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Geochemistry of Buried Midcontinent Rift Volcanic Rocks in Iowa: Data From Well Samples

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We analyzed well cores and cuttings from deep wells into Precambrian igneous rocks from five separate parts of the buried Midcontinent Rift System in Iowa for major and trace elements. A total of 21 samples, 9 cores and 12 cuttings, were analyzed for trace elements by instrumental neutron activation analysis (INAA) and 11 of these, 9 cores and 2 cuttings, were analyzed for major elements by inductively coupled plasma (ICP) analysis.

Incompatible trace element concentrations of the Iowa well samples, especially the relatively immobile rare earth elements, indicate most samples are basaltic in composition, although three samples appear andesitic in composition. Major element compositions and textures indicate that low-temperature weathering and/or high-temperature burial metamorphism effects are abundant and most samples are extensively oxidized and hydrated. A notable alteration feature is the almost total depletion of sodium, without an accompanying loss of other soluble elements, perhaps resulting from selective removal by solutions.

KEY WORDS: Precambrian Geology, Midcontinent Rift, Volcanic Rocks

The Midcontinent Rift System (MRS) is exposed around Lake Superior in southern Ontario, northern Minnesota, and Wisconsin, and extends beneath Phanerozoic sediments southwest through Iowa into Kansas (Fig. 1). Shorter arms extend southeast into Michigan and north into Ontario. The MRS lies between two Archean terranes in the Lake Superior region (Sims and Peterman 1983) and cuts across older Precambrian terranes including the Archean-Proterozoic boundary (Windom et al. 1993). Development of the MRS included two distinct phases. During the first phase, tensional stresses induced rifting, the subsidence of axial grabens, and mafic-dominated bimodal volcanism, estimated at a volume near 1×10^6 km^3 (Green 1982). Igneous rocks were emplaced quickly around 1.1 Ga (Paces and Miller 1993) in Mesoproterozoic time. The second phase was characterized by compressional stresses which reversed the downward movement of the grabens and produced axial horsts and flanking clastics-filled basins. These events were apparently contemporaneous with the Grenville Orogeny in northeastern North America, about 1000 km east of the MRS, although the peak of Grenville orogenic activity appears to have occurred about 1.03–0.97 Ga, during the second phase of MRS development. Together the MRS volcanics and clastic sedimentary rocks comprise the Keweenawan section, named for exposures on Keweenaw Point, Michigan, an area described during early copper exploration.

This study discusses the petrogenesis of the buried MRS volcanic rocks in Iowa from petrographic and geochemical data on well samples. The MRS volcanic rocks are not exposed at the surface in Iowa. Southerly portions of the MRS are known largely from geophysical data (Anderson 1992) augmented by a few studies of well samples. The rift is conspicuous on gravity and aeromagnetic maps, forming the pronounced midcontinent gravity high or midcontinent geophysical anomaly (Van Schmus and Hinze 1985) and is defined by a strong gravity high over the central basalts between deep gravity lows over the younger flanking clastic sediments. Samples of the rift in Iowa have been obtained from deep wells, including the 5,442 meter Amoco well in Carroll County that passed through a 4,299 meter section of Keweenawan clastic rocks (Ludvigson et al. 1990) adjacent to, but missing, the volcanic core. Earlier descriptions of some of the MRS volcanic well samples have been reported by Yoho (1967), Yaghubpur (1979) and Fischer (1982). In this study we have described and analyzed the Iowa MRS volcanic rocks for major and trace element compositions and compared these data with the North Shore Volcanic Group (NSVG) exposed in northeastern Minnesota.

IOWA MIDCONTINENT RIFT WELL SAMPLES

Well cores and cuttings from 24 deep wells sampling igneous rocks from five separate parts of the buried MRS in Iowa (Fig. 2) were obtained for study from material stored in the Iowa Geological Survey Bureau (DNR) core repository at Oakdale. The well samples are listed by Wnumber, the number used by the Iowa Geological Survey Bureau to access their stored well data. Seven of the 24 igneous samples are from cores and one of the 7 cores consists of three separate flow units that were each sampled, giving a total of 9 separate core samples studied. The other 17 samples are well cuttings obtained from the upper-most, and often weathered, portion of the covered MRS igneous rocks. Five of the cuttings contain too little Precambrian sample for any type of chemical analysis. The remaining 21 samples, 9 cores and 12 cuttings, were analyzed for trace elements by instrumental neutron activation analysis (INAA) and 11 of these, 9 cores and 2 cuttings, were analyzed for major elements by inductively coupled plasma atomic emission spectroscopy (ICP-AES or ICP) analysis (Table 1). Considerably more sample is required for a complete major element ICP analysis than is necessary for INAA of trace elements. Most of the samples are highly altered, by weathering, high-temperature alteration or both, often leaving little sign of the original mineralogy or texture.

Midcontinent Rift well samples are listed by increasing Wnumber as used by the Iowa Geological Survey Bureau core repository well record program (Table 1). Samples were taken from near the bottom

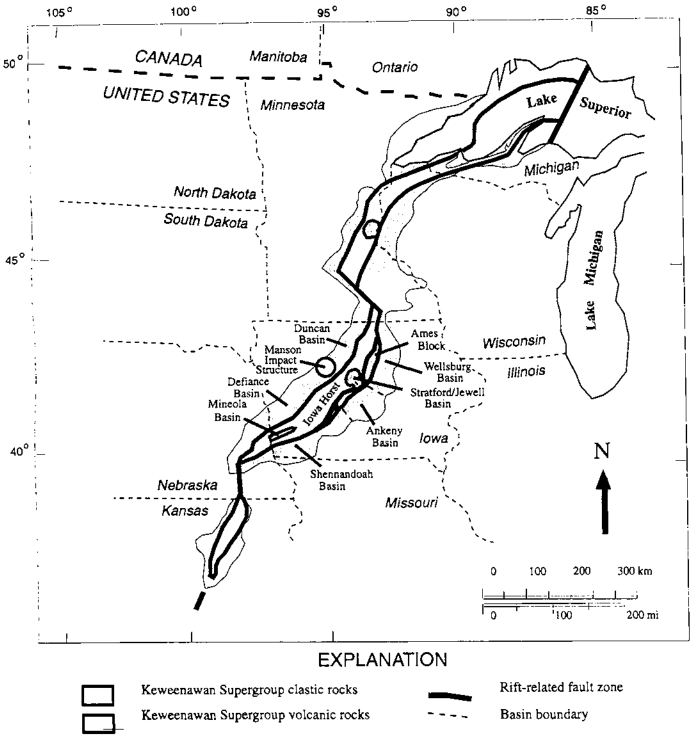

Fig. 1. Map of the large southwestern arm of the Midcontinent Rift showing the axial volcanics flanked by clastic sedimentary rocks. The dark lines between the volcanic horst and clastic basins are the faults responsible for elevating the slightly older central volcanics. Only the portion of rift around Lake Superior is exposed at the surface.

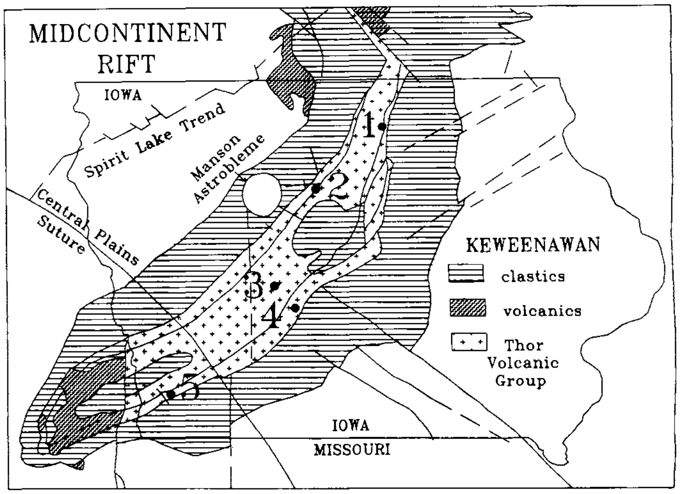

Fig. 2. Sample location map showing the five regions of the Iowa Midcontinent Rift from which the 21 analyzed well cores and cuttings have been obtained. Site 1—1 sample from Cerro Gordo County; Site 2—11 samples from Humboldt and Webster Counties; Site 3—2 samples from Gutherie County; Site 4—6 samples from Dallas County; Site 5—1 sample from Mills County. All five sites sample the Keweenawan Thor Volcanic Group of the Midcontinent Rift System. Most solid lines around and within the MRS mark faults rather than lithologic contacts. Precambrian geology modified from Anderson (1988; 1992).

of the well and as deep below the Precambrian surface as possible in order to avoid surface samples that have been strongly weathered. The five wells with insufficient cuttings for chemical analysis are not described in this report. All core samples and two samples of cuttings, Kinney A-1 and Knapp #3, contained sufficient sample for both INAA for trace elements and ICP for major elements. All other cuttings samples had only sufficient sample for INAA, which re-

Table 1. List of analyzed well samples from the Iowa Midcontinent Rift.

