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Studies of the Precambrian Geology of Iowa: Part 1. The Otter Creek Layered Igneous Complex

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Rocks from a buried igneous body, herein called the Otter Creek layered igneous complex, were recovered by drilling in Archean rocks in northwestern Iowa. This complex consists of layers of ultramafic and mafic cumulate rocks, including bronzitite, harzburgite, dunite, gabbro, and anorthosite. These rocks have been subjected to low-grade metamorphism with a paragenesis including serpentine, chlorite, talc, uralitic amphiboles, magnetite, albite, epidote, sericite, and minor quartz and calcite. During its intrusion, the magma which gave rise to the layered body engulfed a large block of rock consisting of banded iron formation and thin lamprophyre dikes. Both the iron formation and the lamprophyre show evidence of high-temperature metamorphism followed by a retrograde event. Chemical compositions of the layered rocks and the lamprophyre are indicative of both having been derived from a primitive to slightly depleted mantle source. Comparison with similar rocks in the Superior Province indicate that the Otter Creek complex is part of a greenstone belt and was probably generated near the terminal stages of its development.

INDEX DESCRIPTORS: Archean, layered intrusive, gabbro, dunite, lamprophyre, banded iron formation, greenstone belts

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Rock core from an ultramafic to mafic layered igneous complex was recovered from the subsurface basement of northwestern Iowa as part of an exploratory drilling program conducted by New Jersey Zinc Company in 1963. Drilling centered around a pronounced circular magnetic anomaly located near the town of Matlock in Lyon and Sioux counties (Fig. 1). This anomaly is over 1000 gammas above the regional background (Zietz et al., 1976). Contours of the magnetic intensity project to the surface near a small stream named Otter Creek and we hereby refer to the anomaly and the layered complex as the Otter Creek magnetic anomaly and the Otter Creek layered igneous complex, respectively.

The Otter Creek anomaly is one of several that form a linear trend extending from extreme northeastern Nebraska through southeastern South Dakota, northwestern Iowa, and into Minnesota (Hildenbrand, 1987) (Fig. 2). These anomalies lie north of and parallel to a discontinuity in the magnetic patterns of the Iowa basement known as the Spirit Lake trend (SLT) (Anderson, 1987). The northeast extension of the SLT appears to correlate with the southern edge of the Superior craton in northern Wisconsin (Bickford et al., 1986) and the SLT has thus been described as a boundary between Archean rocks (more than 2.5 billion years old [Ga]) to its north and Proterozoic rocks (younger than 2.5 Ga but older than approximately 600 million years old [Ma]) to its south (Anderson, 1987). Van Schmus and Wallin (1991) determined an Archean age for both the Otter Creek layered complex (2890 ± 90 Ma) and the nearby Lyon County Gneiss (2535 ± 5 Ma) described previously by Tvrdik (1983). South of the SLT, granite was recovered by drilling near the town of Quimby, in Cherokee County; it was determined to be 1433 ± 4 Ma and to have been derived by remelting of rocks that separated from the mantle approximately 1860 Ma (Van Schmus et al., 1989). These results support the interpretation that the SLT represents the southern margin of the Archean terrane.

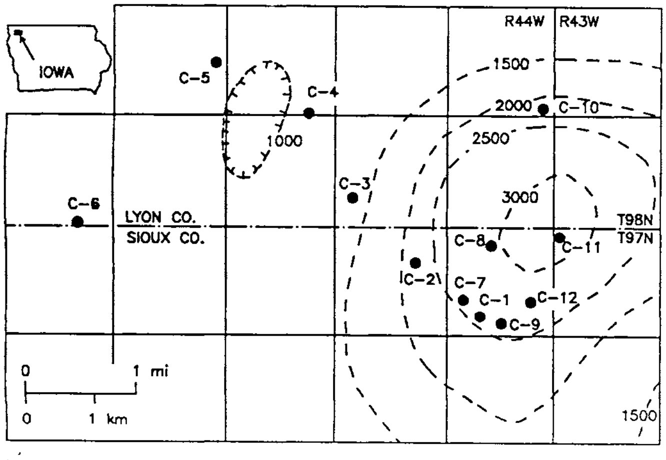

Fig. 1. Location map showing positions of New Jersey Zinc Company's exploration drill holes relative to the Otter Creek magnetic anomaly. Magnetic contours (dashed lines) in gammas.

