Reports

Diatremes with Kimberlitic Affinities in North-Central Montana

Abstract. *Diatremes in the Missouri River Breaks demonstrate systematic subsidence-ring structure, contain inclusions derived from far above and far below, and have been produced by gas-rich eruptions of alkalic ultramafic magmas. Similar magmas have produced diatremes in many localities in the world and are known to be closely associated with and probably parental to kimberlites.*

My purposes are to describe a newly discovered group of ultramafic diatremes with subsidence-ring structure, to discuss their associated intrusions and inferred histories of eruption, and to point out the relation of the ultramafic magma to kimberlites (*1*). The term diatreme was originally used to describe volcanic pipes or vents filled with fragmental material and thought to be produced by gas-rich volcanic activity. Of the world's diatremes that are known to have been eruptive, many exhibit some or all of the following characteristics: (i) a parental magma that is mafic alkalic or ultramafic alkalic in composition; (ii) major subsidence of the pyroclastic filling; (iii) large xenoliths that have descended hundreds or thousands of meters; (iv) xenoliths that have been brought up from great depth. The diatremes in north-central Montana show all these characteristics.

Alkalic ultramafic rocks occur as intrusions and eruptive diatremes in a broad band 160 km long through the Missouri River Breaks (badlands) between the Highwood and Little Rocky mountains (Fig. 1). The occurrences newly recognized as eruptive diatremes occur in the east-central part of the band; dikes and plugs at the ends of the band are in part brecciated but cannot be shown to have reached the surface. The westernmost authenticated occurrence of alkalic ultramafic rocks is the Haystack Butte intrusion (*2*). Reeves (*3*) showed as "intrusive rocks" in his map area eight of the 22 diatremes and three of the 11 major ultramafic dikes found by me; the eastern occurrences are mapped as lamprophyre in the Little Rocky Mountains (*4*).

The intrusive rocks, whether within, adjacent to, or distant from eruptive diatremes, are remarkably uniform in mineralogy: phenocrysts of forsteritic olivine in groundmasses of monticellite or melilite (or both), nepheline, interstitial or poikilitic phlogopite (in part with abnormal absorption, $\alpha > \beta = \gamma$), and tiny crystals of perovskite and opaque minerals. The rocks are characteristically free of pyroxene except where contaminated by siliceous inclusions. The diatreme-producing igneous rocks are ultramafic and alkalic, rich in calcium, and generally richer in potassium than in sodium. These rocks could be termed mica peridotite (*5*) or, more specifically, monticellite peridotite and alnoite, as they were termed by Buie (*2, 6*), who presented chemical analyses and mineralogical data for the host monticellite peridotite, and later alnoite (*7*), in the Haystack Butte intrusion. The newly discovered occurrences of these rock types, distinctly different from the main igneous rocks of the nearby alkalic centers (Fig. 1), provide a firm basis for a lime-rich, silica-poor subprovince, tentatively proposed by Larsen (*8*), within the petrographic province of central Montana (*9*).

Near the diatremes, Precambrian crystalline rocks are overlaid by 1070 m of Paleozoic and Jurassic and 1130 m of Cretaceous sedimentary rocks. Now entirely eroded away, but preserved piecemeal within the diatremes, 950 m or more of beds, late Cretaceous through early Eocene in age (Fig. 3), can be accurately inferred from measured sections in the Bearpaw Mountains (*10*). The eruption surface was at least 1280 m above the deepest present exposures of the diatremes. Inclusions of distinctive igneous rocks, typical of the Bearpaw and Highwood mountains, indicate that at the time of diatreme eruption there was a discontinuous surficial veneer of air-fall and water-transported material derived from those mountain areas (*11*).

The structure of the Cretaceous country rock is characterized by narrow sinuous lineaments, 0.8 to 1.6 km in width, of upfolded and upfaulted beds, separated by strips several kilometers in width of undeformed flat-lying beds (*12*). The ultramafic igneous activity is younger than the fault-fold deformation, where age relations can be determined; stratigraphic and structural evidence indicates that the igneous activity is younger than middle Eocene and is pre-Miocene.

