Petrology and Physiographic Evolution of the Ocate Volcanic Field, North-Central New Mexico

A. The Ocate Volcanic Field—Description of Volcanic Vents and the Geochronology, Petrography, and Whole-Rock Chemistry of Associated Flows

B. Late Cenozoic Physiographic Evolution of the Ocate Volcanic Field

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1478

Petrology and Physiographic Evolution of the Ocate Volcanic Field, North-Central New Mexico

A. The Ocate Volcanic Field—
Description of Volcanic Vents and the
Geochronology, Petrography, and
Whole-Rock Chemistry of
Associated Flows

By J. MICHAEL O'NEILL *and* HARALD H. MEHNERT

B. Late Cenozoic
Physiographic Evolution of the
Ocate Volcanic Field

By J. MICHAEL O'NEILL

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1478

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1988

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, *Secretary*

U.S. GEOLOGICAL SURVEY

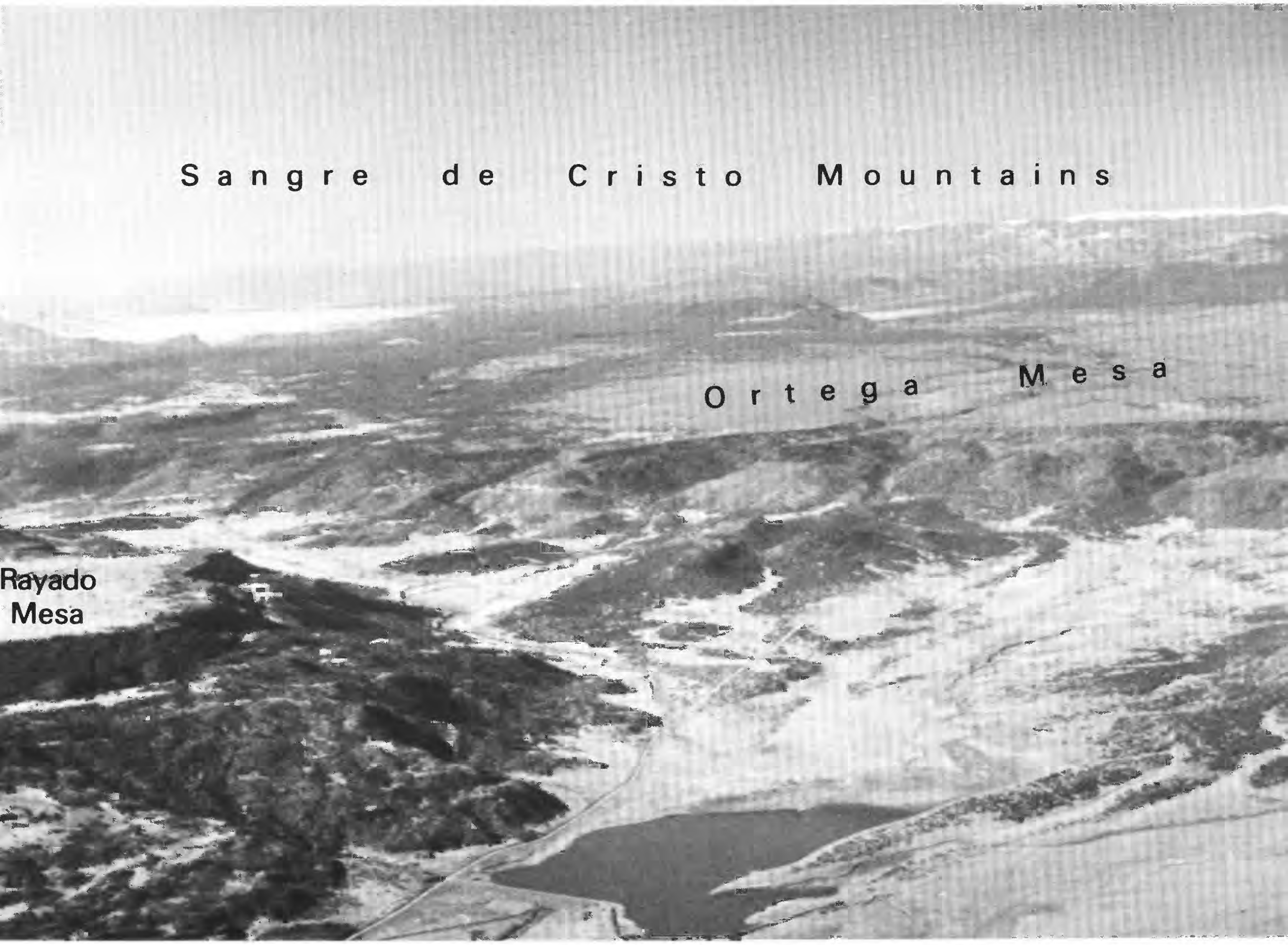
Dallas L. Peck, *Director*

Library of Congress Cataloging-in-Publication Data

Petrology and physiographic evolution of the Ocate volcanic field, north-central New Mexico.

(U.S. Geological Survey professional paper ; 1478–A,B)
Bibliography: p.
Supt. of Docs. no.: I 19.16:1778A,B
Contents: Pt. A. The Ocate volcanic field—description of volcanic vents and the geochronology, petrography, and whole-rock chemistry of associated flows / by J. Michael O'Neill and Harald H. Mehnert—Pt. B. Late Cenozoic physiographic evolution of the Ocate volcanic field / by J. Michael O'Neill.
1. Volcanic ash, tuff, etc.—Sangre de Cristo Mountains (Colo. and N.M.) 2. Volcanic ash, tuff, etc.—New Mexico. 3. Geology, Stratigraphic—Cenozoic. I. O'Neill, J. Michael. Ocate volcanic field—description of volcanic vents and the geochronology, petrography, and whole-rock chemistry of associated flows. 1988. II. Mehnert, Harald H. Late Cenozoic physiographic evolution of the Ocate volcanic field. 1988. III. Geological Survey professional paper ; 1478–A,B. IV. Title: Ocate volcanic field, north-central New Mexico.
QE461.P474 1988 552'.2'09789 87–600260

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



FRONTISPIECE—Ocate volcanic field. View to southwest.

CONTENTS

[Letters designate chapters]

The Ocate Volcanic Field—Description of Volcanic Vents and the Geochronology, Petrography, and Whole-Rock Chemistry of Associated Flows

By J. MICHAEL O'NEILL *and* HARALD H. MEHNERT

PETROLOGY AND PHYSIOGRAPHIC EVOLUTION OF THE OCATE VOLCANIC FIELD, NORTH-CENTRAL NEW MEXICO

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1478-A

Description of composition and age of rocks in the Ocate volcanic field, with suggestions as to their possible relationship to the Rio Grande depression

CONTENTS

ILLUSTRATIONS

TABLES

THE OCATE VOLCANIC FIELD—DESCRIPTION OF VOLCANIC VENTS AND THE GEOCHRONOLOGY, PETROGRAPHY, AND WHOLE-ROCK CHEMISTRY OF ASSOCIATED FLOWS

By J. MICHAEL O'NEILL and HARALD H. MEHNERT

ABSTRACT

The Ocate volcanic field is a series of flows erupted during the last 8 million years. The physiographic expression of these flows reflects their ages: the oldest flows cap the highest mesas; younger flows cap successively lower mesas. The volcanic rocks form two groups: typical flood basalts expelled from low-profile shield volcanos and fissures that are classified as subalkalic, hypersthene-normative basalts rich in alkalies, ferric iron, and alumina; and basic rocks erupted from both shield volcanos and composite cones that include alkali-rich basalt, andesite, minor dacite, and rare nepheline-normative basalt. The composite cones are composed of basalt, basaltic ejectamenta, and tuff interlayered with more viscous and silicic volcanic rocks. Flows from composite cones are generally less extensive than the older and younger basalt flows. Similarities between the major-element composition of the Ocate volcanic rocks and basaltic rocks from the Rio Grande depression to the west suggest that these rocks may have a similar origin. The composition of basalts from both localities may be controlled in part by the intersection of two major tectonic features: the northeast-trending Jemez line and the north-trending Rio Grande depression.

INTRODUCTION

Basaltic rocks of late Cenozoic age, including those of the Ocate volcanic field, are present over much of New Mexico (Luedke and Smith, 1978); many of these rocks appear to be directly or indirectly related to the tectonic development of the Rio Grande depression. The northern part of the depression contains basaltic rocks of the Taos Plateau; farther south in the depression, basalt flows along with volcanic necks and dikes are associated with the massive Jemez volcanic field directly northwest of Santa Fe; and numerous basalt-filled fissures and basalt flows are present in the Albuquerque area. West of the Rio Grande depression, contemporaneous basaltic rocks were expelled in the Zuni Mountains and the Mount Taylor region of the Colorado Plateaus province. Major eruptions to the east of the depression created the Ocate volcanic field, which surrounds the town of Ocate, partly within the Sangre de Cristo Mountains. Other major eruptions to the east of the depression are near Raton on the high plains of northeastern New Mexico.

Volcanic rocks in the vicinity of Ocate (fig. A1) have not previously been studied in detail. These rocks were first mentioned by Stevenson (1881), who described the physiography of the area and gave the name Ocate Mesa to the lava-capped surface that extends southward from the Cimarron Range. This plateau almost completely surrounds Ocate Valley and the village of Ocate. Stevenson also recognized that the basalt-capped mesas in the southern part of the volcanic field were once continuous with Ocate Mesa. In keeping with Stevenson's early descriptions of the region, with his naming of Ocate Mesa, and with the location of Ocate more or less central to the volcanic field, this area will be referred to as the Ocate volcanic field.

The Ocate volcanic field extends from the southern part of the Cimarron Range in the southern Sangre de Cristo Mountains, southeastward to the vicinity of Wagon Mound (fig. A1). The field lies west of Interstate 25 except near the town of Wagon Mound. The field is bounded on the north by State Road 199 and on the west by the valley in which the towns of Moreno and Guadalupita are located (fig. A1). The flows extend as far south as the Turkey Mountains but do not completely surround this domal uplift. Flows vented on the southeast side of the Turkey Mountains and flowed eastward, following the drainage of the Mora and Canadian Rivers.

PREVIOUS WORK

Volcanic rocks in the Ocate area were first noted by Stevenson (1881). Darton (1928) was the first to outline

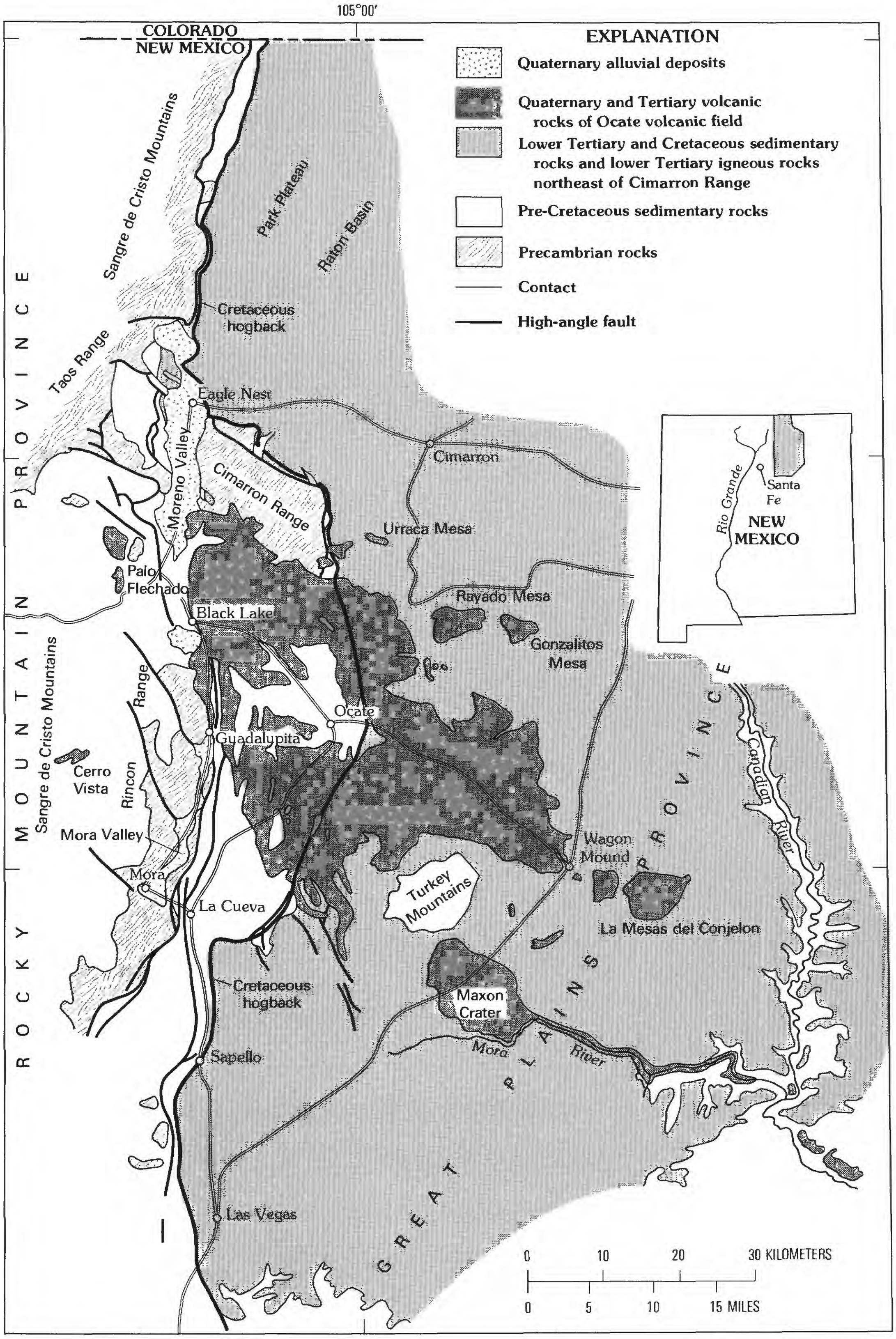


FIGURE A1.—Generalized geologic map of the Ocate volcanic field (Quaternary and Tertiary volcanic rocks) and vicinity, New Mexico (modified from Dane and Bachman, 1965).

the general distribution of volcanic rocks in the Ocate field. More detailed mapping of the volcanic rocks around Ocate was carried out by Bachman (1953), and the areal extent of the field was refined for the State map published in 1965 by Dane and Bachman. Parts of the field have been mapped and described by Smith and Ray (1943) and Robinson and others (1964) at the south end of the Cimarron Range. Simms (1965) described the volcanic centers and associated basaltic flows that cap mesas directly south and east of the Cimarron Range. Schowalter (1969) mapped remnants of basalt flows along the west-central part of the field, and Ray and Smith (1941) and Petersen (1969) mapped similar, small remnants in and near the Moreno Valley. Johnson (1974, 1975) mapped and described basaltic flows in the southern part of the field, west and southwest of the Turkey Mountains. Radiometric age data obtained by Stormer (1972), Hussey (1971), and from ages reported herein, show that many of the volcanic rocks were erupted in Pliocene time. Major element geochemical analyses for volcanic rocks collected along a highway traverse between Wagon Mound and the Moreno Valley were published by Aoki and Kudo (1976) and Lipman and Mehnert (1975). The evolution of the magmatic rocks that compose this field is described by Nielsen and Dungan (1985). As described in chapter B of this report, the physiographic evolution of the volcanic field suggests that volcanism in the Ocate area was coeval with epiorgenic rise of the Sangre de Cristo Mountains and adjacent Great Plains.

GEOCHRONOLOGY

The Ocate volcanic field consists of at least 16 volcanic flows ranging in age from late Miocene to Pleistocene (table A1). The field shows over 1,200 m (4,000 ft) of topographic relief (pl. 1); flows are preserved on mesas and buttes that range in elevation from over 3,000 m (10,000 ft) in the Sangre de Cristo Mountains to less than 1,800 m (5,900 ft) on the Great Plains. The physiographic expression of these flows reflects the relative ages of the volcanic rocks. The oldest flows are preserved on the highest mesas and successively lower mesas are capped by younger flows. Three major levels of volcanic flow-capped mesas define a step-like pattern that decreases in elevation from west to east. The volcanic rocks that cap the physiographically highest mesas range in age from 8.3 to 5.7 m.y. (million years); volcanic rocks present on the intermediate surface range in age from 4.7 to 3.8 m.y., and those in the lower compound surfaces range in age from 3.8 to 0.8 m.y. For convenience, these rocks are discussed in three age groups: older than 5 m.y., between 5 and 4 m.y., and younger than 4 m.y.

DESCRIPTION OF VOLCANIC ROCKS AND RELATED FEATURES

VOLCANIC ROCKS OLDER THAN 5 MILLION YEARS

The following discussion of the flows is presented in order of decreasing age. Volcanic rocks of the oldest age group cap and preserve the highest gravel-covered surfaces in the Ocate volcanic field (pl. 1). The oldest dated flows were erupted 8.3 m.y. ago in the northwestern part of the field. Two major remnants of these flows are present at elevations slightly above 3,000 m (10,000 ft). The larger remnant caps Sierra Montuosa Mesa, northwest of Ocate. The smaller remnant caps buttes along La Grulla Ridge directly northeast of Sierra Montuosa Mesa.

Flows dated between 5 and 6 m.y. were erupted from widely separated vents. Near Wagon Mound, the Jarosa and Santa Clara Mesas west of Interstate 25, and Las Mesas del Conjelon east of this highway mark an east-trending fissure system that has been dated at 5.9 m.y. High flows along the west side of the Ocate volcanic field, at the present drainage divide of the Sangre de Cristo Mountains, yielded a date of 5.7 m.y. An undated flow at Palo Flechado Pass west of the Moreno Valley, also at the drainage divide of the range, probably belongs to this older sequence of flows. High flows cap Black Mesa, Encinosa Mesa, and the high mesa directly south of Rivera Mesa, herein called Apache Mesa (west). These three undated flows are physiographically higher than flows on lower surfaces that are dated between 4 and 5 m.y., and probably these three undated flows are equivalent to flows dated older than 5 m.y.

Sierra Montuosa Mesa.—Sierra Montuosa Mesa is a northwest-elongate mesa capped by basaltic rocks, reaching an elevation of 3,136 m (10,290 ft) (fig. A2). The mesa stands slightly above Ocate Mesa, a flow capping the largely flat lying Permian Glorieta Sandstone.

The flows on Sierra Montuosa Mesa are thickest near its highest point—the probable vent area—and the flow sequence appears to thin away from this area. The base of the flows along the southwest side of the mesa is about 100 m (300 ft) higher than on the northeast side, suggesting that the flows rest on a gently inclined, northeast-dipping surface.

