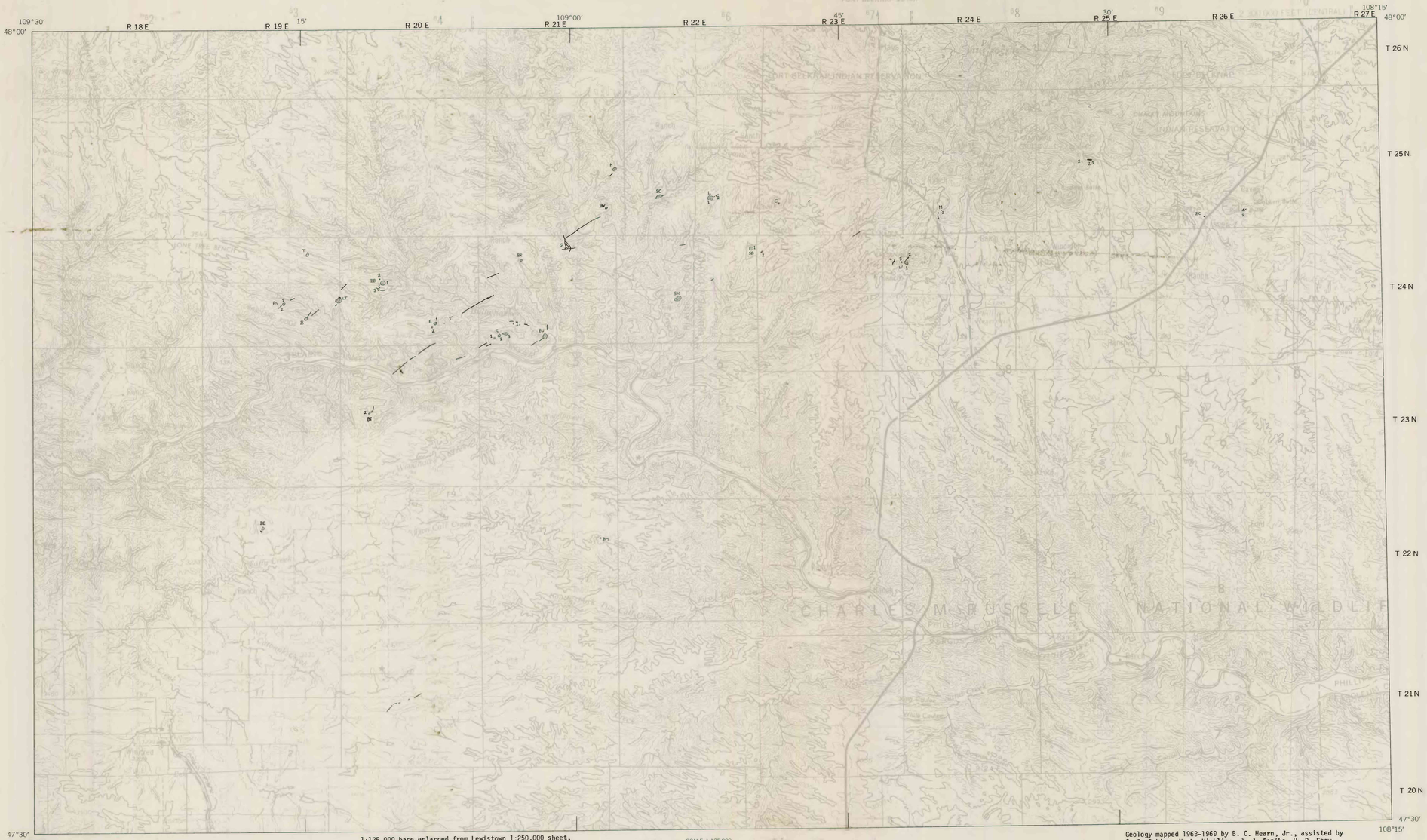
DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