The subsidence-ring structure (Fig. 2) of the diatremes is notably consistent; they are circular to elliptical in plan, ranging from 518 by 290 m to 46 m in diameter, and have nearly vertical contacts with wall rocks of Upper Cretaceous shale and sandstone. Around the larger diatremes the wall rocks commonly have been downwarped or downfaulted within a zone 30 to 60 m in width adjacent to the main ring fracture. The internal structure typically consists of a discontinuous outer collar of downfaulted arcuate slices that have descended as much as 1280 m; the collar surrounds a sequence of bedded pyroclastic rocks dipping inward toward a central or eccentric core of unbedded crosscutting breccia. Intrusive ultramafic rocks occur as dikes and irregular intrusions within the diatremes, and also as discontinuous ring dikes close to the main ring fracture. There are no known flows within or adjacent to diatremes.

All the formations now missing outside the diatremes are represented by downfaulted slices in the collars, although any single diatreme may contain slices of only one or two formations. The higher formations are notably more abundant than the lower formations because of relative thicknesses and proximity to the surface. The downfaulted slices are deformed, tend to be arcuate and elongate parallel to the ring fracture, and range in size from smears 2.5 cm thick to blocks 180 by 30 m. In general, beds within the slices are steep to vertical, strike parallel to the elongation, and are commonly sheared and thinned. In the larger slices, individual beds can be traced for tens of meters. Where two or more slices are adjacent, their downward displacement increases toward the center of the diatreme.

The bedded pyroclastic rocks, predominantly tuff and lapilli tuff, are mixtures of rounded, commonly pelletal fragments of fine-grained ultramafic rocks (*13*) and rounded to angular fragments of sedimentary rocks in proportions varying from about 1:4 to 4:1. The ultramafic fragments closely resemble in composition the fine-grained intrusions, but are more altered, having conspicuous pseudomorphed phenocrysts of olivine. Identifiable fragments of sedimentary rock are derived from all the higher formations and also from Cretaceous formations adjacent to, or as much as 610 m deeper than, the present exposures. Fragments from deeper formations, especially Jurassic or Paleozoic limestone or dolomite, are rare. Pyroclastic bedding is rather even, is commonly graded in particle size and amount of igneous fragments, and typically ranges from 1.2 to 30.5 cm in thickness; it largely resulted from air-fall deposition, since features of subaqueous deposition or reworking are quite rare. Large-scale angular unconformities are present. The bedding commonly shows an overall saucer-shaped structure: steep inward dip near the diatreme margin (exceeding any possible initial dip) becomes progressively shallower inward.

Large pipelike or arcuate bodies of massive breccia are centrally and marginally located and have near-vertical contacts. The massive breccias are similar in composition to the bedded pyroclastic rocks but are coarser and contain a higher proportion of ultramafic igneous fragments. Several breccias contain a few percent of Paleozoic limestone and dolomite inclusions. Abundant inclusions from greater depth, found in only three breccia pipes within diatremes and in one dike, fall into three groups: (i) quartz-bearing schistose rocks; (ii) biotite-pyroxene-carbonate rocks; and (iii) separate garnets, banded garnet-clinopyroxene-plagioclase-rutile granulites, and altered garnet-pyroxene peridotite. The last group is more likely to be from a very

