Geology of the Harney Peak Granite,

Black Hills, South Dakota

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Introduction

The Harney Peak Granite, exposed over about 100 km^2, in the southern Black Hills, South Dakota, is a classic example of a granite that is surrounded by a well-known pegmatite district. It may have had more influence than any other granite in causing general acceptance of the belief that pegmatite districts have a "source granite" that generated the fluids from which pegmatites crystallized. Though many pegmatite districts of the world have only tenuous evidence for an association with a granitic source, the granite and pegmatites of the southern Black Hills do indeed belong to the same magmatic system.

The Harney Peak Granite and its pegmatites are the youngest Precambrian rocks of the Black Hills. Riley (1970) has dated the granite at 1.74 b.y. A granite near Bear Mountain, at the western edge of figure 1, and another granite near Nemo in the northeastern part of the Black Hills have been dated as late Archean, or about 2.5 b.y. old (Ratté and Zartman, 1970; Zartman and Stern, 1967). Most of the rest of the exposed Precambrian rocks of the Black Hills are metamorphosed Proterozoic sedimentary rocks, especially shales, graywackes, and sandstones; amphibolites derived from volcanic and intrusive rocks are prominent in several places. This report centers on the geology of the Harney Peak Granite and treats its relationships to the various kinds of pegmatites. It addresses the metamorphic rocks only to the extent necessary for discussion of the granitic rocks.

Sources of information

The main body of the Harney Peak Granite is exposed in four 7 1/2-minute topographic quadrangles that have a common corner 3 km east-northeast of Harney Peak (fig. 1). Northwest of this point, in the Hill City quadrangle, the granite has been mapped by Ratté and Wayland (1969). To the northeast, in the Mount Rushmore quadrangle, the mapping was by Norton (1976) and Powell and others (1973). Reports thus far published on the work in these two quadrangles contain little data about the granite.

Most of the main body of granite and nearly all of the satellitic bodies are south of the latitude of Harney Peak. Redden has mapped west of 103°30′ and Norton east of 103°30′, but results of this work have not been issued until now. A report on two satellitic intrusions has, however, been published by Kupfer (1963).

Other reports of field studies that bear on the topics of this paper are by Redden (1963, 1968), Redden and Norton (1975), Norton (1975), and Orville (1960). Results of early studies of the granite were reported by Darton and Paige (1925), Balk (1931), and Runner (1943). The most comprehensive report on the pegmatite mines is by Page and others (1953).

Regional geology

The main body of Harney Peak Granite (fig. 1) is in the form of a structural dome and consists of several rather large sills and a multitude of smaller sills and dikes. Inliers of metamorphic rocks are large enough to be shown separately in several places on figure 1, and small remnants of schist are common. The overall structure of the inliers is domal. The intrusions are so numerous that it is impractical to divide the granite into its individual components at any reasonable map scale or even to outline the boundaries of the larger sills. A striking photograph showing the gentle dips of sills within the central part of the granite was published by Connolly and O'Harra (1929, pl. 4), though neither they nor others seem to have noticed its significance.

The gentle dips of the sills suggest that the exposed granite may not be the top of a much larger body extending to great depth, but instead its base may be near the surface and some of the larger inliers of metamorphic rocks may underlie the granite. Inliers in the Harney Peak pluton contain marble, which is otherwise known only in the older part of the Proterozoic section near Bear Mountain and near Nemo, and there are other similarities among the rocks in these three localities that set them apart from the rest of the Black Hills. Both the Bear Mountain and Nemo areas have small exposures of Archean granite. The granite at Bear Mountain is so similar to that of Harney Peak that no one had the least suspicion they were not contemporaneous until an Archean age was obtained at Bear Mountain (Ratté and Zartman, 1970). It is possible that some of the structurally lower parts of what figure 1 shows as Harney Peak Granite are actually Archean granite.

The geologic map of Darton and Paige (1925) shows the Harney Peak Granite as about twice the size shown on figure 1. Their version has been republished many times, most recently in the 1974 edition of the Geologic Map of the United States (King and Beikman, 1974). Our version also has been published