OPEN FILE REPORT 79-1128

HEARN—PRELIMINARY MAP OF DIATREMES AND ALKALIC ULTRAMAFIC INTRUSIONS, MISSOURI RIVER BREAKS AND VICINITY, NORTH-CENTRAL MONTANA



1:125,000 base enlarged from Lewistown 1:250,000 sheet, 1977 revision of 1954 edition

SCALE 1:125 000

5 MILES

10 KILOMETERS

Geology mapped 1963-1969 by B. C. Hearn, Jr., assisted by C. P. Sabine, N. L. Hickling, J. J. Papike, H. R. Shaw, J. M. Garihan, F. H. Fowler, and H. T. Southworth.

This map shows the distribution of diatremes and intrusions formed by alkalic ultramafic magma in the Missouri River breaks area in Eocene time. Earlier geologic maps which show many of the occurrences were published by Reeves (1924) and Knechtel (1944, 1959). A small-scale location map in Hearn (1968) shows most of the diatremes and intrusions. Detailed mapping of each diatreme and studies of the geochemistry and geochronology of the igneous rocks and their inclusions are in progress by the author and other U.S. Geological Survey personnel. Table 1 summarizes location, size, inclusions and other characteristics of specific diatremes and intrusions.

The diatremes are significant because (1) they are some of the best exposed diatremes in the United States; (2) they provide evidence of the eruptive mechanisms and evolution of gas-rich volcanoes; (3) they contain inclusions (xenoliths) of upper crustal, lower crustal, and rarely, upper mantle rocks, thus providing information on the chemical compositions and history of deep layers of the earth; (4) as an important constituent of the north-central Montana alkalic province, they constitute a genetic link between alkalic ultramafic magmas and kimberlites, and possibly between alkalic ultramafic magmas and carbonatites; (5) rare-earth elements and uranium are concentrated in alkalic ultramafic magmas and in carbonatites; and (6) some could contain diamonds, on the basis of their kimberlitic affinity and upper mantle inclusions.

IGNEOUS ROCKS

The igneous rocks can be generally termed mica peridotite, or more specifically, monticellite peridotite, and alnoite or turjaite, which have quite low SiO_2 contents, ranging from about 32 to 41 percent. According to the original definitions, alnoite is a melilite-olivine-pyroxene-nepheline-phlogopite rock, and turjaite is a pyroxene-free rock of the same mineralogy. However, the name alnoite has been used by many workers, including Bule (1941) for melilite-bearing rocks which lack pyroxene. Following that usage, alnoite is used here as a general name for the melilite-bearing rocks. The igneous rocks contain phenocrysts of forsteritic olivine, phlogopite, monticellite and rarely melilite, in a groundmass of monticellite, phlogopite, nepheline, perovskite, magnetite, apatite, ± melilite, ± sodalite (?), and ± rare clinopyroxene. In the Haystack Butte intrusion, phlogopite is barium-rich (Wendlandt, 1977) and kalsilite occurs as small inclusions in monticellite (Wendlandt, oral commun. 1978).

Many of the occurrences of intrusive rocks are unquestionably magmatic: they contain phenocrysts in a fine-grained chilled groundmass, and have baked the wall rocks and inclusions of wall rocks. Some occurrences are dike-like or plug-like in form but are dominantly fragmental, and contain variable amounts of igneous fragments and baked fragments of wall rocks. A few small occurrences consist mainly of fragments of sedimentary rocks that were mobilized from wall rocks and were injected as mixtures of these fragments plus gas (carbon dioxide or steam) or plus an aqueous fluid.

Diatremes contain dominantly fragmental deposits which are bedded or unbedded, and contain fragments of igneous rocks and rounded, pelletal autoliths derived from the same magmas which solidified as cross-cutting dikes and plugs within and outside of the diatremes. Most of the fragmental deposits within diatremes are altered. Their primary mineralogy consisted of phenocrysts of forsteritic olivine, microphenocrysts of tabular phlogopite, lath-shaped melilite (?), and equant nepheline (?) in a fine-grained groundmass. These fine-grained rocks in unaltered state would be closely similar to rocks that have been termed olivine nephelinite or olivine melilitite.

