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Relations of zoned pegmatites to other pegmatites, granite, and metamorphic rocks in the southern Black Hills, South Dakota

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ABSTRACT

The pegmatite field and the Harney Peak Granite of the southern Black Hills, South Dakota, form an igneous system that progresses from slightly biotitic muscovite granite through layered pegmatitic granite, with alternating sodic and potassic rocks, to simple plagioclase-quartz-perthite pegmatites, and on to zoned pegmatites. The zoned pegmatites range from rather simple ones, which have been mined for sheet muscovite or potassium feldspar, to complex ones with minerals of Li, Be, Nb, Ta, Sn, and Cs.

Most of the country rocks are Lower Proterozoic mica schists that were isoclinally folded and metamorphosed to biotite and almandine grades before granitic activity began. At 1700 Ga, intrusion of the Harney Peak Granite created a large dome in these rocks, a thermal aureole with a staurolite, a first sillimanite isograd, and a small area of metamorphism above the second sillimanite isograd. The estimated pressure is 3.7 kbar.

The granite has an area of 104 km^2, mostly in a single pluton consisting of thousands of sills and dikes. The pegmatite field is exposed over an area of 711 km^2. An isogram map of the abundance of pegmatites has many local irregularities. Calculations from the isograms show a total of 24000 pegmatites. About 2% of these are zoned pegmatites.

The zoned pegmatites have a strong tendency to occur in clusters, and the types of pegmatites are different in different clusters. A less obvious tendency is a regional zonation in which rare-mineral pegmatites become more abundant and muscovite pegmatites less abundant toward the outskirts of the region. This trend is parallel to a drop in crystallization temperatures from more than 660 °C in parts of the granite, some of which have primary sillimanite instead of muscovite, to less than 600 °C in inner zones of a few rare-mineral pegmatites, many of which are outside the first sillimanite isograd.

The composition of the granite indicates that its magma originated by partial melting of metasedimentary mica schists similar to those at the present surface. The pegmatitic nature of most of the granite probably reflects exsolution of an aqueous phase. The resulting processes continued into the simple pegmatites and zoned pegmatites, which are 4% and 0.5% of the exposed granitic rocks. For rare-element pegmatites, residual concentration in granitic magma can account for their modest contents of Be, Sn, Ta, Nb, and Cs, but Li presents complications because a large share of the Li in the exposed parts of the system is in Li-rich zoned pegmatites. The clustering of zoned pegmatites shows them to be products of localized subsystems that behaved differently.

INTRODUCTION

The Harney Peak Granite pluton and its several satellitic plutons in the southern Black Hills, South Dakota, are surrounded by a region containing about 24000 pegmatites. Approximately 300 of these are zoned well enough to have been mined or intensively explored for commercially valuable minerals. The zoned pegmatites are also the ones that have attracted the most petrologic interest. A major purpose of this article is to examine the distribution of zoned pegmatites across the region and thus to add to the body of information that bears on the issue of how they emerge from the evolution of the granitic system.

The pegmatites and granite are exposed over an area of 824 km^2 (318 sq. mi.). Granite in the main pluton has an area of 84 km^2 (32 sq. mi.) and outlying bodies add 20 km^2 (8 sq. mi.). The pegmatite region is narrow around the north side of the granite but very broad to the southwest and south (Fig. 1). The pegmatite field goes under

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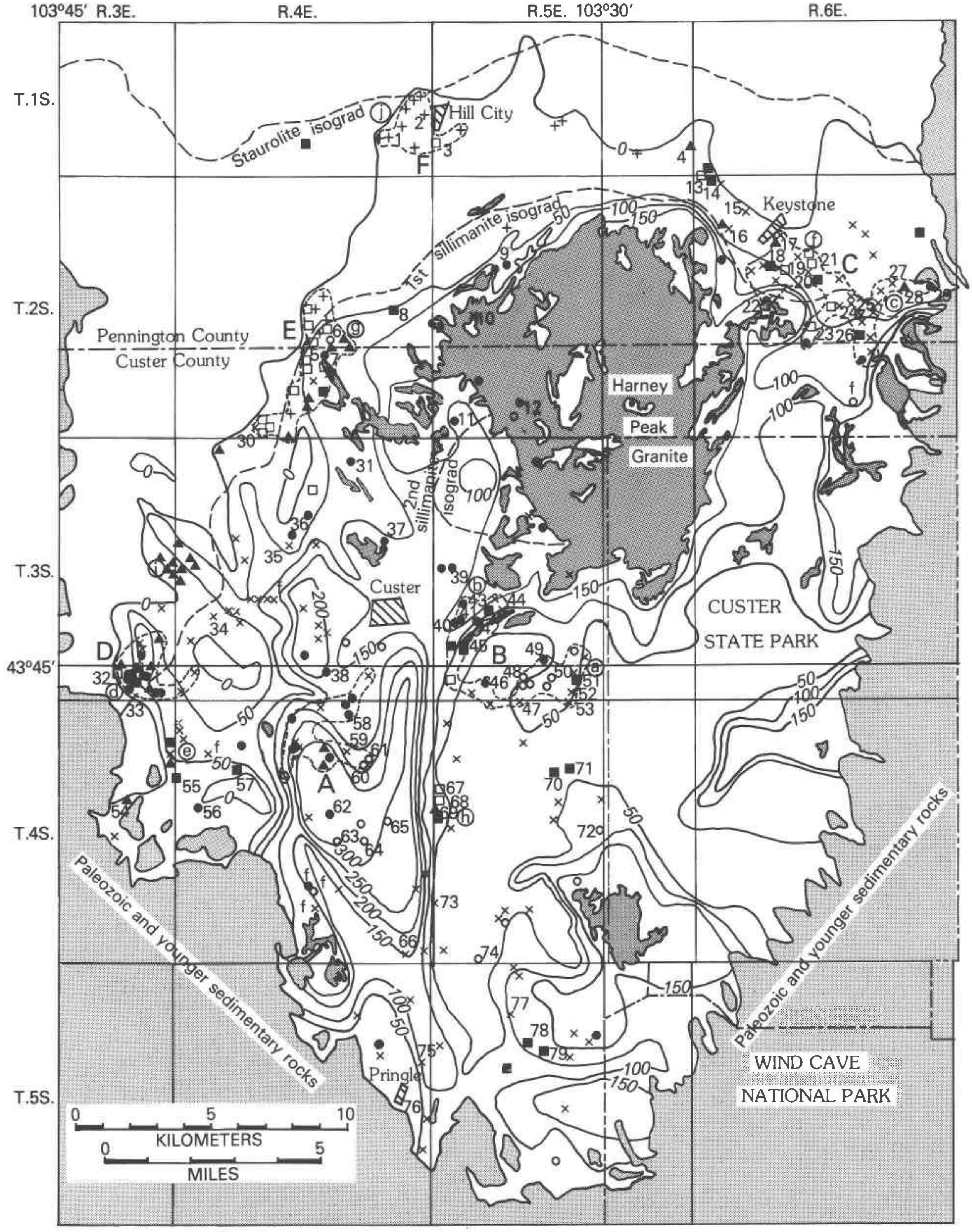
103°45′ R.3E.
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R.5E. 103°30′
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T.5S.
Staurolite isograd
Hill City
Keystone
1st sillimanite isograd
2nd sillimanite isograd
Pennington County
Custer County
Harney
Peak
Granite
Custer
CUSTER
STATE PARK
Pringle
WIND CAVE
NATIONAL PARK
Paleozoic and younger sedimentary rocks
Paleozoic and younger sedimentary rocks
A
B
C
D
E
F
0
5
10
KILOMETERS
0
5
MILES
0
50
100
150
200
250
300

Paleozoic sedimentary rocks on its southwest, south, and east sides.

The granite is a sodic leucogranite with textures ranging from fine grained to pegmatitic. The chemical compositions of the granite and the pegmatites are very similar. Pegmatites of the variety generally called layered pegmatites closely resemble the more pegmatitic parts of the granite. About 80% of the pegmatites, however, are simple coarse-grained bodies consisting almost entirely of albite, quartz, perthite, and muscovite. The simplest zoned pegmatites have wall zones rich in muscovite or inner zones rich in perthite. Others are more complex; a few have numerous zones and contain concentrations of several economically important minerals. The locations of zoned pegmatites are in Figure 1, and the names of the principal ones are listed in the caption.

Long ago Van Hise (1896, especially p. 687–688) said the Black Hills have a regional change from a granite center to pegmatites nearby and on to banded veins (presumably zoned pegmatites) and ultimately to highly quartzose veins. Regional zonation has since been described in many articles about pegmatite districts throughout the world. Though Van Hise was right in a general way, the actual distribution in the Black Hills has many irregularities and complexities that cannot be reconciled with the simplicity of the concept of regional zonation.

More recently, the tendency in discussing regional zonation has been to treat the distribution only of zoned pegmatites, especially those containing certain rare elements. This, for example, has been done in the Black Hills on the basis of Li, Rb, and Cs by Černý and Trueman (1978, p. 372–373).

Our own approach depends heavily on the distribution and abundance of unzoned pegmatites as indicators of the intrusive pattern because these are far more common than the zoned pegmatites. The literature about other regions is vague about whether unzoned pegmatites are generally as abundant as in the Black Hills or whether some regions contain proportionately many more zoned pegmatites.

The Black Hills district has an unusually great variety of zoned pegmatites. This diversity allows the zoned pegmatites to be divided into several categories. Differences in the distribution of the pegmatites of these categories suggest that genetic processes were somewhat different from one place to another.

REGIONAL SETTING

The Black Hills are an elongate Laramide dome having a north-northwest-trending Precambrian core flanked by Paleozoic and Mesozoic sedimentary rocks. The region treated in this report (Figs. 1 and 2) occupies the southern half of the Precambrian core. Pegmatites are absent to the north except in two small localities so far away as to have no interpretable relation to the Harney Peak system.

The most recent summary of the Precambrian geology of the Black Hills was published by Redden and French in 1989. The region has folds of several ages, numerous faults, and significant facies changes. The most obvious structural trend is in a north-northwest direction.

The latest known Precambrian event was the crystallization of the Harney Peak Granite and its pegmatites at 1.7 Ga (Riley, 1970). The rest of the pegmatite region consists almost wholly of Early Proterozoic metamorphic rocks, predominantly of sedimentary origin. By far the most abundant rocks are metamorphosed graywackes and several kinds of metamorphosed shales. Other rocks include quartzite, amphibolite from basalt flows and from gabbro, and metamorphosed conglomerate, arkose, iron formation, and dolomite. Figure 2 shows the distribution of the rock types.

The last major Precambrian tectonic event was the development of domes during the intrusion of granite in the southern Black Hills. The largest of these is the Harney Peak dome, which resulted from the growth of the main pluton by the emplacement of a succession of sills and other intrusions. The surrounding area has one small dome with granite and several others that gravity data show are probably underlain by granite (Duke et al., 1990).

The Bear Mountain area, which is in T.2S., R.3E., 13 km (8 mi.) west of the Harney Peak Granite, is also a

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Fig. 1. Map showing distribution and abundance of pegmatites and granite in the southern Black Hills, South Dakota. Isograms show the number per sq. mi. of pegmatites and small bodies of layered granite. Symbols show the zoned pegmatites by category: 1, dot; 2, circle; 3, x; 4, solid square; 5, open square; 6, triangle; 7, plus sign. The letter f signifies a zoned fracture filling in a small body of layered granite. Short dashed lines outline the large clusters A to F of Table 7. Small clusters of the same table are labeled a to j. The names of numbered pegmatites are as follows (asterisks designate large mines of Tables 6 and 8): 1. Cowboy 2. Mohawk 3. Mateen* 4. Hardesty 5. Hunter-Louise 6. Oreville Spar 7. High Climb 8. Tin Queen 9. Dewey 10. Gap 11. Westinghouse No. 4 12. November 13. Bob Ingersoll No. 2* 14. Bob Ingersoll No. 1* 15. Sitting Bull 16. Dan Patch* 17. Peerless* 18. Hugo* 19. Etta* 20. White Cap* 21. Edison* 22. Hesnard 23. Dyke 24. Eureka 25. Big Chief* 26. Mountain Lion (Soda Spar) 27. Barker-Ferguson 28. Wood Tin 29. Star (Nichols) 30. Wilhelm 31. Old Mike* 32. Tin Mountain* 33. Warren Draw 34. Highland* 35. Rachel D. 36. Crown* 37. Lost Bonanza* 38. White Spar* 39. Victory* 40. Florence 41. Harbach 42. Climax* 43. Shamrock and L5 No. 3* 44. Agnew* 45. Custer Mountain 46. Glenwood 47. Bull Moose* 48. Burt 49. Earl 50. Elkhorn 51. Hot Shot* 52. Triangle A 53. St. Louis* 54. Michaud Beryl 55. Helen Beryl 56. New York* 57. Tiptop* 58. Buster* 59. Pine Top 60. Silver Dollar 61. White Bear 62. MacArthur 63. Jack Rabbit 64. Ruby Reef 65. Midas 66. White Elephant* 67. Beecher No. 2* 68. Beecher Lode* 69. Beecher No. 3—Black Diamond* 70. Number 9 71. Rose Quartz 72. Red Deer* 73. Roadrunner 74. Ann 75. Charles Pringle 76. Townsite* 77. Dakota Feldspar 78. Greene 79. Smith*