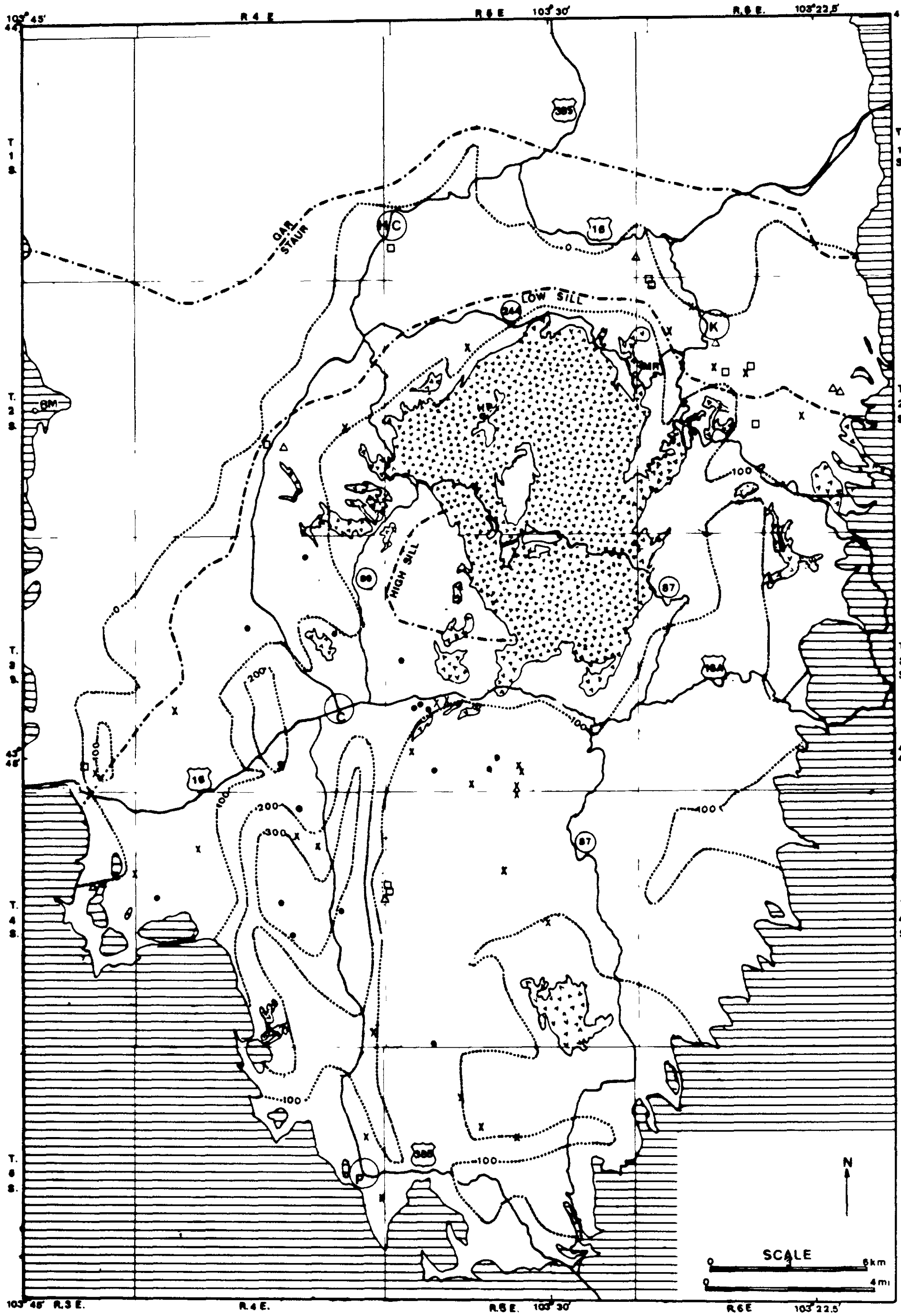

Figure 1.--Geologic map of the southern Black Hills showing distribution of the Harney Peak Granite (v's), metamorphic rocks (unpatterned), and Paleozoic and younger rocks (horizontal lines). Labels for metamorphic zones are: GAR--garnet, STAUR--staurolite, and SILL--sillimanite. Dotted lines are isograms showing the number of pegmatites per square mile. Symbols for the principal pegmatite mines indicate their main products: X--potash feldspar, dot--sheet mica, square--lithium minerals, triangle--beryl and scrap mica. Geographic localities are: C--Custer, HC--Hill City, K--Keystone, P--Pringle, HP--Harney Peak, BM--Bear Mountain, MR--Mount Rushmore.

elsewhere, but without an explanation of the discrepancy. The Darton and Paige map shows three categories of granitic terrane: (1) mostly granite, (2) "granite containing many inclusions of schist " and (3) schist cut by many bodies of granite and pegmatite. Their first category has much the same distribution as our version of the granite. Their third category--schist with many pegmatites--is in an area south of Custer that does indeed have many pegmatites, and has caused no confusion because it was shown on the Darton and Paige map as mostly schist. The problem lies in the second category, which on their map is widely distributed south and southeast of the main body of granite, but is not mentioned in their text. This should have been described as schist and quartzite with pegmatites and small bodies of granite, but because it was called granite with inclusions of schist it was colored a shade of red on the map, giving it a misleading appearance of similarity to the main body of granite.

Figure 1 shows the abundance of pegmatites in different parts of the region by means of isograms indicating the number of pegmatites per square mile. The isograms were drawn mostly from data on geologic maps at a scale of 1:24,000. South and southeast of the Harney Peak pluton, however, they are based on reconnaissance. Calculations from the isograms indicate a total of about 22,000 pegmatites. Only about 1 percent of these are zoned pegmatites, which are the pegmatites attracting the most petrologic and commercial interest. As the isograms indicate, the pegmatite region is narrow north of the granite, widens on the west and east sides, and to the south extends throughout the Precambrian terrane. The greatest concentration of pegmatites is in an area south of Custer and southwest of the Harney Peak pluton.

Pegmatite mines are shown on the map in four categories, according to their principal commodity: potash feldspar, sheet mica, lithium minerals, or beryl and scrap mica. In many respects these represent four recognizably different kinds of zoned pegmatites (Norton, 1975, p. 137-140). On the other hand, many deposits have been important sources of several minerals, and the distinctions among the categories are not clearcut.

The map shows no mines southeast of the pluton. This area is in Custer State Park, where mining has, in practice at least, been prohibited since about 1920. Mines exist up to the Park boundary, and there is no obvious reason why deposits should be absent within the Park. Feldspar mining did not begin in the Black Hills until 1923, and many of the sheet mica deposits were undiscovered until after the beginning of World War II. These, rather than rare-mineral pegmatites, are most likely to exist in the park. The major rare-mineral pegmatites of the Black Hills were discovered during exploration for tin and lithium long before 1920, and their apparent absence or sparsity in the Park is likely to be real.

The country rock consists chiefly of metamorphosed graywackes, shales, and quartzites. Deformation prior to emplacement of the granitic rocks produced a regional pattern of north-northwest-trending isoclinal folds with steep dips. Bedding and schistosity are approximately parallel in the noses as well as limbs of major folds, but outcrops of the noses of some small folds have an axial plane schistosity that crosses bedding. The pattern of the main isoclines is disrupted by small cross-folds, faults, and domes.

The largest of the domes is the one around the Harney Peak pluton. Schistosity and bedding dip generally outward from the granite, and isoclinal folds nearly as far away as Hill City have been rotated into parallelism with the domal structure. Schist screens within the granite also have the domal pattern, and have a few isoclinal folds older than the doming. The attitudes place the top of the dome near the center of the granite.

Structures near individual granitic or pegmatitic bodies reflect forces accompanying intrusion. Schist has reverse dips above the tops of some vertical dikes, thus locally disrupting the domal shape. Abundant boudinage structures in schist northeast of Custer, on the southern flank of the dome, indicate stretching in a north-south direction. Plastic thinning has affected some of the stratigraphic units on the flanks of the dome. Small pegmatites with pinch and swell structures are common in several places near the granite; these resemble boudinage structure, but are the result of intrusion of fingers of pegmatite.

