The Canadian Mineralogist
Vol. 37, pp. 163-175 (1999)

MINERALOGY AND GEOCHEMISTRY OF PROTEROZOIC BASALTIC INTRUSIONS, SPIONKOP RIDGE, SOUTHWESTERN ALBERTA

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Abstract

Three suites of basaltic intrusions occur on Spionkop Ridge in southwestern Alberta. The oldest consists of glomeroporphyritic, alkaline sills and dikes offset by Proterozoic faults, along which a second generation of amygdaloidal alkaline to transitional dikes have been emplaced. The youngest is a tholeiitic diabasic sill containing abundant epidote. The basaltic suites can be distinguished by their TiO_2, Al_2O_3, P_2O_5 and Yb concentrations. The glomeroporphyritic intrusions have ~3.7% TiO_2, 15% Al_2O_3, 0.74% P_2O_5 and 4.1 ppm Yb, the amygdaloidal intrusions ~2.5% TiO_2, 16% Al_2O_3, 0.47% P_2O_5 and 3.3 ppm Yb, and the diabasic intrusions ~4% TiO_2, 12% Al_2O_3, 0.49% P_2O_5 and 2.4 ppm Yb. Petrographic and geochemical data for similar intrusions and lava flows from locations throughout the Lewis Thrust Sheet are consistent with this three-fold subdivision.

Keywords: Purcell Supergroup, Lewis Thrust Sheet, basalt, chemical composition, Alberta.

Sommaire

Trois venues basaltiques sont présentes sur l'arête de Spionkop, dans le sud-ouest de l'Alberta. La plus précoce se présente sous forme de filons-couches et filons gloméroporphyritiques à tendance alcaline. Ceux-ci sont déplacés par des failles protérozoïques, le long desquelles a été mise en place une seconde génération de filons, à texture amygdulaire et à tendance alcaline ou transitionnelle. La venue la plus récente a donné un filon-couche de diabase tholéiitique contenant une forte proportion d'épidote. On peut distinguer ces suites basaltiques par leur teneurs en TiO_2, Al_2O_3, P_2O_5 et Yb. Les roches gloméroporphyritiques contiennent environ 3.7% TiO_2, 15% Al_2O_3, 0.74% P_2O_5 et 4.1 ppm Yb, les roches amygdulaires, environ 2.5% TiO_2, 16% Al_2O_3, 0.47% P_2O_5 et 3.3 ppm Yb, et les intrusions de diabase, environ 4% TiO_2, 12% Al_2O_3, 0.49% P_2O_5 et 2.4 ppm Yb. Les observations pétrographiques et les données géochimiques servant à caractériser les intrusions et les extrusions semblables ailleurs dans la région affectée par la nappe de Lewis concordent avec cette classification tripartite.

(Traduit par la Rédaction)

Mots-clés: Supergroupe de Purcell, nappe de Lewis, basalte, composition chimique, Alberta.

Introduction

Three distinctive suites of basaltic rocks intrude the Proterozoic sedimentary rocks of the Appekunny, Grinnell and Siyeh formations on Spionkop Ridge, immediately to the north of Waterton Lakes National Park, Alberta (Figs. 1, 2). A prominent, brownish weathering, glomeroporphyritic basaltic sill occurs just beneath the top of the Appekunny Formation (Appekunny Sill, Figs. 1, 2); the sill is discordant in part. A basaltic sill with a diabasic texture and abundant epidote is present in the lower Siyeh Formation throughout the area (Siyeh Sill, Figs. 1, 2). Black, amygdaloidal basaltic dikes (Grinnell Dikes, Figs. 1, 2) intrude two or more faults

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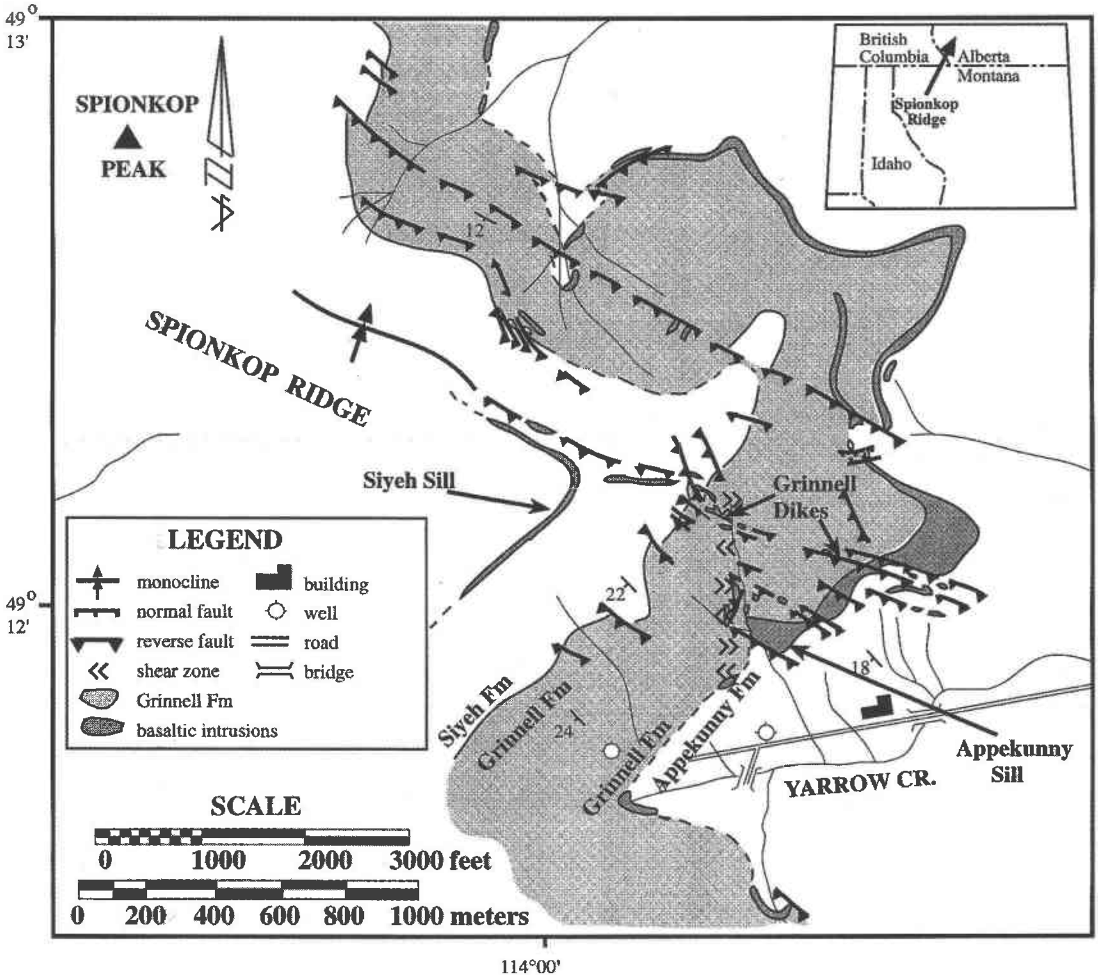


FIG. 1. Geological map for southeastern Spionkop Ridge, Alberta.

