

Composition of rift-related igneous and sedimentary rocks of the Keweenaw Supergroup in the Poersch no. 1, OZ-1, Finn, and Friederich wells, northeastern Kansas

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Abstract A series of wells have been drilled up to a depth of 3,444 m (113,000 ft) into the midcontinent rift system (MRS) in northeastern Kansas. The age of a gabbro sill in the upper portion of the Precambrian rocks was determined to be $1,097.5 \pm 3$ Ma, and the magnetic polarity of the gabbro correlated to the lower Keweenaw rocks in the northern MRS (Van Schmus et al., 1990). The rocks below 2,259 m (7,411 ft) in the deepest well [Poersch no. 1, total depth 3,435 m (11,270 ft)] consist mostly of arkoses with subordinate amounts of shale, siltstone, and basalt. The rocks above 2,265 m (7,431 ft) in the Poersch well consist of basalt with minor siltstone, arkose, gabbro, and felsite. A proposed high-angle reverse fault could have juxtaposed the upper igneous rocks over the lower sedimentary rocks to produce a reversed stratigraphy. This would make the development of the southern MRS similar to that of the northern MRS. Thus, in the initial extensional phase of the MRS, broad subsidence coincided with abundant volcanism and little sediment production. Grabens formed in the later stages of rift development and were filled with abundant sedimentary rocks along with lesser volcanic rocks. The chemical characteristics of the basalts in the southern MRS are similar to those in the north. The southern basalts are subalkalic to alkalic and follow tholeiitic trends; a number of them are high-alumina basalts. Although there is a lot of scatter, Al_2O_3 , Ni, and Cr concentrations decrease and Fe_2O_3 , TiO_2 , K_2O , rare earth elements, Ba, Hf, and Sc concentrations increase with decreasing Mg number. These trends are consistent with plagioclase, olivine, pyroxene, or spinel fractionation from primary basalts. One basalt could represent a primary magma because it has a high Mg number (0.68), high Ni (638 mg/kg) and Cr (233 mg/kg) concentrations, low incompatible element concentrations (e.g., La = 4.2 mg/kg), and a slight positive Eu anomaly. This possible primary magma could have formed by partial melting (20–25%) of an undepleted spinel peridotite at 30–40 km depth. Most basalts have not been contaminated by crustal rocks or silicic magmas. The mineralogy, chemical composition, and U-Pb geochronology of detrital zircons of the arkoses, siltstones, and shales are consistent with their derivation from the surrounding granitoid highlands with little or no input from the basalts. Even siltstones and arkoses within the mostly basaltic sequences are derived mostly from the granitoids, although the siltstones may have some input from the basalts (e.g., higher Ni concentration than the sandstones).

Rocks associated with the midcontinent rift system (MRS) extend in the subsurface from south-central Kansas northward through Nebraska, Iowa, and Minnesota, where they are exposed in the Lake Superior region, northern Wisconsin, northern Michigan, and Ontario (fig. 1) (Dickas, 1984, 1986; Van Schmus and Hinze, 1985). The surface rocks are a bimodal suite of mostly tholeiitic basalts and some alkaline basalts along with minor silicic rocks (Basaltic Volcanism Study Project, 1981; Van Schmus and Hinze, 1985). The alkaline basalts are most abundant in the lower portion of the section, and the tholeiites become more abundant up-section

(Basaltic Volcanism Study Project, 1981). Subsidence of the basins resulted in deposition of a thick sequence of continental sedimentary rocks over the basalts (Morey and Green, 1982). The age range of igneous and sedimentary activity in the rift has been estimated to be 1,087–1,109 Ma (Davis and Sutcliffe, 1985; Palmer and Davis, 1987; Van Schmus et al., 1989, 1990; Davis and Paces, 1990; Van Schmus, 1992). The subsurface rocks are recognized by large gravity and magnetic anomalies, presumably reflecting the abundance of basalts along the rift (Van Schmus and Hinze, 1985).

We have analyzed cuttings and cores from four wells drilled into the southern portion of the MRS in northeastern Kansas and have compared the composition of these rocks to the composition of similar rocks in the northern MRS. The Texaco Poersch no. 1 well (fig. 2) was drilled to a depth of 3,435 m (11,270 ft) in Washington County, Kansas (Berendsen et al., 1988). In addition, a test hole, OZ-1, is located adjacent to the Poersch well. Most of the cuttings and all the core were

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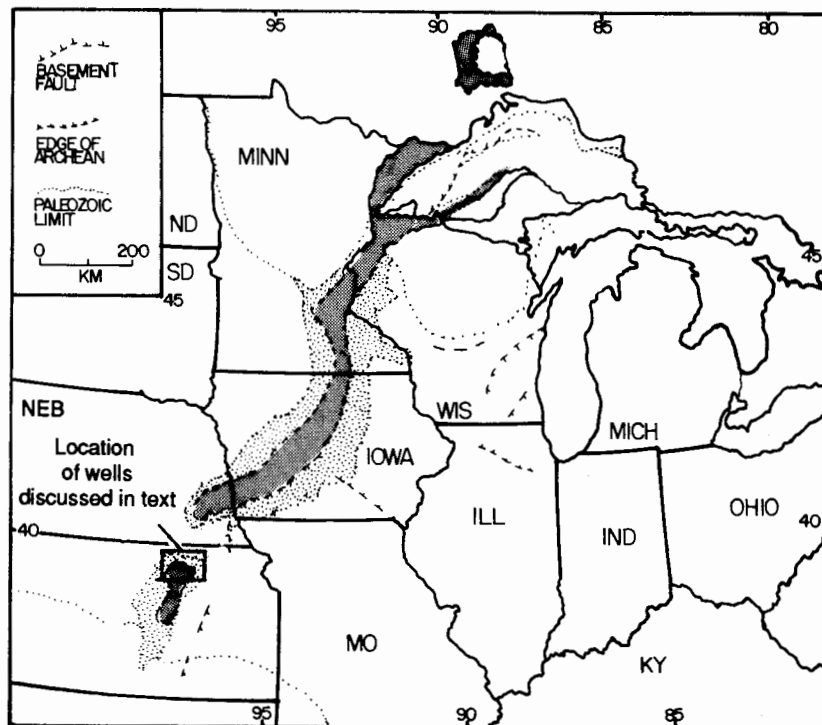


Figure 1. The midcontinent rift system (shaded area) extends from the surface in Minnesota, northern Michigan, and northern Wisconsin into the subsurface in Iowa, Nebraska, and Kansas.

obtained from the Poersch and OZ-1 wells. In addition, some cuttings were obtained from the Finn and Friederich wells, drilled to depths of 1,208 m (3,975 ft) and 1,350 m (4,440 ft), respectively, in the rift. Most of the discussion here centers on the results obtained from the Poersch well.

Geology

The portion of the Poersch well below 7,430 ft (2,265 m) consists of mostly arkosic sandstone and conglomerate with minor siltstone, shale, and basalt (fig. 3). The Poersch well from 2,840 ft (866 m) to 7,430 ft (2,265 m) and the OZ-1 well are mostly basalt with minor siltstone, arkose, gabbro, and felsite (fig. 3). A U-Pb age on baddeleyite of $1,097.5 \pm 3$ Ma from gabbro in the upper portion of the Poersch well (Van Schmus et al., 1990) and a high-angle reverse fault interpreted from seismic (COCORP) data, which juxtaposes the upper igneous and lower sedimentary section (Woelk and Hinze, 1991), suggest that the basic igneous activity took place before the deposition of abundant arkosic basin fill from the surrounding highlands of the rift.

In the Friederich well a thick gabbro sill overlies basaltic rocks with minor interflow clastic sedimentary rocks. In the Finn well mostly arkosic sedimentary rocks overlie basaltic rocks near the bottom of the well. The stratigraphic succes-

sion in the Friederich well is similar to that in the upper portion of the Poersch well, probably because of the location of the wells in the same structural block (fig. 2). The rocks in the Finn well, however, cannot be correlated with those in the Friederich and Poersch wells because of structural complexity in the area (Berendsen et al., 1988).

Methods

Sampling procedure The OZ-1 well was cored and completed in the same unit that tops the Precambrian section in the nearby Poersch well (fig. 3). This drilling allowed us to sample fresher portions of the cored interval. The Poersch no. 1 well was cored at selected intervals (Berendsen et al., 1988, appendix 3). The mafic rocks are all altered. The intensity of alteration is discussed in a later section. The interflow sedimentary rocks appear to be affected by the heat from the enclosing mafic rocks. The sedimentary rocks below 7,430 ft (2,265 m) are relatively unaltered and appear not to have been metamorphosed.