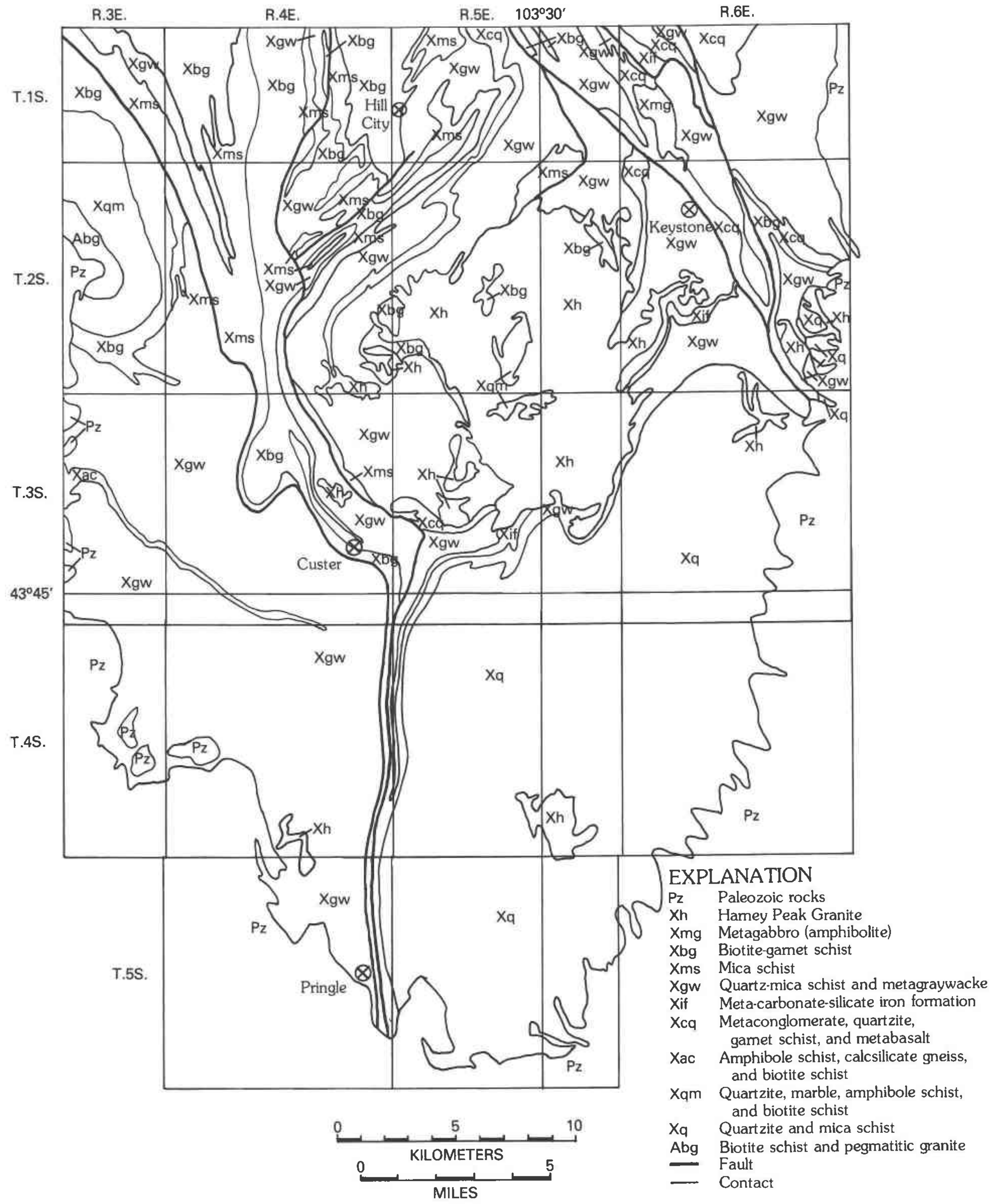

Fig. 2. Generalized geologic map of the southern Black Hills, South Dakota. The Harney Peak Granite and the Precambrian-Paleozoic contact are shown in greater detail on Figure 1. Metamorphic units shown by rock type; stratigraphic order not implied by list of units.

large dome and probably has a 1.7-Ga granite beneath it (Duke et al., 1990). At the surface, mica schist is intruded by very late Archean granite and pegmatite. Unconformably above these Archean rocks is metamorphosed conglomerate containing clasts of granite and pegmatite. Overlying rocks include arkose, quartzite, amphibole schist, dolomitic marble, and garnetiferous schist (Redden, 1968; Ratté, 1986). Similar rocks are exposed in screens and inclusions in granite in the center of the Harney Peak dome. Whether Archean rocks are also exposed is unknown. If they are, the lower part of what is mapped as Harney Peak Granite may include Archean granite, equivalent to the granite exposed at Bear Mountain, which is similar to the Harney Peak Granite.

All of the metamorphic rocks shown on Figure 2 are above the almandine isograd. Metamorphic intensity increases to the south. A staurolite isograd and then a first sillimanite isograd roughly follow the northern boundary of the pegmatite region. Andalusite first appears near the staurolite isograd but slightly farther from the granite. Cordierite also occurs in some of the schists of suitable composition. Staurolite disappears a few kilometers inside the first sillimanite isograd. The highest grade of metamorphism is marked by the second sillimanite isograd on the southwest side of the Harney Peak pluton and has been noted in isolated places to the southeast in the area of quartzite and schist. Sillimanite also occurs sparsely in the granite in southerly parts of the pluton and in some nearby pegmatites. Kyanite is absent in the metamorphic rocks near the granite but occurs in the Bear Mountain dome and in a few places to the south.

The metamorphism consists of a thermal event and an earlier regional event. The effects of the regional metamorphism, which is almost entirely below staurolite grade, extend throughout the Precambrian core of the Black Hills. The thermal metamorphism is related to the emplacement of the granite. Not only is this apparent from the regional relation to the main pluton, but also small areas around outlying granite bodies show local increases in metamorphic grade.

HARNEY PEAK GRANITE

The Harney Peak Granite pluton is a multiple intrusion that consists of perhaps a few dozen large sills, which have gentle dips in accord with the domal pattern, and thousands of smaller sills, dikes, and irregularly shaped intrusions. The largest sills are probably no more than about 100 m thick and extend laterally for only a few kilometers. Detailed mapping has not been practicable because of the multiplicity of the intrusive bodies and their similarities in composition. The extreme complexity of parts of the granite is shown by the work of Duke et al. (1988) on one of the satellite localities. The principal minerals of the main pluton and the smaller outlying plutons are, in order of abundance, albite-oligoclase, quartz, perthite, and muscovite. The most common accessory minerals are tourmaline (schorl), biotite, garnet, and apatite. The texture ranges from aplitic to granitic to pegmatitic, but nearly all outcrops have at least some pegmatitic aspects. Pegmatitic segregations and fracture fillings or dikes are common. Most of the perthite occurs as megacrysts in a phaneritic plagioclase-quartz matrix and in lenses and layers parallel to the nearest contact. The granite has recently been described in some detail by Redden et al. (1985), and further information is in Shearer et al. (1987).

Several indicators point to a trend from less evolved granite in the central and southeastern parts of the main pluton to more evolved and more pegmatitic granite to the northeast, north, and west, and in the outlying plutons. Shearer et al. (1987) showed that the K-Rb ratios of samples from interior intrusions are generally higher than in samples from several marginal intrusions. Unpublished K-Rb data from bulk samples of Norton and McLaughlin confirm these results. A parallel change is an increase in the amount of coarse perthitic lenses and layers and in the abundance of pegmatitic fracture fillings. The muscovite content increases from less than 5% in much of the central and southeastern parts of the main pluton to 10–15% to the north and northeast. The biotite content is low everywhere but does exceed 1% where the muscovite content is low, yet becomes almost nil to the north, where tourmaline is the principal mafic mineral. The median Li content in the granite is 30 ppm (Norton, 1981), and the richest analyzed sample, with 171 ppm (Shearer et al., 1987, Table 18), is at the north border of the main pluton. The anorthite content of plagioclase, which ranges from An_0 to at least An_{21} (Shearer et al., 1987, p. 475), also tends to be highest in the less pegmatitic parts of the granite. All of these remarks are generalizations. Detailed mapping of the granite accompanied by thorough sampling to find differences between intrusions and within single intrusions would show far more complex patterns.

The most conspicuous source of heterogeneity is the layering caused by the alternation of plagioclase-rich rock with pegmatitic perthite-rich lenses and layers. Locally, the plagioclase-rich rock is aplitic and layered on a much smaller scale, forming line rock in which layers 0.5–10 cm thick have sharp differences in the abundance of their minerals, especially tourmaline, feldspar, garnet, muscovite, and quartz. Most of the line rock is near the edge of the main pluton or in satellitic plutons or pegmatites.

The heterogeneity of the granite causes obvious difficulties in determining bulk composition. In about 130 samples used by Redden et al. (1985) and Shearer et al. (1987), the total of SiO_2, Al_2O_3, Na_2O, and K_2O is generally 97–98%. The remainder is mostly H_2O, CaO, and iron oxides. The median muscovite content is 8% (Redden et al., 1985, Fig. 2) and the total of feldspar and quartz is about 90%. This allows the rock to be represented on Ab-Or-Q ternary diagrams, which has been done by Redden et al. (1985, Fig. 5) and Shearer et al. (1987, Fig. 4). The diagrams show a wide scatter. One reason for the scatter is that many of the samples do not, and were not intended to, represent the entire rock.

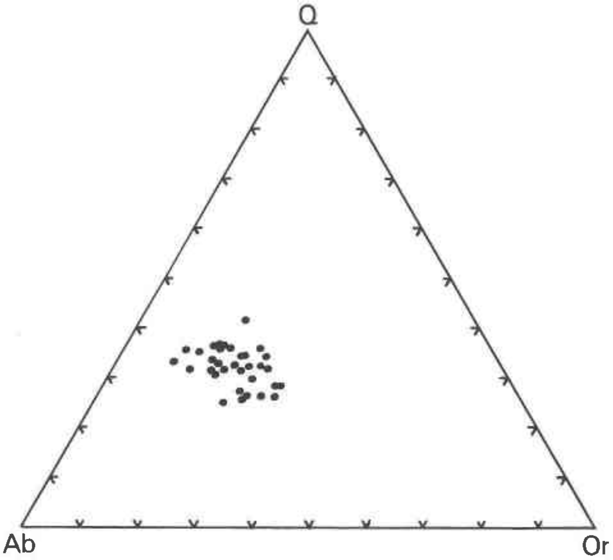

Fig. 3. Ternary diagram showing Ab-Or-Q contents of small layered intrusions calculated from visually estimated modes. Sources of modes are: Redden (1963b, Table 10), Lang and Redden (1953, Table 1), and unpublished notes. In the calculations, all plagioclase is assigned to Ab, perthite is assigned 25% to Ab and 75% to Or, 70% of the muscovite is assigned to Or, and quartz is assigned to Q. Where graphic granite is reported in the mode, 90% of it is assigned to perthite and 10% to Q.

Another reason is differences in different parts of single intrusions, probably caused mostly by an increase in K and a decrease in Na from the bottoms to the tops. Several samples of Redden et al. (1985, Fig. 5) that are from near the edge of the main pluton have a high content of albite relative to orthoclase, much like the albitic wall zones of zoned pegmatites. Most determinations are between 30 and 45% quartz, 25 and 50% albite, and 15 and 35% orthoclase, but probably the bulk compositions of the larger sills and dikes have a smaller range than this. The average normative composition is approximately plagioclase (Ab + An), 40%; quartz, 35%; and orthoclase, 25%.

SMALL LAYERED INTRUSIONS

The pegmatite region contains many small intrusions that previously have been called layered pegmatites (e.g., Redden, 1963b) but that actually differ from pegmatitic granite mainly in their size. We will refrain from calling them pegmatites in the text of this article, but it is impossible to avoid treating them as pegmatites in Figure 1 and in some of the tables.

In total quantity of rock the layered bodies far exceed the true pegmatites. Some of them are hundreds of meters long and tens of meters thick. At the other extreme are small layered bodies only about a meter thick and a few meters long. Most of the small ones are dikes, crosscutting foliation and bedding of the enclosing rocks. Some narrow dikes, especially near Keystone, are more than a kilometer long. The large intrusions, however, are highly irregular and both concordant and discordant.

Microcline is most abundant in coarse-grained layers, plagioclase is most abundant in the rest of the rock and is of low anorthite content, tourmaline is common, and biotite is rare. The layering results principally from the parallelism of lenses and layers of coarse-grained perthitic rock surrounded by finer-grained rock consisting of plagioclase and quartz. Contacts between layers are ordinarily gradational, but some are sharp. The intrusions can have hundreds of lenses and layers from the footwall to the hanging wall. In the outer parts of the intrusions the layering gradually fades out through the disappearance of coarse layers. The proportions of the two kinds of layers have a wide range; the average is probably about one-fourth coarse grained to three-fourths finer grained.

Line rock is more abundant than in the large plutons or in true pegmatites. Though it is a rather uncommon rock and of small areal extent in individual localities, it occurs in hundreds of places. Most of it is near contacts, especially footwall contacts.

Some of the small layered bodies, like the large plutons, are multiple intrusions. They have a structure that is similar but not identical to layering if the separately intruded members have perthitic cores and albitic border zones, or if they are perthite-rich at the top and albite-rich at the bottom (cf. Redden, 1963b, p. 235). Spectacular drawings of such multiple intrusions have been published by Orville (1960, Figs. 4–6) and Duke et al. (1988, Fig. 5).

Bulk compositions of layered bodies plotted on Figure 3 show a wide scatter, as in the granite. They are closer to the albite apex, but this is partly because plagioclase of the granite has more anorthite.

SIMPLE PEGMATITES

The simple pegmatites, which in previous publications have been called homogeneous pegmatites, differ from layered granite and zoned pegmatites by lacking easily discernible internal structure, though they do ordinarily have a fine-grained border zone a few cm thick. They consist of the same minerals as the layered bodies but are somewhat coarser grained. Perthite again forms the largest crystals. Some of the simple pegmatites have vague layering and others have rudimentary zoning, for they are transitional between pegmatitic granite and zoned pegmatites.

Most of the simple pegmatites are small, and though the total number of such bodies is large, the quantity of rock contained in them is modest. They generally are tabular to lenticular sills concordant with the foliation or bedding of the host rock. Most of them are between 10 and 100 m long, and only a few are more than 300 m long.

Figure 4 shows that the estimated compositions of simple pegmatites have a much wider scatter than the layered intrusions of Figure 3. The pegmatites are homogeneous in the two horizontal dimensions, which is why they have previously been called homogeneous pegmatites, but they almost certainly have vertical changes in composition. Hence the erosion level influences the observations and is probably a major cause of the scatter. The open circles on Figure 4, which are from study of an apparently simple pegmatite, show how compositions from one pegmatite can extend from the orthoclase-poor to the orthoclase-rich parts of the field containing the dots on this graph.

ZONED PEGMATITES

The zoned pegmatites have attracted the most geologic attention because of their commercial importance and their petrologic peculiarities. They have also yielded the most information because extensive mining and exploration have facilitated detailed study. Thus they are the best-known kind of pegmatite, even though by far the least abundant. The principal descriptions of the individual zoned pegmatites are in Page and others (1953), Sheridan (1955), Sheridan et al. (1957), Redden (1959, 1963a, 1963b), Norton et al. (1962), Staatz et al. (1963), and Norton and others (1964).