The flows consist of dense, platy rocks that are dark-gray to greenish-black on weathered surfaces and that contain sparse phenocrysts of olivine. The upper flows tend to be much more vesicular and massive and weather medium gray. Scoriaceous, highly oxidized flows are most common in the vicinity of the rounded knob in the northwestern part of the mesa. The lowermost,

TABLE A1.—*Late Cenozoic K-Ar ages of volcanic rocks of the Ocate volcanic field*

[Constants: $K^{40}=0.581X10^{-10}$/yr; $\lambda\beta=4.963X10^{-10}$/yr; $K^{40}/K=1.167X10^{-4}$]

Locality	Field no.	Location (Lat N., Long W.)	K_2O (percent)	$Ar^{40}(10^{-10})$ (moles/gram)	Ar^{40} (percent)	Age (m.y.±2)
		Flows less than 4 m.y. old				
Cerro del Oro............	CNV-1	36°04′,105°55′	1.94	0.022	15.1	0.81±0.14
Maxon Crater............[1]	68L-189	35°53′,104°52′	1.15	0.023	20.9	1.37±0.15
Wagon Mound (lower mesa)[1]	68L-228	36°03′,104°42′	1.30	0.041	32.3	2.20±0.17
Charette Mesa[1]...........	68L-187	36°01′,104°42′	0.74	0.033	21.5	3.07±0.34
White Peak...............	OMV-2WPA	36°07′,105°02′	2.08	0.098	8.3	3.53±1.20
		Flows 4 to 5 m.y. old				
Guadalupita Valley.......	1C2a	36°04′,105°17′	2.39	0.132	18.0	3.83±0.46
Guadalupita Valley.......	1C2b	36°04′,105°17′	2.37	0.155	52.7	4.53±0.18
.........Do..............	2C2	36°04′,105°16′	2.65	0.165	25.4	4.32±0.44
El Cerro Colorado........	4C2	36°04′,105°15′	2.12	0.128	48.2	4.12±0.24
La Mesa (south end)......	1L2	36°03′,105°09′	1.31	0.078	47.2	4.19±0.25
Black Lake...............	68L-196	36°17′,105°16′	1.97	0.127	57.9	4.47±0.23
Gonzalitos Mesa..........	GV-2	36°08′,105°11′	1.64	0.106	35.9	4.52±0.34
Cerro Montoso............	GMV-2	36°23′,104°47′	1.18	0.079	40.7	4.67±0.32
		Flows more than 5 m.y. old				
Cerro Vista..............	6CV-3	36°08′,105°26′	1.48	0.122	47.3	5.74±0.34
Las Mesas del Conjelon[1]..	68L-188	36°00′,104°42′	1.17	0.100	55.7	5.94±0.40
Sierra Montuosa..........	GV-6	36°14′,105°09′	1.80	0.214	46.9	8.34±0.50

[1]Samples collected by P.W. Lipman.

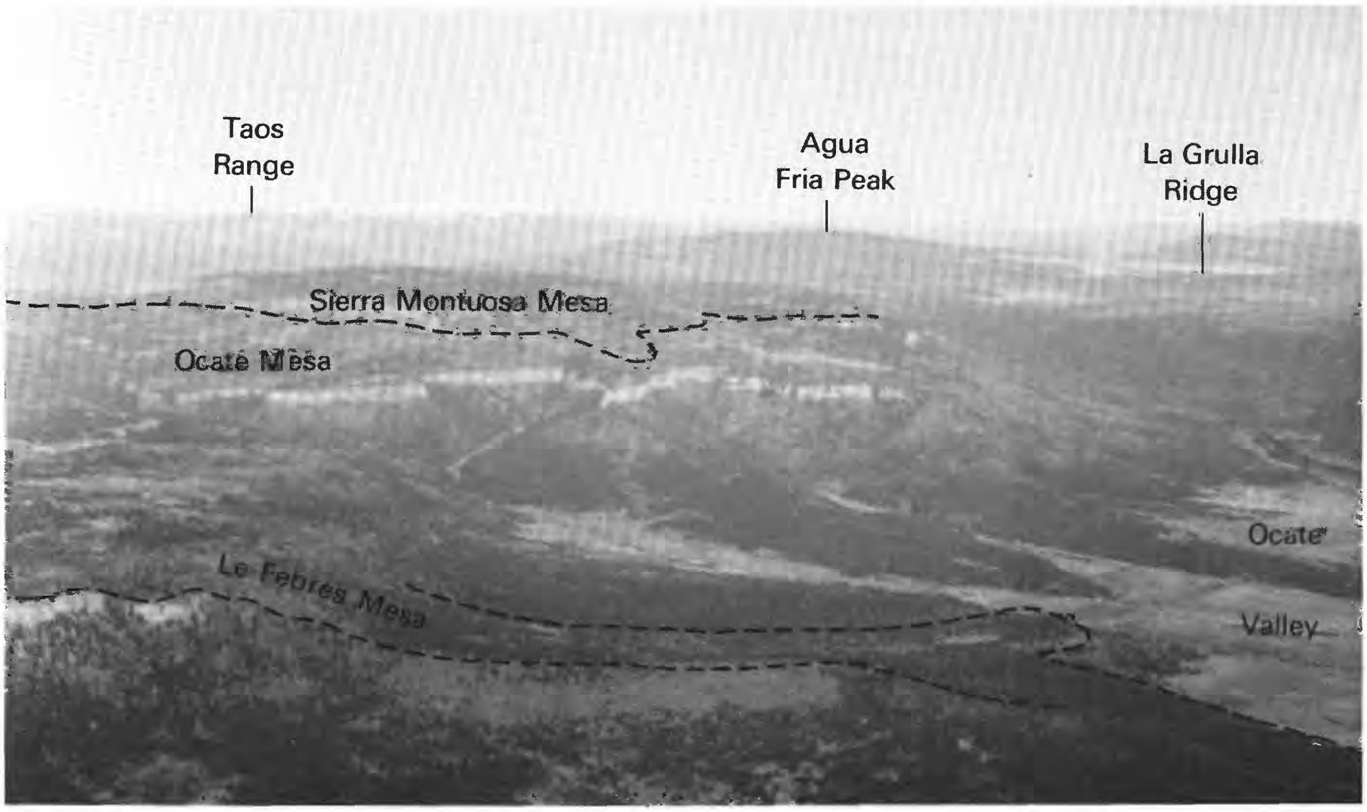


FIGURE A2.—Sierra Montuosa and Ocate Mesas. View to north; Taos Range in background. Agua Fria Peak, a shield volcano, lies directly north of Sierra Montuosa Mesa. Younger flows on Le Febres Mesa, left foreground, cascade over valley wall into Ocate Valley. Lines outline flow boundaries.

platy flow in the southeastern part of the mesa was dated at 8.3 m.y. (table A1).

The rock contains phenocrysts of olivine, biotite, and rare plagioclase in a very finely crystalline groundmass composed mainly of prismatic plagioclase, pyroxene(?), and equant magnetite. Olivine occurs as euhedra with weak to moderate alteration to iddingsite along internal fractures and around grain peripheries. Minor magnetite is enclosed in these rinds. Larger olivine crystals have been embayed by the groundmass. Locally, olivine contains spherical cavities filled with chlorite. Irregularly shaped plates of biotite enclose magnetite and pyroxene groundmass grains. Plagioclase occurs as thin, slender laths or as anhedral interstitial grains showing well developed Carlsbad and albite twinning.

La Grulla Ridge.—Basaltic rocks directly northeast of Sierra Montuosa Mesa cap the 3,000 m (10,000 ft) high La Grulla Ridge (fig. A2). The underlying thin veneer of pediment gravels and Paleozoic sedimentary rocks are well exposed, except along the northwest side of the ridge, where younger flows have covered this contact. The source of the La Grulla Ridge flows is not known; because they lie at a slightly lower elevation than the basalts on Sierra Montuosa, they may represent the more distal parts of the same flow system. The basalts on La Grulla Ridge are dense, platy, aphanitic porphyritic, and contain phenocrysts of plagioclase and olivine. These flows become more vesicular upsection.

These rocks contain phenocrysts of olivine and plagioclase and xenocrysts of quartz suspended in a finely crystalline diabasic matrix. Olivine and plagioclase occur as moderately to strongly embayed euhedra. All olivine shows peripheral alteration to iddingsite. The larger plagioclase phenocrysts show diffuse twinning; they are composed of a clear core locally enclosing opaque oxides that is surrounded by a magmatically corroded mantle that in turn is enclosed by a very thin, clear outer rind of plagioclase. The rind, mantle, and core are all embayed by the groundmass grains. Smaller plagioclase phenocrysts are corroded. Quartz occurs as rounded xenocrysts surrounded by clinopyroxene reaction coronas. Groundmass grains consist of slender plagioclase (An_{59}), stubby augite, and equant olivine-iddingsite and magnetite.

Cerro Vista Area.—Olivine basalts in the Cerro Vista area, the westernmost flow in the Ocate volcanic field (pl. 1), cap a northeast-trending ridge about 3 km (2 mi) in length. The base of the basalts is inclined to the southwest, ranging in elevation from about 3,017 m (9,900 ft) on the northeast to near 2,895 m (9,500 ft) at the southwesternmost exposure. The base of the basalts also decreases from southeast to northwest, normal to the length of the exposures, which suggests that the flows occupy a southwesterly inclined paleovalley. The basalts were deposited mainly on the Sandia Formation of Pennsylvanian age; locally, pebbles and cobbles of well-rounded Precambrian rocks are present at the contact.

The flows at Cerro Vista are medium to dark gray, commonly vesicular, locally strongly oxidized, aphanitic porphyritic basalt that weathers medium gray to orange-red. Phenocrysts of olivine and plagioclase are common. Maximum thickness of the flow system is about 45 m (150 ft). The source of these flows is not known. A sample collected from the southeast side of these flows yielded an age of 5.7 m.y.

These flows contain phenocrysts of olivine, plagioclase, and pyroxene. Olivine is generally strongly embayed by the mesostasis and commonly carries an oxidation rind. A few crystals show a clear unaltered core surrounded by iddingsite that is in turn mantled by optically continuous, unaltered olivine. Plagioclase phenocrysts are typically subhedral rounded forms, locally zoned, poorly twinned, and commonly partly replaced by the groundmass. Some plagioclase crystals are choked with inclusions and almost all carry a thin, clear syntaxial rind. Minor subhedral augite phenocrysts are present. Xenocrystic quartz, where present, is surrounded by outward radiating reaction coronas of clinopyroxene. Groundmass consists of intergrown, slender to locally stubby plagioclase (An_{58}), equant olivine-iddingsite, and pyroxene.

Palo Flechado area.—Several basalt flows near Palo Flechado Pass west of the Moreno Valley are thin, local deposits resting on lag gravels of the Miocene Carson Conglomerate (Just, 1937). The flows aggregate less than 15 m (50 ft) in thickness. These rocks, described by Petersen (1969), contain phenocrysts of plagioclase (An_{60}), and olivine commonly altered to iddingsite. Xenocrysts of orthoclase and quartz are locally present. The groundmass consists of pilotaxitic plagioclase, augite, and opaque oxides. Although the age of these flows is not known, they are exposed in the present drainage divide of the Sangre de Cristo Mountains at elevations similar to those flows known to be older than 5 m.y. (see chap. B).

Las Mesas del Conjelon.—Basaltic rocks at Wagon Mound, in the eastern part of the Ocate volcanic field, stand as a series of east-trending buttes and mesas (pl. 1; fig. A3). The main sequence of flows caps Las Mesas del Conjelon; these flows were erupted from a series of vents and fissures that are aligned with or parallel to the east-trending line defined by the two dissected vents that lie west of the mesas: Santa Clara Mesa and The Wagon Mound. Flows on the mesas radiate outward from the individual vents. Thickness of the flows ranges from about 75 m (250 ft) near the vents to 20–30 m

(70–100 ft) at the present margins of the mesas. Specimens collected from these flows are dated at 5.8 m.y.

The basalts consist of massive to locally platy flows that become more vesicular near the top. The basalts are dark gray on fresh surfaces and contain phenocrysts of olivine and plagioclase.

These rocks are subophitic, glomeroporphyritic, and locally pilotaxitic. The olivine phenocrysts are round to subround and locally embayed by groundmass grains; iddingsite rinds are common. Plagioclase phenocrysts occur as crystal aggregates showing well-developed polysynthetic twinning. Groundmass plagioclase is present as slender laths with distinct Carlsbad and albite twins; these crystals tend to be pilotaxitic, and also wrap around phenocrysts. Groundmass plagioclase also occurs as anhedral, interstitial crystals showing diffuse twinning and minor zoning. Composition of the plagioclase is near An_{52}. Augite up to 1 mm (0.04 in.) in diameter also occurs as clusters; crystals are round to subhedral and twinned; commonly a thin, optically continuous rind surrounds the crystal and encloses groundmass grains. Slender, prismatic pale-green augite is present in the groundmass. Opaque oxides, constituting as much as 10 per cent of the rock, are evenly distributed throughout the matrix.

Apache Mesa (west), Encinosa Mesa and Black Mesa.—Three basalt capped mesas, east and south of Ocate, are 60 m (200 ft) above the widespread surface on which 4- to 5-m.y.-old flows lie (pl. 1); therefore, these mesas are interpreted to be older than 5 m.y. (see chap. B). They are Apache Mesa (west) which is northeast of Ocate, and Encinosa and Black Mesas, south of the town of Ocate.

These basalts are similar to one another in mesoscopic character and flow morphology. The surfaces of the flows are smooth, without the hummocky morphology and flow forms that characterize the younger deposits. The basalts are made up of multiple flows; individual flows are as much as 10 m (30 ft) thick. The flows are typically vesicular near the base and top with platy to massive interior parts.

These rocks are similar to one another in composition but somewhat varied in texture. All contain the essential minerals of olivine, clinopyroxene, plagioclase, and abundant, small crystals of opaque oxides. Alteration of olivine to iddingsite is common, especially in the Black Mesa flows where all crystals less than 0.5 mm (0.02 in.) across are completely altered to iddingsite. Augite is present as groundmass grains and less commonly as equant phenocrysts. Plagioclase phenocrysts are not present in the specimen collected from Encinosa Mesa. At Black Mesa and Apache Mesa (west), plagioclase phenocrysts are common as euhedra; the plagioclase is near An_{68} in composition. The phenocrysts show no evidence of resorption. Groundmass plagioclase, near An_{58} in composition, is crudely pilotaxitic.

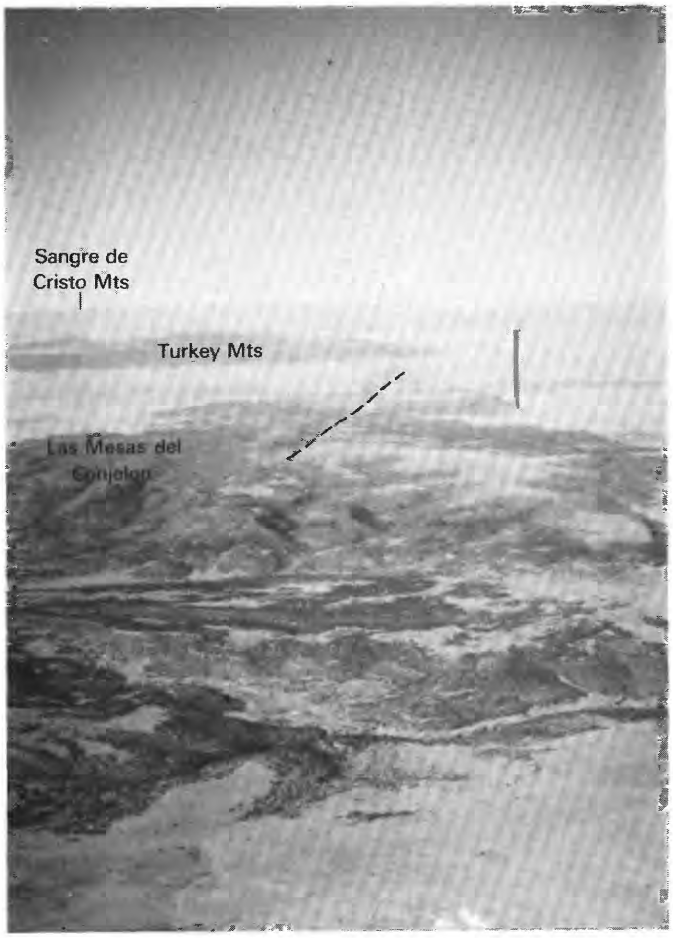


FIGURE A3.—Las Mesas del Conjelon. View to west. Turkey Mountains in middle ground; Sangre de Cristo Mountains on horizon. Dashed line marks alignment of vents from which these basalts were expelled.

VOLCANIC ROCKS ERUPTED BETWEEN 4 AND 5 MILLION YEARS AGO

Volcanic rocks of the intermediate-age group are most abundant in the northern part of the volcanic field (pl. 1). These flows cap Urraca and Fowler Mesas in the northeastern part of the field, and Rayado and Gonzalitos Mesas located east-southeast of the Cimarron Mountains. They are the lowermost flows on Ortega and Rivera Mesas northeast of Ocate (pl. 1). Most of the flows in and around Agua Fria Peak (pl. 1; fig. A2) appear to be of this age group; some of these flows interfinger with volcanic rocks erupted from vents near Black Lakes. Flows erupted from the north end of La Mesa and from Cerro Montoso flooded the southern part of La Mesa and parts of Le Febres Mesa. The basalt-capped Gallina Mesa, directly north of Ocate, is at equivalent elevation and distance above the present day streams and is interpreted to belong to this period of volcanism. Four- to five-m.y.-old flows are present in the valley south of Guadalupita (4.3 m.y. old), to the north along Coyote Creek (4.7 m.y. old), and cap El Cerro Colorado (4.1 m.y. old), located directly east of Los Chupaderos. Flows of this age group were deposited on an erosion surface that ranges in elevation from near 3000 m (10,000 ft) directly south of the Cimarron Mountains, to 2100 m (7,000 ft) on the adjacent Great Plains (pl. 1).

Volcanic rocks east and south of the Cimarron Mountains.—Numerous small volcanic flows cap high mesas in the northeastern part of the Ocate volcanic field. Vents for flows on Urraca and Fowler Mesas are located on these mesas and at Rayado Peak, a small cone directly southwest of Fowler Mesa. Both Rayado and Gonzalitos Mesas contain small vents. Basaltic eruptions on Ortega and Rivera Mesas to the south appear to have been much more extensive than flows to the north; vents for these flows include Rayado Peak, but source areas are also present farther west, near Agua Fria Peak.

Volcanic rocks on these mesas are olivine basalts, platy to massive and variable in degree of vesiculation. Phenocrysts of olivine and less commonly plagioclase are set in a dense, dark-gray aphanitic matrix.

Neither Urraca nor Fowler Mesas were visited. Flows on Urraca Mesa were sampled by Hussey (1971) and dated at 4.3 m.y. He described these basalts as aphanitic porphyritic, containing phenocrysts of plagioclase, olivine, and biotite in a groundmass of plagioclase, pyroxene, olivine, and opaque oxides. Alteration of olivine to iddingsite is common. These rocks were expelled, in part, from a vent on Urraca Mesa now marked by a small plug surrounded by volcanic bombs and scoriaceous material (Simms, 1965).

Simms (1965) mapped and described volcanic rocks on Fowler Mesa and Rayado Peak as medium-gray, finely crystalline olivine basalt. Thickness ranges from about 15 m (50 ft) on Fowler Mesa to nearly 100 m (300 ft) on the northeast side of Ortega Mesa. Vents at Rayado Peak and Fowler Mesa contain abundant volcanic bombs and scoriaceous material. Simms (1965) described the basalts as containing phenocrysts of olivine, partly altered to iddingsite, set in a matrix of plagioclase (An_{64-62}), olivine, clinopyroxene, and magnetite. Minor quartz xenocrysts with clinopyroxene reaction coronas are present.

