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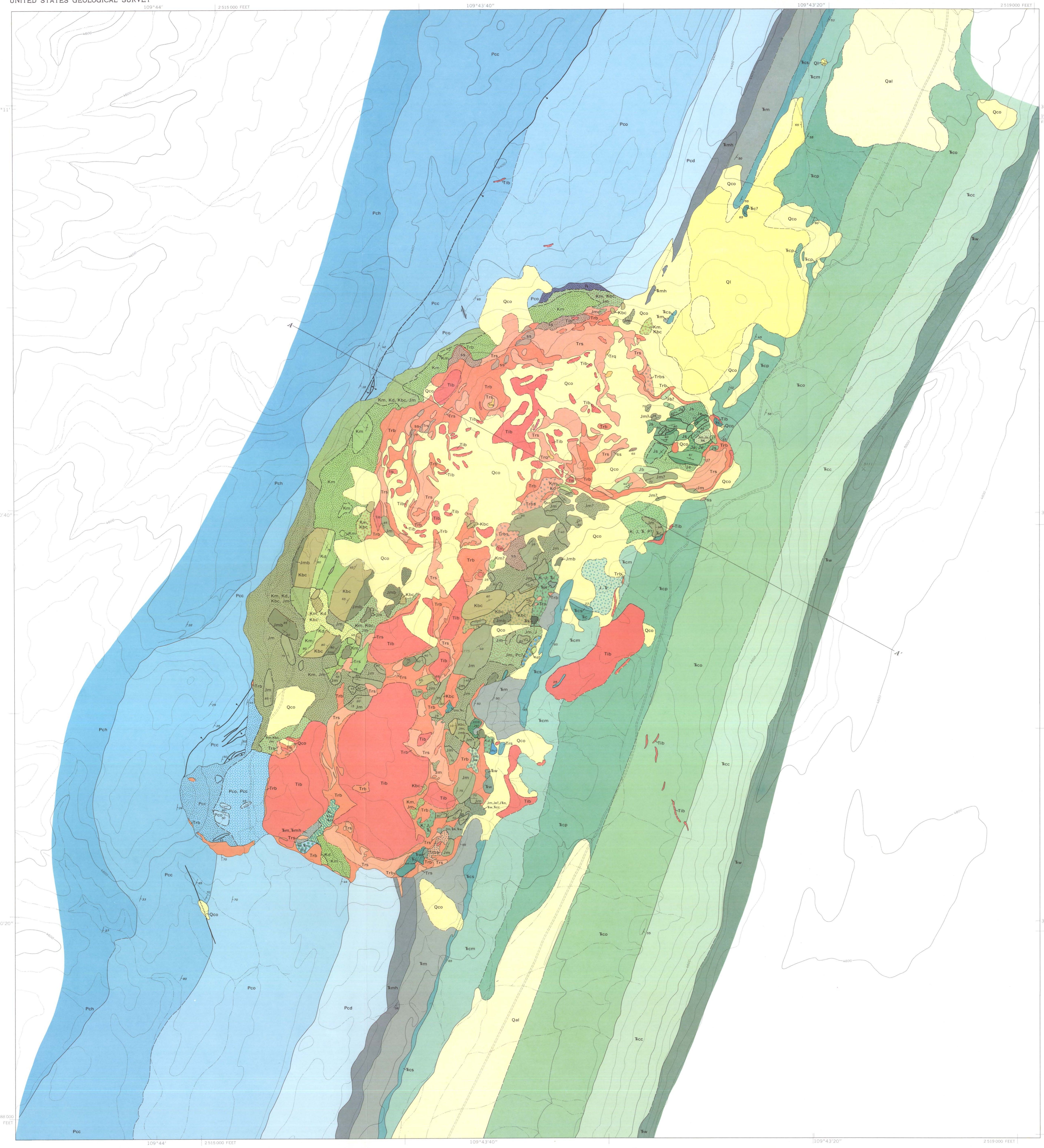


Base compiled from plane-table survey by E. M. Shoemaker, C. N. Brown, C. Duren, B. Brown, and H. J. Moore, 1956-57, from enlargement of San Juan River Survey of U.S. Bureau of Reclamation, 1947, and from enlargement of Boundary Butte, Utah, 15' quadrangle, U.S. Geological Survey, 1962

1,000-foot grid based on Utah coordinate system, south zone

SCALE 1:2400

CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL

Geology by E. M. Shoemaker and H. J. Moore, 1957; H. J. Moore and R. V. Lugn, 1962; D. E. Stuart-Alexander and D. B. Burke, 1967; and Stuart-Alexander, 1968