Metamorphism and metasomatism

Most of the Precambrian rocks of the central Black Hills are in the biotite and almandite zones of metamorphism (Redden and Norton, 1975), but the metamorphic grade increases in the granite and pegmatite region. The staurolite isograd crosses the north part of figure 1. The sillimanite zone begins just north of the granite and includes the entire area southwest, south, and east of the pluton. The peak of metamorphism is above the high sillimanite isograd, at the southwest edge of the pluton, where muscovite is absent and many sillimanite aggregates are more than 2 cm long. Bodies of country rock within the granite preserve evidence of this increase in metamorphism except where they have been further changed by contact metasomatism. In general their grain size and abundance of metamorphic minerals increases to the south, and some of them are gneissic.

Andalulsite and cordierite occur in schists of suitable composition. Andalusite-bearing schist is abundant enough to show that the andalusite isograd would lie slightly outside the staurolite isograd. Kyanite is absent around the Harney Peak Granite but occurs in the central part of the Bear Mountain dome. The lack of kyanite indicates a pressure less than 5.5 kilobars and probably less than 3.75 kilobars (Greenwood, 1976, p. 217-220).

The most obvious retrograde metamorphic effects are replacement of andalusite and staurolite by micaceous minerals. Sillimanite aggregates are locally replaced by muscovite, especially in areas with many intrusions.

A conspicuous metasomatic effect of the granite is tourmalinization of schist remnants within the granite or of schist along discordant contacts. Muscovite-apatite or biotite-rich selvages also occur along contacts. Albitized schist, called granulite by Page and others (1953), occurs along parts of the contacts of many pegmatites. Microcline metacrysts have developed in mica schist near some pegmatites, and like the alteration of aluminosilicates to form muscovite indicate potassium metasomatism.

The carbonate inliers within the granite are locally modified to skarn-like rocks or marbles rich in diopside, altered forsterite, and scapolite. A few of them are metasomatized to feldspathic rocks; the chemical composition of one sample is virtually identical to the average composition of the world's anorthosite.

The distribution of Li in schists indicates that some of it was transported outward from the granite (Norton, 1981). Haloes enriched in Li, Cs, and Rb occur around some of the lithium-rich pegmatites. Preliminary data near Keystone suggest that the Cs content of the schist is well above normal levels. Trace-element changes in metamorphic rocks within the granite have not been investigated.

Internal structure of granite and pegmatite

The granitic rocks of the southern Black Hills range from leucocratic granite with few pegmatitic features to highly differentiated pegmatites. The sole major generalization possible is that bodies in the outer part of the region are smaller and generally more pegmatitic, and those in the inner part are larger and generally more granitic.

Texturally, the Harney Peak Granite ranges from fine- to coarse-grained granite through fine- to medium-grained pegmatite, but the first-time observer is more impressed by its pegmatitic than its granitic textures. The granite is generally unfoliated, although a few sills of fine-grained biotite-bearing granite have a foliation parallel to the contacts. The most striking feature of the granite is the textural and compositional layering in virtually all of the larger exposures. The layering is caused largely by concentrations of coarse graphic perthite in lenses a fraction of a meter to several meters thick that are surrounded by a much finer grained, more sodic rock of essentially granitic texture. Locally, the finer grained rock is also layered on a much smaller scale through differences in the abundance of such minerals as tourmaline, feldspar, garnet, and muscovite. This is the "line rock" of many authors. Most of these layers are between 0.5 and 2 cm thick. They occur not only in granite but also in outer zones of some pegmatites.

The layering, both coarse and fine, is essentially parallel to the contacts of the intrusive, but the layers tend to pinch out or otherwise lose their identity along strike. Many intrusives are in part layered and in part more or less homogeneous pegmatite.

The granite also contains segregations of pegmatite and is cut by many pegmatitic dikes. The segregations are mainly coarse-grained perthite-rich bodies, generally lenticular or pod-shaped but also of irregular form. Some of the dikes are merely bodies of granite intruding other bodies of granite. Others range from plagioclase-perthite-quartz through perthite-quartz to monomineralic quartz fracture fillings. Kupfer (1963, p. E9) pointed out that closely spaced parallel fracture fillings can give a misleading appearance of primary layering.

The layered structure also appears in many of the pegmatites, especially these of large size, or near bodies of granite, or in the region of abundant pegmatites south of Custer. Most of them are single rather than multiple intrusions, and thus lack the internal structural complexity of the Harney Peak pluton. They probably, on the whole, have less rock approaching granite in texture than do the bodies shown as granite on the map. Nonetheless, the distinction between them and granite is so nearly imperceptible that the only real difference is in size--a small body, in the literature on the Black Hills and in many places elsewhere in the world, has traditionally been called pegmatite and a large one granite or pegmatitic granite.

Most of the other pegmatites are structually simple intrusives consisting predominantly of albite, quartz, and perthite. Though numerous, their size is so small that the total quantity of rock in them is much less than in the layered pegmatites. They are commonly called homogeneous pegmatites because, except for a thin fine-grained border zone, they show little differentiation in the two dimensions generally available for examination. Many such pegmatites are sills no more than a few meters thick. Perthite megacrysts in an albite-quartz matrix may be tabular and parallel to the strike and dip, giving such pegmatites a slightly noticeable form of layering. The abundance of perthite is generally nearly uniform throughout the pegmatite or slightly greater on the hanging wall side, but a few pegmatites show a large increase in perthite content from the bottom to the top. Most pegmatites with lenticular or rounded shapes and simple mineralogy appear to lack inhomogeneities, but the only one that has been tested in three dimensions has less than 10 percent perthite near its bottom and more than 30 percent at the top (Norton, 1970).

Zoned pegmatites range from very slightly differentiated to exceedingly complex. Nearly all of the mining and most of the literature centers on zoned pegmatites. Data now exist for about 215 of these pegmatites plus a few zoned fracture fillings in granite that have attracted commercial interest. The diversity of the internal structures is illustrated by the maps and cross sections of Page and others (1953). The differentiation effects are partly from the contact inward, thus yielding the concentric pattern common for zones, but vertical differentiation and localized effects complicate the internal structure in many different ways. No pegmatite in the Black Hills is known to have the simple wholly concentric series of zones that some published diagrams have implied are characteristic of zoned pegmatites.

The least complicated zoned pegmatites differ from homogeneous pegmatites only in having a muscovite-rich wall zone. Some potash feldspar mines are in pegmatites that have only perthite-rich and perthite-poor units. More complex pegmatites have muscovite-rich wall zones, one or more perthite-rich zones and perthite-poor zones, and perhaps a quartz core. The highest degree of complexity is achieved by pegmatites with such zones as these plus inner zones containing lithium minerals.

