

MINERALOGY OF THE SLOAN DIATREME,
A KIMBERLITE PIPE
IN NORTHERN LARIMER COUNTY, COLORADO

M. E. MCCALLUM, *Colorado State University, Fort Collins, Colorado*

AND

D. H. EGGLE, *Texas A & M University, College Station, Texas.*

ABSTRACT

The fault-controlled kimberlitic Sloan diatreme penetrates Precambrian granitic rocks near Prairie Divide in northern Colorado. The kimberlite is predominantly an intrusive breccia in which clasts consist of serpentine pseudomorphous after olivine and pyroxene, with variable amounts of magnesian ilmenite, perovskite, pyrope, chrome diopside, phlogopite, biotite, chromite, picotite, and magnetite. The matrix of the breccia consists of finely crystalline serpentine, calcite, dolomite, phlogopite, hematite, chlorite, and talc.

Chemical analyses of the kimberlite show low concentrations of SiO_2 , Al_2O_3 , and K_2O and relatively high amounts of MgO and H_2O . These chemical trends and a low phlogopite content suggest a basaltic kimberlite affinity.

Included in the pipe are numerous xenoliths of Precambrian felsic rocks, Upper Ordovician to Silurian (?) carbonates, kimberlite and lherzolite nodules (and mineral inclusions), and phlogopitic carbonate nodules. Stable carbon and oxygen isotope analyses of carbonate inclusions suggest a magmatic origin for the phlogopitic and a few other carbonates, which probably represent a carbonatite liquid that was associated with the original kimberlitic magma.

A very Late Silurian to Early Devonian age of emplacement is postulated.

INTRODUCTION

Several kimberlitic diatremes that penetrate Precambrian crystalline rocks and contain inclusions of sedimentary rocks have recently been recognized in the northern Front Range of Colorado and southern Wyoming (Chronic *et al.*, 1965; D. H. Egger, 1967, Ph.D. thesis, Univ. Colorado, p. 115; McCallum and Egger, 1968; Chronic *et al.*, 1969). The Sloan diatreme, largest of the structures yet discovered in the region, is located near Prairie Divide on the Sloan ranch, about 40 miles northwest of Fort Collins, Colorado (Fig. 1). It has been quarried intermittently for many years as a source of building materials, soil additives, and rock collectors' curios. The pipe penetrates granite of the Precambrian Log Cabin batholith. Both the pipe and the granite were truncated by a Late Tertiary to Pleistocene erosion surface (Sherman surface). Because the kimberlite is rather easily weathered, the pipe surface area, which is approximately 1800 feet by 350 feet, is somewhat lower than that of the more resistant adjacent granitic rocks.

Emplacement of this steep-walled pipe was partially fault-controlled,

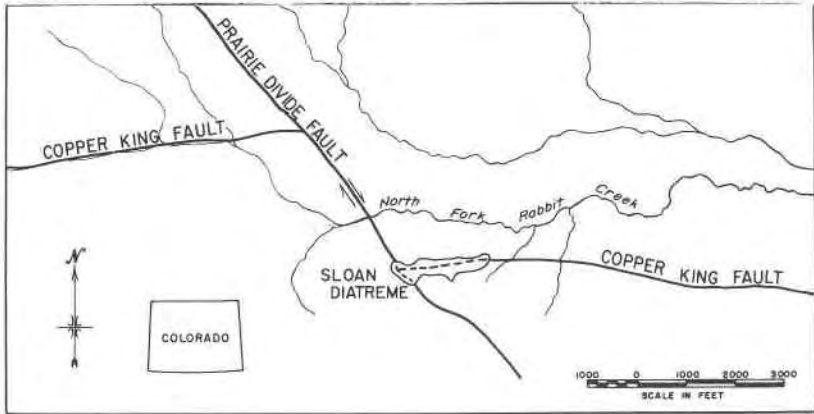


FIG. 1. Location map of the Sloan diatreme.

although prominent joint sets also played an important role. The long dimension coincides with an east-west fault zone (Copper King fault) that is offset at the western edge of the diatreme by a northwest-trending fault zone (Prairie Divide fault) (Fig. 1). Intrusion of volcanic material into the intersection of the fault zones has produced the crudely bilobate surface outline of the pipe. Smaller projections from the main body parallel a set of northwest-trending vertical joints.

PETROGRAPHY

Serpentinized rock in the Sloan diatreme is very similar to ultramafic rocks in pipes from Arkansas (Miser and Ross, 1922), Arizona (Malde, H. E., 1954; Shoemaker *et al.*, 1962; Watson, K. D., 1967), Utah (McGetchin and Silver, 1970), Kansas (Byrne *et al.*, 1956; Rosa and Brookins, 1966), Montana (Hearn, B. C. Jr., 1968), Africa (Dawson, J. B., 1962; Edwards and Howkins, 1966; Nixon *et al.*, 1963), Canada (Watson, K. D., 1955), Czechoslovakia (Kopecky, L., 1967), and Russia (Moor, G. G., 1941; Davidson, C. F., 1957, 1967; Smirnov, G. I., 1959) and has been classified accordingly as kimberlite.