Work performed on behalf of the National Aeronautics and Space Administration under contract No. R-66

EXPLANATION

DIATREME ROCKS

Tib — Intrusion breccia

A mixture of altered igneous materials, possibly of pyroclastic origin, and of xenoliths and xenocrysts primarily from the Precambrian basement complex below. Green color due mainly to presence of chlorite and talc. Poorly consolidated and friable except within 1-15 feet of units Trs *and* Trb

Trs, Trb, Trbs, Trbw, Trq — Reconstituted sedimentary material

Trs, *dikes of reconstituted sandstone mainly cemented by magnesium carbonate, locally by silica. Most sand grains derived from disaggregated sedimentary rocks and a few from igneous or metamorphic sources. Contains less than 10 percent breccia fragments; locally grades into or contains areas of unit* Trb. *Typically reddish brown, some is lighter brownish orange*

Trb, *dikes of breccia and reconstituted sandstone, mainly in a carbonate cement. Breccia fragments constitute 10 percent or more of total unit; most fragments are less than 30 cm in maximum diameter but some are as large as 10 m. Locally grades into or contains areas of unit* Trs. *Most* Trs *is brownish orange, some is darker reddish brown*

Trbs, *dikes of breccia with large blocks of sandstone*

Trbw, *dikes of breccia with blocks of Wingate Sandstone*

Trq, *reconstituted sandstone with the appearance of quartzite. Tough, indurated, with variable amounts of silica cement. Restricted to small areas within or adjacent to units* Trs *or* Trb

HETEROLITHOLOGIC BRECCIAS

Boxes not coincident with age braces

Km, Kd, Kbc — Mancos, Dakota, and Burro Canyon Formations

Km, Kd, Kbc, Jm — Mancos, Dakota, Burro Canyon, and Morrison Formations

Km, Kbc — Mancos and Burro Canyon Formations

Km, Kbc, Jm — Mancos, Burro Canyon, and Morrison Formations

Km, Jm — Mancos and Morrison Formations

Kbc, Jm — Burro Canyon and Morrison Formations

Kbc, Jm, Jmb — Burro Canyon and Morrison Formations and Brushy Basin Shale Member of the Morrison Formation

K, J, Ŧ — Cretaceous, Jurassic, and Triassic rocks, undivided

K, J, Ŧ, P? — Cretaceous, Jurassic, Triassic, and Permian rocks, undivided
Queried where identification uncertain

Jmb, Jsr — Brushy Basin Shale Member of Morrison Formation and San Rafael Group

Jm, Js, ss — Morrison and Summerville Formations and undated sandstone

Jm, J — Morrison Formation and other Jurassic rocks, undivided

Jm, Je, JŦn, Ŧw, Ŧcc — Morrison, Entrada, Navajo, Wingate, and Chinle Formations
Queried where identification uncertain

Jm, Ŧk, Ŧw — Morrison, Kayenta, and Wingate Formations

Jm, Ŧc — Morrison and Chinle Formations

Jm, Pc — Morrison and Cutler Formations
Queried where identification uncertain

Js, Je — Summerville and Entrada Formations

Jsr, Ŧw — San Rafael Group and Wingate Sandstone

Je, JŦn, Ŧ — Entrada and Navajo Formations and Triassic rocks, undivided
Shown in cross section only

J, Ŧ — Jurassic and Triassic rocks, undivided

Ŧc, Ŧcs, Ŧm — Chinle Formation, Shinarump Member of the Chinle Formation, and Moenkopi Formation

Ŧm, Ŧmh — Moenkopi Formation and Hoskinnini Member

Ŧc, Ŧm, Pcc — Chinle and Moenkopi Formations and Cedar Mesa Member of Cutler Formation

Pco, Pcc — Organ Rock and Cedar Mesa Members of Cutler Formation

ss — Sandstone
Stratigraphic identification uncertain; solid pattern, single block; black stippled overprint, two or more blocks

BLOCKS AND MONOLITHOLOGIC BRECCIAS

Solid color, single block; black stippled overprint, area of two or more blocks, in which most blocks are less than 40 feet in maximum diameter

Km — Mancos Shale
Medium- to dark-gray, yellowish-weathering shale. A few thin fine-grained limestone beds. Gryphaea *in some blocks*

Kd — Dakota Sandstone
Carbonaceous films on laminae and carbonaceous to coaly shale layers. Cross-laminated and scour-fill structures

Kbc — Burro Canyon Formation
Dominantly fine- to medium-grained sandstone but contains gravel of chert and some clay pebbles up to 3 or 4 inches in diameter. Cross-laminated and scour-fill structures