Cuttings were collected at 10-ft intervals in the well and forwarded to the Wichita Well Sample Library for washing and archiving. Our samples from the drill holes are unique in that they represent the deepest drill holes completed in the MRS in Kansas. The average sample weight was about 100

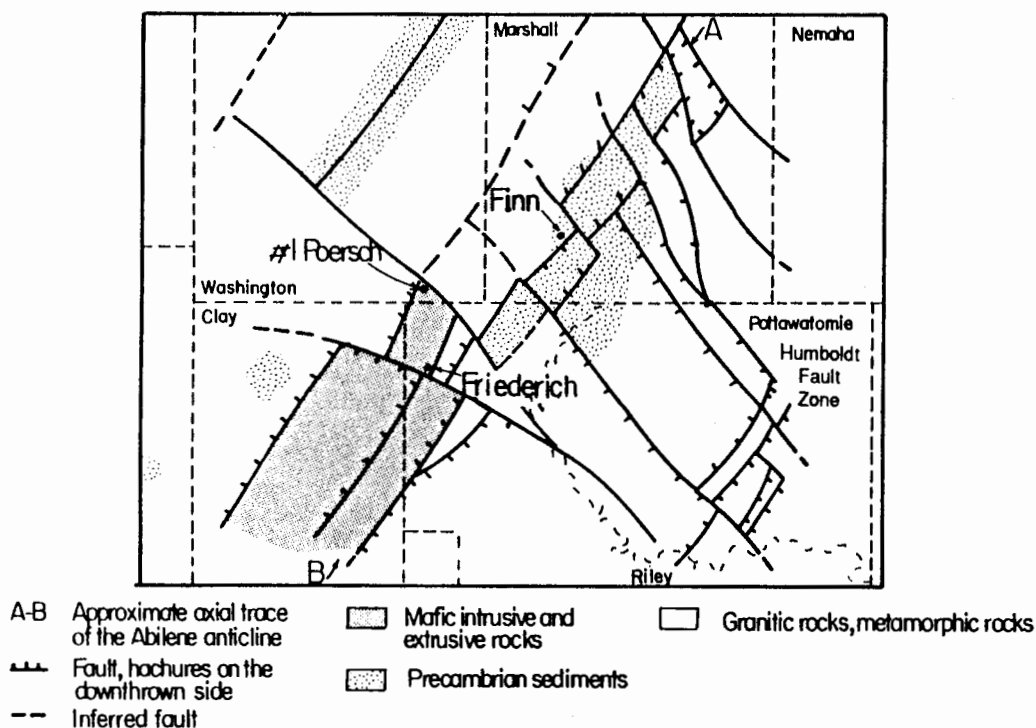


Figure 2. Location of the Poersch, Friederich, and Finn wells in northeastern Kansas.

g, although some samples weighed up to about 500 g. The samples were handpicked using a binocular microscope to exclude any contaminants.

Analytical techniques Cuttings from the Poersch no. 1, Friederich, and Finn wells were analyzed for major elements by atomic absorption at the Kansas Geological Survey; major elements of cores from the Poersch well and some cuttings were analyzed by atomic absorption at Kansas State University following the methods of Buckley and Cranston (1971).

Most trace elements, Fe_2O_3 , and Na_2O were analyzed by neutron activation analysis at Kansas State University using the methods of Gordon et al. (1968) and Jacobs et al. (1977). Also Nb, Y, Rb, Sr, Zr, and Ni were analyzed by x-ray fluorescence at Kansas State University. Estimates of precision and values obtained on standard rocks using these methods can be found in the articles by Cullers et al. (1979, 1985).

Petrology

Details of the petrology of the Poersch well can be found in the report by Berendsen et al. (1988). The rocks are described briefly here so that the chemical composition of these rocks can be better interpreted. For example, some of the basalts are considerably altered so that elements such as Rb, Ba, and Sr have been mobilized (Wood et al., 1976).

The gabbro sill at the top of the section [OZ-1, 2,823–2,872 ft (860.5–875.4 m) depth; Poersch no. 1, 2,846–3,150 ft (867.5–960.1)] is 88 m (290 ft) thick. The gabbro is fine- to medium-grained and slightly serpentinized; it contains epidote, so it was undoubtedly altered. Five samples of the gabbro from core material were analyzed (table 1).

The predominantly basalt sequence from 3,150 to 4,140 ft (960.1–1,262 m) contains the least altered basalts, although they are deuterically and hydrothermally altered (Berendsen et al., 1988). Fibrous actinolite, chlorite, albite, and saussurite were observed in the altered zones. The amount of magnetite varies from a few percent to 20% in some basalts. The basalt cuttings analyzed at 3,720–3,730 ft (1,134–1,137 m) are the least altered rocks in this sequence. No sedimentary rocks occur in this interval.

Basalts in the sequence of rocks from 4,140 to 5,719 ft (1,262–1,743 m) are more hydrothermally and deuterically altered than those from 3,150 to 4,140 ft (960.1–1,262 m) (Berendsen et al., 1988). Some of the basalts are completely altered to albite and epidote, and we avoided analyzing these intervals (table 1). This interval also has arkoses and siltstones that alternate with the basalts. An arkose [5,396 ft (1,645 m)] and a siltstone [5,404 ft (1,647 m)] were sampled from a core adjacent to the basalt at 5,399 ft (1,646 m).

The predominantly basalt sequence from 5,719 to 7,429 ft (1,743–2,264 m) depth is also commonly altered to epidote and albite (Berendsen et al., 1988). Again, we sampled four of the least altered basalts for analysis (table 1). One siltstone

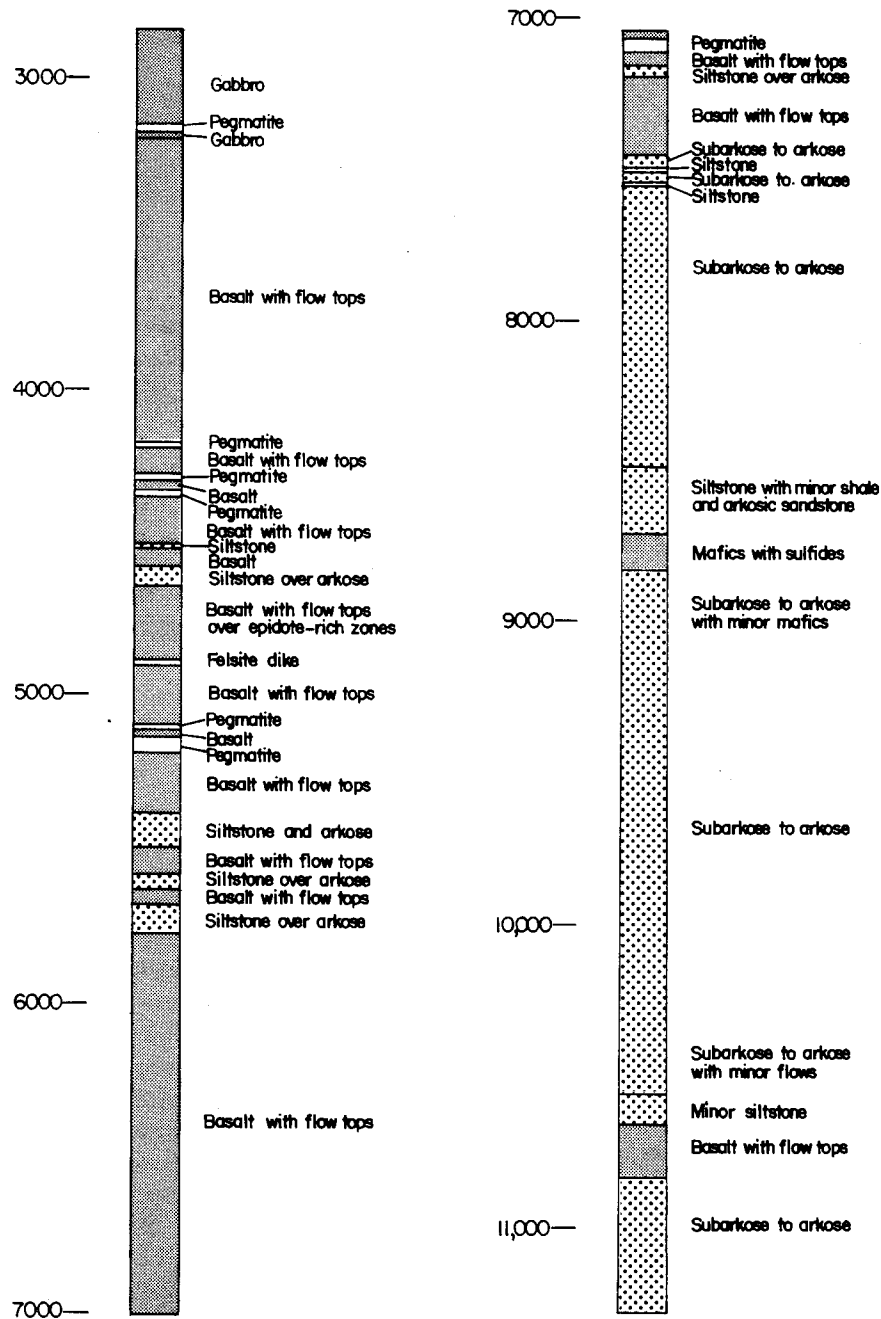


Figure 3. Schematic columnar section of the Poersch well [after Berendsen et al. (1988); depth in feet].

at 7,153 ft (2,180 m) was sampled from a core adjacent to the basalt at 7,159 ft (2,182 m).