The zoned pegmatites are, with few exceptions, rather small. The mineable concentrations within them, which are zones or parts of zones, are smaller still, generally very much smaller. Most of the pegmatites are between 10 and 100 m long and less than 15 m thick. The smallest shown on Figure 1 are sheet muscovite pegmatites that are as little as 20 m long and 1 m thick. Countless zoned pegmatites of still smaller size are scattered through the schists of the region but are ignored for obvious reasons. Thousands of small zoned bodies in granite or in simple pegmatites are also ignored because they are merely units of the larger intrusion that is their host, but the map does show several zoned pegmatites in the granite and seven zoned fracture fillings in small layered intrusions because they are large enough to have been of economic interest. The four largest Black Hills zoned pegmatites that are reasonably well known in three dimensions are the Hugo and Peerless at Keystone and the Helen Beryl and Beecher No. 3–Black Diamond near Custer. Each of these contains at least 500 000 t of rock, and the largest has about 3 000 000 t. These are large by any standard, but the world does have a few zoned pegmatites containing tens of millions of tons of rock.

The compositions and arrangements of the zones reflect differentiation from the outer to the inner parts of the pegmatites, but this is accompanied in many places by a vertical component of differentiation that causes an upward increase in the abundance of K relative to Na (Norton, 1983). Fracture-filling units are numerous but small. Maps and descriptions of individual pegmatites indicate the existence of fewer replacement bodies than are said to exist in many complex pegmatites, but the Black Hills have had an ample share of advocates of massive replacement (cf. discussion in Norton et al., 1962, p. 100–103).

In zoned pegmatites the many differences in the compositions and sizes of zones are major obstacles to estimating bulk composition. Nevertheless, the overall composition even of a very complex pegmatite can be estimated if surface exposures, together with underground workings and perhaps drill holes, allow reasonably complete three-dimensional interpretation. At the Hugo pegmatite the size of each of seven zones and two small replacement bodies was calculated from a series of vertical and horizontal cross sections, and the results were combined with estimated modes of these units to compute the bulk composition of the pegmatite. Norton et al. (1962, p. 111–118) described the procedures and discussed the improbability of having significant errors. A similar calculation of the bulk composition of the Peerless pegmatite, which is also highly complex, was based on vertical cross sections made with the assistance of data from numerous drill holes (Sheridan et al., 1957, p. 17–18). The points on Figure 7 for the bulk compositions of these two pegmatites show them to be more silicic than nearly all the compositions of simple pegmatites. The Hugo, which has been a large producer of potassic feldspar, is much nearer the orthoclase-quartz sideline than the Peerless, which is less potassic than most pegmatites and has been commercially notable mostly for beryl and scrap muscovite mined from an outer zone.

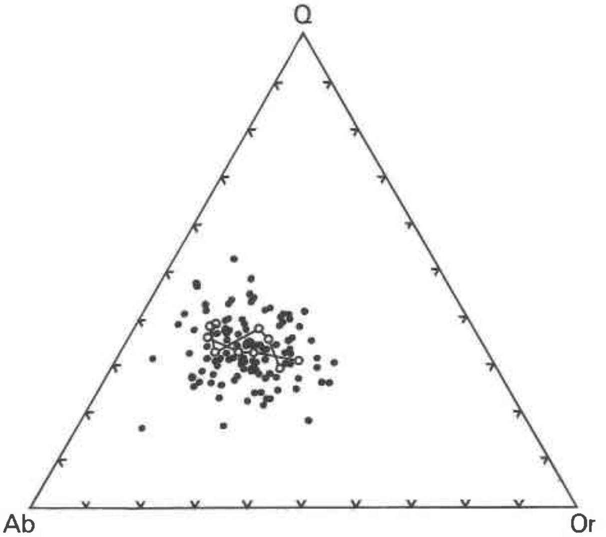

Fig. 4. Ternary diagram showing Ab-Or-Q contents of simple pegmatites. The dots are calculated from modes in the same way as for Figure 3 and from the same sources. The open circles and the lines connecting them are from Norton (1970, Fig. 4). They show changes in composition in two drill holes from the footwall to the hanging wall of a pegmatite that at the surface appears to be simple.

The elaborate geometric work done on the Hugo and Peerless pegmatites is not possible nor practicable with most other zoned pegmatites because of difficulties in determining the geology above the surface or below the deepest mine workings. The principal difference from simple pegmatites and granite is the presence in numer-

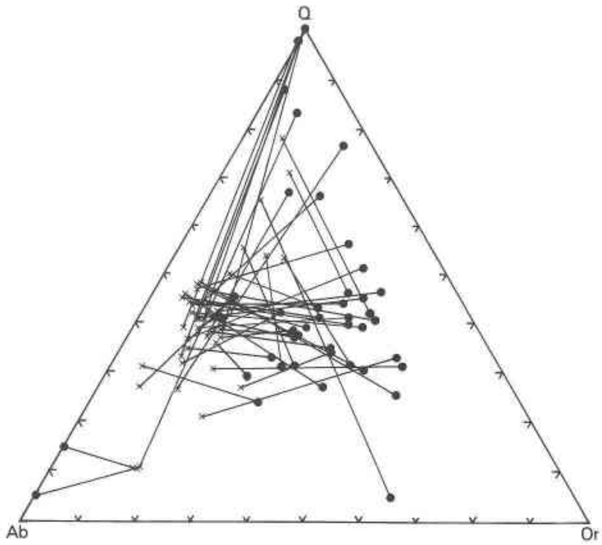

Fig. 5. Ternary diagram showing Ab-Or-Q contents of wall zones and cores of pegmatites that have only two zones. X = wall zones. Dots = cores. Calculated as for Figure 3. Sources of modes are: Redden (1963b, Table 7), Lang and Redden (1953, Table 2), Page and others (1953, p. 82), Staatz et al. (1963, p. 164), and unpublished notes.

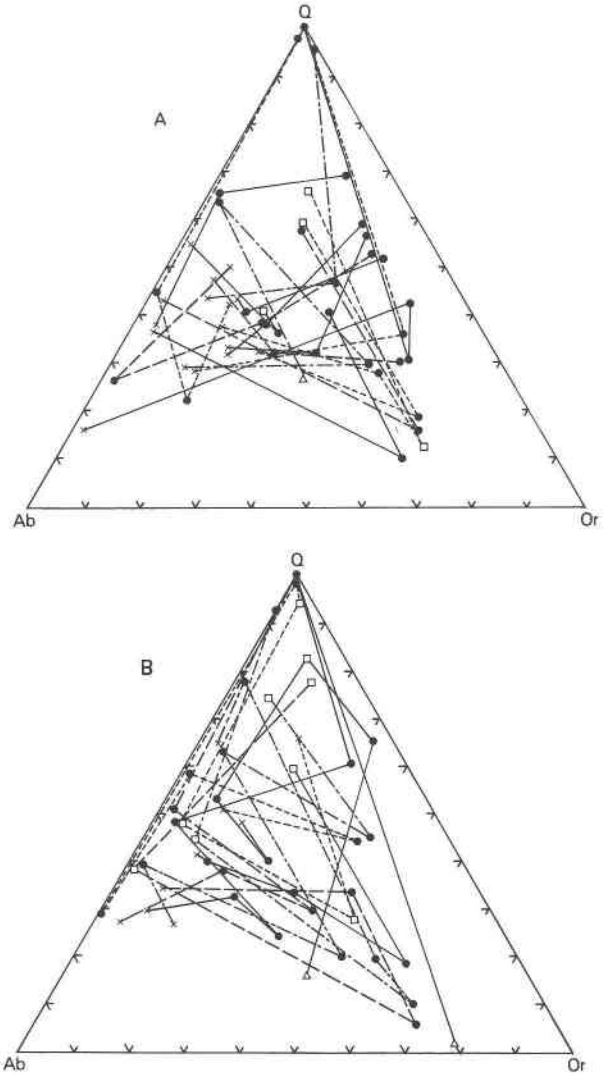

Fig. 6. Ternary diagram showing Ab-Or-Q contents of zoned pegmatites that have three or four zones (A) or five or more zones (B). X = wall zones. Squares = spodumene-rich zones. Triangles = lepidolite or lithian muscovite zones. Dots = other zones. Calculated as for Figure 3. Several line patterns are used so that the pegmatites can be distinguished from each other. Sources of modes are Redden (1963b, Table 7), Lang and Redden (1953, Table 2), Page and others (1953), Norton and others (1964), Staatz et al. (1963), Sheridan (1955, Table 1), Sheridan et al. (1957, Table 3), Redden (1959, p. 543), Redden (1963a, p. 2–8), Norton et al. (1962, Tables 19 and 20), Jolliff et al. (1986, Fig. 20), and unpublished notes.

ous zoned pegmatites of large quartz-rich inner zones—either quartz cores or quartz-feldspar zones or quartz-spodumene zones. Sn pegmatites near Hill City contain so much quartz that they are often called quartz veins. On the other hand, many zoned pegmatites, expecially among those mined for muscovite or potassic feldspar, lack highly quartzose zones and appear to be near the simple pegmatites and granite in bulk composition.

Figure 5, which shows the compositions of the zones in pegmatites that have only two zones, offers a way of estimating the range of bulk compositions. In these pegmatites, most wall zones are near the albite-quartz sideline, and most cores are rich in orthoclase or quartz or both. If the exposed parts of the two zones are representative of the entire pegmatite, the bulk composition is somewhere along the line between the points for the two zones. If a second pegmatite has the same bulk composition, the intersection of the lines for the two pegmatites shows that composition. About 80% of the intersections on Figure 5 are between 35 and 50% Q, which indicates that many of the pegmatites are more silicic than simple pegmatites and granite, and most of the others are in the silicic parts of the fields for simple pegmatites and granite. The wall zones and the inner zones of Figure 5 each have a median quartz content of 41%, which is notably higher than the medians of simple pegmatites and granite.

Figure 6 shows that the compositions of the zones of 26 pegmatites with more than two zones are scattered across nearly all of the Q-Ab-Or diagram. Again, compositions of wall zones are near the albite-quartz sideline. These generally are followed by orthoclase-rich intermediate zones and then by silicic zones, but the graph shows many twists and turns along the way caused by inner zones rich in albite and quartz, some of which have spodumene. Three pegmatites—the Bob Ingersoll No. 1, the Hugo, and the Peerless—have lepidolite or lithian muscovite cores that follow silicic inner zones.

The median quartz content of the zones of Figure 6 is 41%, just as it was for the bizonal pegmatites of Figure 5. The quartz contents of the Hugo and the Peerless are slightly greater. Probably pegmatites with many zones have about the same range of bulk composition as pegmatites with two zones, but one cannot determine this from Figure 6 because the zones have a wide range in size.

Figure 7 shows an appraisal of how zoned pegmatites compare in bulk composition with the other pegmatites and with granite. The most notable feature is the similarity in the composition of the four kinds of rocks; every field on Figure 7 overlaps every other field. The granite minimum is within all fields. The granite field juts out toward the quartz-orthoclase sideline, but probably would not do so if its An content were added to its albite so as to include all the plagioclase and thus make the calculation more like that of the pegmatites, in which all plagioclase is treated as albite. The diameter of the field for simple pegmatites indicates a greater spread of bulk compositions than is likely to be correct, for reasons already discussed. The zoned pegmatite field overlaps the more silicic parts of the other fields and extends from there toward the quartz apex. It would reach much more silicic levels if the highly quartzose Sn-bearing pegmatites or "veins" were not excluded from the diagram.

Some of the zoned pegmatites have been mined for Li, Be, Ta, Nb, Sn, and Cs. A few pegmatites have enough Li to have been mined for spodumene almost from wall to wall. Beryl has been a major product from several pegmatites. Nonetheless, the amount of rare elements is small even in ore bodies and is so much smaller elsewhere in pegmatites that few analyses are available. As for noncommercial trace constituents, anions as well as cations, the body of data is still slight. Knowledge in this field is being increased by Papike and others in numerous publications from the Institute for the Study of Mineral Deposits of the South Dakota School of Mines and Technology (e.g., Jolliff et al., 1986, 1987; Walker et al., 1986a, 1986b; Shearer et al., 1985, 1987).

CATEGORIES OF ZONED PEGMATITES

The region has a remarkable variety of kinds of zoned pegmatites, perhaps more so than in any other pegmatite field in the world. It has muscovite-rich pegmatites like those mined in sheet mica districts the world over; it has Li deposits that dominated the industry for many decades; it has major sources of beryl; it has many feldspar mines; it has pegmatites that have been intensively explored for cassiterite; and it has produced white and rose quartz, tantalum-niobium minerals, and pollucite. Table 1 shows the characteristics of the pegmatites that have been used to separate them into seven categories. Each of the zoned pegmatites shown on Figure 1 has been assigned to one of the categories. Figures 8 and 9 show horizontal and vertical sections of pegmatites that are examples of the various categories.

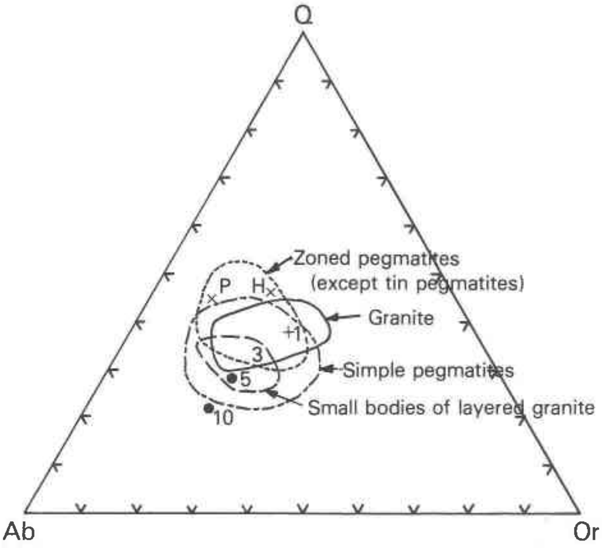

Fig. 7. Ternary Ab-Or-Q diagram showing the fields that contain most of the granite in the large bodies and approximately 90% of the small bodies of layered granite and the simple and zoned pegmatites. The field for large bodies of granite is based on Redden et al. (1985, Fig. 5) and Shearer et al. (1987, Fig. 4). The other fields are based on Figures 4–6. *H* and *P* are the bulk compositions of the Hugo and Peerless pegmatites (Norton et al., 1962; Sheridan et al., 1957). The numbers 1, 3, 5, and 10 are granite minima and eutectics from Luth et al. (1964) in kbar.