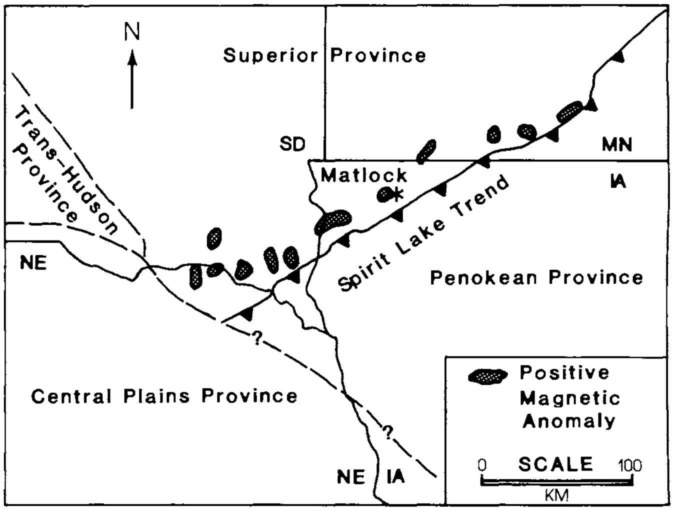

Fig. 2 a) Location map showing relationship of Otter Creek magnetic anomaly (next to the star) and other associated magnetic anomalies relative to the inferred boundaries of the Superior Province. Abbreviations: IA = Iowa, MN = Minnesota, SD = South Dakota, NE = Nebraska.

Archean rocks are exposed in Canada and parts of northern and central Minnesota. They comprise numerous subprovinces, i.e., spatially and temporally related packages of rocks with relatively well-defined boundaries. Rocks in the various subprovinces occur primarily

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in one of two geologic settings distinctive of the Archean; high-grade gneiss terranes and granite-greenstone belts (Sutton, 1976; Windley, 1976, 1977). These subprovinces collectively form a single large crustal block known as the Superior Province. High grade gneiss and amphibolite exposed in the Minnesota River Valley and dated to be as old as 3550 Ma (Goldich et al., 1970) represent the southern-most exposed part of the Superior Province. Younger sedimentary rocks cover the Archean rocks farther to the south into Iowa.

ANALYTICAL PROCEDURES

Rock cores and thin sections of the Otter Creek layered igneous complex were investigated for this study from material supplied by the Iowa Department of Natural Resources Geological Survey Bureau in Iowa City. The cores have been described previously (Yaghubpur, 1979; Tvrdik, 1983). Our analysis included petrographic examinations, x-ray diffraction, and whole-rock major and trace element determinations. Major element determinations were done by a commercial laboratory (X-ray Assay, Ontario, Canada) using x-ray fluorescence (XRF). In addition, XRF was used for Sr, Rb, Y, Zr, Ba, and Nb; these determinations were performed in the Department of Geological and Atmospheric Sciences at Iowa State University (ISU) except for sample C1-704, for which all elemental determinations were done by X-ray Assay. Other trace elements were determined by instrumental neutron activation analysis (INAA), done partly at the University of Missouri Research Reactor (MURR) and partly at Washington University in St. Louis, Mo., although all of the sample irradiations were at MURR. U.S. Geological Survey standards BCR-1, GSP-1, and BHVO-1 were used for INAA analysis and the ISU XRF analyses.

CORE DESCRIPTIONS

Rocks assigned to the Otter Creek complex were encountered in 10 of 12 holes drilled on the Otter Creek magnetic anomaly. Several of these holes form a rough traverse across the anomaly that serves as the basis for the cross section shown in Fig. 3. The layered rocks dip approximately 25° to the northwest and appear to have a total stratigraphic thickness of at least 2.5 km.

The lowest recovered portion of the complex consists of highly altered bronzitite, harzburgite, and dunite, in ascending order. This lower portion is at least 1.25 km thick; total thickness is unknown, however, because the basal contact was not recovered. Thin (1-5 cm thick) bands of concordant chromitite can be correlated between two of the cores and appear to be continuous. Original minerals occurring in these lower rocks were olivine, orthopyroxene, and chromite. Alteration, primarily hydration with minor carbonation, converted olivine to serpentine, magnetite, chlorite, and minor talc; pyroxene was replaced by serpentine, chlorite, uralitic amphiboles, magnetite, and minor calcite. Only chromite remains relatively fresh in appearance. Despite the alteration, relict textures can still be recognized in the ultramafic rocks and indicate little, if any, penetrative deformation.

Clinopyroxene and/or plagioclase may have been present originally in some of the ultramafic rocks; three samples (one dunite, the harzburgite, and the bronzitite) contain normative diopside, anorthite, and albite (Table 1). However, alteration has obliterated conclusive petrographic evidence of either modal clinopyroxene or plagioclase.