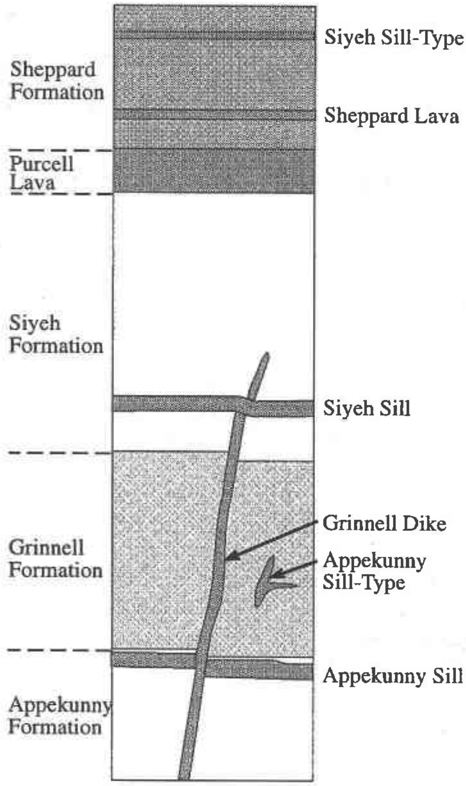
that cut and offset the rocks of the upper Appekunny Formation, the Appekunny Sill, and the rocks of the Grinnell Formation on the southeastern flank of Spionkop Ridge; the faults do not cut the Siyeh Sill. Other small basaltic intrusions on Spionkop Ridge appear to be of one of these three types and are referred to as such below.

Basaltic intrusions similar to those described above are found throughout the Proterozoic sediments of the Lewis Thrust Sheet of southwestern Alberta and southeastern British Columbia. Basaltic flows are present within the Purcell Lava and Sheppard formations; reported basaltic flows within the Grinnell and Kintla formations probably represent misidentified intrusions.

Data were collected from a total of seventy-five samples of the basaltic rocks in the Spionkop Ridge area. These data were examined to determine whether the three basaltic suites could be distinguished mineralogically, texturally and geochemically, and were likely to have been derived from the same magma. A comparison was then made with data collected from one hundred and fifty-two specimens of basaltic rocks from other areas of the Lewis Thrust Sheet to determine whether subdivision of the basaltic rocks into three categories is valid beyond the immediate area of Spionkop Ridge.

BACKGROUND INFORMATION

The number, timing, character and relationship among episodes of basaltic magmatism within the rocks of the Lewis Thrust Sheet have not, as yet, been fully



Appekunny Sill	Grinnell Dikes	Siyeh Sill
Primary Mineralogy:		
Plagioclase	Plagioclase	Plagioclase
Titanaugite	Hornblende	Augite
Olivine	Ilmenite	Orthopyroxene
Biotite	(Quartz)	Olivine
Alkali Feldspar		Hornblende
Apatite		Apatite
Magnetite		Magnetite
Ilmenite		Ilmenite
Sulfides		
Titanite		
Major Distinguishing Characteristic:		
Glomeroporphyritic	Amygdaloidal	Diabasic with abundant epidote
Normative Mineralogy:		
olivine-hypersthene	olivine-hypersthene	olivine-hypersthene
Distinguishing Chemical Characteristics:		
~15% Al_2O_3	~16% Al_2O_3	~12% Al_2O_3
~3.7% TiO_2	~2.5% TiO_2	~4.0% TiO_2
~0.74% P_2O_5	~0.47% P_2O_5	~0.49% P_2O_5
~4.1 ppm Yb	~3.3 ppm Yb	~2.4 ppm Yb
Relative Ages:		
Oldest ←	→	Youngest

FIG. 2. Idealized stratigraphic section for Spionkop Ridge and adjacent areas illustrating the relative ages of the formations, Proterozoic faults and basaltic intrusions and lava flows. Characteristics are listed for the three types of intrusions. The Grinnell Dikes are discontinuously exposed in fault zones that cut the Appekunny and Grinnell formations but pass upward into folds in the Siyeh Formation.

resolved. Daly (1912) described basic lavas in the Grinnell, Purcell Lava, Sheppard and Kintla formations, as well as basic sills and dikes in the Appekunny, Grinnell and Siyeh formations. He concluded that the Purcell sequence of lavas is genetically related to the sills and dikes. Fenton & Fenton (1937) briefly described a basaltic "lava flow" in the Grinnell Formation at Blakiston Brook in Waterton Park that is similar in appearance to the Purcell Lava and concluded that it is cogenetic with dikes in the Altyn, Appekunny and Grinnell formations. They noted that the latter differ from dikes and sills found in the Siyeh Formation. Douglas (1952) mapped the basaltic "lava flow" on Blakiston Brook, as well as other basaltic igneous rocks in the Altyn, Appekunny, Grinnell and Siyeh formations, as sills and dikes. Hunt (1961) concluded that "sills" mapped by Douglas (1952) in the Grinnell Formation on Ruby Ridge and Blakiston Brook in Waterton Park are lava flows. Mejstrick (1975) considered basaltic sills and dikes in the Grinnell Formation to be feeders for the sills in the Siyeh Formation. McGimsey (1985) mapped a basaltic sill in the Siyeh Formation, found it to be chemically distinguishable from the Purcell lava, and concluded that it is younger than the Purcell Lava. Ghazi (1992) subdivided the basaltic intrusions in the Lewis Thrust Sheet into four groups, two diabasic suites that occur in the Siyeh Formation and above, and an amygdaloidal and a porphyritic suite that both occur below the Purcell Lava. Ghazi (1992) suggested a genetic connection between the Purcell Lava and the amygdaloidal intrusions.

Petrographic descriptions of the basaltic intrusions [Finlay (1902) in Willis (1902), Daly (1912), Hunt (1961), Mejstrick (1975), McGimsey (1985), Ghazi (1992)] show that the sills and dikes have two distinctive mineralogical assemblages. The Siyeh sills are characterized by the presence of hornblende, granophyric material (orthoclase, albite and quartz), and two pyroxenes. The porphyritic and amygdaloidal sills and dikes in the Appekunny and Grinnell formations are characterized by titanaugite as the sole pyroxene, and by the presence of large stellate aggregates of plagioclase.

TABLE 1. AVERAGE MAJOR, TRACE, RARE-EARTH ELEMENT AND NORMATIVE DATA FOR THE THREE TYPES OF BASALTIC INTRUSIONS FOUND IN THE SPIONKOP RIDGE AREA, ALBERTA.