Zoned pegmatites tend to be in groups, such as the group near Keystone and the group east of Custer(fig. 1), but this tendency has no known relation to other aspects of the geology. The distribution of zoned pegmatites does, however, have systematic relationships with the abundance pattern indicated by the isograms. More than 80 percent of the zoned pegmatites are between the 0 and 100 isograms, though only about two-thirds of the pegmatite region is between these isograms. Of the several kinds of zoned pegmatites, only those that have been mined chiefly for sheet mica may be unrelated to the isogram pattern; the data show them to be more abundant above the 100 isogram than below it, but the difference is slight. The most noticeable point about the distribution of sheet mica pegmatites is that all of the large mines and nearly all of the small ones are southwest of the granite, in the region of high metamorphic grade and probably above the pathway followed by the granite

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magma. The potash feldspar deposits occur throughout the region, but 85 percent of them are below the 100 isogram. The most highly differentiated pegmatites, including nearly all of the major lithium mineral deposits and the beryl-scrap mica pegmatites, are below the 100 isogram. These also contain the most rare minerals, such as beryl, tantalum minerals, and iron-manganese phosphates. Lithium pegmatites have a pronounced tendency to be near the edge of the pegmatite region.

Mineralogic and chemical composition of the granite

The principal minerals of the granite are albite-oligoclase, quartz, perthite, and muscovite. Accessory minerals include biotite, tourmaline, garnet, and apatite, each of which may exceed 1 percent in single outcrops. Sillimanite is locally abundant in the southeast part of the granite. Hornblende occurs in a few outcrops near the center of the granite in places where remnants of the country rock are rich in amphibole. Zircon is very rare. Monazite has been identified south and southeast of the center of the granite in heavy-mineral separates in which thorium, yttrium, and rare earths had been found by spectrographic analyses. Marsden (1933) also found pyrrhotite, magnetite, and cassiterite in several samples, and clinozoisite, anthophyllite, and spinel, each in a single sample. Beryl crystals as much as 0.3 m long and triphylite-lithiophilite occur in pegmatitic fracture fillings. We do not recollect seeing amblygonite in any of the fracture fillings nor can we find mention of it, but it may exist. Spodumene, however, has not been reported and is probably absent.

Plagioclase is less sodic in the granite than in the pegmatites. Many of the highly differentiated zoned pegmatites in the outer part of the region have nearly pure albite. The calcium content is somewhat greater in areas with many pegmatites, but the anorthite content is still mostly less than An_{10}. In the granite, however, the average composition may exceed An_{10}; optical determinations indicate values at least as high as An_{16}.

The graph on figure 2 shows the wide range in the muscovite content of 30 samples from the main body of granite and from satellites. Muscovite separates were obtained from each sample, and each sample was also analyzed for K_2O and Na_2O. The principal variable in the composition of the granite is the relative abundance of sodic and potassic minerals, but figure 2 shows that the muscovite content is independent of the ratio K_2O/K_2O+Na_2O. Graphs of muscovite content plotted against percent K_2O and percent Na_2O are so similar to figure 2 that they are not reproduced here.

A molar excess of Al_2O_3 over the alkali oxides is, of course, necessary for the crystallization of muscovite. The Harney Peak Granite intrudes aluminous rocks, and the same applies to most muscovite-rich pegmatites, not only in the Black Hills but also elsewhere in the world. This has generally been taken to mean either that Al was extracted from the host rocks or that alkalis escaped from the magma to create a local peraluminous condition. The possibility that the magma was originally highly aluminous is less likely, as experimental studies indicate that granitic magma has a low ability to carry excess Al, and modal data (Redden, 1963, table 10) show that few unzoned pegmatites of the Black Hills contain more than 5 percent muscovite.