Jmb, Jm — Morrison Formation

Jmb, *Brushy Basin Shale Member, uppermost member of Morrison Formation. Not always differentiated. Red, green, and variegated claystone; white, almost aphanitic altered tuffaceous rock; and conglomeratic sandstone*

Jm, *Morrison Formation, undivided; queried where identification uncertain. Primarily light-colored sandstone with some varicolored shale, mainly pink, green, or variegated. Sandstone, very fine- to medium-grained with colored chert granules and pebbles and green and red mudstone pebbles. Interstitial clay and clay specks common. Cross-laminated and scour-fill structures*

J — Sandstone probably of Morrison or Bluff Formations

Jb — Bluff Sandstone
White, fine- to medium-grained sandstone with laminar concentrations of coarser quartz and white chert grains. Wedging sets of cross laminae; thin parallel laminae and beds in lower part

San Rafael Group

Js — Summerville Formation
Reddish-brown sandy siltstone and shale and lighter sandstone. Parallel bedded and laminated to structureless. Amber-stained quartz grains generally not as abundant as in Entrada Sandstone. Queried where identification uncertain

Je — Entrada Sandstone
Reddish-orange, very fine- to fine-grained sandstone with common coarse amber-stained quartz grains

Glen Canyon Group

JŦn — Navajo Sandstone
Light-tan, very fine- to fine-grained well-sorted quartz-rich sandstone. The typical sweeping, high-angle crossbeds are hard to identify in the few small (<40 ft.) blocks in the diatreme. Individual blocks shown only in the cross section

Ŧk — Kayenta Formation
Pale-red or lavender, fine- to coarse-grained, locally conglomeratic sandstone with minor parallel interbedded siltstone and shale. Small-scale crossbeds

Ŧw — Wingate Sandstone

Ŧc, Ŧcp, Ŧcs — Chinle Formation
Ŧc, *Chinle Formation, undivided*
Ŧcp, *Petrified Forest Member*
Ŧcs, *Shinarump Member*

Pc, Pco, Pcc — Cutler Formation
Pc, *Cutler Formation, undivided*
Pco, *Organ Rock Tongue*
Pcc, *Cedar Mesa Sandstone Member*

P̶ — Pennsylvanian and older rocks
Blocks up to 20 feet in diameter of Pennsylvanian limestone and of mainly Precambrian gneiss, schist, quartzite, and granitic rocks

COUNTRY ROCKS

QUATERNARY

Qal, Ql, Qco — Alluvial deposits
Qal, *alluvium*
Qco, *colluvium*
Ql, *landslide deposits*

TERTIARY

CRETACEOUS

JURASSIC

TRIASSIC(?) AND JURASSIC

TRIASSIC(?)

Ŧw — Wingate Sandstone
Reddish-orange, very fine- to fine-grained sandstone with iron-stained quartz grains. Large-scale crossbedding

TRIASSIC

Ŧcc, Ŧco, Ŧcp, Ŧcm, Ŧcs — Chinle Formation

Ŧcc, *Church Rock Member; reddish-brown fine-grained silty sandstone and siltstone. Massive sandstone near top with large crossbeds. Basal contact gradational, chosen at color change*

Ŧco, *Owl Rock Member; lavender to pale-reddish-brown or pink siltstone with interbedded dense pinkish limestone and limestone-pebble conglomerate. Basal contact at oldest dense limestone*

Ŧcp, *Petrified Forest Member; variegated, mainly structureless bentonitic claystone with lenses of gray calcareous sandstone and conglomerate. Petrified wood common. Basal contact at top of youngest flaggy sandstone or base of variegated claystone*

Ŧcm, *Monitor Butte Member; highly bentonitic gray-green claystone, variegated near base. Some lenses of flaggy medium- to very coarse-grained calcareous sandstone, 6-12 inches thick*

Ŧcs, *Shinarump Member; grayish-white coarse-grained quartz sandstone and conglomerate and underlying bentonitic claystone*

Ŧm, Ŧmh — Moenkopi Formation

Ŧm, *upper part; reddish-brown ripple-marked shale and siltstone and minor very fine grained sandstone. Shale highly fissile*

Ŧmh, *Hoskinnini Member; reddish-brown siltstone and sandstone and nonfissile claystone in upper part. Beds 1-4 feet thick*

PERMIAN

Pcd, Pco, Pcc, Pch — Cutler Formation

Pcd, *De Chelly Sandstone Member; brick-red, very fine- to fine-grained massive sandstone with large, sweeping crossbeds. Minor siltstone intervals. Gradational basal contact*

