Ash-flow Eruptive Megabreccias of the Manhattan and Mount Jefferson Calderas, Nye County, Nevada

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1471

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By DANIEL R. SHAWE *and* DAVID B. SNYDER

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Megabreccias associated with the Manhattan and Mount Jefferson calderas possess characteristics that suggest origin by ash-flow eruption rather than by caldera-wall collapse

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1988

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, *Secretary*

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging-in-Publication Data

Shawe, Daniel R., 1925-
Ash-flow eruptive megabreccias of the Manhattan and Mount Jefferson calderas, Nye County, Nevada.

(U.S. Geological Survey professional paper ; 1471)
Bibliography: p.
Supt. of Docs. no.: I 19.16:1471
1. Breccia—Nevada—Nye County. 2. Volcanic ash, tuff, etc.—Nevada—Nye County. 3. Calderas—Nevada—Nye County. I. Snyder, David B. II. Title. III. Series.
QE471.15.B7S525 1988 552'.2 87-600088

For sale by the Books and Open-File Reports Section, U.S. Geological Survey,
Federal Center, Box 25425; Denver, CO 80225

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ASH-FLOW ERUPTIVE MEGABRECCIAS OF THE MANHATTAN AND MOUNT JEFFERSON CALDERAS, NYE COUNTY, NEVADA

By DANIEL R. SHAWE and DAVID B. SNYDER

ABSTRACT

The Manhattan and Mount Jefferson calderas in the southern Toquima Range formed about 25 and 27 Ma, respectively. The Manhattan caldera formed with eruption of silicic ash-flow tuffs of the Round Rock Formation, interspersed in which are several megabreccia units, some containing immense clasts (hundreds of meters long). The presence of some clast lithologies that are nowhere recognized in caldera walls, the evidence that some clasts became brecciated in sub-caldera levels prior to emplacement of megabreccia, and the occurrence of some megabreccia units as outflow suggest an origin by eruption rather than by collapse of caldera walls. Varied development of indurated ash rinds on clasts that occur side by side in the megabreccia suggests differences in temperature of clasts when they were incorporated into the ash matrix of the megabreccia, again indicating derivation of some materials from deep and hot levels. The Mount Jefferson caldera formed with eruption of silicic ash-flows of the tuff of Mount Jefferson; a megabreccia unit also appears to have been erupted. This unit contains an ash-flow-tuff matrix locally welded to black vitrophyre, suggesting eruption of ash-flow megabreccia at very high temperatures.

INTRODUCTION

Volcanic megabreccia in the San Juan Mountains caldera field in southwestern Colorado (Lipman, 1976; Hon and others, 1983) has been attributed to collapse of oversteepened caldera walls into ash deposits within the caldera; however, some volcanic megabreccias observed in this study in the Great Basin provide evidence of an origin largely by the mechanism of ash-flow eruption and appear unrelated to collapse of caldera walls. Evidence includes extensive brecciation of clast materials prior to ash eruption, differential heating of clasts prior to ash eruption, derivation of clasts from sub-caldera levels rather than from caldera walls, distribution and form of intracaldera megabreccia units similar to those of associated ash-flow deposits, decrease in clast size outward from apparent vent zones, and deposition of tabular megabreccia units as outflow beyond the structural margins of calderas. Not all the described megabreccias exhibit all these attributes, though their general similarity suggests a common origin. An important factor in interpretation of the eruptive origin of a megabreccia is its content of indurated ("healed") brecciated clasts that appear identical to "explosion-breccia" formed in the root zones of Tertiary calderas and other igneous centers elsewhere, as discussed later in this report. Although the cited evidence suggests to us an eruptive origin of the megabreccias described here, the occurrence of collapse breccias in these and other calderas of the Great Basin also is possible.

The features of ash-flow eruptive megabreccias described here were observed in and near the Manhattan caldera and along the southwest margin of the Mount Jefferson caldera, both in the southern Toquima Range, northern Nye County, Nev. These features were delineated during field studies by the senior author during the past 15 years (Shawe, 1981a,b). Recent geophysical studies by the junior author provide a more complete definition of the Manhattan caldera and its volcanic fill, and his calculations of physical conditions during ash-flow eruptions provide corroboration for the eruptive transport of large megabreccia clasts.

ACKNOWLEDGMENTS

Comments on the manuscript by P.D. Rowley, R.F. Hardyman, G.R. Osburn, and T.H. Druitt clarified our presentation and tempered our interpretations. R.F. Hardyman, P.W. Lipman, and H.J. Moore directed the authors to useful references that describe various features and mechanisms of origin of "explosion-breccias," pyroclastic flows, "co-ignimbrite lag-fall" deposits, "proximal-facies" deposits, and related phenomena. Moore aided in the mathematical analysis of ash-flow eruption of megabreccia. David Jones made modal point-count analyses of thin sections of samples of the tuff of Round Mountain and of the Round Rock and the Diamond King Formations. R.E. Schoenfeld kindly photographed hand specimens. Margaret Clemensen typed and proofread the manuscript.

GEOLOGIC SETTING OF THE MANHATTAN AND MOUNT JEFFERSON CALDERAS

REGIONAL SETTING

The western part of the Great Basin, in which lie the Manhattan, Mount Jefferson, and numerous other calderas of Tertiary age, is a region of great geologic complexity. It spans the continental margins that existed in the Paleozoic and Mesozoic Eras, and its geology preserves a fragmentary history of repeated crustal-plate interactions that occurred sporadically throughout that long interval of time. Stewart (1980) has summarized the Paleozoic, Mesozoic, and Tertiary geologic history of the region. During extensive silicic volcanism in the Tertiary, numerous calderas were formed, and some appear to be localized along major northwest- or northeast-trending strike-slip structural zones (for example, Snyder and Healey, 1983). In a general way, calderas and their associated voluminous ash-flow deposits in the western Great Basin lie in a broad northeast-trending zone of low gravity (Woollard and Joesting, 1964). The low gravity suggests that the crust in this part of the Great Basin may contain numerous large silicic batholiths at depth. Evidence is lacking, however, as to whether some of these batholiths are related to the Tertiary calderas and their silicic volcanic rocks, or whether they were emplaced at an earlier time.

SOUTHERN TOQUIMA RANGE SETTING

The southern Toquima Range typifies the block-faulted and uplifted mountains, bounded by young alluvium-filled valleys, of the Basin and Range province. The southern Toquima Range is made up of Paleozoic sedimentary and metamorphic rocks invaded by two large Cretaceous granite plutons, in turn intruded by or overlain by a variety of Tertiary hypabyssal and volcanic rocks (fig. 1) (Ferguson, 1921, 1924; Kleinhampl and Ziony, 1985; Shawe, 1977, 1981a,b).

The Paleozoic rocks are marine sedimentary rocks: quartzite, silty argillite, argillite, and limestone of Cambrian age; and argillite, limy argillite, limestone, dolomite, chert, and quartzite of Ordovician age. In places, Paleozoic argillite has been metamorphosed to phyllitic argillite; near granite contacts it consists of chloritoid and muscovite-biotite schist. Locally near granite contacts, limestone has been metamorphosed to tremolite and other calc-silicate minerals.

Cretaceous granite crops out in two large plutons, one southeast of Round Mountain and one south of Manhattan (fig. 1). Southeast of Round Mountain, the pluton referred to here as the granite of Shoshone Mountain extends for more than 20 km southeastward to near Belmont. It is a compound body consisting of an oval mass, here called the Round Mountain lobe, about 13 km long and composed of coarse-grained granite separated from porphyritic coarse-grained granite on its south side by a narrow screen of Paleozoic schist. A second oval mass of similar size, the Belmont lobe, adjoins the Round Mountain lobe on its southeast side. The Belmont lobe consists of an outer broad annular zone of porphyritic coarse-grained granite that grades inward to a core of coarse-grained nonporphyritic granite. The pluton south of Manhattan, here called the granite of Pipe Spring, forms an irregular-oval body of coarse-grained granite about 15 km long. The granite plutons are intruded locally by dikes and other small masses of aplite and pegmatite. A swarm of rhyolitic and subordinate andesitic dikes and a small stock of granodiorite—all of Oligocene age—intrude the granite and adjacent Paleozoic rocks east and south of Round Mountain.

The Manhattan and Mount Jefferson calderas formed during eruption of voluminous silicic ash-flow tuffs in late Oligocene time (fig. 1 and pl. 2). The 25-Ma Manhattan caldera forms a crude oval structure about 11×17 km in size whose long axis trends west-northwest. The 27 Ma Mount Jefferson caldera is at least 15 km in diameter, and the nearby Meadow Canyon caldera (fig. 1), not discussed further in this paper, is at least 10 km in diameter. The Manhattan caldera, whose structural margin is well defined by inward-dipping, high-angle faults, several shallow-level igneous plugs, and concentrations of megabreccia (pl. 1), is filled with more than 1,000 m of silicic ash-flow and ash-fall tuff layers. The Mount Jefferson caldera, incompletely defined, is bounded on its southwest side by a steep fault (pl. 3) and apparently is filled with several thousand meters of silicic ash-flow tuffs.

The Manhattan and Mount Jefferson calderas are well defined by their geophysical properties. A substantial gravity low coinciding with the Manhattan caldera suggests 1–2 km of volcanic fill (Snyder, 1983) (pl. 1; cross section *A–A'*). Aeromagnetic data (pl. 2) indicate, by curvilinear trends of parallel magnetic contours, the oval caldera boundary along its northern, southeastern, and southwestern margins, and show the general form of a late andesitic stock that may represent a phase of resurgence, discussed in more detail later in this report. The form of the Mount Jefferson caldera is indicated by its magnetic properties (pl. 2). The Manhattan and Mount Jefferson calderas, since their formation, have been modified by Basin-range faults (Shawe, 1981a,b). The faults, however, have not significantly disrupted

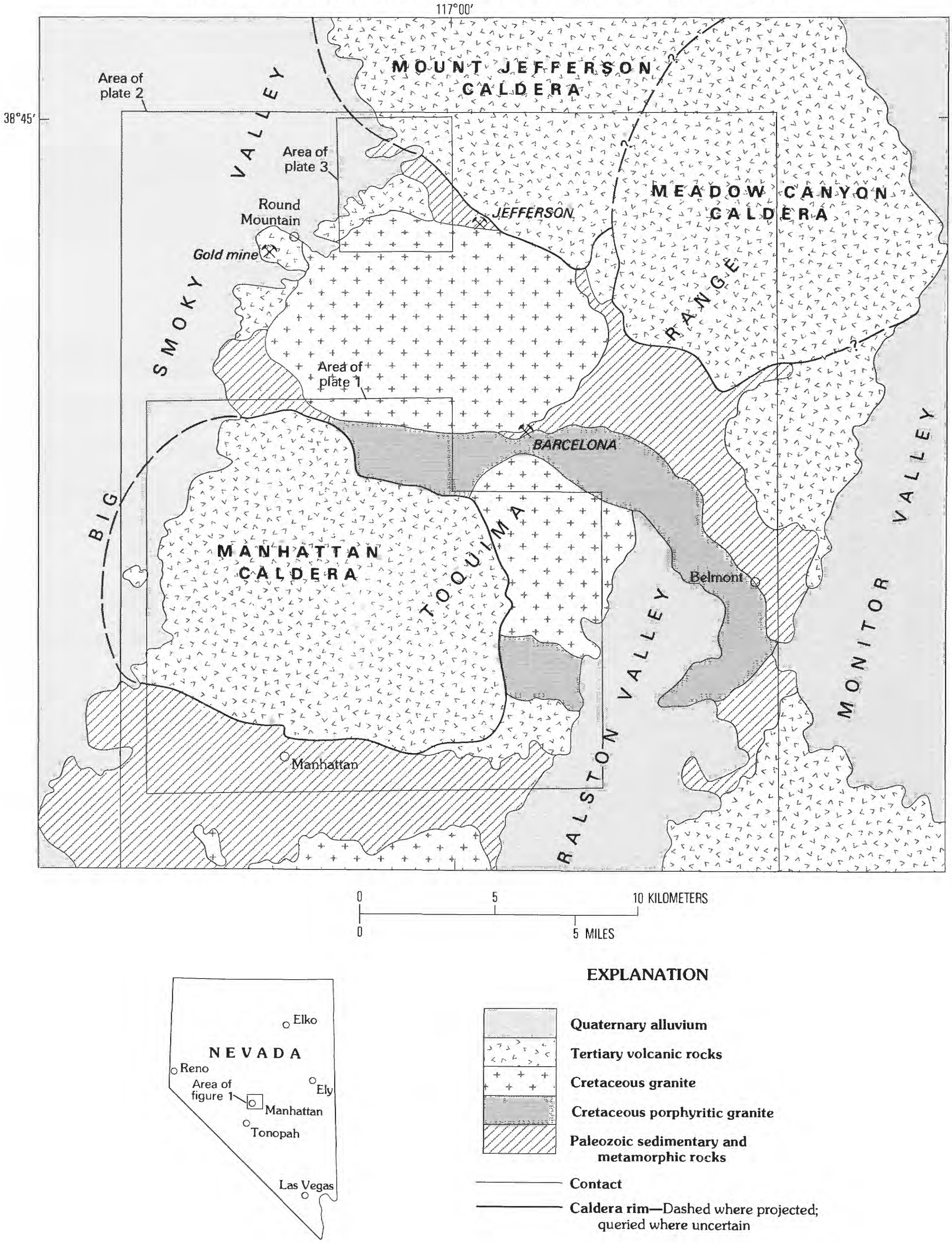

FIGURE 1.—Generalized geologic map of the southern Toquima Range, showing locations of Manhattan, Mount Jefferson, and Meadow Canyon calderas, and areas of plates 1–3.

or obscured the forms of the calderas. Plate 1 shows the insignificant effect of Basin-range faults on the Manhattan caldera.