Basalt on the north side of Gonzalitos Mesa aggregates some 20 m (70 ft) in thickness; maximum thickness may be more than 60 m (200 ft) near vents. These olivine basalts weather medium gray and are platy to massive in the lower parts, becoming more vesicular upsection. The basalts are underlain by pebbles and cobbles of Precambrian rocks locally strongly cemented by calcium carbonate. The surface of the flows on this mesa, like Rayado Mesa to the west, is somewhat irregular, containing small vents of low relief; the upper surface of these basalts everywhere dips away from these centers, but basalts appear to have flowed mainly eastward. The basal flow on the north side of Gonzalitos Mesa gave a K–Ar date of 4.5 m.y.

These flows are glomeroporphyritic, containing clusters of olivine, augite, and plagioclase as well as individual phenocrysts of these minerals. Euhedral to subhedral olivine is characteristically embayed by groundmass grains, and peripheral surfaces are altered to iddingsite. Plagioclase occurs as slender, polysynthetically twinned laths and as anhedral phenocrysts that tend to be zoned and enclose groundmass grains. Idiomorphic augite is common. Groundmass consists of prismatic, randomly oriented plagioclase and augite and equant olivine and magnetite evenly distributed throughout the matrix. Interstitial to the groundmass crystals is anhedral plagioclase showing diffuse zoning.

Ortega and Rivera Mesas (pl. 1) actually comprise a large single mesa that has been given distinct names corresponding to areas that lie either north or south of the east-flowing Sweetwater Creek. The smoothly arcuate plan of the mesa north of the creek is called Ortega Mesa; the more irregular, dissected part to the south is called Rivera Mesa. The lowermost basalts on these mesas lie on the same surface as the 4.3- and 4.5-m.y.-old flows on Urraca and Gonzalitos Mesas, respectively. However, volcanism on the Ortega-Rivera Mesa was more complex: one small, slightly higher mesa capped by basalts that are probably older than 5 m.y. is incorporated within this flow system on Rivera Mesa; and basaltic rocks, dated at 3.5 m.y., were erupted from White Peak, one of the higher points on Ortega Mesa, and these rocks partly buried the older flows.

Volcanic rocks in the Agua Fria Peak area.—The 4.0- to 5.0-m.y.-old flows that include Ortega and Rivera Mesas extend from Gonzalitos and Apache Mesas on the east in the Great Plains, westward to the Moreno Valley and Black Lakes, within the Sangre de Cristo Mountains. These flows are bounded on the north by the Cimarron Mountains and on the southwest by Sierra Montuosa Mesa.

Flows on Rivera Mesa connect with the intermediate-level flows that cap the northwest-trending, slightly sinuous Apache Mesa. The higher mesa directly west of Apache Mesa, herein called Apache Mesa (west), is capped by flows interpreted to be older than 5 m.y. The basal flows on Rivera Mesa can be traced around to Laguna Salada Mesa, northwestward to Agua Fria Peak on a surface that dips gently southeast. These flows lie more than 60 m (200 ft) below the base of the basalts older than 5 m.y. that cap Sierra Montuosa Mesa.

Most of the vents that expelled these flows are shield volcanos with flanks that dip less that 5°. Vents are marked by abundant scoria, highly oxidized basalt, and, locally, orange-yellow weathering tuff and tuff breccia. Notable vents in the higher, western part of the area are Aspen Hill, Willys Tip, Spruce Hill, Peak 10192, Apache Peak, and Agua Fria Peak (pl. 1).

Flows on Ortega and Rivera Mesas and on mesas that represent the same surface to the northwest are olivine basalts. These flows are divided into two complexly mixed textural groups: microcrystalline, aphanitic porphyritic, pilotaxitic basalt; and diabase. All rocks carry phenocrysts of olivine, plagioclase, and clinopyroxene. Anhedral to subhedral olivine is locally embayed by the groundmass grains. A peculiarity of this olivine is that alteration to iddingsite is present not only along the edges of the crystals, but locally also in the crystal cores, or as a thin rind within the crystal that is mantled by unaltered olivine (fig. A4); these crystals were apparently oxidized both early and late in their crystallization history. Plagioclase phenocrysts are also present as two distinct types. Euhedral phenocrysts (An_{56}) showing well-developed polysynthetic twinning are most abundant; anhedral to subhedral, generally equant, zoned crystals are less common. The zoned crystals have cores that are characteristically partly or wholly corroded by magmatic fluids. Mantling the zoned crystals are thin, clear rinds that are in turn embayed by groundmass grains. Pyroxene phenocrysts are present in some specimens; where present, they occur as subhedral augite whose rounded cores are mantled by rinds that define crystal faces and enclose groundmass grains. Clinopyroxene also occurs as clusters of radiating crystals; the core of the cluster is marked by rounded blebs of olivine, iddingsite, and magnetite. Minor quartz xenocrysts are also present and carry reaction coronas of clinopyroxene. Groundmass grains consist of slender plagioclase (An_{55}) laths, prismatic augite, and equant crystals of magnetite and olivine-iddingsite. The flows on Apache Mesa contain rare biotite.

Volcanic rocks along the western side of the Ocate volcanic field.—Volcanic rocks along Coyote Creek from Black Lakes south toward the village of Guadalupita (fig. A5) consist of olivine basalt flows locally more than 50 m (165 ft) thick, overlain by thick stream gravels composed mainly of Precambrian quartzite and quartz-feldspar-muscovite gneiss. The distal, southern end of the flows is largely confined to the valley floor. Northward, these flows occupy a much larger area west of the creek but end abruptly against the east wall of the valley. The surface on which these flows lie appears relatively flat, rising gently toward Black Lakes. Two vents directly south of Black Lakes appear to be the main source of these flows and are considerably different in character. The more northerly, principal vent is a rounded, elongate knob capped by strongly oxidized scoria, volcanic breccias, and blocky flows. The vent is largely surrounded by yellow-orange to cream-colored tuff and tuff breccia, volcanic bombs, and local laharic deposits below the basal flows. A slightly younger vent directly southeast is circular in plan and dome-shaped in cross section. Basalts everywhere dip away from a central basaltic knob that is capped by minor scoriaceous material. This feature appears to be a basaltic intrusion, satellitic to the main vent, which domed the overlying basalts and expelled very little basalt as flows. State Road 38 passes through the eastern part of this structure.

Basalt at the southern end of this sequence of flows in Guadalupita Canyon yielded a K-Ar age of 4.8 m.y. (Stormer, 1972); those flows directly south of Black Lakes are 4.5 m.y. old (table A1).

These flows are locally diabasic, generally pilotaxitic and vesicular. Vesicules are commonly filled with calcite. All are porphyritic, locally glomeroporphyritic, containing clusters of olivine and clinopyroxene. Olivine is present as subhedral to euhedral crystals partly altered to iddingsite, which commonly occurs as thin rinds or along internal fractures and locally as iddingsite cores surrounded by optically continuous olivine. Some crystals show strong embayment by groundmass grains. Augite occurs as phenocrysts in most specimens. Crystals are typically euhedral showing either (1) a thin syntaxial rind or overgrowth on an inclusion-choked core (fig. A6*A*), or (2) an inclusion choked core, or (3) strong embayment by the groundmass grains (fig. A6*B*). Plagioclase phenocrysts are of two types, either well-formed polysynthetically twinned laths or equant to prismatic phenocrysts showing magmatically corroded cores mantled by clear, syntaxial rims, all embayed by groundmass grains. Quartz xenocrysts mantled by clinopyroxene reaction coronas are also present (fig. A7). The groundmass contains varied amounts of slender plagioclase laths, stubby prisms of augite, equant olivine-iddingsite, and euhedra of evenly distributed magnetite. Minor biotite was observed in one specimen collected from Guadalupita Canyon. Anhedral, diffusely twinned plagioclase enclosing

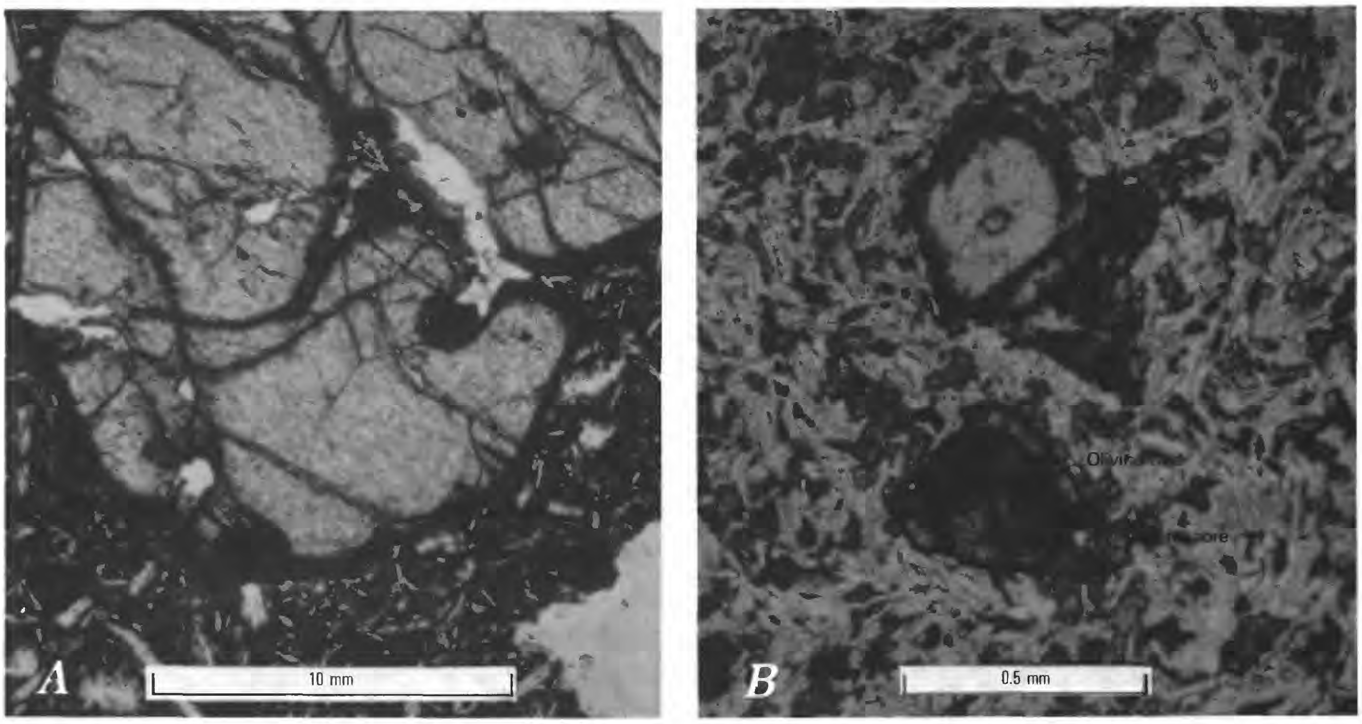


FIGURE A4.—Olivine crystals from intermediate-age basalts. *A*, olivine phenocryst embayed by groundmass grains; sample collected from small vent in northern part of Ortega Mesa; *B*, olivine crystals partly altered to iddingsite; note clear, unaltered olivine rind enclosing iddingsite; sample collected from Aspen Hill, located south of Agua Fria Peak.

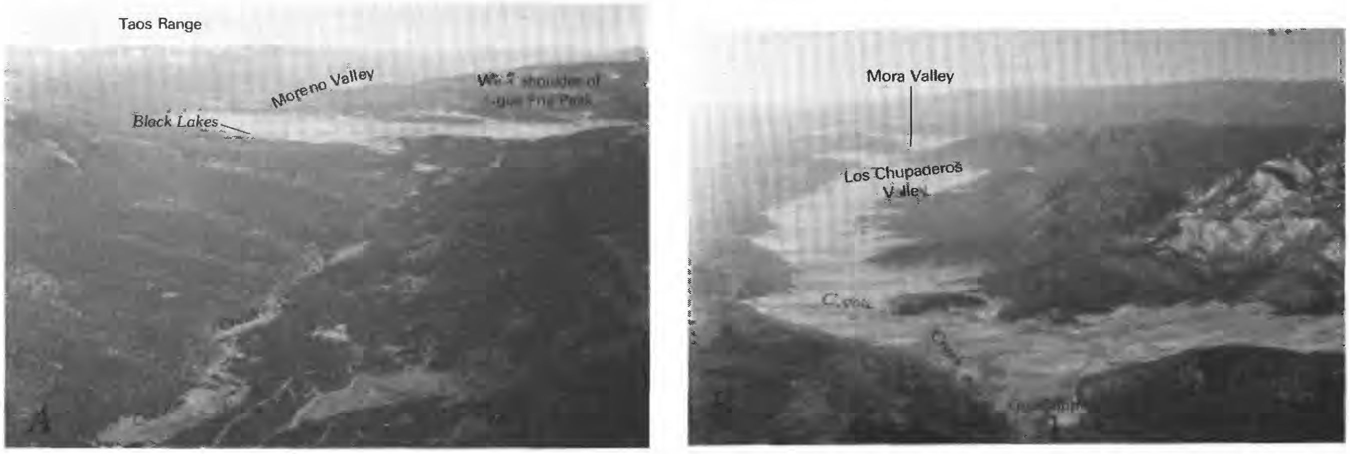


FIGURE A5.—Moreno-Guadalupita-Mora valley system, a significant topographic and structural depression some 100 km (60 mi) long. *A*, view to north. Taos Range on left, Black Lakes in middle ground, basalt-filled Guadalupita Canyon in foreground; *B*, view to south. Mouth of Guadalupita Canyon in foreground.

slender laths of augite occupy interstices between individual groundmass grains.

La Mesa area.—La Mesa is located directly east of Coyote Creek. Basalts on La Mesa rest on thick stream gravels composed mainly of Precambrian metasedimentary rocks that veneer a gently inclined, south-dipping surface cut on Permian and Pennsylvanian sedimentary rocks. These flows lie several tens of meters below the 8.3-m.y.-old basalts that cap Sierra Montuosa Mesa.

The La Mesa flows extend southward from their vents, merging with the flows expelled from the composite cone of Cerro Montoso, and continue southward toward Black Mesa (pl. 1). The lowest flows exposed along State Highway 21 were dated at 4.2 m.y.; basalts erupted from Cerro Montoso are 4.5 m.y. old (table A1).

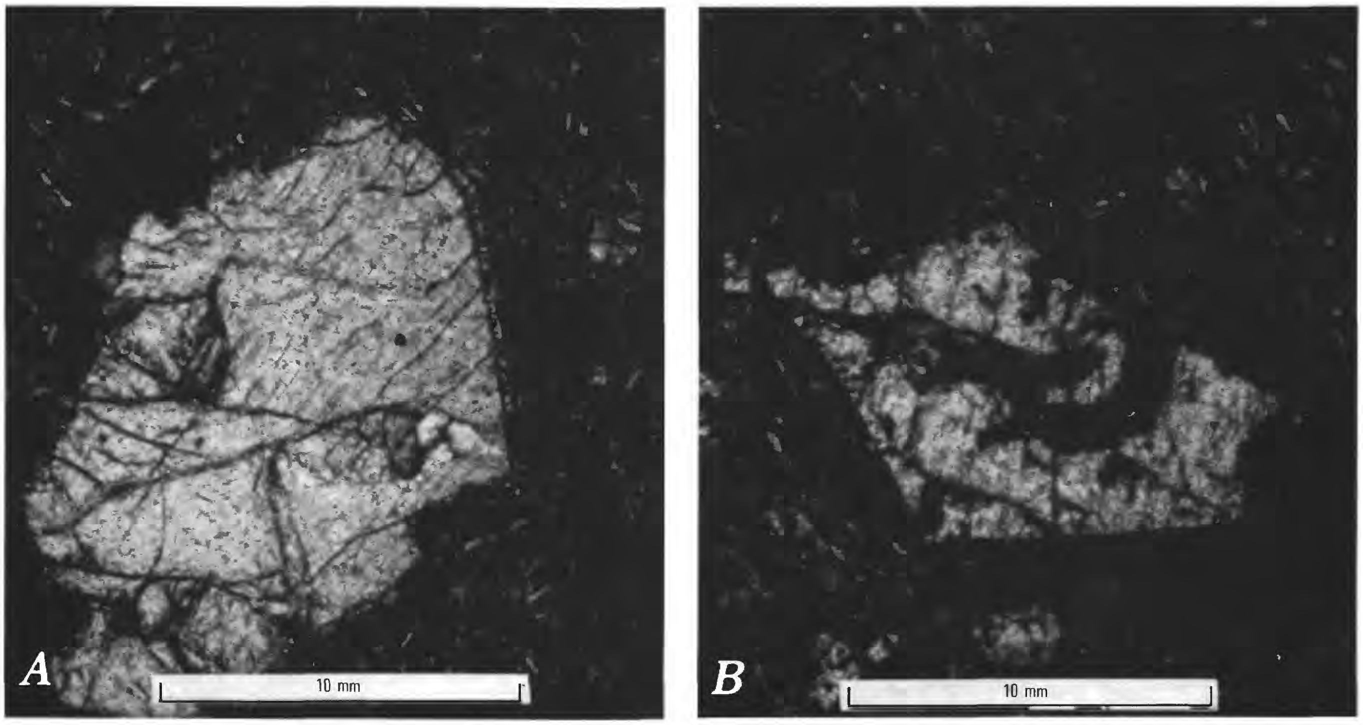


FIGURE A6.—*A*, Partly eroded augite crystal showing a thin syntaxial rind; *B*, strongly resorbed augite in basaltic groundmass. Sample collected from smaller of two vents directly south of Black Lakes.

La Mesa flows cap the mesa on the north and south and underlie Le Febres Mesa on the east. The Glorieta Sandstone of Permian age is exposed in the north-central part of this area. A thick deposit of stream gravels lies between the flows and the underlying Glorieta Sandstone. West of the village of Ojo Feliz, flows lap up against bedrock ridges and buttes and rest on a remnant of an east-trending, gravel-capped pediment. The basalts of El Cerro Colorado, which yielded a K–Ar date of 4.1 m.y., rest on what is probably a remnant of the same pediment. Also, basalts of El Cerro Colorado are essentially coeval with the 4.2-m.y.-old basalts that lie on what is probably this same surface along State Highway 21 near Ojo Feliz.

Vents for the La Mesa flows are present at the north end of the mesa and at Cerro Montoso. The northernmost vent on La Mesa is along a north-trending fissure, about 1.5 km (1 mi) long, on which are built three minor cones. The fissure is aligned parallel to the strike of the underlying, steeply dipping Paleozoic sedimentary rocks. The elongate cones consist of abundant, highly oxidized, strongly vesiculated basalt and scoria.

These basaltic rocks contain abundant phenocrysts of olivine, plagioclase, and clinopyroxene. Subhedral to euhedral olivine occurs as crystal clusters and as individuals showing peripheral alteration to iddingsite. Subhedral augite is common as zoned crystals in which the outer rinds enclose groundmass grains. Idiomorphic, partly resorbed augite is also present. Plagioclase phenocrysts, as much as 0.5 mm (0.02 in) across, occur as equant to prismatic crystals containing clear cores enclosed by magmatically corroded mantles that are rimmed by clear plagioclase rinds; all are embayed and partly resorbed by the groundmass grains (fig. A8). Groundmass crystals include randomly oriented plagioclase laths (An_{59}) enclosing interstitial, euhedral clinopyroxene and olivine-iddingsite. Locally, clinopyroxene occurs as curved to circular bands of small, outward radiating prisms, similar to reaction coronas on xenocrystic quartz present elsewhere; however, here no vestige of the quartz remains.