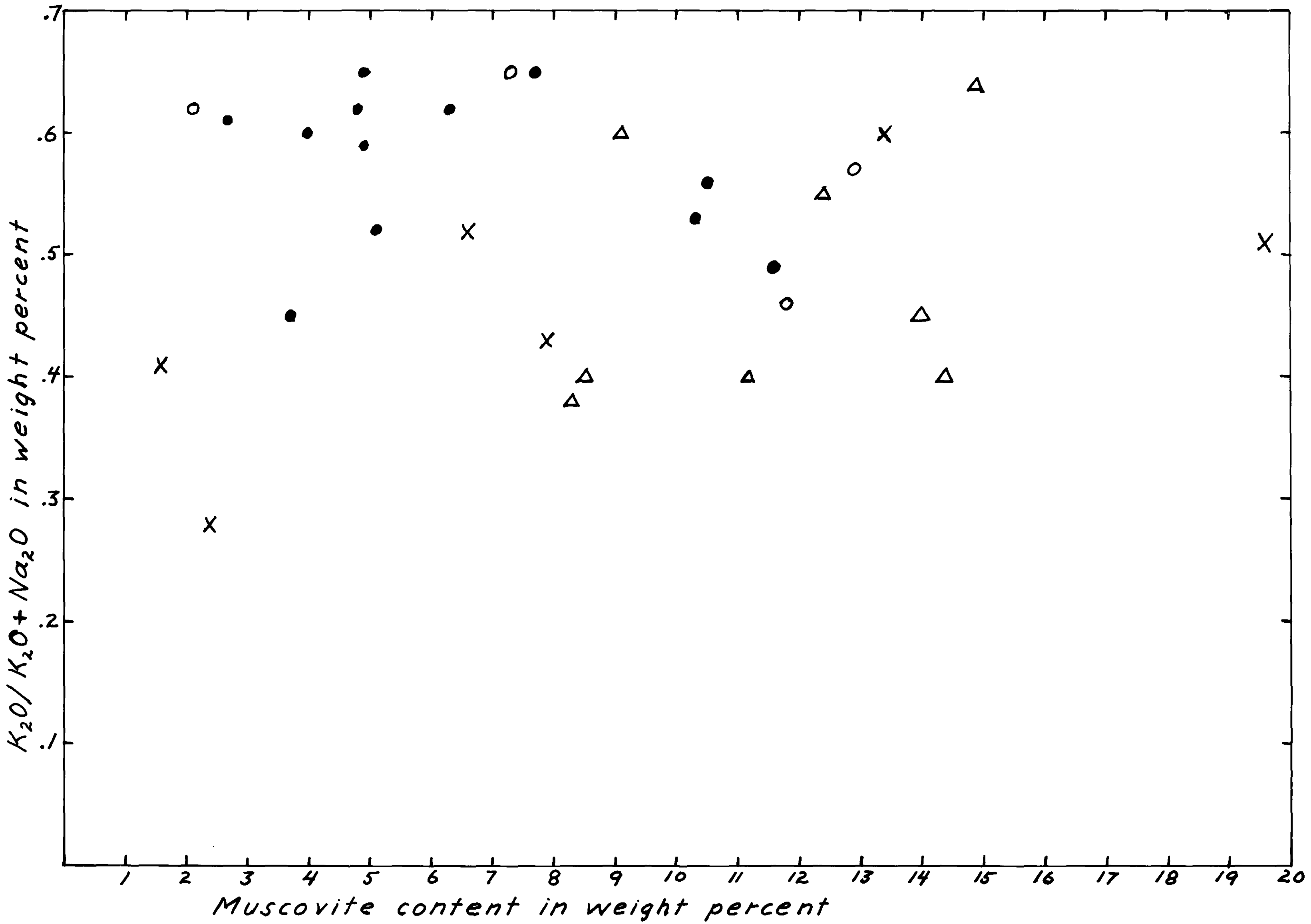

Figure 2.--Graph showing relationship between muscovite content and K_2O/K_2O+Na_2O in 30 bulk samples of Harney Peak Granite. Triangles--from within 150 m of outer contact of the main body of granite. Open circles--from within 150 m of schist inliers. Solid circles--all other samples from within the main body. X--from satellites. Analyses for K_2O and Na_2O by Lois B. Schlocker.

To examine this problem in the Harney Peak Granite, the symbols for the points on figure 2 show whether the sample site is well within the granite or whether it is near a large schist inlier, or near the edge of the pluton, or in a satellite. The muscovite content ranges from 1.6 to 19.6 percent, and the median is 8 percent. Samples from well within granite have a much smaller range and a median of 5 percent muscovite, and the few samples from near schist inliers are not significantly different. The muscovite contents of samples from satellites are at the two extremes of the graph as well as in intermediate positions. The eight samples from near the contact of the pluton, however, all have more than 8 percent muscovite.

Figure 3 shows the abundance of muscovite plotted against the total of K_2O and Na_2O for all samples of figure 2 that came from the Harney Peak pluton. Though the graph has a wide scatter, the general trend suggests that total alkalis decrease with increasing muscovite content. Most of the samples from near contacts with schist have a relatively low alkali content. The graph implies a loss of alkalis to the country rock to cause muscovite to crystallize. On figure 2, most of the samples from near the contact have a low ratio of K_2O to K_2O+Na_2O, thus implying that K is the principal alkali removed from the magma. Some zoned pegmatites of the Black Hills, however, have albitized schist sporadically distributed along the contact, indicating removal of Na from the pegmatitic fluid.

Excess Al is expressed as sillimanite in some granitic and pegmatitic bodies near the southeast edge of the Harney Peak pluton. The sillimanite may be disseminated through the granite or concentrated along shear planes in deformed granite. Where the sillimanite is disseminated, muscovite is absent or, if present, obviously of late origin. In contrast, some pegmatites have pseudomorphs of sillimanite after large (20 cm) muscovite books, and some of these sillimanite pseudomorphs have been replaced by later muscovite. A few sills contain 2-5 cm thick knots of myrmekitic quartz, microcline, and sillimanite.

Efforts to determine the chemical composition of the granite face obvious obstacles in the large number of intrusions and the heterogeneity of those intrusions. Nevertheless, data from many samples collected with the aim of being representative of their locality do allow judgments about the range in composition and probable average composition. Figure 4 shows the K_2O and Na_2O contents of 41 samples, including 29 from within the main pluton and 12 from satellites. Most of the samples from within the pluton and far from its contact have between 4 and 5.5 percent K_2O and 3 to 4 percent Na_2O. Some of the samples from near the contact are in the same range, but others are much less potassic and more sodic. Samples from satellites have a far wider range than any other category.

Figure 5 shows the approximate normative contents of albite, orthoclase, and quartz in 30 of these samples. The norms are based on the alkali analyses and on modal data obtained from making separates of heavy minerals, biotite, and muscovite. The steps in the procedure were to: (1) calculate the approximate total of Ab+An+Or+Q from the modal data, (2) calculate Ab and Or from the Na_2O and K_2O analyses, (3) subtract An from the total on the basis of an assumption that the plagioclase is An_{10}, (4) determine the Q content by subtraction, and (5) recast the Ab, Or, and Q contents to total 100. Figure 5 also includes the seven determinations of chemical composition shown in table 1.