WNUMBER	WELL NAME	MAP SITE	DEPTH	SAMPLE	LITHOLOGY	MAJOR ELEMENTS	TRACE ELEMENTS
2971	Mason City #12	1	1580–1585′	cuttings	basalt	—	INAA
6365	Nelson #1	4	2833.3′	core	diabase	ICP	INAA
6579	Maher #1	4	2916′	core	andesite	ICP	INAA
6903	Hummell #1	4	2788′	core	diabase	ICP	INAA
11749	Peterson #1	2	2185′	core	altered basalt	ICP	INAA
15523	Sharp #1, Flow 1	2	2166′	core	altered basalt	ICP	INAA
15523	Sharp #1, Flow 2	2	2206.4′	core	altered basalt	ICP	INAA
15523	Sharp #1, Flow 3	2	2210.4′	core	altered basalt	ICP	INAA
16511	Nelson #9	4	2875–2880′	cuttings	basalt	—	INAA
16939	Anderson #1	2	2142′	core	andesite	ICP	INAA
17028	Olson #1	2	2385′	cuttings	basalt	—	INAA
17036	Hodgson #1	2	2200′	cuttings	andesite	—	INAA
17798	Sharp #3	2	2170′	cuttings	basalt	—	INAA
18670	Nessa #2	2	2220–2230′	cuttings	altered basalt	—	INAA
26322	Kinney, A-1	3	2355–2360′	cuttings	fresh basalt	ICP	INAA
26336	Morrison #1	2	2940′	cuttings	basalt	—	INAA
26580	Turner #1	4	2960–2970′	cuttings	basalt	—	INAA
26976	Knapp #3	4	2887′	cuttings	basalt	ICP	INAA
27206	Anderson #3	2	2210′	cuttings	basalt	—	INAA
27233	Coddington #3-24	5	3820–3823′	cuttings	basalt	—	INAA
27272	Finnegan, A-1	3	2702.5′	core	ophitic basalt	ICP	INAA

Table 2. Major element composition of Iowa Midcontinent Rift well samples; also recalculated dry.

WNUMBER	6365	6579	6903	11749	15523	15523	15523	16939	26322	26976	27272
WELL ADD.	NELSON	MAHER	HUMMELL	PETERSON	SHARP	SHARP	SHARP	ANDERSON	KINNEY	KNAPP	FINNEGAN
DESC.	#1	#1	#1	#1	#1 FLOW 1	#1 FLOW 2	#1 FLOW 3	#1	A-1	#3	A-1
SAMPLE	(core)	(core)	(core)	(core)	(core)	(core)	(core)	(core)	(cuttings)	(cuttings)	(core)
DEPTH	2833.3′	2916′	2788′	2185′	2166′	2206.4′	2210.4′	2142′	2355–2360′	2887′	2702.5′
SiO2	45.6	64.0	42.1	56.1	34.5	39.7	39.5	36.9	46.7	42.3	46.5
TiO2	1.88	4.50	1.40	1.68	2.59	1.80	1.53	3.09	1.45	1.67	1.69
Al2O3	16.9	18.7	14.8	14.3	23.9	16.3	16.7	28.0	16.5	16.0	16.1
Fe2O3	8.36	4.19	3.41	4.51	24.9	8.93	12.2	18.4	2.88	8.54	2.49
FeO	2.92	0.41	7.35	1.91	0.57	4.16	0.33	0.49	8.59	4.86	8.97
MnO	0.12	0.01	0.17	0.11	0.04	0.19	0.14	0.08	0.16	0.17	0.18
MgO	7.08	0.43	6.42	4.45	1.46	13.3	1.07	0.25	6.03	8.99	7.45
CaO	6.50	0.14	5.71	4.24	1.13	2.05	21.5	0.03	9.18	6.43	9.95
Na2O	3.55	0.01	3.87	0.19	0.22	2.99	0.17	0.04	3.24	0.08	2.37
K2O	0.66	1.31	2.89	5.80	1.45	1.50	0.30	0.05	0.66	2.36	0.27
P2O5	0.20	0.09	0.16	0.30	0.75	0.23	0.21	0.08	0.17	0.15	0.16
LOI	4.66	6.65	10.3	7.26	8.50	6.47	5.25	10.7	2.32	6.46	2.07
Total	98.43	100.44	98.58	100.85	100.01	97.62	98.90	98.11	97.88	98.01	98.20
SiO2	48.6	68.2	47.7	59.9	37.7	43.6	42.2	42.2	48.9	46.2	48.4
TiO2	2.00	4.80	1.59	1.80	2.83	1.97	1.63	3.54	1.52	1.82	1.76
Al2O3	18.0	19.9	16.8	15.3	26.1	17.9	17.8	32.0	17.3	17.5	16.7
Fe2O3	8.92	4.47	3.86	4.82	27.2	9.80	13.0	21.1	3.01	9.33	2.59
FeO	3.11	0.44	8.33	2.04	0.62	4.56	0.35	0.56	8.99	5.31	9.33
MnO	0.13	0.01	0.19	0.12	0.04	0.21	0.15	0.09	0.17	0.19	0.19
MgO	7.55	0.46	7.27	4.75	1.60	14.6	1.14	0.29	6.31	9.82	7.75
CaO	6.93	0.15	6.47	4.53	1.23	2.25	23.0	0.03	9.61	7.02	10.4
Na2O	3.79	0.01	4.38	0.20	0.24	3.28	0.18	0.05	3.39	0.09	2.47
K2O	0.70	1.40	3.27	6.20	1.58	1.65	0.32	0.06	0.69	2.58	0.28
P2O5	0.21	0.10	0.18	0.32	0.82	0.25	0.22	0.09	0.18	0.16	0.17
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

quires considerable less sample than is necessary for ICP of majors, loss on ignition (LOI) and ferrous iron. ICP analyses were performed at a commercial laboratory (Chemex) and INAA analyses were performed at the Missouri University Research Reactor in Columbia, Missouri.

The large majority of these Midcontinent Rift samples appear to have originally been basalts or diabases that have undergone one or more alteration processes. The least altered samples are compositionally similar to intermediate olivine tholeiites described by Brannon (1984) from the NSVG exposed north of Duluth along the shore of Lake Superior. Most other samples appear to have started with rather similar compositions and altered to their present compositions. One of the most characteristic signs of the alteration for these well samples, both cuttings and cores, is an almost total depletion in sodium. Descriptions of individual well samples are presented in Appendix A.