Cerro Montoso is a composite volcanic vent that stands more than 200 m (660 ft) above the surrounding mesa. The cone is composed of alternating layers of scoria, volcanic breccia, agglomerate, and flow-banded andesite. Viscous flows of dacite were emplaced as outward radiating dikes emanating from the base of the cone during the last stages of eruption. The dacites are porphyritic vitrophyres, are more than 20 m (66 ft) thick, and extend no more than 3/4 km (½ mi) from the base of the cone. These flows contain plagioclase phenocrysts more than 1.5 cm (0.6 in) across and also

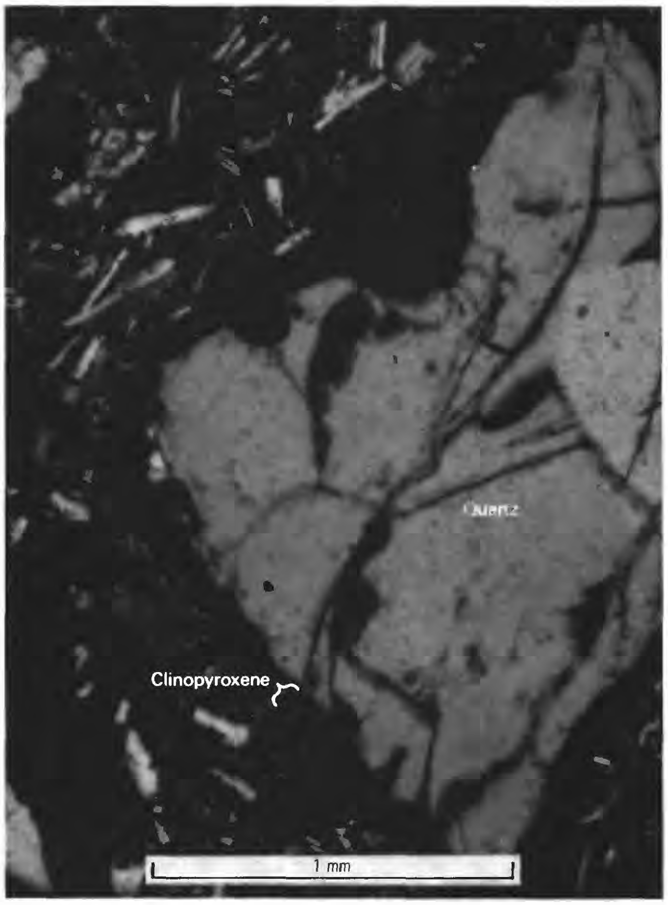


FIGURE A7.—Quartz xenocryst mantled by clinopyroxene corona. Sample collected from basal flow along Coyote Creek, north of the village of Guadalupita.

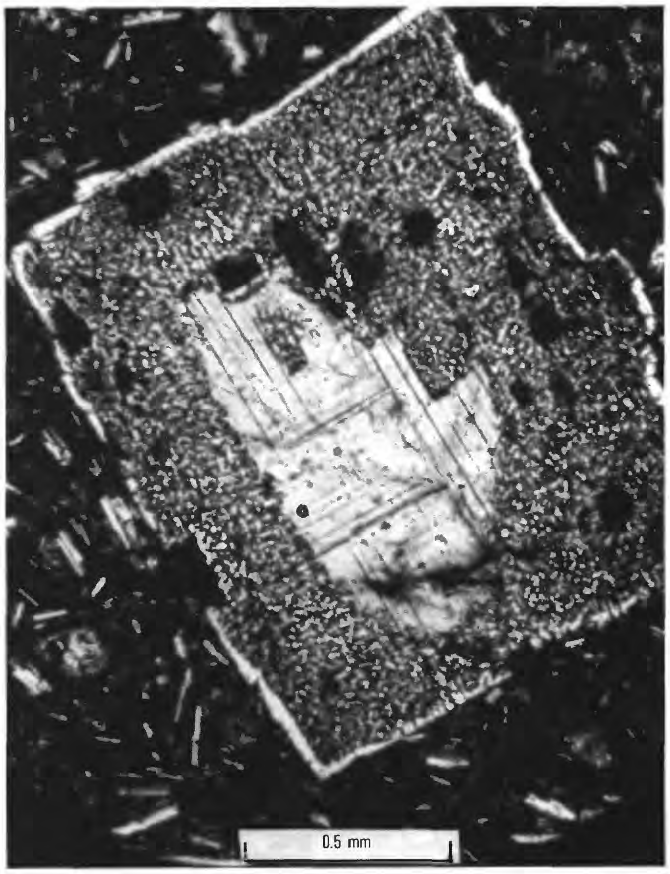


FIGURE A8.—Plagioclase phenocryst showing unaltered core, magmatically corroded mantle, and clear syntaxial rind, all embayed by basalt groundmass. Sample collected from basal platy flows at north end of La Mesa.

carry xenoliths of olivine basalt and fragments of Precambrian rock.

Basaltic flows from Cerro Montoso are glomeroporphyritic, pilotaxitic, and contain thin, alternating seams of very finely crystalline basaltic layers. Olivine, augite, and plagioclase are all subhedral to euhedral and show moderate to strong resorption by the groundmass. The groundmass consists of aligned plagioclase laths (An_{49}), prismatic augite, and olivine partly altered to iddingsite. Magnetite is evenly distributed throughout the mesostasis as small (0.01 to 0.02 mm (0.0004 to 0.0008 in.)) equant grains. Small circular-to-elliptical areas contain anhedral-to-subhedral plagioclase that enclose small, very slender prisms of augite. Augite also occurs in local concentrations around cavities and is texturally similar to reaction coronas observed around quartz in nearby basalts. Quartz was not observed in these specimens.

The dacite contains crystals of plagioclase and augite ranging in size from 1.5 cm (0.6 in.) to 0.5 mm (0.2 in) or less. Many plagioclase crystals show wormy intergrowths of glass only in the interior parts of the crystal and not in the clear, sodium-rich rinds that mantle the crystal. Composition of the plagioclase is known only approximately; the crystals are zoned, with cores near An_{45} and rinds near An_{25}. Clinopyroxene occurs in crystal clusters associated with plagioclase and as individual phenocrysts. Some augite has been partly resorbed by the groundmass. The plagioclase and augite crystals are suspended in a glassy, flow-banded matrix of very small euhedral-to-subhedral crystals or crystal clusters with smoothly rounded edges. Rounded blebs up to 3 mm (0.1 in.) across and composed of magnetite, biotite, iddingsite and minor patches of olivine are present and apparently represent alteration of olivine phenocrysts.

El Cerro Colorado.—The olivine basalts of El Cerro Colorado consist of at least two southeast-trending flows that rest on stream gravels composed mainly of clasts of Precambrian rocks (fig. A9). The mesa is inclined to the southeast, across the strike of the underlying, nearly vertical Paleozoic sedimentary rocks. Basalt also caps small colinear mesas to the southeast. The total length of the exposure is about 3 km (2 mi).

The basalts of El Cerro Colorado occupy a southeasterly inclined paleostream valley truncated on the west by the north-trending valley that contains the small villages of Los Chupaderos and Guadalupita. To the south at Mora, geophysical work by Mercer and Lapalla (1970) and geologic mapping by Baltz and O'Neill (1980, 1984) suggest that the Mora Valley is a half graben bounded on the east by a normal fault (fig. A5). The Mora Valley is continuous with the valley west of El Cerro Colorado and with Guadalupita Canyon to the north (fig. A5) which contains basalts dated at 4.8 m.y. (Stormer, 1972) and 4.5 m.y. The basalts of Guadalupita Canyon terminate abruptly against the east wall of the canyon, locally extend some distance west of the canyon floor, and lie some 300 m (1000 ft) below the basalts of equivalent age on La Mesa, directly to the east.

Directly west of El Cerro Colorado, in the valley some 275 m (900 ft) below the mesa, is a small exposure of basalt (fig. A9). The K-Ar date of this exposure is 4.3 m.y.; the basalts of El Cerro Colorado are 4.1 m.y. The basalts in the valley, within the margin of error, are coeval, suggesting that they are offset along a significant post-4 m.y.-old fault present along the east side of the valley system. The fault is superimposed on a high-angle reverse fault of Laramide age throughout its length and it probably represents the southern extension of major Tertiary-Quaternary down-to-the-west normal faulting that has occurred in the Moreno Valley to the north (Ray and Smith, 1941).

A small volcanic center located on the west side of the valley directly west of El Cerro Colorado consists of a central plug of dense basaltic andesite surrounded by inward dipping, massive, vesicular flows. These

FIGURE A9.—Flows of El Cerro Colorado. View to southwest. Basalts underlain by coarse stream gravels cap these isolated mesas and are separated from basalts of same age in the valley west of the flows of El Cerro Colorado by a high-angle normal fault.

flows were dated at 3.8 m.y. and are more silicic than the flows of El Cerro Colorado. Rocks from this small center contain phenocrysts of olivine, plagioclase, augite, and xenocrysts of quartz. Olivine occurs as subhedral to euhedral crystals which commonly are altered to iddingsite around their peripheries and along fractures; locally, alteration is restricted to the cores of the crystals. Augite is rare in some flows; in others, it is abundant and glomeroporphyritic. Some crystals are weakly zoned and are rimmed by a syntaxial rind. Plagioclase phenocrysts, up to 0.4 cm (0.2 in.) across, occur as equant to prismatic zoned crystals. The cores of these crystals show local magmatic corrosion and commonly enclose groundmass grains; less commonly, the cores contain coarse crystals of augite, calcite, and magnetite. Plagioclase crystals are mantled by clear rinds, and both the cores and the rinds are embayed by the groundmass. Quartz occurs as anhedral xenocrysts mantled by clinopyroxene reaction coronas. Groundmass grains show well-developed diabasic to pilotaxitic texture. Plagioclase (An_{60}) occurs as slender to stubby crystals. Those crystals showing sharply defined albite twins tend to have straight, well-formed crystal boundaries; whereas diffusely twinned varieties are subhedral and merge with and enclose adjacent grains. Prismatic augite and equant olivine-iddingsite are everywhere present. Euhedral, equant opaque oxides are ubiquitous and locally line vesicles. Calcite fills some vesicles.

VOLCANIC ROCKS YOUNGER THAN 4.0 MILLION YEARS OLD

Basalts of the youngest age group are the most abundant flows in the Ocate volcanic field (pl. 1). Although all basalts of this age group are younger than 4 m.y., in the field these rocks can be divided into three groups on the basis of superposition and physiographic expression. The oldest rocks (Tvl) consist of olivine basalt flows erupted onto gravel-covered surfaces that are 50–75 m (160–250 ft) above the surrounding lowlands. These basalts include the flows of Charette Mesa, the uppermost flows of Ortega and Rivera Mesas, and flows capping several mesas east of and below Rivera Mesa. Age dates for these flows ranges between 3.1 and 3.3 m.y. The next group (Qtv) consists of olivine basalt flows erupted onto gravel-covered surfaces 15 m (50 ft) above the surrounding lowlands. These basalts include the flows of Cerrito Pelon which moved south and east to the base of Apache Mesa, the flows of Cerro Negro and several nearby vents, and the flows of Cerro Pelon and a number of nearby vents, the flows of Le Febres area, and the flows of a small mesa on the eastern edge of Charette Mesa north of Wagon Mound; one age date of 2.2 m.y. confirms that these flows are older than the youngest flows of the Ocate area. The youngest group of flows (Qv) consists of olivine basalt erupted onto surfaces that have been only weakly eroded and dissected. These basalts include the flows of Cerro del Oro and its nearby vents, the flows of a small crater west of Interstate 25 and south of Wagon Mound, and Maxon Crater and its associated flows. The age of these youngest rocks ranges from 0.8 to 1.4 m.y.

Charette Mesa flows.—Flows that cap Charette Mesa are the oldest flows in this age group and define the major surface on which the basalts younger than 4 m.y. lie. Charette Mesa is a broad flat feature named for Charette Lakes (fig. A10). In this report, the name is applied to the surface that extends westward from Wagon Mound to Cerro Pelon and to near the village of Ocate. The eastern part of the mesa is capped by multiple basalt flows that aggregate about 5–10 m (15–30 ft) in thickness, forming a flat surface. In the central part of the mesa, basalt flows expelled from local vents form small knobs and isolated buttes and small mesas that rise above the flat surface and give it a slightly hummocky relief. The youngest basalts in the Ocate volcanic field are in this part of Charette Mesa.

Basalt-capped mesas and buttes directly east of Rivera Mesa and south of Rayado Mesa are the same elevation as the Charette Mesa flows and lie 60 m (200 ft) lower than the surface on Ortega and Rayado Mesas capped by 4- to 5-m.y.-old basalts. Flows on Charette Mesa are also 60 m (200 ft) below the older flows that cap Apache Mesa.

The lowermost and oldest volcanic rocks on Charette Mesa are multiple flows of olivine basalt. The flows are underlain locally by coarse stream gravels composed mainly of Precambrian metasedimentary and igneous rocks and minor basalt that are locally well cemented with calcium carbonate. The lowest Charette Mesa flows exposed at Wagon Mound have been dated at 3.3 m.y. and 3.1 m.y. (table A1). Westward, these flood basalts are overlain by successively younger, less voluminous flows erupted from composite cones that stand as rounded knobs and mounds with 30–100 m (100–300 ft) of relief. The vents can be divided into three major groups: an older series from which the basalts now present in the eastern part of the mesa may have been expelled, an intermediate age group which expelled subdued flows, and a very young series of flows associated with moderately eroded cinder cones that show well-preserved flow morphology.

Flanks of the older cones generally dip between 5° and 10°. Dikes and small plugs intruded these cones and resulted in locally steep cone flanks (fig. A11). Volcanic breccia, scoriaceous material, and oxidized vesicular

FIGURE A10.—Charette Mesa and Charette Lakes. View to west. Sangre de Cristo Mountains in background. Ocate Creek is the small stream that has dissected part of the mesa.

basalt compose these vent structures; most of these rocks occur as thin layers that dip gently toward the center of the vent. Radial dikes are common, and some vents appear to have held small lava lakes in their centers.

Intermediate age vents south of Apache Mesa and along both sides of State Highway 120 expelled most of the basalts that cover the central part of Charette Mesa. Cooks Peak and Cerrito Pelon northeast of Ocate are the vents that expelled basalts that also flooded the area between Apache Mesa and Encinosa Mesa. These basalts interfinger with each other and are contemporaneous.

Cerro Negro area.—Cerro Negro, located directly south of State Highway 120 and 23 km (14 mi) northwest of Wagon Mound (pl. 1), is a large, irregularly shaped volcanic vent composed of layers of platy to massive basalt, vesicular basalt, scoria, and agglomerate. Cinders and smaller volcanic ejecta are generally absent, but volcanic bombs are scattered about the nearby area. Agglomerate, best developed near the peak of Cerro Negro, contains flattened cavities as much as 15 cm (6 in.) across. The main peak appears to be formed by a large intrusion that has domed the overlying flows and has strongly deformed layered volcanic rocks along the south side of the structure into a series of folds; traces of the axial planes are roughly tangential to the domal feature. Along the north side of Cerro Negro is a volcanic cauldron, elliptical in shape, in which constituent basalts everywhere dip toward the central depression (fig. A12). Smaller vents, similar to Cerro Negro, are present directly to the west. Flows from these vents are small and were expelled mainly to the east.

The more massive flows are aphanitic porphyritic, slightly vesicular, and crudely pilotaxitic. Phenocrysts of olivine, plagioclase, orthopyroxene and clinopyroxene, and xenocrystic quartz are set in a very finely crystalline matrix. Olivine occurs as subhedral to euhedral crystals, locally enclosing magnetite and showing strong alteration to iddingsite. Minor augite euhedra are present. Hypersthene occurs as subhedral laths corroded by the groundmass grains and locally rimmed by finely crystalline clinopyroxene. Euhedral plagioclase laths, less that 0.5 mm (0.02 in.) long, are evenly distributed throughout the groundmass. Xenocrystic quartz is rare and is marked by reaction coronas of augite. Phenocrystic plagioclase is abundant, occurring as equant to prismatic, rounded crystals and crystal fragments. These crystals are characterized by a clear core, magmatically corroded mantle choked with opaque inclusions, and a clear, thin rind. The outermost rind is present only on the outer parts of the corroded mantle and does not enclose angular crystal fragments. These crystals are not strongly zoned; locally, the outer rind is slightly more calcic than the core of the crystal.

Groundmass consists of very finely crystalline plagioclase and clinopyroxene; plagioclase is pilotaxitic except adjacent to larger phenocrysts where it is tangential to the crystal boundary. Opaque oxides are equant, euhedral, and ubiquitous. Thin, slightly more coarsely crystalline layers are present in the matrix. These zones, less than about 0.5 mm (0.02 in.) thick, carry minor magnetite and are composed of plagioclase that locally has grown around augite euhedra.

Cerro Pelon area.—Cerro Pelon (pl. 1) is a large, composite cone built directly on the Dakota hogback that is interpreted to mark the eastern boundary of the Rocky Mountain province in this area. The height of the peak is not totally constructional but is partly due to the pre-existing topography of the hogback. The volcano is composed of a series of flows that radiate outward more than 6 km (10 mi). These flows are overlain by less widespread, apparently more viscous flows, erupted from small satellitic vents. The youngest flows were erupted from a small vent on the east flank of the volcano. The peak of Cerro Pelon is built of older flows and consists of a southwest-facing, horseshoe-shaped ridge composed of several small vents that are marked by inward dipping layers of agglomerate, scoriaceous material, volcanic breccia, minor, strongly oxidized basalt, and loosely welded cinders.

Two small cones south of Cerro Pelon are built on the distal parts of the basaltic apron around Cerro Pelon. These small vents expelled olivine basalts southward, in part covering the 4- to 5-m.y.-old basalts located to the southwest.

Lower flows from Cerro Pelon range from strongly vesicular aphanitic porphyritic rocks to massive, seriate varieties. Porphyritic varieties contain phenocrysts of olivine, augite, euhedral plagioclase, and locally xenocrysts of quartz. Olivine is typically partly altered to iddingsite and magnetite. Augite is locally glomeroporphyritic and twinned and locally is mantled by a thin (0.03 mm (0.001 in.)) syntaxial rind. Plagioclase phenocrysts characteristically show magmatically corroded cores or mantles surrounding unaltered cores, rimmed by thin, clear, sodium-rich rinds, all of which show variable degrees of resorption by the groundmass. Xenocrystic quartz shows reaction coronas of outward radiating clinopyroxene. The groundmass consists of diabasic plagioclase, olivine, and augite plus abundant, evenly distributed opaque oxides. Groundmass plagioclase ranges in composition from An_{52} to An_{56}.

Flows on the flanks of Cerro Pelon are petrographically nearly identical to those just described, except that olivine phenocrysts show minor resorption by the groundmass and matrix plagioclase appears to be slightly more calcic, near An_{58}.

Late-stage pyroclastic debris and ejecta atop Cerro Pelon consist largely of glass enclosing altered and partly resorbed plagioclase, quartz, augite, minor olivine, and rare apatite. Local holocrystalline lenses interlayered in these rocks consist of plagioclase, olivine-iddingsite, and abundant magnetite. The matrix also becomes more crystalline adjacent to gas cavities.