RELATION OF ALKALIC ULTRAMAFIC MAGMAS TO KIMBERLITES

Numerous authors have noted that elsewhere in the world, kimberlites and alkalic ultramafic rocks are commonly associated, in that they form separate occurrences within single broad geographic areas or petrographic provinces, and in addition, carbonatites tend to occur within these broad areas (summarized in Dawson, 1967). Some occurrences are even more closely associated, as at Saltpetre Kop, South Africa, where all three rock types are present, with trachyte as well, within and on the flanks of a single volcano (McIver and Ferguson, 1979).

A typical kimberlite is a brecciated, altered rock of porphyritic appearance, rich in olivine, xenoliths and xenocrysts of deep origin, and rich in inclusions of shallow wall rocks (Hearn, 1968). Kimberlite is the end product of one or more processes of fragmentation and alteration which tend to obscure the evidence of the nature of the primary fluid. Clement and others (1977) list the following characteristics in their definition of kimberlite: (1) Chemically kimberlite is ultrabasic and relatively rich in potassium, water and/or carbon dioxide, (2) kimberlite contains phenocrysts of primary olivine, with or without phenocrysts of primary phlogopite, in a fine-grained matrix that consists of several of the following primary minerals: olivine, phlogopite, diopside, monticellite, serpentine, carbonate, perovskite, spinels, ilmenite, and apatite. Serpentine and carbonate may also be secondary. (3) In addition, kimberlite must contain xenocrysts or megacrysts or both, of one or more of the following minerals: olivine, phlogopite, magnesian ilmenite (picroilmenite), magnesian garnet (pyrope), chromian diopside, and enstatite. (4) Kimberlite also commonly contains ultramafic xenoliths of peridotite, pyroxenite and eclogite. (5) Diamond may or may not be present but is an extremely rare component.

Among the Montana occurrences, only the Williams diatremes can be considered kimberlites on the basis of included garnet peridotite xenoliths and megacrysts and xenocrysts of chromian garnet, magnesian ilmenite and chromian diopside. The other diatremes have chemical and mineralogical affinities to kimberlite but are not true kimberlites, as they lack xenocrysts, megacrysts and xenoliths of deep origin. The presence of kimberlite diatremes and alnoite-monticellite peridotite diatremes of similar age in the same swarm supports a genetic link between kimberlite and alkalic ultramafic magmas. Here and elsewhere in the world, the mineralogy of both is similar in many respects, they hold several characteristics of chemical composition in common, and they share numerous features of emplacement and inferred mechanism of eruption. Most kimberlites probably are produced by parental alkalic ultramafic magmas that originate at depth in the upper mantle. Although the presence of magma at near-surface depths in kimberlite pipes has been widely debated, magma was present at least during the deeper part of the ascent path of many kimberlites. Magmas responsible for kimberlite formation are likely to have compositions within the whole spectrum between carbonatitic compositions and alkalic ultramafic compositions, depending on the composition of the upper mantle, pressure during melting, degree of melting, and other factors.

AGE

Potassium-argon dating indicates that the swarm of diatremes formed between 46 and 52 m.y. ago, slightly overlapping or after igneous activity in the nearby Bearpaw and Highwood Mountains and Eagle Buttes between 50 and 55 m.y. ago, and after some Eocene igneous activity in the Judith Mountains (Hearn and others, 1977, age ranges recalculated to new IUGS constants). Most of the diatremes and intrusions cut across upper Cretaceous rocks in the upper plates of gravity-slide sheets which slid off of the Bearpaw Mountains uplift (Reeves, 1924; Hearn, 1976). In several diatremes, inclusions and tectonic slices of Fort Union Formation of Paleocene age contain pebbles from porphyries in the Little Rocky Mountains. (The porphyry intrusions have K/Ar ages of 60 to 67 m.y., Hearn and others, 1977, age ranges recalculated to new IUGS constants). Twenty-three diatremes contain inclusions and tectonic slices of Wasatch Formation of early Eocene age (Table 1). In some diatremes, distinctive pebbles that were derived from intrusions late in the igneous sequence of the Bearpaw Mountains (Table 1) indicate that the diatremes penetrated a surficial blanket of erosional debris from the nearby Bearpaw Mountains and possibly from the Highwood Mountains.