Category 1 includes most of the sheet muscovite pegmatites and nearly all the important mines. The muscovite is in wall zones with quartz and sodic plagioclase. Most of the mineable concentrations are on the hanging-wall side of the pegmatite, and the greatest concentrations are in rolls in the contact, where the muscovite content can be as great as 50% (e.g., the Crown mine, Page and others, 1953, p. 95–96). Muscovite crystals are generally most abundant and largest near the contact and decrease in abundance and size toward the inner part of the pegmatite. Some of the pegmatites have quartz cores, and some have as many as three feldspar-quartz inner zones. Most of these pegmatites have a lenticular shape.

Category 2 differs from Category 1 only by having perthite as well as plagioclase in the wall zone. Many of these are similar to simple pegmatites except for the enrichment in muscovite near the contact. Others are well-zoned pegmatites, and in some of these the muscovite books are largest and most abundant in the inner part of the wall zone, which may be mapped as the first intermediate zone. A feature of several pegmatites in Category 2 is an unusual abundance of schist remnants in the wall zone.

Category 3 consists of pegmatites in which the most prominent unit is an intermediate zone or core rich in large crystals of perthite. The mining of potassic feldspar has centered on these deposits. The most productive pegmatites are of large size and of lenticular or irregular shape, but much thicker than the pegmatites of Categories 1 and 2. The wall zone is ordinarily thin, and its muscovite

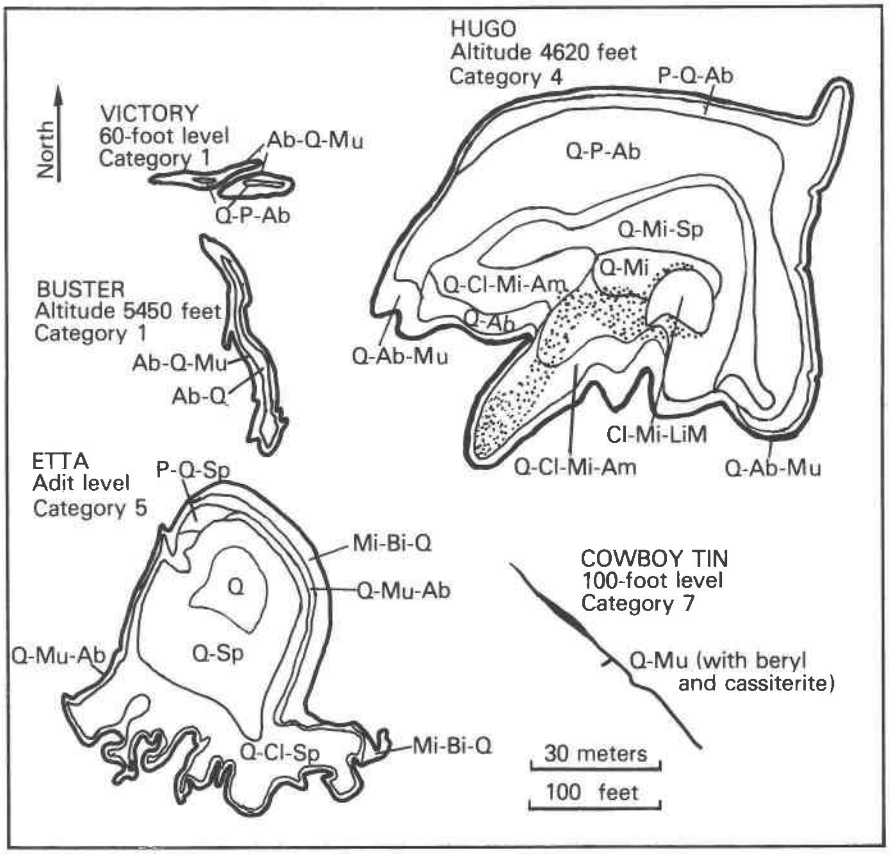

Fig. 8. Horizontal sections of zoned pegmatites. Essential minerals of the zones are shown in the order of their abundance. Q = quartz. Ab = albite. Cl = cleavelandite variety of albite. P = perthite. Mi = microcline. Mu = muscovite. LiM = lithian muscovite. Sp = spodumene. Am = amblygonite. Bi = biotite. Stippling indicates replacement, mostly by albite, lithian muscovite, and microcline.

sparse and of low quality. The perthite commonly is concentrated in a hood-shaped unit in the upper part of the pegmatite; such units carry quartz and albite as well as perthite, but they grade downward into units with lesser amounts of perthite or none at all. The geologic section of the Dan Patch pegmatite (Fig. 9) has an unusual sharp roll in the hanging wall that divides the pegmatite into two nearly independent segments, but each of the segments has the uncomplicated nature of most of these deposits. The Dan Patch is much larger than most pegmatites of Categories 1 and 2, but many of the other pegmatites of Category 3 are far larger than it. All of the ones labeled as large mines in the list on the page facing Figure 1 are in large pegmatites. In contrast, many of the major muscovite mines are in very small pegmatites because the high price of sheet mica at times in the past has caused small deposits to be important mines. The Climax pegmatite (Fig. 9), which is only 45 m long, mostly less than 3 m thick, and was mined to a depth of 50 m, was a major source of sheet mica, but a potassic feldspar pegmatite of this size would never have been important enough to be listed by name, and might have so completely escaped notice as not to be shown at all on Figure 1.

Not everywhere is it certain whether a pegmatite belongs to Category 1 or Category 3. Vertical sections of the White Spar muscovite pegmatite (Page and others, 1953, Plate 45) show that the upper part of it is occupied mainly by a perthite-rich unit and that the muscovite-rich wall zone is well developed only in the lower part of the pegmatites. The Buster has a similar arrangement: it was first developed as a feldspar mine, and the muscovite deposit was not discovered until later. When it was still a feldspar mine, the available exposures would have caused it to be assigned to Category 3, as a small feldspar mine, rather than to Category 1, as the large muscovite mine it later became.

Potassic feldspar pegmatites that have inner zones with Li minerals are assigned to Category 4. The prime example is the Hugo (Figs. 8 and 9), which, in addition to being a very large source of feldspar, has also been mined for amblygonite-montebrasite and spodumene, and has lithian muscovite in its core. At the Bob Ingersoll No. 1 pegmatite, the core has lepidolite, which has been the

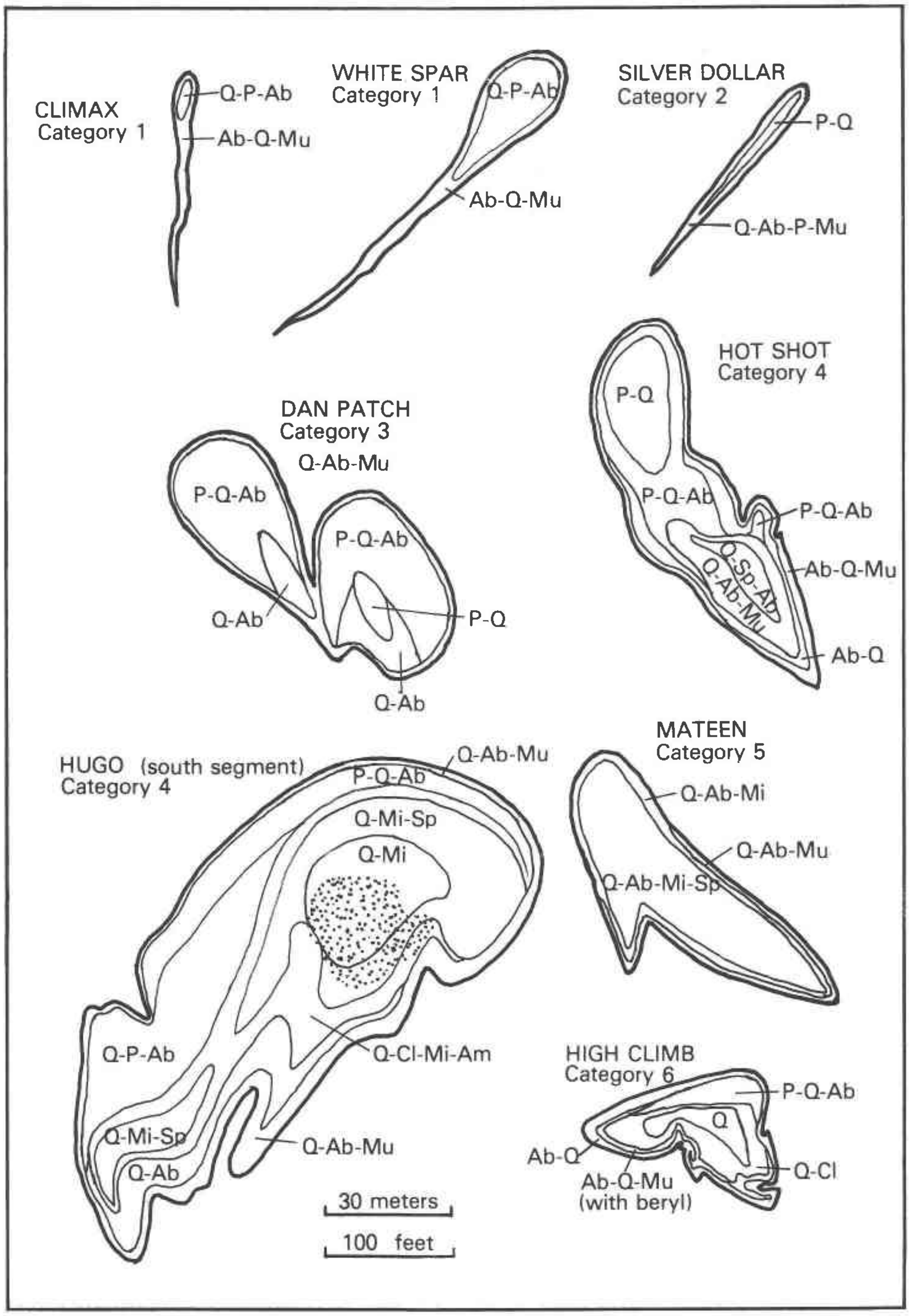

Fig. 9. Vertical sections of zoned pegmatites. Symbols are the same as in Figure 8.

most important commercial product. It is the only such pegmatite known in the Black Hills and is grouped with the pegmatites of Category 4 because it is geologically most similar to them.

Pegmatites with abundant spodumene are in Category 5. The Etta (Fig. 8) is the most widely known and also rather large. Some pegmatites of Category 5 have sizeable perthite-rich zones and differ from pegmatites of Category 4 only in having much larger spodumene units.

Category 6, which emerged unexpectedly during compilation of the data used to establish the categories, consists of beryl-bearing pegmatites in which the beryl is concentrated in the inner part of the wall zone or in the first intermediate zone and is accompanied by abundant muscovite saleable only as scrap mica. The Peerless pegmatite is the most notable example, for it has been the largest source of beryl and scrap mica among Black Hills pegmatites (Sheridan et al., 1957). A smaller and thus more typical example is the High Climb (Fig. 9). Because most of the pegmatites of Category 6 have units rich in platy albite (cleavelandite variety), perthite, or amblygonite-montebrasite, and some have spodumene, they resemble pegmatites of Categories 4 and 5, but perthite is much less prominent than in Category 4 and Li minerals are much less abundant than in Category 5.

Category 7 consists of tabular quartz-rich pegmatites that have enough cassiterite to have attracted interest as sources of Sn. The Cowboy is one of the larger ones, though it is smaller than the other examples of pegmatites on Figures 8 and 9. The quartz-cassiterite bodies are similar to quartz veins and much different from the other pegmatites, but their content of plagioclase, beryl, and muscovite, as well as their proximity to other pegmatites, suggests that they are part of the pegmatite system. Several small quartz veins northwest and northeast of the Harney Peak Granite have been prospected for W, but they are ignored in this article.

The pegmatites of Categories 4–7 are the ones that can most appropriately be called rare-mineral pegmatites. They have yielded the spodumene, amblygonite-montebrasite, tantalum-niobium minerals, cassiterite, and pollucite produced in the region, as well as most of the beryl, and have many other rare minerals that lack commercial value.

Every kind of zoned pegmatite can have monomineralic quartz units, and all except the Sn category can have quartz-potassium-feldspar zones. The supposition, perhaps still widespread, that all zoned pegmatites have quartz cores is incorrect. Only about 20% of the zoned pegmatites in the Black Hills are known to have quartz cores.

DISTRIBUTION AND ABUNDANCE OF PEGMATITES

Figure 1 shows the distribution of the pegmatites by means of isograms that indicate the abundance of pegmatites in various parts of the area. The area contains about 24000 pegmatites, according to a calculation to be described later. The most numerous of these are simple pegmatites, and most of the rest are layered granite. Figure 1 shows 278 zoned pegmatites.

The isograms show the number of pegmatites per sq. mi., which is the size of the sections in the land grid of the western United States shown on all topographic maps. The interval between isograms is 50 pegmatites per sq. mi., which is equivalent to about 20 pegmatites per km^2.

The isograms are most accurate near Custer, Hill City, and Keystone because these areas have been mapped at scales of 1:24000 and larger. Elsewhere the isograms are based mostly on reconnaissance and on the study of aerial photographs. The pegmatites form resistant outcrops and are generally easy to detect. Information from Custer State Park is scant.

The most precise isogram is the one for the outer border of the pegmatite region. The isogram goes from the Keystone region west to Hill City and then southwest to the Paleozoic contact. One small outlying group of pegmatites, 10 km northwest of Custer, is surrounded by a zero isogram. Another outlier, 5 km west of Hill City, has no isogram because the site contains only a single pegmatite, a zoned one shown on the map. Three inliers surrounded by the zero isogram are northwest, west, and southwest of Custer. Though these areas contain no mappable pegmatites, they may contain smaller pegmatites. On the other hand, each of these closed zero isograms is in a place where the zero and 50 isograms are widely separated, and the top of the pegmatite field may well dip below the surface.

The pegmatite region is narrow along the north side of the Harney Peak Granite. Elsewhere the pegmatites extend over a much broader area; the greatest abundance is southwest of the granite. If one visualizes the isograms as topographic contours, they can be said generally to describe a rolling surface with modest hills in several places, a sharp ridge south of Custer with a steep slope on its east side, and local highs around some of the small granite plutons. How far the pegmatite region extends beneath the Paleozoic rocks is, of course, not known, but it could be small.