Cerrito Pelon and Cooks Peak.—Cerrito Pelon expelled basalts that flooded the area south and west of Apache Mesa (pl. 1). The vent is inset in a small valley that heads in the southern part of Rivera Mesa; the vent is surrounded on three sides by older basalts. The lower part of the cone consists of yellow-orange weathering tuff and tuff breccia overlain by layers of inward dipping volcanic breccia, agglomerate, and scoriaceous material. The cone is capped by dark-gray basalts that probably formed a small lava lake in the now eroded crater. The cone is intruded by radial dikes.

These basalts contain phenocrysts of olivine and, less commonly, augite and plagioclase. Phenocrysts occur as subhedral to euhedral crystals that show moderate alteration to iddingsite and minor magnetite along fractures and around their peripheries. One crystal consists of optically continuous, rounded blebs of olivine separated by wormy lenses of optically continuous pyroxene. Augite occurs as single euhedra and as glomeroporphyritic clusters of hypidiomorphic, locally twinned crystals. Some euhedra have inclusion-choked cores and rinds, separated by clear mantles. Plagioclase (An_{54}) occurs principally as subhedral to euhedral laths. Minor equant phenocrysts are characterized by inclusion-choked cores mantled by clear rinds that are embayed by the groundmass grains. These crystals are commonly zoned and show migratory, diffuse twin planes. Only one quartz xenocryst was observed, and minor, anhedral biotite was observed in one specimen. Groundmass locally shows well-developed diabasic texture, with randomly oriented plagioclase laths

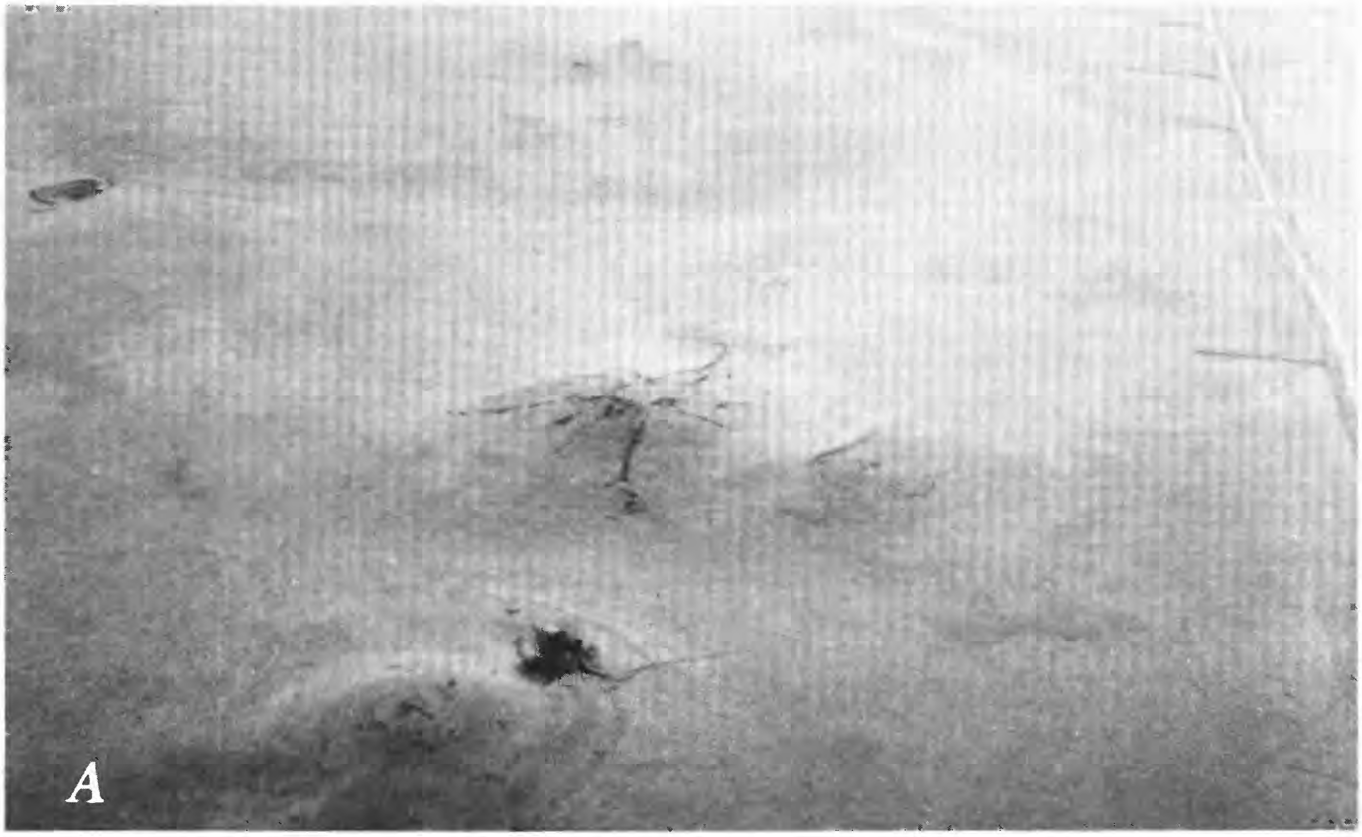


FIGURE A11 (above and facing page).—Older vents on Charette Mesa. Vents are partly dissected and consist of inward-dipping layers of basaltic rock. *A*, radial dikes cut through the small cone; *B*, remnants of small lava lake that spilled out onto cone flanks. State Highway 120 shows scale.

(An_{52}) intergrown with prismatic augite and equant olivine and magnetite.

Cooks Peak, directly west of Cerrito Pelon, is a steep sided, rounded knob rising nearly 150 m (500 ft) above the surrounding basalts. The vent is composed almost entirely of agglomerate with poorly developed layering. The center of the vent was intruded by north- to northwest-trending dikes containing conspicuous phenocrysts of plagioclase and dark-green pyroxene. Cooks Peak appears to be a late stage vent resting on 4- to 5-m.y.-old basalts; it extruded small flows to the north and east and built up a large spatter-like cone above the vent.

The late-stage dikes contain phenocrysts of plagioclase, olivine, and glomeroporphyritic clinopyroxene and orthopyroxene. Plagioclase phenocrysts can be divided into two, somewhat gradational types: prismatic, well twinned, randomly oriented euhedra; and anhedral to subhedral, diffusely twinned, locally strongly embayed crystals near An_{63} in composition. Olivine is anhedral, strongly resorbed by the groundmass, and rimmed by opaque oxides. Clinopyroxene occurs as individual crystals or as crystal clusters; the crystals are locally twinned and commonly show magmatically corroded margins. Orthopyroxene (hypersthene) occurs as prismatic to stubby crystals, locally partly enclosed by augite. Individual euhedra are strongly embayed by the groundmass grains.

Groundmass consists of plagioclase laths (An_{59}), abundant clinopyroxene and minor orthopyroxene, and evenly distributed euhedra of magnetite. Calcite fills some vesicles.

White Peak area.—White Peak is a large shield volcano whose basalts covered 4- to 5-m.y.-old basalts over much of the eastern part of the Ortega Mesa. Flows from this volcanic center are roughly triangular in plan; most of the basalts flowed east and southeast from the main vent. The White Peak cinder cone is composed of cindery and scoriaceous material and agglomerate intruded by thin vertical dikes built on a shield volcano whose flanks are inclined less than 5°. The peak is cone shaped and occupies a small depression bounded on all but the southeast side by a ridge of basalt.

That the basalts of White Peak are significantly

younger than the basal flows on Ortega Mesa is shown by the rough, hummocky topography and the well defined flow patterns still preserved around the vent. A basalt collected 1.5 km (1 mi) south of White Peak yielded a K-Ar date of 3.5 m.y. The rather youthful flow topography and the large magin of error on this age determination suggests that at least some of the basalts are younger than 3.5 m.y.

Basalt flows that cap mesas and buttes east of and about 60 m (200 ft) lower than the eastern edge of Ortega and Rivera Mesas probably came from White Peak, the only young volcanic vent in the area. These basaltic rocks were deposited on the same surface as the one beneath the basaltic rocks on Charette Mesa. The basal flows expelled from White Peak are separated from the older, underlying flows on Ortega Mesa by a thin veneer of lithic sands and gravels derived principally from volcanic rocks, suggesting a significant period of erosion between deposition of flows. Those flows above the sand and gravel were erupted from the White Peak vent, flowed east-southeast, and apparently cascaded over the older mesa scarp and spilled onto the lowlands below.

The flows from White Peak are strongly vesicular, aphanitic porphyritic rocks. Phenocrysts of olivine occur as euhedral to subhedral crystals showing well-developed alteration to iddingsite along internal fractures and around their peripheries. Phenocrysts of plagioclase and xenocrysts of quartz are common. Plagioclase occurs as locally glomeroporphyritic, subhedral twinned crystals containing irregularly shaped, unaltered cores, magmatically corroded mantles and clear rinds. Some individuals are fragments of larger crystals. Quartz shows outward radiating clinopyroxene reaction coronas. Groundmass consists of prismatic plagioclase (An_{57}), equant opaque oxides, and clinopyroxene crystal aggregates, locally lining cavity walls, and minor orthopyroxene.

Le Febres area.—Three young vents of low relief are present in the Le Febres area. The only vent on Le Febres Mesa is northeast of Cerro Montoso; it is a shield cone. Basalts erupted from this vent flowed mainly to the south, then southeast into Ocate Valley, cascading over the valley edge and flowing toward Ocate Creek (fig. A2). According to a local rancher, a water well drilled near this vent penetrated more than 60 m (200 ft) of basalt.

The other two vents in the Le Febres area are located to the south of Le Febres Mesa. One vent is directly east of Cerro Montoso; the vent is circular and consists

FIGURE A12.—Cerro Negro cauldron. View to east; Las Mesas del Conjelon on horizon. Cauldron, in middle ground, is built on the north flank of Cerro Negro. Cauldron is an elliptical depression (long axis about 100 m (300 ft) across) with a smooth, concave-upward surface surrounded by a raised rim consisting of inward-dipping layers of basaltic rock.

of an outermost ridge standing about 15 m (50 ft) above the surrounding mesa, encircling a small central basaltic dome, but separated from the dome by a low-lying moat (fig. A13). Basalts erupted from this vent cascaded into Ocate Valley, building a basaltic fan at the base of the valley wall. The vent and the basaltic fan in the valley below are cut by at least three minor north- to northeast-trending faults.

A third vent, located south-southwest of Cerro Montoso, is circular in plan and contains two subdued central knobs. Olivine basalts, interlayered with scoriaceous lavas, dip inward toward the knobs. Expelled basalts flowed south on La Mesa, and southeast into Ocate Valley.

Specimens collected from these vents are diabasic and locally glomeroporphyritic. Subhedral to euhedral phenocrysts of olivine with poorly developed iddingsite rinds are common. In less oxidized specimens, magnetite euhedra are preferentially concentrated around the periphyry of the crystals or along internal fractures. Plagioclase (An_{65}) is present as stubby to elongate prisms showing well-defined polysynthetic twinning and as subhedral, partly resorbed crystals that are locally glomeroporphyritic and show diffuse twinning. Phenocrystic augite is present as individual crystals and as crystal clusters, locally zoned and mantled with a syntaxial rind. The groundmass consists of equant olivine, small stubby augite crystals, and slender augite laths enclosed in anhedral plagioclase crystals, randomly oriented plagioclase laths (An_{61}) and ubiquitous, equant opaque oxides.

Youngest basalt-capped mesa.—A small basalt-capped mesa, located 4.5 km (3 mi) north of Wagon Mound, lies 20 m (70 ft) below the Charette Mesa flows and about 15 m (50 ft) above the adjacent lowlands. Basalts on this mesa, dated at 2.2 m.y., were erupted from a low shield vent directly to the west on Charette Mesa. The vent structure is subdued, with dips on its flanks of less than 3°. A satellitic vent, located about 100 m (300 ft) west of the center of the mound, is composed of platy, vesicular to dense basalt that stands 0.25 to 0.5 m (0.8 to 1.6 ft) above the surrounding flows; flow layering is horizontal on all sides except the west where layering is steeply inclined toward the center.

Basalts from the main center form a broad, elliptical apron that defines the shield structure. Some basalts flowed northwest, down a small gully, spilling onto the lowlands below; however, east-flowing basaltic flows cascaded over the Charette Mesa scarp.

The basalts are dense, medium to dark gray, finely crystalline, and contain phenocrysts of olivine and plagioclase. The basalts at the central vent may aggregate more than 20 m (70 ft) in thickness, but thin to 1–3 m (3–10 ft) at the distal parts of the flows.

The rock shows crude alignment of plagioclase laths in a dense, very finely crystalline matrix of opaque oxides, anhedral plagioclase, olivine and pyroxene, and minor glass. Phenocrysts of olivine are subhedral, locally glomeroporphyritic, and are partly altered to iddingsite. Olivine crystals are anhedral as the result of strong resorption by the groundmass. Plagioclase phenocrysts contain cores which enclose groundmass grains and are mantled by clear, syntaxial, slightly more calcic rinds. Smaller crystals are euhedral laths near An_{62} in composition. Augite phenocrysts are not common, tend to be small and glomeroporphyritic, and enclose numerous opaque oxides.

Maxon Crater.—Maxon Crater, a large basaltic shield volcano, is located about 12 km (7 mi) south of Wagon Mound and directly west of Interstate 25 (I–25). Basalts expelled from this volcano flowed east. The crater vent is located at the western end of the flow system and is marked by a large east-trending depression 0.25 km (0.16 mi) wide and more than 1 km (0.6 mi) long. Vesicular basalt, scoriaceous material, and locally ropy lava compose the greater part of the rim of the depression. Minor, strongly vesiculated and oxidized basalt within the crater, contains xenoliths of Precambrian and Paleozoic, and Mesozoic rock fragments. In general, all basalts dip away from the central crater. The north rim of the crater contains numerous small basalt tumuli, spatter cones and products of fissure eruptions that are surrounded by small aprons of basalt that dip away from these minor vents.

Northeast of Maxon Crater is a small basalt tumulus

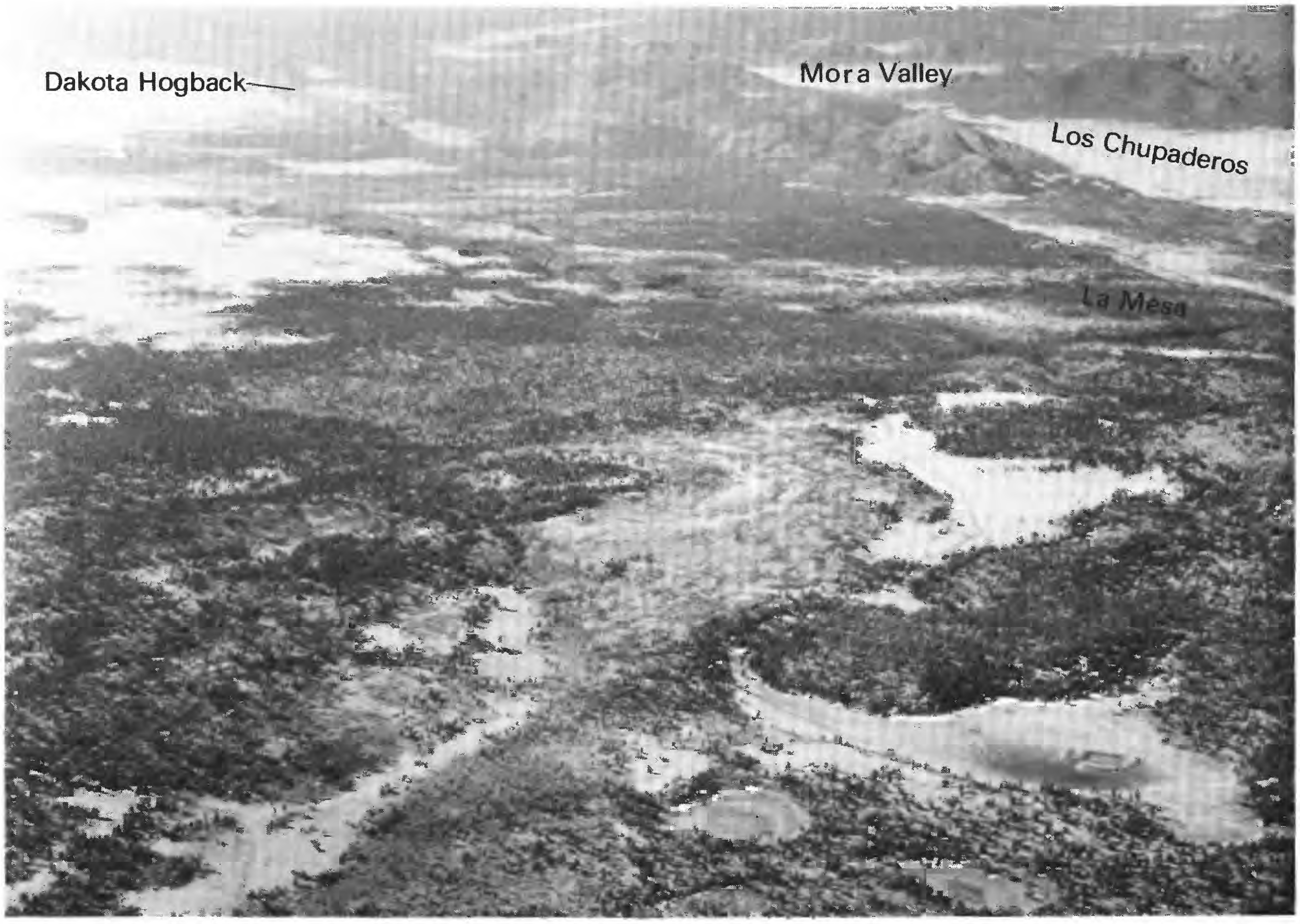


FIGURE A13.—Vent directly east of Cerro Montoso—one of the three vents in Le Febres area. Vent is circular in plan, consisting of an outer ridge, interior moat, and central basalt knob. Left (east) side of vent is cut by a small fault. Dakota hogback in background marks eastern edge of uplifted basement block of the Sangre de Cristo Mountains.

and a secondary basaltic shield cone. The basalt tumulus rises from 4 to 10 m (13 to 33 ft) above the underlying flows and is composed of at least three distinct, inward dipping layers of moderately vesicular to massive basalt. A small shield vent, located directly west of I-25, is less than 3/4 km (½ mi) in diameter and rises about 50 m (160 ft) above the underlying basalts. Its center is marked by irregularly shaped pods of basalt which stand 0.25-0.5 m (0.8-1.6 ft) above the smooth shield surface. Basalts collected from flows exposed in the roadcut along I-25 gave a K-Ar date of 1.4 m.y.

Basalts expelled from Maxon Crater flowed 90 km (60 mi) eastward, through the canyon carved by the Mora River, and flowed then a short distance beyond the confluence of the Mora and Canadian Rivers (fig. A14). At the confluence of the two rivers the flows lie 100 m (300 ft) below the rim of the canyon, and 125 m (400 ft) above the present level of the rivers.