Inclusions of banded iron formation (BIF) were recovered in one drill core. The BIF occurs stratigraphically above the harzburgite, but the contact relations are not readily discernable from the recovered drill core. The BIF has been intruded by thin lamprophyre dikes and both the BIF and the lamprophyre show evidence of having been subjected to high-temperature metamorphism, followed by retrograde metamorphism. Tvrdik (1983) interpreted the BIF as a large xenolith that was engulfed by the magma which gave rise to the layered complex. We concur with this interpretation.

The upper 1.5 km (approximately) of the layered complex consists of thin rhythmic layers varying in lithology from gabbro to anorthosite. Original mineralogy consisted of plagioclase, clinopyroxene, and orthopyroxene. Olivine may have also been present; the anorthosite and all but one of the gabbros contain normative olivine (Table 1). If modal olivine did occur in these rocks, alteration has obliterated conclusive evidence of its presence. As with the ultramafic rocks, the original minerals of the mafic layers have been replaced by serpentine, chlorite, uralitic amphiboles, albite, epidote, sericite, and minor calcite and quartz. Relict textures in the mafic layers show no indication of penetrative deformation.

GEOCHEMISTRY

Major element concentrations and CIPW norms for rocks of the layered series and the lamprophyre dike are given in Table 1. CIPW norms were determined from major element oxide data recalculated to an anhydrous basis and assuming $Fe_2O_3/FeO = 0.15$. The normative mineral compositions agree well with those determined and/or inferred by Tvrdik (1983) and comprise mainly olivine, hypersthene, diopside, Fe-oxide minerals (magnetite, chromite, and minor il-

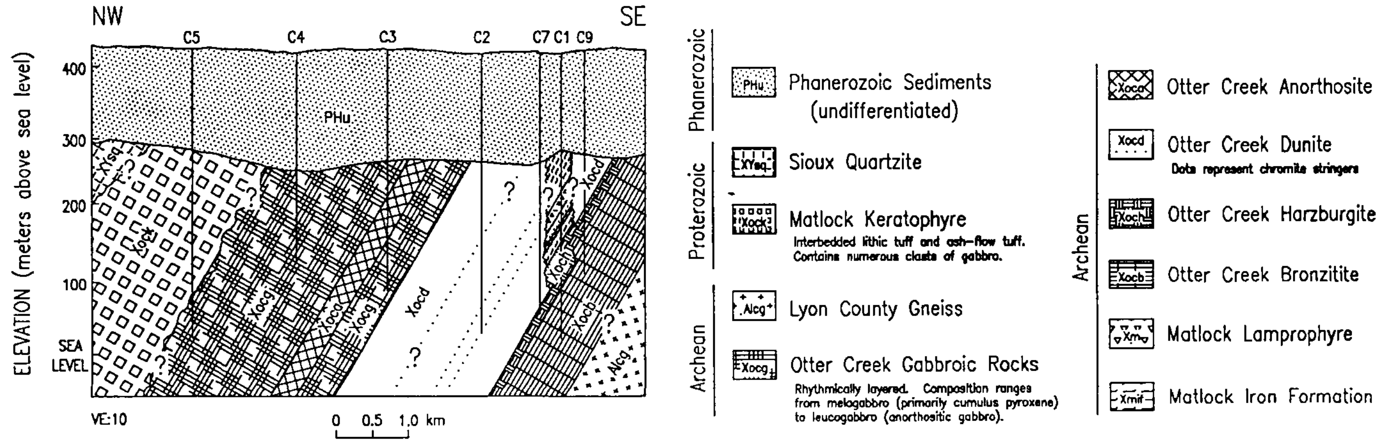

Fig. 3. Geological cross-section of the Otter Creek layered igneous complex and spatially associated rocks, based on rock samples recovered from drill core. Note vertical exaggeration of 10, which makes the dip of the layers appear steeper than actually occurs.

Table 1. Major Element Compositions and Normative Mineral Compositions[a] of Rocks from Otter Creek Igneous Complex and Associated Rocks (in weight percent).