	<-----------APPEKUNNY SILL----------->					APPEKUNNY SILL-type		SIYEH SILL	GRINNELL DIKES	
	Lower Margin	Olivine Zone	Biotite Zone	Porphyritic Zone	Upper Margin	Unaltered	Altered		Unaltered	Altered
#Maj	4	14	10	8	5	8	5	7	4	11
SiO_2	46.12	45.63	45.65	45.94	46.47	47.44	47.70	48.37	49.63	49.82
TiO_2	3.90	3.74	3.67	3.70	3.58	3.95	4.03	4.10	2.46	2.57
Al_2O_3	14.91	14.66	15.15	16.08	18.51	15.62	16.80	11.68	15.29	16.76
$Fe_2O_3^T$	15.83	17.31	16.40	15.61	11.13	16.83	12.29	14.00	14.70	10.55
MnO	0.19	0.20	0.18	0.19	0.17	0.20	0.17	0.18	0.19	0.11
MgO	6.15	6.06	6.13	5.45	9.88	5.71	9.50	8.20	6.26	8.27
CaO	7.13	6.91	7.62	7.12	4.19	4.95	3.33	8.99	6.27	6.50
Na_2O	3.05	2.30	2.87	3.25	3.58	2.61	2.21	2.42	2.97	2.65
K_2O	2.05	2.46	1.55	1.93	1.82	1.96	2.16	1.56	1.76	2.31
P_2O_5	0.76	0.73	0.75	0.73	0.67	0.73	0.72	0.49	0.48	0.46
LOI	2.95	2.79	2.72	2.17	3.99	3.58	3.37	2.28	2.56	6.66
#Tr	1	7	4	5	1	8	4-6	4-5	4	3-4
La	45	43	45	43	44	42	45	35	41	37
Ce	102	94	98	94	100	90	97	85	85	78
Pr	12.7	11.7	12.1	11.5	12.1	11.2	12.2	11.4	10.3	9.5
Nd	53.0	49.5	51.8	49.1	50.6	47.9	51.2	50.0	41.7	40.3
Sm	11.6	10.2	11.0	10.2	9.9	10.0	10.5	10.6	8.4	8.4
Eu	3.1	3.1	3.1	3.1	1.8	3.1	2.9	3.0	2.5	2.4
Gd	11.4	10.7	10.8	10.4	9.7	10.0	11.3	10.1	8.7	8.3
Tb	1.5	1.5	1.5	1.4	1.2	1.4	1.6	1.3	1.2	1.2
Dy	8.5	8.6	9.0	8.3	6.9	8.3	9.0	7.3	7.2	6.9
Ho	1.6	1.6	1.6	1.6	1.4	1.5	1.6	1.2	1.3	1.2
Er	4.4	4.3	4.4	4.4	4.1	4.1	4.4	2.8	3.8	3.4
Tm	0.70	0.64	0.63	0.62	0.64	0.60	0.66	0.40	0.54	0.49
Yb	4.0	4.0	4.1	4.0	4.0	3.9	4.3	2.4	3.2	3.4
Lu	0.60	0.56	0.57	0.55	0.52	0.58	0.63	0.35	0.46	0.48
Ag		0.08	0.06	0.05					1.15	
Ba	698	926	690	754	141	1025	564	461	609	1052
Bi		0.6	0.6	0.6					0.2	
Co	40	50	46	41	26	47	40	48	52	28
Cr	72	109	79	55	52	63	53	438	76	102
Cu	97	69	66	84	41	80	33	94		31
Ga	35	28	26	30	23	32	27	22		32
Hf	8.8	8.1	7.4	8.3	8.0	7.4	7.4	8.0	6.4	7.0
Mo	3.9	3.0	5.2	3.0	2.0	4.6	2.8	2.3		3.6
Nb	37	37	38	35	33	42	50	38	26	29
Ni	146	267	236	169	116	225	173	280	207	155
Pb	32	9	50	84	58	9	16	7	409	18
Rb	40	46	35	37	16	46	70	38		44
Sc	26	27	26	25	24	25	26	28	27	24
Sr	333	349	311	396	21	363	79	475	238	55
Ta	3	2	2	2	2	14	3	1		1
Th	3.7	3.3	3.1	3.5	3.1	2.8	3.1	5.1	4.1	4.3
U	1.2	0.7	0.7	0.9	1.0	0.7	0.7	1.4	0.4	0.7
V	202	191	169	165	145	149	169	432	33	168
Y	46	47	46	45	42	43	45	34		37
Zn		157	249	273					167	
Zr	331	305	290	303	301	289	276	312	251	263
Q						0.26	2.74			
Ne				0.35						
Hy	1.53	9.16	7.81		7.61	30.54	33.69	15.55	21.91	17.08
Ol	17.37	15.01	16.19	19.04	18.88			5.25	5.60	9.21

Compositions are in weight percent oxide, parts per million element
#Maj is the number of samples analyzed for major elements
#Tr is the number of samples analyzed for trace elements
Oxide data are recalculated to 100% total on a water-free basis, trace element data are not
Q, Ne, Hy, Ol are CIPW norm minerals

Hunt (1961, 1962) obtained K/Ar ages of 1075 to 1100 Ma for the basaltic "flow" on Blakiston Brook, the Siyeh Sill at Logan Pass, and the Purcell Lava. Mudge *et al.* (1968) obtained a K/Ar age of 750 Ma from rocks found south of Glacier Park that are similar to the Siyeh Sills. Ghazi (1992) obtained K/Ar ages of 796–797 Ma for hornblende from the Siyeh Sills and minimum K/Ar and Ar/Ar ages of approximately 1000 Ma for the Grinnell Dikes on Spionkop Ridge; there is considerable spread in the latter data. Goble (1977) and Ghazi (1992) obtained K/Ar ages of 1453 and 1500 Ma, respectively, for biotite from the Appekunny Sill on Spionkop Ridge. Ghazi (1992) obtained an Ar/Ar age of 1400 Ma from this same biotite. Aleinikoff *et al.* (1996) obtained a SHRIMP U–Pb age of 1443 Ma for zircon from the Purcell Lava. These older ages correspond closely to U–Pb zircon ages of 1445 and 1468 obtained by Hoy (1989) and Anderson & Davis (1995) for the Moyie sills, which intrude the lower Belt–Purcell rocks in the Kimberley–Cranbrook area.

The isotope data support injection of the Siyeh Sills at approximately 800 Ma and emplacement of both the Appekunny Sill and Purcell Lava at approximately 1450 Ma but leave the age of the Grinnell Dikes unresolved, though older than approximately 1000 Ma. The determined ages for these three mafic magmatic suites correspond closely to mafic magmatic events both within and outside the Belt Basin, at approximately 1455–1430, 1130–1070 and 760–740 Ma (Wooden *et al.* 1978).

Igneous Rocks

The basaltic intrusions were subdivided on the basis of field and macroscopic properties into three types: glomeroporphyritic sills and dikes (*e.g.*, Appekunny Sill, Fig. 1), cross-cutting amygdaloidal dikes and amygdaloidal sills (*e.g.*, Grinnell Dikes, Fig. 1), and the diabasic Siyeh Sill (Fig. 1). Basic mineralogical and chemical characteristics are summarized in Figure 2.