Rocks collected near the vent are equigranular to porphyritic, vesicular, and diabasic. Subhedral to euhedral phenocrysts of olivine carry characteristic iddingsite alteration rinds; others are rimmed by magnetite. Plagioclase phenocrysts are glomeroporphyritic, euhedral laths; plagioclase xenocrysts tend to be equant and show strong zoning and inclusion-choked cores. Groundmass grains consist of plagioclase laths (An_{62}), locally zoned with outer rims near An_{40}, slender augite needles, olivine, and euhedral opaque oxides which appear to have grown on the surfaces of crystals in cavities.

Cerro del Oro.—The youngest volcanic rocks of the Ocate volcanic field are in the central part of Charette Mesa, south of State Highway 120. The basalts consist of two thick, viscous flow systems. Each erupted from one major and at least one minor vent and covered about 16 km^2 (6 mi^2) (fig. A15). The surfaces of the

FIGURE A14.—Basalt-capped terrace at confluence of Mora and Canadian Rivers is about 100 m (300 ft) below surface of the Las Vegas Plateau, and 125 m (400 ft) above the present stream level; view to southeast. Basalt erupted from Maxon Crater and flowed eastward through the Mora River canyon beyond its confluence with the Canadian River.

flows are hummocky and scattered with volcanic bombs and scoriaceous material. Numerous pressure ridges and flow ramparts are present, which stand as elliptical knobs 7–10 m (20–30 ft) above the surrounding basalts. The cores of these structures show blocky, oxidized basal flows overlain by dense, aphanitic, nonvesicular and somewhat platy basalt. The flows that show these features best were erupted from the Cerro del Oro cinder cone. The flanks of this cone consist of outward dipping cinders, ash, bombs, volcanic breccia, and agglomerate. The original crater has been partly eroded and is now marked by a south-draining gully. Basalts flowed mainly southward from this cone. A specimen collected from basalt interlayered in the cinder cone was dated at 0.8 m.y.

Basalts interlayered with cinders at Cerro del Oro consist of glass containing small crystals of magnetite and plagioclase microlites, and enclosing phenocrysts of plagioclase and clusters of olivine and augite. Plagioclase occurs as euhedral laths that show minor corrosion adjacent to gas vesicles; composition is near An_{55}. Plagioclase is also present as fragments of zoned xenocrysts that generally contain inclusion-choked cores mantled by clear rinds that are partly embayed by the groundmass glass. Olivine and augite phenocrysts also show minor embayment and reaction with the groundmass.

PETROGRAPHIC SUMMARY AND WHOLE-ROCK CHEMISTRY

The groundmass of most of the basaltic rocks collected from the Ocate volcanic field typically consists of plagioclase (An_{55-60}), clinopyroxene, olivine, and abundant magnetite. Textural features of olivine,

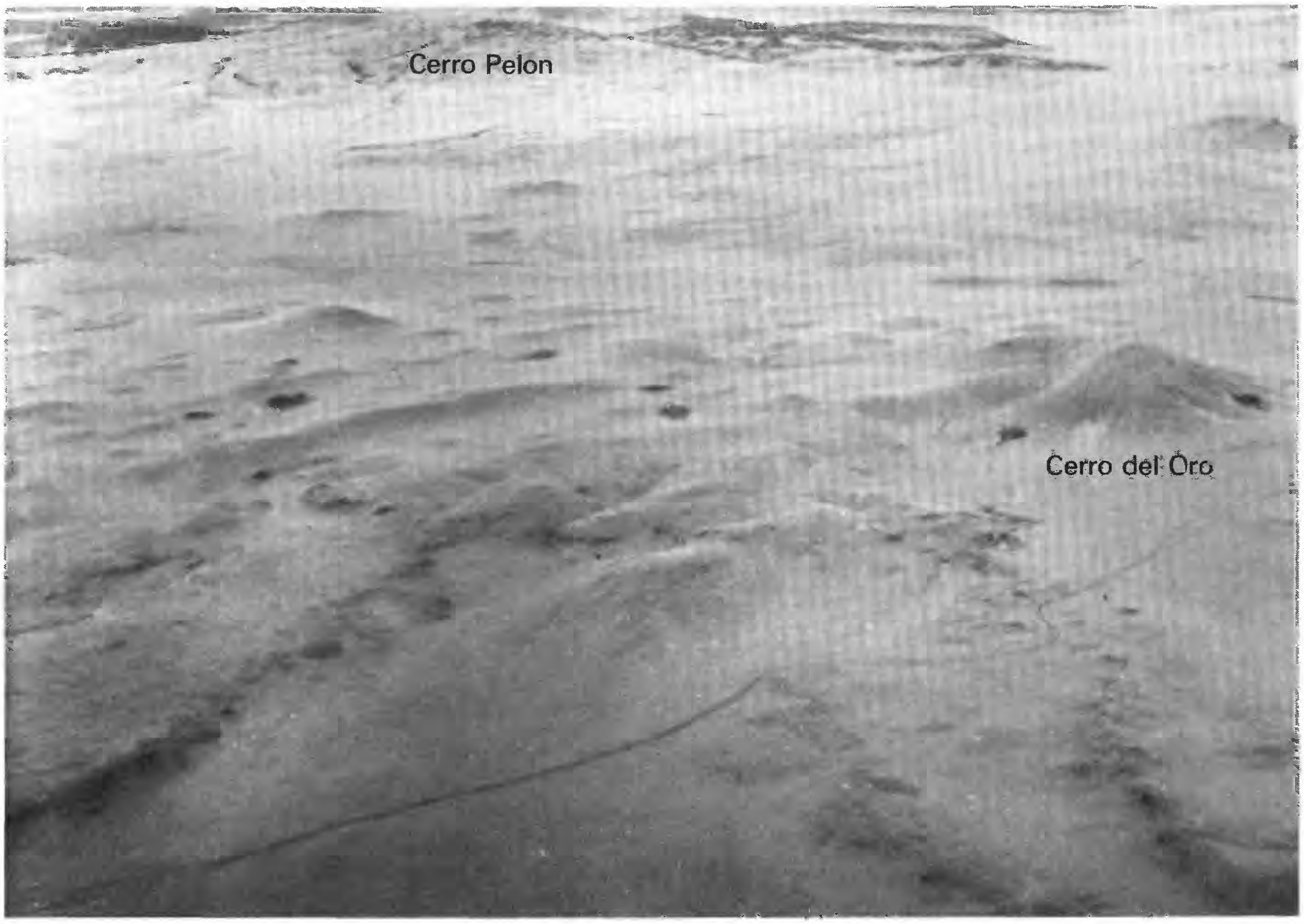


FIGURE A15.—Cerro del Oro cinder cone and minor cones and associated flows. View to west-southwest. Cerro Pelon in distance. Note irregular surface on lavas that flowed southward from Cerro del Oro.

plagioclase, and clinopyroxene phenocrysts suggest a complex crystallization history. Almost all olivine phenocrysts are rimmed by iddingsite and some are rimmed by magnetite; a few of these phenocrysts contain iddingsite-magnetite cores mantled by unaltered olivine. These textural relationships suggest that oxidation of olivine occurred not only during or after the last stages of crystallization of the basalt but also at some time during the early crystallization of the phenocrysts. Plagioclase phenocrysts commonly show complex alteration. In general, these crystals contain irregularly shaped, unclouded cores surrounded by magmatically corroded, locally inclusion-choked mantle containing abundant magnetite. This mantle is rimmed by a thin, syntaxial, unclouded rind that is commonly embayed by the groundmass. These textural relations indicate partial resorption of the original crystal, later grain growth which enveloped some groundmass grains, followed by a second period of crystallization and partial resorption. Magnetite inclusions within the mantle zone suggests that oxidizing conditions existed in the magma early in the crystallization history of the plagioclase. Clinopyroxene commonly carries a rounded, locally magnetite-bearing core enclosed by a hypidiomorphic, syntaxial rind. Biotite, present in minor amounts in some flows, indicates hydrous conditions during crystallization. Minor xenocrysts of quartz and xenoliths of basement rocks suggest that contamination of the magma during rise to the surface was minimal.

Chemical analyses of volcanic rocks from the Ocate volcanic field have been published by Petersen (1969, 1 analysis), Lipman and Mehnert (1975, 7 analyses), and Aoki and Kudo (1976, 6 analyses). In addition, 14 new analyses are included in this report. The analyses, along with their CIPW normative calculations, are listed in tables A2, A3, and A4. The 27 total samples are grouped according to age: older than 5 m.y. (4 samples), 4–5 m.y. (11 samples), and younger than 4 m.y. (13 samples).

TABLE A2.—*Chemical analyses and CIPW normative calculations for volcanic rocks older than 5 m.y. from the Ocate volcanic field*

[Major oxide analyses performed by rapid methods described under "single solution" in Shapiro (1975). Leaders (---), not present. Analyses by K. Coates, H. Smith, Z.A. Hamlin, and N. Skinner]

Constituent	Sample no. 1	2	3	4	Constituent	Sample no. 1	2	3	4
	Chemical composition				Normative composition (wt %)				
SiO_2..........	49.6	47.56	52.1	50.4	Qz.........	---	---	---	---
Al_2O_3.........	16.2	12.84	16.2	15.5	Or.........	7.83	6.9	8.77	11.1
Fe_2O_3.........	5.2	3.58	2.8	5.5	Ab.........	27.59	20.6	27.64	30.13
FeO...........	5.0	7.96	7.2	4.8	An.........	25.67	22.47	24.71	20.3
MgO...........	7.5	8.76	7.3	7.0	Ne.........	---	---	---	---
CaO...........	9.5	11.01	8.3	7.9	Wo.........	7.05	25.12	5.67	5.9
Na_2O..........	3.3	2.22	3.3	3.6	En.........	13.98	9.56	14.73	14.46
K_2O...........	1.3	1.13	1.5	1.9	Fs.........	1.98	---	6.89	1.28
H_2O...........	1.63	-2.53	-0.2	-1.92	Fo.........	3.36	8.07	2.28	1.95
....					Fa.........	0.52	---	1.18	0.19
TiO_2..........	1.5	1.78	1.6	1.8	Mt.........	7.54	3.87	4.01	7.89
P_2O_5..........	0.68	0.39	0.37	0.66	Hm.........	---	---	---	---
MnO...........	0.16	0.22	0.13	0.13	Fl.........	2.9	2.87	3.01	3.38
CO_2...........	-0.05	---	-0.01	-0.01	Ap.........	1.62	0.83	0.87	1.55
....					Di.........	14.1	19.12	11.34	11.8
....					Hy.........	8.91	---	15.95	9.84
Sum.........	101.62	97.45	101.01	101.12					

SAMPLE LOCALITIES AND COMMENTS

Sample No.	Field No.	Locality	Reference	Age (m.y.)
1	---	Las Mesas del Conjelon; Wagon Mound.	Lipman and Mehnert (1975), analysis No. 19, table 3.	5.5
2	---	Palo Flechado Pass.	Petersen (1969).	
3	6CV-3	Cerro Vista 7 1/2-minute quadrangle. (30 km (20 mi) west of Ocate).		5.6
4	GV6	Sierra Montuosa Mesa.		8.3

Chemical analyses of volcanic rocks older than 5 m.y. and younger than 4 m.y. show them to be subalkaline (fig. A16) and to grade between calc-alkaline and tholeiitic types (fig. A17). These rocks are classified as basalts (fig. A18) that contain olivine and hypersthene or less commonly hypersthene and quartz in the norm. For tholeiitic basalts, their alkali, ferric and alumina contents are high (table A5). When plotted on the alkali-silica variation diagram of MacDonald and Katsura (1964) (fig. A19) the higher alkali contents tend to group these rocks largely within the silicic alkalic basalt field. The average alumina content in these rocks is less than the 16–17 percent value generally used, in part, to define high-alumina basalts (Kuno, 1967).

The chemical compositions of the intermediate-age (4- to 5-m.y.-old) volcanic rocks are variable (fig. A16). These rocks include basalts that are petrographically similar to the basalts of the oldest and youngest rocks but are also locally interlayered with andesite, tholeiitic andesite, and dacite. One specimen from this group is nepheline-normative.

On the AMF diagram (fig. A20) these rocks show alkali and silica enrichment trends. The interlayering of basalts with andesites and dacites in small, individual volcanic vents, as at Cerro Montoso, suggests that these rocks are genetically related.

Figure A21 is a titania-solidification index diagram in which specimens collected from the Ocate volcanic field have been plotted. Almost all these rocks plot below the 1.75 dividing line of Chayes (1964). Their average titania values are only slightly greater than those values in basalts present within the Rio Grande depression, which have been interpreted to have generated at shallow depths (Lipman, 1969).

TABLE A3.—*Chemical analyses and CIPW normative calculations for volcanic rocks 5.0 to 4.0 m.y. old from the Ocate volcanic field*

[Major oxide analyses performed by rapid methods described under "single solution" in Shapiro (1975). Leaders (---), not present. Analyses by K. Coates, H. Smith, Z.A. Hamlin, and N. Skinner]

Constituent	Sample no. 1	2	3	4	5	6	7	8	9	10	11
Chemical composition											
SiO_2....	52.54	52.6	55.9	52.9	49.1	49.9	50.96	49.81	49.81	49.99	64.72
Al_2O_3...	15.07	17.7	16.5	16.6	16.0	16.7	15.63	15.61	15.34	15.24	14.71
Fe_2O_3...	3.18	8.0	4.8	5.2	3.4	5.4	5.27	5.97	4.45	6.63	1.99
FeO.....	6.66	1.4	2.7	3.5	7.2	6.3	5.57	4.47	6.73	3.27	2.39
MgO.....	6.58	3.8	3.2	4.7	8.8	6.4	5.47	7.16	5.74	7.03	1.79
CaO.....	8.9	7.2	6.2	7.7	8.9	9.2	8.66	9.05	8.11	9.11	3.58
Na_2O....	3.81	4.2	3.8	3.7	3.1	3.0	3.58	3.58	3.76	3.66	3.58
K_2O.....	1.81	2.3	2.5	2.1	1.3	0.85	1.39	1.29	2.47	1.78	4.18
H_2O.....	---	-1.3	-2.27	-1.53	-1.01	-0.79	-1.17	-0.73	-1.17	-0.78	-1.91
TiO_2....	1.62	1.6	1.3	1.6	1.8	1.7	1.69	1.59	2.08	1.48	0.79
P_2O_5....	0.43	0.95	0.44	0.46	0.47	0.33	0.43	0.61	0.42	0.89	0.01
MnO.....	0.15	0.13	0.09	0.12	0.14	0.19	0.14	0.14	0.22	0.12	0.06
CO_2.....	---	-0.05	0.01	-0.04	-0.01	-0.05	-0.03	---	-0.04	-0.01	---
Sum...	100.75	101.25	99.71	100.15	101.23	100.86	99.99	100.01	100.34	99.97	99.71
Normative composition (wt %)											
Qz......	---	2.47	9.03	3.92	---	1.84	1.63	---	---	---	18.61
Or......	10.69	13.77	14.81	12.38	7.58	5.01	8.23	7.63	14.62	10.53	24.68
Ab......	32.25	35.15	32.24	31.26	25.91	25.64	30.07	30.29	28.73	30.99	30.28
An......	18.66	22.85	20.64	22.45	25.58	29.37	22.44	22.71	17.67	19.87	11.75
Ne......	---	---	---	---	---	---	---	---	1.67	---	---
Wo......	7.25	2.76	3.03	5.19	6.23	5.73	7.32	7.61	8.19	8.1	1.67
En......	12.8	9.59	7.99	11.68	8.67	15.85	13.63	15.3	5.44	12.85	4.46
Fs......	5.63	---	---	---	3.04	4.52	3.34	0.79	2.15	---	1.55
Fo......	2.51	---	---	---	9.09	---	---	1.77	6.2	3.26	---
Fa......	1.21	---	---	---	3.52	---	---	0.1	2.7	---	---
Mt......	4.61	0.37	5.24	7.02	4.87	7.91	7.65	8.65	6.45	6.61	2.88
Hm......	---	7.75	1.19	0.34	---	---	---	---	---	2.07	---
Il......	3.08	3.08	2.47	3.03	3.37	3.26	3.21	3.02	3.95	2.82	1.49
Ap......	0.98	2.26	1.04	1.08	1.1	0.91	1.01	1.44	0.98	2.11	0.73
Di......	14.5	5.52	6.06	10.38	12.46	11.46	14.64	5.22	15.78	16.2	3.34
Hy......	11.18	6.83	4.96	6.49	5.48	14.64	9.65	8.48	---	4.75	4.34

SAMPLE LOCALITIES AND COMMENTS:

Sample No.	Field No.	Location	Reference	Age (m.y.)
1	---	Black Lake.	Aoki and Kudo (1976), table 2E, No. 33.	
2	---	Pass south of Black Lake.	Lipman and Mehnert (1975), table 3,	4.3±
3	2C2	Los Chupaderos-Guadalupita Valley.	No. 25.	4.2±0.4
4	4C2	El Cerro Colorado.		4.0±0.2
5	1L2	State Highway 21, 3.5 km (2 mi) east of Ojo Feliz.		4.0±0.3
6	---	State Highway 21, 3.5 km (2 mi) east of Ojo Feliz.	Lipman and Mehnert (1975) table 3, No. 21.	
7	TT5	Laguna Salada Mesa.		
8	GMV2	Gonzalitos Mesa.		
9	MRV2	Apache Mesa.		
10	GV2	Cerro Montoso, late flows.		
11	GV2A	Cerro Montoso, viscous flows.		