	Dunites				Harzburgite	Bronzitite	Anorthosite
	C2-644[b]	C2-970	C2-1005	C7-574	C1-903	C1-1127	C3-855
SiO_2	28.8	34.3	34.8	32.3	38.6	47.9	45.8
TiO_2	0.06	0.03	0.03	0.04	0.13	0.17	0.04
Al_2O_3	1.50	0.39	0.34	0.54	2.43	3.38	31.9
Cr_2O_3	8.18	1.13	1.08	2.59	0.56	0.44	<0.01
FeOt	8.14	6.64	6.86	6.16	14.1	11.8	0.72
MnO	0.19	0.10	0.08	0.09	0.14	0.19	<0.01
MgO	36.1	40.9	41.0	40.0	31.4	25.1	1.35
CaO	0.02	0.54	<0.01	<0.01	1.89	3.38	11.9
Na_2O	0.01	0.02	0.01	0.01	0.07	0.08	3.09
K_2O	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	1.14
P_2O_5	0.01	0.01	0.01	0.01	0.02	0.02	0.01
LOI	16.5	15.4	14.8	17.7	8.54	5.47	4.62
SUM	99.5	99.5	99.0	99.4	97.9	97.9	100.6
H_2O^+	10.1	11.3	13.4	15.4	8.3	4.3	2.4
CO_2	1.19	1.35	0.67	0.95	0.04	<0.01	0.56
			Normative Mineralogy				
QZ	—	—	—	—	—	—	—
OR	—	—	—	—	—	0.06	7.04
AB	—	0.22	—	—	0.69	0.73	20.58
AN	0.05	1.23	—	—	7.21	9.55	61.60
CO	1.84	—	0.42	0.66	—	—	4.37
DI	—	1.53	—	—	3.56	6.67	—
HY	1.34	11.60	17.82	4.55	26.11	70.32	—
OL	83.24	82.09	78.16	89.35	60.86	8.79	3.13
NE	—	—	—	—	—	—	3.02
MT	2.23	0.44	1.85	1.67	3.56	2.81	0.14
HM	—	1.01	—	—	—	—	—
IL	0.14	0.08	0.08	0.09	0.28	0.35	0.08
CM	11.13	1.75	1.63	3.66	0.84	0.65	—
AP	0.03	0.04	0.03	0.03	0.07	0.07	0.02

[a] Normative mineral compositions calculated assuming $Fe_2O_3/FeO = 0.15$.

[b] Sample numbers refer to core hole and depth below the surface (in feet), i.e., sample C2-644 was taken 644 feet from the top of core C-2.

menite), and minor plagioclase for the ultramafic rocks and plagioclase, diopside, hypersthene, olivine, and minor oxide phases in the gabbros. Normative quartz is present in one gabbro sample. Anorthosite is dominated by normative plagioclase. Normative corundum occurs in three dunites; this probably arises from Al_2O_3 in the spinel phase that is not taken into account by the normative calculation. The anorthosite also contains normative corundum as well as nepheline. All the anorthosite recovered from the drill core shows extensive alteration, however, and these normative minerals may result from elemental redistribution (especially SiO_2 and alkalis) during the alteration process.

Most of the variation in the major element abundances reflect the cumulate nature of the various rock types, which presumably formed by fractional crystallization of cumulus phases during solidification. Some evolving liquid was probably trapped in the interstices of the cumulus crystals, but the predominance of cumulus minerals masks the chemistry of these liquids. Therefore, this precludes determining the exact chemical path of liquid fractionation from major element concentrations in these rocks.

Mean trace element compositions for the various Otter Creek rocks are given in Table 2 and mean rare earth element (REE) patterns for these rocks are plotted in Fig. 4. Rare earth elements, in contrast to major elements, are strongly incompatible in all mafic minerals; therefore, whole rock relative abundances of REEs reflect the compositions of the parent magmas.

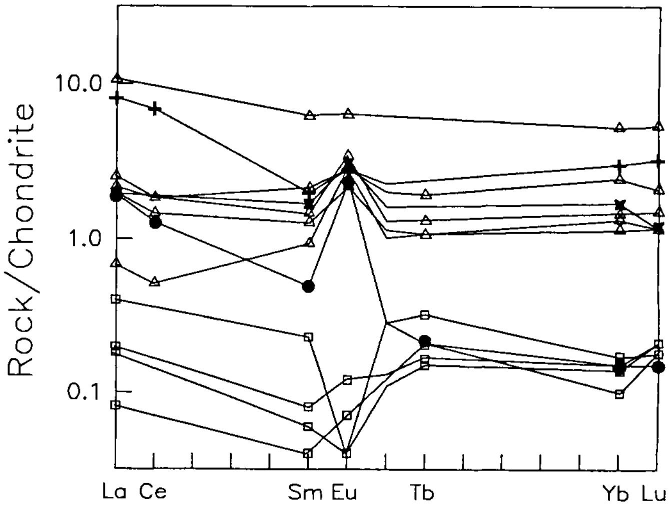

Fig. 4. Chrondite normalized rare earth element diagram for the rocks of the Otter Creek layered igneous complex. Symbols: open square = dunite; x = harzburgite; + = bronzitite; open triangle = gabbro; solid circle = anorthosite.