MAJOR ELEMENT GEOCHEMISTRY

All of the Midcontinent Rift well samples except three, Maher #1, Anderson #1 and Hodgson #1, are interpreted to have originally been basaltic in composition. However, extensive alteration has greatly modified the composition and texture of most samples, making primary rock type uncertain. To eliminate the diluting effect of high LOI contents, up to 10.7 wt.%, major element compositions have been recalculated on a dry basis (Table 2). On a dry basis five samples have SiO_2 in or near the range expected for basalts (47–51 wt.%), although six samples fall above and below the basalt range. Four badly weathered or altered samples have dry SiO_2 contents in the range 37–43 wt.%, too low for basalt and obviously depleted by alteration processes. Two samples have dry SiO_2 values far above the basalt range at 59.9 and 68.2 wt.%. These two samples, Maher #1 and Peterson #1, are also highly altered and contain abundant quartz crystals that make them very silica rich. However, Peterson #1 has the incompatible trace element composition of basalt and probably represents a highly altered basalt. Mayer #1 has much higher incompatible trace element concentrations and may represent a more evolved rock that is also highly altered, although its high Cr (258 ppm) is suspicious. The Anderson #1 thin section exhibits an undulating streaky layering which suggests it is a highly altered welded tuff with SiO_2 depleted (42.2 wt.% dry) by lateritic surface weathering. The Nelson #1 and Hummell #1 core samples are coarser grained samples that must represent massive flow interiors or perhaps intrusive rocks.

Weathering alteration should be common since most samples, all of the cuttings, represent the uppermost Precambrian erosion surface only covered by younger Phanerozoic sediments after a long hiatus. However, high-temperature alteration is at least equally common in these samples. The correlation observed between alteration and stratigraphic position in exposures of NSVG lavas along Lake Superior by Schmidt (1993) suggests that most of the high temperature alteration is due to burial metamorphism rather than hydrothermal effects during or shortly after eruption. Both types of alteration have caused extensive oxidation and hydration, and the removal of sodium from

Table 3. Trace element composition of Iowa Midcontinent Rift well samples in ppm.

WNUMBER WELL ADD. DESC. SAMPLE DEPTH	2971 MASON CITY #12 (MC12) (cuttings) 1580–1585′	6365 NELSON #1 (N1) (core) 2833.3′	6579 MAHER #1 (M1) (core) 2916′	6903 HUMMELL #1 (H1) (core) 2788′	11749 PETERSON #1 (P1) (core) 2185′	15523 SHARP #1 FLOW1 (SF1) (core) 2166′	15523 SHARP #1 FLOW2 (SF2) (core) 2206.4′	15523 SHARP #1 FLOW3 (SF3) (core) 2210.4′	16511 NELSON #9 (N9) (cuttings) 2875–2880′	16939 ANDERSON #1 (A1) (core) 2142′	17028 OLSON #1 (O1) (cuttings) 2385′
La	10.5	13.1	58.1	7.43	10.4	14.2	11.0	11.4	6.49	30.9	7.17
Ce	22.6	32.7	128	17.9	25.2	36.3	26.0	25.0	16.0	70.8	16.0
Nd	—	20.9	74.1	11.7	18.0	—	—	15.5	10.8	—	—
Sm	2.98	5.31	15.5	3.51	4.55	6.53	4.57	4.19	3.07	13.4	2.72
Eu	1.13	1.61	3.88	1.28	1.75	2.08	1.33	1.57	1.12	4.33	1.00
Tb	—	1.12	1.06	—	0.87	0.94	0.69	0.64	0.74	1.45	0.56
Yb	2.69	2.91	3.15	1.83	2.25	3.75	2.79	2.53	2.05	3.17	1.60
Lu	0.35	0.41	0.43	0.26	0.33	0.53	0.39	0.36	0.29	0.42	0.23
Sc	44.6	29.2	53.8	46.5	30.2	40.9	30.6	27.6	25.4	46.9	27.1
Co	36.8	47.5	16.6	42.8	72.6	200	62.9	4.92	70.5	15.3	46.7
Cr	95.8	99.4	258	19.8	123	139	147	124	122	168	247
Ni	—	84.2	—	—	131	621	130	61.5	209	76	197
Hf	1.86	3.85	5.62	2.23	2.76	4.76	3.93	3.55	2.81	6.24	2.23
Ta	0.36	0.76	0.87	0.38	0.50	0.92	0.66	0.59	0.58	1.13	0.36
Th	0.96	1.22	1.53	0.68	0.83	1.27	1.39	1.08	0.78	1.94	0.56
Sr	97.0	—	—	121	—	—	80.0	430	—	—	121
Rb	16.9	8.8	—	30.0	27.3	25.2	25.9	8.6	76.8	—	59.7
Cs	—	0.43	0.53	0.37	0.87	—	0.45	0.24	3.20	—	3.15
Ba	1208	—	—	269	52.2	—	430	—	—	—	—
Zr	—	107	175	—	63.6	89.4	92.7	91.5	69.5	187	—
Zn	129	123	—	141	128	474	269	—	80.2	—	99.1
Na	23565	23394	<174	25482	823	929	19637	191	1167	977	841

WNUMBER WELL ADD. DESC. SAMPLE DEPTH	17036 HODGSON #1 (Ho1) (cuttings) 2200′	17798 SHARP #3 (S3) (cuttings) 2170′	18670 NESSA #2 (N2) (cuttings) 2220–2230′	26322 KINNEY A-1 (K A-1) (cuttings) 2355–2360′	26336 MORRISON #1 (Mo1) (cuttings) 2940′	26580 TURNER #1 (T1) (cuttings) 2960–2970′	26976 KNAPP #3 (K3) (cuttings) 2887′	27206 ANDERSON #3 (A3) (cuttings) 2210′	27233 CODDINGTON #3-24 (C3) (cuttings) 3820–3823′	27272 FINNEGAN A-1 (F A-1) (core) 2702.5′
La	28.6	12.8	10.4	9.93	5.38	8.93	8.76	17.3	16.9	10.8
Ce	—	—	24.9	23.6	13.4	20.3	19.7	36.7	38.2	24.7
Nd	41.1	10.8	—	—	7.65	11.2	—	—	17.7	—
Sm	10.8	2.72	4.35	3.95	2.13	2.97	3.54	2.65	4.24	4.12
Eu	3.83	0.93	1.42	1.50	0.59	1.00	1.22	0.71	1.41	1.41
Tb	1.36	0.62	0.98	0.90	—	—	—	0.47	0.92	0.82
Yb	3.28	2.18	2.53	2.52	1.04	1.92	2.40	1.63	2.39	2.60
Lu	0.46	0.31	0.37	0.32	0.18	0.29	0.33	0.24	0.35	0.34
Sc	46.9	28.7	34.2	28.3	20.9	29.1	32.0	24.1	32.4	30.0
Co	39.2	66.8	72.8	49.0	64.9	31.0	67.0	126	55.3	54.4
Cr	196	140	184	144	101	147	166	134	93.7	141
Ni	215	158	—	83.2	246	81.8	184	187	146	106
Hf	4.40	4.89	3.47	3.18	2.12	2.78	3.03	3.01	3.28	3.29
Ta	0.79	0.84	0.67	0.47	0.42	0.47	0.44	0.48	0.54	0.54
Th	1.33	1.88	0.94	0.89	0.67	0.94	0.84	0.83	0.85	0.93
Sr	—	—	—	221	—	—	123	—	125	125
Rb	—	70.7	36.2	14.4	64.3	70.3	37.0	30.9	19.5	—
Cs	—	3.30	2.09	0.30	1.99	3.05	2.44	0.87	0.61	0.36
Ba	—	222	—	137	99.8	—	—	—	191	133
Zr	126	109	90.2	101	74.4	61.8	—	—	88.1	70.2
Zn	171	134	127	117	76.2	70.0	119	188	125	122
Na	612	4387	1802	21149	3010	771	515	1289	21841	15953

Table 4. Major and trace element composition of the North Shore Volcanic Group rock types from Brannon (1984).