Silicic ash-flow tuffs whose eruption led to collapse of the Manhattan caldera are referred to the Round Rock Formation (Shawe, 1987). The Round Rock Formation in the southern Toquima Range is virtually confined within the Manhattan caldera, leading to the interpretation that it came from the caldera. We do not know whether or not significant outflow was deposited around the caldera nor the extent to which erosion may have removed possible outflow.

The Round Rock Formation has been dated (K-Ar method on biotite; fission-track method on zircon) as about 25 Ma (latest Oligocene) (Shawe and others, 1986). The formation consists of a lower tuff member which includes two megabreccia units, a middle member that is itself a megabreccia unit, and an upper tuff member which includes two megabreccia units. The lower and upper members are light-colored, poorly consolidated latitic, quartz latitic, and rhyolitic ash-flow and ash-fall tuff layers, apparently randomly associated, that occur in several cooling units. The lower member (unit Trl, pl. 1 and cross sections) is probably at least 1,000 m thick, and the upper member (unit Tru, pl. 1 and cross sections) is 200–300 m thick. The poorly consolidated ash-flow and ash-fall tuffs of these members are characterized by abundant lithic and pumice fragments. Lithic fragments may constitute from 1 to almost 40 percent of the rocks. They are crystal-poor rocks that contain about 10–27 percent phenocrysts (mostly 1–2 mm) consisting of about 50 percent sodic plagioclase and lesser subequal amounts of quartz, sanidine, and mafic minerals. Mafic minerals are mostly biotite, though hornblende is also present in some rocks. Iron-titanium oxide minerals, apatite, and zircon are accessory minerals. The upper and lower members contain relatively thin units of strongly welded ash-flow tuff, of vitrophyric ash-flow tuff, of air-fall tuff, and of volcanic breccia other than the megabreccia units, all of whose compositions are generally similar to those of the main parts of the upper and lower members. The megabreccia units locally overlap rocks beyond the structural margin (ring-fracture zone) of the Manhattan caldera, and they appear to form intrusive masses (vent material) in the structural margin of the caldera.

Near the southwest margin of the caldera, 3 km northwest of Manhattan, a small hill composed almost entirely of reddish-brown rhyolite is believed to be a plug and associated dikes (unit Trmr, pl. 1) that are related to the middle member of the Round Rock Formation. The reddish-brown rhyolite intrudes the middle member and is lithologically similar to much of the clast material in the megabreccia of the middle member.

Small rhyolite and quartz latite plugs along the east margin of the Manhattan caldera (unit Tr, pl. 1) probably were emplaced in the ring-fracture zone of the caldera. The rhyolite is a light-brownish-gray, flow-layered, crystal-poor rock containing conspicuous biotite phenocrysts. The quartz latite is a light-gray, crystal-poor rock containing sparse biotite. The age of one of the rhyolite plugs is 24.8±0.9 Ma (K-Ar method on biotite; Shawe and others, 1987, p. 6).

Overlying the Round Rock Formation in the southern Toquima Range is the Diamond King Formation (Shawe, 1987) of latest Oligocene age (about 25 Ma) (Shawe and others, 1986). The Diamond King Formation (unit Tdk, pl. 1) is exposed extensively within the Manhattan caldera, where it is about 150–200 m thick. The Diamond King is a light-buff to light-pinkish-brown, generally welded, rhyolitic ash-flow tuff that contains about 25–50 percent crystals (mostly 1–3 mm) of dominantly quartz and lesser amounts of sanidine and sodic plagioclase. Traces to a few percent of biotite and iron-titanium oxides are present; zircon, apatite, and allanite are accessories. The Diamond King is characterized in hand specimens by conspicuous smoky quartz dipyramids and by much fewer lithic and pumice fragments than found in the underlying Round Rock Formation.

The source of the Diamond King is unknown. The Diamond King possibly was derived from a caldera now buried beneath the alluvium of Big Smoky Valley west of Round Mountain.

Overlying the Diamond King Formation are buff-colored lacustrine claystone and siltstone beds and fluvial sandstones and conglomerates of the Bald Mountain Formation (Shawe, 1987), also of latest Oligocene age (Shawe and others, 1986). These beds are made up mostly of volcanic detritus. The formation is about 200–250 m thick.

The tuff of Peavine Creek (Shawe, 1987) is the youngest stratigraphic unit in the volcanic succession in the southern Toquima Range (together with the underlying Bald Mountain Formation, designated as unit Tvy on pl. 1). This informal unit consists of poorly consolidated, light-greenish-buff and buff, quartz-latitic and rhyolitic ash-flow and ash-fall tuff, and of interlayered light-brown, highly welded ash-flow tuff. The tuff of Peavine Creek is about 24.6 Ma (Shawe and others, 1986). In the southern Toquima Range the unit is present only within the Manhattan caldera where it overlies the Bald Mountain Formation; its maximum remnant thickness is about 250 m. The tuff probably was erupted from a caldera mapped by G.F. Brem (Brem and Snyder, 1983; Brem, written commun., June 1983) in the southern Toiyabe Range near Peavine Creek, 20–30 km west-northwest of Manhattan. The poorly consolidated tuffs and the welded tuffs both contain low to moderate amounts of phenocrysts as varied amounts of quartz, sanidine, and sodic plagioclase. Biotite is present in small but locally conspicuous amounts; it appears to be most abundant in the lower part of the unit. Iron-titanium oxide minerals, apatite, and zircon are accessories.

At Round Mountain, north of the Manhattan caldera, an ash-flow tuff unit has been dated as 26.1 Ma (K-Ar method on sanidine; Silberman and others, 1975) and more recently was dated as 27 Ma (K-Ar method on biotite and on sanidine; Shawe and others, 1987, p. 5). This unit, referred to here as the tuff of Round Mountain, is likely correlated with parts of the tuff of Mount Jefferson that have been dated as about 26 Ma (Marvin and others, 1973). The tuff at Round Mountain contains about 20–40 percent phenocrysts; these consist of relatively more plagioclase and biotite, and less sanidine and quartz, than do phenocrysts of the Diamond King.

The Crone Gulch Andesite was emplaced into volcanic rocks within the Manhattan caldera about 3 km northeast of Manhattan primarily in the form of an andesite stock about 3 km long and 1 km wide (Shawe, 1987). Numerous associated sills were intruded near the stock, mostly into the Bald Mountain lake beds, and abundant andesite dikes and plugs of similar composition were emplaced in volcanic rocks within the Manhattan caldera. The Crone Gulch Andesite (unit Tc, pl. 1) is an olive-brown porphyritic rock that contains about 25 percent labradorite and lesser amounts of augite, set in a groundmass of plagioclase laths, minor augite, and iron-titanium oxide minerals embedded in a devitrified glassy matrix. Apatite is a relatively abundant accessory mineral. Some of the sills contain numerous vesicles filled with chalcedony or calcite. The rocks give suspect isotopic ages of about 22 Ma (Shawe and others, 1986); they are probably older, based on geologic evidence cited later in this report.

Two large plugs and satellitic dikes and sills of flow-layered volcanic rock identified by Ferguson (1924, p. 53) as dacite (unit Td, pl. 1) form a low hill 5 km north-northwest of Manhattan. The rocks are about 24.5 Ma (Shawe and others, 1986). Petrographic studies suggest that these rocks are varied in composition. They are crystal-poor rocks whose phenocryst compositions indicate a range from biotite latite to biotite-quartz latite. About 85 percent of the rock is a devitrified glassy matrix. Black vitrophyric layers occur locally.

Late in the history of the Manhattan caldera, probably as a result of resurgence, an apparent gravity slide moved a large mass of the younger volcanic units (unit Tvy, pl. 1) westward into the western part of the caldera.

DISTRIBUTION, FORM, AND CHARACTER OF THE MEGABRECCIA UNITS

Five significant megabreccia units occur around the periphery of and within the Manhattan caldera (see inset map, pl. 1). They are, in apparent sequence from oldest to youngest, the megabreccia unit of Sloppy Gulch (unit Trls) and the megabreccia unit of Mariposa Canyon (unit Trlm), both part of the lower member of the Round Rock Formation; the middle member of the Round Rock Formation (unit Trm), a member composed wholly of megabreccia; a rhyolite megabreccia (unit Trur) within the upper member of the Round Rock; and the megabreccia unit of Silver Creek (unit Trus) near or at the top of the upper member of the Round Rock and beneath the Diamond King Formation (pl. 1). A sixth unit, the megabreccia of Jefferson Canyon (unit Tjc) near the southwest margin of the Mount Jefferson caldera (pl. 3), is also described here because certain well-developed features suggest an ash-flow eruptive origin for it. A few thin lenses of megabreccia that occur sporadically in the Round Rock and younger formations in the southern Toquima Range are not described here.

The five Manhattan caldera megabreccia units occur either as vent facies near the structural wall of the caldera, as intracaldera facies, or as outflow facies. Some units consist of all three facies. The megabreccia of Jefferson Canyon appears to be outflow related to the Mount Jefferson caldera (pl. 3). Southwest of the mouth of Jefferson Canyon, the megabreccia of Jefferson Canyon and the overlying tuff of Mount Jefferson appear to correlate with a lithologically similar megabreccia unit and the overlying tuff of Round Mountain. The similar megabreccia and the tuff of Round Mountain both thicken outward from Round Mountain, suggesting that a paleotopographic high underlies Round Mountain.

DESCRIPTION OF THE MEGABRECCIA UNITS

The megabreccia units described here have common characteristics that suggest their eruptive origin, although all of the criteria that we interpret to indicate an eruptive origin are not evident in each of the megabreccia units. Caldera-wall collapse may have formed some megabreccia, but that cannot have been a major cause of megabreccia emplacement. Each unit has differences in the character of matrix material and clasts that point to variations in the sources of contained rocks and in mechanisms of eruptive formation. Distinctions among matrix materials are made on the basis of their composition, structure, and degree of welding. Distinctions among clasts are made on the basis of their size,

FIGURE 2.—Middle member of the Round Rock Formation, showing large clasts in dominant tuff matrix. Faceted clast at lower right is part of a 50-m-long fragment of rhyolite (pick at arrow on left-facing faceted surface of clast gives scale). View to east in southwest part of Manhattan caldera.

distribution, shape, composition, internal structure, and rinds. Commonly, but with notable exceptions, clast lithology is similar to that of nearby caldera walls; this relation suggests that clasts were derived either by vent plucking during eruption along the ring-fracture zone or by gravity collapse of the walls into the vent. Characteristics that we describe in later pages lead us to believe that vent plucking was the dominant process.

Clasts of all sizes, in all of the megabreccia units, vary in shape from angular to rounded, and shapes having varied degrees of rounding may occur side by side. Large fragments generally are more rounded than small fragments, which grade in size down to particles that disappear in tuff matrix. Most fragments are more or less equidimensional, although some large clasts of the Paleozoic sedimentary rocks tend to be well layered and slablike. Large blocky clasts generally have rounded corners. Some large clasts show well-faceted, somewhat striated surfaces (fig. 2) suggestive of abrasion.

MEGABRECCIA UNIT OF SLOPPY GULCH

This unit, well exposed near Sloppy Gulch just north of Manhattan (pl. 1), was described by Ferguson (1924, p. 43–44) as a talus breccia and originally was named by him the Hedwig Breccia Member of the Esmeralda Formation. This name is now abandoned and these rocks are reassigned to the informal Sloppy Gulch unit of the lower member of the Round Rock Formation (Shawe, 1987). Ferguson described the unit as consisting of breccia of small angular fragments of the various Paleozoic rocks and granite, but he remarked that none of the materials were mixed and thus he inferred that they were from a local source, even though topographically higher areas of appropriate granite and Paleozoic rock sources generally are not evident. Ferguson stated, surprisingly, that the unit contains no volcanic material, even though it locally contains significant exposed tuff and some large—as long as

100 m—volcanic clasts embedded in tuff matrix. Apparently he considered that the tuff of the Round Rock Member simply inundated his Hedwig unit following talus deposition.

The megabreccia unit of Sloppy Gulch is exposed in a broad arc along the south margin of the Manhattan caldera (pl. 1). Near Manhattan the Sloppy Gulch is believed to be dominantly a vent facies megabreccia because it occurs at the structural margin of the caldera, shows steep contacts with Paleozoic wall rocks, and occupies a position where later venting of the reddish-brown rhyolite took place. Curvilinear faults that bound the caldera near Manhattan are steep faults, dipping into the caldera; the sharply curving segment 2 km east of Manhattan (pl. 1) is well exposed in a steep ravine, where it strikes N. 40° E. and dips 80° NW. In this area the megabreccia is exposed through vertical relief of more than 200 m. Drill holes in a small patch of megabreccia inside the caldera margin about 3 km east of Manhattan bottom in the megabreccia at a depth of about 200 m. We believe that a steep gravity gradient at the margin of the caldera near Manhattan (pl. 1) indicates locally deep volcanic fill that may correlate with a vent zone near or along the caldera ring fracture. The steep gravity gradient, however, also could simply indicate a steeper walled caldera with somewhat less tuff fill. Because geologic evidence suggests a vent zone here, we prefer the vent interpretation.

Layers of the megabreccia unit of Sloppy Gulch are intercalated in the lower member of the Round Rock Formation and occur at the top of the lower member, about 1 km north of Manhattan (pl. 1, cross section *A-A'*), where they are interpreted to be intracaldera facies. None of the Sloppy Gulch, however, is known to occur in or at the top of the lower member in the central part of the caldera where those rocks are exposed through a distance of several kilometers.