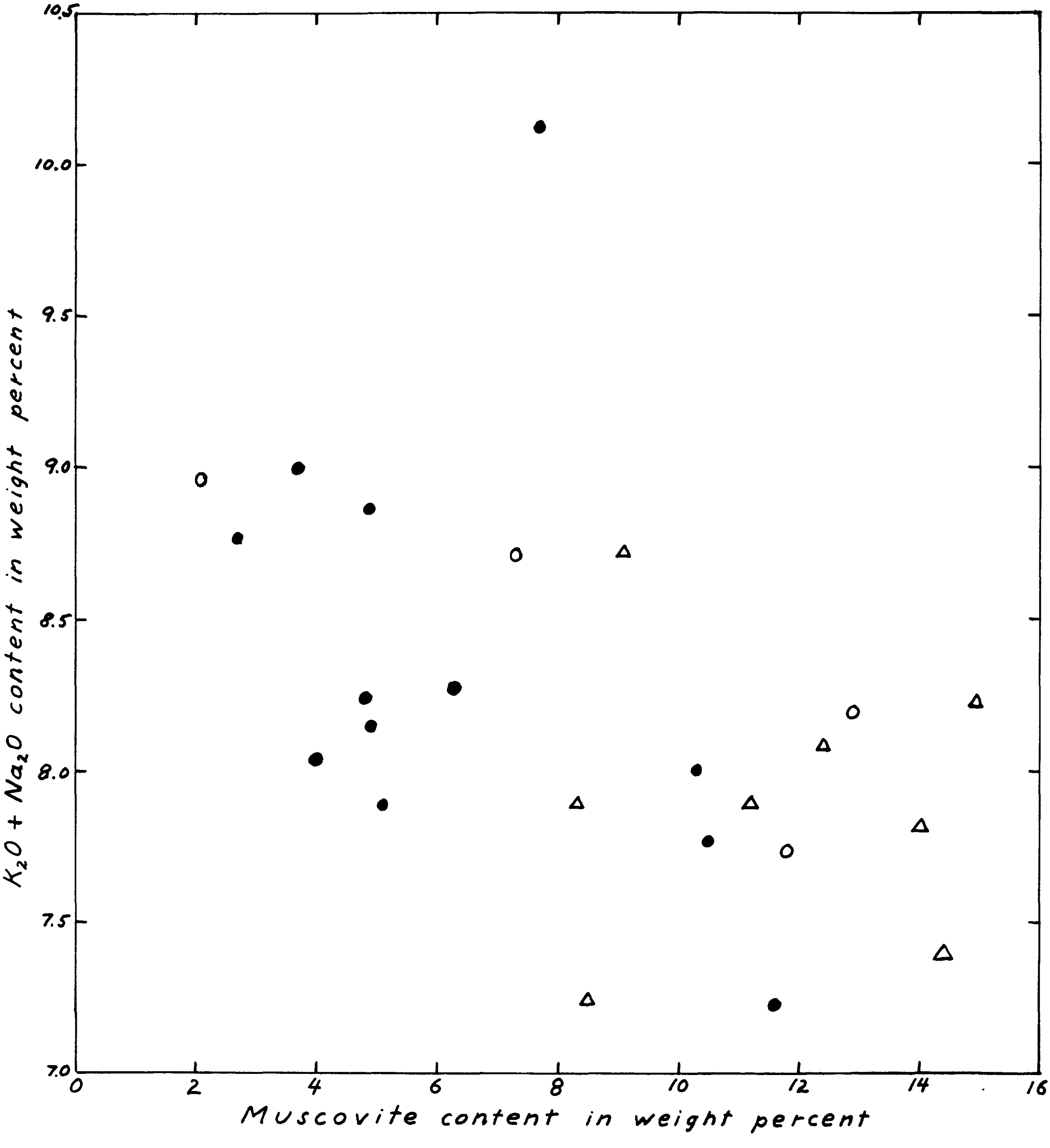

Figure 3.--Graph showing relationship between muscovite content and the total of K_2O and Na_2O in the main body of granite. Symbols are as on figure 2.

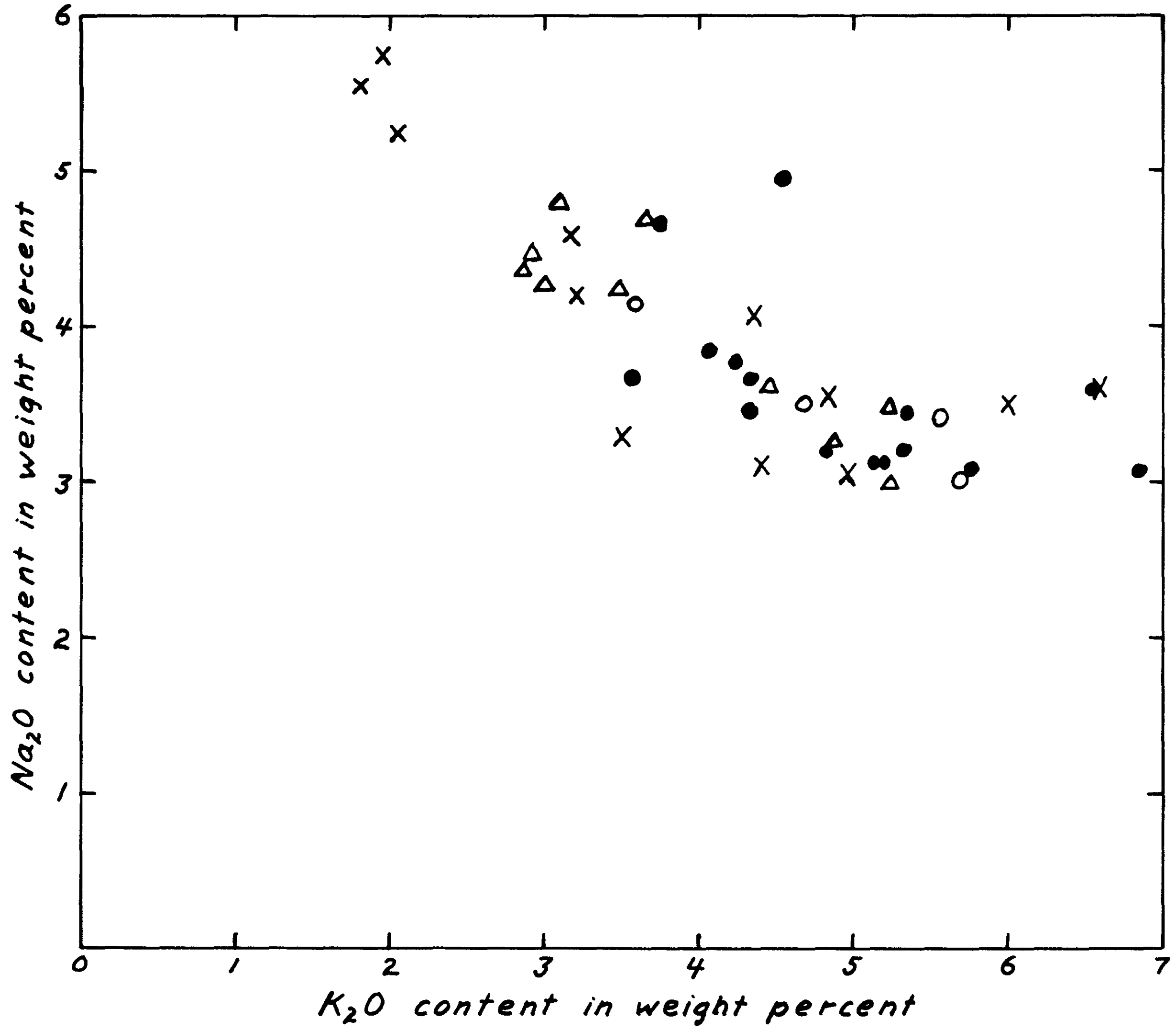

Figure 4.--Graph showing the content of K_2O and Na_2O in the 30 samples of figure 2 and in 11 additional samples. Symbols are as on figure 2.