	PRIMITIVE THOLEIITE (P)	INTERM. THOL (IOT)	BASALT. ANDESITE (BA1)	FE-RICH THOL (FOT)	QUARTZ THOL (QT)	TRANS BASALT (T)	BASALT. ANDESITE (BAII)	ANDESITE (A)	FERRO-ANDESITE (FA)	INTER-QT LAT (IQL)	RHYOLITE (R)
SiO2	49.5	48.1	52.8	47.5	51.8	47.4	53.8	52.3	57.2	66.3	72.5
TiO2	0.8	1.71	1.04	2.33	1.57	2.96	1.79	2.71	1.9	0.99	0.43
Al2O3	18.2	16.8	16.4	16.2	15.4	14.7	15.2	13.6	12.0	12.3	12.3
FeOt	8.37	12.2	9.18	14.0	11.5	15.7	10.9	13.8	16.0	8.47	4.7
MnO	0.13	0.16	0.17	0.2	0.18	0.22	0.17	0.24	0.3	0.17	0.06
MgO	8.83	6.98	7.16	6.36	6.24	5.65	5.08	5.19	2.35	2.0	0.1
CaO	11.4	10.9	9.54	10.0	9.58	9.52	7.83	5.85	2.84	1.62	0.64
Na2O	2.38	2.48	2.87	2.53	2.7	2.15	3.14	3.53	3.53	3.74	3.01
K2O	0.19	0.28	0.58	0.49	0.66	0.81	2.08	2.13	2.96	4.01	6.1
P2O5	0.06	0.17	0.1	0.24	0.16	0.32	0.2	0.34	0.61	0.28	0.02
La	4.16	10.6	12.1	15.0	16.4	18.6	23.6	36.6	73.2	91.0	153
Ce	10.3	25.5	25.1	36.2	38.4	44.1	54.8	85.2	172	208	330
Sm	1.91	4.32	3.34	5.72	5.46	6.94	6.52	11.3	23.4	24.9	33.4
Eu	0.83	1.46	1.18	1.86	1.58	2.22	1.84	2.78	5.54	4.68	4.15
Tb	0.41	0.91	0.56	1.16	1.03	1.35	1.25	2.06	4.41	4.63	5.78
Yb	1.38	2.54	1.83	3.17	3.38	3.72	3.59	5.8	11.6	13.3	17.7
Lu	0.21	0.39	0.28	0.47	0.51	0.58	0.54	0.89	1.84	2.08	2.56
Sc	26.9	31.5	26.1	32.3	33	38.2	27.4	31.8	31.1	13.5	6.5
Co	48.8	54	42.6	55.7	52.1	54.5	39.4	40.1	12	6.8	0.8
Hf	1.37	3.3	2.6	4.63	4.76	5.78	6.09	10.3	22.5	26.5	31.2
Ta	0.16	0.57	0.37	0.87	0.72	1.16	1.06	2	4.09	5.15	6.58
Th	0.26	1.09	1.74	1.68	2.8	2.1	3.77	6.1	10.9	16.6	26.3
Ni	277	270	150	150	88	130	81	89	105	84	—
Cr	361	280	291	185	129	145	149	53	11	8.8	1.7
Ba	58	113	191	174	269	242	445	531	730	931	924
Cs	0.1	0.09	0.14	0.39	—	2.7	0.9	10.7	1.5	1.62	2.4
Rb	4	6	11.6	8.2	13.4	22.1	45	92	110	140	181
Sr	207	209	215	211	178	174	270	287	121	92	15

many samples serves as an indicator of the extensive alteration (Table 3). The extensive loss of sodium without an accompanying loss of other soluble elements during alteration is unusual and must reflect a selective dissolution in the deeply buried flows. Both cores and cuttings are Na depleted from this portion of the MRS. Two samples, the Sharp #1 flow 1 core sample and the Anderson #1 core sample, exhibit unusually high abundances of TiO_2 and Fe_2O_3, high Fe_2O_3/FeO ratios, and high LOI abundances indicating large scale removal of the more soluble components, including SiO_2. This chemical pattern indicates lateritic weathering with alternating wet-dry seasons to remove silica. Many other samples contain epidote, actinolite or other minerals indicative of high-temperature alteration, perhaps caused by burial metamorphism. Usually Na and occasionally Ca is removed by this process but high-temperature Ca metasomatism of flow #3 of the Sharp #1 core sample produced abundant epidote and increased CaO to 23 wt.% calculated on a dry basis. Flow 2 of Sharp #1 has gained Mg (14.6 wt.% dry) and Na (3.28 wt.% dry) during alteration, apparently supplied from saline solutions, which is compositionally distinct from typical surface weathering changes. The composition of the three highly altered flows from the Sharp #1 well are very different, representing three distinct alteration mechanisms.

The two least altered samples from the MRS in Iowa are the Kinney A-1 well cuttings and the Finnegan A-1 core sample, both from Gutherie Country map Site 3 (Fig. 2). These two Gutherie County samples have major and trace element compositions similar to intermediate olivine tholeiites (IOT) analyzed by Brannon (1984) from the NSVG (Table 4). Both samples have low LOI contents (1.07 and 2.32 wt.%), low Fe_2O_3/FeO ratios (0.28 and 0.34), low TiO_2 contents (1.52 and 1.76 wt.% dry), and normal basalt SiO_2 contents (48.9 and 48.4 wt.% dry).

TRACE ELEMENT GEOCHEMISTRY

Most of the Iowa MRS samples have incompatible trace element concentrations typical of basaltic rocks and similar to the NSVG IOT (Table 4). The Iowa MRS incompatible trace element concentrations more closely match NSVG basalt concentrations than do the compatible trace elements Ni and Cr, which typically have lower concentrations in the Iowa MRS rocks. Geochemically the NSVG are the most thoroughly studied Keweenawan MRS volcanics (Brannon 1984; Dosso 1984) and they exhibit a wider variation of rare earth element (REE) concentrations (Fig. 3a) than do our Iowa MRS rocks (Fig. 3b). Most of the Iowa MRS rocks are similar to the NSVG basalts with low La concentrations (La from 5 to 17 ppm), REE patterns inclined gently from light REE (LREE) to heavy REE (HREE), giving a slight LREE/HREE enrichment, and either small negative Eu anomalies or no Eu anomalies. The two least altered Iowa MRS rocks, Kinney A-1 and Finnegan A-1, have REE patterns almost identical to NSVG IOT (Fig. 3c). The relative immobility of the REE is illustrated by highly altered Iowa sample, Sharp #1, flow 3, which has an unaltered appearing REE pattern similar to NSVG IOT that is in marked contrast to its highly altered major element

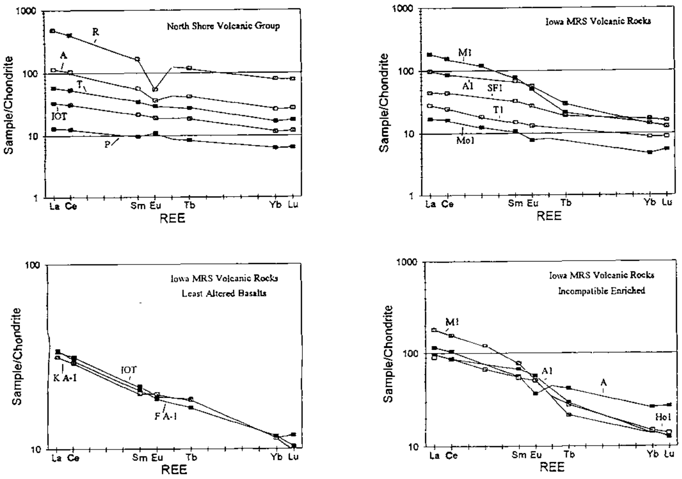

Fig. 3. Chondrite normalized REE diagrams of samples from the NSVG and the Iowa MRS. a. Total range of REE patterns for average NSVG rocks (Brannon, 1984) from Table 4; b. Total range of REE patterns for Iowa MRS rocks from Table 3; c. Comparison of the REE patterns of the two least altered MRS samples, K A-1 (Kinney A-1) and F A-1 (Finnegan A-1), with the average NSVG IOT basalt; d. Comparison of the REE patterns of the three most incompatible trace element rich samples, Ml (Maher #1), Al (Anderson #1), and Hol (Hodgson #1), with the average NSVG andesite (A). Normalization values are from Cl chondrites (Anders and Grevasse 1989) and multiplied by 1.36 to maintain consistency with the older ordinary chondrite normalization values.