TABLE A4.—*Chemical analyses and CIPW normative calculations for volcanic rocks younger than 4 m.y. from the Ocate volcanic field*

[Major oxide analyses performed by rapid methods described under "single solution" in Shapiro (1975). Leaders (---), not present. Analyses by K. Coates, H. Smith, Z.A. Hamlin, and N. Skinner]

	Sample no.												
Constituent	1	2	3	4	5	6	7	8	9	10	11	12	13
Chemical composition													
SiO_2	50.67	51.0	49.6	50.7	51.4	49.6	49.02	55.58	49.66	54.72	48.85	48.99	51.77
Al_2O_3	15.91	16.6	16.2	15.8	16.1	15.9	16.75	14.63	16.54	15.48	15.56	15.08	16.01
Fe_2O_3	3.41	2.8	3.8	2.0	2.9	3.87	3.32	2.54	2.68	3.06	5.94	4.93	3.75
FeO	7.52	7.5	7.6	8.0	7.1	8.05	8.09	5.75	7.95	5.82	6.34	6.7	5.73
MgO	6.76	7.3	7.8	8.3	7.3	7.24	6.89	5.64	6.44	5.52	7.03	7.29	5.73
CaO	9.20	9.1	8.7	8.4	8.6	8.69	9.07	6.98	9.1	7.3	8.62	9.27	7.9
Na_2O	3.12	3.0	3.2	3.0	3.2	3.6	3.5	3.41	3.6	3.45	3.37	3.33	3.75
K_2O	0.95	1.1	1.0	1.3	1.3	0.85	0.6	2.03	0.87	2.07	0.90	1.18	2.07
H_2O	-.90	-0.65	-0.53	-1.04	-0.95	-0.71	-1.09	-1.75	-0.89	-0.97	-0.89	-0.63	-0.97
TiO_2	1.16	1.2	1.6	1.6	1.5	1.08	1.65	1.23	1.55	1.18	1.70	1.17	1.48
P_2O_5	0.37	0.34	0.34	0.54	0.38	0.39	0.26	0.53	0.41	0.43	0.50	0.62	0.67
MnO	0.22	0.17	0.18	0.14	0.16	0.19	0.49	0.17	0.15	0.11	0.19	0.17	0.15
CO_2	---	-0.05	-0.05	-0.03	0.05	---	---	---	---	---	-0.04	---	-0.01
Sum	100.19	100.81	100.60	100.90	100.94	100.17	100.37	99.74	99.82	100.31	99.93	99.36	99.69
Normative composition (wt %)													
Qz	---	---	---	---	---	---	---	5.74	---	4.39	---	---	---
Qr	5.62	6.56	5.96	7.79	7.76	5.01	3.56	12.02	5.12	12.27	5.33	6.99	12.26
Ab	26.32	25.61	27.25	25.75	27.37	30.46	29.62	28.84	30.46	28.37	28.51	28.36	31.77
An	26.65	28.29	26.82	25.63	25.45	24.73	28.2	18.61	26.42	21.98	24.66	22.62	20.69
Ne	---	---	---	---	---	---	---	---	---	---	---	---	---
Wo	6.93	6.06	5.82	5.28	6.12	6.61	6.32	5.27	6.7	5.13	6.1	8.06	5.87
En	15.57	14.54	11.76	13.36	15.13	8.42	8.31	14.04	7.78	13.75	16.45	11.68	11.88
Fs	8.77	7.79	6.1	6.85	6.98	4.75	4.71	16.74	4.89	6.41	3.89	3.61	4.37
Fo	0.89	2.49	5.3	5.16	2.1	6.73	6.20	---	5.78	---	0.75	4.54	1.67
Fa	0.55	1.47	2.54	2.91	1.07	4.19	3.88	---	3.99	---	0.20	1.55	0.67
Mt	4.95	4.1	5.55	2.94	4.25	5.6	4.82	3.68	3.89	4.43	8.62	7.15	5.44
Hm	---	---	---	---	---	---	---	---	---	---	---	---	---
Fl	2.2	2.3	3.06	3.08	2.88	2.05	3.14	2.34	2.94	2.25	3.39	3.37	2.82
Ap	0.85	0.81	0.81	1.27	0.91	0.92	0.59	1.21	0.95	1.03	1.17	1.47	1.59
Di	13.86	12.12	11.64	10.56	12.24	13.17	12.64	10.51	12.67	10.26	12.2	16.12	11.74
Hy	12.41	16.27	11.04	14.83	15.98	6.56	6.7	25.51	5.57	15.03	14.24	7.23	10.38

SAMPLE LOCALITIES AND COMMENTS

Sample No.	Field No.	Locality	Reference	Age (m.y.)
1	---	Maxon Crater.	Aoki and Kudo (1976), table 2E, No. 28	
2	---	Maxon Crater.	Lipman and Mehnert (1975), table 3, No. 23	1.36
3	---	Charette Mesa, basal flows at Wagon Mound.	Lipman and Mehnert (1975), table 3, No. 20	3.0
4	---	Lowest mesa, 2 km (1 mi) N. of Wagon Mound.	Lipman and Mehnert (1975), table 3, No. 22	2.15
5	---	Flows of Charette Mesa.	Lipman and Mehnert (1975), table 3, No. 24	
6	---	Flows of Charette Mesa.	Aoki and Kudo (1976), table 2E, No. 29	
7	---	Flows of Charette Mesa.	Aoki and Kudo (1976), table 2E, No. 30	
8	---	Flows of Charette Mesa.	Aoki and Kudo (1976), table 2E, No. 31	
9	---	Flows of Charette Mesa.	Aoki and Kudo (1976), table 2E, No. 32	
10	OMV-2WP	White Peak.		3.2
11	104	Cerro Pelon, lower flow in Ocate Valley.		
12	OV4	Small vent, directly E. of Cerro Montoso.		
13	CNV1	Cerro del Oro.		0.76

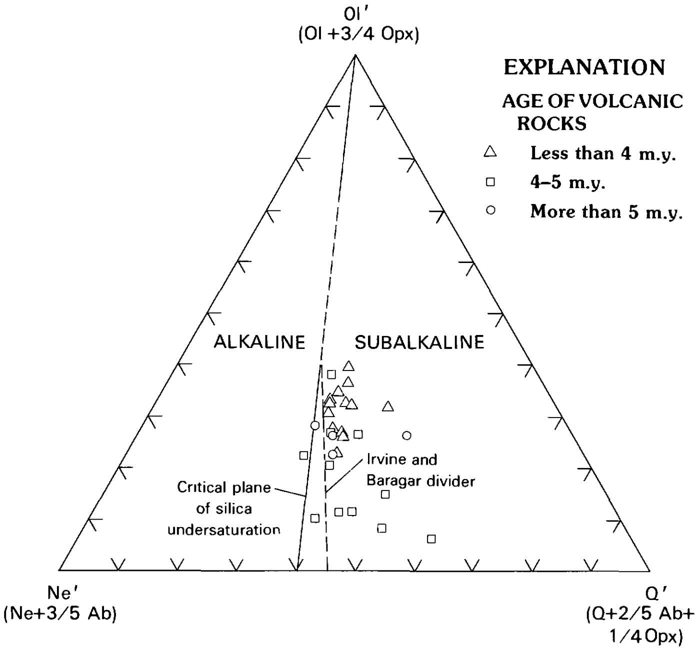


FIGURE A16.—Normative plots of 28 samples of volcanic rocks from the Ocate volcanic field on the base of the basalt tetrahedron of Yoder and Tilley (1962) (after Irvine and Baragar, 1971).

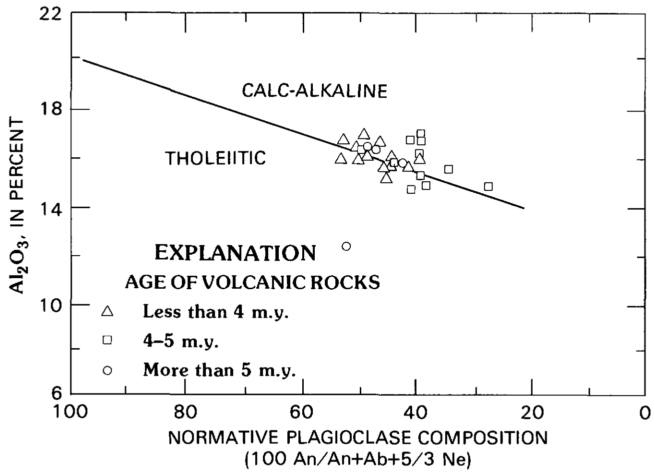


FIGURE A17.—Plot of alumina-normative plagioclase composition of 28 samples of volcanic rocks from the Ocate volcanic field (after Irvine and Baragar, 1971). Line separates calc-alkaline field from tholeiitic field.

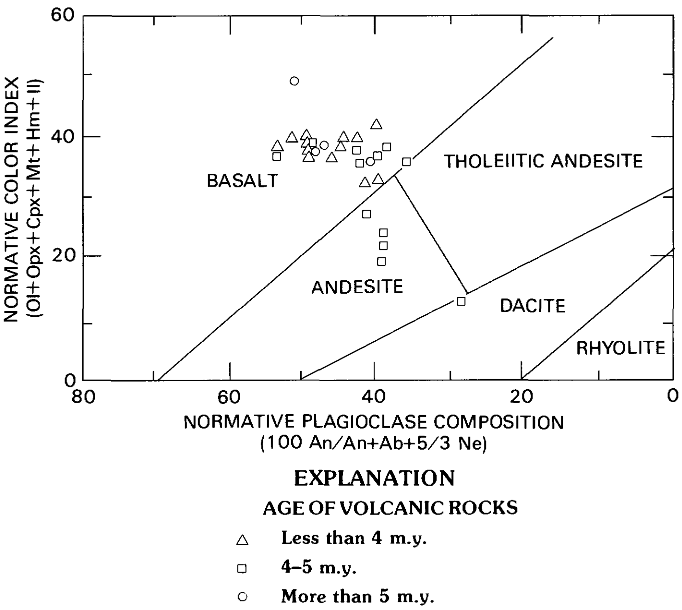


FIGURE A18.—Plot of normative color index-normative plagioclase composition of 28 samples of volcanic rocks from the Ocate volcanic field (after Irvine and Baragar, 1971).

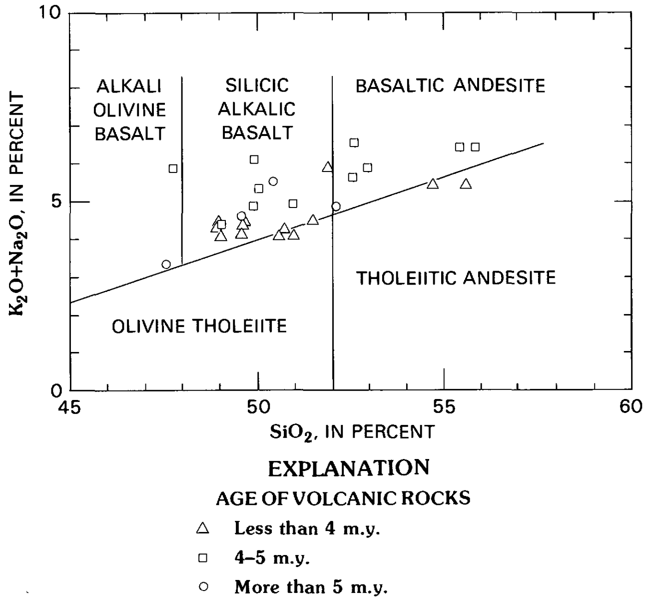


FIGURE A19.—Plot of total alkali-silica of 28 samples of volcanic rocks from the Ocate volcanic field (after MacDonald and Katsura, 1964).

PETROGENESIS

Interpretation of the petrogenetic evolution of the rocks of the Ocate volcanic field is beyond the scope of this report; however, a detailed study of the petrogenesis of these volcanic rocks based on numerous major and minor element geochemical analyses was made by Nielsen and Dungan (1985) who collected and interpreted their data while this report was in preparation. They concluded that:

(1) The alkali olivine basalts were derived from physically discrete source regions and probably were products of small degrees of melting and(or) melting at great depths.

TABLE A5.—*Average chemical composition of tholeiitic basalts*

	Analysis			
Constituent	1	2	3	4
SiO_2...........	50.66	50.83	47.9	50.9
Al_2O_3..........	15.72	14.07	11.84	16.3
Fe_2O_3..........	3.65	2.88	2.32	2.7
FeO............	6.88	9.06	9.8	8.8
MgO............	7.04	6.34	14.07	7.4
CaO............	8.68	10.42	9.29	8.9
Na_2O..........	3.28	2.23	1.66	3.0
K_2O...........	1.29	0.82	0.54	0.6
TiO_2..........	1.53	2.03	1.65	1.2
P_2O_5..........	0.46	0.23	0.19	0.1
MnO............	0.15	0.18	0.15	0.1
Sum.........	99.34	99.09	99.41	100.00

ANALYSES

1. Average of 17 analyses of oldest and youngest basalts in the Ocate volcanic field.
2. Average of 137 analyses of tholeiitic basalt (Nockolds, 1954).
3. Average of 28 analyses of tholeiitic olivine basalts (Nockolds, 1954).
4. Average of 19 olivine tholeiite basalts, Taos Plateau (Lipman, 1969).

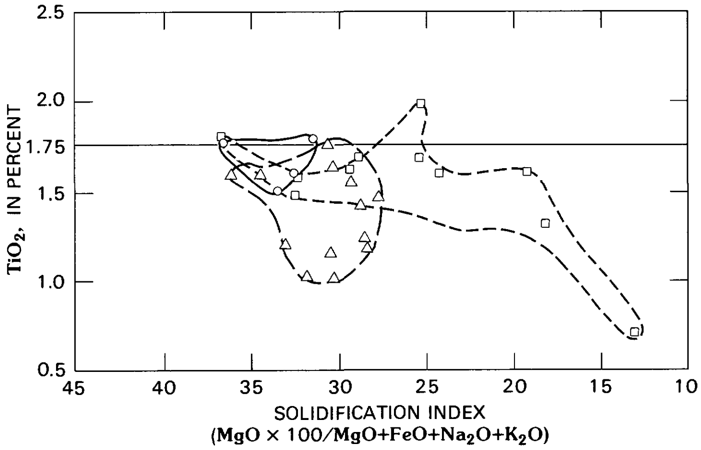


FIGURE A21.—Plot of titania-solidification index of 28 samples of volcanic rocks from the Ocate volcanic field.

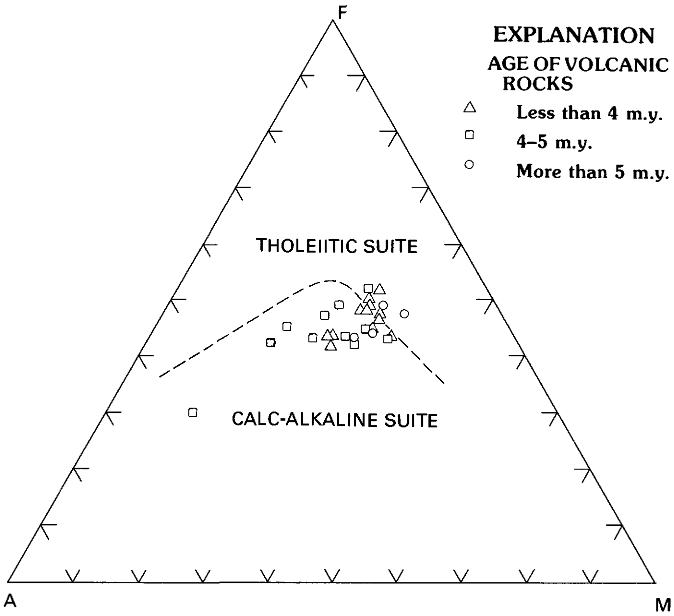


FIGURE A20.—AMF plot of 28 samples of volcanic rocks from the Ocate volcanic field. Dashed line separates tholeiitic suite from calc-alkaline suite.

(2) Intermediate lavas were derived from basaltic magma differentiated by mechanisms of crystal fractionation and crustal assimilation.
(3) Andesitic lavas were derived mainly by crystal fractionation and crustal assimilation.

BASALTIC VOLCANISM IN AND ADJACENT TO THE RIO GRANDE DEPRESSION

The Rio Grande depression or rift is a Neogene tectonic feature of extensional faulting that trends north from a poorly defined region of merger with the Basin and Range Province in southern New Mexico, incorporating at least five distinct tectonic basins arranged en echelon (Kelly, 1952). The graben-like character of the depression disappears north of the Arkansas Valley graben in central Colorado, but young faults are present northward along this trend to near the Wyoming border (Tweto, 1978).

Basaltic volcanic rocks erupted during the tectonic development of the depression are present within the rift and along its margins. The southern part of the San Luis Basin contains numerous volcanic vents and is filled with the predominantly tholeiitic Servilleta Basalt that ranges in age from 4.35 to 2.43 m.y. (Ozima and others, 1967); the massive Jemez volcanic field is associated with basalt flows, necks, and north-trending dikes that range in age from 10.4 m.y. (Luedke and Smith, 1978) to 1.96 m.y. (Manley, 1976); and small cones, fissure eruptions, and flows dated between 1.3 m.y. (Bachman and others, 1975) and 0.14 m.y. (Kudo, 1976) are present in the vicinity of Albuquerque. West of the Rio Grande depression, contemporaneous basaltic rocks were expelled in the Zuni Mountains and in the Mt. Taylor region of the Colorado Plateau (Luedke and Smith, 1978). Major eruptions also occurred east of the depression in the vicinity of Ocate and near Raton in northeastern New Mexico.

Two general petrogenetic schemes, based on depth of origin and subsequent crystallization paths, have been used to interpret the genesis of some of the volcanic rocks in the Rio Grande depression west of Ocate. Tholeiitic basalts in the depression near Taos are interpreted to have been derived from the partial melting at depths near 30 km or less of an upwelling of mantle material beneath the depression (Lipman, 1969). Tholeiitic basalts to the south also have been interpreted to have originated by partial melting of mantle material at shallow depths, but alkali olivine basalts are interpreted to have originated at greater depths (Baldridge, 1979). The depth of generation of basaltic magma in the Ocate area, if constrained by a postulated 45–55 km thickness of the crust beneath the southern Rocky Mountains (Jackson and Pakiser, 1965) should have originated at depths greater than 50 km. However, the titania content of these rocks, which has been used to indirectly estimate depth of generation of basaltic magma (for example, see Renault, 1970), suggests partial melting of mantle material at somewhat shallower depths. MacGregor (1969) has shown experimentally that the titania in volcanic rocks increases directly with increasing pressure of partial melting of basalt up to 20 kb (75 km depth). Chayes and Velde (1965) used titania content to discriminate between oceanic island and circumoceanic basalts; titania values greater than 1.75 percent are characteristic of the compositionally variable oceanic island basalts; conversely, values less than this amount are characteristic of the typically subalkaline circumoceanic varieties (Chayes, 1964). These combined data suggest that basalts with titania contents less than about 1.75 percent are typically subalkaline, have circumoceanic affinities, and were derived from magma reservoirs formed at shallow depths.

The titania content of the Ocate volcanic rocks is, on the average, less than 1.75 percent, slightly greater than the values measured from tholeiitic basalts in the Rio Grande depression near Taos (Lipman, 1969) and similar to the values measured from subalkaline and alkaline basalts present in the central part of the Rio Grande depression (fig. A22). In contrast, titania contents of basalts older than 0.5 m.y. and erupted from beneath the thick crust beneath the Colorado Plateau west of the depression are greater than 1.75 percent and attain values greater than 3 percent.

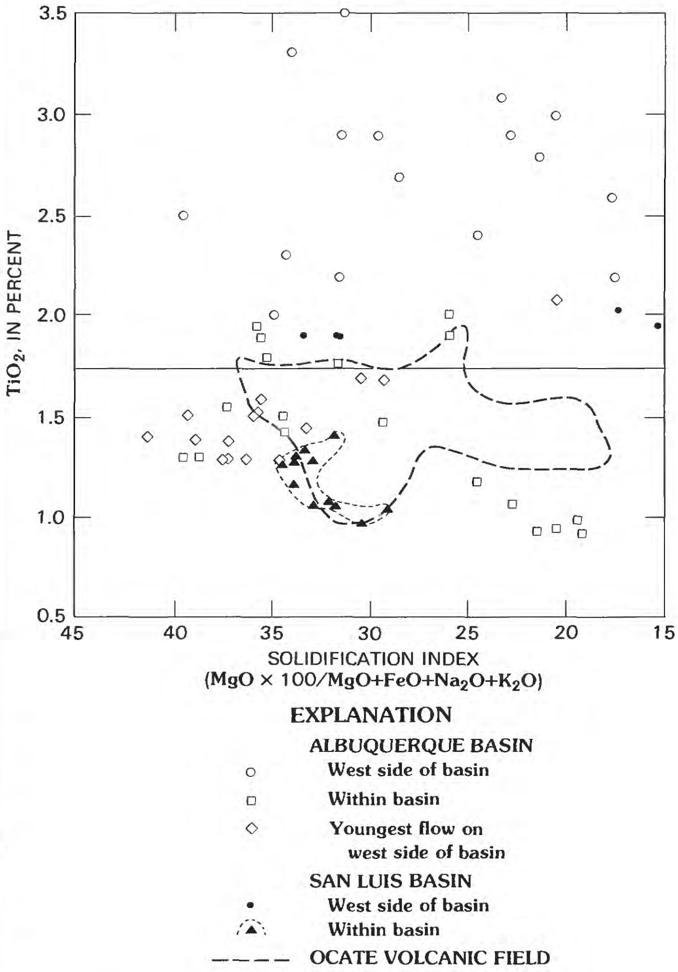


FIGURE A22.—Comparison of titania-solidification index between basaltic rocks from the Rio Grande depression of north-central New Mexico and rocks from the Ocate volcanic field. Sources of data: Ocate area—Aoki and Kudo (1976), Lipman and Mehnert (1975), and this report; San Luis Basin—Lipman and Mehnert (1975) and Ozima and others (1971); San Juan and Tusas Mountains—Lipman and Mehnert (1975); Mt. Taylor area—Lipman and Moench (1972); Zuni Mountains—Aoki and Kudo (1976) and Laughlin and others (1972); and Albuquerque-Belen Basin—Aoki and Kudo (1976), Kelley and Kudo (1978), and Bachman (U.S. Geological Survey, unpub. data).