The kimberlite is a light- to dark-green or gray-green rock that typically is decomposed at the surface. The poorly consolidated, highly oxidized pale-green to yellow-green surface material closely resembles the well known "yellow ground" of several famous kimberlite localities. Relatively undecomposed rock is exposed in numerous prospect pits, a 70-foot shaft, a 130 foot drift and in the face of a small quarry (Fig. 2).

Both intrusive breccia and massive varieties of kimberlite are present. No bedded breccia has been recognized. The intrusive breccia (Figs. 3a and 3b), by far the most abundant type, consists of subangular to subrounded mineral and rock fragments (average size about 1 to 5 cm.) set in a fine- to medium-grained matrix. Rock fragments (xenoliths) are chiefly limestone, dolomite, granite, gneiss, and schist with lesser amounts of early generation kimberlite and phlogopitic carbonate, and a few altered lherzolite nodules. Mineral fragments and crystals (xenocrysts or phenocrysts) are mainly derived from deep-seated ultramafic sources, which were almost certainly peridotite or early generation kimberlite, although a few fragmental grains of country rock are also present. Serpentinized olivine

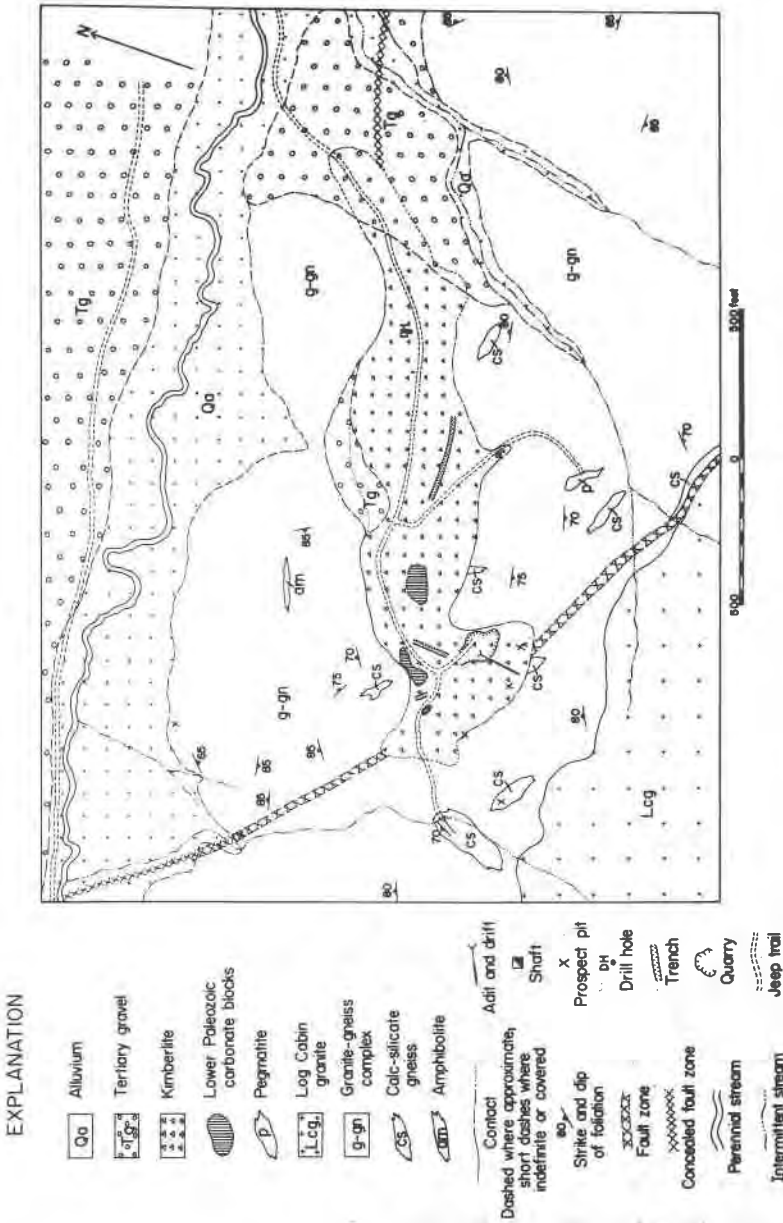


FIG. 2. Generalized geologic map of the Sloan diatreme.

and pyroxene are most abundant; some of the serpentine pseudomorphs are zoned, suggesting former pyroxene (enstatite) coronas on olivine. Lesser amounts of magnesian ilmenite, perovskite, pyrope, chrome diopside, phlogopite, biotite, chromite, picotite, and magnetite are also present as xenocrysts. Some of the biotite crystals and rare grains of quartz and microcline may be derived from the surrounding granite and felsic gneisses and schists. The breccia matrix consists of a finely-crystalline mosaic of serpentine, calcite, and dolomite with minor amounts of phlogopite, hematite, perovskite, ilmenite, chlorite, talc, and a few tiny grains of zircon and apatite.

The less abundant massive kimberlite is porphyritic (Figs. 3c and 3d) and contains very little fragmental material. Serpentine pseudomorphs after olivine and pyroxene xenocrysts or phenocrysts comprise up to 60 percent of the rock, and euhedral to anhedral crystals of phlogopite, perovskite, ilmenite, pyrope, chrome diopside, spinels, and iron ore minerals are usually present. The matrix of the massive kimberlite is similar to that of the intrusive breccia.