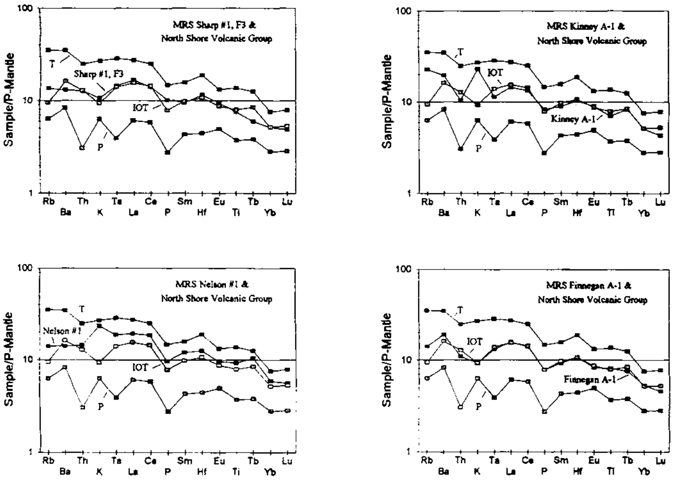

Fig. 4. Comparison of spidergrams for the four Iowa MRS samples, Sharp #1 flow 3, Nelson #1, Kinney A-1, and Finnegan A-1, most similar in incompatible element content to NSVG IOT. The Iowa MRS well samples are shown by dark squares whereas NSVG IOT is shown by light squares. All samples have been normalized to primitive mantle (P-Mantle) using values from Sun and McDonough (1989) and a modified elemental sequence from Seifert and Brunotte (1996).

Table 5. Mineral compositions in Nelson #1 and Hummell #1 cores.

	NELSON PUMP-ELLYITE	NELSON EPIDOTE	NELSON ALBITE	HUMMELL ALBITE
SiO2	37.5	37.3	67.5	66.9
TiO2	0.02	0.07	0.01	—
Al2O3	27.2	23.5	20.2	20.7
FeOt	5.73	14.2	0.33	0.13
MnO	0.22	0.08	—	—
MgO	4.97	0.86	0.28	0.11
CaO	20.3	22.7	0.29	1.20
Na2O	0.03	0.05	10.9	10.6
K2O	0.31	0.04	0.27	0.36

Table 6. Average mineral compositions in the lower unaltered layer of the Finnegan core sample from Fischer (1982).

MINERAL NO. ANALY-SES	LABRA-DORITE (32)	AUGITE (36)	ILMENITE (13)	MAGNE-TITE (3)
SiO2	54.0	52.9	0.99	0.97
TiO2	0.09	0.92	49.1	7.40
Al2O3	28.5	1.65	0.48	2.81
FeOt	1.16	10.8	50.5	85.3
MnO	0.06	0.22	1.81	0.42
MgO	0.17	15.5	0.18	0.30
CaO	12.7	19.3	0.22	0.18
Na2O	4.51	0.07	0.08	1.08
K2O	0.28	0.11	0.01	—
Cr2O3	0.08	0.26	0.06	0.32

composition and modal mineralogy. The only three Iowa MRS well samples, Maher #1, Anderson #1 and Hodgson #1, with significantly higher total REE concentrations, La from 29 to 58 ppm, and REE patterns with slightly inclined LREE and HREE separated by steeply inclined middle HREE, are more similar to the REE concentration of the average NSVG andesite (Fig. 3d), although they have lower HREE concentrations. Most of the Iowa MRS samples have REE patterns similar to IOT and appear to have had a basaltic composition prior to alteration, with the REE remaining unchanged by the later alteration. Similar REE patterns are found in buried Keweenawan basalts from Nebraska (Marchall and Lidiak 1996). It is interesting to note that the average Iowa MRS rock, and NSVG IOT, has an REE pattern similar to the average enriched mid-ocean ridge basalt (E-MORB), using values from Sun and McDonough (1989).

Only a few of the Iowa MRS well samples have any incompatible trace elements that are enriched relative to those considered typical of basaltic rocks, despite the large variations in major element compositions. Of the two Iowa well samples with high SiO_2 contents, only Maher #1, with SiO_2 = 68.2 wt.% dry, has the correspondingly high concentrations of incompatible trace elements expected of an evolved nonbasaltic rock. The second highest SiO_2 rock, Peterson #1 with SiO_2 = 59.9 wt.% dry, has the incompatible trace element abundances expected of basalt and probably is a highly-altered basalt. The Anderson #1 core sample, with an unusually low SiO_2 content, has the texture of a welded tuff and a high incompatible trace element content similar to NSVG andesite. Among the cuttings with no major element analyses, only Hodgson #1 has an incompatible trace element content that is significantly higher than that expected for basalt. Four of the Iowa MRS basaltic rocks that show the most regular spidergram patterns are compared to selected average NSVG rocks (Table 4) to look for additional small degrees of alteration not obvious from the data but visible in spider diagrams (Fig. 4). The four samples with the cleanest appearing spidergrams are; Sharp #1, flow 3, Nelson #1, Kinney A-1, and Finnegan A-1. All four of these samples have spidergrams similar to NSVG IOT, as expected from the REE plots in figure 3. However, two of the samples, Nelson #1 and Finnegan A-1, show enrichment in K, whereas the other two samples, Sharp #1, flow 3, and Finnegan A-1, do not show enrichment in K relative to the REEs and high field strength elements (HFSEs) on their spidergrams. The Kinney A-1 sample also shows strong enrichment in Rb and Ba. Enrichment in K, and other large ion lithophile elements (LILEs), relative to the REE and HFSE is typically attributed to mobility of the LILE in hydrous solutions relative to the REE and HFSE, which are relatively insoluble in hydrous solutions.

DISCUSSION

Most of the Iowa MRS samples are basalts, but with highly altered major element compositions and less altered trace element compositions caused by secondary high- and low-temperature alteration events. High-temperature alteration is similar to that attributed to burial metamorphism in deeply buried portions of the NSVG flows in Minnesota (Schmidt 1993). She reported widespread albitization of plagioclase, similar to that observed in the Nelson #1 and Hummell #1 cores, by burial metamorphism in lower portions of the NSVG, with increasing removal of Ca from plagioclase with depth. The prevalence of high-temperature alteration with albitization indicates most of the basalt flows now exposed at the Precambrian surface in Iowa correlate with the deeper portion of the NSVG flows along the north shore of Minnesota. The presence of abundant epidote, along with actinolite, pumpellyite, chlorite and relatively pure albite with a composition of An_5, indicates some of the Iowa rocks correlate with the lowermost part of the NSVG sequence buried to depths estimated at 7 to 8 km (Schmidt 1993). The relatively unaltered Guthrie County basalts from map Site 3 (Fig. 2) represent far less deeply buried flows that escaped the extensive burial metamorphism observed in many of the Iowa MRS samples. The Knapp #3 and Coddington #3-24 samples appear to have undergone deep burial metamorphism followed later by surface weathering.

The low-temperature surface weathering of the dominantly subaerial MRS flood basalts (Green 1982) can be attributed to prolonged exposure on the Precambrian surface. The tropical lateritic weathering required for the removal of silica agrees with the suggested position of Iowa near the equator at the end of Precambrian time. Perhaps the most interesting alteration patterns are those exhibited by the lower two Sharp #1 flows. Both flow 2 and flow 3 have compositions that would normally be attributed to ocean floor hydrothermal alteration. The presence of saline waters in wells drilled into the deep Midcontinent Rift (Morton and Ameel 1985) may provide a source of the salts necessary to explain these alteration patterns. The abundance of epidote in flow 3 indicates high temperatures and deep burial whereas the alteration pattern of the upper two flows indicates near surface processes that must have occurred later after considerable uplift. There is increasing evidence for the existence of saline solutions deep in the earth's crust and saline groundwater is found everywhere in the Canadian Shield at depths below 1 km (Fritz and Frape 1982). The presence of saline solutions with chlorine, sodium, and calcium in wells into the MRS (Morton and Ameel 1985) might explain some of the alteration features observed in these rocks. The presence of solutions is required to produce the hydrous metamorphic minerals that have replaced primary anhydrous igneous mineral during burial metamorphism in deeply buried MRS rocks. It seems likely that these same solutions could be responsible for the widespread removal of Na from these highly-altered rocks, making the solutions saline or more saline. The suggested presence of pure authigenic potash feldspar in the Peterson #1 core would indicate solutions were acidic, but observed saline solutions in the NSVG are typically basic (Morton and Ameel 1985). Some of the severely altered Iowa samples are characterized by an abundance of opaque minerals that suggests extreme concentration by removal of other components.