Oriented samples of 4 dikes and plugs in the diatreme swarm show normal remanent magnetic polarities (K. Books, written communication, 1966) which suggest that within the 46-52 m.y. time span, these masses cooled during the periods of normal polarity of either anomaly 20 or 21 of the ocean flooor, according to the most recent age assignments for those anomalies (Mankinen and Dalrymple,1979).

MECHANISM OF EMPLACEMENT

Diatremes show evidence that they formed by repeated eruptions through the same conduit; each diatreme contains fragmental deposits derived from its own eruptions. The currently exposed wall rocks are mainly of late Cretaceous age (Bearpaw Shale, Judith River Formation, Claggett Shale, and Eagle Sandstone). The diatremes have incorporated small inclusions, larger blocks and descended arcuate slices of wall rocks as much as 30 by 200 m, from formations of late Cretaceous age (upper Bearpaw Shale, Fox Hills Sandstone, Hell Creek Formation), Paleocene age (Fort Union Formation), and early Eocene age (Wasatch Formation) that were present as much as 1400 m above the present levels of exposure of most diatremes. However, for the Williams 1 diatreme, longer descent of inclusions is possible, for the upper part of the Wasatch Formation would have been 1700 m stratigraphically above the lower Cretaceous wall rocks, 2100 m above the Mississippian wall rocks, and, if allowance for 45° dip of wall rocks is made, upper Wasatch Formation would have been 2400 m and 2900 m above respectively.

Contacts of diatreme fill with wall rocks are dominantly fault contacts, marked by slickenside surfaces with or without tectonic breccia. Descended arcuate slices on diatreme margins have probably been emplaced tectonically rather than by descent in a fluidized mixture; the slices have moved down the pipes as the fragmental fill subsided. Large intact blocks a few meters and larger in size which are more centrally located also may have descended tectonically for part or most of the distance from their higher-level sources. Repeated eruptions have caused subsidence of fragmental deposits from their initial level of deposition near the surface, about 1400 m higher than present. Steepening of bedding of pyroclastic deposits, from expected initial dips of less than 35° to present dips of as much as 90° near the margins of some diatremes is a result of subsidence in pipes which narrow with depth. Such subsidence has produced a saucer-shaped configuration of bedding of pyroclastic rocks: steeply inward near the margins, and more gentle in the central part. Later eruptions in the same pipe were fed through cross-cutting conduits that are now filled by solid igneous rocks or by unbedded breccia. Many of the features observed in the field, and the stages of evolution deduced from the field relations, have been duplicated in experimental models of diatreme eruption (Woolsey and others, 1975; McCallum and others, 1976). McCallum and others (1976, p. 525) favor a quiescent bed-fluidized state ("adjacent grains in particulate mass are slightly separated from one another but do not circulate") for the subsidence of bedded tuffs. Although that mechanism could explain the subsidence of some unbedded, massive tuffs or cryptically-bedded tuffs, the preservation of common fine-scale bedding features, such as those at Black Butte (McCallum and others, 1976, fig. 1) is unlikely in a quiescent bed fluidized system.

The time span of activity within each diatreme is unknown, but is probably rather short, on the order of a few days to a few years rather than tens or hundreds of years, on the basis of the lack of extensive channelling or pronounced unconformities in the exposed portions of bedded pyroclastic deposits.

The diatremes tend to be aligned with dikes. Only a few diatremes have closely adjacent dikes, and thus may have developed by local channelled flow within a pre-existing dike. Most of the diatremes lack adjacent dikes and appear to have developed independently without dike predecessors. However, large diatremes could have removed short dikes which preceded the initial pipe development, and many diatremes could be located above dike intrusions which are laterally continuous at depth in more competent beds.