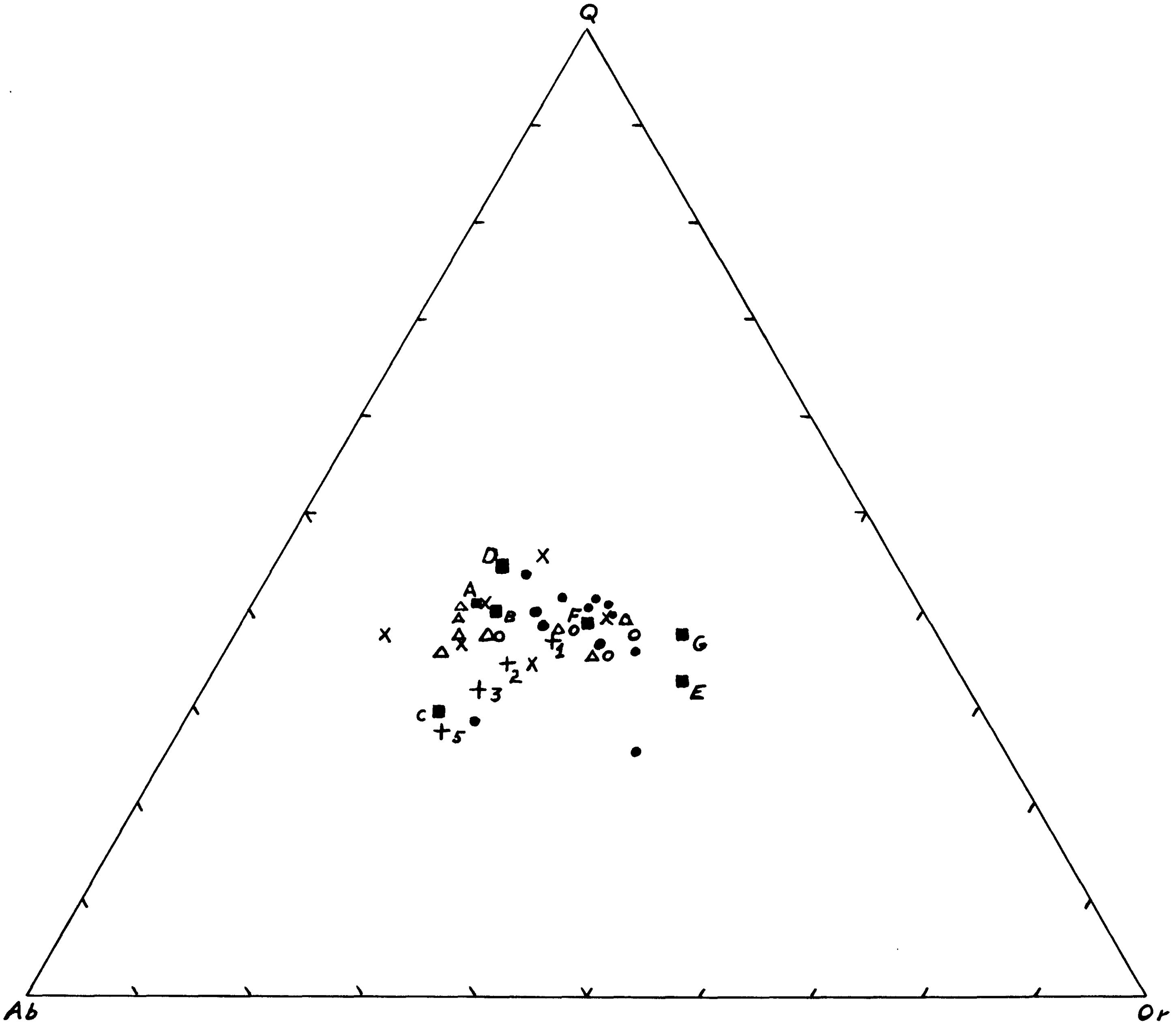

Figure 5.--Ternary diagram showing the content of normative albite, orthoclase, and quartz in samples of the Harney Peak Granite. Black squares labeled A through G are for the analyses of table 1. Other samples are those of figure 2, calculated as described in the text and shown by the symbols used on figure 2. Plus signs show the haplogranite minima at 1, 2, and 3 kilobars and the eutectic at 5 kilobars (Luth and others, 1964).

Table 1.--Chemical compositions and norms of Harney Peak Granite [1]

	A	B	C	D	E	F	G
				Chemical composition			
SiO_2	74.66	74.54	73.2	75.85	74.50	74.75	75.00
TiO_2	0.03	0.04	--	0.05	0.05	0.07	0.10
Al_2O_3	15.55	14.96	15.9	14.97	14.15	14.25	13.89
Fe_2O_3	.17	.25	--	.17	.12	.38	.15
FeO	.42	.87	--	.34	.20	.42	.40
MnO	.07	.09	--	.06	.02	.03	.02
MgO	.02	.19	--	.09	.06	.17	.20
CaO	.42	.72	.6	.74	.34	.90	.60
Na_2O	4.29	4.08	5.3	3.76	2.84	3.31	2.57
K_2O	3.08	3.41	3.5	3.10	6.90	4.79	6.30
H_2O+	.66	.66	.3	.70	.56	.68	.69
H_2O-	.04	.09	--	--	--	--	--
P_2O_5	.15	.07	--	.05	.12	.05	.05
F	.04	--	--	--	--	--	--
Co_2	.02	--	--	.06	.06	.14	.05
Totals...	99.62	99.97	98.8	99.94	99.92	99.94	100.02
				Norms			
Q	37.4	36.3	27.5	40.5	31.2	35.5	34.9
Or	18.4	20.0	20.6	18.4	40.6	28.4	37.3
Ab	36.2	34.6	45.1	32.0	24.1	27.8	21.5
An	1.1	3.3	3.1	3.3	.8	4.2	2.8
C	4.8	3.7	2.2	4.2	1.7	2.1	1.8
Mt	.3	.4	--	.3	.3	.5	.3
Ap	.3	.1	--	.1	.3	.1	.1
Water	.7	.7	.3	.7	.6	.7	.7
Totals...	99.2	99.1	98.8	99.5	99.6	99.3	99.4

[1] Analysis for A is from Huang and Wyllie (1981); sample site is in northeast corner of SE 1/4 sec. 19, T. 2 S., R. 6 E. Compositions of B and C are from Orville (1960). B was from southwest corner of sec. 28, T. 2 S., R. 5 E., and C from the summit of Harney Peak. Data for D through G were furnished by Petr Černý. D and E represent the aplitic and pegmatitic parts of a layered slab from Mt. Rushmore Memorial. F and G are from SE 1/4 NW 1/4 sec. 26, T. 2 S., R. 5 E.