Pco, *Organ Rock Tongue; dark-reddish-brown interbedded siltstone and sandy siltstone*

Pcc, *Cedar Mesa Sandstone Member; mainly pastel-colored siltstone and claystone with gypsiferous beds and limestone. Thick wedge of grayish-yellow and orange sandstone, calcareous sandstone, and limestone interbeds with minor red calcareous siltstone*

Pch, *Halgaito Tongue; deep-reddish-brown siltstone and very fine-grained silty sandstone*

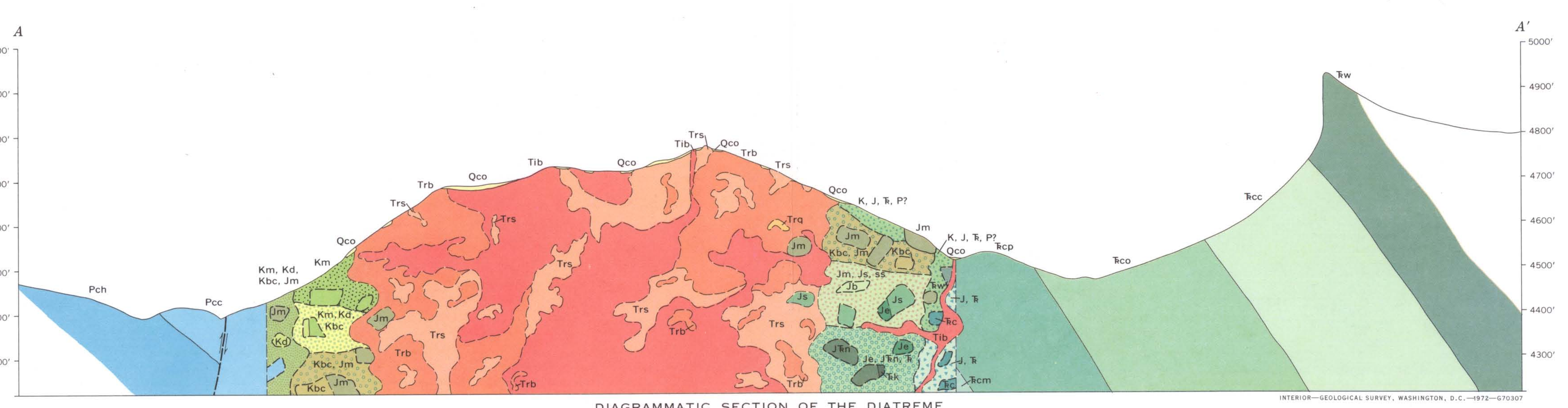
PENNSYLVANIAN AND OLDER

Contact
Dashed where approximately located; dotted where concealed

Block boundary
Dashed where approximately located

Fault
Dashed where approximately located; dotted where concealed. Bar and ball on downthrown side. Arrows indicate relative horizontal movement

Inclined — Vertical — Overturned
Strike and dip of beds
Dot indicates top of bed determined from primary features



DIAGRAMMATIC SECTION OF THE DIATREME

SUMMARY OF THE GEOLOGY

The Mule Ear diatreme is one of several diatremes in or adjacent to the Comb Ridge monocline of the Monument upwarp in southeastern Utah and northern Arizona (see Shoemaker, 1956). At its present exposure level, the diatreme contains a mixture of blocks of sedimentary rocks that have been displaced downward, some apparently more than 3,500 feet, and basement-complex xenoliths that have been transported upward, some probably tens of thousands of feet.

In the horizontal plane the diatreme is crudely zoned into a thick outer zone of dominantly downdropped blocks of sedimentary rocks, an irregular middle zone of reconstituted clastic sedimentary materials with minor admixed debris from igneous and metamorphic rocks, and an inner core of uplifted xenoliths and pulverized debris that may be altered foreign igneous material or altered material related to the diatreme. Evidence for reconstitution of the sedimentary rocks includes the admixtures of debris from igneous rocks in addition to the dikelike distribution of this unit and the discontinuous pebble layers unrelated to any sedimentary structures. In plan, the inner zone seems to be a series of pipes, although these are undoubtedly connected below and may have been connected above. The outer zone can be further divided into subzones of downdropped blocks of sedimentary rocks representing different narrow stratigraphic ranges and into a disordered outer ring, or rind, of sedimentary rocks displaced both upward and downward. Many blocks in both subzones are embedded in a matrix of smaller breccia fragments derived from above and below. Locally this is intrusive breccia (Tib), particularly in the rind subzone. Each subzone of downdropped blocks represents a different amount of vertical displacement, and presumably these differences continue at depth. San Rafael Group rocks in the northeast corner of the diatreme have dropped the least, only 1,775 feet stratigraphically, whereas the blocks of Mancos Shale along the northwest edge have been displaced downward the greatest amount, 4,100 feet stratigraphically. Assuming that the dip of the strata (average 45°) has not changed significantly since the diatreme was emplaced, the stratigraphic displacements correspond to 2,450 and 3,600 vertical feet, respectively.