RELATION TO REGIONAL STRUCTURAL TRENDS

The overall trend of the diatreme swarm is N.75°E. over a distance of about 140 km from Haystack Butte near the Highwood Mountains to Ricker Butte southeast of the Little Rocky Mountains. This trend indicates a major zone of access of deep-source magma. In contrast, the dominant alignments of dikes, and of some groups of pipes, are more northerly, from about N.60°E. to N.45°E. These alignments may be a result of the stress pattern and fractures normal to the direction of movement, approximately S.30°E. to S.45°E., of the pre-dike gravity slide sheets off of the Bearpaw Mountains uplift. Neither the overall trend of the diatreme swarm nor the dominant dike trend correspond to any known large-scale tectonic features of the nearby Montana plains. Dike trends show only partial correspondence with inferred structural trends in the buried Precambrian basement that are inferred to be north-northeast to northeast on the basis of aeromagnetic anomalies in the area (Zietz and others, 1971).

INCLUSIONS FROM BELOW PRESENT EXPOSURES

Inclusions (xenoliths) derived from below the present exposures are uncommon in the diatremes. Inclusions of sedimentary rocks of Paleozoic age, dominantly limestone, have been found in six diatremes. Inclusions of shallow Precambrian basement (2000 m and deeper below the present surface), or upper crustal rocks (granitic gneiss, granite, pelitic schist), or probable lower crustal rocks (gabbroic granulite, amphibolite) are rare and occur in abundance only in 4 diatremes. Inclusions of upper mantle rocks (spinel and garnet peridotites) are particularly rare and so far are known only in 2 diatremes of the Williams group (Table 1). On the basis of their included garnet peridotite xenoliths and megacrysts and xenocrysts of chromian garnet, magnesian ilmenite and chromian diopside, the Williams diatremes are the only true kimberlites. Composition of pyroxenes from six garnet lherzolites (peridotites that contain olivine, clinopyroxene, and orthopyroxene) indicate a range of pressures and temperatures of equilibration which suggest a steep geothermal gradient (Hearn and Boyd, 1975). Although such pyroxene pressures and temperatures can be calculated in several ways and are subject to a variety of interpretations, the inferred pressures and temperatures increase with increasing degree of deformation of the xenoliths and lie either below or above, but close to, the experimentally determined graphite-diamond stability curve (Kennedy and Kennedy, 1976).

The occurrence of garnet lherzolite xenoliths and their calculated pressures and temperatures of equilibration in the upper mantle suggest that diamond could possibly be present in the Williams group of diatremes. No diamonds have been found in those diatremes. Although the other diatremes have chemical and mineralogical affinities to kimberlites, the lack of upper mantle xenoliths or megacrysts indicates a much lower probability of diamond occurrence. Elsewhere in the world, diamond-bearing kimberlites which contain no lithic inclusions from the upper mantle are rare; one example is the Prairie Creek kimberlite diatreme in Arkansas (Meyer and others, 1977). In general however, only about 1 in 10 kimberlite occurrences is diamond-bearing, and of these only about 1 in 10 is economically feasible for mining (A.J.A. Janse, in Brummer, 1978).

LOCATION OF ADDITIONAL DIATREMES

It is probable that most of the existing diatremes in the deeply dissected area of the Missouri breaks have been found. To the east, more diatremes could be present near or within the Little Rocky Mountains where widespread terrace and pediment gravels and forest cover could conceal their distinctive outcrop patterns. To the west, more diatremes or intrusions are likely in the 70 km interval between Haystack Butte and the westernmost diatremes in the main part of the swarm, but are probably concealed under the extensive glacial and terrace deposits. A second occurrence of alnoite, reported by Bule (1941) in the Martin Creek area in the southeast part of the Highwood Mountains, about 32 km southwest of Haystack Butte, could not be found by the author.