Near East Manhattan Wash and the mouth of Bald Mountain Wash, 4–10 km east of Manhattan and just west of the Maris Mine, the megabreccia unit of Sloppy Gulch occurs widely as a relatively thin layer on an almost flat surface of Paleozoic rocks (pl. 1, cross sections *C-C'* and *D-D'*), extending perhaps 1 km beyond the structural margin of the Manhattan caldera. Megabreccia clasts in this area are as long as 250 m (pl. 1). A small patch of the Sloppy Gulch lies about 4 km south of the south margin of the Manhattan caldera (see inset map, pl. 1); it is at an altitude of 7,400 ft, about the same as that of the caldera margin near Manhattan. This patch of megabreccia, characterized by clasts of Paleozoic rocks probably no more than a few meters in size in tuff matrix identical in appearance to that of the Sloppy Gulch north of Manhattan, is about 0.5 km south of the north contact of the granite of Pipe Spring. It and megabreccia east of Manhattan south and east of the structural margin of the caldera are considered to be outflow facies.

Because the southeast margin of the Manhattan caldera cannot be correlated with sharp differences in the gravity field (pl. 1), the nature and configuration of the megabreccia unit of Sloppy Gulch here are somewhat uncertain. The presence of breccia dikes in the Round Rock Formation (pl. 1), of large clasts within the megabreccia unit of Sloppy Gulch (pl. 1, cross section *D-D'*), and of small rhyolite plugs about 1 km north of the area of megabreccia (pl. 1) suggests that a vent zone for breccia and rhyolite eruption marks this segment of the caldera margin. Part of the megabreccia west of the Maris Mine thus is interpreted to be vent facies, and part is inferred to be outflow facies (pl. 1, cross section *D-D'*).

The matrix of the megabreccia unit of Sloppy Gulch is identical in character to ash-flow tuff of the lower member of the Round Rock Formation. The matrix typically contains abundant small (1–2 cm) lithic fragments consisting of the common Paleozoic rock types and less abundant granite, aplite, and volcanic rocks. Structure in the tuff matrix generally is poorly defined; locally in the vent zone along the south margin of the Manhattan caldera, compaction foliation manifested by flattened pumice lapilli strikes about east-west and dips steeply north. Near the mouth of Bald Mountain Wash, gently east dipping (outflow?) layers of megabreccia (with Round Rock tuff matrix) that contain abundant Paleozoic clasts and some granite and aplite clasts are interlayered with thin conformable layers that contain clasts generally less than 1 m in size—termed "mesobreccia" by Lipman (1976, p. 1398)—in Round Rock tuff matrix and with layered tuff of the lower member of the Round Rock Formation (pl. 1, cross section *D-D'*, and fig. 3). Fragments in megabreccia in places dominate the tuff matrix to the extent that at the surface no tuff is visible. In some areas where megabreccia fragments of disparate lithologies are large (in the order of tens to hundreds of meters across), and tuff matrix is not evident at the surface, the senior author spent much time fruitlessly attempting to map rational structural relations before discovering—in prospect pits (fig. 4), mine workings, and road cuts—small amounts of interstitial tuff matrix that proved the true character of the material. Locally the tuff matrix may constitute half or more of the megabreccia, and megabreccia fragments can be seen to be embedded in tuff matrix.

The largest blocks (as large as 200×300 m) in the megabreccia unit of Sloppy Gulch are found in what we believe to be vent facies because of its position along the structural margin where gravity data suggest a

FIGURE 3.—Megabreccia unit of Sloppy Gulch. Megabreccia and mesobreccia interlayered with ash-flow tuff of the lower member of the Round Rock Formation near mouth of Bald Mountain Wash 1 km southeast (outside) of inferred structural margin of Manhattan caldera; view to northeast. Mesobreccia layer about 3 m thick overlies ash-flow tuff layer in cliff, and is overlain on higher slope by interbedded ash-flow and mesobreccia layers; megabreccia layers cap hills in background and underlie older ash-flow tuff of the lower member a few hundred meters to the left of the view. (See also pl. 1, cross section *D–D'*.)

vent. One of these blocks, northwest of Manhattan, is Ordovician limestone and argillite (pl. 1); and another, near the mouth of Bald Mountain Wash (pl. 1, cross section *D–D'*), is Cretaceous granite. However, some large blocks are found in what we believe to be outflow facies near the structural margin of the caldera but close to inferred vents. One large block of Paleozoic limestone 120×250 m in size occurs near East Manhattan Wash (pl. 1), and a huge slab of Paleozoic limestone and argillite about 650 m long is found near the mouth of Bald Mountain Wash (pl. 1, cross section *D–D'*).

Most clasts in the megabreccia unit of Sloppy Gulch are Paleozoic sedimentary rocks. Near Manhattan, Ordovician argillite and limestone dominate. Quartzite, probably from Cambrian and Ordovician formations, is common; one large clast of Lower Cambrian brown siltstone was mapped (pl. 1). Knotted schist, including some of the Lower Ordovician(?) Mayflower Schist, is a common component of clasts. Cretaceous aplite and granite are less abundant but they are conspicuous where found. Olive-brown argillite, siltstone, sandstone, and conglomerate (containing pebbles as large as 4 cm) of the Permian Diablo Formation (Ferguson, 1924, p. 25–26; Ferguson and Cathcart, 1954) form an immense clast (more than 300 m long) 2 km northwest of Manhattan (pl. 1), and small fragments of clastic rocks of the Diablo Formation are scattered elsewhere in the megabreccia unit of Sloppy Gulch near Manhattan. Occasional clasts of rhyolitic tuffs, one as wide as 100 m, are found. The tuffs are unlike any mapped in the southern Toquima Range. Compositions of clasts in the megabreccia unit of Sloppy Gulch in the vicinity of East Manhattan Wash and Bald Mountain Wash are similar to those near Manhattan. However, no clasts of the

FIGURE 4.—Megabreccia unit of Sloppy Gulch, showing a margin of immense, locally brecciated clast of Permian Diablo Formation (dark-colored indurated layered clastic sedimentary rock) bounded by tuff matrix (light-colored lithic tuff).

Diablo were recognized in the eastern areas, and white vein quartz in small fragments was observed near East Manhattan Wash.

All of the Cambrian and Ordovician rock types, and the Cretaceous aplite and granite, occur at the surface south or southeast of the Manhattan caldera. The nearest outcrop of the Diablo Formation, however, now lies more than 10 km to the southwest. There the Diablo in part is overlain by thrusted Cambrian and Ordovician rocks (Poole and Wardlaw, 1978) lithologically similar to the Cambrian and Ordovician rocks at Manhattan; the Diablo thus also may be present at depth near Manhattan. If the Diablo once overlay the lower Paleozoic rocks near the Manhattan caldera prior to late Cenozoic erosion, there are no vestiges remaining there now.

Almost all of the clasts of the megabreccia unit of Sloppy Gulch are themselves intensely brecciated. This fact of course led Ferguson (1924, p. 43–44) to describe the rocks as talus that contains fragments mostly only 1–2 in. across. The individual clasts consist of monolithologic breccias, even where groups of clasts are of a great variety of lithologies.

Some of the megabreccia clasts have been so intensely brecciated that the materials within them appear to have been crushed, milled, and stirred. One such clast, an immense slab of Paleozoic limestone about 200 m long and enclosed in vent facies of the megabreccia unit of Sloppy Gulch about 1.5 km east of Manhattan (pl. 1), has been thoroughly "mixed" (fig. 5). Matrix of this clast appears to consist entirely of comminuted limestone. The clast was mineralized by minor though pervasive thin quartz and calcite veins, locally abundant iron oxides, and minor patches of abundant manganese oxide minerals. Another large clast, about 100 m across, of fine-grained, orangish-buff, intensely brecciated tuff occurs in the megabreccia unit of Sloppy Gulch northwest of Manhattan. Within the clast, small fragments of this tuff are surrounded by a fine-grained matrix of fragmental material ranging to as small as submicroscopic size. In addition, weblike seams of fine-grained material that merges with the matrix appear to ramify through the larger fragments. None of the wall rocks of the Manhattan caldera are brecciated in the manner of the clasts described here, nor is it likely that upper parts of the structural margin of the caldera were so brecciated and then removed entirely by post-caldera erosion. For example, just beyond the east structural margin of the caldera the Diamond King Formation overlies Cretaceous granite, the megabreccia unit of Sloppy Gulch, and the megabreccia unit of Silver Creek, indicating uneven erosion (locally almost no erosion) of the caldera margin at the time of emplacement of the Diamond King shortly after caldera collapse. Local preservation of the Diamond King in this area indicates that not much more erosion has occurred since the Diamond King was deposited, and therefore higher parts of the original caldera wall locally remain, which exhibit no brecciated rocks similar to those of the megabreccia clasts.

Some clasts in the megabreccia unit of Sloppy Gulch, large and small, are silicified, iron mineralized, replaced by calc-silicate minerals, or otherwise mineralized. A number of the larger mineralized clasts contain prospect pits. Anomalous metal contents, as high as 2 ppm (parts per million) Ag, 30 ppm Mo, 300 ppm Cu, 700 ppm Zn, and 100 ppm Ni have been detected in geochemical samples collected from prospects in the larger clasts. Much mineralization probably occurred before emplacement of the megabreccia, as suggested by the fact that mineralized clasts are embedded in unmineralized tuff, although some of the mineralization was fault controlled and appears to have postdated megabreccia emplacement.

Rinds of indurated tuff on clasts in the megabreccia unit of Sloppy Gulch are neither conspicuous nor common. A few large fragments, however, show distinctive rinds of tuff a few centimeters thick. One large clast of tuff is surrounded by a finely layered rind of fine-grained tuff surrounded in turn by coarser grained tuff matrix of the megabreccia (fig. 6). Microscope study shows that the rind consists of tuff that contains a mixture of abundant noncompacted devitrified shards, phenocrysts, and rock particles occurring as thin layers that appear to be successively plated onto the surface of the clast. The surrounding tuff matrix is coarser grained and contains more crystal and lithic fragments and fewer identifiable shards. Most fragments seem to be surrounded by porous tuff identical to that of the common tuff matrix of the megabreccia. An example of a clast without a rind of tuff is the immense clastic rock fragment of the

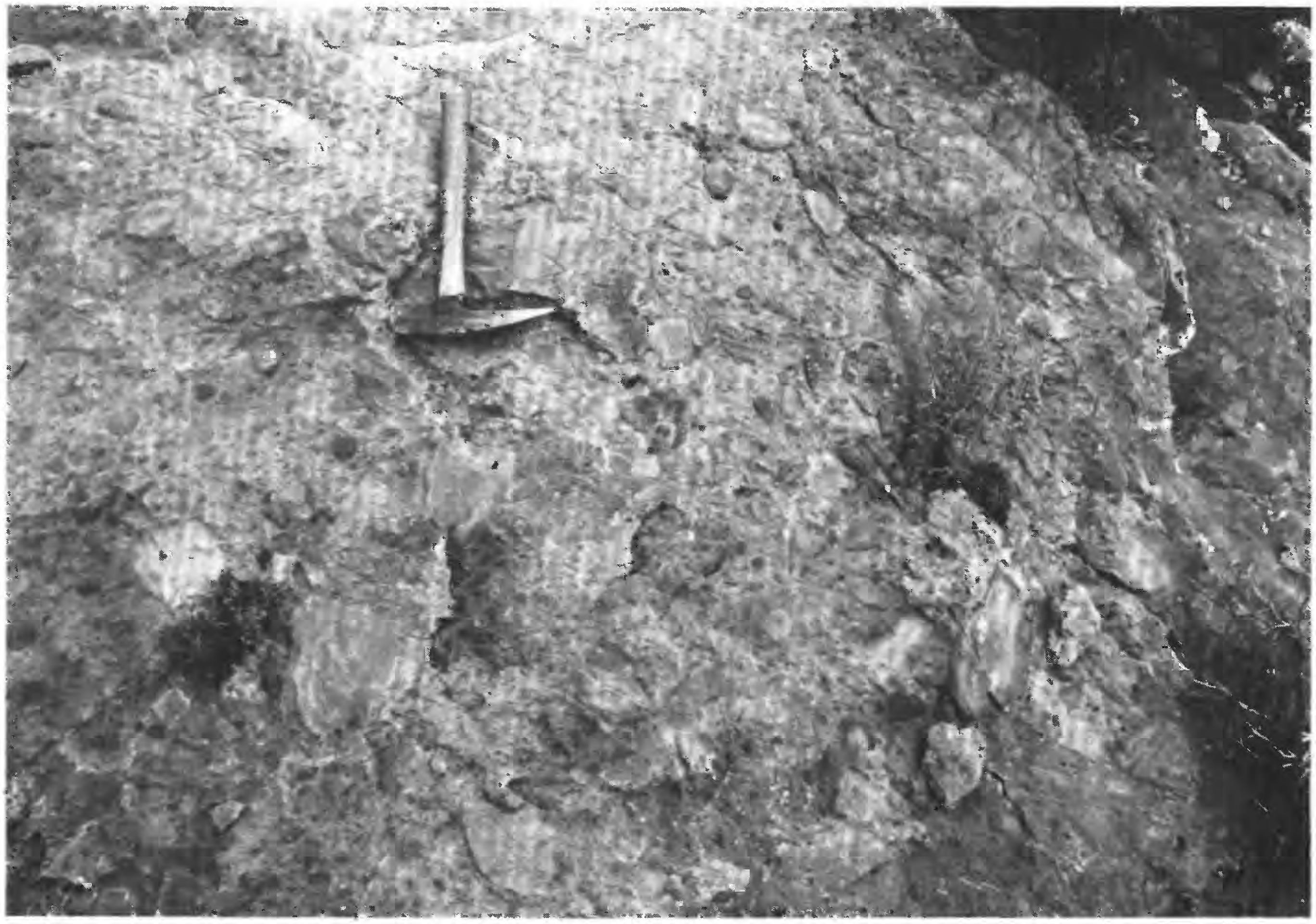

FIGURE 5.—Brecciated limestone, forming part of an immense clast in the megabreccia unit of Sloppy Gulch. Breccia fragments appear to be intensely crushed, milled, and stirred.

Diablo Formation northwest of Manhattan (fig. 4). The few clasts in the megabreccia unit of Sloppy Gulch seen to have rinds are all volcanic rocks.