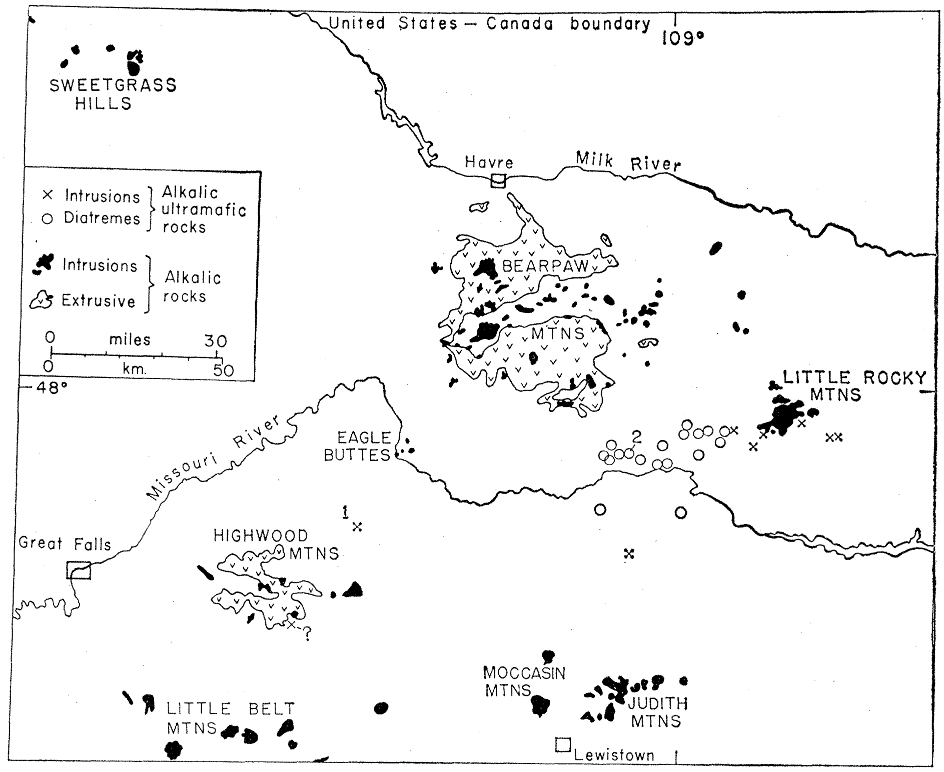

Fig. 1. North-central Montana: locations of diatremes and intrusions of alkalic ultramafic rocks in relation to alkalic igneous centers of the Bearpaw, Highwood, Little Rocky, Judith, Moccasin, and Little Belt mountains, Sweetgrass Hills, and Eagle Buttes. *1*, Haystack Butte; *2*, Black Butte. [Geology modified from Geologic Map of Montana (*22*)]

deep source. The separate garnets and the garnets in the granulites have refractive indices and cell dimensions indicating a high content of the pyrope component. The Navajo diatremes contain similar granulites, and occurrence of such granulites in pipes in Australia, Africa, and the U.S.S.R. has been taken to indicate similarity of the lower crust beneath several continents (*14*).

On the basis of observed internal

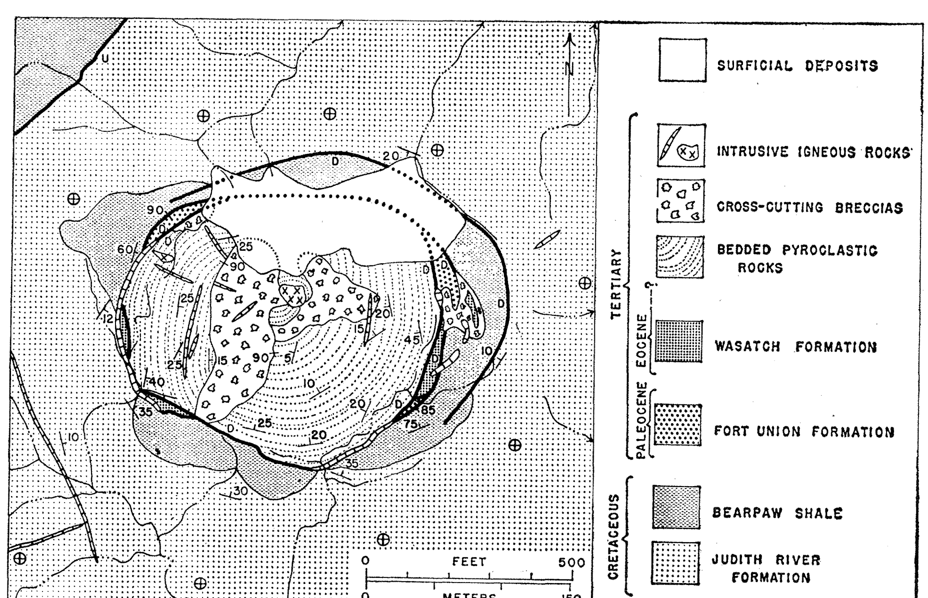

Fig. 2. Generalized geologic map of Black Butte diatreme in NE¼NE¼ sec. 20; T, 24N; R, 20E, Blaine County, Montana; geologic symbols are standard. Fault in northwest corner is northwest boundary of uplifted horstlike block within a linear fault-fold structure penetrated by the diatreme.