Preliminary chemical analysis and density determinations of the two kimberlite types show a basic similarity, although abundant fragmental material in the breccia produces slightly lower density values and higher CaO and CO₂ contents. Density determinations on five samples using a balance and Beckman air-comparison pycnometer range from 2.66–2.72 g./cc. Two whole-rock analyses (Table 1) show low SiO₂, Al₂O₃, and K₂O values and relatively high MgO and H₂O contents, which are indicative of basaltic kimberlites (Dawson, 1962, p. 553). Low phlogopite content also suggests a basaltic rather than micaceous kimberlite affinity.

MINERALOGY

The mineralogy of the Sloan diatreme kimberlite has been studied by petrographic and X-ray diffraction methods. Unit cells were refined by the least-squares method of Evans *et al.* (1963). Microprobe studies were conducted on a few selected samples of garnet, chrome diopside, and ilmenite (Table 2). Several grains of each sample were analyzed on an ARL-AMX electron microprobe analyzer. Dead-time, background, and matrix corrections were made utilizing the Bence and Albee (1968) method. Standards, which are synthetic unless otherwise noted, included: SiO₂ and Al₂O₃, natural kyanite; MgO, enstatite glass and periclase; FeO, fayalite and basalt glass; TiO₂, sphene glass; CaO, diopside glass; Cr₂O₃, natural chromite; MnO, rhodonite glass; Na₂O, nepheline and natural albite; K₂O, natural orthoclase. FeO and TiO₂ were determined on ilmenite with a natural ilmenite standard. Other analyses done by this procedure and analyses of analyzed glasses indicate that results are within five percent of the amount present.

Additional microprobe analyses of several mineral groups are in progress.

Primary Minerals

Pyrope, ilmenite, chrome diopside, spinels, and phlogopite are the most abundant primary minerals preserved in the Sloan kimberlite. All

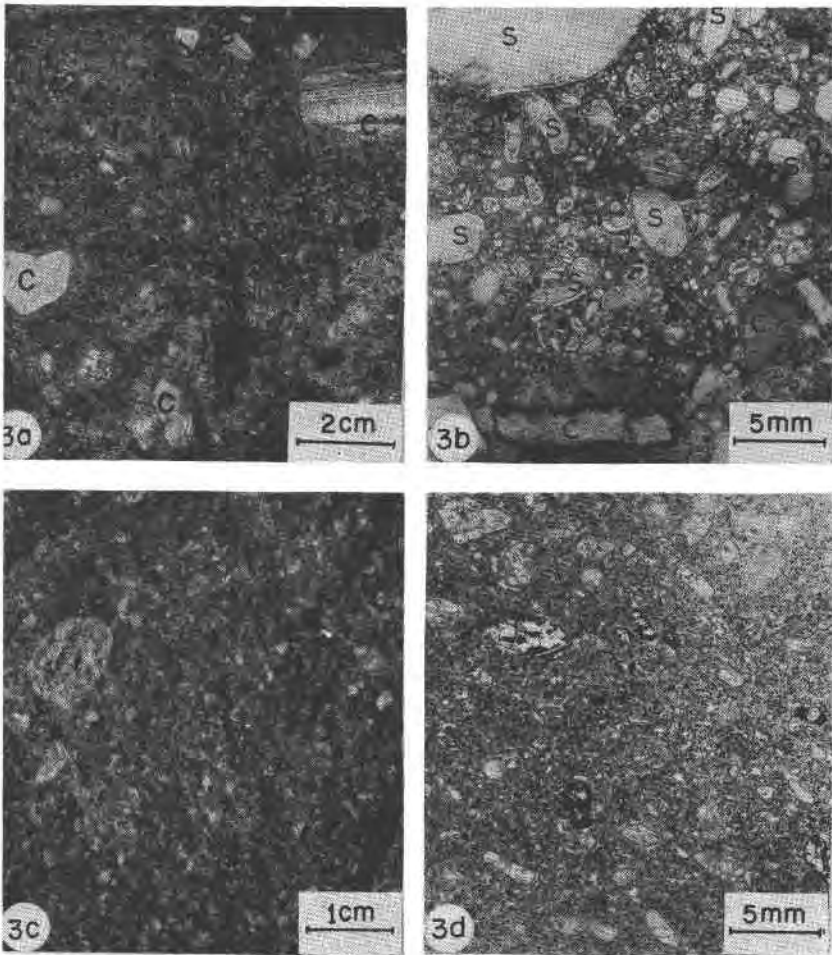


FIG. 3. Hand sample (a) and photomicrograph (b) of kimberlite breccia. Subrounded xenocrysts of serpentine (s) (after olivine and enstatite) and pyrope (p) (with dark kelyphitic rims) and fragments of limestone and dolomite (c) in a serpentine-calcite-dolomite-phlogopite matrix. Opaque grains are magnesian ilmenite, picotite, and chromite.

(c) and (d): Hand sample and photomicrograph respectively of massive porphyritic kimberlite. Subrounded xenocrysts (phenocrysts) of pseudomorphically serpentinized olivine and enstatite in a fine-grained matrix similar to that of kimberlite breccia. Mottled black subrounded grains are serpentinized olivine with abundant finely disseminated magnetite. Small opaque grains are magnesian ilmenite, picotite, chromite, and perovskite.