MEGABRECCIA UNIT OF MARIPOSA CANYON

The megabreccia unit of Mariposa Canyon occurs in a small area along the north margin of the Manhattan caldera about 1 km north of Mariposa Canyon (pl. 1). Much of the unit contains large fragments of Paleozoic rocks; here the unit is interpreted to fill a vent (pl. 1, cross section *A–A'*). A steep gravity gradient at the margin of the caldera in this area and the presence of a gravity "low" just south of exposed megabreccia (pl. 1) suggest thick caldera fill and a possible vent zone; alternatively a steeper caldera wall and thinner fill are possible. Thin layers of mesobreccia as intracaldera facies extend into the lower member of the Round Rock Formation, to which this unit is assigned, southward from the interpreted vent. The matrix of the megabreccia unit of Mariposa Canyon is similar to that of the megabreccia unit of Sloppy Gulch.

Blocks as large as 100 m occur in the megabreccia unit of Mariposa Canyon. Most of the fragments in the megabreccia unit of Mariposa Canyon are schist that is lithologically similar to schist that forms the wall rock of the Round Mountain lobe of the granite of Shoshone Mountain. Other clast lithologies (granite, for example) are present in small amounts, but the megabreccia was not studied in enough detail to allow description of all the rock types that make up the clasts. Insufficient study of clasts in the megabreccia unit of Mariposa Canyon prohibits a description of their internal structure and mineralization, and no information was recorded on possible clast rinds.

MIDDLE MEMBER OF THE ROUND ROCK FORMATION

The middle member of the Round Rock Formation consists mostly of fragments of reddish-brown rhyolite

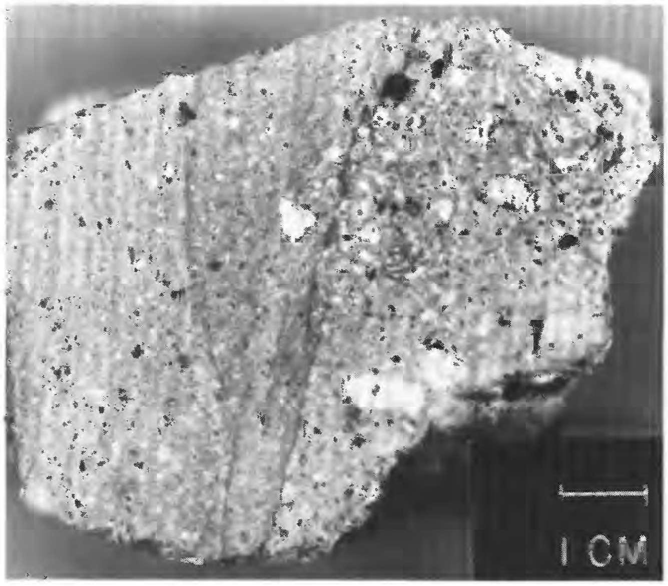

FIGURE 6.—Sample of fine-grained rind broken from margin of a large (several meters) clast of tuff in the megabreccia unit of Sloppy Gulch. Rind consists of the finely layered tuff on left half of sample. Right half of specimen is typical tuff matrix of the megabreccia.

and gray andesite. The rhyolite previously was considered to compose a separate formation that originally was named (Ferguson, 1924, p. 50–51) the Maris Rhyolite, for outcrops in the vicinity of the Maris Mine east of the mouth of Bald Mountain Wash. Ferguson and Cathcart (1954) subsequently abandoned the name Maris Rhyolite in favor of the Oddie Rhyolite, and Shawe (1987) restricted the Oddie Rhyolite from the Manhattan area and reassigned the rhyolite to the middle member of the Round Rock. The middle member is widely distributed as intracaldera facies throughout the Manhattan caldera (pl. 1), forming a more or less regular, thin layer averaging about 40 m thick (pl. 1, and cross sections). Near a rhyolite plug and dikes (unit Trmr), 3–4 km northwest of Manhattan, the member appears to be much thicker and is interpreted there to be in part vent facies (pl. 1, cross section *B–B'*). The vent zone of the middle member probably is within the interpreted principal vent zone of the megabreccia unit of Sloppy Gulch near the plug and dikes. Small patches outside the caldera near East Manhattan Wash and the Maris Mine are considered to be outflow facies. The initial volume of the member was about 2 km^3.

Tuff matrix is virtually absent from much of the middle member of the Round Rock Formation, particularly in the northern third of the Manhattan caldera. Where matrix is absent, small to large fragments of gray andesite are contained in reddish-brown rhyolite, or conversely, small to large fragments of reddish-brown rhyolite are contained in gray andesite. These relations will be described in more detail in the discussion of the megabreccia clasts. In the southern two-thirds of the caldera, where tuff matrix is irregularly present, the matrix may constitute only thin weblike seams separating breccia fragments of great size range, or it may make up half or more of the megabreccia (fig. 2). The tuff matrix of the middle member of the Round Rock appears identical in character to tuff of the upper member.

Distribution and size of clasts in the middle member of the Round Rock Formation have been difficult to evaluate. For example, zones where significant tuff matrix is present appear to have random distribution throughout the southern two-thirds of the Manhattan caldera, and only where appreciable ash-tuff matrix is present at the ground surface can sizes of individual clasts be discerned. Locally large clasts more than 10 m across lie in tuff, isolated by a few hundred meters from other clasts. Blocks of reddish-brown rhyolite and gray andesite 10 m across are common in the matrix; smaller blocks are much more abundant, however. One large faceted block (fig. 2) is about 50 m long. Where the tuff matrix appears to be absent and the only lithologies evident are rhyolite and andesite, blocks of one lithology within the other commonly are 10 m across and rarely are much larger. No consistent pattern of size distribution of megabreccia clasts in the middle member throughout the Manhattan caldera was recognized.

Clast material of the middle member of the Round Rock Formation varies in composition between reddish-brown rhyolite and gray andesite. Compositions of the clasts range from about 56 to 76 percent SiO_2, and other major oxides display more or less straight-line trends between the end members of the series (Shawe and Lepry, 1985). Rock types that are represented include rhyolite, quartz latite, latite, and andesite, although reddish-brown rhyolite and gray andesite are the conspicuous types seen in outcrops. These rocks are extensively brecciated and large masses of one type commonly contain small to large fragments of the other type. At several localities where rhyolite and andesite occur together, andesite dominates in the upper part and rhyolite dominates in the lower part of the member.

The reddish-brown rhyolite is a heterogeneous rock type that varies in character throughout. In places, it appears to be a strongly brecciated flow-layered rhyolite containing sparse small phenocrysts, in which are embedded somewhat rounded fragments of crystal-rich structureless rhyolite. In other places, the rhyolite may be entirely an autobrecciated(?) flow-layered rock. In yet other places, it consists of welded ash-flow tuff, with well-defined flattened pumice lapilli, that is partly to extensively brecciated. Disrupted welded ash-flow tuff locally contains rounded fragments of crystal-rich structureless rhyolite (fig. 7). At one locality 3 km northwest of Manhattan, a large area of mostly unbrecciated

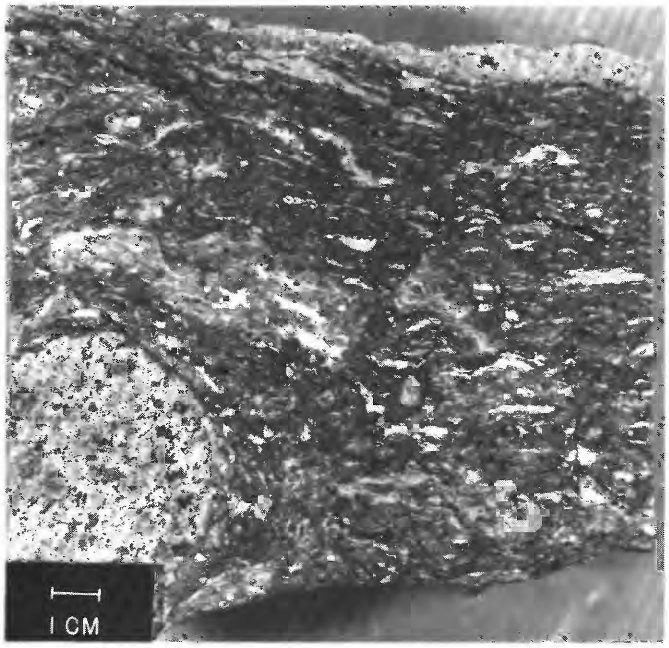

FIGURE 7.—Deformed reddish-brown rhyolite of the middle member of the Round Rock Formation. Welded ash-flow tuff that contains conspicuous flattened pumice lapilli is cut by healed diagonal fractures that offset pumice fragments. Note rounded clast of crystal-rich structureless rhyolite at lower left, sheared tangentially along a diagonal fracture. Thin light-gray edge at top is part of a clast of gray andesite embedded in the reddish-brown rhyolitic welded tuff.

rhyolite contains conspicuous flattened pumice lapilli striking about N. 70° E. and dipping 75° N. This large slab apparently is an undeformed but rotated remnant of ash-flow tuff deposited initially near an eruptive center now marked by the plug and dikes of reddish-brown rhyolite (Trmr). Small (boulder-size) clasts of undeformed welded ash-flow tuff are common in the middle member of the Round Rock near the mouth of Bald Mountain Wash.

Andesite of the middle member is plagioclase-rich, generally brecciated rock that contains conspicuous phenocrysts of hornblende and biotite in varied amounts. Ferguson (1924, p. 52–53) described these rocks as hornblende and biotite andesite porphyry dikes that "cut the Round Rock member and apparently also the Maris rhyolite, although no clear proof of this could be found." Hornblende- and biotite-dominant types tend to be segregated within the megabreccia, and are not known to be extensively mixed in particular localities. The internal structure of the andesite is more simple than that of the rhyolite. Commonly it consists of a breccia of subrounded fragments of hard gray andesite 0.1–0.5 m across in a soft (pulverized?) andesite matrix. In places the clasts of gray andesite are themselves internally brecciated.

At one locality at the margin of the Manhattan caldera about 0.5 km southwest of the plug of reddish-brown rhyolite (unit Trmr), conformable layers of flow-layered (non-brecciated) andesite strike about N. 65° W. and dip 75° SW. The flow-layered andesite appears to be interlayered with megabreccia and tuff. Possibly these layers formed on the flank of a volcano, once located near the site of the reddish-brown rhyolite plug but later destroyed. Subsequent eruption(s) from the volcano (to emplace the middle member of the Round Rock) and intrusion of the rhyolite plug may have caused steep tilting of the andesite layers.

None of the rhyolite-to-andesite rock types that dominate the middle member of the Round Rock Formation are known more than a few hundred meters beyond the margin of the Manhattan caldera. The source of the material appears to have been the eruptive center now marked by the rhyolite plug and dikes just within the caldera northwest of Manhattan.

In some areas of megabreccia near Manhattan, the middle member contains not only brecciated rhyolite and andesite clasts but also abundant brecciated clasts of a variety of Paleozoic lithologies derived from the megabreccia unit of Sloppy Gulch. These areas, because of dominance of Paleozoic fragments, were mapped as the megabreccia unit of Sloppy Gulch, and they were not subsequently remapped as the middle member following recognition of their true identity. Incorporation of material from the older Sloppy Gulch into the middle member probably occurred close to an eruption vent when the middle member was erupted through the Sloppy Gulch.

The middle member of the Round Rock Formation is complex in that the various types of clast materials each also constitute a matrix for fragments of the other types. Whether as clasts in tuff or as matrix to the other rock type, the distinctive lithology of the rhyolite and andesite is maintained. Little evidence of mineralization of clasts in the middle member has been observed.

Clasts in the middle member of the Round Rock Formation show rinds only where they are embedded in tuff matrix. Only the reddish-brown rhyolite possesses rinds. One large faceted rhyolite clast (shown in fig. 2) has a thin rind of hard tuff that is "plastered" onto the lightly striated surface of the clast.