The rocks at depths greater than 7,429 ft (2,264 m) consist mostly of arkosic sandstones and conglomerates. They appear to be a series of fining-upward sequences containing conglomerate or sandstone at the base with or without a siltstone at the top (Berendsen et al., 1988). The arkoses consist of clasts composed mostly of polycrystalline quartz and alkali feldspar (unaltered microcline, orthoclase, or

perthite) with lesser plagioclase (slightly to very altered). The accessory minerals are micas, sphene, zircon, and opaque minerals. The minor siltstones contain more abundant hematite staining than do the coarser fractions (Berendsen et al., 1988). Four arkoses and one siltstone were analyzed in this sequence. Minor basalts and gabbros occur below 7,429 ft (2,264 m), except for 43-m-thick (141-ft-thick) and 72-m-thick (236-ft-thick) units at 8,680 and 10,622 ft (2,646 m and 3,238 m) depth, respectively. Six basalts or gabbros were

Table 1. Major element oxide (wt %) and trace element (mg/kg) concentrations of the igneous rocks in the OZ, Texaco, no. 1 Poersch, Finn, and Friederich wells

	Well, depth (in feet), rock type, and sample type ^a									
	OZ 2,823 Gabbro CO	OZ 2,836 Gabbro CO	OZ 2,837 Gabbro CO	OZ 2,872 Gabbro CO	Poersch 2,860-70 Gabbro CU	Poersch 3,120-30 Felsite CU	Poersch 3,720-30 Basalt CU	Poersch 4,760-70 Basalt CU	Poersch 5,399 Basalt CO	Poersch 6,130-40 Basalt CU
SiO ₂	46.23	46.6	46.6	45.2	45.4	64.1	44.86	47.4	44.8	48.86
TiO ₂	1.06	1.09	1.08	1.16	2.78	0.85	1.30	3.48	1.51	3.23
Al ₂ O ₃	15.8	15.6	17.1	17.3	15.71	14.30	14.7	13.74	16.70	13.35
Fe ₂ O ₃	11.2	11.9	11.3	11.2	12.1	5.31	13.35	13.71	13.1	13.04
MnO	0.13	0.15	0.13	0.14	0.16	0.057	0.18	0.21	0.19	0.18
MgO	9.71	9.47	9.33	8.84	8.98	1.84	13.84	5.12	9.52	6.64
CaO	9.69	10.9	9.80	9.16	8.87	5.33	8.17	8.76	5.78	8.40
Na ₂ O	1.65	1.73	1.93	2.15	2.00	4.83	1.43	4.07	3.33	3.17
K ₂ O	0.44	0.48	0.56	0.59	0.39	1.74	0.12	0.26	1.56	0.57
LOI ^b	4.08	1.80	2.05	4.17	3.50	1.90	2.91	3.09	2.77	3.03
Total	100.0	99.7	99.88	99.9	99.91	100.2	100.2	99.84	99.3	100.47
La	5.3	7.2	6.5	7.6	7.9	25.1	4.2	12.3	13.2	12.4
Ce	11.0	14.0	13.4	16.4	16.5	53.1	10.0	28.6	34.7	26.9
Sm	2.04	2.70	2.61	2.93	2.66	6.08	1.58	4.34	3.73	4.12
Eu	0.77	0.98	0.98	1.05	0.99	1.23	0.68	1.64	1.03	1.45
Tb	0.36	0.45	0.48	0.53	0.49	0.87	0.29	0.82	0.72	0.79
Yb	1.09	1.49	1.41	1.67	1.54	3.16	1.0	2.74	2.37	2.54
Lu	0.20	0.27	0.24	0.28	0.27	0.49	0.15	0.43	0.46	0.39
Σ REE ^c	36	46	45	52	51	139	31	85	89	81
(La/Lu) _{cn}	2.6	2.7	2.7	2.7	3.0	5.1	2.7	2.9	2.9	3.2
Rb	13	13	10	12	30	36	-	6	68	19
Ba	47	106	93	91	90	201	45	251	141	238
Th	0.71	0.74	0.72	0.9	1.2	8.8	0.58	1.1	1.6	1.7
Hf	1.6	1.9	1.8	2.0	2.3	5.8	1.2	3.5	3.3	3.4
Ta	0.3	0.44	0.4	0.48	0.5	1.1	0.21	0.96	0.9	0.68
Co	62	60	67	61	64	8.6	89.3	46.6	61.3	50.3
Sc	18.3	21.3	22.3	23.3	23.2	15.5	20.7	30.6	28.6	32.0
Cr	132	164	169	173	164	101	233	109	311	146
Sr	158	200	170	242	188	-	169	241	70	146
Cs	1.0	0.8	1.2	0.8	1.2	0.2	2.5	-	7.8	0.81
Nb	6.9	4.5	-	5.7	-	-	-	-	11.0	-
Y	11	16	14	16	-	-	-	-	24	-
Zr	72	75	50	63	-	-	-	-	145	-
Ni	273	267	240	227	347	-	638	144	225	179

Table continues on pp. 60-61.

sampled in this interval. Many of these mafic rocks are altered to some degree, containing chlorite, serpentine, epidote, carbonates, albite, pyrite, or chalcopyrite (Berendsen et al., 1988).

Geochemistry

Alteration The chemical composition of the basalts and gabbros can be compared with that of rocks exposed along the MRS further to the north, even though most samples are

altered. Again, however, we sampled the least altered samples for analysis. Also, elemental correlations in variation diagrams are similar to those expected for rocks controlled by igneous processes rather than for rocks affected by alteration.

Igneous rocks The igneous rocks range from subalkalic to alkalic (fig. 4). They tend to follow tholeiitic trends toward iron enrichment in AFM diagrams (fig. 5). Most of these rocks plot in the basalt field in an alkali versus silica plot (fig. 6). In addition, although the database is small, the stratigraphically lower basalts [deeper than 7,159 ft (2,182 m)] in

Table 1 (continued)

	Well, depth (in feet), rock type, and sample type ^a								
	Poersch 6,780-90 Basalt CU	Poersch 7,159 Basalt CO	Poersch 7,180-90 Basalt CU	Poersch 8,112 Basalt CO	Poersch 8,730-40 Gabbro CU	Poersch 10,649 Basalt CO	Poersch 10,674 Basalt CO	Poersch 10,730-40 Basalt CU	Poersch 12,907 Basalt CO
SiO ₂	47.51	42.0	45.7	45.3	45.52	47.8	49.4	51.27	45.7
TiO ₂	2.62	1.65	2.68	2.21	4.08	1.33	1.13	2.53	2.24
Al ₂ O ₃	14.45	14.5	15.0	14.6	13.34	16.2	16.7	13.81	14.5
Fe ₂ O ₃	3.20	17.53	15.79	15.90	16.38	11.76	10.47	11.32	16.4
MnO	0.20	0.24	0.21	0.22	0.27	0.31	0.36	0.26	0.24
MgO	7.67	8.40	5.21	7.03	6.15	9.17	8.87	6.28	6.79
CaO	9.34	6.52	8.11	8.37	8.63	2.73	2.81	5.93	7.61
Na ₂ O	2.68	3.36	3.16	2.80	2.30	5.02	5.67	5.17	2.48
K ₂ O	.24	0.87	0.87	0.74	0.73	0.64	0.67	0.71	0.90
LOI ^b	1.88	5.27	3.10	3.28	3.05	4.79	3.61	2.44	1.25
Total	99.79	100.34	99.83	100.45	100.4	99.75	99.69	99.72	98.11
La	10.0	27.8	21.3	12.3	11.2	21.4	24.5	19.7	10.3
Ce	21.3	56.7	44.9	25.3	25.7	48.8	49.7	43.0	21.5
Sm	3.39	6.05	6.15	4.80	4.56	6.84	6.42	5.86	4.35
Eu	1.25	1.51	2.11	1.58	1.61	1.42	1.26	1.26	1.37
Tb	0.66	0.82	1.14	0.85	0.85	1.22	1.20	1.09	0.74
Yb	2.19	2.67	4.02	3.08	2.75	5.37	4.82	4.65	2.60
Lu	0.35	0.48	0.63	0.49	0.49	0.77	0.77	0.75	0.49
Σ REE ^c	66	145	131	85	81	143	143	125	71
(La/Lu) _{cn}	2.8	5.7	3.4	2.5	2.3	2.8	3.2	2.6	2.1
Rb	8	30	23	29	43	21	22	21	36
Ba	132	693	606	403	402	359	375	659	359
Th	1.4	1.3	1.6	0.83	0.83	2.4	2.3	2.0	0.8
Hf	2.9	2.6	4.5	2.9	3.0	5.2	4.9	5.1	2.5
Ta	0.57	0.3	0.55	0.65	0.88	0.4	0.35	0.59	0.65
Co	68.4	63.7	51.6	54.5	50.2	54.6	54.1	44.8	50.7
Sc	24.8	32.8	34.0	34.7	31.6	30.6	33.2	34.4	30.9
Cr	100	336	110	91	90	182	231	214	79
Sr	187	102	155	168	220	58	114	130	95
Cs	2.0	2.4	1.2	-	1.4	1.0	0.8	0.44	1.4
Nb	-	4	-	10	-	8	6	-	7
Y	-	27	-	26	-	53	49	-	32
Zr	-	113	-	125	-	249	215	-	95
Ni	221	236	131	101	141	112	131	125	133

the Poersch well are all fairly rich in potassium (0.64–0.90 wt % K₂O). The basalts at less than 7,159 ft depth vary more in composition, ranging from 0.12 to 1.56 wt % K₂O. The chemical characteristics of the basalts and gabbros from the southern MRS are similar to those in the northern MRS (see table 3) (Green, 1972, 1982; Basaltic Volcanism Study Project, 1981; Weiblen, 1982).

Nine of 29 analyses of the basalts fall in the high-alumina field (greater than 16 wt % Al₂O₃). Most pre-Tertiary plateau basalts range from 13 to 15.5 wt % Al₂O₃ (Godlevskiy, 1959; Green, 1972; Ruegg, 1976; Basaltic Volcanism Study Project, 1981). In contrast, high-alumina basalts in the northern MRS

make up a major part of some sequences (Green, 1982). Thus the basalts and gabbros from the southern MRS resemble those to the north.

Some major element correlations in the southern MRS basalts are similar to those in the northern MRS basalts. For example, TiO₂ increases and Al₂O₃ decreases with decreasing Mg number (fig. 7) [compare to Basaltic Volcanism Study Project (1981)].