Though the isograms show how many pegmatite intrusions are in a locality, they are not a measure of the quantity of pegmatitic rock because a single large intrusion may contain as much rock as dozens of smaller ones. Data on quantity are far more difficult to obtain, though they might be more meaningful. In the Fourmile and Berne quadrangles, which are southwest and northwest of Custer, enough information is available to compare quantity of pegmatitic rock and number of intrusions per sq. mi. (Fig. 10). In several places the two kinds of isograms are drastically different; the greatest differences are caused by the presence of large bodies of layered granite. The isograms for 0.5% and 1% pegmatitic rock have a general similarity to the isograms for 50 and 100 pegmatites per sq. mi. Above the 1% isogram, discordancies become conspicuous. About 60% of the pegmatite field of the southern Black Hills is below the isogram for 100 pegmatites per sq. mi., and probably about the same amount is below the 1% isogram for quantity of pegmatite. The higher isograms for quantity of pegmatite may indicate centers of intrusive activity that perhaps are related to irregularities in the distribution of zoned pegmatites that will be discussed later.

Calculation of the total number of pegmatites depends on measuring the area in sq. mi. between each pair of isograms and then multiplying by the number of pegmatites per sq. mi. The numbers to use as the multipliers—that is, the number of pegmatites per sq. mi. between each pair of isograms—were obtained from the detailed examination of the distribution of pegmatites in the Fourmile and Berne quadrangles shown in Table 2. These data lead to the calculations in Table 3 that show a total of 23700 pegmatites in the 275 sq. mi. (711 km²) between the outermost isogram and the granite bodies. The area between the 0 and 50 isograms, which includes about 40% of the pegmatite region, has only about 1800 pegmatites. Between the 50 and 200 isograms, which is about 54% of the region, there are about 17400 pegmatites. The small area above the 200 isogram has 4500 pegmatites.

Table 2 also shows that 80% of the pegmatites in the Fourmile and Berne quadrangles are simple and most of the rest are layered. Table 4, however, shows that the quantity of rock in simple pegmatites is far smaller than in layered intrusions. Zoned pegmatites are at the same low level in both methods of measurement.

Further calculations yield an estimate of the abundance of rock in simple and zoned pegmatites relative to all granitic rocks at the present surface. The area of the different kinds of pegmatites was obtained by multiplying the totals in the Fourmile and Berne quadrangles (Table 4) by 6.2, which is the ratio of the entire pegmatite area to the area in these quadrangles. The result added to the area of granitic bodies on Figure 1 is a total of 121 km² (47 sq. mi.) of granitic and pegmatitic rock. The large granitic bodies constitute 86% of this total. The percentage is 9.6 for the small layered intrusions, 3.9 for simple pegmatites, and 0.5 for zoned pegmatites. The 0.5 percentage for zoned pegmatites is divided into about 0.1% muscovite pegmatites, 0.2% potassic feldspar pegmatites, and 0.2% rare-mineral pegmatites.

These percentages are not necessarily representative of the entire igneous system above and below the present surface. Information is also lacking for the part of the pegmatite field covered by Paleozoic rocks, but such information probably would not cause significant changes in the calculations, for the exposed sample is a large one, comparable in size with many other major pegmatite fields.

As for how far the system extended above the present surface, the appearances are in accord with the orthodox view that pegmatites are above granitic plutons. The Harney Peak pluton could be the highest of these plutons, and others may be in the subsurface elsewhere in the region. Presumably pegmatites once existed above the main pluton, and pegmatites near its border are above its down-dip extensions. There is a slight possibility that Sn granites and Sn deposits once lay far above the pegmatite system, because numerous Sn districts in the world have abundant Li and some have concentrations of Be. The Cornwall Sn district even has a remarkable Li-rich dike called the Meldon Aplite dyke, which according to Beer et al. (1978, p. 286) is 3.5 km long and 12 m thick and has 1951–7400 ppm Li in seven samples. It consists mostly of medium-grained albite, quartz, potassium feldspar, and lepidolite but has accessory petalite, spodumene, and amblygonite-montebrasite. At Macasuni, Peru, samples of rhyolitic glass contain about 3000 ppm Li (Barnes et al., 1970, p. 1545; Pichavant et al., 1987, Table 1) and otherwise resemble Li pegmatites in composition.

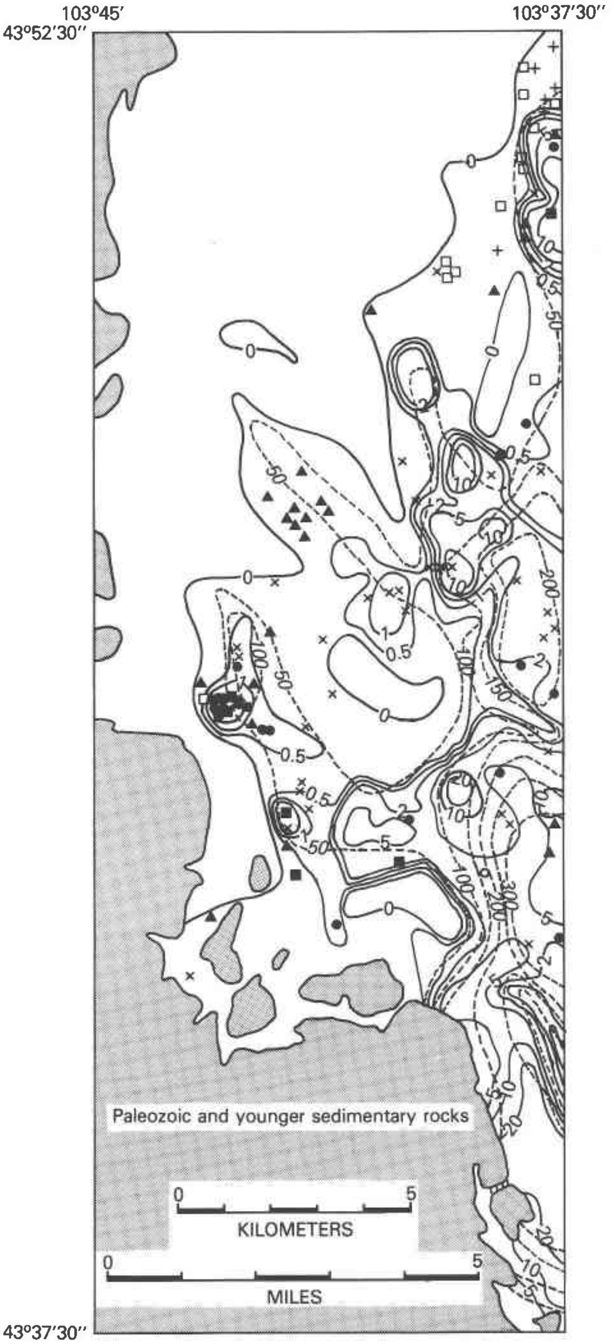

Fig. 10. Map of the Fourmile and Berne quadrangles showing relations among (1) the quantity of pegmatite rock, (2) the number of intrusions per sq. mi., and (3) the locations of zoned pegmatites. Quantity is expressed by solid-line isograms at 0, 0.5, 1, 2, 5, 10, and 20%, based on measurements of areas of ¼ sq. mi. Dashed lines show the number of intrusions per sq. mi., and symbols show the zoned pegmatites in the same way as in Figure 1.

TABLE 1. Categories of zoned pegmatites in the southern Black Hills

		Dominant economic units			Other large units		
Category	Number of pegmatites shown on Figure 1	Structural position	Major industrial minerals	Other abundant minerals	Abundant minerals of outer units	Abundant minerals of inner units	Distinctive characteristics
1	49	Wall zone	Sheet mica	Quartz Albite (rarely oligoclase) Tourmaline		Quartz ± Albite ± Perthite ± Muscovite	Quartz and plagioclase are the dominant minerals. Perthite is ordinarily also present, but only in inner zones, in which it is accompanied by quartz or by quartz + albite.
2	23	Wall zone or first intermediate zone	Sheet mica	Quartz Albite (rarely oligoclase) Perthite Tourmaline	Quartz Albite (rarely oligoclase) Perthite Muscovite	Quartz Perthite Albite ± Muscovite	The main difference from Category 1 is that perthite occurs in the mica zone. Quartz and perthite are ordinarily much more abundant than albite in inner zones. Zoning is commonly less distinct than in Category 1.
3	111	Intermediate zone or core	Potassium feldspar	Quartz ± Albite ± Muscovite	Quartz Albite ± Perthite Muscovite Tourmaline	Quartz ± Albite ± Muscovite	Contain minable deposits of potassium feldspar, mostly in hood-shaped units. Li minerals are absent or rare. Generally contain few zones and have relatively simple structure.
4	24	Intermediate zone or core	Potassium feldspar (lepidolite at Bob Ingersoll No. 1 mine)	Quartz ± Albite ± Muscovite	Quartz Albite ± Perthite Muscovite Tourmaline	Quartz Albite (commonly cleavelandite) ± Perthite or microcline ± Muscovite ± Amblygonite ± Spodumene ± Lepidolite	Resemble pegmatites of Category 3 but carry Li minerals and generally have many zones.
5	23	Intermediate zone or core	Spodumene	Quartz ± Albite (generally cleavelandite) ± Perthite or microcline ± Amblygonite	Quartz Albite (comonly cleavelandite) ± Perthite or microcline Muscovite ± Amblygonite Tourmaline	No large inner units other than the spodumene units	Contain abundant Li minerals. Many have numerous zones.
6	29	First intermediate zone or inner part of wall zone	Beryl and scrap mica	Quartz Albite (commonly cleavelandite) ± Perthite	Quartz Albite (commonly cleavelandite) ± Perthite Muscovite Tourmaline	Quartz ± Albite ± Perthite or microcline ± Spodumene ± Amblygonite ± Muscovite	Beryl concentrated at inner edge of wall zone. Inner zones ordinarily contain Li minerals.
7	19	Wall zone or entire pegmatite	Cassiterite	Quartz Muscovite		Quartz ± Albite ± Muscovite ± Spodumene	Quartz-rich. Contain Sn.

These samples show that magmas with the composition of Li pegmatites can reach the surface. The Black Hills, however, have no known physical evidence for the passage of significant quantities of granitic magmas to higher levels or for thermal conditions that would create the biotitic granites characteristic of Sn districts and drive the magmas to shallow depths.

The amounts of granite and pegmatite in the subsurface may be the largest cause of error in the percentage calculations. The world literature on pegmatite districts contains examples ranging from localities with few or no proved granitic associates to localities with few zoned pegmatites and huge quantities of contemporaneous granitic rocks. The Black Hills are between these two extremes. Pegmatites probably are overrepresentated at the present surface because granite bodies may exist as far down as the magmatic sources. If so, the zoned and simple pegmatites are an even smaller percentage of the entire system than the calculations show.

TABLE 2. Abundance of zoned, simple, and layered pegmatites in the Fourmile and Berne quadrangles

Isograms	Number of pegmatites: Zoned	Simple	Layered	Total	Percentage of each kind of pegmatite: Zoned	Simple	Layered	Area: km²	sq. mi.	Number of pegmatites per sq. mi.*
0–50	44	283	19	346	12.8	81.7	5.5	55.4	21.4	16
50–100	33	562	73	668	4.9	84.2	10.9	25.1	9.7	70
100–150	6	346	84	436	1.4	79.4	19.3	9.1	3.5	125
150–200	3	387	133	523	0.6	74.0	25.4	7.8	3.0	175
200–250	6	665	268	939	0.6	70.8	28.5	10.9	4.2	225
250–300	2	166	25	193	1.0	86.0	13.0	1.8	0.7	275
>300	4	483	25	512	0.8	94.3	4.9	3.9	1.5	340
Entire area	98	2892	627	3617	2.7	80.0	17.3	114.0	44.0	

Note: Determined from maps by Redden (1963b, 1968) and isograms of Figure 1.
* Rounded to nearest 5 except between 0 and 50 isograms.

DISTRIBUTION OF ZONED PEGMATITES

The map (Fig. 1) shows that the distribution of zoned pegmatites is much more complex than simple regional zonation around the exposed granite or around any hypothetical unexposed bodies of granite. Though zoned pegmatites are scattered widely across the region, they have a strong tendency to congregate in clusters, and the clusters differ in the kinds of pegmatites they contain. A still broader aspect of the distribution has at times caused the region to be regarded as three separate mining districts: a muscovite district at Custer, Sn at Hill City, and Li and Be at Keystone. The two categories of muscovite pegmatites are in different parts of the Custer region, though the only difference between them is the presence or absence of perthite in the wall zone. Nearly all pegmatites of Category 2 are in an area extending 2 to 10 km west of Custer State Park, and nearly all pegmatites of Category 1 are farther west and northwest. The potassic feldspar pegmatites (Categories 3 and 4) are abundant in a small area near Keystone and in a broad area south and southwest of the granite. Some spodumene pegmatites of Category 5 are near Keystone; others are in a belt near the zero isogram from Hill City southwest to the Tin Mountain mine; and still others are along the east side of the steep ridge in the isograms south of Custer. The beryl-scrap muscovite pegmatites of Category 6 are chiefly along the west side of the pegmatite region, but the two that have produced the most beryl are the Peerless mine at Keystone and the Beecher No. 3 mine south of Custer. All the Sn pegmatites are northwest and north of the granite. Some of these characteristics of the distribution reflect a regional zonation in which rare-element pegmatites tend to be at low isogram levels and muscovite pegmatites at high isogram levels. The zonation is somewhat vague but no more so than it appears to be in most of the districts reviewed by Heinrich (1953).

Tables 5 and 6 allow assessment of regional zonation and Tables 7 and 8 show the clustering behavior of the zoned pegmatites in Figure 1. The map shows no zoned pegmatites in Custer and Wind Cave parks; some do exist and a few were once worked, but almost nothing is known about them because prospecting and mining have been prohibited for many decades. The 278 zoned pegmatites on Figure 1 include only those large enough for mining or prospecting. The region undoubtedly contains more zoned pegmatites than are on the map. Yet it is clear that only a few hundred, or about 2%, of the pegmatites in the southern Black Hills are of the zoned variety.