Table 1. Chemical Analyses of Sloan Diatreme Kimberlite and Average Analyses for Basaltic and Micaceous Kimberlites

	3-23b	3-500	1	2
SiO ₂	31.42	32.24	35.02	36.33
TiO ₂	0.85	1.08	1.22	1.89
Al ₂ O ₃	2.20	3.05	3.90	5.09
Cr ₂ O ₃	0.15	0.16	--	--
Fe ₂ O ₃	5.58	7.41	5.15	7.43
FeO	1.58	1.09	4.14	3.40
MnO	0.13	0.15	0.06	0.10
MgO	27.94	27.13	31.29	26.63
CaO	9.92	8.63	6.80	6.78
Na ₂ O	0.10	0.06	0.34	0.37
K ₂ O	1.27	0.84	1.05	2.43
H ₂ O ⁺	10.42	9.74	7.43	7.25
H ₂ O ⁻	2.23	2.65	--	--
P ₂ O ₅	0.42	0.54	0.87	0.66
CO ₂	5.84	5.20	2.73	1.64
	100.05	99.97	--	--

3-23b. Kimberlite, intrusive breccia, Sloan diatreme, Colorado.
Analyst, Hiroshi Asari.

3-500. Kimberlite, massive, Sloan diatreme, Colorado.
Analyst, Hiroshi Asari.

1. Average chemical composition of basaltic kimberlite,
10 analyses (Nockolds, 1954, p. 1023)

2. Average chemical composition of micaceous kimberlite,
4 analyses (Nockolds, 1954, p. 1023)

occur as subangular to rounded xenocrysts; pebble-shaped fragments of pyrope and ilmenite up to two inches in diameter have been found. Some of the ilmenite and pyrope show surface polishing, pitting, and striations caused by fragment abrasion during emplacement. The mineral inclusions

Table 2. Microprobe Analyses of Selected Minerals from the Sloan Kimberlite

	Garnet		Diopside		Ilmenite
	SD 1	3-29C	SD-P1	SD20	SD50I
SiO ₂	39.8	40.1	54.8	55.1	.02
TiO ₂	.58	.84	.20	.16	50.6
Al ₂ O ₃	19.1	21.3	1.35	1.19	.62
Cr ₂ O ₃	6.5	3.03	1.39	1.47	3.17
FeO*	7.7	8.2	2.02	2.70	30.9
MnO	.39	.29	.13	.11	.24
CaO	7.6	5.0	20.9	20.2	.01
MgO	19.3	21.3	18.0	19.1	13.4
Na ₂ O	.00	.00	1.11	1.14	n.d.
K ₂ O	.01	.01	.02	.04	n.d.
Σ	100.98	100.07	99.92	101.21	98.96

* Total Fe as FeO

are apparently disaggregation products from a previously-consolidated kimberlite or possibly from lherzolite and eclogite (?).

Pyrope grains are highly fractured and range in color from deep red to reddish-black and rarely pale purple to orange. Fractures are filled with calcite, chlorite, and/or chrysotile, and smaller grains are usually rimmed by kelyphite. Kelyphite rinds were apparently stripped off most of the larger pyrope xenocrysts during intrusion of the pipe. Refractive indices and unit cell dimensions of several garnet grains range from 1.746 to 1.755 and 11.547 to 11.584 (Å) respectively, indicating an average pyrope-molecule content in excess of 75 percent (Sriramadas, 1957, p. 297). Microprobe data for the two garnet samples analyzed show high Cr₂O₃ contents (Table 2) characteristic of chrome pyropes (Nixon *et al.*, 1963, p. 1105).

Ilmenite occurs as common breccia fragments and as abundant microcrysts and megacrysts in kimberlite matrix. Leucoxene coatings are typical, particularly on smaller grains, which also may be surrounded with granular perovskite. X-ray powder data for Sloan ilmenite samples compare favorably with those of magnesian ilmenite from Basutoland kimberlites (Nixon *et al.*, 1963, p. 1121). The *d*-spacings and the refined unit cell dimensions indicate moderate substitution of Fe²⁺ by Mg²⁺, and density values of Sloan ilmenite also indicate the presence of appreciable geikielite molecule. Cell dimensions and density values for ilmenite-geikielite are as follows:

	<i>a</i> (Å)	<i>c</i> (Å)	ρ
Ilmenite ^a	5.09	14.16	4.72
Geikielite ^a	5.10	14.12	4.05
Sloan ilmenite	5.062	13.922	4.43

^a After Deer, Howie, and Zussman, 1962, p. 31

Microprobe analysis of a Sloan ilmenite sample shows an MgO content of 13.4 percent (Table 2). Analysis of another ilmenite sample from a nearby diatrema (Schaffer diatrema-Chronic *et al.*, 1969) shows an MgO content of 4.5 percent.