The compatible trace elements (Ni and Cr) decrease and the incompatible trace elements [rare earth elements (REEs), Ba, Hf, Ta, Sc] increase with decreasing Mg number. For example, the Ni concentration ranges from a high of 638

Table 1 (continued)

	Well, depth (in feet), rock type, and sample type ^a									
	Friederich							Finn		
	F-1 2,750-60 Basalt CU	F-3 2,840-50 Basalt CU	F-5 3,120-30 Basalt CU	F-6 3,500-10 Basalt CU	F-8 3,980-90 Basalt CU	F-10 4,070-80 Basalt CU	F-12 4,160-70 Basalt CU	Fi-4 3,640-50 Basalt CU	Fi-5 3,750-60 Basalt CU	Fi-8 3,880-90 Basalt CU
SiO ₂	46.8	46.9	45.5	45.6	46.0	46.5	46.2	44.7	45.9	43.4
TiO ₂	2.08	3.09	3.42	1.87	1.85	1.87	2.49	1.44	2.00	2.02
Al ₂ O ₃	16.4	15.9	15.0	17.5	16.5	16.2	16.7	15.8	15.4	15.3
Fe ₂ O ₃	11.1	11.74	13.67	10.21	10.10	10.10	10.18	12.82	12.95	14.48
MnO	0.14	0.15	0.15	0.14	0.14	0.15	0.15	0.17	0.23	0.19
MgO	8.12	6.73	6.55	7.94	6.28	8.58	7.57	7.90	7.86	8.98
CaO	5.60	8.97	8.22	10.75	11.84	10.00	10.20	10.08	9.08	8.22
Na ₂ O	4.26	3.26	3.52	2.54	2.99	2.70	2.52	2.84	2.54	2.59
K ₂ O	0.62	0.63	0.56	0.49	0.81	0.54	0.59	0.53	0.58	0.63
LOI ^b	3.98	2.30	3.20	2.96	3.45	3.10	3.39	3.21	3.60	3.49
Total	99.1	99.67	99.79	100.0	99.96	99.74	99.98	99.49	100.1	99.30
La	8.8	9.2	12.1	7.2	8.0	7.3	7.9	5.2	4.9	5.5
Ce	20.0	20.5	28.0	15.4	16.5	16.1	17.3	11.4	12.0	12.7
Sm	3.29	3.09	4.43	2.53	2.55	2.61	2.91	2.34	2.31	2.49
Eu	1.25	1.36	1.65	1.04	1.05	0.93	1.01	1.00	0.95	0.96
Tb	0.66	0.53	0.79	0.49	0.46	0.44	0.53	0.46	0.50	0.46
Yb	1.82	1.94	2.78	1.69	1.72	1.67	2.01	1.77	1.76	1.65
Lu	0.33	0.36	0.44	0.27	0.33	0.29	0.31	0.29	0.32	0.28
∑ REE ^c	56	62	85	49	51	50	55	40	41	43
(La/Lu) _{cn}	2.7	2.6	2.7	2.7	2.4	2.5	2.6	1.4	1.5	1.9
Rb	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Ba	66	104	96	59	96	68	114	168	146	163
Th	1.1	1.0	1.1	0.83	1.1	1.6	1.1	0.78	0.81	0.83
Hf	2.4	2.6	3.1	2.0	2.1	2.0	2.2	1.4	1.4	1.3
Ta	0.61	0.54	0.71	0.44	0.48	0.42	0.57	0.24	0.30	0.26
Co	46.0	45.4	45.5	47.3	41.7	46.2	49.8	54.3	58.4	48.2
Sc	26.7	25.3	29.5	21.6	22.3	21.8	22.6	31.6	30.0	26.8
Cr	178	140	192	128	251	194	188	302	301	271
Sr	293	229	578	264	349	172	197	244	220	218
Cs	4.4	0.28	0.30	0.89	0.96	0.54	<0.3	-	-	-
Nb	-	-	-	-	-	-	-	-	-	-
Y	-	-	-	-	-	-	-	-	-	-
Zr	-	-	-	-	-	-	-	-	-	-
Ni	156	131	103	163	95	180	183	213	218	195

a. CO, core; CU, cuttings.

b. Loss on ignition.

c. ∑ REE is 14 REE concentrations, including those estimated from chondrite-normalized plots.

mg/kg at the highest Mg number of 68 to a low of 95–133 mg/kg at the lowest Mg numbers (fig. 8a); correspondingly, the Cr concentration ranges from a high of 233 mg/kg to a low of 79 mg/kg. This range in Ni and Cr concentrations is similar to that observed in basalts in the northern MRS (Corwall and Rose, 1957; Basaltic Volcanism Study Project, 1981; Klewin and Berg, 1991). The REE concentrations tend to increase

with decreasing Mg number (fig. 8b). Although the tendency is not completely clear-cut, the Eu anomaly size tends to change from a positive anomaly at the higher Mg number and low REE concentrations to a more negative anomaly at the lower Mg number and high REE concentrations (fig. 9). The results are similar to those obtained for the Keweenaw reference suite (Basaltic Volcanism Study Project, 1981).

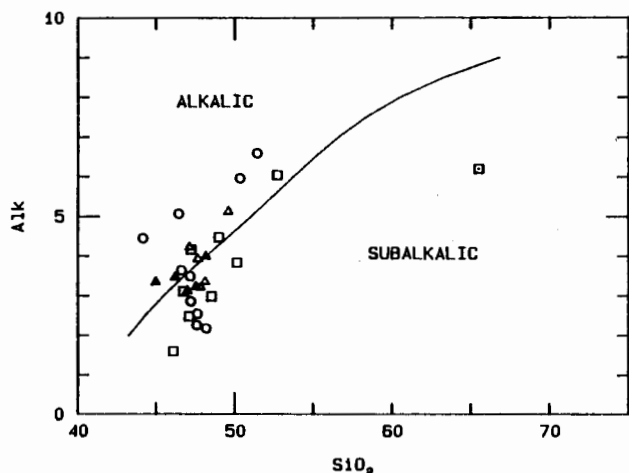


Figure 4. Total alkali versus silica concentrations of the MRS basalts and gabbros [after Irvine and Barager (1971)]. Open circles, Poersch and OZ cores; open squares, Poersch cuttings; squares with dots, Poersch cutting of felsite; open triangles, Friederich cuttings; triangles with dots, Finn cuttings. The plotted results in this and other plots are recalculated to 100% without H₂O, as recommended by Irvine and Barager (1971).

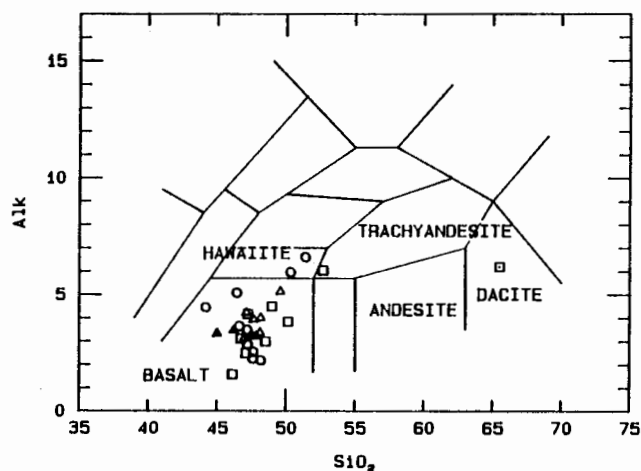


Figure 6. Most of the MRS samples plot in the basalt field of an alkali-silica plot [after Cox et al. (1979)]. Symbols defined in fig. 4.

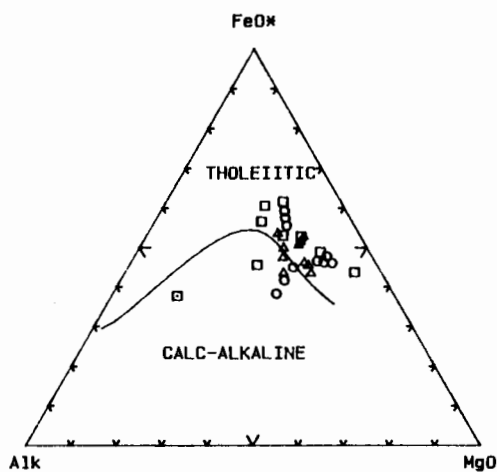


Figure 5. AFM diagram of the MRS rocks [after Irvine and Barager (1971)]. Symbols defined in fig. 4.

Sedimentary rocks The arkoses, with their feldspar-quartz mineralogy have major element concentrations (table 2) that reflect their derivation from the nearby granitic highlands with little chemical weathering. The shales and siltstones contain higher TiO₂, Al₂O₃, Fe₂O₃, MgO, REE, Rb, Cs, Co, Sc, Cr, and Ni concentrations and lower SiO₂ concentrations than the arkoses. This probably reflects the higher clay and ferromagnesian mineral content and the lower quartz content of the shales and siltstones compared with the arkoses. For example, the REEs are concentrated in clay minerals relative to quartz or feldspar (Cullers et al.,

1987; Cullers, 1988), thus explaining the higher REE content of the shales and siltstones compared with the arkoses.

The REE patterns and Eu anomaly size (fig. 10) of the sedimentary rocks are similar to those observed in continental platform sediments or the North American shale composite, which is presumably derived from granitoids [e.g., compare to Ronov et al. (1974), Cullers et al. (1975), and Gromet et al. (1984)]. Most elemental concentrations of the sedimentary rocks in this study are similar to an average of the post-Archean average Australian shale (PAAS) (fig. 11) (Taylor and McLennan, 1985). The exceptions are the depleted Nb and Sr contents in these sediments compared with the PAAS and the depleted Co, Ni, and Cr contents of the arkoses relative to the PAAS. The arkoses may be depleted in Co, Ni, and Cr because of the depleted ferromagnesian mineral content of the source. The siltstones may have inherited higher concentrations of Ni, Cr, Sr, and MgO from the associated basalts or from the ferromagnesian minerals from the granites. Perhaps the basalts or ferromagnesian minerals from the granites were weathered so rapidly relative to the felsic minerals that little of the ferromagnesian minerals remained in the arkoses. More of the finer weathered products from the ferromagnesian minerals could have then collected in the shales and siltstones. It is not understood why Nb or Sr might be depleted in the arkoses, siltstones, and shales relative to the PAAS.