structure and the presence of inclusions derived from above and below, deeply eroded diatremes can be extrapolated diagrammatically upward to the eruption surface (Fig. 3). The downward displacement of slices and inclusions by thousands of meters in pipes a few hundred meters in diameter, which would be extraordinary in most igneous and structural frameworks, is commonplace in diatremes (*15, 16*). Subsidence of bedded pyroclastic rocks also is common in diatremes, but is more difficult to establish. Two lines of evidence indicate that the pyroclastic beds were not initially deposited at their present levels: (i) the wall rocks are much too weak to have tolerated open pipes several thousand meters in depth during the time necessary for incremental filling; (ii) the only logical mechanism for emplacing the downfaulted slices is by drag of parts of the higher wall rocks that were caught and sheared between the descending pyroclastic fill and the wall of the narrowing pipe (*17*).

The diatremes were bored during ascent of a gas-rich magma having the composition of monticellite peridotite or alnoite. At deeper levels, boring was perhaps initially effected by a convection-spalling mechanism (*18*); at shallower levels, boring was more likely accomplished by a gas-coring mechanism (*16*). The internal features of the Montana diatremes indicate that repeated eruptions alternated with subsidence to keep the pipe filled to a level near the surface. The coarseness of pyroclastic rocks, rather wide separation of diatremes, and lack of features of aqueous deposition require that each diatreme was filled by its own eruptions, not by eruptions from another vent. Ring dikes, plugs, and crosscutting breccias are probable channels for repeated eruptions that produced pyroclastic beds at higher levels than the preserved sections.

The Montana diatremes provide a definitive relation among alkalic ultramafic magma, kimberlite, and the diatreme type of eruption; many of their features can be duplicated in other diatremes, including the kimberlite diatremes. Another similarity to kimberlite diatremes is in the composition and mineralogy of the igneous rocks: Kimberlite occurrences can be grouped according to the presence or absence of closely associated magmatic rocks occurring as inclusions, as intrusions within the pipes, and as the dominant component of pyroclastic rocks. It has long been recognized that such magmatic rocks are probably parental to kimberlites, and are mica peridotite, monticellite peridotite, alnoite, meimechite (*19*), and other relatives of the subsilicic, melilite-bearing suite of rocks. For example, Wagner (*20*) defined the two major mineralogic varieties of South African kimberlite, basaltic and micaceous, as porphyritic monticellite-olivine peridotite and porphyritic mica peridotite closely allied to alnoite. Thus,