Kimberlites elsewhere have been located by finding the indicator minerals pyrope, magnesian ilmenite and chromian diopside in stream or terrace deposits and tracing them upstream to their source. Other possible indicator minerals are perovskite or minerals derived from upper or lower crustal inclusions. Alkalic ultramafic intrusions produce pronounced magnetic anomalies, but many of the known occurrences are small, and could be missed in aeromagnetic surveys that have flight lines spaced more than 0.4 km (0.25 mile) apart. Diatremes which lack internal igneous dikes or plugs would probably have less magnetic expression, as a result of the fragmental character and typical alteration of the pyroclastic fill.

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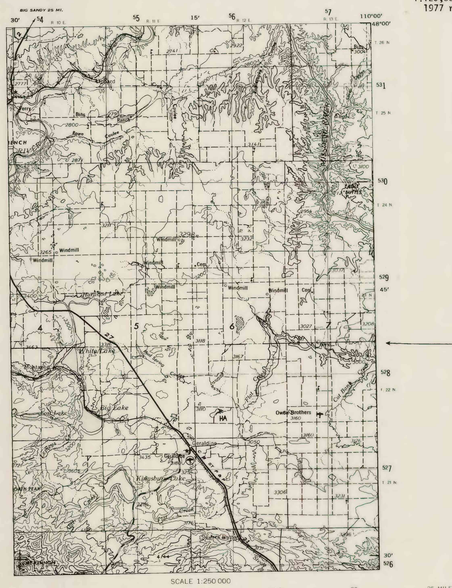

Inset map for location of Haystack Butte intrusion (HA), from Great Falls 1:250,000 sheet, 1972 revision of 1954 edition

EXPLANATION

Diatreme, dominantly fragmental material, outline includes large descended blocks