RHYOLITE MEGABRECCIA

Thin layers of rhyolite megabreccia probably no more than 10 m thick are interlayered in the upper member of the Round Rock Formation within the Manhattan caldera near its northeast margin (pl. 1). All of the rhyolite megabreccia is considered to be intracaldera

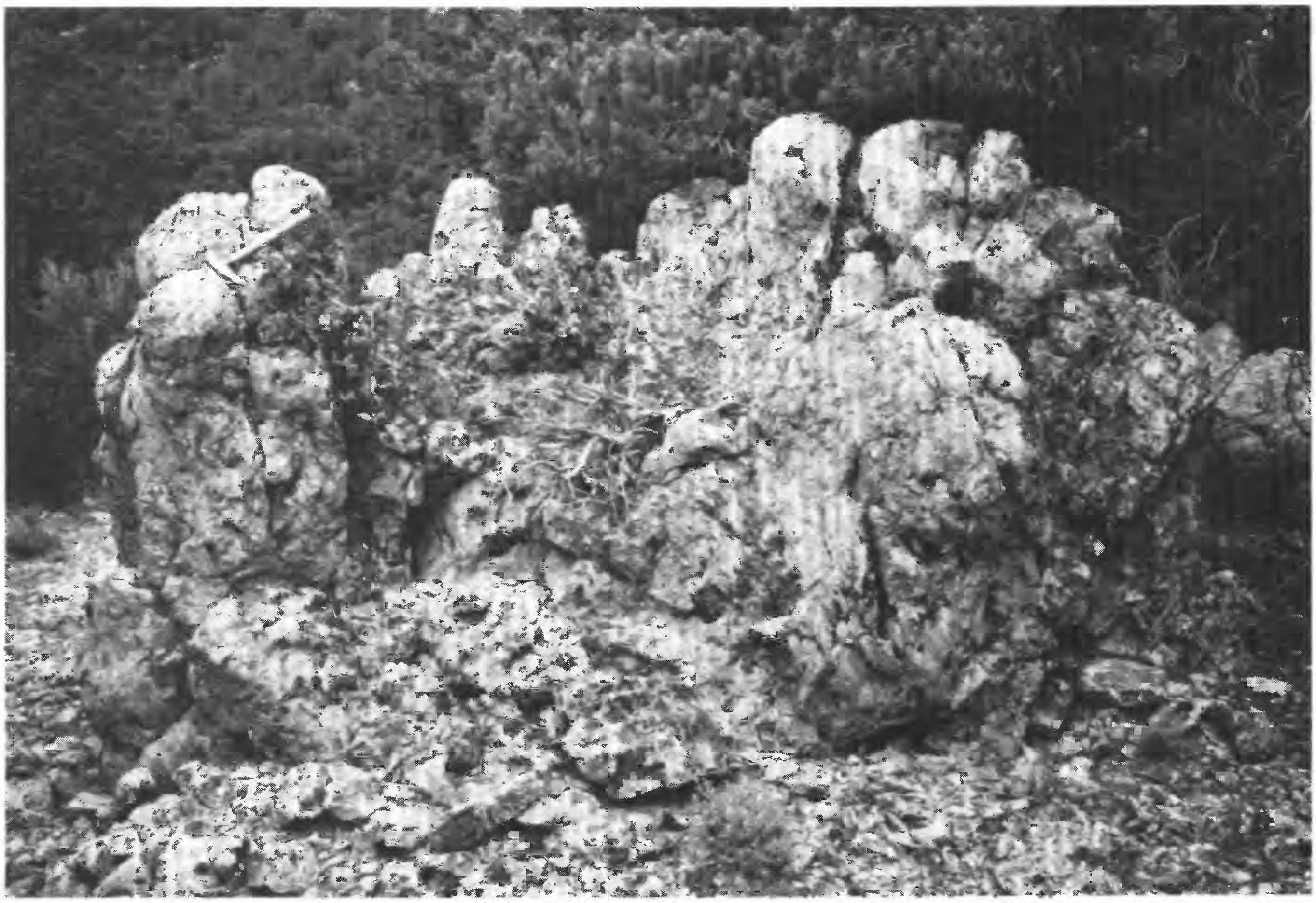

FIGURE 8.—Large (2×3 m) rhyolite clast in the rhyolite megabreccia of the upper member of the Round Rock Formation (pick at upper left gives scale). Note knobby rounded surface that may have formed by a process of spalling, abrasion, or both, in which erosion was greatest along fractures.

facies. The matrix of the rhyolite megabreccia unit is the same as that in the enclosing upper member ash-flow tuff.

Clasts in the rhyolite megabreccia are smaller on average than those in the other megabreccias. Maximum size is about 5 m. No areal pattern of size distribution was observed. The rhyolite megabreccia unit contains clasts that are generally more rounded than those of the other megabreccia units. Some large rounded fragments in the rhyolite megabreccia unit display a knobby surface (fig. 8), formed possibly by fracture-controlled spalling or abrasion or by a combination of these mechanisms. Some clasts in the rhyolite megabreccia have irregularly curved surfaces that show a high polish. The clasts consist almost wholly of light-gray rhyolite that contains a moderate amount of phenocrysts of quartz, sodic plagioclase, sanidine, and biotite in a devitrified glass matrix. Quartz phenocrysts are particularly conspicuous in some clasts. Rhyolite of this character has been recognized only in the rhyolite megabreccia. Granite boulders occur locally as clasts in the rhyolite megabreccia.

Clasts in the rhyolite megabreccia unit in the upper member of the Round Rock Formation are both brecciated and unbrecciated. Brecciated clasts consist of porphyritic rhyolite, with devitrified glassy groundmass, broken into fragments a few centimeters and less in size, set in a matrix of pulverized rhyolite. In hand specimens the matrix is not conspicuous, but it is marked by a generally vuggy character. As seen in thin section the matrix is locally cemented by minute ramifying seams of silica (microcrystalline quartz or chalcedony). No rinds have been observed on clasts in the rhyolite megabreccia unit.

MEGABRECCIA UNIT OF SILVER CREEK

The megabreccia unit of Silver Creek covers a large area along the northeast margin of the caldera (pl. 1).

Small areas of exposure occur for several kilometers northwest and south of the main patch of megabreccia. A cluster of small rhyolite plugs within the megabreccia mark a vent zone that is believed to have been also a principal conduit for earlier eruptions of the megabreccia (pl. 1, cross section *F–F'*). The megabreccia in this area is exposed through a vertical relief of at least 200 m. Again, a steep gravity gradient here at the caldera margin and proximity to a gravity low within the caldera (pl. 1) are interpreted to indicate a vent zone at the caldera margin. Within the caldera and no more than 1 km from its structural margin, the megabreccia forms a thin layer of intracaldera facies rock lying at the top of the upper member of the Round Rock Formation and beneath the Diamond King Formation (pl. 1, cross sections *E–E'* and *F–F'*). The megabreccia unit of Silver Creek occurs also as outflow facies (pl. 1, cross sections *E–E'*, *F–F'*, and *G–G'*) where it extends as far as about 4 km outside the caldera margin at about the same altitude as the margin. In one locality outside the structural margin of the caldera (pl. 1, cross section *G–G'*) the megabreccia lies on a rather steep (25°) slope that is suggestive of a caldera topographic wall.

Much of the matrix of the megabreccia unit of Silver Creek consists of tuff identical in appearance to much of the tuff of the upper member of the Round Rock Formation. In places, however, the matrix of the megabreccia appears to be entirely comminuted granite (fig. 9). The matrix as seen under the microscope consists of pulverized crystals of the granite; the fragments range in size down to nearly submicroscopic. Some of this material, however, as viewed in thin section, contains small particles as large as 1 mm that may be devitrified glass, and finer grained (in part submicroscopic) material that may also be in part devitrified glass.

FIGURE 9.—Megabreccia unit of Silver Creek. Clasts (as much as 2 m across) are virtually all granite in a comminuted granite matrix (pocket knife at arrow gives scale). Note general rounding of fragments.

The megabreccia unit of Silver Creek contains mostly granite clasts, some of which are as much as 10 m across. The larger clasts show a systematic distribution such that fragments as much as 8–10 m across are concentrated near the cluster of rhyolite plugs near the south fork of Silver Creek, those of 4–5 m maximum size occur as much as 1 km outward from the cluster of plugs, and those of 1–2 m maximum size are found beyond (pl. 1). Most of the clasts are nonporphyritic coarse-grained granite; some are aplitic or porphyritic granite. All are identical in appearance to comparable types in the Belmont lobe. In a few places small clasts of flow-layered rhyolite are evident, and in the south half of the outcrop area of the megabreccia unit of Silver Creek, brown to reddish-brown clasts of welded ash-flow tuff that contain prominent large flattened pumice lapilli are present. Fragments of other lithologies such as the common Paleozoic rock types and brown andesite have been seen only rarely in the megabreccia. The brown ash-flow tuff fragments may have been derived from similar-appearing welded ash-flow tuff layers in the Round Rock Formation, which in this area would be buried deeply within the caldera; no such material is exposed outside the caldera in this vicinity.

Virtually all of the clasts in the megabreccia unit of Silver Creek appear to be unbrecciated internally. Like clasts in the rhyolite megabreccia unit in the upper member of the Round Rock Formation, those in the megabreccia unit of Silver Creek are generally more rounded than those in the other megabreccia units. No rinds have been observed on clasts in the megabreccia unit of Silver Creek.

MEGABRECCIA OF JEFFERSON CANYON

The megabreccia of Jefferson Canyon is widely exposed through an area of several square kilometers southwest of the margin of the Mount Jefferson caldera (pl. 3). The megabreccia consists of a relatively thin layer of large areal extent lying upon a nearly flat surface of Paleozoic rocks (pl. 3, cross sections *H–H'* and *I–I'*). Much of the unit lies outside any known caldera structure and thus is considered to be outflow. Vent-facies megabreccia is nowhere exposed along the mapped margin of the Mount Jefferson caldera (pl. 3), although vent-facies materials are suggested to occur, partly faulted out, in the subsurface (pl. 3, cross section *H–H'*). The presence of immense (100–300 m) megabreccia blocks (pl. 3) may indicate proximity to a vent zone near the edge of Big Smoky Valley.

The matrix of the megabreccia of Jefferson Canyon is similar in appearance to, though generally it is less welded than, the tuff of Mount Jefferson, to which we believe it to be related. In most places the matrix of the megabreccia of Jefferson Canyon is more welded than that of megabreccias of the Manhattan caldera, and flattened pumice lapilli are locally evident. Commonly, tuff is strongly layered adjacent to megabreccia blocks a meter or more in diameter, and layering manifested by flattened pumice lapilli is deflected conformably around blocks; these relations suggest compaction of hot ash around blocks during welding. The tuff matrix in places contains only sparse small lithic fragments that locally are more abundant near large megabreccia clasts; elsewhere the matrix is charged with small lithic fragments. The matrix shows a chemical kinship with the tuff of Mount Jefferson in that it has a similar content of SiO_2 (about 69–70 percent) and of other major components, although slightly less of Al_2O_3 and Na_2O (data from Shawe and Lepry, 1985).

At one place on the north side of Jefferson Canyon (shown near the middle of pl. 3), the matrix of the megabreccia appears to be entirely black crystal-rich (quartz-latitic) glass. Crystals are euhedral to fragmental sodic plagioclase, quartz, biotite, augite, and sanidine, with accessory apatite, zircon, and iron-titanium oxides, set in a groundmass of foliated black glass. As seen in thin section, small lithic particles as much as 5 mm across are present; larger fragments are megascopically visible. The black glass matrix is interpreted to be the vitrophyric basal part of a welded ash-flow tuff deposit which here forms the matrix of the megabreccia of Jefferson Canyon. Clasts as much as 50 m in dimension occur in the black vitrophyre unit.

Fragments in the megabreccia of Jefferson Canyon are of many sizes; one block of Cambrian Gold Hill Formation quartzite and Paleozoic limestone (pl. 3) is longer than 300 m. Some of the larger blocks occur within what appears to be a channel-fill of megabreccia outflow, extending from an inferred vent near the margin of the Mount Jefferson caldera east of the area of plate 3. Geologic cross section *I–I'* (pl. 3), drawn approximately along the longitudinal axis of the possible channel, suggests that transport of megabreccia was westward, if no significant warping of the surface took place following megabreccia emplacement. Fragment distribution in the megabreccia of Jefferson Canyon is irregular (fig. 10). At one locality, megabreccia consisting of large closely spaced blocks of Paleozoic rock in tuff matrix gives way laterally to ash-flow tuff in which megabreccia clasts, except for scattered particles as small as a few centimeters, are virtually absent.

Clasts of the megabreccia of Jefferson Canyon are of a great variety of lithologic types. Most abundant are fragments of Paleozoic limestone (fig. 11), quartzite (including that of the Cambrian Gold Hill Formation), argillite, silicified limestone and argillite (in part jasperoid), and Cretaceous granite (some aplitic and some pegmatitic). Lesser amounts of knotted and phyllitic schist, rhyolite welded ash-flow tuff, and black vitrophyre, and minor medium-grained granodiorite and andesite have been seen locally. Most of these rock types are present just south of the Mount Jefferson caldera. A possible source for the rhyolite welded ash-flow tuff and black vitrophyre clasts, however, has not yet been identified, but it is probably the Mount Jefferson caldera. Black vitrophyre occurs dominantly as a vitrophyric basal part of the megabreccia, as previously described.

Near the west end of the "channel-fill" of the megabreccia of Jefferson Canyon (pl. 3), a group of quartzite blocks of the Gold Hill Formation, some as much as 20 m across, are linearly disposed within the megabreccia. Such groupings of clasts of the same lithology are not as common as groupings of clasts of varied lithology.

Clasts in the megabreccia of Jefferson Canyon are commonly either unbrecciated or only slightly or partly so, particularly at their margins (fig. 11), or they are intensely brecciated throughout (fig. 12). Intensely brecciated quartzite (fig. 13) consists of angular to subrounded fragments varying in size from a few tens of centimeters to tiny particles, all embedded in indurated comminuted quartzite. Brecciated quartzite almost identical to that illustrated in figure 13 has been described and illustrated by Bowes and Wright (1961, p. 300; Plate XVIIA) and ascribed by them (1961, p. 307–311) to formation as deep-level "explosion-breccia" more or less in place in the Kentallen, Argyll igneous complex, Scotland.

Brecciated granite clasts in the megabreccia of Mount Jefferson are similar in appearance to those of quartzite;

FIGURE 10.—Megabreccia of Jefferson Canyon. Large isolated block in foreground is Cambrian quartzite embedded in ash-flow tuff; low hills beyond contain numerous closely spaced large blocks of Paleozoic rock of various lithologies in a less conspicuous tuff matrix. View is westward along axis of a probable megabreccia channel fill.

microscope study shows that they consist of subrounded fragments in a matrix of angular particles of pulverized granite. Considerable pore space in the fine-grained matrix commonly is cemented by iron oxide minerals (deposited as pyrite before near-surface weathering?).

A large clast—several meters in size—of brecciated rhyolitic welded ash-flow tuff as seen in thin section consists of angular to subrounded fragments set in a shard-charged groundmass in which shards appear to be molded around or deflected against fragments. Sparse interstitial porosity in this rock has been filled with chalcedonic silica.