The crude zoning of the rocks probably reflects differences in the movement pattern within the diatreme. Stoping seems to have been the primary mechanism of enlarging the diatreme, loosening the blocks in the outer zone so that the larger blocks would be lowered as smaller fragments were removed. Active disaggregation or comminution of the sedimentary rocks occurred in the middle zone, followed by limited mobilization and injection of the fragmented rocks in the form of sandstone dikes. Deformative forces were strongest and blocks were transported the greatest distances in the innermost zone. Evidence for stoping includes the sharp but irregular contacts between diatreme and country rocks, the more limited vertical movement of most blocks near the diatreme contacts (rind subzone) than in the other areas, and the lack of folding of the sedimentary blocks. If stoping did not occur simultaneously or at a constant rate along all of the diatreme border, the blocks of sedimentary rock would have had different amounts of time in which to be downdropped, thus accounting for the variations in vertical displacement. The disaggregation process was most complete in the reconstituted sandstone units and least in the reconstituted breccia units. Many sandstone blocks in the breccia appear to have been partly disaggregated and recemented; in some blocks primary structural features are obliterated mainly by veins of the recementing agent, and in others the block outline is blurred, suggesting in-place disaggregation. On the other hand, the dikelike distribution of the reconstituted sandstones, scattered layers of pebbles, and the few dispersed inclusions of igneous and metamorphic particles derived from the basement below indicate some movement of the disaggregated materials in addition to comminution of the sedimentary blocks.

One of the problems posed by the Mule Ear diatreme is the nature of the intruding and transporting material. One line of evidence was contributed by C. W. Naeser who dated the diatreme by using fission tracks in apatite and sphene from two granitic xenoliths. The apatite fission-track ages are 28±3 and 30±3 m.y., and the one sphene age is 500±100 m.y. The apatite ages represent the age of the diatreme because all previous tracks were totally annealed by the heat associated with emplacement of the diatreme; the sphene age is not diagnostic because only some of the tracks were lost. The different reactions of the sphene and apatite place the temperature of the intrusion between 300° and 550° C. These significantly low temperatures show that the granitic xenoliths were not immersed directly in a basaltic magma and suggest that the transporting and eruptive material was a gaseous and solid or particulate mixture. Petrographic examination of the intrusion breccia confirms the fragmental nature of the particles. Petrographic and X-ray investigations reveal an abundance of chlorite-talc alteration products and magnesium-carbonate cement, which indicate a carbon dioxide-rich hydrous transporting agent in which the water was probably above the critical point. The only line of evidence as to the source of the gases comes from the correspondence of the diatreme fission-track dates of 28 and 30±3 m.y., with a potassium-argon date of 27 m.y. (Zany, 1966) for one of the many minette dikes within 35 miles of Mule Ear, suggesting that minette magma and its gases may have played a role in the formation of all diatremes in this area. In addition, these Oligocene dates show that this diatreme is not directly related to the much younger diatremes of Hopi Buttes, Arizona, which are mid-Pliocene from a paleontologic date (Stirton, 1936; Lance, 1954; Shoemaker and others, 1962).

Most of the rocks from the Cretaceous Mancos Shale down through the Triassic Wingate Sandstone originally overlying the diatreme are represented by fragments at the present level of exposure. L. C. Craig pointed out that the blocks of Cretaceous Burro Canyon Formation in the diatreme mark the westernmost known extent of the formation in the Monument Valley area. Omissions in the column can be ascribed in part to the stratigraphic zoning within the diatreme and perhaps in part to the difficulty of identifying small isolated blocks of grossly similar lithology. The descriptions in the explanation of this map are brief, giving only the most diagnostic characteristics by which a block could be recognized. For more detailed descriptions see, for instance, Stewart (1959), Stewart, Williams, Albee, and Raup (1959), Witkind and Thaden (1963) and O'Sullivan (1965). Stratigraphic annotations are useful for identification of many of the larger blocks.

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GEOLOGIC MAP OF THE MULE EAR DIATREME, SAN JUAN COUNTY, UTAH

By
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1972

For sale by the U.S. Geological Survey, price $1.25