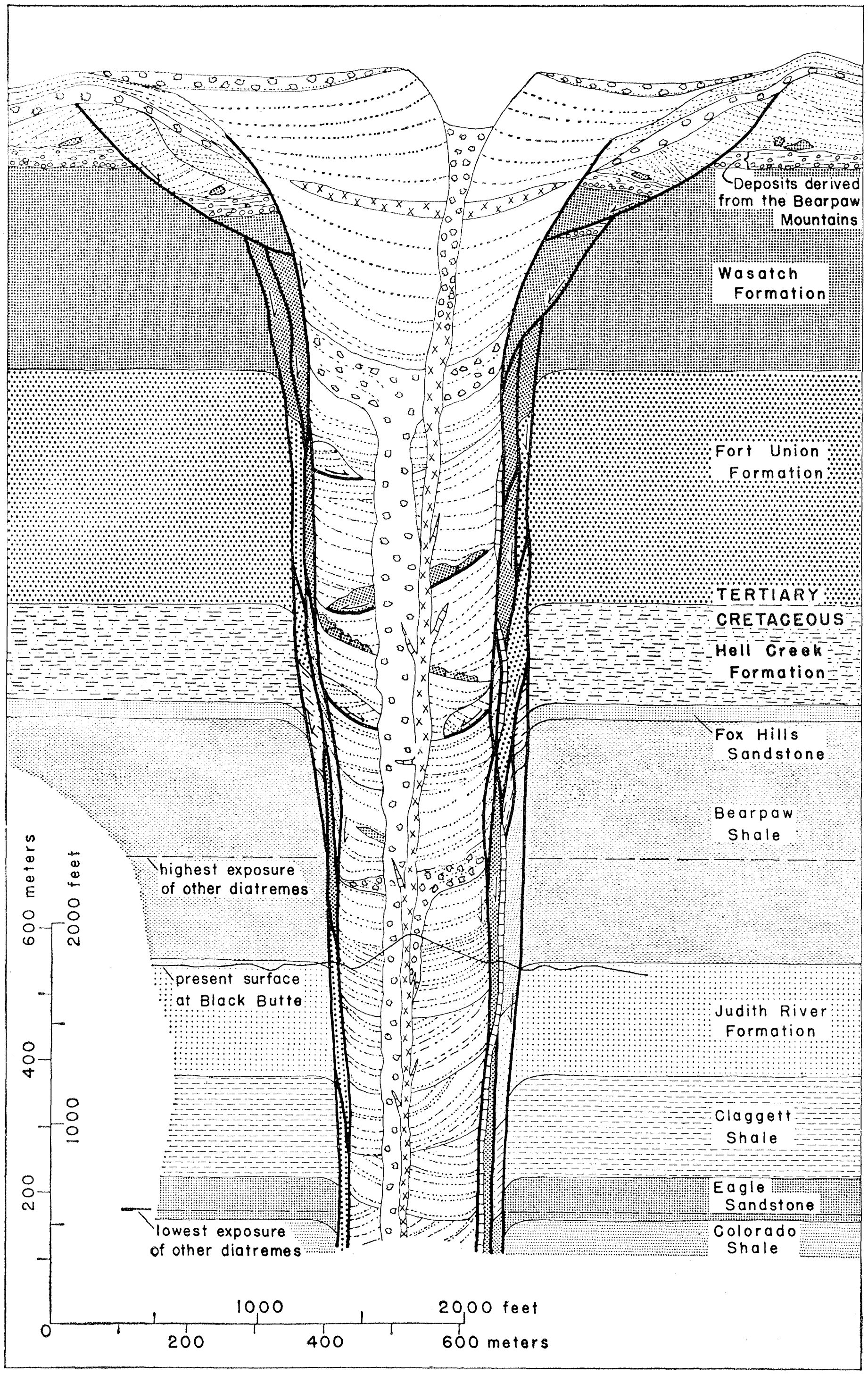

Fig. 3. Diagrammatic cross section, based on the Black Butte diatreme, showing inferred geologic structure up to the surface of eruption. Structure inferred below the surface of eruption is generalized from features seen in other diatremes in north-central Montana. Note the present surface at Black Butte, and the upper and lower limits of exposure of wall rocks of other diatremes. Igneous units patterned as in Fig. 2.

the magma that produced the Montana diatremes closely resembled magmas known to be parental to kimberlite in diatremes in Arkansas, Africa, Siberia, and elsewhere. Although inclusions of eclogite and garnet peridotite that are typical of most kimberlites are lacking in most Montana diatremes, some inclusions in these diatremes may derive from the lower crust or the upper mantle.

Despite recent allegations that kimberlite and its crystalline inclusions have rather shallow origins (*21*), the evidence provided by the inclusions argues for a deep, probably mantle, origin of the material now observed as kimberlite and of the associated alkalic ultramafic magmas; the evidence implies a substantial source of calcium, sodium, potassium, and gas (partly carbon dioxide) in the mantle.