Numerous xenocrysts of chrome diopside, an emerald-green clinopyroxene, are present in the kimberlite; they are particularly abundant in dump material from a shallow shaft near the south margin of the pipe (Fig. 2). Grains are typically subrounded, range up to an inch in diameter, and commonly are rimmed by thin rinds of a finely-crystalline serpentine-calcite mixture. Most of the chrome diopside shows little internal alteration, although in a few grains minor amounts of serpentine and chlorite (?) were observed along well-developed planes of cleavage and parting. The chromian clinopyroxene is normally nonpleochroic, although a faint pleochroism from light gray-green to yellow-green may be observed. The optic axial angle ($2V_z$) ranging from 58 to 60° tends to be slightly higher than for non-chromian diopsides, and $Z \wedge c$ is 38 to 40°. Preliminary microprobe analyses indicate Cr₂O₃ contents of approximately 1 to 1.5 percent (Table 2).

Small euhedral to anhedral crystals of spinel-group minerals typically occur in kimberlite matrix. Magnetite and reddish-brown picotite up to about 0.5 mm are most common, and a few grains of brownish-black to gray-black chromite have been recognized. Some of the magnetite may be a secondary product of serpentinization. Perovskite is associated with and occasionally mistaken for groundmass spinel. Perovskite occurs in abundance as tiny dark brown grains (commonly cubes) and semi-opaque brownish-black aggregates. Individual crystals range up to about 0.8 mm

and may be zoned. Both crystals and aggregates are usually leucoxenized, and the aggregates commonly contain corroded grains of ilmenite.

Phlogopite occurs as medium-sized (several mm.) euhedral to subhedral crystals in the kimberlite groundmass and is generally at least partially altered to chlorite. The phlogopite absorption formula is normal, $Z = Y > X$ with pleochroism of X = pale yellow orange, Y and Z = reddish orange. X-ray data suggest a (1M) phlogopite with appreciable Fe^{2+} replacing Mg^{2+} . Phlogopite is also an important constituent of a number of carbonate xenoliths.

Minor amounts of biotite and zircon are also present in the kimberlite. These may be accidental inclusions from adjacent granitic and schistose rocks, but close association of many grains with phlogopite suggests a primary kimberlitic origin for at least some.

Only a few small crystals of apatite have been recognized in the Sloan kimberlite. However, a significant submicroscopic content is inferred from appreciable quantities of P_2O_5 in chemical analyses (Table 1).

Carbonate minerals in the Sloan diatreme are clearly derived from several sources. Excluding xenoliths, carbonates occur as finely-crystalline matrix constituents, secondary alteration products, and vein fillings. Although some of the matrix material may have been derived from local calcareous rocks, most of it and many carbonate xenoliths are magmatic in origin (see section on stable isotopes). Calcite is the predominant carbonate, but dolomite is also abundant, and magnesite has been tentatively identified. Aragonite is also present, but appears to be exclusively a secondary vein-filling mineral.

Secondary Minerals. Secondary or alteration minerals comprise the greatest proportion of the Sloan diatreme kimberlite. Of these, serpentine-group minerals are by far the most important.

Serpentine minerals occur chiefly as pseudomorphs after olivine and orthopyroxene xenocrysts and phenocrysts, as fine-grained lamellae and platelets in the groundmass, and as secondary rims on many xenocrystic and xenolithic fragments. Several types of serpentine have been recognized by optical and X-ray data, but the most common appears to be a mixture of both single- and double-layered lizardite-chrysotile (Whitaker and Zussman, 1956). Aluminian serpentine (Bailey and Tyler, 1960) is also present, and antigorite pseudomorph after enstatite (bastite) is fairly abundant. Fibrous chrysotile is a common vein-filling constituent, and fine-grained serpophite has been identified in the kimberlite groundmass. X-ray data for some of the serpentines are compiled in Table 3.

Much of the serpentine that is pseudomorphous after olivine contains abundant small grains of magnetite formed during the serpentinization

Table 3. X-ray Powder Data for Serpentine Minerals from the Sloan Kimberlite (CuK α radiation)

SD 1 d λ	SD 2 d λ	SD 10 d λ	SD 11 d λ	SD 12 d λ	SD 13 d λ
I	I	I	I	I	I
7.26	7.17	7.25	7.28	7.28	7.28
vs	vs	vs	vs	s	vs
4.55	4.55	4.57	4.48	4.53	4.52
m	w	w	s	w	w
3.62	3.61	3.60	3.62	3.64	3.65
vs	s	vs	vs	m	vs
2.84			2.80		
w			m		
2.65	2.63	2.63	2.69	2.69	
m	w	w	m	m	
2.491	2.502	2.495	2.592	2.506	2.508
s	m	s	m	m	m
2.455	2.476		2.491	2.452	2.433
m	m		s	s	m
2.279			2.281	2.273	
w			m	s	
2.087			2.285		2.141
m			w		w
			2.151		2.083
			w		v
			2.089		2.092
			w		w
			1.792		1.814
			w		s
1.533	1.536	1.538	1.532	1.537	1.534
m	w	m	s	s	w
	1.514				
	m				
1.472	1.471	1.506			1.501
w	vw	m			w
				1.451	1.472
				w	w
1.153			1.184	1.180	1.196
vw			w	w	w
				1.152	1.157
			1.046	1.045	vw
			w	vw	

SD 1 Chrysotile-lizardite mixture in kimberlite matrix.

