular pegmatites. These studies describe separate areas of gently dipping tabular pegmatites, of steeply dipping tabular pegmatites, and of lensoid pegmatites with moderate to steep dips enveloped by schistosity or gneissosity. Although the descriptive evidence is not completely diagnostic, there is evidence that the changing orientation and shape may be related to different depths in the brittle domain and in the transition zone, and that both lithostatic and directed stresses, as well as strength anisotropies, controlled the intrusion.

Some pegmatite families of the Yellowknife area in the Northwest Territories of Canada present quite different sets of emplacement conditions from those already outlined. In the northeast portion of the Prosperous Lakes map sheet (Joliffe, 1945; Kretz, 1968), the host rocks into which the pegmatites were emplaced have a large number of pre-intrusive strength anisotropies, including vertical and dipping joints, steeply dipping cleavage, and contorted bedding. Sites into which the pegmatites have intruded include all types of anisotropies (without regard to strike), but only those with very steep dips. The controlling factors here are the stength anisotropies, a simple lithostatic stress condition, and the absence of directed horizontal stress. Figure 6 shows the likely brittle domain conditions for this area.

Pegmatites of the Quartz Creek pegmatite district in Colorado (Staatz and Trites, 1955) are examples of preferred orientation emplacement along one strength anisotropy and not along others. Pegmatites occupy fractures interpreted by the authors as joints, but do not invade the foliation that they cut across. Other pre-intrusive joint directions are present but do not host the pegmatites, suggesting a directed stress field. The preferred orientation of the pegmatites changes from place to place in the district; however, at present the significance of these changes is problematic.

Some pegmatite districts are characterized by lens-shaped, bulbous, or irregular pegmatites with concordant schistose envelopes. Norton and others (1964) described the Barker-Ferguson pegmatite, the Dan Patch pegmatite, and the Expectation pegmatite, of the Black Hills pegmatite district in South Dakota as examples of this type. Norton's (1960) interpretation of the form of the Hugo pegmatite in the same district also suggests this type. In these examples, the schistosity served as an anisotropy control in the early stages of intrusion. As the pegmatite continued to intrude, resistance to dilation of the site appears to have been hydrostatic, and strain rates appear to have been low. As a result, bulbous, lobate, and irregular shapes evolved. Ductile domain conditions similar to those depicted in Figure 8 were probably in effect.

The clearest examples of the emplacement of pegmatites in a ductile domain, with low strain rates, and under hydrostatic conditions are presented by Simmons and Heinrich (1980) in their treatment of pegmatites of the South Platte district, Colorado. These authors interpreted the emplacement of ellipsoidal and vertically elongate pegmatite bodies enclosed within the Pikes Peak granite as a result of the rise of bubblelike masses of low-density pegmatite fluids through ductile silicate melt of higher density. Changes in ductility at higher levels in the granite body resulted in trapping a large number of these pegmatites at one level in the batholith.

Acknowledgments

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