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APPENDIX A

Description of individual Iowa Midcontinent Rift well samples in order of increasing Wnumber as listed by the Iowa Geological Survey Bureau core repository well record program Table 1). The depths listed for well cuttings and core samples typically correspond to near the bottom of the well, which may reach ten to twenty meters below the depth at which the Precambrian Midcontinent Rift basement was first encountered.

Wnumber 2971—Mason City #12, 1580–1585′ depth well cuttings from map Site 1 (Fig. 2)—The cuttings from this well form a gray powder when crushed for INAA analysis. Insufficient sample was available to analyze for major elements. No thin section was prepared for this sample, but examination of the cuttings under the binocular microscope indicate it is a typical gray basalt. The chondrite normalized REE pattern is straight, inclined downward from La to Lu, typical of the NSVG basalts (Basaltic Volcanism Study Project 1981; Brannon 1984). The Mason City sample is one of only seven Iowa Precambrian samples in this study that is not depleted in Na (23565 ppm) by alteration (Table 3).

Wnumber 6365—Nelson #1, 2833.3′ depth core sample from map Site 4 (Fig. 2)—The Nelson core sample is a red and green altered diabase with pockets of quartz and epidote. Plagioclase is red and the altered mafics are green; no trace of the original mafics remains. Plagioclase comprises 60–70% of the rock and is badly saussuritized, although igneous twinning and zoning are still visible in some crystals. Microprobe traverses indicate that Ca has been removed from the plagioclase to produce albite, although no recrystallization has occurred. The original mafic minerals have been completely replaced by pumpellyite, epidote, fibrous minerals and opaque minerals (Table 5). Opaque minerals now make up about 3% of the rock and are usually associated with the fibrous mineral and minor amounts of hematite.

Epidote occupies isolated corners of the quartz pockets, and is typically fine grained, although coarse crystals occur. Quartz ranges from fine grained near pocket walls to much coarser in pocket centers. Sometimes the small quartz along pocket walls forms elongated crystals perpendicular to the walls. This alteration assemblage results from high temperatures, perhaps burial metamorphism, rather than low temperature weathering. As with all core samples, both major elements (ICP) and trace elements (INAA) were analyzed (Tables 2 and 3).

Both oxidation and hydration reactions have changed the composition of this sample (Table 2). The Fe_2O_3/FeO ratio (2.87) is higher than expected for diabase indicating oxidation during alteration. LOI is 4.66 wt.% which could largely represent water added to change the anhydrous primary mineral assemblage to an hydrous alteration assemblage. Na_2O is high (3.79 wt.%) but other soluble components are not; K_2O is 0.70 wt.% and Rb (Table 4) is 8.8 ppm. Ca is low relative to Na, perhaps because it was lost during the plagioclase conversion.

Wnumber 6579—Maher #1, 2916′ depth core sample from map Site 4 (Fig. 2)—This reddish strongly altered, crushed and sheared rock with a shiny sheared surface luster may have originally been a granodiorite or some similar rock. Relict stretched and fractured opaques appear too large for a volcanic rock, suggesting an origin as an intrusive rock or massive flow center. Many quartz crystals, large and small, have either been introduced after the deformation by hydrothermal solutions or represent residual concentrates and further obscure the origin of this rock. The quartz and deformed opaques are the only identifiable minerals observed in thin section. Microprobe analysis of quartz-rich regions reveals that fine particles of altered potash feldspar going to clay minerals are mixed with the pockets of quartz.

The major and trace element composition (Tables 2 and 3) of this core sample suggests the original rock had an andesite composition rather than a basaltic composition. However, alteration is so intense no definite conclusion is possible. Perhaps the presence of fine altered potash feldspar is the strongest evidence for an evolved parentage rather than a basaltic origin. Or perhaps the abundant silica and some potash were introduced by hydrothermal solutions in the manner suspected for the Peterson #1 core sample. SiO_2 is 68.2 wt.% dry and iron is relatively low, although alteration may have removed some iron as it has removed CaO and Na_2O during the destruction of the primary plagioclase that must have been present. The LOI is probably in the hydrous clay minerals forming from spotty remnants of potash feldspar. The Na content is so low that INAA can only indicate it to be less than 174 ppm. The REE content and pattern are consistent with NSVG andesitic values rather than lower basaltic values, although the high Cr value (258 ppm) is difficult to explain, but could result from residual concentration.

Wnumber 6903—Hummell #1, 2788′ depth core sample from map Site 4 (Fig. 2)—The Hummell core is a red and dark green altered diabase similar in appearance to the Nelson #1 core sample but coarser grained. The red plagioclase is slightly more abundant than the green mafic mineral mixtures, with the ratio ranging from 50–60% plagioclase to 50–40% mafic minerals. Crystal size typically ranges from 2 mm to 6 mm with plagioclase crystals being tabular and mafic minerals equidimensional. In thin section the plagioclase is oxidized and saussuritized and the mafic mineral(s) are totally uralitized to amphibole, chlorite and epidote, producing the unusual color in a diabasic rock. The alteration is high temperature, perhaps burial metamorphism, rather than a low temperature weathering alteration. Both major and trace elements were analyzed (Tables 2 and 3).

Mafic minerals are often interstitial to the larger cumulus plagioclase crystals. Although plagioclase appears moderately altered it has an elongated lath morphology and exhibits complex igneous twinning, with many Carlsbad growth twins, similar to labradorite in basalt. However, optical angles taken perpendicular to the crystallographic a axis indicate a composition near An_5. Microprobe study confirms that Ca has been removed from the plagioclase to produce albite near An_5 (Table 2), similar to plagioclase from the Nelson #1 core sample. No recrystallized plagioclase was observed. Chloritic portions of mafic mineral intergrowths occasionally exhibit spherulitic patterns with progressive extinction. In addition, the rock contains approximately one percent complex opaque skeletal crystals and long apatite needles.

The major element analysis (Table 2) includes 10.3 wt.% LOI indicating extensive hydration, although little oxidation is evident. The Fe_2O_3/FeO ratio of 0.46 indicates that the high temperature alteration of this diabase was far less oxidizing than the alteration which has affected most samples. When the major element composition is recalculated dry to eliminate the diluting effect of 10.3% LOI hydration on sample composition, both Na_2O and K_2O values are too high for a diabasic rock. Na is very high relative to Ca, perhaps because of the plagioclase conversion to albite. The unusual composition and degraded mineralogy of this sample is similar to that produced by spilitization. Perhaps aqueous solutions accompanying burial metamorphism carried soluble components into the diabase since Rb (Table 3) is also very high (30 ppm). The less soluble elements, REE and high field strength elements (HFSE), have the expected concentrations for a diabase.

Wnumber 11749—Peterson #1, 2185′ depth core sample from map Site 2 (Fig. 2)—This core consists of reddish-brown highly altered amygdaloidal basalt with the sparse vesicles filled with zeolites. Only fine scattered opaque minerals can be recognized in thin section, brownish fine-grained material covers the remainder of the rock except for abundant scattered quartz, potash feldspar and altered potash feldspar going to hydrous clay minerals.