Glomeroporphyritic basaltic intrusions of the Appekunny Sill type

The most prominent of the porphyritic basaltic intrusions, a 1.5- to 27-meter sill, occurs 1 to 7 m below the top of the Appekunny Formation throughout most of the area (Appekunny Sill, Figs. 1, 2). A complete section was sampled at the thickest and best exposure, on the southern side of Spionkop Ridge, at the point of the labeled arrow in Figure 1. The sill can be traced for approximately five km to the north, and a similar sill is present at this stratigraphic position at Blakiston Brook approximately 10 km to the south; the latter is the "lava flow" described by Fenton & Fenton (1937) and Hunt (1961).

The Appekunny Sill consists primarily of plagioclase (An_{45-65}) and clinopyroxene (titanaugite, ~1.8% TiO_2), with lesser amounts of forsterite (~Fo_{60}) and titaniferous phlogopite (~6.8% TiO_2); mineral compositions were determined by electron microprobe; plagioclase compositions were determined both by electron microprobe and optical methods. Common accessories are apatite, ilmenite, magnetite and sulfides. Traces of alkali feldspar occur in the interstices between plagioclase laths and as a rim on some plagioclase crystals. Secondary white mica, chlorite, epidote, talc and carbonate are common. The talc is a high-iron variety, containing approximately 25% FeO (total iron expressed as FeO). The chlorite occurs in aggregate grains. Secondary quartz is locally common, as are small xenoliths of quartz-bearing siltstone and xenocrysts of quartz. Prehnite, pumpellyite (?), chlorite and albite locally replace the plagioclase. On the basis of the presence of titanaugite, olivine and interstitial alkali feldspar, the Appekunny Sill is classified as an alkali basalt.

The sill can be subdivided into five sections (Table 1, Fig. 3). From bottom to top, these are the Lower Margin (lower ~1 m), Olivine Zone (~1 to ~12 m from the base), Biotite Zone (~12 to ~8 m from the base), Porphyritic Zone (~18 to ~25 m from the base), and Upper Margin (upper ~2 m). The Olivine Zone lacks plagioclase megacrysts; the first appearance of plagioclase megacrysts marks the beginning of the Biotite Zone. The beginning of the Porphyritic Zone is marked by an abrupt change from sparse to abundant megacrysts of plagioclase. It is interpreted as representing the boundary between two separately injected bodies of magma, based in part upon a change in chemical composition (Fig. 3); other smaller intrusions show internal chilled margins consistent with this interpretation.

Within the groundmass, there is a gradual increase in modal plagioclase upward through the sill from 56 to 67%, accompanied by a gradual decrease in modal clinopyroxene, from 17 to 12%. There is no discernible vertical pattern to the plagioclase compositions.

Veins of epidote and stilpnomelane – chlorite – fibrous ferro-actinolite – quartz – carbonate up to 1 cm across occur in a shear zone just below the boundary between the Biotite and Porphyritic zones. The stilpnomelane – chlorite – fibrous ferro-actinolite – quartz – carbonate veins were produced by alteration of titanaugite to ferro-actinolite, followed by alteration of the ferro-actinolite to stilpnomelane. The stilpnomelane has been altered to chlorite; quartz and calcite are late phases.

Other small (0.25 to 5 m) porphyritic sills and dikes (Appekunny Sill type, Table 1, Fig. 2) are found throughout the upper Appekunny and Grinnell formations on Spionkop Ridge. They are mineralogically similar to the Appekunny Sill, but show extensive alteration of the primary minerals to chlorite, white mica, kaolinite, talc, epidote, and carbonate, particularly at their margins. Geochemically, samples of these altered basaltic rocks can be distinguished by their low Sr content, resulting from the breakdown of their plagioclase. Disseminated copper sulfides are locally abundant in the altered margins.

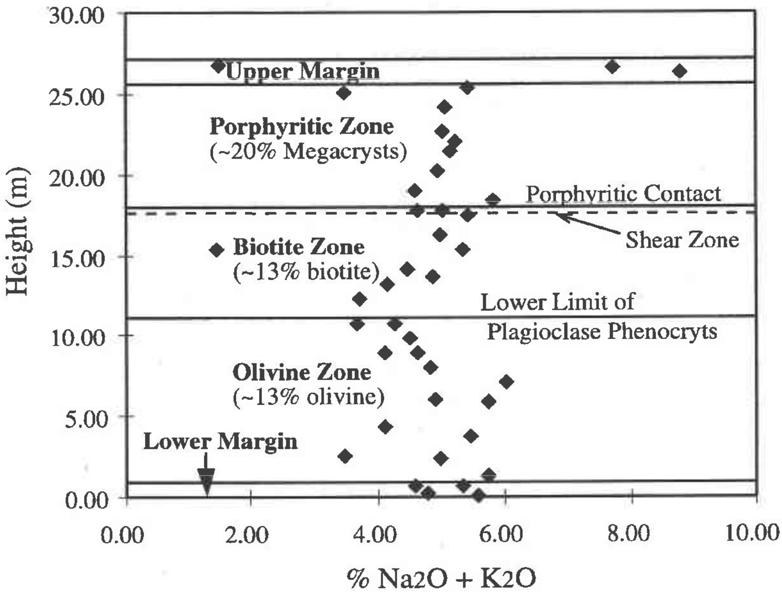


FIG. 3. Concentration of alkalis *versus* height for samples of the Appekunny Sill. The sill is subdivided on the basis of mineralogy.

Amygdaloidal basaltic intrusions of the Grinnell Dike type

Two amygdaloidal basaltic dikes (Grinnell Dikes, Figs. 1, 2) are discontinuously exposed in fault zones that extend across the southeastern flank of Spionkop Ridge, cutting and offsetting the Appekunny Sill. The dikes have intruded and, therefore, clearly postdate the Appekunny Sill. They can be distinguished from it in that they are finer-grained, darker, highly amygdaloidal, brittle in character, and more extensively altered; they lack both the large plagioclase megacrysts and the altered, copper-sulfide-rich margins that characterize the glomeroporphyritic intrusions.

The amygdaloidal dikes contain plagioclase and skeletal ilmenite in a groundmass of chlorite and brownish amphibole, with minor amounts of quartz and apatite. Plagioclase is extensively converted to white mica, mafic minerals other than hornblende are completely altered to chlorite and brownish iron oxides, and secondary carbonate and chlorite are abundant. The mineralogical data are insufficient to classify the Grinnell Dikes as alkali or tholeiitic basalts. Other mineralogically similar, but more altered amygdaloidal sills and dikes are present throughout the Spionkop Ridge area.

The Siyeh Sill

In the Spionkop Ridge area, a single diabasic sill is present in the lower Siyeh Formation. It appears to be an altered quartz diabase, with primary quartz and no observable olivine or orthopyroxene.