Table 1: (Continued)

	Gabbros					Lamprophyre
	C3-605	C3-1074	C4-757	C5-1266	C5-1324	C1-704
SiO_2	45.3	47.0	48.7	53.1	49.7	45.6
TiO_2	0.08	0.08	0.08	0.37	0.15	0.79
Al_2O_3	23.8	19.9	16.0	4.63	13.9	13.7
Cr_2O_3	<0.01	0.02	<0.01	0.11	0.06	0.04
FeOt	4.46	3.78	5.46	7.87	5.80	12.25
MnO	0.07	0.07	0.14	0.16	0.12	0.19
MgO	6.44	8.70	9.38	14.9	12.1	10.7
CaO	12.1	14.3	13.5	15.9	13.0	7.63
Na_2O	2.24	1.18	1.92	0.20	1.67	1.21
K_2O	0.35	0.07	0.32	0.02	0.12	2.10
P_2O_5	0.02	0.01	0.01	0.02	0.02	0.02
LOI	5.16	5.23	4.70	2.23	3.23	3.08
SUM	100.0	100.3	100.2	99.5	99.9	97.3
H_2O^+	3.6	4.5	1.8	1.8	2.5	3.5
CO_2	0.82	1.16	1.78	0.02	0.10	0.05
			Normative Mineralogy			
QZ	—	—	—	5.06	—	—
OR	2.18	0.45	1.98	0.11	0.72	13.15
AB	18.67	9.54	15.52	1.68	13.94	10.85
AN	57.55	51.82	36.54	11.64	31.50	27.28
CO	—	—	—	—	—	—
DI	4.56	18.09	26.94	53.40	28.05	10.35
HY	0.92	16.44	11.32	25.50	17.88	14.43
OL	14.87	2.57	6.25	—	6.17	19.43
NE	—	—	—	—	—	—
MT	1.03	0.88	1.26	1.73	1.32	2.86
HM	—	—	—	—	—	—
IL	0.16	0.17	0.16	0.71	0.29	1.59
CM	—	0.02	—	0.15	0.09	—
AP	0.05	0.03	0.02	0.03	0.03	0.05

All of the Otter Creek rocks are strongly depleted in the trace alkali elements. The four dunites are characterized by enriched LREE and flat to slightly depleted HREE patterns with small negative Eu anomalies, very high concentrations of Cr (7,380-56,000 ppm) and Ni (2,300-2,680 ppm) and very low incompatible element concentrations. Concentrations of several of the REE in the dunites are very near the analytical detection limits, however, meaning that too much emphasis should not be placed on the shapes of the chondrite-normalized REE patterns. The harzburgite has a moderately high concentration of Cr (3,897 ppm) and Ni (1,569 ppm) and displays a near-flat chondrite-normalized REE pattern with a positive Eu anomaly. This pattern is virtually indistinguishable from those exhibited by the gabbros. The bronzitite contains the highest REE abundances of any ultramafic sample analyzed. It has a light REE-enriched pattern with small positive Eu anomaly, and very low incompatible-element concentrations.

The gabbros have flat REE patterns with very low total REE at near-chondritic abundance and positive Eu anomalies, low incompatible-element concentrations, and an average TiO_2 content of only 0.11 wt%. Their low REE abundances are consistent with these rocks being mafic cumulates. This is also true of the anorthosite, which has a plagioclase-type REE pattern of light-REE to heavy-REE enrichment and a large positive Eu anomaly, and which contains the highest Sr, Rb, Ba, and Cs content of any Otter Creek rock.

An unknown amount of the layered complex has been removed by erosion or faulting, so it is impossible to calculate an overall composition of the original magma. Averaging the available trace element data from all the layered rocks, however, suggests strongly that this magma was derived from a mantle with near chondritic abundances.

Major element data were also obtained from the lamprophyre. These data fall within the limits given by Rock (1984) for calc-alkaline (shoshonitic) lamprophyres, except for FeOt, which is higher in the Otter Creek rocks. However, the Otter Creek lamprophyre intruded banded iron formation, and may have gained Fe during either the intrusion event or subsequent high-temperature metamorphism (see section on METAMORPHISM below). Trace element abundances in the lamprophyre are lower than those given by Rock (1984) as being typical for this group of rocks, suggesting the Otter Creek lamprophyre was derived from a primitive to slightly depleted mantle. Such an interpretation is consistent with the ϵNd(t) value near zero determined by Van Schmus and Wallin (1991) for the Otter Creek layered complex/lamprophyre complex.