This rock has an unusual composition with high K_2O and very low Na_2O (Tables 2 and 3). The soda depletion is typical of altered samples but the enrichment of potash is unusual. The abundant hydrous clay minerals could explain the LOI value of 7.26 wt.% whereas the quartz and altered potash feldspar would appear to explain the enrichment in SiO_2 (56.1 wt.%) and K_2O (5.80 wt.%). However, the strong depletion of Na_2O (0.19 wt.%) indicates the potash feldspar is an unusually pure potassium variety. The unusually pure potassium feldspar, combined with relatively low values of Rb and Ba (27.3 and 52.2 ppm), suggests growth of pure authigenic potash feldspar from acidic saline solutions (Long and Lyons 1992). The high silica value could be due to residual concentration or introduction with potash from the saline solutions. Despite intense alteration, the REE pattern and incompatible trace element concentrations are typical for basalt, suggesting incorporation of these elements in growing alteration minerals rather than removal, and suggesting this rock is a highly altered basalt.

Wnumber 15523—Sharp #1, 3 samples of 3 flows from map Site 2 (Fig. 2)—Flow 1, 2166′—This is a reddish flow of highly altered basalt. A primary basaltic texture remains visible in hand specimen with the aid of a hand lens, but the basalt is now totally altered with selective removal of the more soluble elements. In thin section only opaque minerals and a fine grained material remain visible, the primary minerals have been totally altered. The opaque minerals have 0.3 to 0.4 mm diameters which may be their primary crystal size. Both major elements and trace elements were analyzed in all three flows (Tables 2 and 3).

The composition of flow 1 indicates that alteration has increased the concentration of insoluble elements, such as Ti, Fe, Al, Ni, and the REE, relative to soluble elements, such as Mg, Ca, and Na. However, Si and Mn have also been removed whereas K, Rb, and P appear to be slightly concentrated. Highly soluble K and Rb must have been incorporated or adsorbed by one of the new minerals being formed to prevent their removal, otherwise they should have been removed with the other soluble elements. These chemical changes were accompanied by strong oxidation with the Fe_2O_3/FeO ratio now at 43.7 and considerable hydration with LOI at 8.5 wt.%. These chemical changes are consistent with lateritic surface weathering if it occurred under tropical conditions with alternating wet and dry seasons to remove silica.

Flow 2, 2206.4′—This is a darker basalt flow than flow 1, but it still has a reddish-brown tint that suggests oxidation. In thin section relict plagioclase laths are visible, but highly altered, among the opaque minerals and other fine grained material. The relative elemental change pattern is similar to that of flow 1 but with some significant differences.

The composition of flow 2 (Tables 2 & 3) suggests removal of Si, oxidation (Fe_2O_3/FeO = 2.15) and hydration (LOI = 6.47 wt.%) similar to that in flow 1, but less pronounced. In contrast to flow 1, both Mg and Na have increased relative to other elements. The addition of Mg and Na are more typical of alteration by sea water (Hajash and Archer 1980) or seawater-type solutions rather than continental surface weathering. The experimental studies of Hajash and Archer (1980) indicate that seawater alteration typically removes Si, Ca, Mn and Fe from the basalt, although Mn and Fe are removed slowly at low water/rock ratios. Similar reactions could be expected between basalts and brackish water of the type observed in deep wells in the Midcontinent Rift.

Flow 3, 2210.4′—This flow is a yellow green epidosite with pockets, up to several cm long, filled with white calcite. The entire basalt (diabase?) core has been converted to moderately coarse grained epidote, except for the calcite. The epidote is highly birefringent and displays the typical yellow-green pleochroism characteristic of iron-rich epidote. The calcite is frequently twinned. No trace of the primary minerals or textures remains to indicate the original nature of the rock.

This highly altered core sample is oxidized (Table 2) with Fe_2O_3/FeO = 37.7 and has a high volatile content (LOI = 5.25 wt.%), which may be partly water and partly carbon dioxide in this rock. The very high CaO content (23 wt.%) indicates that Ca metasomatism was the major type of alteration and the presence of epidote indicates it was a high temperature metasomatism. Studies of alteration patterns in oceanic rocks would seem to indicate that epidosites are produced by Ca metasomatism from upwelling evolved hydrothermal solutions at temperatures near 400–450°C (Harper et al. 1988). However, in the Midcontinent Rift the most likely alternative is reaction with high temperature brackish waters. High water/rock ratios are required for such extreme rock conversion. Both Na and Mg were removed during the introduction of Ca in this layer and the resulting major element composition is unusual (Table 2). It is interesting to note that REE abundances for the three flows are similar (Table 3) despite the wide differences in their present major element compositions. This suggests that all three flows initially had similar compositions and that present variations are due largely to the different alteration processes they have undergone.

Wnumber 16511—Nelson #9, 2875–2880′ depth well cuttings from map Site 4 (Fig. 2)—Grinding these well cuttings produced a gray powder that was used for INAA analysis. Binocular microscope observation indicates this sample is a slightly altered basalt. The REE pattern is typical of the NSVG basalts although Na (1167 ppm) is strongly depleted, indicating that some alteration has occurred.

Wnumber 16939—Anderson #1, 2142′ depth core sample from map Site 2 (Fig. 2)—This highly altered reddish volcanic rock has the texture of a welded tuff with undulating streaky layering visible in both hand specimen and thin section. A few welded tuffs have been observed among the Midcontinent Rift volcanics (John Green, per. comm.). Opaque oxides, including hematite, are abundant and widespread, often surrounding relict plagioclase laths that are now completely altered to a fine-grained material that could be clay. Opaques are the only identifiable minerals present.

The composition (Tables 2 and 3) of this sample shows evidence for lateritic-type weathering with high TiO2 (3.09 wt.%), Al_2O_3 (28.0 wt.%) and Fe_2O_3/FeO (18.4 wt.%/0.49 wt.%) relative to SiO_2 (42.2 wt.%). The more soluble oxides have been almost totally removed, MgO = 0.25 wt.%, CaO = 0.03 wt.%, Na_2O = 0.04 wt.% and K_2O = 0.05 wt.%, whereas the LOI is at a high 10.7 wt.%. The removal of silica relative to titania, alumina and ferric iron indicates that the alternating wet-dry tropical climate conditions typically regarded as necessary for the removal of silica prevailed during the weathering of this rock. The high concentration of insoluble incompatible elements REE, Hf, Zr, Ta and Th relative to the soluble elements trace elements, Rb, Sr, Cs and Ba were not detected by INAA analysis, suggests concentration by selective removal of soluble components. The high insoluble trace element concentrations suggests a similarity to NSVG andesite.

Wnumber 17028—Olson #1, 2385′ depth well cuttings from map Site 2 (Fig. 2)—This highly altered and oxidized sample formed a red powder when crushed for INAA analysis. In thin section the rock consists of small to medium pieces of irregular brown dusty material, hematite and other fine grained material. Some relic plagioclase laths remain. This sample has low total REE with a straight pattern inclined downward from La to Lu with no Eu anomaly. Sodium (841 ppm) is strongly depleted and both Cr (247 ppm) and Ni (197 ppm) are enriched (Table 3) relative to most other Iowa Midcontinent Rift samples, suggesting it was a basalt.

Wnumber 17036—Hodgson #1, 2200′ depth well cuttings from map Site 2 (Fig. 2)—The cuttings are highly oxidized, forming a red powder when ground for INAA analysis. The only minerals visible in thin section are abundant opaques, hematite and quartz surrounded by fine grained material. The outlines of a few relic plagioclase laths are present. The Hodgson sample is one of three Midcontinent Rift samples in this study with an LREE-enriched REE pattern relative to most Iowa MRS samples (Fig. 3d) and the NSVG (Basaltic Volcanism Study Project 1981; Brannon 1984). The sample also has an FeO_t content of 18.6% that could represent residual enrichment by weathering. The Ni (215 ppm) and Cr (196 ppm) contents are enriched relative to other samples whereas Na (612 ppm) is strongly depleted (Table 3).