SD 2 Aluminian serpentine in kimberlite matrix.

SD 10 Chrysotile-lizardite xenocryst.

SD 11 Antigorite-lizardite mixture; serpentine pseudomorphous after olivine.

SD 12 Red hematitic serpentine: antigorite-lizardite mixture; serpentine pseudomorphous after olivine.

SD 13 Bastite (antigorite-lizardite) corona on pseudomorphous olivine.

reaction. A deep-red variety is apparently also an alteration product of olivine and derives its color from finely disseminated hematite concentrated along cleavage planes. Some of the serpentine pseudomorphs are rimmed by an optically-inhomogeneous serpentine with pronounced cleavage (or parting) and parallel extinction. Rims appear to be more antigoritic than cores and probably reflect chemical differences between former olivine crystals and enstatite coronas.

Thin, second-generation serpentine rinds on many xenocrysts and xenoliths appear to consist of mixed serpentine minerals, with chrysotile generally predominant.

Serpentine xenocrysts are typically partially replaced by carbonate minerals, particularly by dolomite and, to a lesser extent, calcite. Many carbonate xenoliths display a thin surface rind in which magnesian carbonate has replaced (dolomitized) the more calcic parent material.

Other secondary minerals reported from the Sloan kimberlite are the phyllosilicates chlorite, talc, and montmorillonite. These minerals are most prevalent in the deeply-weathered "yellow ground" areas of the diatreme surface. Small amounts of limonite, chalcedonic chert, and mixed clays are also present locally.

XENOLITHS

Xenoliths in the Sloan diatreme include Lower Paleozoic carbonates, Precambrian crystalline rocks, and kimberlite, lherzolite, and carbonatite nodules (commonly phlogopitic). Alteration of most xenoliths is minor and chiefly involves surface hydration and/or carbonation of constituent minerals. Many of the xenoliths (as well as xenocrysts) have thin serpentine and carbonate rinds, and carbonate inclusions commonly have partially dolomitized border zones.

Sedimentary carbonate xenoliths are most abundant and consist of small subrounded fragments to large angular blocks of limestone, dolomite, and dolomite breccia. Three major chaotic block concentrations have been mapped (Fig. 2) where individual xenoliths range up to 10 feet across. All of the sedimentary carbonates represent formations that have been stripped away by erosion subsequent to kimberlite emplacement. Fossils indicate an Upper Ordovician and Silurian age for the sedimentary xenoliths (Chronic *et al.*, 1969, p. 154).

Abundant smaller carbonate inclusions which are not obviously sedimentary in origin are found in kimberlite, together with nodules of phlogopitic carbonatite. These rounded to subrounded carbonate nodules have been observed at many localities in the diatreme. No equivalent rocks are known in nearby bedrock outside of the pipe, and isotope studies suggest that they are chiefly carbonatites derived from a magma related to the kimberlite.

Crystalline rock xenoliths consist of pebble- to boulder-sized blocks of granite, gneiss, and schist, similar to Precambrian rocks in the immediate vicinity. These inclusions are generally not significantly altered, although some show saussuritization of plagioclase and/or oxidation and chloritization of biotite and hornblende.

A few small nodules (up to 10 cm.) of serpentized lherzolite have been found in the quarried area of the diatreme (Fig. 2). These consist chiefly of coarsely crystalline, serpentized olivine and orthopyroxene (enstatite) with abundant unaltered emerald green chrome diopside. Most of the lherzolites contain small to moderate amounts of dark brown to black spinel, and some contain garnet and/or phlogopite. Several small rounded cognate kimberlitic nodules, similar in composition to the enclosing kimberlite, are also present but are much less abundant than kimberlitic mineral xenocrysts.

No nodules of eclogite have yet been found at the Sloan locality; however, a well preserved four inch eclogite inclusion was recently collected from the Schaffer 3 diatreme several miles to the north.

STABLE ISOTOPES OF CARBONATE INCLUSIONS

Stable carbon and oxygen isotope ratios have been determined on calcite from several samples of Sloan diatreme rocks by Dr. Peter Deines. Nine carbonate inclusions from serpentized kimberlite group closely about an average value of δO^{18} (‰, relative to SMOW, standard mean ocean water) = +13, δC^{13} (‰, relative to PDB, Pee Dee belemnite calcite) = -4. Two samples of calcite-phlogopite marble (carbonatite) average δO^{18} = +17, δC^{13} = -6.5, and a late carbonate vein has δO^{18} = +27, δC^{13} = -3.5.

Samples of obvious Paleozoic limestone from the pipe have very different isotopic composition: δO^{18} = +23, δC^{13} = 0. Carbonate inclusions analyzed cannot, therefore, be xenoliths of unaltered limestone. They could be limestone which was recrystallized during upward transport in the pipe. However, not only recrystallization, but complete isotopic exchange with a fluid phase would be necessary to produce the ratios observed. Partial exchange should produce a range of values. The δC^{13} ratio is particularly diagnostic, since exchange with carbon-free country rocks lower in the pipe would not change δC^{13} . Because the range of ratios found in inclusions so far sampled is restricted (δC^{13} = -7.5 to -4.5), we tentatively conclude that most carbonate inclusions are primary, possibly from a carbonatite magma. The calcite-phlogopite inclusions, which fall into a different range, are more conclusively magmatic, and may represent a different carbonatite stage.