Discussion

Igneous rocks The chemical characteristics of the southern MRS igneous rocks are similar to those of the northern MRS igneous rocks (table 3). We are cautious about putting much significance on quantitative modeling of the igneous

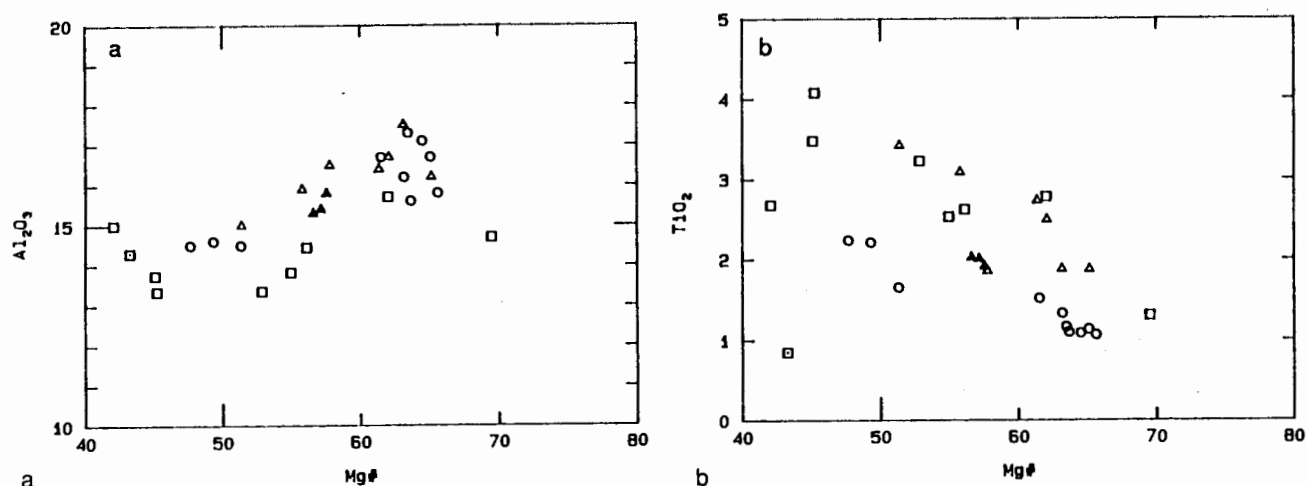


Figure 7. (a) Variation diagram of alumina versus Mg number in the MRS rocks. (b) Variation diagram of TiO_2 versus Mg number. Symbols defined in fig. 4.

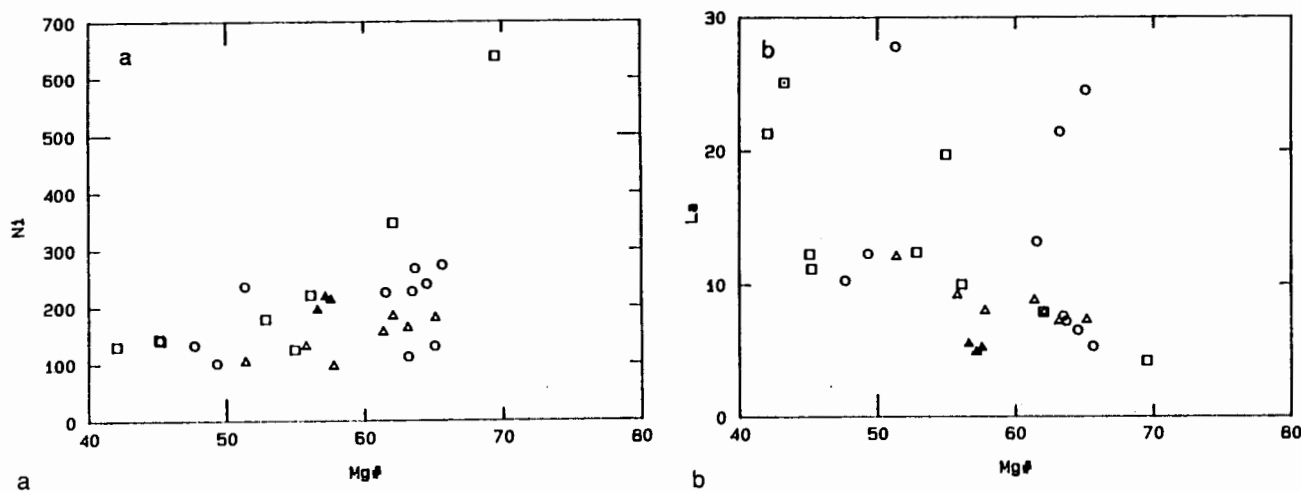


Figure 8. (a) Variation diagram of Ni (mg/kg) versus Mg number. (b) Variation diagram of La (mg/kg) versus Mg number. Symbols defined in fig. 4.

processes because some of the scatter in the data could have resulted from fractionation of cuttings in the wells or from alteration. For example, at least four of the Poersch cuttings fall below the trend established by other samples in the Al_2O_3 versus Mg number plot (fig. 7a). Also, gabbro cuttings from Poersch 2860–70 were analyzed over the same interval as the nearby OZ core gabbros (table 1). Most elements are fairly similar in the two sets of samples, although the TiO_2 and Rb contents are much higher and the Al_2O_3 content is lower in the cuttings than in the corresponding core samples.

The best candidate for a primitive magma formed by direct melting of the mantle would be the basalt at 3,720 ft (1,134 m) because it has high Mg number (0.68), high Ni (638 mg/kg) and Cr (233 mg/kg) concentrations, low incompat-

ible element concentrations, low K_2O content (0.12 wt %), low TiO_2 content (1.3 wt %), low REE concentrations (e.g., La = 4.2 mg/kg), and a slight positive Eu anomaly [e.g., see criteria by Roeder and Emslie (1970), Cox (1980), Prestvik and Goles (1985), and Basaltic Volcanism Study Committee (1981)]. The REE patterns do not show depletion of light REEs relative to the heavy REEs, as is seen in basalts from midocean ridges (fig. 9). Thus the primitive MRS basalt must have formed from mantle that was not previously melted (Basaltic Volcanism Study Committee, 1981; Green, 1982). These chemical characteristics are consistent with the primitive basalt at 3,720 ft (1,134 m) having been formed by partial melting (20–25%) of undepleted spinel peridotite at a depth of 30–40 km (Green and Ringwood, 1967; Basaltic Volcanism Study Committee, 1981; Green, 1982).

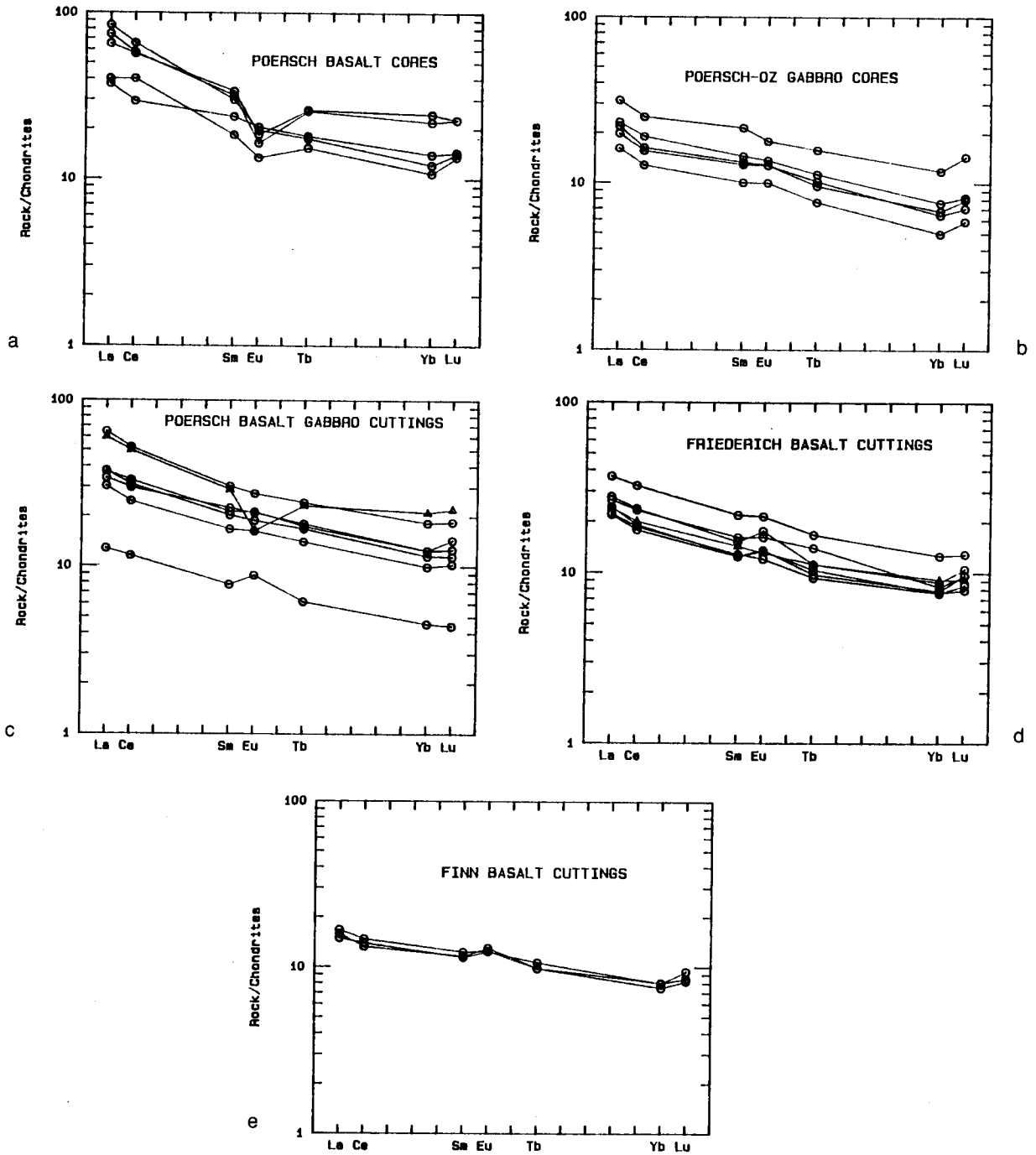


Figure 9. REE patterns of the mafic rocks in the Poersch, Friederich, and Finn wells obtained by normalizing to chondrites [chondrite values from Nakamura (1974)].