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References and Notes

1. Considerable controversy has long been associated with the definition and origin of kimberlite. Kimberlite is a mixture of the end products of several processes of fragmentation and alteration, all of which tend to obscure the parental role of alkalic ultramafic magmas in the genesis of many but not all kimberlites. The generally accepted and descriptively useful definition of kimberlite is a brecciated, altered rock of porphyritic appearance, rich in altered olivine, rich in inclusions of wall rocks, and rich in deep-seated xenoliths and xenocrysts (characteristically pyropic garnet, chromian diopside, and magnesian ilmenite).
2. B. F. Buie, in *Geol. Soc. Amer. Bull.* 52 (1941), pp. 1799–1805 [Buie mentioned another ultramafic occurrence (queried in fig. 1) not specifically located on the map by E. S. Larsen (pl. 1)].
3. F. Reeves, in *U.S. Geol. Surv. Bull. 751-C* (1924), pl. 13, pp. 96–7 (totals include one diatreme and one dike outlined but not colored in pl. 13).
4. M. M. Knechtel, *U.S. Geol. Surv. Oil Gas Invest. Prelim. Map 4* (1944); in *U.S. Geol. Surv. Bull. 1072-N* (1959), pl. 52.
5. Mica peridotites are a broad group of alkalic ultramafic rocks that are rich in olivine (commonly of two compositions) and mica (commonly phlogopite), with varying amounts of melilite, nepheline, pyroxene, apatite, and perovskite. Monticellite peridotite and alnoite can be considered varieties of mica peridotite.
6. Monticellite peridotite is a forsterite-monticellite-nepheline-phlogopite rock. Alnoite is a forsterite-melilite-nepheline-phlogopite rock; it was originally defined as an olivine-clinopyroxene-melilite-biotite-nepheline rock, but the term has been used by many workers, including Buie, for alkalic ultramafic rocks bearing melilite and free of pyroxene. Such rocks, containing from 32 to about 40 percent silica, are among the least-silicic igneous rocks known.
7. Relative age determined by detailed mapping by me.
8. E. S. Larsen, in *Geol. Soc. Amer. Bull.* 51 (1940), p. 891; in *Geo. Soc. Amer. Bull.* 52 (1941), p. 1862. An alnoite from a sill west of Winnett in central Montana was described in detail by C. S. Ross, *Amer. J. Sci.* **11**, 218 (1926); that sill is part of a group of alkalic ultramafic occurrences geographically separate from the Missouri Breaks diatremes.
9. L. V. Pirsson, *Amer. J. Sci.* **20**, 35 (1905); E. S. Larsen, in *Geol. Soc. Amer. Bull.* 51 (1940), p. 887.
10. B. C. Hearn, Jr., W. T. Pecora, W C Swadley, in *U.S. Geol. Surv. Bull. 1181-B* (1964), pp. 20–7. Lithologic characteristics of most of the sandstones of the Wasatch and Fort Union formations are so distinctive that the rocks can be identified even when they occur as 2.5-cm inclusions.
11. A Bearpaw Mountains source is clearly shown in one diatreme by rounded pebbles of igneous rocks closely resembling some of the youngest dikes, dated as middle Eocene or possibly late Eocene in age, in Bearpaw Mountains.
12. F. Reeves, in *U.S. Geol. Surv. Bull. 751-C* (1924), p. 71; in *Geol. Soc. Amer. Bull.* 57 (1946), p. 1033. Reeves's mapping of these structures provided the basis for his hypothesis of gravitational sliding of the volcanic rocks and their floor in the vicinity of Bearpaw Mountains.
13. Similar pelletal fragments of igneous rock in ultramafic diatremes elsewhere have been described and illustrated by G. W. Rust, *J. Geol.* **45**, 60, figs. 8–14 (1937); and H. Cloos, *Geol. Rundschau* **32**, 716, fig. 10 (1941).
14. J. F. Lovering and A. J. R. White, *J. Petrology* **5**, 195 (1964).
15. P. A. Wagner, *The Diamond Fields of Southern Africa* (Transvaal *Leader*, Johannesburg, 1914), pp. 19–23, 49–50; A. F. Williams, *The Genesis of the Diamond* (E. Benn, London, 1932), pp. 258–62, 274–5, 291–2, 298; G. W. Rust, *J. Geol.* **45**, 56 (1937); H. Cloos, *Geol. Rundschau* **32**, 709 (1941); V. S. Sobolev, *Pacific Sci.* **17**, 453 (1963); J. Chronic, M. E. McCallum, C. S. Ferris, in *Geol. Soc. Amer. Spec. Paper 87* (1966), p. 280.
16. E. M. Shoemaker, in *Physics and Astronomy of the Moon*, Z. Kopal, Ed. (Academic Press, New York, 1962), pp. 283–359; in *Petrologic Studies: A Volume to Honor A. F. Buddington*, A. E. J. Engel, H. L. James, B. F. Leonard, Eds. (Geol. Soc. Amer., 1962), pp. 327–55.
17. A less-likely alternative is that some slices could be remnants of a cylindrical volume of rock that subsided during the initial formation of the diatreme and that has since been cored out by further subsidence or eruption. Emplacement of the slices by descent in an open ring fracture is unlikely in view of the distances involved, the considerable evidence of lateral compression in the pipes, and the probability that the pipes narrow with depth.
18. A. R. McBirney, *Amer. J. Sci.* **257**, 431 (1959).
19. Meimechite is an ultrabasic rock rich in olivine (usually altered) in a sepentine-rich groundmass; it has been called the extrusive equivalent of kimberlite by Russian geologists.
20. P. A. Wagner, in *Handbuch der Regionalen Geologie*, vol. 7, pt. 7a, *The Union of South Africa*, G. Steinmann and O. Wilckens, Eds. (Winters Universitatsbuchhandlung, Heidelberg, Germany, 1929), p. 152.
21. C. F. Davidson, *Econ. Geol.* **59**, 1368 (1964); **60**, 1735 (1965); **61**, 786 (1966).
22. C. P. Ross, D. A. Andrews, I. J. Witkind, U.S. Geol. Surv., 1955.
23. I thank C. P. Sabine, N. L. Hickling, J. M. Garihan, J. J. Papike, and H. R. Shaw (U.S. Geological Survey) for assistance and stimulating discussion; and D. R. Seely, P. H. Masson, and J. G. Bond (Jersey Production Research Co., Tulsa, Okla.) for calling my attention to an occurrence of pyroclastic rocks. Publication authorized by the director, U.S. Geological Survey.