Stable isotope ratios for all these non-sedimentary carbonate inclusions lie within the range of values from other carbonatite and kimberlite

sequences, in particular the exceptionally well-studied Oka carbonatite-alkalic complex (Deines, 1967). The values from the Sloan diatreme are heavier in both carbon and oxygen than material Taylor *et al.* (1967) consider to be primary carbonatite. These heavier values may reflect differentiation of a primary carbonatite magma before intrusion or incorporation in a kimberlite pipe.

NATURE AND AGE OF EMPLACEMENT

Mechanisms for the emplacement of kimberlitic diatremes have been subject to controversy for many years. However, most current workers seem to favor some form of fluidization process. An excellent review of the subject of emplacement mechanisms has been compiled by J. B. Dawson (1967, p. 246-247).

In the initial stages of kimberlitic magma intrusion, upward migration was apparently controlled by some deep-seated zone of crustal weakness such as a system of tension fractures as suggested by Dawson (1967, p. 246). The site of surface penetration of the gas-charged magma, or fragments of consolidated magma, is in turn determined by near-surface structures such as joint sets and faults. Emplacement of the Sloan diatreme was determined by the presence of intersecting fault zones, the geometry of which is well expressed by the surface configuration of the pipe (Figs. 1 and 2). Intrusion apparently occurred through a gas-solid streaming mechanism, which we infer from the presence of abundant rounded to subrounded rock and mineral fragments, and from the surface polishing, striations, and pitting of many pyrope and ilmenite inclusions. Surface velocities of such a stream can approach Mach 3 (McGetchin, 1969). A relatively low temperature of intrusion is indicated by the nearly complete lack of contact metamorphism (pyrometamorphism) of wall rocks and included xenoliths.

Since the kimberlite contains sedimentary rock xenoliths of Upper Ordovician and Silurian age, the intrusion must have penetrated a Lower Paleozoic rock sequence that was subsequently removed by erosion. Subsidence of the sedimentary rock slabs and fragments several hundreds to thousands of feet into the pipe, where they were preserved as xenoliths in the kimberlite, has provided the sole remaining record of Early Paleozoic sedimentation in the Northern Front Range of Colorado (Chronic, *et al.*, 1969).

The time of kimberlite emplacement is uncertain, but paleontological evidence and local geology indicate a post-Silurian or very Late Silurian, pre-Pennsylvanian age. Since no Upper Paleozoic rocks appear to be present in the diatreme, and since the Lower Paleozoic cover must have been stripped off well before local Pennsylvanian arkoses were deposited and very possibly was removed before deposition of Devonian sedi-

ments, emplacement of the Sloan diatreme most likely occurred prior to the pre-Devonian erosional cycle (Chronic *et al.*, 1969, p. 155). A very late Silurian or Early Devonian age of emplacement is postulated.

ACKNOWLEDGMENTS

The study was supported in part by Colorado State University, FIC Grant No. 5301-80. The authors wish to acknowledge the assistance of R. K. Corbett, J. W. Creasy, W. M. Oriel, and E. M. Warner in the plane table preparation of topographic and geologic maps of the area. Appreciation is also expressed to Mr. and Mrs. George Gibbs of the Sloan Ranch for their cooperation and hospitality during the course of our field studies, and to Mr. Frank Yaussi for his assistance in the area. Thanks are also extended to B. C. Hearn, Jr., B. F. Leonard, S. A. Schumm, and G. L. Millhollen for critical reading of the manuscript. We gratefully acknowledge the use of the electron microprobe in the Mineral Constitution Laboratories, College of Earth and Mineral Sciences, Pennsylvania State University. The isotope analyses were very kindly performed by Peter Deines in the Pennsylvania State University mass spectrographic laboratories.