Table 2. Major weight percent element oxide and trace element (mg/kg) concentrations of the sedimentary rocks in the Texaco no. 1 Poersch and the Finn Wells.

Well, depth, rock type, and sample type ^a										
	Poersch 5,396 ft Arkose CO	Poersch 5,404 ft Siltstone CO	Poersch 7,153 ft Siltstone CO	Poersch 8,052 ft Arkose CO	Poersch 8,476 ft Siltstone CO	Poersch 9,160 ft Arkose CO	Poersch 9,170 ft Arkose CO	Poersch 10,513 ft Arkose CO	Finn (Fi-10) 2,330–60 ft Shale CU	Finn (Fi-11) 2,410–20 ft Shale CU
SiO ₂	59.8	60.3	56.2	71.7	57.5	71.9	70.5	71.3	60.3	55.1
TiO ₂	0.98	0.97	0.72	0.3	0.92	0.46	0.53	0.43	1.60	1.69
Al ₂ O ₃	16.0	16.0	13.4	12.9	17.9	12.2	13.2	13.0	14.8	14.3
Fe ₂ O ₃	5.76	7.76	6.42	2.37	8.73	3.03	3.43	3.13	6.95	6.82
MnO	0.081	0.077	0.074	0.031	0.079	0.031	0.041	0.027	0.04	0.09
MgO	3.50	3.52	2.48	0.55	3.59	0.44	0.84	0.53	4.34	3.65
CaO	1.48	1.48	8.62	2.56	1.05	2.62	3.21	1.63	1.55	5.32
Na ₂ O	3.31	3.42	3.18	3.32	2.53	3.95	3.50	4.86	1.93	1.88
K ₂ O	4.69	4.69	2.57	4.08	5.03	3.38	3.65	2.88	3.38	3.49
LOI ^b	5.17	2.48	6.80	2.23	3.00	1.77	1.60	1.14	4.92	6.83
Total	100.77	100.7	100.5	100.0	100.3	99.77	100.5	98.93	99.84	99.2
La	15.6	34.9	33.4	22.3	38.1	37.9	33.3	22.5	43.8	33.5
Ce	38.2	81.7	69.7	47.1	92.3	74.9	71.5	51.4	81.6	63.8
Sm	5.78	5.56	6.59	3.83	5.47	6.01	5.84	4.35	8.36	7.09
Eu	1.19	1.48	1.24	0.89	1.02	1.09	1.13	0.91	1.42	1.16
Tb	0.78	0.87	0.86	0.48	0.86	0.75	0.75	0.57	1.06	0.90
Yb	2.83	2.78	3.06	1.90	4.32	2.89	3.17	2.34	4.53	3.95
Lu	0.42	0.54	0.47	0.29	0.76	0.43	0.49	0.34	0.69	0.60
Σ REE ^c	101	183	165	115	201	176	172	121	210	169
(La/Lu) _{cn}	3.7	7.1	7.1	7.6	5.0	8.8	6.8	6.7	6.4	5.6
Rb	83	177	124	177	246	108	121	95	166	159
Ba	583	1030	531	739	879	653	671	557	391	356
Th	8.9	8.4	10.9	6.7	20.5	12.2	11.6	7.3	14.6	12.3
Hf	7.5	4.5	5.0	4.4	6.5	6.7	8.3	4.6	5.9	5.3
Ta	0.9	1.1	1.2	0.7	1.8	1.2	1.1	0.87	1.6	1.3
Co	7.9	33.1	23.0	5.4	21	4.1	7.7	5.8	23.7	20.1
Sc	10.0	21.8	14.2	4.6	22	5.6	6.8	6.6	18.2	15.1
Cr	58	57	57	20	94	27	32	27	93	75
Sr	77	65	95	113	22	119	292	86	48	100
Cs	.4	9.9	6.9	2.4	12.7	1.1	1.6	1.2	5.0	5.2
Nb	6.5	7.7	1	3	10	9	12	7.8	–	–
Y	33	26	38	22	37	31	26	26	–	–
Zr	315	150	180	183	225	272	285	155	–	–
Ni	18	47	47	12	52	9	11	20	27	17

a. CO, cores; CU, cuttings.

b. Loss on ignition.

c. Σ REE is 14 REE concentrations, including those estimated from chondrite-normalized curves.

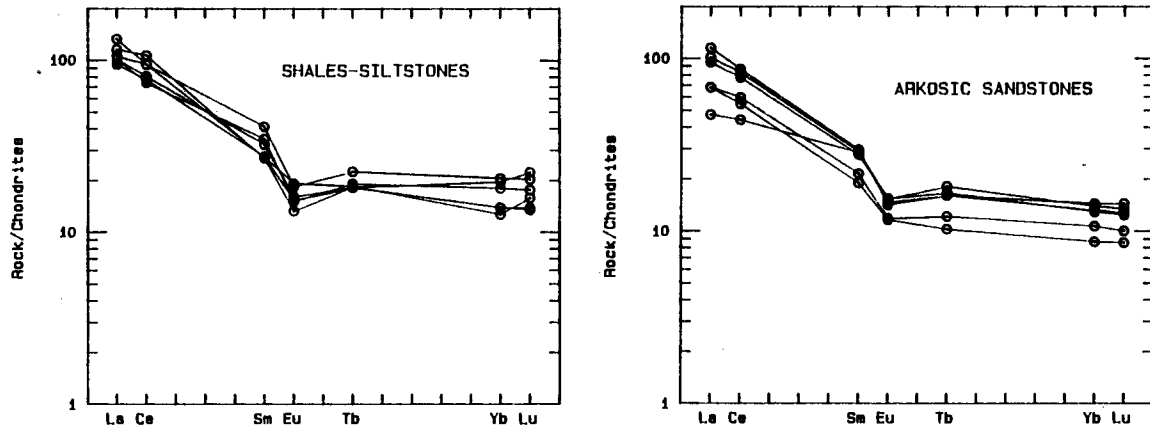


Figure 10. Chondrite-normalized REE patterns of sedimentary rocks in the Poersch and Finn wells.

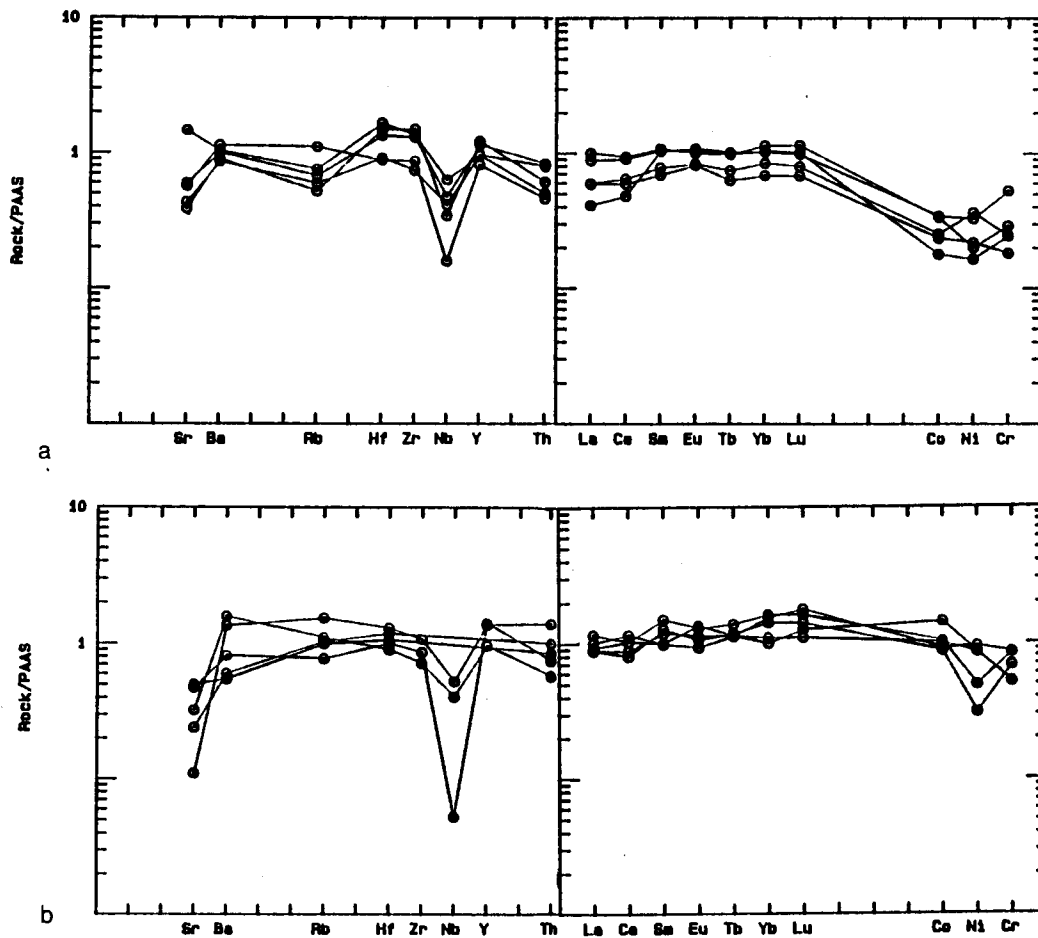


Figure 11. (a) Elemental concentrations of arkoses normalized to the PAAS. (b) Elemental concentrations of shales and siltstones normalized to the PAAS. Values for PAAS from Taylor and McLennan (1985).