One or more Siyeh sills, discordant in part, are present within the lower part of the Siyeh Formation throughout most of the Lewis Thrust Sheet (Finlay 1902, Daly 1912, Fenton & Fenton 1937, Douglas 1952, Price 1962, 1965, Mejstrick 1975, McGimsey 1985, Ghazi 1992). Northern outcrops are thinner and occur higher in the Siyeh Formation than those to the south. The sills have a diabasic, or subophitic to ophitic texture, and consist of plagioclase, augite, orthopyroxene, olivine, hornblende, skeletal opaque minerals, granophyric patches, and biotite, with accessory apatite and titanite (Mejstrick 1975). Quartzite and dolomite xenoliths show evidence of assimilation, and account for the granophyric material. Extensive deuteric alteration was observed by Mejstrick (1975); secondary minerals include epidote, white mica, kaolinite, chlorite, calcite, biotite, hornblende, and biotite; the abundant epidote distinguishes these sills from the other two basaltic types.

Mejstrick (1975) classified the Siyeh Sill as an alkaline olivine basalt. However, the presence of two pyroxenes and lack of titanaugite and interstitial alkali feldspar indicate that it should be classified as a tholeiitic basalt.

GEOCHEMISTRY

Averages for major-, minor- and trace-element data for the Appekunny Sill, Grinnell Dikes, Siyeh Sill, and other basaltic igneous rocks of similar type found on Spionkop Ridge are presented in Table 1. Total iron is expressed as Fe_2O_3 Data were obtained by a combination of X-ray fluorescence (XRF) spectrometry and inductively coupled plasma – mass spectrometry (ICP–MS). A combination of synthetic and U.S. Geological Survey rock standards was used. Samples from porphyritic and amygdaloidal specimens were selected to exclude megacrysts and amygdules. Samples from the Appekunny Sill are subdivided by zone; those from other intrusions are subdivided by degree of alteration, determined mineralogically.

The Appekunny Sill

Major-element data for samples of the interior of the Appekunny Sill show little variation between zones (Table 1), apart from a slight upward increase in SiO_2, Al_2O_3, CaO, Na_2O and Sr, and a decrease in Fe_2O_3, consistent with the observed changes in modal mineralogy of the groundmass. Apparent upward decreases in the concentration of Cr, Co, Ni and TiO_2 probably reflect the observed modal proportions of titanaugite and olivine. A plot of alkalis *versus* height (Fig. 3) shows poorly defined chemical trends within the three main zones of the sill, with breaks in the trends consistent with multiple injections of magma.

Samples from the upper margin and from some of the smaller sills and dikes (Appekunny Sill type) show considerable alteration both in hand specimen and thin section. Geochemically, these samples show considerable depletion in Sr, from greater than 300 ppm for unaltered samples to less than 100 ppm for altered samples (Table 1), probably due to breakdown of plagioclase. The Sr depletion correlates moderately with depletions in Fe_2O_3, CaO, Cu and Ba (correlation coefficients, R, of 0.67, 0.65, 0.61 and 0.59), and less strongly with depletions in Eu, Co and Ni (R of 0.48, 0.47 and 0.44, respectively). Enrichments in MgO, Al_2O_3 and possibly TiO_2 are also present (R –0.80, –0.55 and –0.38, respectively). The correlations among Sr, CaO and Eu are consistent with reduction of Eu^{3+} to Eu^{2+} (Brookins 1989), and removal of Eu^{2+}, Ca and Sr during breakdown of the plagioclase. The slight relative enrichments observed in Al and Ti probably result from density changes accompanying replacement of relatively heavy Ca and Fe with lighter Mg and with hydration. With the exception of Eu, the rare-earth elements (*REE*) show consistent enrichment in the altered (low-Sr) samples of the same relative magnitude as that observed for Al_2O_3. The depletion in Cu is unusual in that many of these samples are from sills and dikes with notable accumulations of disseminated copper sulfide in their margins, although these particular samples were selected for their lack of sulfide.

Most of the Appekunny Sill chemical data are consistent with classification as an alkali basalt. Most unaltered samples are orthopyroxene–olivine-normative (Table 1), suggesting a transitional basalt rather than an alkali basalt; the Porphyritic Zone is nepheline-normative, consistent with classification as an alkali basalt. A few samples are quartz-normative because of minor amounts of siltstone xenoliths, xenocrysts and secondary quartz. The data plot in the alkaline field on an alkali–silica diagram (Fig. 4), consistent with the mineralogical classification of the Appekunny Sill as an alkali basalt. Data on a normative nepheline – olivine – quartz diagram (Fig. 5) plot in the alkaline and olivine tholeiite (transitional basalt) fields. On a Nb/Y–Zr/TiO_2 diagram (Fig. 6), they plot in the alkali basalt field.

The Siyeh Sill

Major-element concentrations (Table 1) for the Siyeh Sill are distinctive and characterized by higher SiO_2, MgO and CaO and lower Al_2O_3, Fe_2O_3, K_2O, and P_2O_5 than the Appekunny Sill. The concentrations of Cr, Sr, Th, U and V are also slightly higher, and those of Ba, Mo and Y are slightly lower.

Chemical data for the Siyeh Sill are generally inconclusive with regard to classification. Whole-rock compositions in this study (Table 1) and those of McGimsey (1985) are olivine–orthopyroxene normative, indicating a transitional basalt. Higher reported Na_2O values in Mejstrick's (1975) study yield compositions that are nepheline-normative, indicating an alkaline basalt. Alkali–silica data from this study plot mainly in the subalkaline field (Fig. 4), but are consistent with a field for transitional basalts outlined by Hyndman (1985).

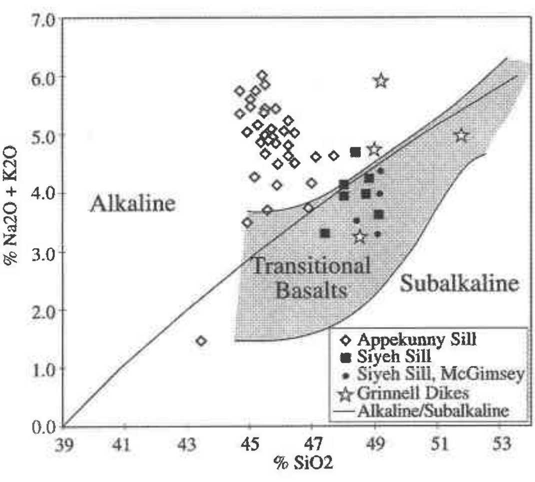


FIG. 4. Total alkali–silica discrimination diagram for the basaltic intrusions on Spionkop Ridge. Data for the Siyeh Sill from McGimsey (1985) also are shown. The alkaline–subalkaline line is from Irvine & Baragar (1971). The shaded field for transitional basalts is from Hyndman (1985).