Many clasts in the megabreccia of Jefferson Canyon have well-formed devitrified welded-tuff rinds or hard layered non-welded-tuff rinds. Clasts with diverse rinds or without rinds may be side by side within megabreccia matrix; some large clasts appear to have different types of rinds on different parts of their surfaces. One granite clast 4 m in diameter, so thoroughly brecciated and pulverized that it appears megascopically to be jasperoid, is surrounded by a rind a few centimeters thick of layered ash-flow tuff that contains numerous devitrified flattened pumice lapilli and glass shards oriented parallel with the margin of the clast. The layered rind grades outward through a zone about 10 cm thick into more-or-less structureless ash-flow tuff matrix of the megabreccia. A second clast of similar size, but of light-gray rhyolitic welded ash-flow tuff, is surrounded by a devitrified glass rind about 3 cm thick that merges outward through several centimeters into more-or-less structureless tuff (fig. 14). Microscope study of the contact of the rind and the clast shows small microbrecciated streaks of the clast penetrating the rind tangentially. Within the inner 1 cm of the devitrified glass rind are small wisps of flattened glass shards. Outward the rind merges into a zone 1–2 cm thick of strongly layered devitrified welded ash-flow tuff

FIGURE 11.—Large clast of partly silicified Paleozoic limestone in the megabreccia of Jefferson Canyon. Thin-bedded limestone was isoclinally folded (in late Paleozoic or Mesozoic time) and later was silicified along bedding layers before incorporation in the megabreccia.

FIGURE 12.—Intensely brecciated quartzite clast in the megabreccia of Jefferson Canyon. Tuff rind still clings to part of the upper left surface of the clast.

marked by numerous flattened small pumice lapilli and oriented glass shards. This layer of the rind in turn merges outward through several centimeters into nearly structureless less welded ash-flow tuff. Another rhyolite welded tuff clast 3 m in diameter is surrounded by a layered rind 5-15 cm thick of gray welded tuff that has a glassy matrix marked by numerous small flattened pumice lapilli conformable with the surface of the clast. This fragment is embedded in black glass matrix of the megabreccia of Jefferson Canyon.

BASAL CONTACT OF A MEGABRECCIA OUTFLOW

A basal contact of a megabreccia outflow unit is well exposed only on the south side of Jefferson Canyon; here the megabreccia of Jefferson Canyon rests on Paleozoic limestone just north of an immense quartzite clast of the Gold Hill Formation (pl. 3). At the contact buff-colored ash-flow tuff matrix of the megabreccia contains numerous clasts of limestone and phyllitic

FIGURE 13.—Close view of intensely brecciated quartzite clast in the megabreccia of Jefferson Canyon. Angular to subrounded fragments of quartzite are embedded in an indurated matrix of comminuted quartzite.

schist. Tuff locally penetrates the limestone, which is brecciated and pulverized for about 20 cm below the contact (fig. 15). Apparently the motion of the megabreccia during emplacement was sufficient to disrupt the underlying bedrock. Penetration of ash as irregular seams into the disrupted limestone demonstrates a probable incipient stage in the plucking of wall rock and in its incorporation into the megabreccia.

DISCUSSION

An eruptive origin of the megabreccia units related to the Manhattan and Mount Jefferson calderas is indicated by several facts. Much of the clast material in the megabreccia units of the Manhattan caldera is not known outside the Manhattan caldera. For example, the clastic rocks of the Permian Diablo Formation in the megabreccia unit of Sloppy Gulch, the reddish-brown rhyolite and gray andesite of the middle member of the Round Rock Formation, and the light-gray rhyolite of the rhyolite megabreccia unit in the upper member of the Round Rock are not found outside the caldera. Nor does it seem likely that some of these rocks could have existed in caldera walls that were removed by erosion. That these rocks originated at depth beneath the caldera seems more plausible than that they originated as gravity slides into the caldera resulting from collapse of oversteepened topographic walls. The locally jumbled (mixed) association of clasts of a great variety of lithologies in both the megabreccia unit of Sloppy Gulch and the megabreccia of Jefferson Canyon suggests that the clasts were not derived by landsliding of masses of wall rocks, which should have left a megabreccia containing spatially associated groups of clasts of the same lithology, reflecting distribution of lithologies in the collapsed wall rocks. Many of the clasts, as in the megabreccia unit of Sloppy Gulch, in the middle member of

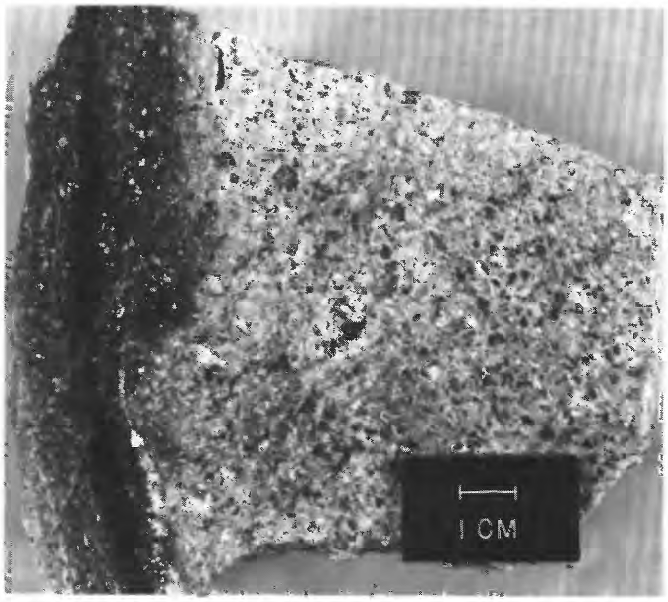

FIGURE 14.—Devitrified glass rind on rhyolitic welded ash-flow tuff clast in the megabreccia of Jefferson Canyon. Dark-gray devitrified glass rind at left is welded against light-gray rhyolite at right, part of a large clast about 3 m in diameter. (See text for additional explanation.)

the Round Rock, in the rhyolite megabreccia in the upper member of the Round Rock, and in the megabreccia of Jefferson Canyon are intensely brecciated in a manner unrecognized in any of the wall rocks of the calderas or reasonably inferred to have occurred in higher, now eroded, zones in the structural margins of the calderas. Many of these clasts were brecciated and indurated ("healed") before emplacement of the megabreccias. Such seems particularly true of brecciated clasts that have unbroken glass rinds. The sources of the clasts likely were at depth within the root zones of the calderas.

The general size distribution of large clasts of the megabreccia units of Sloppy Gulch and of Silver Creek suggests point sources at the margin of the Manhattan caldera, probably vent zones along the ring fracture of the caldera. The similarity of the graded-size distribution of large clasts to that of large clasts in "co-ignimbrite lag-fall" deposits in the Acatlan Ignimbrite of west-central Mexico described by Wright and Walker (1977) and in "proximal-facies" ash-flow deposits from Mount Mazama in Oregon described by Bacon (1984) is noteworthy. Maximum dimension of clasts in the Mount Mazama proximal-facies deposits is about 7 m.

FIGURE 15.—Contact of light-colored tuff of the megabreccia of Jefferson Canyon on dark Paleozoic limestone. Limestone is brecciated and pulverized below contact, and tuff penetrates limestone in an apparent incipient stage of plucking of wall rock by an erupting ash flow.

A pyroclastic-flow lag deposit that formed during a 1980 phreatic explosion eruption at Mount St. Helens, Wash., contains blocks as long as 3 m near the lip of the explosion pit, and a lithic clast in a pyroclastic flow deposit "derived from great depth" is about 5 m in maximum diameter (Rowley and others, 1981, p. 506). The megabreccias of the Manhattan caldera may be more akin to proximal-facies ash-flow deposits than to lag-fall deposits inasmuch as large clasts in the Manhattan caldera megabreccias also are interpreted by us to have been transported by pyroclastic flows. (See also Bacon, 1984.) Druitt and Sparks (1982) considered lag-fall deposits to be proximal pyroclastic-flow deposits.

The interpretation that megabreccia outside the ring-fracture zones of the Manhattan and Mount Jefferson calderas constitutes outflow material in part depends on whether or not significant topographic walls were developed around the calderas. If initially steep topographic walls can be demonstrated, then megabreccia that forms relatively flat sheets just outside the ring-fracture zones (structural walls) of the calderas could be interpreted as the result of caldera wall collapse that moved brecciated material on a listric surface from perhaps as far as 5 km outside the caldera structural margin onto this margin, as well as into the caldera. This question cannot be resolved unambiguously on the basis of present knowledge.

The middle member of the Round Rock Formation occurs as apparent outflow lying upon a nearly flat surface of Paleozoic rocks and the megabreccia unit of Sloppy Gulch (pl. 1, cross section *C–C'*). This configuration suggests that collapse of an oversteepened caldera wall did not contribute to formation of the middle member of the Round Rock here.

The presence of the megabreccia unit of Sloppy Gulch lying on the granite of Pipe Spring 4 km south of the Manhattan caldera seems impossible to account for by collapse of caldera walls. If rock had slid northward toward the caldera because of an oversteepened topographic margin formed during caldera collapse, slide material in the patch of megabreccia would have consisted only of granite.

Because part of the megabreccia of Jefferson Canyon has a matrix that is analogous to the common black vitrophyric basal part of many welded ash-flow tuffs, it is inferred to have been emplaced in like manner, as a hot ash-flow eruption. Presence of the vitrophyre on a relatively flat surface outside any known calderas in the southern Toquima Range implies deposition as outflow.

Virtual confinement of the middle member of the Round Rock Formation within the Manhattan caldera and a more or less even distribution of the member within the caldera, except near the southwest margin of the caldera where the member is appreciably thicker (pl. 1, cross section *B–B'*), are analogous to the distribution of some ash-flow tuff units within calderas.

Rinds and other features that characterize the surfaces of clasts in the megabreccia units provide important clues to the emplacement of the megabreccia. Clasts that have no apparent rinds probably indicate near equilibrium between the temperature of the clast and that of the enclosing ash matrix at the time of emplacement, probably by heating of the clasts before or during eruption. Equilibrium between the temperature of clasts and of enclosing ash matrix likely also existed during emplacement of the rhyolite megabreccia in the upper member of the Round Rock Formation and that of the megabreccia unit of Silver Creek. However, during eruption of other megabreccia units, erupting ash incorporated relatively cool wall-rock fragments, upon which the hot ash apparently formed chilled rinds. Perhaps in some eruptions, clast materials of the megabreccia were derived from wall rocks at different levels within the vent, so that deep highly heated fragments became mixed with cool fragments incorporated near the surface. As a result fragments both with and without rinds, and with rinds in various stages of development, were mixed in the erupting ash column and were deposited side by side when the megabreccia flow came to rest. Such a deposit is represented by the megabreccia of Jefferson Canyon. Probably eruption of the megabreccia unit of Sloppy Gulch took place during conditions under which deeper Paleozoic rocks were relatively hot and nearer surface volcanic rocks were relatively cool, with the result that generally only the volcanic clasts developed rinds. Likewise, at the time of eruption of the middle member of the Round Rock Formation, only reddish-brown rhyolite was near the surface and sufficiently cool to develop rinds in hot ash. After emplacement on a cool surface outside the caldera, the hot ash in basal parts of some ash flows fused into vitrophyre.

Rhyolite blocks picked up during eruption of the rhyolite megabreccia in the upper member of the Round Rock were tumbled and eroded in the erupting column such that their surfaces were plucked, rounded, and in some cases polished. The large faceted blocks of rhyolite seen in the middle member of the Round Rock probably rose in the erupting column more slowly than ash and other small particles. Such a condition could abrade and facet lower sides of large clasts; spurts or lags in the erupting ash, or contact with other large clasts or with vent walls, might tumble the clasts and bring new surfaces into position to be faceted.

The presence of large isolated blocks within ash-flow tuff implies that the blocks became entrained in ash and transported by the ash flow to their present sites, rather than that they collapsed from an oversteepened caldera wall into tuff newly emplaced within the caldera. Nowhere is there evidence of large blocks "plowing" into and disrupting a previously emplaced ash flow.

DEEP-LEVEL, SUBVOLCANIC "EXPLOSION-BRECCIA"

The brecciated clasts of the megabreccia units of the Manhattan and Mount Jefferson calderas are quite similar to breccia described in the root zones of some deeply eroded Tertiary calderas and other igneous centers elsewhere in the world. This similarity suggests that the Manhattan and the Mount Jefferson brecciated clasts may have formed in a manner similar to that interpreted for formation of the deep-level subvolcanic breccia. In this report we make no distinction between "gas-explosion" breccia and "hydrothermal" breccia formed in deep levels, inasmuch as criteria for their distinction have not yet been defined.

Bowes and Wright (1961) described a breccia pipe about 200×500 m across within the Kentallen, Argyll, Scotland igneous complex and attributed it to a deep-level gas explosion origin. They suggested (1961, p. 310–311) that "sudden increase in gas pressure *** caused cushioned explosions in the joints and fractures of *** quartzite" to form a pipe. "Gas streaming through the pipe caused erosion and transport of the boulders." Subsequent intrusion of magma, possibly explosive, incorporated large blocks of breccia into the magma. Similar subvolcanic breccias in other of the British Tertiary volcanic centers have been described by Richey (1940), Richey and Thomas (1932, p. 805–811), Tyrell (1928), and Bailey and others (1925).

Gilluly and Gates (1965, p. 51) described a breccia associated with granodiorite in the northern Shoshone Range, Nev., that appears to have formed as a precursor to granodiorite emplacement, the granodiorite having invaded the breccia locally. They stated, "The breccia is made up of angular fragments and blocks, some as much as 10 feet long, of the immediately adjacent sedimentary rocks ***. The breccia is cemented by cream-colored quartz and chalcedony ***. Perhaps it formed during the intrusion by rock bursting along a crack opened by granodiorite magma."

Tweto (1951, p. 527) described wall-rock breccia at the edges of sills near Pando, Colo., that he interpreted to have formed just in advance of sill emplacement by "explosive introduction of fluids or tenuous magma."