Table 5 shows that the ratio of zoned pegmatites to other kinds of pegmatites increases sharply at the lower isogram levels but that the abundance of zoned pegmatites per sq. mi. increases at a much more modest rate. That is, the distribution does reflect regional zonation, at least in the sense that anyone searching for an undiscovered zoned pegmatite would have to examine far fewer pegmatites and a smaller area if he looked only in places below the 100 isogram.

In the pegmatite literature, the kinds of regional zonation most commonly discussed depend on changes in mineral content and in the abundance of rare elements, which here would cause changes in the abundance of the categories of zoned pegmatites at different isogram levels. Table 6 has the pertinent data. The abundance of muscovite pegmatites (Categories 1 and 2) relative to other kinds of zoned pegmatites increases from the zero isogram to above the 150 isogram. A large share of the po-

TABLE 3. Calculated abundance of pegmatites in the southern Black Hills

Isograms	Area: km²	sq. mi.	Number of pegmatites per sq. mi.*	Calculated number of pegmatites**
0–50	284.6	109.9	16	1800
50–100	150.5	58.1	70	4100
100–150	123.0	47.5	125	5900
150–200	110.1	42.5	175	7400
200–250	17.6	6.8	225	1500
250–300	13.2	5.1	275	1400
>300	12.2	4.7	340	1600
Total	711.2	274.6		23700†

* From Table 2.
** Rounded to nearest 100.
† Does not include pegmatites in the 2.6 sq. mi. of metamorphic inliers in the Harney Peak pluton. Only a few pegmatites are exposed in these inliers, perhaps partly for geomorphic reasons. The total number of pegmatites in the inliers is probably only about 100.

TABLE 4. Area of pegmatites of different kinds and sizes in the Fourmile and Berne quadrangles

Size		Layered intrusions*		Simple pegmatites		Zoned pegmatites		All pegmatites	
m²	sq. ft.	Number	Area (sq. mi.)	Number	Area (sq. mi.)	Number	Area (sq. mi.)	Number	Area (sq. mi.)
10–500	100–5000	456	0.02	2745	0.15	84	0.01	3285	0.18
500–5000	5000–50000	80	0.07	137	0.09	9	0.01	226	0.17
5000–15000	50000–150 000	52	0.18	8	0.02	5	0.02	65	0.22
15000–40000	150 000–400 000	30	0.24	1	0.01	—	—	31	0.25
>40000	>400 000	9	0.21	1	0.02	—	—	10	0.23
Total		627	0.72	2892	0.29	98	0.04	3617	1.05

* Excludes bodies shown as granite on Figure 1.

tassic feldspar pegmatites of Category 3 is below the 100 isogram. Most of the rare-mineral pegmatites are below the 100 isogram. The distribution of large mines, also shown on Table 6, has variations from the general pattern, but none of them appears to be significant.

The map has many clusters of zoned pegmatites, and it also has large areas in which zoned pegmatites are absent. The clusters and the barren areas can extend across low or high isograms and can be near granite or far away from it, and their positions have no obvious relation to other known aspects of the regional geology.

The clustering effects are expressed quantitatively in Table 7 for the six large clusters that are outlined on Figure 1 and labeled with uppercase letters, and for the the small clusters labeled with lowercase letters enclosed in circles. The large clusters include all areas with 10 or more zoned pegmatites in which each is within 1 km of its nearest neighbor. The small clusters have five or more pegmatites at a spacing of 0.6 km or less. These are not outlined on the map because of their small size. The sequence for each set of clusters in the table is from the one with the smallest to the one with the largest percentage of rare-mineral pegmatites. All except three of the small clusters are a part of one of the large clusters. Only one large cluster does not contain a small cluster.

The six large clusters contain a total of 135 zoned pegmatites, which is about half of all the zoned pegmatites, but the total area of these clusters is only 39 km², which is a trifling share of the pegmatite region. The ten small clusters occupy a total area of only about 18 km², yet contain 97 zoned pegmatites, which is about a third of all the zoned pegmatites. Table 8 shows that the six large clusters contain about half of the pegmatites in Categories 1, 2, 4, and 6. The ten small clusters contain about a third of all these categories except number 6, which is more abundant in the small clusters because Cluster i (Table 7) contains five pegmatites of this kind. The simple feldspar pegmatites (Category 3) are somewhat fewer than half the pegmatites in the large clusters and fewer than a third of those in the small clusters. The Li and Sn pegmatites (Categories 5 and 7) are the only kinds of pegmatites that have more tendency to be in the clusters than elsewhere, for most of them are in the large clusters and more than half of them are in the small clusters. The 33 large mines, as Table 8 also shows, behave in much the same way as smaller pegmatites, except that most of the major muscovite mines are outside the clusters.

TABLE 5. Regional abundance of zoned pegmatites

Location	sq. mi.	Number of pegmatites	Number of zoned pegmatites	Percentage zoned pegmatites	Number of zoned pegmatites per sq. mi.
0–50 isograms	86.6	1400	113	8.1	1.3
50–100 isograms	41.4	2900	77	2.7	1.9
100–150 isograms	34.5	4300	27	0.6	0.8
Above 150 isograms and outside granite	43.9	9300	42	0.5	1.0
In granite or layered pegmatites	—	—	19	—	—

Note: Calculated as in Table 3. Excludes areas in Custer State Park and Wind Cave Park.

The clusters have startling differences. Cluster A, with 16 pegmatites south-southwest of Custer, has 57% mica pegmatites, and the only rare-mineral pegmatites are two small ones of the beryl-scrap muscovite category. Cluster B, containing 25 pegmatites east-southeast of Custer, also has many muscovite pegmatites, but they are accompanied by several rare-mineral pegmatites. This large cluster contains two small clusters (a and b) that consist mostly of muscovite pegmatites. Cluster C, east-southeast of Keystone, is the largest in Table 7, for it has 34 pegmatites and six of them are large mines. It has 62% potassic feldspar pegmatites, 29% in the rare-mineral categories, and only a few small muscovite pegmatites. The Keystone district is best known for its rare-mineral pegmatites, but it also has numerous feldspar mines. In two small clusters in this district, the one near Keystone (f) has nearly as many rare-mineral pegmatites as feldspar pegmatites, and the one farther away (c) consists predominantly of feldspar pegmatites. Clusters D and d, 10 km west of Custer, cover virtually the same area. Muscovite pegmatites are most common, but this is misleading because the muscovite pegmatites are small and the area is best known for its rare minerals. Clusters E and g, on the west side of the granite, also cover much the same area, and each consists mostly of small rare-mineral pegmatites. Cluster F, at Hill City, has nine Sn pegmatites and

TABLE 6. Distribution of the varieties of zoned pegmatites in relation to the isograms

Location	Category 1	2	3	4	5	6	7	Total	Percentage of muscovite, potassic feldspar, and rare-mineral pegmatites: Muscovite pegmatites	Potassic feldspar pegmatites	Rare-mineral pegmatites
All pegmatites											
0–50 isograms	12	2	43	10	14	15	17	113	12	38	50
50–100 isograms	10	8	28	10	8	11	2	77	23	36	40
100–150 isograms	9	1	12	4	—	1	—	27	37	44	19
Above 150 isograms and outside granite	13	9	18	—	—	2	—	42	52	43	5
In granite or layered pegmatites	5	3	10	—	1	—	—	19	42	53	5
Total	49	23	111	24	23	29	19	278	26	40	34
33 large mines											
0–50 isograms	2	—	5	2	5	1	—	15	13	33	53
50–100 isograms	1	1	3	2	2	1	—	10	20	30	50
100–150 isograms	3	—	1	2	—	—	—	6	50	17	33
Above 150 isograms	2	—	—	—	—	—	—	2	100	—	—
Total	8	1	9	6	7	2	0	33	27	27	45

Note: Muscovite pegmatites are Categories 1 and 2. Potassic feldspar pegmatites are Category 3. Rare-mineral pegmatites are Categories 4–7.

one rather important spodumene mine, and Cluster j is the same except that it lacks the spodumene mine and two of the Sn pegmatites.

The three small clusters that are not a part of any large cluster are e, h, and i. All have very few pegmatites. None contains a muscovite pegmatite. One of the clusters (e) has one more of the feldspar pegmatites than of the rare-mineral pegmatites, but the others consist mostly (Cluster h) or entirely (Cluster i) of rare-mineral pegmatites. Cluster h has three of the most important rare-mineral mines in the Black Hills.

To sum up, both the large and the small clusters have wide ranges in the kinds of pegmatites they contain. The clusters have as much as 83% muscovite pegmatites, as much as 75% feldspar pegmatites, and as much as 100% rare-element pegmatites. Most of the spodumene and Sn pegmatites are in the clusters. One small cluster consists entirely of Sn pegmatites, and another consists entirely of beryl-scrap muscovite pegmatites. The clustering effect is a major aspect of the distribution. The clusters may be near the exposed granite or in the farthest reaches of the pegmatite region, where granite is either absent or is beneath the surface. They may be at high or low isogram levels. The distribution suggests that ultimately nearby

TABLE 7. Zoned pegmatites in the clusters

Cluster*	Location**	Number of pegmatites	Number of pegmatites in each category: 1	2	3	4	5	6	7	Percentage distribution: Muscovite pegmatites	Potassic feldspar pegmatites	Rare-mineral pegmatites
Large clusters												
A	1–4 mi. SSW of Custer	16	6	3	5	0	0	2	0	57	31	12
B	1–4 mi. ESE of Custer	25	5	6	9	4	1	0	0	44	36	20
C	0–4 mi. ESE of Keystone	34	3	0	21	3	5	2	0	9	62	29
D	6 mi. west of Custer	21	10	0	4	2	1	4	0	48	19	38
E	4–8 mi. SSW of Hill City	29	1	1	3	1	11	6	6	7	10	83
F	Adjacent to Hill City	10	0	0	0	0	1	0	9	0	0	100
Total		135	25	10	42	10	19	14	15	26	31	43
Small clusters												
a	4 mi. ESE of Custer	6	0	5	1	0	0	0	0	83	17	0
b	2 mi. east of Custer	7	4	0	2	1	0	0	0	57	29	14
c	3 mi. SE of Keystone	16	1	0	12	1	1	1	0	6	75	19
d	6 mi. west of Custer	18	9	0	2	2	1	4	0	50	11	39
e	6 mi. WSW of Custer	7	0	0	4	2	0	1	0	0	57	43
f	1 mi. south of Keystone	11	0	0	6	2	3	0	0	0	55	45
g	6 mi. SSW of Hill City	15	1	1	1	0	5	3	4	13	7	80
h	4 mi. SSE of Custer	5	0	0	1	1	2	1	0	0	20	80
i	5 mi. WNW of Custer	5	0	0	0	0	0	5	0	0	0	100
j	1 mi. west of Hill City	7	0	0	0	0	0	0	7	0	0	100
Total		97	15	6	29	9	12	15	11	22	30	48

* The sequence is according to the percentage of rare-mineral pegmatites in each cluster.
** Locations are shown on Figure 1.

TABLE 8. Comparison of the abundance of the various categories of zoned pegmatites in the entire region and in the clusters

		Number of pegmatites in each category							Percentage in each category						
	Total	1	2	3	4	5	6	7	1	2	3	4	5	6	7
All pegmatites															
Entire region	278	49	23	111	24	23	29	19	18	8	40	9	8	10	7
Large clusters	135	25	10	42	10	19	14	15	19	7	31	7	14	10	11
Small clusters	97	15	6	29	9	12	15	11	15	6	30	9	12	15	11
33 large mines															
Entire region	33	8	1	9	6	7	2	0	24	3	27	18	21	6	0
Large clusters	15	2	0	5	3	4	1	0	13	0	33	20	27	7	0
Small clusters	13	1	0	4	2	5	1	0	8	0	31	15	38	8	0

unzoned intrusions will also be found to have localized differences.

RELATION OF DISTRIBUTION OF PEGMATITES TO STRUCTURE, LITHOLOGY, AND METAMORPHISM OF HOST ROCKS

Comparison of the pegmatite distribution map (Fig. 1) and the geologic map (Fig. 2) shows little evidence for a relationship between the distribution of pegmatites and the structure of the metamorphic rocks. Some of the isograms follow the domal structure around the granite, but elsewhere the isograms cross structural trends nearly everywhere. An exception is the east side of the area of abundant pegmatites south of Custer, which is almost exactly along the faults that run north from Pringle. Structural control by the faults seems unlikely, but the metagraywackes to the west may have been more suited to intrusion by pegmatites than the quartzites and mica schists to the east. Generally, however, any tendency to favor one kind of rock type over another is slight. One example is the small low in the isograms northwest of Custer, which coincides with a narrow strip of biotite-rich schist. Another is the indentations in the isograms 3 km southwest of Custer, where they cross a thin unit containing various mica schists, amphibole rocks, and quartzites, all of which seem to have been unreceptive to the emplacement of pegmatites. Elsewhere any preferences for different kinds of host rocks are not obvious, but we do believe that pegmatites tend to be more abundant in rocks of moderate competency (the quartz-mica-feldspar schists of the metagraywackes) than in the very competent rocks (the quartzites and amphibolites) or the very incompetent rocks (the mica-rich schists). Such differences, however, have no effect on the broad aspects of the isogram patterns.

TABLE 9. Distribution of zoned pegmatites in relation to the first sillimanite isograd

		Pegmatites above sillimanite isograd		Pegmatites below sillimanite isograd	
Category of zoned pegmatites	Total in category	Number	Percent of total in category	Number	Percent of total in category
1	49	38	78	11	22
2	23	23	100	0	0
3	111	91	82	20	18
4	24	17	71	7	29
5	23	12	52	11	48
6	29	11	38	18	62
7	19	5	26	14	74
Entire area	278	197	71	81	29

The distribution of zoned pegmatites also has little or no relation to the kinds of host rocks. Most of them are in metagraywacke, but they occur in other metamorphic rocks also. The many zoned pegmatites below the 50 isogram can be in any host rock, regardless of rock type or structure. No known evidence indicates that the host rock has an important part in determining whether an intrusion is zoned, simple, or layered.

Metamorphism has at least some correlation with the abundance of pegmatites. The outer isograms tend to be parallel to isograds. North of the granite the staurolite isograd is very nearly parallel to the zero isogram and generally to the north of it. The first sillimanite isograd is mostly between the zero and 50 isograms. The area above the second sillimanite isograd has only two small zoned pegmatites and a low in the isograms. Metamorphism in the southeastern part of the region is not known well enough to judge its relationship with the distribution of pegmatites.