COMPARISON WITH OTHER ARCHEAN LAYERED INTRUSIONS

Layered ultramafic-mafic intrusions have been described from several Archean localities. Loferski (1986) noted two types of Archean layered complexes: 1) an anorthosite-leucogabbro association such as the Fiskenaesset in Greenland (Windley et al., 1973; Windley and Smith, 1974) and certain intrusions in the Limpopo Belt of southern Africa (Hor et al., 1975), and 2) an ultramafic-gabbro-anorthosite association such as in certain other intrusions in southern Africa (Robertson, 1973; Smit, 1984), in the Lewisian of NW Scotland

Table 2. Trace Element Concentrations of Rocks from Otter Creek Igneous Complex and Associated Rocks (in parts per million).

	Dunites				Harz-burgite	Bronz-itite	Anor-thosite
	C2-644	C2-970	C2-1005	C7-574	C1-903	C1-1127	C3-855
Ba	6	8	<5	6	8	13	77
Rb	<2	4	3	5	5	5	17
Th	0.23	0.10	0.62	—	0.09	0.09	0.024
Nb	4	2	2	2	2	3	2
La	0.131	0.059	0.066	0.026	0.67	2.65	0.64
Ce	—	—	—	—	—	6.15	1.09
Sr	4	15	7	5	14	15	147
Sm	0.042	0.01	0.014	0.008	0.30	0.36	0.09
Eu	0.003	0.003	0.008	0.005	0.20	0.19	0.16
Zr	—	—	—	—	2	5	2
Hf	—	—	0.09	—	0.12	0.24	0.01
Tb	0.015	0.007	0.008	0.01	—	—	0.01
Y	<2	<2	<2	<2	<2	<2	<2
Yb	0.034	0.027	0.029	0.02	0.33	0.60	0.03
Lu	0.006	0.007	0.007	0.006	0.04	0.11	0.005
Sc	3.77	3.44	3.92	3.38	3.90	18.1	0.97
Co	157	119	116	111	119	41.4	3.37
Cr	56000	7760	7380	16000	3897	3084	19
Ni	2300	2680	2580	2500	1569	—	—
Cs	0.13	0.18	0.14	0.06	0.2	0.8	0.74

	Gabbros					Lamprophyre
	C3-605	C3-1074	C4-757	C5-1266	C5-1324	C1-704
Ba	25	11	21	7	22	225
Rb	8	3	9	3	5	71
Th	0.09	0.12	—	0.26	0.06	—
Nb	3	3	2	2	3	<10
Ta	—	—	—	0.18	—	—
La	0.83	0.71	0.22	3.54	0.72	—
Ce	1.60	1.26	0.45	—	1.61	—
Sr	119	75	111	22	102	232
Sm	0.26	0.23	0.17	1.12	0.38	—
Eu	0.23	0.15	0.19	0.43	0.19	—
Zr	7	5	3	15	9	<10
Hf	0.13	0.11	—	0.47	0.15	—
Tb	0.06	0.05	0.05	—	0.09	—
Y	2	<2	<2	12	6	24
Yb	0.29	0.27	0.23	1.01	0.48	—
Lu	0.05	0.04	0.04	0.18	0.07	—
Sc	15.0	21.3	33.7	68.4	34.7	—
Co	29.5	32.5	47.5	63.7	50.5	—
Cr	31.5	119	11.3	870	432	278
Ni	125	163	—	326	—	—
Cs	0.43	0.10	0.93	0.30	0.37	—

(Bowes et al., 1964; Davies, 1974), in Brazil (Girardi and Kurat, 1982), and in Montana (Lofeski, 1986). This second association has also been described from localities in the Superior Province including the Abitibi greenstone belt (Naldrett and Mason, 1968; MacRae, 1969) and the Crow Lake-Savant Lake greenstone belt (Davis et al., 1982; Morrison et al., 1985; 1986).