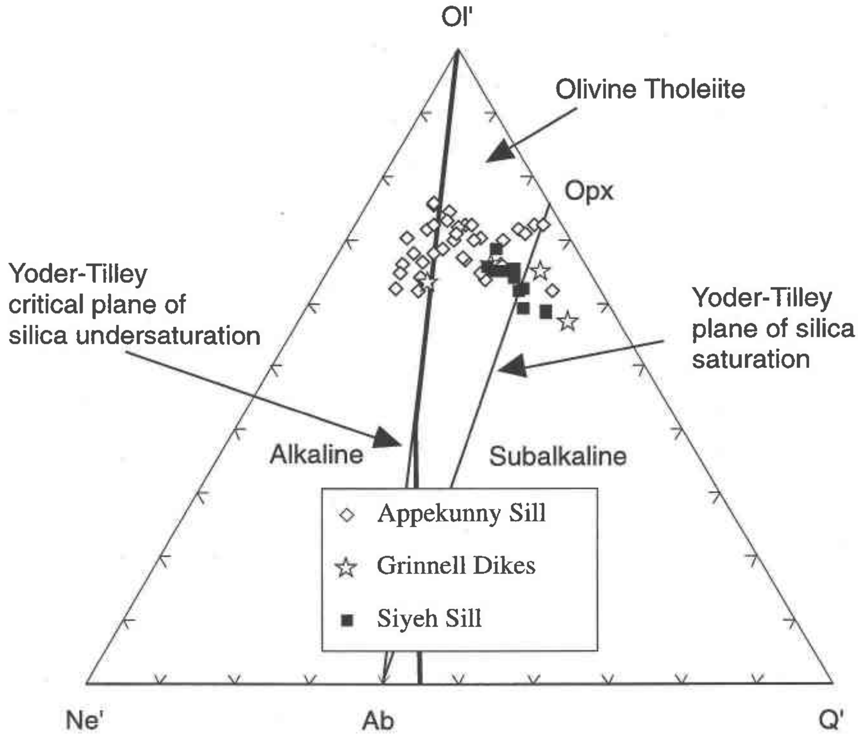


FIG. 5. Olivine' – nepheline' – quartz' discrimination diagram for the basaltic intrusions on Spionkop Ridge. Data have been recalculated as cation norms with Ol' = Ol + 3/4 Opx, Ne' = Ne + 3/5 Ab, Q' = Q + 2/5 Ab + 1/4 Opx (Irvine & Baragar 1971).

Normative olivine' – nepheline' – quartz' plot both in the olivine tholeiite (transitional basalt) and subalkaline fields (Fig. 5). A plot of Nb/Y *versus* Zr/TiO_2 indicates an alkaline basalt (Fig. 6).

The Grinnell Dikes

In general, major- and trace-element concentrations in the amygdaloidal Grinnell Dikes (Table 1) resemble those in the Appekunny Sill. The most noteable differences in major-element concentrations are slightly lower Fe_2O_3 and P_2O_5, slightly higher SiO_2, and much lower TiO_2. Alteration is extensive in the majority of samples, and is again reflected in a loss of Sr; even the "unaltered" samples shown in Table 1 are partially altered. Patterns of enrichment and depletion for altered *versus* unaltered samples generally mirror those of the Appekunny Sill type of intrusions, except that in the Grinnell Dikes, Ca shows little change, and Ba increases with alteration. Loss-on-ignition (LOI) values are significantly higher than for samples from the Appekunny Sill. The concentrations of incompatible elements (*REE*, Sc, Y, Nb, Hf) are lower than those in the Appekunny Sill by an average of approximately 20%; TiO_2 and P_2O_5 are approximately 35% lower.

Chemical data for the Grinnell Dikes are generally inconsistent with regard to classification. Unaltered samples are olivine–orthopyroxene-normative, indicating transitional basalts, although the normative mineralogy may in part reflect partial alteration in the "unaltered" samples of Table 1. Alkali–silica and normative olivine' – nepheline' – quartz' data plot in the subalkaline and transitional basalt fields (Fig. 4, 5). Nb/Y *versus* Zr/TiO_2 data plot in the alkali basalt field (Fig. 6).

Rare-earth and trace elements

Rare-earth-element data for the Appekunny Sill section show little variation, aside from an increase in the ratio Ce/Yb at the margins (Table 1). The samples have a small negative Eu anomaly, which is more pronounced in samples from the upper sill margin and altered samples (Fig. 7). Chondrite-normalized *REE* data for other

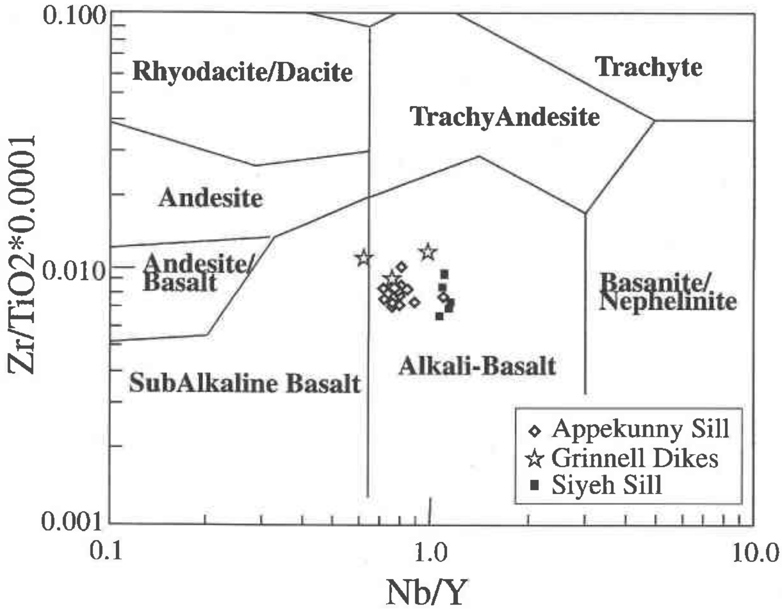


FIG. 6. Nb/Y *versus* Zr/TiO_2 discrimination diagram for the basaltic intrusions on Spionkop Ridge. Boundaries between rock types are from Winchester & Floyd (1977).

basalts of this and other types show patterns similar to that of the Appekunny Sill, although with somewhat greater scatter in the data for altered samples. The Siyeh Sill data show significant heavy-*REE* depletion relative to the Appekunny Sill (Fig. 7) and indicate a lack of Eu anomaly. Data for the Grinnell Dikes closely parallel the pattern for the Appekunny Sill, although all *REE* concentrations are slightly lower (Fig. 7). Figure 7 also contains comparative data for the transitional to mildly alkaline basalts and ferrobasalts of the Southern Gregory Rift in the eastern branch of the East African Rift (Baker *et al.* 1977). The data for these basalts, and for the ferrobasalts in particular, closely parallel those for the Spionkop Ridge basaltic suites.

Figure 8 is a chondrite-normalized trace-element variation diagram for the three suites of Spionkop Ridge basaltic rocks and for the southern Gregory Rift basalts (data from Baker *et al.* 1977). The data for the East African Rift ferrobasalts again closely parallel those for the Spionkop Ridge rocks, consistent with the latter also being transitional to mildly alkaline.