The abundance of the various kinds of zoned pegmatites above and below the first sillimanite isograd is shown in Table 9. About 70% of the zoned pegmatites are above the isograd and about 30% below it. Most of the muscovite pegmatites and an only slightly smaller share of the feldspar pegmatites are above the isograd. Half of the spodumene and a majority of the beryl-scrap mica pegmatites are below the isograd, and most of the rest are either near it or are on the east side of the ridge in the isograms south of Custer. Three-fourths of the Sn pegmatites are below the isograd, and the rest are only slightly above it.

PRESSURE AND TEMPERATURE

In Figure 11, which shows various field boundaries that limit the *P-T* regime, the haplogranite minimum should be about equivalent to the solidi for the Harney Peak Granite compositions because they are almost entirely albite, orthoclase, and quartz. The most abundant of the other constituents is excess Al_2O_3. A solidus fewer than

20 °C lower was obtained by Huang and Wyllie (1973) for a muscovite-rich bulk sample of Harney Peak Granite in which the content of normative corundum is 4.8% and the composition of the normative plagioclase is An_3. Burnham and Nekvasil (1986) found a solidus that is nearly identical to the haplogranite minimum for a bulk sample of a feldspar-quartz-muscovite pegmatite at Spruce Pine, North Carolina, which has 1.25% normative corundum and normative plagioclase of An_{11}. Neither of these solidi is shown on Figure 11 because of their similarity to the haplogranite minimum.

The boundary between muscovite + quartz and sillimanite + potassium feldspar + H_2O (the second sillimanite isograd) crosses the haplogranite minimum at 3.7 kbar and 660 °C. This is likely to approximate the natural conditions in the Black Hills because granite crystallized on both the muscovite and sillimanite sides of the boundary. Confirmation comes from a temperature of 670 °C determined from calcite-dolomite intergrowths in an inlier near the southwest edge of the main pluton (Redden et al., 1985, p. 238).[1] The surrounding granite contains primary sillimanite and primary muscovite, and a short distance to the west the second sillimanite isograd abuts the contact of the main pluton.

The Al_2SiO_5 field boundaries and triple point on Figure 11 are from Robie and Hemingway (1984, p. 305), who put the triple point at 4 kbar and 517 °C. In the graphs of a review article, Essene (1982) placed the point at the slightly lower pressure and temperature of Holdaway (1971). Salje (1986, p. 1369) obtained generally similar results with coarse-grained sillimanite, but with a sample of fibrolite the boundary with andalusite was at much higher temperatures, yielding a triple point at 5.9 kbar and 663 °C. In contrast, Kerrick (1987, especially Fig. 4) found that fibrolite derived mainly from biotite in a thermal aureole appeared at a temperature about 100 °C lower than the coarse sillimanite isograd and about 0.3 km away from it. In the Black Hills, coarse sillimanite is abundant near the southwest border of the granite and has been seen adjacent to the first sillimanite isograd at the Custer–Pennington County line west of the granite, but most of the sillimanite is fibrolite that formed from muscovite and other micaceous minerals (Redden, 1963b, p. 260). According to Holdaway (1971, p. 125–128) the reaction with muscovite would be at approximately the equilibrium temperature, unlike the reaction in which fibrolite forms from andalusite, which would be higher by 200 °C or more. Because the first sillimanite isograd is well inside the staurolite isograd in the Black Hills, the low temperature of the triple point with respect to the staurolite curve in Figure 11 may mean that the isograd for fibrolite in the natural conditions is at a somewhat higher temperature than on the graph and that staurolite formed at a lower temperature than the reaction used on Figure 11. On the other hand, Milton (1986) has shown from the study of a North Carolina locality that the staurolite curve is indeed at a higher temperature than the Al_2SiO_5 triple point. In short, the Al_2SiO_5 field boundaries of Figure 11 are likely to be close to the natural conditions in the Black Hills. Because andalusite and sillimanite are the Al_2SiO_5 minerals in the Harney Peak aureole, the maximum pressure is less than that of the triple point.

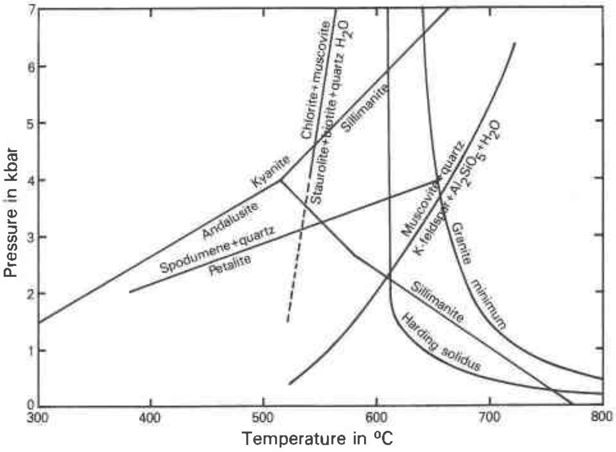

Fig. 11. Field boundaries relevant to the environment of pegmatites in the southern Black Hills. The reaction of petalite to spodumene + quartz is from London (1984). The reaction yielding staurolite is from Hoschek (1969); it represents the staurolite isograd according to Winkler (1974, p. 199). The kyanite-andalusite-sillimanite boundaries are from Robie and Hemingway (1984). The reaction of muscovite + quartz to form potassium feldspar + sillimanite (the second sillimanite isograd) or andalusite is from Chatterjee and Johannes (1974). The solidus for the Harding pegmatite is from Burnham and Nekvasil (1986). The granite minimum is from Luth et al. (1964).

The minimum possible pressure is above that of the petalite-spodumene reaction (Fig. 11) because all of the spodumene of the southern Black Hills is primary and petalite has never been found. Burnham and Nekvasil (1986) showed that the H_2O-saturated solidus of a composite sample from drill holes in the Harding pegmatite, Dixon, New Mexico, which is rich in lepidolite and spodumene, is at 610 °C at pressures above 2 kbar (Fig. 11). Stewart (1978) found a eutectic at 640 °C and 2 kbar in the system albite-quartz-eucryptite-H_2O. The temperature would be depressed to somewhat below 600 °C by the presence of potassium feldspar, excess Al_2O_3, and other constituents (Stewart, 1978, p. 976–977). London (1986) traced the evolution of the fluid to lower temperatures by a study of fluid inclusions in spodumene in the Tanco pegmatite, Manitoba, where nearly all the spodumene is from the breakdown of petalite, but some is primary. The inclusions contain a dense hydrous fluid that is exceedingly rich in B, also rich in Li, Na, and Cs, and

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[1] The data were inadvertently omitted from the original publication. Hand-picked separates of the calcite contain 48.83 and 50.76% CaO and 4.11 and 4.00% MgO; the calcite-dolomite solvus used was the one in Essene, 1982, Figure 6. C. K. Shearer obtained similar results from microprobe analyses (oral communication, 1987). The samples were from a marble quarry located at SW ¼ SE ¼ sec. 33, T.2S. R.5E.

has 14% Al_2O_3 and 38% SiO_2. Experiments in the system $LiAlSiO_4$-$NaAlSi_3O_8$-SiO_2-$Li_2B_4O_7$-H_2O at 2 kbar indicated that the composition proceeded from Stewart's eutectic at 640 °C to 500 °C at a point near the $NaAlSi_3O_8$-$Li_2B_4O_7$ sideline of the tetrahedron (London, 1986, Fig. 4). London showed that this fluid probably formed the albitites that are the source of the Ta mined at Tanco and are also enriched in Sn, and that it did so between 470 °C and 420 °C when the B went into tourmaline in the wall rocks and the wall zone of the pegmatite. London said the B-rich fluid was the final stage of primary magmatic crystallization, and he regarded a subsequent low density fluid as the beginning of hydrothermal subsolidus activity.

The circumstances are reminiscent of the replacement units in the Hugo pegmatite (Figs. 8 and 9), which has the largest such units in the southern Black Hills. They consist largely of introduced albite and lithian muscovite and contain cassiterite and tantalite-columbite, and the wall rock and the outer part of the wall zone near these replacement bodies have a much higher content of tourmaline than elsewhere along the border of the pegmatite. The replacement units extend from a small albite (cleavelandite variety)–microcline–lithian-muscovite core across all intermediate zones and into the wall zone, but most of the replacement is in three quartzose intermediate zones (Norton et al., 1962, especially p. 86–96 and 102–103). The replaced minerals include large spodumene crystals. The Hugo magma was emplaced at a temperature high enough to cause fibrolitic sillimanite to form in adjacent quartz-mica schist, though the pegmatite is 1 km outside the first sillimanite zone. About 75% of the magma crystallized as feldspar-quartz outer zones (Norton et al., 1962, Table 19) before spodumene appeared in inner zones, at presumably about 600 °C. The replacement bodies, if generated in the manner described by London, formed at temperatures extending down to less than 500 °C. The replacement units constitute only about 2% of the rock in the Hugo pegmatite, and thus their formation and temperature regime were only a minor part of the history of crystallization of the pegmatite.

The Etta pegmatite, which is only a few hundred meters from the Hugo and is in the same unit of quartz-mica schist, consists mostly of spodumene-rich zones (Fig. 8). Sillimanite is absent from the wall rocks. Thus the maximum magmatic temperatures for the Etta and Hugo pegmatites were on each side of the sillimanite-andalusite field boundary, and the pressure for both pegmatites was above that of the petalite-spodumene boundary. The Etta pegmatite lacks replacement bodies like those in the Hugo pegmatite, and it has a small quartz core rather than a core of aluminosilicates, but it has heavily feldspathized rocks along its contacts, and at least some of them contain enough Sn and Ta to have caused expensive efforts aimed at mining them. Thus the geology is compatible with London's (1986) scenario, though the normal supposition would be that the feldspathization preceded rather than followed crystallization of the pegmatite.

The sillimanite-andalusite and the petalite-spodumene boundaries on Figure 11 intersect at 550 °C and 3.25 kbar. If actual crystallization temperatures of the Etta and Hugo spodumene were above 550 °C, the fibrolite stability field would be at higher temperatures than shown on the figure. The same applies for the other spodumene pegmatites of Category 5 that are outside the sillimanite zone (Table 9). Minimum pressures indicated by the petalite-spodumene curve are between 3.25 kbar at 550 °C and 3.6 kbar at 600 °C.

The evidence points to crystallization temperatures ranging from somewhat more than 660 °C in parts of the granite to well below 600 °C in inner units of a few of the zoned pegmatites at a vapor pressure of about 3.7 kbar. If the load pressure were 3.7 kbar and if the overlying rocks were similar to those at the present surface, the depth would be about 13 km. The vapor pressure is unlikely to be much less than the load pressure, for otherwise, according to Barton (1986, especially Fig. 9), chrysoberyl instead of beryl would be the stable Be mineral, and beryl is common and chrysoberyl very rare, though it does occur (Roberts and Rapp, 1965, p. 64).

At the inferred depth and maximum regional temperature, the geothermal gradient would be 50 °C per km, which is exceedingly high but not as high as that suggested for a similar terrane in Colorado (Nesse, 1984, p. 1158). Because most of the Black Hills outside the Harney Peak aureole is at almandine and biotite grades of metamorphism, the temperature prior to heating by granite magma may be as much as 200 °C lower (Winkler, 1974, p. 199 and 210). This yields a gradient of 35 °C per km, which is plausible (Barker, 1983, p. 7). A gradient of 35 °C per km would intersect the muscovite solidus and liquidus (Burnham, 1979, Fig. 3.4) at a depth of 19 km, and a gradient of 30 °C per km would do the same at 22 km. These depths are 6 to 9 km below the present surface, which is possible for the deeper parts of metasedimentary schists in Proterozoic synclines of the southern Black Hills.

EVOLUTION OF THE IGNEOUS SYSTEM

Černý and Meintzer (1988) have recently reviewed current information and interpretations about the geologic processes that yield pegmatitic magmas. They trace the petrogenesis from anatexis in highly deformed metasedimentary troughs to granite magmas and on to pegmatitic granites and thence to zoned pegmatites. Their review shows that the literature has a shortage of the kinds of field data that have been presented in this article. The discussion here will center on interpretations of specific aspects of the field data, with a minimum of comment about how they are related to interpretations in other pegmatite regions.

The high initial Sr^{87}/Sr^{86} content (Riley, 1970, Fig. 2), the low calcium content, and the peraluminous composition indicate that the granite is an anatectic product of metasedimentary micaceous schists. The low content of Fe and Mg in the granite shows that the anatectic temperatures were mostly below the biotite solidus or that the source rocks themselves had a low content of biotite. One consequence of melting below the biotite solidus would be the observed contrast between about 30 ppm Li in the granite and about 50 ppm Li in the mica schists (Norton, 1981). If the melting left biotite behind, it is likely to have left much of the Li behind, for biotite probably attracts more Li than muscovite in the schists (e.g., Shearer et al., 1986).

Walker et al. (1986a) concluded from Sm-Nd isotopic data that the source rocks cannot be among the metasediments exposed at the present surface. The mica schist unit that is exposed over a large area west of Hill City and extends south almost to Custer (Fig. 2) seems to us to be an attractive candidate as one of the source rocks, but even if it is not, it is useful in describing how the anatectic process might have functioned. Modes of 11 samples of this schist show an average of 40% muscovite, 26% quartz, 16% biotite, 8% plagioclase (oligoclase), and 10% other minerals (Redden, 1968, Table 5). The amount of combined H_2O would be about 1.8% from the muscovite and 0.6% from the biotite, for a total of 2.4%. The H_2O in the muscovite would allow melting of about 20% of the rock, and the melt would contain about 8.4% H_2O (Burnham, 1979, p. 98–99; and Burnham and Ohmoto, 1980, p. 2–3). Unless the temperature went to the higher levels required to melt biotite, the magma would be low in Fe and Mg.

Some small plutons are so far away from the main pluton that their locations imply the existence of several magma sources. The best examples are near the southwest corner of Custer State Park and northwest of Pringle, but the granite southeast of Keystone may be added to the list if it extends a long way beneath Paleozoic cover. All of these are accompanied by highs in the isogram levels. Other highs in the isograms and small domes in various places may be surface expressions of granite centers. The isolated cluster of Sn pegmatites at Hill City and its proximity to gently dipping rocks at the edge of the Harney Peak dome may also reflect the existence of subsurface granite. Gravity modeling by Duke et al. (1990) from the data of Kleinkopf and Redden (1975) shows that granite probably underlies the Hill City area and several other outlying areas in the pegmatite region.