Table 3. Comparison of the range of elemental compositions of the basalts in the southern MRS to those in the north

	Southern MRS (this study)				Range of all mafic samples (n = 28)	North Shore Volcanic Group, ^a range of mafic rocks (n = 17)	Osler Group tholeiites, ^b range of tholeiites (n = 14)	Mamainse Point lavas, ^c range of mafic rocks (n = 17)	Potato River Instrusion, ^d range of mafic rocks (n = 11)
	Gabbro cores (n = 5)	Basalt cores (n = 5)	Gabbro cuttings (n = 2)	Basalt cuttings (n = 16)					
SiO ₂	45.2-46.6	42-49.4	45.4-45.5	43-51	42.0-51.0	45.9-53.2	49.0-52.0	42.0-50.6	40.9-52.0
TiO ₂	1.06-2.24	1.2-2.2	2.8-4.1	1.3-3.5	1.06-4.1	0.72-4.9	1.13-3.02	0.70-3.74	0.46-3.5
Al ₂ O ₃	14.5-17.3	14.5-16.7	13.3-15.7	13.4-17.5	13.3-17.5	9.0-18.4	8.2-15.9	8.9-16.6	6.1-23.4
Fe ₂ O ₃ ^e	11.2-16.4	10.5-17.5	12.1-16.4	10.1-15.8	10.1-17.5	2.2-10.1	11.5-15.3		0.96-5.1
FeO ^e						3.0-14.2		8.3-16.4	3.5-23.3
MnO	0.13-0.24	0.19-0.36	0.16-0.27	0.14-0.26	0.13-0.36	0.11-0.24	0.14-0.24	0.12-0.30	0.05-0.33
MgO	6.79-9.71	7.0-9.5	6.2-9.0	5.1-13.8	5.1-13.8	2.3-11.7	3.7-12.3	3.4-17.0	2.9-19.7
CaO	7.61-10.9	2.7-8.4	8.6-8.9	5.6-11.8	2.7-11.8	4.8-12.4	6.9-13.8	7.0-11.6	4.8-11.7
Na ₂ O	1.65-2.48	2.8-5.7	2.0-2.3	1.4-5.2	1.4-5.7	1.6-5.4	1.2-3.9	0.68-3.94	0.86-3.75
K ₂ O	0.44-0.90	0.64-1.6	0.39-0.73	0.12-0.87	0.12-1.6	0.12-1.9	0.24-1.7	0.05-2.07	0.16-0.76
LOI or H ₂ O ⁺	1.25-4.17	2.8-5.3	3.1-3.5	1.9-4.0	1.25-5.3	1.2-3.3		2.53-10.52	0.87-2.8
La	5.3-10.3	12.0-28	7.9-11.2	4.2-21.0	4.2-28.0	2.9-68.0	10.7-45.2	4.1-47.5	
Ce	11.0-21.5	25-57	16.5-26	10.0-45	10.0-57	6.8-143	28-102	8.5-107	
Sm	2.04-4.35	4.8-6.8	2.7-4.6	1.6-6.2	2.0-6.8	1.5-15.0	3.9-10.4	1.4-11.0	
Eu	0.77-1.37	1.0-1.6	0.99-1.6	0.68-2.1	0.68-2.1	0.74-4.2	1.3-3.1	0.56-3.06	
Tb	0.36-0.74	0.72-1.2	0.5-0.85	0.29-1.1	0.29-1.2	0.34-2.3	0.61-1.2	0.25-1.36	
Yb	1.09-2.6	2.4-5.4	1.5-2.8	1.0-4.0	1.0-5.4	1.15-5.0	1.3-3.3	0.77-4.08	
Lu	0.20-0.49	0.46-0.77	0.27-0.49	0.15-0.63	0.15-0.77	0.17-0.74	0.18-0.50	0.12-0.59	
Rb	10.0-36	21-68	40-43	6.0-23	6.0-68	1.0-65	1.8-42.0	0.0-53	1.4-21.0
Ba	47-359	141-693	90-402	45-659	45-693	51-740		38-1223	51-232
Th	0.71-0.9	0.8-2.4	1.2-0.83	0.58-2.0	0.58-2.4	0.33-7.4		0.3-5.4	
Hf	1.6-2.5	2.6-5.2	2.3-3.0	1.2-5.1	1.2-5.2	1.1-10.9		1.1-7.8	
Ta	0.3-0.65	0.3-0.9	0.5-0.9	0.21-0.96	0.21-0.96	0.15-3.9		0.11-3.6	
Co	51-67	54-64	50-64	42-89	42-89	29-70		41-111	24-128
Sc	18-31	29-35	23-32	21-34	18-35	12.0-35		20-44	9.0-29
Cr	79-173	91-336	90-164	100-302	79-336	1-890	34-1385	16-2102	28-553
Sr	95-242	50-168	188-220	130-578	50-578	184-973	196-616	131-400	141-450
Cs	0.8-1.4	0.8-7.8	1.2-1.4	0.3-2.5	0.3-7.8	0.3-12			
Nb	4.5-7.0	4.0-11			4.0-11	3.0-49			
Y	11.0-32	24-53			11.0-53		6.7-19.0	1.9-62.0	0.2-27
Zr	50-95	113-242			50-242	40-412	16.7-34	8.6-49.0	2.0-53
Ni	133-273	101-236	141-347	95-638	95-638	60-270	22-280	34-352	1-246
								32-1234	27-678

a. Basaltic Volcanism Study Project (1981).

b. Lightfoot et al. (1991).

c. Klewin and Berg (1991).

d. Klewin (1990).

e. Fe₂O₃ (total) if no FeO is given; FeO (total) if no Fe₂O₃ is given.

Basaltic magmas with the chemical characteristics of the 3,720-ft (1,134-m) basalt could have been the parents of the rest of the basalts with lower Mg number (Basaltic Volcanism Study Committee, 1981; Klewin and Berg, 1991). The less primitive basalts contain successively lower Al_2O_3 , Ni, and Cr concentrations and higher Fe_2O_3 , TiO_2 , K_2O , REE, Ba, Hf, and Sc concentrations with decreasing Mg number than the 3,720-ft basalt. Also, the lower Mg number rocks tend to have more negative Eu anomalies than the higher Mg number rocks. In addition, Sr is anomalously depleted in Thompson (1982) plots (fig. 12). These trends are consistent with formation from a magma similar in composition to the basalt at 3,720 ft that crystallized plagioclase, olivine, pyroxene, or spinel (Phinney, 1970; Green, 1972, 1982; Annells, 1974; Weiblen and Morey, 1980; Basaltic Volcanism Study Project, 1981; Carlson and Hart, 1988; Klewin and Berg, 1991). Indeed, least-squares modeling of the average compositions of the basalts at different Mg numbers gives low residuals only if olivine, clinopyroxene, plagioclase, and spinel crystallize in a 0.24:0.20:0.53:0.03 ratio. Also, plagioclase crystallization results in lower Sr concentrations and more negative Eu anomalies in residual melts, whereas olivine and pyroxene crystallization results in lower Ni and Cr concentrations in residual melts. The large scatter in the data in variation diagrams is certainly not consistent with the differentiated rocks coming from a single homogeneous magma to form the range of basaltic compositions. Rather, there must have been a series of magmas formed over a long period of time, perhaps at different depths, that fractionated in a similar fashion (Brannon et al., 1979; Klewin and Berg, 1991). A similar conclusion that no single model, such as partial melting of a single source followed by fractional crystallization, can produce the range of data of the northern MRS samples was reached by Klewin and Berg (1991).

The absence of negative Nb-Ta anomalies or the presence of small negative Nb-Ta anomalies in most basalts (fig. 12) suggests that there has been little or only modest crustal contamination of the basalts (Carlson and Hart, 1988; Mahoney, 1988; Cox and Hawkesworth, 1985). Contamination of the basalts by silicic crustal melts should produce enrichment in Ba, Th, La, and Ce and depletion of TiO_2 and P in Thompson plots (Thompson et al., 1983; Marsh, 1989; Klewin and Berg, 1991). These characteristics are not observed in the basalts or gabbros (fig. 12); thus contamination by silicic melts is unlikely. Also, fractional crystallization rather than contamination is the most significant process for the observed elemental variation among the MRS rocks, as illustrated in a plot of Ce/Yb versus Mg number [fig. 13; after Lightfoot et al. (1991)]. Only Poersch sample 7159 has a significantly higher Ce/Yb ratio (fig. 13) than the other basalts; it also has the most negative Nb-Ta anomaly (fig. 11b). Thus sample 7159 may have had the most crustal contamination of any of the samples. Isotopic studies done on the uppermost gabbro sill suggest that crustal contamina-

tion was insignificant in that intrusion (Van Schmus et al., 1990). This gabbro also had no significant negative Nb-Ta anomaly, consistent with this conclusion.

Sedimentary rocks Sedimentary rocks of the northern MRS have been reasonably well studied (Catacosinos, 1981; Daniels, 1982; Kalliokoski, 1982; Merk and Jirsa, 1982; Morey and Ojakangas, 1982; Ojakangas and Morey, 1982; Elmore, 1984). They have been divided into three sequences (Weiblen and Morey, 1980; Green, 1982; Morey and Green, 1982; Weiblen, 1982). The oldest sequence consists of a prevolcanic suite of mature quartz-rich sandstones, suggesting stable cratonic deposition (Ojakangas and Morey, 1982). The second sequence of immature red bed sedimentary rocks is less voluminous. It consists of coarse-grained arkosic conglomerates to siltstones containing volcanic rock fragments interbedded with volcanic rocks (Ojakangas and Morey, 1982; Merk and Jirsa, 1982). The third sequence is mostly postvolcanic rift basin sedimentary rocks that become increasingly more mature and contain more material from outside the rift higher in the sequence (Daniels, 1982; Morey and Ojakangas, 1982; Van Schmus and Hinze, 1985). These rocks consist of conglomerate, sandstone, siltstone, and shale.