DISCRIMINATION OF BASALTS USING TRACE-ELEMENT DATA

Spionkop Ridge

The three types of basaltic rocks can be discriminated using combination plots of TiO_2, Al_2O_3, P_2O_5, and Yb (Fig. 9); altered samples show a greater spread in the data, as would be expected. The Appekunny Sill averages approximately 3.7% TiO_2, 15% Al_2O_3, 0.74% P_2O_5 and 4.1 ppm Yb, the Grinnell Dikes average approximately 2.5% TiO_2, 16% Al_2O_3, 0.47% P_2O_5 and 3.3 ppm Yb, and the Siyeh Sill averages approximately 4% TiO_2, 12% Al_2O_3, 0.49% P_2O_5 and 2.4 ppm Yb. Data for unaltered (high-Sr) samples of the Appekunny Sill type of intrusions are similar to data from the Appekunny Sill; data from altered samples of the Grinnell Dikes and the Appekunny Sill type of intrusions show somewhat greater spread than unaltered samples of these rocks, but follow the same general geochemical patterns. Plots of P_2O_5 *versus* TiO_2 and Yb *versus* TiO_2 for the Appekunny Sill and Grinnell Dikes show approximately linear trends in Figure 9, suggesting a possible genetic relationship between these two basaltic suites; the corresponding Siyeh Sill data lie off these apparent trends.

Other areas in the Lewis Thrust Sheet

TiO_2, Al_2O_3, P_2O_5 and Yb concentrations for basaltic rocks from other locations throughout the Lewis Thrust Sheet are plotted in Figure 10, together with data for samples analyzed by Mejstrick (1975), McGimsey (1985) and Verstraeten-Gless (1987); shaded fields are from Figure 9. The classification of basaltic intrusions described by McGimsey (1985) is based upon an inter-

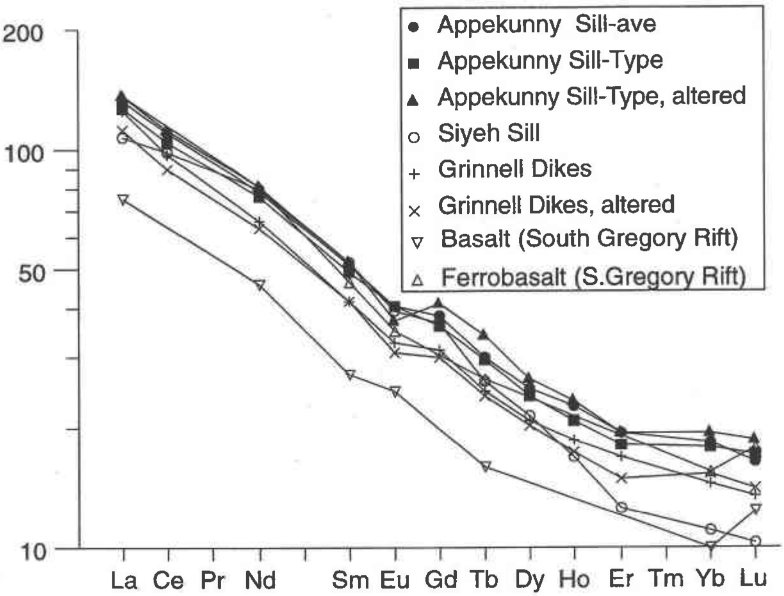


FIG. 7. Chondrite-normalized rare-earth-element data for the basaltic intrusions on Spionkop Ridge. Data from the Southern Gregory Rift (Baker *et al.* 1977) are shown for comparison.

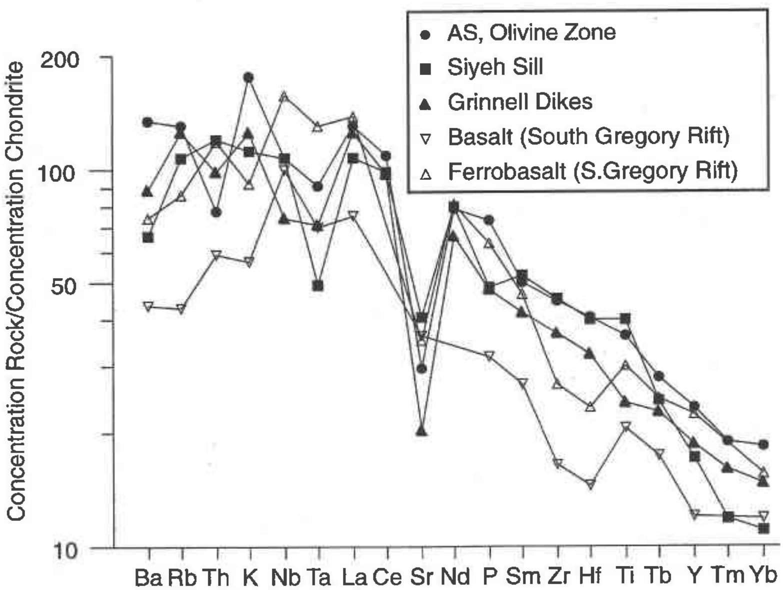


FIG. 8. Chondrite-normalized trace-element data (normalization after Thompson *et al.* 1984). Data for transitional to mildly alkaline basalts of the eastern branch of the East African Rift (Baker *et al.* 1977) are shown for comparison.

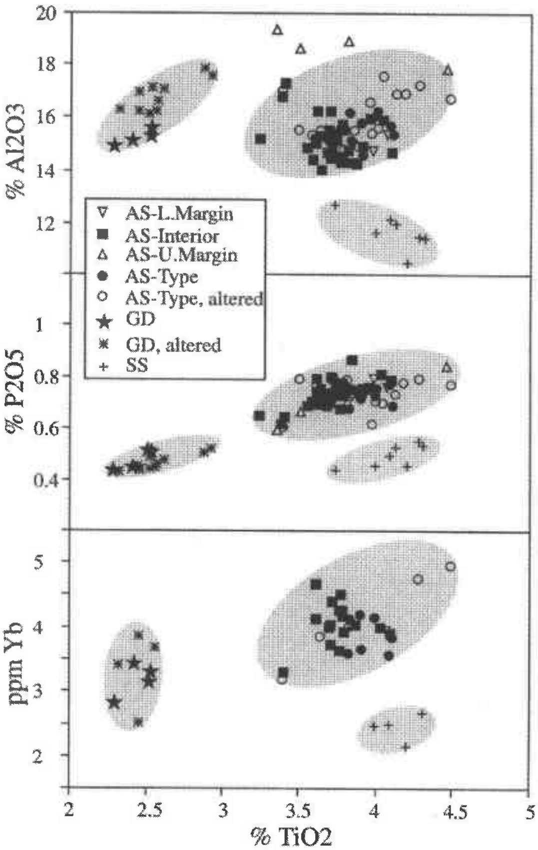


FIG. 9. Element-element plots for samples of the three types of basaltic intrusions found on Spionkop Ridge. Shaded areas are drawn to enclose the majority of samples from each suite. AS: Appekunny Sill, GD: Grinnell Dikes, SS: Siyeh Sill.

pretation of his rock descriptions. The Siyeh Sill type of intrusions are similar in mineralogy, texture and geochemistry to the Siyeh Sill, but occur higher in the stratigraphic sequence (Fig. 2), and were considered by Ghazi (1992) as a geochemically separate igneous suite; such a geochemical distinction is not supported by the data in Figure 10.