REFERENCES CITED

- BAILEY, S. W., AND S. A. TYLER (1960) Clay minerals associated with the Lake Superior iron ores. *Econ. Geol.* **55**, 150-175.
- BENCE, A. E., AND A. L. ALBEE (1968) Empirical correction factors for the electron microanalysis of silicates and oxides. *J. Geol.* **76**, 382-403.
- BYRNE, F. E., K. L. PARISH, AND C. F. CRUMPTON (1956) Igneous intrusions in Riley County, Kansas. *Amer. Assoc. Petrol. Geol. Bull.* **40**, 377-387.
- CHRONIC, J., M. E. MCCALLUM, AND C. S. FERRIS, JR. (1965) Lower Paleozoic rocks in diatremes in southern Wyoming and northern Colorado (abstr.). *Geol. Soc. Amer. Spec. Pap.* **87**, 280.
- CHRONIC, J., M. E. MCCALLUM, C. S. FERRIS, JR., AND D. H. EGGLEER (1969) Lower Paleozoic rocks in diatremes, southern Wyoming and northern Colorado. *Geol. Soc. Amer. Bull.* **80**, 149-156.
- DAVIDSON, C. F. (1957) The diamond fields of Yakutia. *Mining Mag. (London)* **97**, 329-337.
- (1964) On diamantiferous diatremes. *Econ. Geol.* **59**, 1368-1380.
- (1967) The kimberlites of the U.S.S.R. In P. J. Wyllie, ed. *Ultramafic and Related Rocks*, John Wiley and Sons, 251-261.
- DAWSON, J. B. (1962) Basutoland kimberlites. *Geol. Soc. Amer. Bull.* **73**, 545-560.
- (1967) A review of the geology of kimberlite. In P. J. Wyllie, ed. *Ultramafic and Related Rocks*, John Wiley and Sons, 241-251.
- DEER, W. A., R. A. HOWIE, AND J. ZUSSMAN (1962) *Rock-forming Minerals*, Vol. 5. John Wiley and Sons, Inc.
- DEINES, P. (1967) *Stable Carbon and Oxygen Isotopes of Carbonatite Carbonates and Their Interpretation*. Ph.D. Thesis, Penn. State Univ.
- EDWARDS, C. B., AND J. B. HOWKINS (1966) Kimberlites in Tanganyika with special reference to the Mwadui occurrence. *Econ. Geol.* **61**, 537-554.
- EVANS, H. T., JR., D. E. APPLEMAN, AND D. S. HANDWERKER (1963) The least-squares refinement of crystal unit cells with powder diffraction data by an automatic computer indexing method (abstr.) *Amer. Crystallogr. Assoc. Meet. Cambridge, Mass., Abs.* **42**.
- HEARN, B. C., JR. (1968) Diatremes with kimberlitic affinities in north-central Montana. *Science* **159**, 622-625.

- KEITH, M. L., AND J. N. WEBER (1964) Carbon and oxygen isotopic composition of selected limestones and fossils. *Geochim. Cosmochim. Acta* **28**, 1787-1816.
- KOPECKY, L., J. PISOVA, AND L. POKORNY (1967) Pyrope-bearing diatremes of the České středohoří Mountains. *Sb. Geol. Ved* **12**, 81-126.
- MALDE, H. E. (1954) Serpentine pipes at Garnet Ridge, Arizona. *Science* **119**, 618.
- MCCALLUM, M. E., AND D. H. EGGLEER (1968) Preliminary report on mineralogy of kimberlitic diatremes in the Northern Front Range, Colorado-Wyoming (abstr.) *Geol. Soc. Amer. Spec. Pap.* **121**, 192.
- MCGETCHIN, T. R. (1969) Source and emplacement of kimberlite at Moses Rock, Utah (abstr.) *Trans. Amer. Geophys. Union* **50**, 345.
- , AND L. T. SILVER (1970) Compositional relations in minerals from kimberlite and related rocks in the Moses Rock dike, San Juan County, Utah. *Amer. Mineral.* **55**, 1738-1771.
- MISER, H. O., AND C. S. ROSS (1922) Diamond-bearing peridotite in Pike County, Arkansas. *U. S. Geol. Sur. Bull.* **735**, 279-322.
- MOOR, G. G. (1941) Micaceous kimberlite in the north of central Siberia. *Dokl. Akad. Nauk S.S.S.R.* **31**, 363-365.
- NIXON, P. H., O VON KNORRING, AND J. M. ROOKE (1963) Kimberlites and associated inclusions of Basutoland: A mineralogical and geochemical study. *Amer. Mineral.* **48**, 1090-1132.
- NOCKOLDS, S. R. (1954) Average chemical composition of some igneous rocks. *Geol. Soc. Amer. Bull.* **65**, 1007-1032.
- ROSA, F., AND D. G. BROOKINS (1966) The mineralogy of the Stockdale kimberlite pipe, Riley County, Kansas. *Trans. Kan. Acad. Sci.* **69**, 335-347.
- SHOEMAKER, E. M., C. H. ROACH, AND F. M. BYERS, JR. (1962) Diatremes and uranium deposits in the Hopi Buttes, Arizona. *Geol. Soc. Amer., Buddington Vol.*, 327-355.
- SMIRNOV, G. I. (1959) Mineralogy of Siberian kimberlites. *Tr. Yakutskogo Fil. Akad. Nauk S.S.S.R.*, No. 4, 47-74. [Transl. *Int. Geol. Rev.* **1**, 21-39 (1959)]
- SRIRAMADAS, A. (1957) Diagrams for correlation of unit cell edges and refractive indices with chemical composition of garnets. *Amer. Mineral.* **42**, 294-298.
- TAYLOR, H. P., JR., J. FRECHEN, AND E. T. DEGENS (1967) Oxygen and carbon isotope studies of carbonatites from the Laacher See District, West Germany and the Alnö District, Sweden. *Geochim. Cosmochim. Acta* **31**, 407-430.
- WATSON, K. D. (1955) Kimberlite at Bachelor Lake, Quebec. *Amer. Mineral.* **40**, 565-579.
- (1967) Kimberlite pipes in northeastern Arizona. In P. J. Wyllie, ed. *Ultramafic and Related Rocks*, John Wiley and Sons, 261-269.
- WHITTAKER, E. J. W., AND J. ZUSSMAN (1956) The characterization of serpentine minerals by X-ray diffraction. *Mineral. Mag.* **31**, 107-126.

Manuscript received, February 18, 1971; accepted for publication, April 19, 1971.