At the Grizzly Peak cauldron complex in the Sawatch Range, Colo., "exotic" breccia described by Cruson (1972) is similar to brecciated clasts of the megabreccia units in the southern Toquima Range. Cruson attributed formation of the breccia both to cauldron subsidence and to degassing of an underlying magma chamber (gas explosion). Much of the breccia deep in the Grizzly Peak cauldron, presumably formed by gas explosion, consists of brecciated Precambrian rocks devoid of volcanic matrix; some breccia is cemented with "rock flour" and other with coarse-grained quartz. A nearly circular, pipelike body 1,000 m in diameter is choked with large rounded boulders of brecciated Precambrian rocks surrounded by a jacket of similar boulders in a tuff matrix.

At the Mt. Lewis cauldron in the Northern Shoshone Range, Nev., subvolcanic breccia pipes 1–2 km in diameter are exposed at a level of erosion that has removed all but local remnants of the cauldron fill (Wrucke and Silberman, 1975; Gilluly and Gates, 1965). The breccia pipes, some of which contain ash-flow materials, are eroded to a depth probably no more than 100–200 m below the pre-caldera surface; they exhibit features of ash-flow vents in the upper reaches of the caldera root zone. The breccia pipes within the Mt. Lewis cauldron demonstrate a sequence of development (Gilluly and Gates, 1965, p. 66–75) consistent with that inferred for the emplacement of some of the megabreccia and ash-flow tuff units of the Manhattan and Mount Jefferson calderas. Gilluly and Gates stated, "The primary factor in forming the pipes was the rise of a plug of volatile-rich magma" (p. 75). Initial activity consisted of the development of coarse breccia that occurs now as remnants in discontinuous patches along the margins of pipes. The breccia is a mixture of small to large fragments, ranging from microscopic size to "acre size" and consisting chiefly of material of the adjacent wall rocks (mostly Paleozoic sedimentary rocks). The large blocks commonly are internally fractured. Some of the large blocks may have slumped into position from wall rock as much as 100 m higher. Gilluly and Gates (1965, p. 73–75) suggested that the breccia may have formed through the explosive action of eruptive volatiles and a process of rock bursting into a rising gas stream.

Following its formation, the coarse breccia was invaded and largely displaced by fine breccia that consists of abundant fragments of Paleozoic sedimentary rocks and of Tertiary volcanic rocks, particularly intrusive porphyries, presumably derived at depth. In addition to Paleozoic rocks and Tertiary volcanic rocks, the fine breccia in one pipe contains abundant fragments of collapsed pumice and perlitic glass.

Following development of the fine breccia, pumiceous vitrophyre was emplaced in one of the pipes (Gilluly and Gates, 1965, p. 71–72). The vitrophyre is charged with fragments of Paleozoic rocks, Tertiary porphyritic rocks, and tuffaceous and pumiceous Tertiary volcanic rocks. According to Gilluly and Gates (1965, p. 72), the vent probably "was once largely filled with breccia, both coarse and fine, much of which became incorporated in the pumiceous vitrophyre, while the remainder was carried to the surface and there deposited as tuffs and extrusive breccia." A quartz latite breccia unit lying on Paleozoic rocks adjacent to a breccia pipe on Mt. Lewis, described by Gilluly and Gates (1965, p. 75–77) as intrusive, was described by Wrucke and Silberman (1975, p. 13) as containing pumice lapilli and as closely resembling a welded ash flow. The pumiceous vitrophyre in the breccia pipe probably represents magma in a stage of eruption just prior to fragmentation into a gas-charged column of pumice and glass shards, loaded with fragments of wall rocks, that was discharged at the surface as an ash flow or ash-flow breccia.

Large blocks of Tertiary conglomerate and bedded tuff, one almost 1,000 m long, have foundered in the breccia pipes perhaps as far as 300–400 m from their original positions (Gilluly and Gates, 1965, p. 68, 72–73). No evidence indicates whether the blocks subsided as a result of magma withdrawal at depth in the pipe or as a result of sinking within a rising column of vesiculating magma or gas-charged ash. Some of the bedded tuff contains lithic blocks as much as 2 m in diameter that according to Gilluly and Gates (1965, p. 73) "clearly record explosive eruptions older than the pumiceous vitrophyre." Gilluly and Gates concluded that the pipes demonstrate alternating intrusion, eruption, and subsidence in a "two-way pump action."

Clasts in the megabreccia of the Manhattan caldera and of the Mount Jefferson caldera that consist of monolithologic indurated breccia are believed to be analogous to the coarse breccia of the breccia pipes in the root zone of the Mt. Lewis cauldron. Megabreccia in the Manhattan and Mount Jefferson calderas that has sparse matrix is similar to erupted equivalents of the fine breccia of the Mt. Lewis pipes that carries large clasts of coarse breccia, and megabreccia with significant to dominant ash matrix is similar to erupted equivalents of the pumiceous vitrophyre that carries large clasts of coarse breccia.

At the localities cited, deep-level subvolcanic "explosion-breccia" developed in a series of steps: initial fracturing of country rock by streaming gases derived from invading magma; rotation of breccia fragments (in some cases, disruption by a process of fluidization); cementation by rock flour produced by fluidization or subsequently by precipitated minerals (for example, quartz and chalcedony); further fracturing; and incorporation of breccia clasts either in erupting tuff or in intruding magma. These steps are the same as those inferred for formation of brecciated clasts and their incorporation in ash-flow tuffs during development of the Manhattan and the Mount Jefferson calderas. The mechanism of fracturing, brecciation, and fluidization of solid rocks by gas or other fluid streaming was described in detail by Reynolds (1954). Myers (1975) clarified some of the applications of fluidization.

PHYSICS OF MEGABRECCIA ERUPTION

The mechanism of emplacement described here can account for the presence of megabreccia clasts with typical dimensions of 10–300 m within a matrix that commonly makes up less of the total rock unit volumetrically than do the clasts. The primary question to resolve is whether or not clasts could have been emplaced in a megabreccia as a result of upward displacement, rather than solely as a result of downward, gravity-induced displacement. Previous theoretical work has considered fragments smaller than those observed at Manhattan and at Mount Jefferson: fragments less than 10 m long in explosive, maar-type eruptions (McGetchin and Ullrich, 1973) and fragments less than 0.5 m long in sustained eruptive column events (Sparks and others, 1978). Expulsion of material at the scale that occurred at Manhattan and at Mount Jefferson has never been observed in historic times (Francis, 1983). Earlier workers have made simplifying assumptions and estimated eruption parameters given certain initial conditions. Some of these assumptions are not strictly appropriate to the ejection of abundant large blocks.

Volcanic eruptions can generally be divided into two types: explosive eruptions that consist of very low density, gaseous matrix material or fluid, and gas-streaming eruptions that consist of denser, spatially more continuous fluid material. In explosive eruptions (McGetchin and Ullrich, 1973), rock fragments have limited ballistic ranges. A rock fragment with an average density of 2,400 kg/m^3, upon which the force of gravity is exactly balanced by the upward pressures exerted by the erupting gas column, is characterized as follows: mass×gravity=pressure×area. Then,

$$L=p/(D_f g)=480 \text{ m}$$

if L is the dimension of the fragment, D_f is the fragment's density, g is gravity, and p is the pressure exerted, taken here as 100 bars. Any fragment within the eruptive blast smaller than 480 m would be accelerated upward while acted upon by a pressure of 100 bars. For example, if L=100 m,

$$\text{Force}=pL^2\text{-}D_f L^3 g=7\times10^{10} \text{ nt}$$

The acceleration, a, neglecting all drag, would be

$$a = \text{Force}/D_f L^3 = 30 \text{ m/s}^2$$

McGetchin and Ullrich (1973) considered explosive, maar-type volcanic eruptions more rigorously than the foregoing analysis, but calculated parameters for entrained fragments only as long as 10 m. By considering friction and dynamic conditions, they found typical conditions to include a maximum dynamic pressure of 96 bars at 500 m depths, decreasing to 9 bars at the surface where the exit velocity was 330 m/s. At these pressures a fragment 100 m in dimension would no longer be accelerating when it left the vent. A fragment 10 m in dimension would accelerate at about 30 m/s^2 and have an exit velocity of about 265 m/s and a vacuum ballistic range of about 6 km (McGetchin and Ullrich, 1973, table 4). No calculations were made for fragments larger than 10 m, but extrapolations of their exit-velocity curves indicate that low velocities (<100 m/s) would be expected. With an increase in the amount of large fragments in an eruptive mass, assumptions about friction with the vent wall, dynamic drag, buoyancy, and turbulent flow become less certain. On the basis of the calculations, the large blocks would not be expected to travel far.

Several other exit-velocity calculations have been based on observed ejecta. Minakami (1980) derived velocities of 180–210 m/s from observations of 1-m blocks, 3.5 to 4.5 km from Asama, Japan. Melson and Saenz (1968) calculated a 220-m/s ejection velocity for fragment impacts 5.5 km from the 1968 eruption site of Arenal, Costa Rica. Kieffer (1981) used an initial reservoir pressure of 125 bars and an initial fluid velocity of 100 m/s to model the May 18, 1980, blast of Mount St. Helens.

Maar-type eruptions are considerably smaller than the voluminous eruptions of tuff envisioned at the site of the Manhattan caldera. Rather than small gas (maar) eruptions, massive, ash-charged eruptive columns of pyroclastic material, with subsequent collapse and basal outflow, are hypothesized. The kinematics of an entrained block fragment in a large eruptive column would be more akin to those of a golf ball in a fountain. The massive scale and catastrophic nature of large volcanic eruptive columns and their gravitational collapse require considerations different from those of small gas eruptions. Fragments 100 m long might be only a minor component of the total eruptive column, and their influence on boundary effects, such as friction along the vent walls, would not be a critical factor in dynamics of the eruption. Sparks and others (1978) modeled the generation, movement, and emplacement of pyroclastic flows by column collapse, and their results provide estimates of conditions surrounding the movement of large blocks in these eruptions. Their calculations indicate that a fragment 0.5 m in radius and 2,500 kg/m^3 in density can remain suspended in a fluid matrix of 500-kg/m^3 density if it moves at 200 m/s; the entrained solids-and-gas mixture resembles a high-velocity jet with a height of as much as several kilometers above the vent, above which the column becomes a thermally driven convective plume (Walker, 1973). The upward velocity of the column was found by Sparks and others (1978) to decrease quickly after leaving the vent. A column leaving a 200-m-radius vent decelerates from 200 m/s to almost 0 m/s about 3 km above the surface and then re-accelerates slightly (fig. 16). In this example, the initial, postcollapse flow velocity would be about 120 m/s and could sustain fragments 0.1 m in radius. An initial vent velocity of 400 m/s would produce an initial flow velocity of about 180 m/s and could sustain fragments 0.4 m in radius.

The large blocks observed in the megabreccia units at the Manhattan and Mount Jefferson calderas appear to have been emplaced by a process similar to that described in the preceding paragraph, but their dimensions are orders of magnitude greater than those considered above. The larger blocks undoubtedly did not rise very far in the eruptive column, but probably were pushed out of the vent area and entrained in the ash flows when they formed immediately after column collapse (fig. 16; pl. 1, cross section *C–C'*).

The hindered-settling ratio for particles in suspension is useful for analysis of an ash eruption that contains large clasts, if the eruptive column over short vertical distances is considered to be a non-accelerating fluid with turbulent flow. The hindered-settling ratio is factored into the equation for the settling velocity of a suspended fragment (Gaudin, 1939) to obtain the hindered-settling velocity, v, in a fluid composed mostly of fragments,

$$v = (8gL/3Q((D_f/D_s)-1))^{1/2}$$

where L is the dimension of the fragment, D_f is the density of the fragment, D_s is the density of the slurry matrix fluid, Q is the coefficient of resistance (varies between 0.4 for a sphere and 5.0 for a prism), and g is gravity. Figure 17 indicates hindered-settling velocities for spherical rock fragments with a density of 2,400 kg/m^3 in slurries of varying density. A 100-m diameter spherical block in a slurry matrix with a density of 800 kg/m^3 would settle at 114 m/s; if the column were moving upward at 200 m/s, the block would move upward relative to the surface (fig. 16).