The outer and structurally higher parts of the main pluton and at least one small pluton are generally more evolved and younger than the inner parts (Shearer et al., 1987; Duke et al., 1990). Shearer et al. (1985) showed, using trace-elements, especially K-Rb ratios, that zoned pegmatites are still more evolved and thus probably younger than the granite. These results are in accord with the long-standing belief in an age sequence from essentially granitic rocks to simple pegmatites and then to zoned pegmatites with concentrations of muscovite and potassic feldspar and on to the rare-element pegmatites. Granite probably overlaps in age with simple pegmatites and with muscovite and feldspar zoned pegmatites, for it contains many fracture fillings of simple pegmatites and zoned pegmatites, some perthite-rich and some with muscovite-rich wall zones, and also has monomineralic quartz fracture fillings. Overlap in age with rare-mineral pegmatites is less evident. Beryl and cassiterite occur in the granite. Amblygonite-montebrasite has not been recorded and spodumene is probably absent in fracture fllings in the main pluton. One satellite located just south of the county line (T.2S. R4E.) has a spodumene pegmatite (Fig. 1). A much smaller body, called the Mountain Lion or Soda Spar, which consists largely of layered pegmatitic rock but has been suspected of also having zonal structure, contains spodumene-bearing fracture fillings (Norton and others, 1964, p. 329–331). Dozens of the zoned pegmatites have spodumene; most are in Categories 4–6, but at least one (the New York) is a muscovite pegmatite.

Crosscutting relations have been unhelpful in establishing relative ages because, in most exposures where one pegmatite cuts across another, the two pegmatites are similar to each other. No large zoned pegmatite of any category has been conclusively shown to cut a pegmatite of another kind. Confirmation that simple pegmatites overlap in age with granite comes from a few places where they are cut by small layered bodies.

Evidence bearing on temperatures of crystallization may be useful in inferring age relations. Both the metamorphism, as shown by the isograds, and the distribution of pegmatites, as shown by the isograms, are indicators of the temperature regimes. Though the age of one is not necessarily the same as that of the other, they do produce similar patterns in the outskirts of the region. Granite crystallized both above and below the temperature of the second sillimanite isograd. Several pegmatites above the second sillimanite isograd have muscovite books that are partly to completely altered to sillimanite, but more commonly the sillimanite is primary and in some places has been partially converted to fine-grained muscovite by retrograde reactions. The pegmatites with muscovite altered to sillimanite obviously formed before the peak of metamorphism, and those with primary sillimanite formed when crystallization temperatures were above the stability field of muscovite.

The spodumene pegmatites are in the outer and thus cooler parts of the region, which is in accord with data showing them to have low crystallization temperatures (Stewart, 1978; London, 1984, 1986). Other rare-mineral pegmatites also tend to be in the apparently cooler areas. The position of the Li and other rare-element pegmatites implies that the magma bodies moved into an environment cool enough so that the differences in temperature between them and the host rocks were too small to allow further movement, and they stopped and crystallized. The Beecher rare-element pegmatites are an especially good example of temperature control because they are east of a very steep gradient in the isograms, which implies a temperature gradient also. Sheet mica pegmatites, in contrast, tend to be in the apparently hotter areas. Their crystallization temperatures may have been similar to those of unzoned pegmatites, though somewhat lower because their more peraluminous composition would depress the temperature at which crystallization began.

The apparent control by temperature can be turned into a means of surmising the age sequence in places that have a variety of kinds of pegmatites in a small area. South of Keystone the Peerless beryl-scrap muscovite pegmatite, the Etta spodumene pegmatite, the Hugo feldspar pegmatite with Li minerals, several ordinary feldspar pegmatites, and a few simple pegmatites (including the one from Norton, 1970, used in Fig. 4) are within a few hundred meters of each other. It seems plausible that these pegmatites were emplaced at different times, under the control of declining regional temperatures. The Etta pegmatite is likely to have had the lowest crystallization temperature and to be the youngest. The Peerless also had a low temperature and late age, for it caused the retrogression of staurolite and andalusite to micaceous aggregates (Sheridan et al., 1957, p. 4–5 and Plate 1). The Hugo, which has much less Li than the Etta, had a higher temperature and presumably a greater age. The feldspar pegmatites and the simple pegmatites probably are somewhat older.

It is now widely agreed, from Jahns and Burnham (1969), that exsolution of an aqueous phase marks the beginning of pegmatitic crystallization processes (Černý and Meintzer, 1988, p. 200). In the exposed rocks of the Black Hills, pegmatitic processes began with the formation of coarse-grained layers in the Harney Peak Granite, and an exsolved aqueous phase almost certainly was involved (Duke et al., 1990). Pegmatitic processes continued among the thousands of unzoned pegmatites. Layering, large crystals, and an upward increase of K relative to Na have all been attributed, probably correctly, to actions of the aqueous phase. The vertical differentiation of K and Na continued into two of the major assemblages of zoned pegmatites (Norton, 1983, Table 3). The separation of potassic from sodic pegmatite was the largest and most widespread step in the evolution of the pegmatitic part of the system.

Differentiation from the contact inward is the dominant feature of zoned pegmatites. In the muscovite and feldspar pegmatites (Categories 1–3), this differentiation is from muscovitic wall zones to feldspathic zones and, in some pegmatites, quartz cores. Muscovite and plagioclase of wall zones are normal early precipitates of pegmatitic magma, according to experimental data of Burnham and Nekvasil (1986), but the amount of muscovite may become greater as the ratio of Al to alkalis is increased by the loss of alkalis to the wall rock via the aqueous fluid (Shmakin, 1973; Morgan and London, 1987). In the rare-element pegmatites, the higher contents of Li, Be, and Sn lead to zones in which these elements form independent minerals. This is a major effect only in pegmatites of Category 5, where spodumene is known from Stewart (1978) to be best interpreted as reflecting an increase in the Li concentration in the rest magma to a level that requires it to be precipitated as a Li mineral.

Rare-element pegmatites are not as different from the other kinds of zoned pegmatites as might be supposed. Except for the Sn category, they too are of essentially granitic bulk composition. They acquire their status as rare-element pegmatites by having enough Li, Be, Sn, Cs, Ta, Nb, or U to form minerals in which these elements are an essential constituent. The most Li in any of the pegmatites is about 7000 ppm; the most Sn certainly is less than 5000 ppm and probably is about 1500 ppm (Page and others, 1953, p. 59, 93, 94); the most Be is about 300 ppm; Cs appears to be in the low hundreds of ppm in the Tin Mountain pegmatite (Walker et al., 1986b), which is the only one known to have pollucite; and Ta, Nb, and U are probably much below 50 ppm in all the pegmatites. The total of rare elements is well under 1% in every pegmatite. The low atomic weights of Li and Be cause their amounts to be deceptively low when measured by weight instead of by atomic abundance (and the contents of heavy rare elements are deceptively high), but even so, the totals are small. Li is by far the most abundant of these elements, and because it forms spodumene, amblygonite-montebrasite, and lithian micas, it adds greatly to the number and variety of zones by giving rise to the existence of assemblages 5, 6, and 9 of Norton (1983, Table 3).

The quantity of Li and Be, and presumably the other rare elements in the rare-element pegmatites, is only a small share of the quantity in the entire system. The main pluton contains an average of about 30 ppm Li and 8 ppm Be, which are close to the abundances in average granite, and the highest analyses are 171 ppm Li and 17 ppm Be (Norton, 1981; Norton et al., 1958, p. 25; Shearer et al., 1987, p. 477). If the Li-rich pegmatites have an average of 5000 ppm Li and beryl-rich pegmatites have an average of 200 ppm Be, they contain, respectively, about 10% of the Li and 2% of the Be in the exposed part of the granitic system. The percentages probably are substantially smaller for the three dimensions of the entire system, but it does seem clear that much more of the Li than of the Be in the system went into zoned pegmatites.

Li and Be behaved quite differently during the evolution from granitic rocks to zoned pegmatites. Spodumene formed in only a few dozen pegmatites, and beryl occurs in probably hundreds of pegmatites and in the granite as well. One of the remarkable properties of beryl is that it can appear in granite of very low Be content (Norton et al., 1958, p. 25).

The content of beryl probably increases gradually and continuously from low levels in granite to higher levels in various kinds of pegmatites until it reaches its highest level in a few zoned pegmatites. In contrast, Li must be concentrated to several thousand ppm before it begins to form spodumene or petalite, and the behavior can be shown on simple phase diagrams (Stewart, 1978). Amblygonite-montebrasite, which is the principal Li phosphate, forms at much lower concentrations of Li, for it is an accessory mineral in numerous pegmatites that lack Li silicates (Page and others, 1953, p. 54; Redden, 1963b,

Table 7). These pegmatites probably contain less than 500 ppm Li. This is a likely limit because 500 ppm is approximately the content of the Peerless pegmatite, which has nearly all of its Li in phosphates but also has lithian muscovite and a few crystals of spodumene (Sheridan et al., 1957).

The processes that gave rise to Li-rich and Be-rich pegmatitic magmas seem to have operated separately more than they operated together. The clusters of Table 7 show a wide range in the ratio of spodumene pegmatites (Category 5) to beryl-scrap muscovite pegmatites (Category 6). Many rare-mineral pegmatites have both Li minerals and beryl, but the most Li-rich pegmatites tend to have modest beryl contents and the most Be-rich pegmatites tend to have low amounts of Li minerals (with the exception of the Bob Ingersoll Nos. 1 and 2). The Beecher No. 2 pegmatite, which is one of the richest in spodumene, has no known beryl, yet the adjacent Beecher Lode and Beecher No. 3–Black Diamond pegmatites are major sources of beryl. At the Edison spodumene mine, the only beryl ever noticed was two crystals a few millimeters in diameter, but the nearby White Cap mine has been a significant producer of beryl, and its only known Li minerals are accessory triphylite-lithiophilite. It may be that in these places the concentrating processes for Li and Be operated at different times.

Among the possible processes by which pegmatitic magmas become enriched in rare elements, the most obvious is that the low ability of the principal minerals of the granite to accept these elements causes them to be concentrated in residual magmas that ultimately crystallize as rare-element pegmatites. This may indeed be the chief process for Be, which in pegmatites reaches no more than 40 times its level in the granite, and also for such elements as Cs, Sn, Ta, Nb, and U. But for Li a concentration factor of 40 would yield only 1200 ppm. As Stewart (1978) has emphasized, most pegmatites contain either very little Li or several thousand ppm. The traditional view that Li-rich magmas formed by concentration in parental granitic magmas is still the dominant opinion (Černý and Meintzer, 1988). Suggestions that the concentrating process was influenced by behavior in the anatectic zone (Norton 1973, p. 368–369; Stewart, 1978, p. 979) or by aqueous fluids that transported Li in schists and may also have interacted with pegmatitic magma (Norton, 1981) have been vigorously opposed (Černý, 1982, p. 441–442; Černý and Meintzer, 1988, p. 170). Unlike much other work on pegmatites—in which researchers can, for example, examine zones within pegmatites and trace the changes and test the possible reasons for them, or can do the same for the various kinds of layering—the issue about Li-rich magmas suffers from a lack of observational data from sites where the process took place because the sites have not been found, or at least not recognized.

Possibly, however, the sites can be found, for Li-rich pegmatites are disproportionately abundant in the clusters, and the clustering itself indicates that localized processes are more important than region-wide processes in causing the development of zoned pegmatites. Granitic magma bodies of surprisingly small size may be adequate to supply the constituents of even the largest and richest lithium and beryllium pegmatites of the Black Hills. If such a magma is able to give up 100 ppm of its Li, which is well below the contents of parts of supposed parent granites elsewhere in the world (e.g., Siroonian et al., 1959, especially Fig. 3; Pye, 1965, p. 52–54), a sill 100 m thick and 300 m in the other two dimensions (0.01 km^3) could be the source of a 400 000 t pegmatite containing 6000 ppm Li, which probably is larger than any spodumene-rich pegmatite of the Black Hills. A sill of the same size would have to give up only 5 ppm Be to form a 400 000 t pegmatite containing 300 ppm Be, which would be equivalent to the Peerless pegmatite. The 6000 ppm Li approaches the maximum found in pegmatites of the world (Stewart, 1978), and the 300 ppm Be is about the most contained in pegmatites (Griffitts, 1973, p. 89). In the places in the world that have much larger rare-element pegmatites, as at Tanco, Manitoba, and Kings Mountain, North Carolina, the volume of the source rock would have to be larger by a factor of as much as 100, which would require a sill of only about 3 km^2 and 300 m thickness. Though this argument is only arithmetic showing that small bodies of granite might yield rare-element pegmatites, it does bring out the possibility that key processes in small subsystems are only slightly understood or have escaped notice entirely (cf. Walker et al., 1989).

The Harney Peak system, from the beginning of regional heating and doming to the end of the emplacement of magmas and their crystallization, yielded tens of thousands of various kinds of granitic and pegmatitic bodies over a long span of time. Obviously conditions must have been different in different places at any single time and must also have changed through time in any single place. When the circumstances are viewed in this way, the vagueness of the regional zonation pattern is unsurprising, and the regional zonation concept itself, though simplistic, retains some validity. Yet the clustering of zoned pegmatites and the differences in the kinds of pegmatites in the clusters are more significant. The clustering behavior points to the existence of subsystems, and indicates that the subsystems behaved differently at different places. Because large areas have no known zoned pegmatites and other broad areas have very few, it is obvious that some parts of the system were unable to create magmas that formed zoned pegmatites. Hence the pegmatitic magmas generated in some layered sills crystallized only as fracture fillings within granite or as simple pegmatites in the country rock. Others went to the stage of ejecting magmas that formed the simpler kinds of zoned pegmatites. And it is likely that only a few reached the extremes of expelling fluids that crystallized as rare-element pegmatites. In a single subsystem the age sequence almost certainly is the conventional one from granitic to pegmatitic rocks, but subsystems in different places may be of different ages, and some localities may have two or more subsystems of different ages.

Geology has not yet reached an end to its decades of debate and its multitude of theories about how zoned pegmatites crystallized, and it clearly is only at the beginning of its understanding of the genesis of the magmas of zoned pegmatites. The localized differences brought out in this article probably result largely from differences in the granitic phase of crystallization, but some of them may have been influenced by differences in the compositions and processes in the anatectic furnaces.

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