The interflow and postvolcanic sedimentary rocks of the Poersch well can, in general, be correlated with those in the northern portion of the rift. Their petrologic and mineralogic composition indicates that they are synrift deposits (Berendsen et al., 1988). This is also consistent with the observation that samples from the upper gabbro sill in the Poersch and OZ wells have a stable magnetic remanence that demagnetizes from shallow reverse inclination to steep reverse inclination and thus may correlate with the lower part of the Keweenaw Supergroup of the Lake Superior region (Van Schmus et al., 1990). The petrography and chemical composition of the abundant arkoses and minor siltstones are consistent with derivation from granitoids of the uplifted blocks adjacent to the rift. Thus erosion of the granitoid highlands must have been rapid enough and the volume large enough to overwhelm the debris formed from the local basalts. This interpretation is consistent with provenance studies of arkosic sedimentary rocks in the lower portion of the Poersch no. 1 well using U-Pb geochronology of detrital zircon and monazite, as their ages are 1.7–1.8 Ga, 1.4–1.5 Ga, and 1.1–1.2 Ga (Mark Martin, personal communication, 1992). This implies that the sedimentary rocks were derived from the older granitoid plutonic and metamorphic rocks (1,800–1,100 Ma) that occur on either side of the rift (Denison et al., 1984).

The style of tectonic activity in the southern MRS is similar to that observed to the north if indeed a high-angle reverse fault thrust the volcanic section in the Poersch well over the sedimentary section. In the northern MRS the early extensional phase of rifting was characterized by broad subsidence with mostly basaltic rocks and little or no sedi-

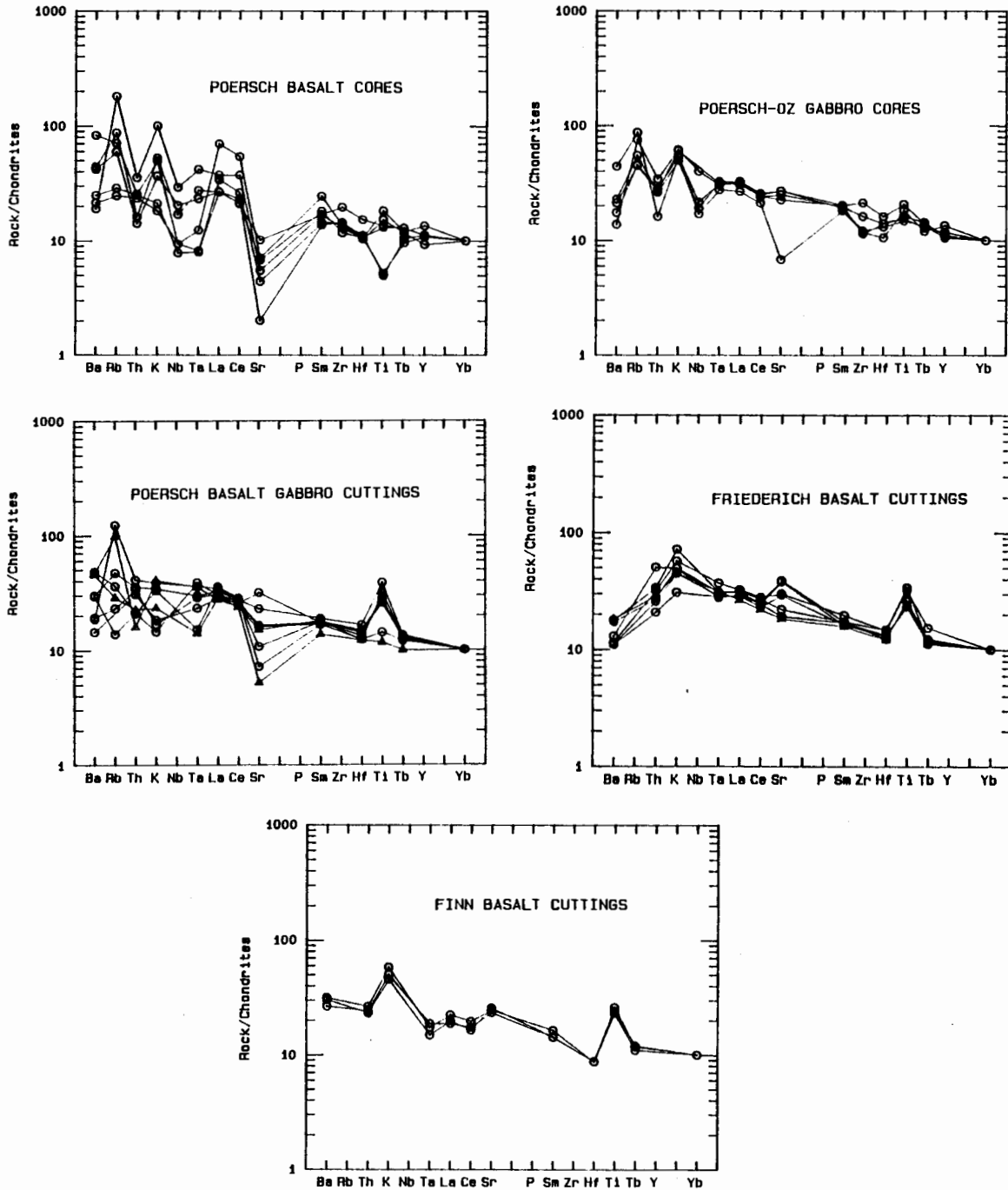


Figure 12. Spidergrams of the southern MRS basalts and gabbros [normalized after Thompson (1982)].

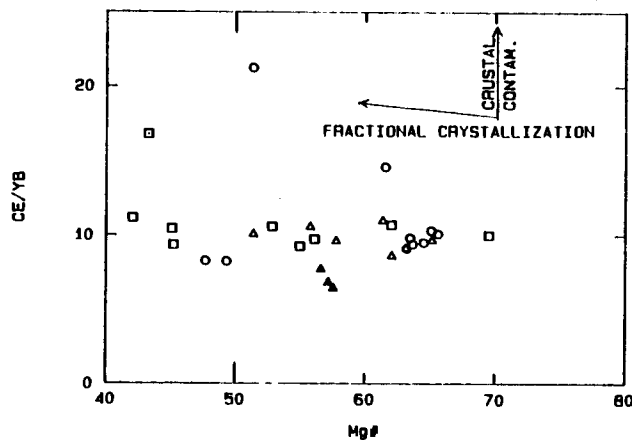


Figure 13. Variation diagram of Ce/Yb ratio versus Mg number [after Lightfoot et al. (1991)]. The trends predicted by contamination of melt by silica-rich rocks or by fractional crystallization are indicated by the arrows. Overall, most samples lie along a slightly increasing Ce/Yb ratio with decreasing Mg number, as expected by fractional crystallization. One basalt (Poersch 7159), however, contains an anomalously high Ce/Yb ratio.

mentary rocks, whereas in the later stages of rifting thermal collapse took place and thick sequences of clastic sedimentary rocks accumulated in the rift (Green, 1983; Behrendt et al., 1988; Cannon et al., 1989). North-northeast-trending high-angle normal and reverse faults are not uncommon along the trace of the rift in Kansas (Berendsen et al., 1989). Petrologic and mineralogic studies, including heavy mineral analysis on cuttings from available wells, indicate that rift development in northeastern Kansas followed a similar course to that in the northern portion of the MRS (Berendsen et al., 1989). Repeated movement on north-northeast-trending and northwest-trending faults, culminating in documented vertical displacement of several thousand feet during the Late Mississippian and Early Pennsylvanian, resulted in complex tectonic patterns that are often difficult to interpret.

Summary

Based on the available data, it is reasonable to assume that the stratigraphic succession at the Poersch and possibly the nearby OZ wells is interrupted by a high-angle reverse fault, causing younger sedimentary rocks to be placed stratigraphically beneath older mafic volcanic and intrusive rocks. The following scenario for the formation of early Keweenawan rocks is thus hypothesized in the vicinity of the Poersch well. The initial opening of the rift was characterized by the outpouring of at least 4,000 ft (1,200 m) of basalt with minor felsite and interflow siltstone. This event was followed by deposition of a minimum of 4,000 ft of arkoses

and siltstones, much of it derived from the rift shoulders. Seismic evidence indicates that a much thicker package of clastic sedimentary rocks was deposited in the subsiding basin (Serpa et al., 1984). Neither the tops nor the bottoms of the sections are exposed; thus the total thickness of the igneous and sedimentary sequence is unknown. A 265-ft-thick (80.8-m-thick) gabbro sill, dated at $1,097.5 \pm 3$ Ma, was intruded near the top of the volcanic sequence, and it is bounded by an unconformity separating it from the overlying Paleozoic sedimentary rocks.

The basalts and gabbros are subalkalic to alkalic and tend to follow tholeiitic trends, although a number of them are high-alumina basalts and thus have a chemical composition similar to mafic rocks in the MRS exposed to the north. The most primitive basalt could have formed by partial melting (20–25%) of a spinel peridotite at a depth of 30–40 km. Further fractionation of olivine, pyroxene, plagioclase, and spinel from magmas with a composition similar to that of the most primitive basalt could explain the chemical variation of the rest of the samples. The moderate scatter of the data in variation diagrams, however, precludes the differentiated rocks forming from a single magma. Rather, it is more likely that a series of undifferentiated magmas that were similar in composition formed at different depths. Fractional crystallization of similar minerals over a range of depths could have fractionated the primary magmas to produce the scatter in the observed variation diagrams.

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