Dike or sill

Plug

BR Letter symbol for name of occurrence

HA Haystack Butte intrusion, shown only on inset map

Table 1: Name, location, size and characteristics of diatremes and intrusions

Letter symbol[1]	Name of diatreme or intrusion	Location[2] County	Section	Township-Range	Size in meters Form: d=dike s=sill p=plug	Intrusions[3] Fragmental deposits: Unbedded breccia[4]	Bedded tephra[4]	Intrusions in diatremes: In ring fracture	Internal dikes or plugs	Inclusions: From above present exposures: Erosional debris from Bearpaw or Highwood Mtns.	Wasatch Fm. (early Eocene)	Fort Union Fm. (Paleocene)	Hell Creek Fm. & Fox Hills Ss. (Late Cret.)	Bearpaw Sh. (late Cret.)	Formations older than Bearpaw sh.	From adjacent or <1000m below	From >1000m below: Paleozoic	Precambrian basement or upper crust	Probable lower crust	Upper Mantle
BS	Big Slide 1	Blaine	SE\27,NE\27	17N,R19E	170x135	X				X	X	X	X?				X	X	X	
	Big Slide 2 southwest	"	NW\NE\27	" "	75x30	X?						X?								
T	Tick	"	SE\11,NE\14	" "	235x130	X	X	X?	X		X	X	X	X						
B	Barnard Ridge	"	SE\26	" "	190x170		X				X?	X?								
LT	Lone Tree Ridge	"	SE\24,SW\19	" R19,20E	375x280	X	X	X	X	X	X	X	X	X	X					
BR	Black Butte 1	"	NE\NW\20	" R20E	270x210	X	X	X	X		X	X				X				
	Black Butte 2 north	"	SE\SE\17	" "	21x18	X?											X			
	Black Butte 3 southwest	"	NE\20	" "	150x67	X		X		X	X							X		
E	Ervin Ridge 1	"	SW\26	" "	200x200	X	X	X	X		X	X?				X				
	Ervin Ridge 2 southwest	"	NW\NW\35	" "	40x30	X				X	X									
S	Sturgeon 1 west	"	C T\31	" R21E	95x88	X?	X				X	X				X				
	Sturgeon 2 central	"	NE\\31,NW\32	" "	160x105	X		X			X					X				
	Sturgeon 3 east	"	NW\32	" "	325x105	X	X	X	X		X					X				
	Sturgeon 4 several NE	"	SE\29,NE\32	" "	up to 60x30	X									X?		X		X	X?
BU	Bullwhacker Coulee	"	C\33	" "	330x240	X	X	X	X		X	X								
BP	Black Rock	"	NE\17	" "	145x115	X	X	X	X	X	X	X				X				
G	Gilmore	"	NE\SE\10	" "	130x90	X			X					X						
BW	Burnt Wagon	"	SW\25	T25N, "	115x61	X	X	X	X	X	X	X		X	X		X			
H	Hay Coulee	"	NE\24	" "	230x205	X	X	X	X		X?	X		X	X		X			
SC	Squaw Creek	"	NW\9	" R22E	550x200	X	X?	X	X	X	X	X	X							
L	Lleurance 1	Phillips	NE\27	" "	395x240	X			X	X	X	X	X							
	Lleurance 2 east	"	NW\26	" "	69x60	X	X		X	X		X		X	X	X	X			
SH	Shellenberger	Blaine	Sh21	T24N, "	520x305	X	X				X	X								
SB	Saskatchewan Butte 1	Phillips	SE\22	" "	300x245	X	X		X	X?		X				X				
	Saskatchewan Butte 2	"	SW\	" R23E	130x33	X				X	X									
C	Cable Creek	"	NE\SE\30	T25N, "	49x47	X					X?	X							X	X
W	Williams 1	"	NW\NW\8	T24N,R24E	350x250	X	X	X		X	X					X?				X?[9]
	Williams 2 northeast	"	NW\NW\8	" "	120x40	X		X			X?					X				X?[9]
	Williams 3 west	"	EW\W\7	" "	34x28	X			X						X				X	
	Williams 4 dike	"	NW\W\7	" "	390x37	X	X		X							X				
M	Mud Creek 1 southwest	"	NE\32	T25N, "	24x5	s										X				
	Mud Creek 2 several NE	"	NE\32	" "	up to 21x9	P	X													
Z	Zortman 1 east	"	SW\16	" R25E	335x76	d?											X			
	Zortman 2 west	"	NE\20	" "	21x12	p														
BC	Beauchamp Creek	"	SW\NW\32	" R26E	73x66	p						X?								
R	Ricker Butte, several	"	NE\33	" "	d	d,s	X									X				
BI	Bird Rapids 1 northeast	Fergus	Sh17	T23N,R20E	160x30	X		X?			X						X			
	Bird Rapids 2 southwest	"	NE\SW\17	" "	76x37	X			X	X?						X				
BM	Baker Monument	"	NW\13	T22N,R21E	78x62	X			X		X	X				X				
BE	Bergum	"	SE\6	" R19E	225x155	X										X				
HA	Haystack Butte[1]	Chouteau	NE\29	" R12E	76x61	d,p	X													

[1]On inset map
[2]Locations taken from 1:24,000 topographic quadrangle maps, and may differ from locations with respect to township-range grid on this 1:125,000 base, due to inaccuracies in that grid on 1:250,000 Lewistown sheet.
[3]Occurrences that are mainly intrusive; breccia is absent or minor; long dikes and dikes close to diatremes omitted from table.
[4]Generally contain pelletal autoliths.
[5]Contain garnet xenocrysts, but no lithic inclusions of deep source have been found.

X = present
X? = presence uncertain
blank = absent

PRELIMINARY MAP OF DIATREMES AND ALKALIC ULTRAMAFIC INTRUSIONS IN THE MISSOURI RIVER BREAKS AND VICINITY, NORTH-CENTRAL MONTANA

By
B. Carter Hearn, Jr.

1979

U.S. Geological Survey
OPEN FILE MAP
This map is preliminary and has not been edited for conformity with Geological Survey standards or nomenclature.