The graph shows a grouping along a line for about 40 percent Q and a wide range in Ab and Or content. Samples from satellites are widely scattered. Several samples from the outer edge of the main pluton are low in Or. Most samples from within the granite have a sufficiently narrow range in content of Ab and Or to suggest that the differences may be caused largely by sampling errors, not just by actual differences in the rock. The average Or content is about 30 percent, which in the mode is microcline plus about 5 percent muscovite and a little biotite. Ab, at about 30 percent, is mainly in plagioclase but is also in solid solution in microcline.

Origin of the granite

The very low Ca content and peraluminous composition of the granite allow little doubt that it has clastic sedimentary rocks somewhere in its ancestry, and the high initial Sr^{87}/Sr^{86} of 0.7143 (Riley, 1970, p. 717) indicates an anatectic origin. Huang and Wyllie (1981) chose Harney Peak Granite as an example of S-type granite for a laboratory study to determine phase relationships.

Three possible source rocks are exposed: (1) Proterozoic metasedimentary schists, (2) Archean schists, and (3) Archean S-type granite. The pegmatitic features of the Harney Peak Granite and of the pegmatites throughout the region require H_2O-rich magma from which aqueous fluid was exsolved during crystallization (Jahns and Burnham 1969; Burnham and Ohmoto, 1980). The Archean granite exposed at Bear Mountain probably contains much less than 1 percent H_2O, and partial melting of such granite seems unlikely to produce the amount of hydrous magma needed. Archean schists are just barely exposed in two domes, and hence not enough is known about them to discuss their potential as source rocks. Proterozoic mica schists and metagraywackes, however, are the predominant rocks in the southern Black Hills. In 35 analyses, most of them published (Redden, 1963, table 2; Ratté and Wayland, 1969, tables 1 and 2; Norton, 1970, table 7) the content of H_2O+ ranges from 0.37 to 2.87 percent and the median is 1.64 percent. The mica is both muscovite and biotite, but some schists are very rich in muscovite. According to Burnham and Ohmoto (1980, p. 2-3), muscovite-bearing metasediments begin to melt at about 670° to 720°C at pressures of 4 to 9 kilobars, and the first melt must contain at least 8.4 percent H_2O, which allows 10 to 12 percent of the source rocks to melt for each percent of H_2O they contain.

The lithostatic load during crystallization of the granite probably was between 2 and 5 kilobars. The stratigraphic thickness of exposed Proterozoic rocks in the Black Hills is at least 10 km, which corresponds to a pressure of 3 kilobars, but the thickness above the granite at the time of emplacement may, through folding and faulting, have been much greater. The presence of spodumene instead of petalite as a primary mineral in the pegmatites indicates the pressure was more than 2 kilobars (Stewart, 1978). Absence of kyanite among the aluminosilicate metamorphic minerals shows the pressure to be less than 5.5 kilobars and perhaps less than 3.75 kilobars. The bulk composition of a closely studied simple Black Hills pegmatite, consisting almost entirely of Ab, Or, and Q, is between the haplogranite minima for 2 and 3 kilobars (Norton, 1970). A suitable approximation for the pressure under which the granite was emplaced is 3 kilobars. At this pressure the minimum in the haplogranite system is 665°C (Luth and others, 1964, fig. 1), and in systems with spodumene the silicate liquid may persist to a low of about 600°C

(Stewart, 1978). At 3 kilobars the high sillimanite isograd has a temperature of about 640°C (Greenwood, 1976, fig. 26).

The pressures and temperatures mentioned by Burnham and Ohmoto (1980) for the beginning of melting in muscovite-bearing schists indicate that the anatectic source for the granite may be only a few kilometers beneath the surface within the map area of figure 1. The position of the high sillimanite isograd (fig. 1) suggests that the magma came up an inclined pathway from the southwest.

Crystallization of the granite began and movement of magma ceased on reaching an environment somewhat cooler than the crystallization temperature of the granite. The solubility of H_2O in granitic magma at 3 kilobars is 8.4 percent (Luth, 1976, fig. 6), or the same as the H_2O content of Burnham and Ohmoto's first melt. The solubility of H_2O decreases sharply with a decrease in pressure, and hence a separate aqueous phase could begin to exsolve before or during emplacement of the magma. Exsolution of this phase would continue as anhydrous minerals were precipitated and H_2O was concentrated in the fluid.

The aqueous phase must eventually escape into the country rock, for little H_2O remains in the granite. It caused metasomatic features in the country rock, but overall its effects were either small or subtle, probably because the country rock was at nearly the same temperature as the granite.

Figure 5 shows the granite to have more normative quartz than the haplogranite system. Excessive SiO_2 is a widely observed feature of pegmatitic rocks. The aqueous phase is likely to be enriched in Si (Burnham, 1967), and possibly it in some way caused the bulk composition to be rich in Si also.

The domal structure around the Harney Peak Granite and several minor structures mentioned in this article imply considerable force accompanying the upward movement, emplacement, and crystallization of the magma. The difference in density between the magma and its surroundings would cause it to rise in the gravitational field, thus contributing to the intrusive force. Another likely cause is overpressure resulting from exsolution of the aqueous phase (Burnham, 1979, p. 110-112). If exsolution began before the magma reached the site of crystallization, the overpressure may have been important in driving the dome upward. With the rise of successive bodies of magma to form the many sills in the pluton, the dome evolved to its present form.

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