In general the trace element pattern of this sample is similar to that of Anderson #1 with high incompatible trace element contents and no detectable concentrations of the soluble alkali and alkaline earth elements. Since the Anderson #1 sample, with a major element analysis, has all the characteristics expected of a sample with lateritic surface weathering, perhaps this sample has been affected in a similar way. Without major elements it is difficult to evaluate whether this sample is an altered basalt or had a more evolved primary composition. However, the higher Cr and Ni contents (196 ppm Cr compared to 168 ppm for Anderson #1 and 215 ppm Ni compared to 76 for Anderson #1) suggests either more extreme lateritic surface weathering or a slightly less evolved parental magma. Existing elemental patterns suggest a similarity to NSVG andesite.

Wnumber 17798—Sharp #3, 2170′ depth well cuttings from map Site 2 (Fig. 2)—This altered basalt produced a brown powder when prepared for INAA analysis. Alteration was observed with the binocular microscope and the typical strong Na depletion (4387 ppm) confirms the alteration. Nevertheless the REE pattern is similar to that of the NSVG basalts with LREE/HREE enrichment expressed along a straight downward slope from LREE to HREE. This sample also has a high Rb content (70.7 ppm).

Wnumber 18670—Nessa #2, 2220–2230′ depth well cuttings from map Site 2 (Fig. 2)—These cuttings are badly altered leaving only outlines of plagioclase laths in a field of brown material and opaque minerals. Occasional pockets of quartz are also present. A limited supply of cuttings allowed only INAA trace element analysis preventing estimates of oxidation and hydration. However, this sample shows the strong Na depletion (1802 ppm) which appears to characterize alteration in many of these well samples.

Wnumber 26322—Kinney, A-1, 2355–2360′ depth well cuttings from map Site 3 (Fig. 2)—The cuttings are light gray basalt thar appear relatively fresh compared to other well cuttings observed in this study. In thin section these cuttings consist largely of plagioclase and augite, or altered augite, plus accessory opaques and apatite, all in crystals up to 1 or 2 mm in length. Augite is partially altered to a fibrous uralitic amphibole, epidote and chlorite, a high temperature alteration assemblage. Epidote has grown on both augite and plagioclase without apparent preference. Sericitized plagioclase shows complex twinning typical of igneous rocks. The long apatite rods have not been noticeably altered. Sufficient cuttings were separated to allow both INAA for trace elements and ICP for major elements.

The composition of this sample (Tables 2 & 3) is similar to that of Finnegan, A-1, and NSVG intermediate olivine tholeiite (Brannon 1984). These cuttings are relatively unaltered (LOI = 2.32 wt.% and Fe_2O_3/FeO = 0.33), as is Finnegan, A-1, making these two Guthrie County well samples the freshest Midcontinent Rift basalts in this study. Both samples have basaltic SiO_2 contents between 48–49 wt.% dry. The K_2O content of this sample (0.69 wt.%) is considerably higher than for the Finnegan sample (0.28 wt.%) and Na_2O is somewhat higher (3.39 wt.% relative to 2.47 wt.%), otherwise they are similar in composition. Their REE patterns are virtually identical (Fig. 3c).

Wnumber 26336—Morrison #1, 2940′ depth well cuttings from map Site 2 (Fig. 2)—In thin section this sample is highly altered to epidote and a variety of fine grained materials; no primary minerals remain. Despite the severe alteration, the REE pattern indicates that the REE may retain their primary concentration (Table 3). On the other hand the typical Na depletion (Na = 3010 ppm) occurs and presumably Ca has either remained constant or increased since epidote is now an abundant alteration mineral. The epidote indicates high temperature alteration, but it is not possible to evaluate the temperature at which the fine grained material was formed.

Wnumber 26580—Turner #1, 2960–2970′ depth well cuttings from map Site 4 (Fig. 2)—This sample is badly altered and insufficient sample was present for analysis of major elements. In thin section only scattered opaques and a brown alteration material are abundant; patches of a green alteration mineral occur in small scattered spots. A relic basaltic texture persists despite the severe alteration. The thin section surface is covered with a reflective material that resembles leucoxene. The REE pattern indicates the rock was a basalt, although it has been enriched in Rb (70.3 ppm) and strongly depleted in Na (771 ppm). Most other trace elements are similar in abundance to the least altered samples from Finnegan A-1 and Kinney A-1.

Wnumber 26976—Knapp #3, 2887′ depth well cuttings from map Site 4 (Fig. 2)—Thin section study indicates this sample may have undetgone two separate types of alteration. The only visible nonopaque mineral is epidote, a high temperature alteration product of plagioclase. Other discernable materials are either opaque minerals or a dark brown material that obscures most portions of the rock and appears similar to material observed in weathered samples. The high temperature alteration that produced epidote may be a product of burial metamorphism and must have preceded the later lower temperature alteration, perhaps weathering, that produced the fine dark brown material. Sufficient cuttings were available to permit both a trace element (INAA) and major element (ICP) analysis of this sample.

The composition of this sample (Tables 2 & 3) indicates some oxidation (Fe_2O_3/FeO = 1.76), considerable hydration (LOI = 6.46 wt.%), and strong depletion of Na (515 ppm). When plagioclase altered to epidote the Ca was retained (CaO = 7.02 wt.%) but the Na was lost. K_2O (2.58 wt.%) is high for a basalt and may have been concentrated by alteration process(es).

Wnumber 27206—Anderson #3, 2210′ depth well cuttings from map Site 2 (Fig. 2)—These altered cuttings produced a brown powder when ground for INAA analysis, but only slight alteration of this basalt was observed with the binocular microscope. Despite the relatively clean appearance of the cuttings, the incompatible trace element content is slightly high for basalt and Na is strongly depleted (1289 ppm), indicating extensive alteration of the plagioclase.

Wnumber 27233—Coddington #3–24, 3820–3823′ depth cuttings from map Site 5 (Fig. 2)—This highly altered basalt now contains only relic pieces of plagioclase surrounded by fine grained brown and green material, opaques, calcite and epidote. Despite the alteration, Na is not depleted in this sample and incompatible trace element contents (Table 3) appear only slightly high for basalt, perhaps concentrated by removal of more soluble elements. Insufficient cuttings were available to allow for major element analysis. Both high and low temperature alteration appears to have occurred, perhaps representing burial metamorphism followed later by exposure and surface weathering.

Wnumber 27272—Finnegan, A-1, 2702.5′ depth core sample from map Site 3 (Fig. 2)—This sample can be described as either an ophitic basalt (this study) or an orbicular gabbro (Fischer, 1982), but the rock is similar to an abundant type of mottled North Shore lava flow sometimes called an ophite (Green 1972). Although the 0.2 mm plagioclase laths are smaller than typical for gabbro, the 6 mm augite oikocrysts are much larger. Regardless of the name used for classification, the rock is dark gray to black and characterized in hand sample by an obvious mottling. Approximately 70 feet of the Midcontinent Rift was penetrated in this well with the bottom near a depth of 2708 feet (Fischer 1982). Lorraine Fischer studied 75 thin sections from the rift basalt recovered from this well, divided the core into three layers, with the upper two being altered, and microprobed the component minerals (Fischer 1982). She found the typical mineralogy of the 28 foot unaltered lower layer to consist of 35–45% augite, 30–40% labradorite, 10–15% amphibole, and 10% opaques. Fibrous uralitic amphibole is forming along the margin of augite crystals by alteration. The opaques consist of ilmenite with magnetite rims and a second generation of ilmenite that concentrates between the large augite crystals. Average mineral compositions are given in Table 6.

The sample analyzed for both majors and trace elements (Tables 2 and 3) is from near the base (2702.5′) of the unaltered layer; the upper two altered layers were not analyzed. The Finnegan lower layer core sample represents the least altered core analyzed in this study with LOI at 1.07 wt.% and an Fe_2O_3/FeO ratio of 0.28; both represent the lowest values obtained for our analyzed samples. Alteration was largely limited to some high temperature uralitic amphibole derived from augite and sericitic alteration of labradorite. This suggests that the elemental abundances are nearly primary. Comparison of this rock analysis (Tables 2 and 3) with North Shore Volcanic Group analyses (Table 4) indicates it most closely resembles intermediate olivine tholeiite (IOT) in composition.