In general, the chemical data for basaltic rocks from other areas in the Lewis Thrust Sheet are consistent with the threefold subdivision developed for the Spionkop Ridge suites, although they show somewhat greater spreads in composition. Samples from the Purcell and Sheppard lavas [Mt. Shields lavas of McGimsey (1985)] have TiO_2, Al_2O_3, P_2O_5 and Yb concentrations similar to those for the Appekunny Sill, suggesting a probable relationship between these suites. The greater spread in compositions is probably due in part to the extensive alteration in these rocks. The high concentration of P_2O_5 found in the Sheppard (Mt. Shields) lavas serves to characterize this suite and suggests a possible subdivision of the lavas.

Empirical boundaries have been drawn in Figure 10 to separate the different suites of basaltic rock. With the inclusion of the Purcell lava and Sheppard lava samples as basalts of Appekunny Sill type, the fields outlined correctly discriminate 96% to 98% of the samples. Those samples that are not correctly discriminated are generally from intrusive margins or flow tops. As with the basaltic rocks on Spionkop Ridge, the P_2O_5 *versus* TiO_2 and Yb *versus* TiO_2 data for samples of the Appekunny Sill type and Grinnell Dike type show approximately linear trends in Figure 10, consistent with a genetic relationship between these two suites.

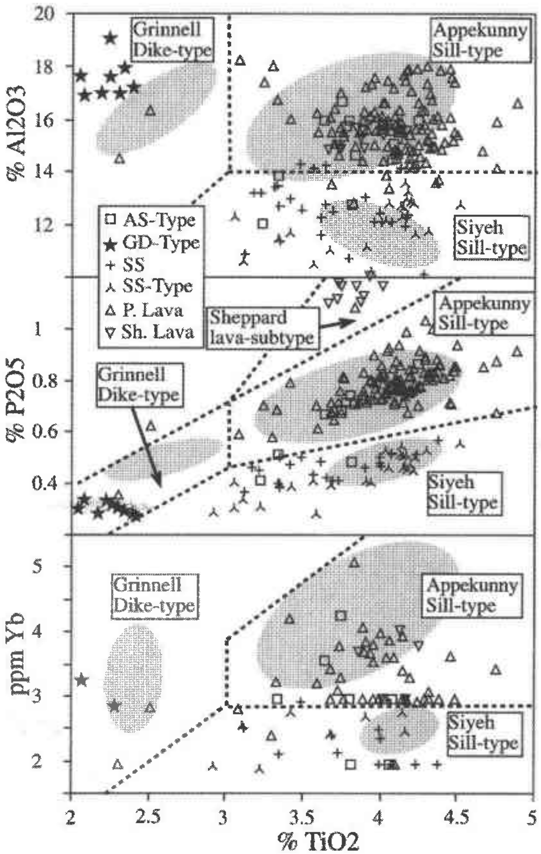


FIG. 10. Element–element plots for samples of basaltic rocks found in other areas of the Lewis Thrust Sheet. Shaded areas are as drawn in Figure 9. Empirical boundaries are drawn to discriminate between rock suites. Data from McGimsey (1985), Mejstrick (1975) and Verstraeten-Gless (1987) are included; McGimsey's (1985) data for Yb are considered valid to one significant figure.

Purcell Mountains and Kootenay Range

Data for the Moyie sills of the Purcell Mountains and Kootenay Range, approximately 125 km to the northwest (Hoy 1989, Tables 3 and 4) do not fit any of the distinctive geochemical signatures noted for the three basaltic suites found in the Lewis Thrust Sheet, thus precluding the application of these discrimination diagrams in areas of the Belt–Purcell Supergroup outside of the Lewis Thrust Sheet. Major-oxide data [SiO_2, Na_2O, K_2O, Fe_2O_3 (total), MgO] also show distinctive differences between the eastern and western basaltic suites. This finding is consistent with differences in composition noted by Hunt (1961), who concluded that the eastern suite of basaltic rocks is more alkaline in nature than the western suite. With the possible exception of the Siyeh Sill and related basaltic intrusions, the basaltic rocks in the Lewis Thrust Sheet are alkaline to transitional, and have trace-element concentrations more characteristic of continental basalts, whereas the Moyie sills described by Hoy (1989) are alkaline to tholeiitic, and show concentrations of elements such as Ti, Zr and Y characteristic of both ocean-floor and continental basalts.

Summary

1. Field relationships, mineralogical and geochemical differences, and isotopic age data are consistent with emplacement of three suites of basaltic intrusions on Spionkop Ridge. These are: (A) a 1400- to 1500-Ma suite of glomeroporphyritic alkaline sills and dikes with TiO_2, Al_2O_3, P_2O_5 and Yb contents of approximately 3.75%, 15%, 0.74% and 4.1 ppm, (B) a 1000-Ma (minimum age) suite of amygdaloidal transitional or mildly alkaline dikes with TiO_2, Al_2O_3, P_2O_5 and Yb contents of approximately 2.5%, 16%, 0.47% and 3.3 ppm, and (C) an 800-Ma suite of diabasic tholeiitic sills with TiO_2, Al_2O_3, P_2O_5 and Yb contents of approximately 4%, 12%, 0.49% and 2.4 ppm.

2. Some trace-element data display approximately linear trends for the two older basaltic suites, suggesting a possible genetic relationship. However, the two suites are associated with different sets of geological structures, have distinctively different contacts with the surrounding sedimentary rocks, and different forms of sulfide mineralization at these contacts. Therefore, we do not believe that the two suites are comagmatic, although they may share a common source as a result of repeated rifting in the area. The youngest suite is tholeiitic in composition and unrelated to either of the two older suites.

3. Chemically, other basaltic intrusions found in the Lewis Thrust Sheet seem to be of the same three types as those found on Spionkop Ridge.

4. Data for the Purcell and Sheppard lavas are consistent with a hypothesis that they are equivalent to the 1400–1500 Ma basalts found on Spionkop Ridge. The higher P_2O_5 content of the Sheppard suite compared to the Purcell lavas suggests that the former may comprise a subgroup of this suite, possibly a result of either fractionation or contamination during emplacement.

5. The Moyie sills, found to the west of the Lewis Thrust Sheet (Hoy 1989), are of a similar age to the 1400–1500 Ma suite but differ geochemically.

Acknowledgements

This research was supported in part by a University of Nebraska – Lincoln Grant-in-Aid to R.J. Goble. We thank the referees for their valuable suggestions.

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Received January 22, 1998, revised manuscript accepted January 2, 1999.