This approximation is not applicable at low slurry densities (<10 kg/m^3), inasmuch as the fluid is no

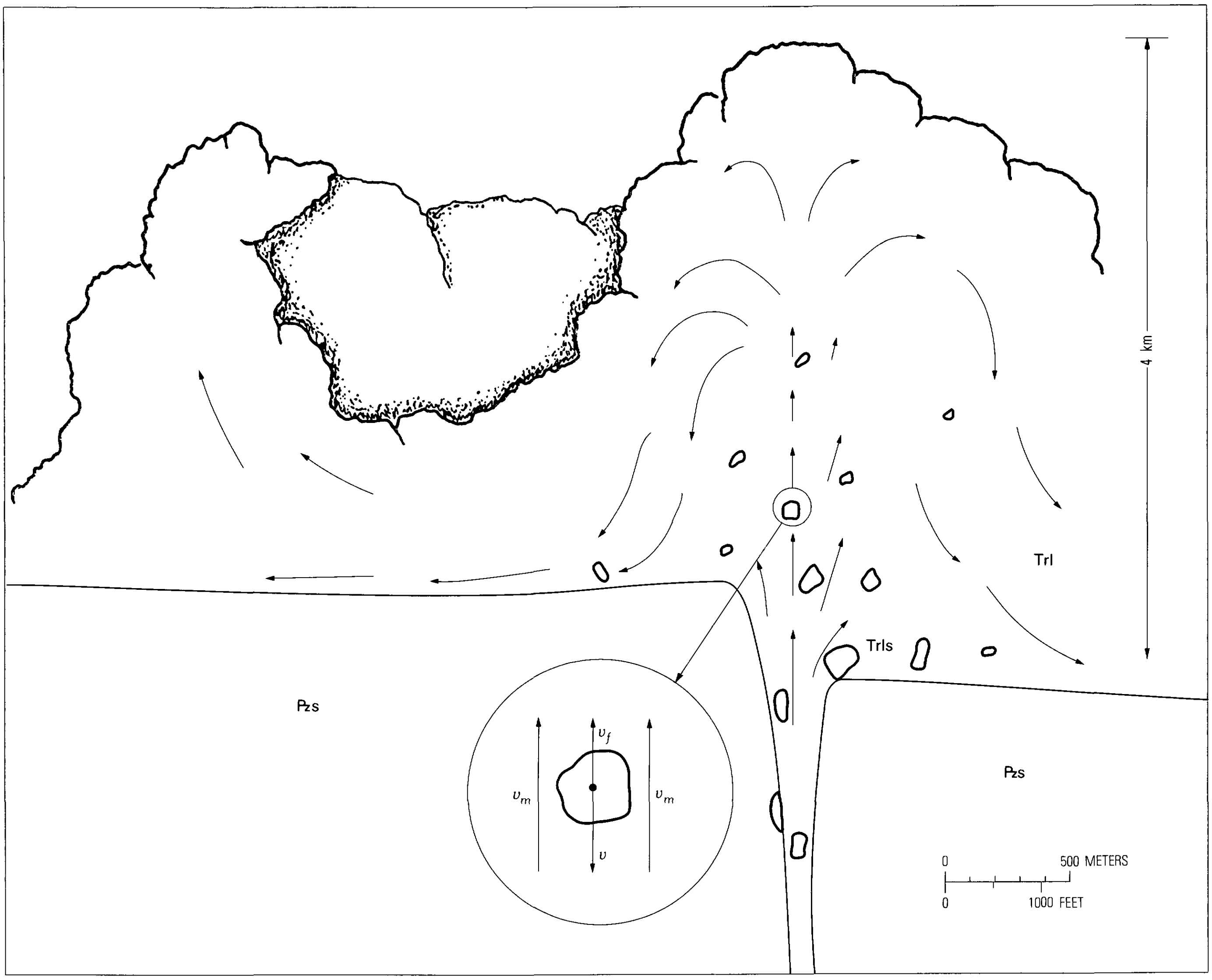

FIGURE 16.—Generation of a pyroclastic flow and megabreccia. Sketch is at same scale as cross section *C–C′*, plate 1; rock unit symbols are as on plate 1; Pzs, Paleozoic rocks; Trl, lower member of the Round Rock Formation; Trls, megabreccia unit of Sloppy Gulch. If hindered settling velocity of an entrained fragment, v (=114 m/s, see text), is exceeded by velocity of erupting matrix material, v_m (=200 m/s), net velocity of fragment, v_f (=86 m/s), is upward. (Modified from Francis, 1983, fig., p. 66–67).

longer truly a suspension, but rather two suspensions, one with large dense particles and one with fine particles. For reference, air at room temperature has a density of about 1.3 kg/m^3. McGetchin and Ullrich (1973) calculated a density of 17 kg/m^3 for material immediately after its exit from the vent, and they calculated densities of 240–250 kg/m^3 for magma several hundred meters beneath the surface. Sparks and others (1978) modeled densities between 1 and 500 kg/m^3 for material in collapsing columns.

Large blocks 100 m in dimension would be expected to move upward while incorporated in the erupting fluid and gas several hundred meters beneath the surface (figs. 16, 17). Upon ejection these blocks would rapidly decelerate, fall out of the rising column, and come to rest near the vent. If deposition were from voluminous ash flow moving across a surface sloping gently away from the vent, large clasts presumably could be transported considerable distances within the ash flow.

SUMMARY

Early in the history of the Manhattan caldera, following emplacement of a large body of magma in the upper part of the crust, initial degassing of the magma

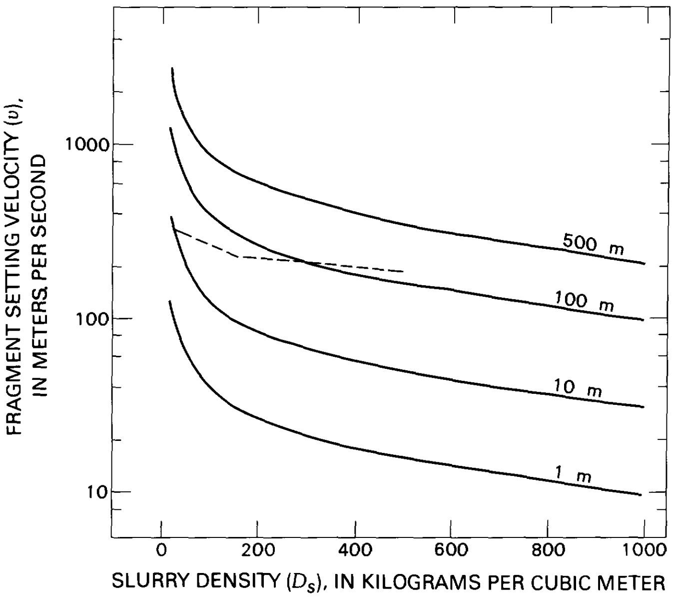

FIGURE 17.—Plot of hindered-settling velocities of entrained fragments as a function of fragment size and matrix/slurry density. Fragment sizes of 1, 10, 100, and 500 m are considered. McGetchin and Ullrich's (1973, table 4) calculations of dynamic slurry velocity and density are plotted (dashed line) for comparison; 100-m curve intersects this plot where the density is defined at depths of 200 m from surface.

resulted in gas streaming upward along fracture zones. The main zone of streaming gas and entrained particles was along what was to become the south margin of the caldera. A general west-northwest trend of this margin, parallel with the main strands of the Walker Lane structural zone, hints that initial localization of the Manhattan caldera was determined by the regional structural grain. Other fractures may have been induced by magma emplacement. Violent, even explosive streaming of gas from the magma chamber resulted in local development of "explosion-breccia" of the type recognized as characterizing some deep parts of intrusive and volcanic igneous centers. The breccia became indurated either through cementation by hot pulverized and fluid-charged (fluidized) rock or through mineralization subsequent to the violent brecciation. The zones of gas-explosion brecciation ultimately reached the surface and allowed venting of ash flows that were deposited as the lower member of the Round Rock Formation. In the initial "throat-clearing" phase of eruption, much vent wall rock was incorporated in the volcanic ash. The wall-rock material consisted of a variety of lithologic types, displaying varied degrees of gas-explosion brecciation depending on how faithfully eruption of this phase followed the earlier-brecciated fracture zones of gas leakage. Also, clasts acquired from wall rocks at deep levels had been preheated because of proximity to the underlying magma chamber and because of gas transfer of heat, whereas clasts from high-level wall rocks were much cooler but perhaps also in part brecciated. Products of these early eruptions were deposited as the megabreccia unit of Sloppy Gulch and the megabreccia unit of Mariposa Canyon. The largest clasts were deposited close to vent zones and smaller clasts were carried farther from vents, as is typical of co-ignimbrite lag fall and proximal-facies ash-flow deposits.

At the Mount Jefferson caldera initial temperatures were higher than at the Manhattan caldera. Thus the ash matrix of the megabreccia of Jefferson Canyon, derived from this caldera, became somewhat welded on emplacement. Temperature was high enough, in fact, that locally the lower part of the megabreccia unit fused after emplacement to form black vitrophyre encompassing large blocks of the megabreccia.

During emplacement of the remainder of the lower member of the Round Rock Formation above the initial megabreccia deposit, the main subsidence of the Manhattan caldera took place. Ash-flow and megabreccia eruptions continued periodically thereafter.

After the lower member was emplaced, a volcano developed at the south margin of the caldera at the locus of what is believed to have been the main vent of the lower member of the Round Rock. This was the first event leading to the formation of the middle member of the Round Rock. Initially, andesitic magma was intruded in the vent zone, perhaps with only minor explosive eruption at the surface. At least two varieties, one hornblende bearing and the other biotite bearing, were emplaced as separate intrusions. Parts of the andesitic intrusions were solidified and even autobrecciated(?) by the time of emplacement of rhyolitic magma in the volcano. Some of the rhyolite was erupted locally at the site of the volcano as small welded ash-flow eruptions, and autobrecciated domes may have formed. At depth part of the rhyolite magma became mixed with andesitic magma, resulting in rocks that are chemically transitional between the end members. Following solidification of rhyolite magma, a cataclysmic explosion destroyed the small compound volcano near the south margin of the Manhattan caldera, blasting the mixed andesite-rhyolite across most of the caldera to form a widespread relatively thin layer of megabreccia. A thicker layer of megabreccia fell back in the vicinity of the explosion vent, and near the vent the older megabreccia unit of Sloppy Gulch became incorporated with the megabreccia of the middle member of the Round Rock. The cataclysmic eruption may have been induced by renewed gas buildup from the continuing degassing of the large magma chamber underlying the caldera. The eruption marked the beginning of a phase that led ultimately to emplacement of the upper member of the Round Rock Formation. Materials that were thrown the farthest from the blast site at the volcano—the initially erupted material—contained no volcanic ash, accounting for the apparent absence of tuff matrix within the middle member of the Round Rock in the northern third of the Manhattan caldera. As the eruption progressed, ash became mixed with clasts of andesite and rhyolite of the small volcano; ash is evident and locally even abundant in the middle member in the southern two-thirds of the caldera. The inference that andesite dominated in the subsurface and that rhyolite dominated near the surface of the volcano could account for the apparent dumping of andesite locally on top of rhyolite in the erupted megabreccia member and for the apparently cooler temperature of rhyolite than andesite when emplaced (as evidenced by the ash rinds on rhyolite clasts). As a final event in this phase of caldera volcanism, a small plug and related dikes of rhyolite were intruded into the vent of the volcano.

Eruption of ash-flow material then continued and the upper member of the Round Rock Formation formed. Midway through emplacement of the upper member of the Round Rock, a vent zone at the northeast edge of the caldera apparently became clogged with rhyolitic magma. Either gas-explosion brecciation or autobrecciation disrupted part of this rhyolite, and then subsequent violent eruption "cleared the throat" of the vent zone to form the relatively small unit of rhyolite megabreccia within the upper member of the Round Rock.

Following emplacement of most of the upper member of the Round Rock, a final gasp of explosive activity of the Manhattan caldera caused eruption of the megabreccia of Silver Creek. Granite wall rocks of the vent had not previously been brecciated by gas explosion, inasmuch as the clasts of the unit are virtually unbrecciated. However, because much of the matrix of the granite clasts of the unit is comminuted granite, we infer that eruption involved gas explosion. Again, size sorting of larger clasts close to the inferred vent zone of the megabreccia suggests a co-ignimbrite lag fall or proximal facies of ash-flow tuff (Bacon, 1984). Presence of both thin outflow and thin intracaldera facies of the megabreccia unit of Silver Creek at the structural margin near the inferred vent zone suggests that the caldera at the time of eruption was not depressed much below the surrounding surface (pl. 1, cross sections *D-D'* and *E-E'*).

After the ash-flow eruption phase of the Manhattan caldera had been completed, small plugs of rhyolite and quartz latite were emplaced along the east margin of the Manhattan caldera. Also, after completion of the ash-flow eruption phase of the Manhattan caldera—within probably no more than about 500,000 years—the Diamond King Formation, the Bald Mountain Formation, and the tuff of Peavine Creek were laid down across the dormant caldera. These units, of course, were derived from sources outside the Manhattan caldera.

We believe that the next event in the evolution of the caldera was intrusion of the olive-brown andesite as a stock and associated sills and dikes. Some uncertainty surrounds this assessment, however. The caldera apparently was resurgently uplifted: the preserved volcanic units in the central part of the caldera that are younger than the Round Rock Formation stand higher than those in the marginal parts and outside the caldera. Resurgence appears to be the most likely mechanism to have elevated the core of the caldera sufficiently to allow gravity sliding of a large mass of volcanic rocks westward to lower terrain within the western part of the caldera (pl. 1). We note that this slide mass is not internally brecciated, as slide masses resulting from oversteepened topography commonly are considered to be. This large slide mass clearly was in place at the time of irruption in the western part of the caldera of the domes or plugs of dacite at about 24.5 Ma (pl. 1), marking the end of caldera activity. The olive-brown andesite, because of its widespread occurrence within the caldera, might be part of a magma body (shallow pluton?) that caused resurgence of the caldera. It remains unresolved, however, whether the andesite was emplaced about 24.5 Ma or whether it was emplaced nearer to its determined age of 22 Ma, and thus was unrelated to caldera activity. Intrusion of andesite now exposed within the Manhattan caldera was at a shallow level, as attested to by the occurrence of abundant vesicles in some of the sills. If andesite of this phase of igneous activity were responsible for resurgence, it must have been emplaced as a large, broad mass at depth, below the levels depicted in the geologic cross sections (pl. 1).

Resurgence of the Manhattan caldera was not a process of doming, as can be seen in the geologic cross section *A-A'* through the caldera (pl. 1). Instead, the volcanic rocks within the core of the caldera were lifted as a more or less undeformed slab, cylindrical in form. But as the slab was raised, the margins beyond the slab slumped and tilted inward, apparently because the inward dip of the ring-fracture zone caused the diameter to increase upward; extension of the intracaldera rocks thereby was required. Thus everywhere in the peripheral zone the volcanic units dip inward toward the core of the caldera. The process is somewhat analogous to that described by Bonham and Noble (1982) for resurgence both of the Mount Jefferson caldera and of the Big Ten Peak caldera about 10–35 km southeast of Manhattan.

We conclude that calderas of this region of the Great Basin are of a genre somewhat different from those of the San Juan Mountains and perhaps of some other localities of the world. The Great Basin calderas occur in a region of relatively low crustal density, but it has not been demonstrated that they are underlain by coeval granitic batholiths. Extensive andesitic volcanism did not precede their formation. Their development was characterized by eruption of abundant ash-flow megabreccias. Walls of some of the calderas may not have been oversteepened significantly as a result of subsidence of caldera floors, implying that intracaldera facies of ash-flow tuffs almost filled collapsing calderas and that outflow facies of ash-flow tuffs were of relatively small volume.

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