The Otter Creek complex falls into the ultramafic-gabbro-anorthosite category. There are numerous similarities between this complex and several of the layered bodies from Archean greenstone belts worldwide. Naldrett and Mason (1968) and MacRae (1969) recognized four types of ultramafic and/or mafic bodies occurring in the Abitibi greenstone belt in Ontario: 1) complex sills in which there is a cyclic repetition of layers; 2) simple differentiated sills showing only one sequence of peridotite, pyroxenite, and gabbro; 3) bodies composed entirely of peridotite and gabbro; and 4) bodies composed wholly of gabbroic rocks. These authors concluded that the four types are variations of a single process and the whole complex represents the lower part of an active volcanic system. Similar types of ultramafic/mafic associations were described from Western Australia (Hallberg and Williams, 1972; Williams and Hallberg; 1973) and similar conclusions were reached regarding their origin.

Lamprophyre has also been described from Archean provinces, including the Superior Province (Sims and Mudrey, 1972; Geldon, 1972; Burrows and Spooner, 1989; Wyman and Kerrich, 1989) and Western Australia (Perring et al., 1989; Rock et al., 1989; Groves et al., 1989). Archean lamprophyres are shoshonitic and commonly occur in dike swarms concentrated near the boundaries of the subprovinces, although they also occur within the interior of some greenstone belts. They are commonly associated spatially and temporally with lode gold deposits.

METAMORPHISM

All rock types associated with the Otter Creek complex have been metamorphosed, but not all to the same degree. The ultramafic and mafic portions of the layered series now consist of secondary minerals, including serpentine, chlorite, uralitic amphibole, albite, and epidote, i.e., minerals indicative of low metamorphic grade. Such greenschist metamorphism is common in mafic and ultramafic rocks of Archean greenstone belts. However, the timing and extent of the metamorphism cannot be determined precisely from available samples. Younger rocks spatially associated with the layered complex also show evidence of secondary mineral formation. The nearby Lyon County Gneiss, dated at 2523 ± 5 Ma by Van Schmus and Wallin (1991), exhibits cataclasis with growth of secondary minerals, especially sericite, concentrated within the most highly deformed zones. The overlying Matlock keratophyre, determined to have an age of 1782 ± 10 Ma (Van Schmus and Wallin, 1991) exhibits evidence of devitrification, secondary mineral growth, and elemental redistribution (Windom et al., 1991). However, it is not evident whether these features formed during a pervasive metamorphic event or are the result of autometamorphism. In either case, none of the recovered samples from these rock bodies shows evidence of more than low-grade metamorphism.

In contrast to the cumulate rocks, the BIF and lamprophyre contain minerals representative of high-temperature metamorphism; for example, Tvrdik (1983) described clinopyroxene and what he deduced as pseudomorphs of orthopyroxene in the BIF and we have determined that the lamprophyre contains edenitic to pargasitic hornblende. This latter identification is based on microprobe analysis of amphibole in the lamprophyre; the average composition was determined to be $(Na_{.46}Ca_{.07}K_{.04})$ $(Ca_{1.77}Fe^{2+}{}_{.21}Mn_{.02})$ $(Mg_{2.49}Fe^{2+}{}_{1.65}Al^{VI}{}_{.82}Ti_{.04})$ $[Si_{6.47}Al^{IV}{}_{1.53}]$ $O_{22}(OH)_2$. This amphibole occurs as large clusters of relatively small but distinct grains. Most of the amphibole grains within a single cluster exhibit a common optical extinction, indicating they replaced a precursor phase (presumably either clinopyroxene or primary amphibole) and that growth of the metamorphic phase was controlled by the crystallographic orientation of the original mineral. In addition to the high-temperature phases, both the BIF and lamprophyre show evidence of retrograde metamorphism. The clino- and orthopyroxenes in the BIF have both been replaced with actinolite — ferro-actinolite and cummingtonite — grunerite amphiboles, respectively (Tvrdik, 1983). Potassium feldspar in the lamprophyre contains abundant sericite along cleavage traces.

DISCUSSION

Geochemical and petrologic data obtained from the rocks of the Otter Creek layered igneous complex allow conclusions about its origin and the tectono-magmatic regime present during the formation of this portion of the Superior Province. The BIF was deposited in a supracrustal environment. Lamprophyric magma subsequently intruded the BIF in thin dikes, which solidified quickly. A short time thereafter, mafic to ultramafic magma intruded the supracrustal pile, probably forming a sill-like body.