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Lunar Gravity: Preliminary Estimates from Lunar Orbiter

Abstract. *Tracking data from the lunar orbiters have been analyzed for information regarding Moon's gravity field. These preliminary results include values of a set of harmonic coefficients through degree 4 in the tesserals and degree 8 in the zonals. Implications regarding Moon's mass distribution are discussed: one implication is that Moon is nearly homogeneous.*

Lunar Orbiter V, launched 1 August 1967, culminated NASA's Lunar Orbiter Program under which four Lunar Orbiters already had been successful. Although the prime mission for these orbiters is photographic, analysis of the Doppler tracking data is providing gravity-field information for the selenodesy experiment.

We are intensively analyzing the tracking data (*1*) in order to map Moon's gravity field and for any other information. Similar work with the same data is being performed elsewhere, but on an immediate, short-term basis; our work is a continuing long-term effort to refine the results. It is hoped that some of the first results will (i) resolve the long-standing question of whether or not the density increases toward the center of Moon, and (ii) establish the degree of north-south asymmetry. These two questions should be answered when numerical values of the 2nd- and 3rd-degree zonal harmonics C_{20} and C_{30} are obtained. We now present some preliminary results that include values for these two harmonics; we emphasize that these results are preliminary and subject to revision as the work of analysis proceeds.

The lunar gravity field is described, in terms of its potential Φ through harmonic coefficients C_{nm} and S_{nm}, by the formula

$$\Phi = \frac{\mu}{r}\left[1 + \sum_{n=2}^{\infty}\sum_{m=0}^{n}\left(\frac{R}{r}\right)^{m} P_n^m(\sin\phi)\,(C_{nm}\cos m\lambda + S_{nm}\sin m\lambda)\right]$$

in which μ is the gravity constant, whose value is taken from Mariner IV estimates as 4902.78 km^3/sec^2; R is the mean radius of Moon, whose value is not critical for these computations, but which is taken as 1738.09 km; $P_n^m(z)$ is the associated Legendre poly-