The simplest explanation for the Otter Creek complex is that it represents Naldrett and Mason's (1968) type 2 simple sill in which only one differentiation sequence is present. This explanation would imply that the entire complex of ultramafic and mafic rocks represents a single co-magmatic sequence related by fractional crystallization processes. Confirming evidence is needed before it can be stated conclusively that only one intrusion was responsible for the Otter Creek complex; other Archean layered complexes originally thought to represent a simple fractionation episode have subsequently been found to have been formed from more than one magmatic intrusion, for example the Stillwater Complex in Montana (McCallum et al., 1980). However, the implications inherent in assuming a single intrusion/fractionation event for the Otter Creek complex are not readily verified with the information obtained from the drill-core samples. For example, if the complex represents a single differentiated intrusion, there should be a troctolitic zone representing co-precipitation of olivine and plagioclase. Several samples contain both normative olivine and normative plagioclase, but alteration prevents establishing conclusively the occurrence of modal plagioclase in the ultramafic portion of the complex or of modal olivine in the mafic portion. Also, the nature of the contact between the lower ultramafic zone and the upper mafic zone is unknown because it was not recovered in the drill cores. Finally, the chondrite-normalized REE patterns of the dunites and gabbros (Fig. 4) are not compatible with a co-magmatic origin of the ultramafic and mafic portions of the complex. However, as noted earlier, the apparent dunite patterns may be the result of REE concentrations near the analytical detection limits rather than being a true reflection of the REE distribution of the magma from which the olivine precipitated. Interestingly, the REE pattern of the harzburgite is virtually identical to that of the gabbros. Therefore, although the simplest explanation for the Otter Creek complex is that it represents a single magmatic episode, multiple intrusions cannot be ruled out with the available data.

Absolute and relative abundances of trace elements in both the lamprophyre and mafic magma(s) indicate these melts were derived from a primitive to slightly depleted mantle. Given standard petrologic theories, the lamprophyre presumably was derived by a relatively small degree of partial melting whereas the magma(s) from which the layered series crystallized originated by much larger amounts of partial melting.

The geochemistry of the lamprophyre suggests formation near the end of the tectonic cycle responsible for creation of the particular subprovince to which these rocks belong. Archean shoshonitic lamprophyres have been related to late deformational tectonic processes focused at subprovince boundaries elsewhere in the Superior Province. Wyman and Kerrich (1989) argued that they are genetically constrained to compressive tectonic environments, which include localized and transitory extensional domains, and that their generation involves depleted mantle locally enriched by subduction or underthrusting. If this interpretation is correct, this southernmost remaining subprovince may have stabilized at approximately 2890 Ga and behaved as a coherent unit during subsequent periods of tectonic and metamorphic activity. No data exist for igneous activity between formation of the Otter Creek complex and the Lyon County Gneiss at approximately 2535 Ga, although the lack of direct evidence of such rocks may be the result of the paucity of samples from this portion of the Iowa basement.

A large block of the BIF/lamprophyre assemblage was apparently engulfed during intrusion of the sill, creating a large xenolith. The heat of the enclosing magma produced high-temperature metamorphism of the rocks in the xenolith. Subsequent greenschist metamorphism produced a prograde paragenesis in the layered intrusion but resulted in retrograde metamorphism of the minerals of the BIF and meta-lamprophyre.

At some time in the history of the complex, it was tilted, uplifted, and eroded although we cannot determine the exact timing of these events. Conceiveably, they occurred during the final stages of stabilization of the Superior Province. Subsequent Proterozoic felsic volcanism (Windom et al., 1991; Van Schmus and Wallin, 1991) covered a portion of the exposed layered complex. The volcanics were also altered and eroded and later covered by quartz arenite which lithified to form the Sioux Quartzite. This entire Precambrian section now lies buried by more than 100 meters of Phanerozoic sediment.

ECONOMIC POTENTIAL

The motivation for the original drilling project that discovered the Otter Creek complex was a search for economic iron-ore deposits. The small amount of BIF recovered was not sufficient to warrant further exploration, and the project was terminated. In 1983, Anaconda Minerals Company relogged the cores and tested for platinum-group elements (PGE). Results of this project were also negative (Cooper, 1984). The current study represents the first recognition of lamprophyre dikes, which have been shown to be spatially and temporally related to Archean lode gold deposits elsewhere (Burrows and Spooner, 1989; Groves et al., 1989; Perring et al., 1989; Rock et al., 1989), associated with the Otter Creek complex. Assays have been done for other rock types recovered during the Matlock project (mainly felsic rocks not discussed in this paper), but no one has evaluated the rocks hosting the lamprophyre dikes for gold or related metals. The occurrence of lamprophyre in these rocks suggests that it is present elsewhere in the southern margins of the Superior Province. Unfortunately, there is no good drilling target associated with a possible swarm of thin dikes and current metal prices do not justify the cost of random exploration. However, this region should be kept in mind as a possible exploration target if the price of precious metals ever reaches a level to justify such a project.

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