The generalized petrogenetic scheme based on experimental studies of basaltic systems suggest that the hypersthene-normative, high-alumina, and low-titania basalts of the Ocate area were generated at depths similar to those of the basalts in the Rio Grande depression: that is, at depths less than the estimated crustal thickness beneath the southern Rocky Mountains. The compositional similarity of the basaltic rocks of the Ocate volcanic field to those in the Rio Grande depression (Aoki and Kudo, 1976; Baldridge, 1979) suggests that the genesis of all these rocks is closely related.

Late Cenozoic basalts, when viewed on a regional scale, are not symmetrically distributed about the Rio Grande depression. Rather, volcanism defines a broad northeast-trending zone extending from east-central Arizona to northeastern New Mexico. This zone has been called the Jemez Line (Mayo, 1958; Luedke and Smith, 1978). South of the intersection of this broad zone of volcanic rocks with the Rio Grande depression, volcanic rocks are similar in many respects to those of the Basin and Range Province and are best described as randomly distributed, limited in quantity, and alkaline (Leeman and Rogers, 1970). Only in the San Luis Basin are there large volumes of basalt present in the Rio Grande depression.

The Jemez Line, perhaps more than the Rio Grande depression, exerts major control over basaltic volcanism in New Mexico (fig. A23). The intersection of the depression and the Jemez Line appears to control the composition of basalts erupted in this region. Predominantly subalkaline, tholeiitic basalts are present in the southern San Luis Basin where the Jemez Line and the depression intersect (fig. A23). Both alkaline and subalkaline basalts are present at some distances from this intersection. To the northeast in the Great Plains

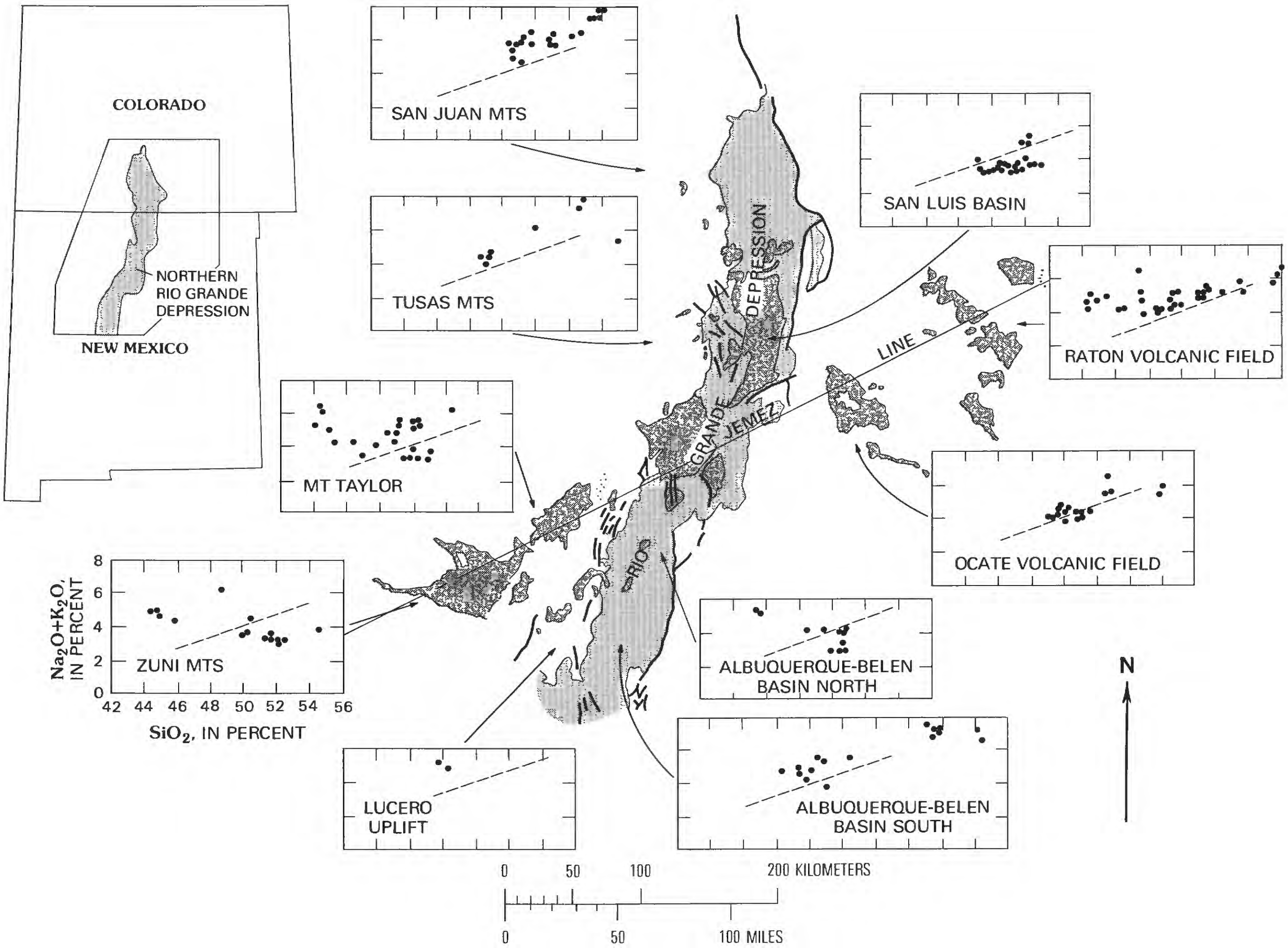


FIGURE A23.—Alkali-silica variation diagrams of basaltic rocks from volcanic fields in and adjacent to the Rio Grande depression of north-central New Mexico. Sources of data: Raton area—Stormer (1972); Ocate area—Aoki and Kudo (1976), Lipman and Mehnert (1975), and this report; San Luis Basin—Lipman and Mehnert (1975) and Ozima and others (1971); San Juan and Tusas Mountains—Lipman and Mehnert (1975); Mt. Taylor area—Lipman and Moench (1972); Zuni Mountains—Aoki and Kudo (1976), and Laughlin and others (1972); and Albuquerque-Belen Basin—Aoki and Kudo (1976), Kelley and Kudo (1978), and Bachman (U.S. Geological Survey, unpub. data). Late Cenozoic volcanic fields are patterned. Heavy lines are faults. Dashed lines in plots show division between alkaline rocks (above line) and subalkaline rocks (below line).

Province, alkaline basalts and their nephelenite and basanite differentiates are present in the Raton area; at Ocate, nearer the depression, the rocks are transitional in composition between alkaline and subalkaline. Northwest of the intersection, young basalts in the Tusas Mountains are alkaline; west of the intersection and along the line in Mt. Taylor and the Zuni Mountains, both subalkaline and alkaline basalts are present. South of the lineament are the alkaline basalts of the Lucero uplift. Directly south of the intersection in the Albuquerque-Belen Basin, both subalkaline and alkaline basalts are present; basalts in the southern part of the basin are predominantly alkaline.

The regional distribution of alkaline and subalkaline basalts suggests that subalkaline basalts were erupted only in areas at or adjacent to the intersection of the Rio Grande depression and the Jemez Line. Away from this intersection, predominantly alkaline volcanic rocks are present. The composition of the basaltic rocks of the Ocate volcanic field may have been in part controlled by the partial melting of mantle material at unusually shallow depths, apparently accommodated by the intersection of these two tectonic features.

REFERENCES CITED

Aoki, Ken-Ichiro, and Kudo, A.M., 1976, Major element variations of late Cenozoic basalts of New Mexico: New Mexico Geological Society, Special Publication no. 5, p. 82–88.

Bachman, G.O., 1953, Geology of a part of northwestern Mora County, New Mexico: U.S. Geological Survey Oil and Gas Investigations Map OM–137.

Bachman, G.O., Marvin, R.F., Mehnert, H.H., and Merrit, V., 1975, K-Ar ages of the basalt flows at Los Lunas and Albuquerque, central New Mexico: Isochron/West, no. 13, p. 3–4.

Baldridge, W.S., 1979, Petrology and petrogenesis of Plio-Pleistocene basaltic rocks from the central Rio Grande rift, New Mexico, and their relation to rift structure: *in* R.E. Reicker, ed., Rio Grande rift, tectonics and magmatism: American Geophysical Union, p. 323–353.

Baltz, E.H., and O'Neill, J.M., 1980, Preliminary geologic map of the Sapello River area, Sangre de Cristo Mountains, Mora and San Miguel Counties, New Mexico: U.S. Geological Survey Open-File Report 80–389, 22 p.

______1984, Geologic map of the Mora River area, Sangre de Cristo Mountains, Mora County, New Mexico: U.S. Geological Survey Miscellaneous Investigations Map I–1456, scale 1:24,000.

Chayes, Felix, 1964, A petrographic distinction between Cenozoic volcanics in and around the open oceans: Journal of Geophysical Research, v. 69, no. 8, p. 1573–1586.

Chayes, Felix, and Velde, D., 1965, On distinguishing basaltic lavas of circumoceanic and oceanic-island type by means of discriminant functions: Americal Journal of Science, v. 263, p. 206–222.

Dane, C.H., and Bachman, G.O., 1965, Geologic map of New Mexico: U.S. Geological Survey, scale 1:500,000.

Darton, N.H., 1928, Geologic map of New Mexico: U.S. Geological Survey, scale 1:500,000.

Hussey, K.M., 1971, A K–Ar date on the Rocky Mountain pediment sequence, north-central New Mexico: Isochron/West, no. 2, p. 45.

Irvine, T.N., and Baragar, R.A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Journal of Earth Science, v. 8, p. 523–545.

Jackson, W.H., and Pakiser, L.C., 1965, Seismic study of crustal structure in the southern Rocky Mountains, *in* Geological Survey Research 1965: U.S. Geological Survey Professional Paper 525–D, p. D85–D92.

Johnson, R.B., 1974, Geologic map of the Fort Union quadrangle, Mora County, New Mexico: U.S. Geological Survey Geologic Quadrangle Map GQ–1164, scale 1:24,000.

______1975, Geologic map of the Rainsville quadrangle, Mora County, New Mexico: U.S. Geological Survey Geologic Quadrangle Map GQ–1276, scale 1:24,000.

Kelley, V.C., 1952, Tectonics of the Rio Grande depression of central New Mexico: New Mexico Geological Society Guidebook, 3rd Field Conference, Rio Grande Country, central New Mexico, p. 93–105.

Kelley, V.C., and Kudo, A.M., 1978, Volcanoes and related basalts of Albuquerque basin: New Mexico Bureau of Mines and Mineral Resources Circular 156, 29 p.

Kudo, A.M., 1976, Volcanism within the Rio Grande rift: Geological Society of America Abstracts with Programs, v. 8, no. 5, p. 597.

Kuno, H., 1967, Volcanological and petrological evidences regarding the nature of the upper mantle, *in* T.F. Gaskill, ed., The Earth's mantle: Academic Press, p. 89–110.

Laughlin, A.W., Brookins, D.G., and Causey, J.D., 1972, Late Cenozoic basalts from the Bandera lava field, Valencia County, New Mexico: Geological Society of America Bulletin, v. 83, no. 5, p. 1543–1551.

Leeman, W.P., and Rogers, J.J.W., 1970, Late Cenozoic alkali-olivine basalts of the Basin-Range Province, USA: Contributions to Mineralogy and Petrology, v. 25, no. 1, p. 1–24.

Lipman, P.W., 1969, Alkalic and tholeiitic basaltic volcanism related to the Rio Grande depression, southern Colorado and northern New Mexico: Geological Society of America Bulletin, v. 80, no. 7, p. 1343–1353.

Lipman, P.W., and Mehnert, H.H., 1975, Late Cenozoic basaltic volcanism and development of the Rio Grande Depression in the southern Rocky Mountains: Geological Society of America Memoir, no. 144, p. 119–154.

Lipman, P.W., and Moench, R.H., 1972, Basalts of the Mount Taylor volcanic field, New Mexico: Geological Society of America Bulletin, v. 83, no. 5, p. 1335–1343.

Luedke, R.G., and Smith, R.L., 1978, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Arizona and New Mexico: U.S. Geological Survey Miscellaneous Investigations Map I–1091–A, scale 1:1,000,000.

MacDonald, G.A., and Katsura, T., 1964, Chemical composition of Hawaiian lavas: Journal of Petrology, v. 5, pt. 1, p. 82–133.

MacGregor, I.D., 1969, The system MgO-SiO_2-TiO_2 and its bearing on the distribution of TiO_2 in basalts: Americal Journal of Science, v. 267–A, p. 342–363.

Manley, Kim, 1976, K-Ar age determinations on Pliocene basalts from the Española Basin, New Mexico: Isochron/West, no. 16, p. 29–30.

Mayo, E.B., 1958, Lineament tectonics and some ore districts of the Southwest: Mining Engineering, v. 10, no. 11, p. 1169–1175.

Mercer, J.W., and Lapalla, E.G., 1970, A geophysical study of alluvial valleys in western Mora County, New Mexico: U.S. Geological Survey Open-File Report, 69 p.

Nielsen, R.L., and Dungan, M.A., 1985, The petrology and geochemistry of the Ocate volcanic field, north-central New Mexico: Geological Society of America Bulletin, v. 96, no. 3, p. 296–312.

Nockolds, S.R., 1954, Average chemical compositions of some igneous rocks: Geological Society of America Bulletin, v. 65, p. 1007–1032.

Ozima, M., Kono, M., Kaneoka, I., Kinoshita, H., Kobayashi, K., Nagata, T., Larson, E.E., and Strangway, D.W., 1967, Paleomagnetism and potassium-argon ages of some volcanic rocks from the Rio Grande gorge, New Mexico: Journal of Geophysical Research, v. 72, no. 10, p. 2615–2621.

Petersen, J.W., 1969, Geology of the Tienditas Creek-La Junta Canyon area, Taos and Colfax Counties, New Mexico: University of New Mexico M.S. thesis, 79 p.

Ray, L.L., and Smith, J.F., 1941, Geology of the Moreno Valley, New Mexico: Geological Society of America Bulletin, v. 52, no. 2, p. 177–210.

Renault, J., 1970, Major-element variations in the Portrillo, Carrizozo, and McCartys basalt fields, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 113, 22 p.

Robinson, G.D., Wanek, A.A., Hays, W.H., and McCallum, M.E., 1964, Philmont Country: The rocks and landscape of a famous New Mexico ranch: U.S. Geological Survey Professional Paper 505, 152 p.

Schowalter, T.T., 1969, Geology of part of the Creston Range, Mora County, New Mexico: University of New Mexico M.S. thesis, 84 p.

Shapiro, Leonard, 1975, Rapid analysis of silica, carbonate, and phosphate rocks: U.S. Geological Survey Bulletin 1401, 76 p.

Simms, R.W., 1965, Geology of the Rayado area, Colfax County, New Mexico: University of New Mexico M.S. thesis, 90 p.

Smith, J.F., and Ray, L.L., 1943, Geology of the Cimarron Range, New Mexico: Geological Society of America Bulletin, v. 54, no. 7, p. 891–924.

Stevenson, J.J., 1881, Report upon geological examinations in southern Colorado and northern New Mexico during the years 1878 and 1879: U.S. Geographical Surveys West of the 100th Meridian (Wheeler), 3rd Supplement, 420 p.

Stormer, J.C., 1972, Ages and nature of volcanic activity on the southern High Plains, New Mexico and Colorado: Geological Society of America Bulletin, v. 83. no. 2, p. 2443–2448.

Tweto, Ogden, 1978, Northern rift guide 1, Denver-Alamosa, Colorado, *in* Guidebook to the Rio Grande Rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, p. 13–22.

Yoder, H.S., Jr., and Tilley, C.E., 1962, Origin of basalt magmas—An experimental study of natural and synthetic rock systems: Journal of Petrology, v. 3, pt. 3, p. 342–532.

Late Cenozoic Physiographic Evolution of the Ocate Volcanic Field

By J. MICHAEL O'NEILL

PETROLOGY AND PHYSIOGRAPHIC EVOLUTION OF THE OCATE VOLCANIC FIELD, NORTH-CENTRAL NEW MEXICO

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1478-B

Physiographic development of the southeastern part of the Sangre de Cristo Mountains and the adjacent high plains

CONTENTS

ILLUSTRATIONS

TABLES

LATE CENOZOIC PHYSIOGRAPHIC EVOLUTION OF THE OCATE VOLCANIC FIELD

By J. MICHAEL O'NEILL

ABSTRACT

The Ocate volcanic field lies at the transition between the Southern Rocky Mountain and the Great Plains physiographic provinces in north-central New Mexico. The field consists of numerous basaltic to dacitic flows ranging in age from late Miocene to Pleistocene. The oldest flows, 8.3–5.7 m.y. old, are underlain by stream gravels and appear to rest on a single surface or a series of nearly equivalent surfaces cut into the interior of the Sangre de Cristo Mountains at elevations near 3,000 m (10,000 ft). Numerous accordant ridgetops, subsummits, and parks in the adjacent Taos and Cimarron Ranges also are at elevations near 3,000 m (10,000 ft), which suggests that this surface was widespread during late Miocene time. This surface cuts across major Laramide structures and the various lithologies of the mountain interior; it extends eastward onto the Great Plains. The early volcanism was followed by episodic uplift and erosion now marked by three lower erosion surfaces. These surfaces are also preserved beneath volcanic rocks which are, respectively, 4.8–4.1 m.y., 3.3–3.1 m.y., and 2.2 m.y. old. Thus, the oldest flows cap the highest mesas; younger flows cap successively lower mesas. Of the four erosion surfaces, the two oldest are warped and locally faulted across the older Laramide fault zones, which indicates that late Cenozoic uplift of the region involved differential movement between the Rocky Mountains and the Great Plains. Young basalts (1.4 m.y. old) followed major stream valleys and are now nearly 125 m (400 ft) above the present stream levels. The youngest basalts (0.8 m.y. old) were deposited mainly on older flows.

PREVIOUS WORK

Darton (1928) was the first to completely outline the distribution of volcanic rocks in the Ocate field. Detailed geologic mapping around Ocate by Bachman (1953) refined the areal extent of the field. Parts of this area have been mapped and described by Smith and Ray (1943) and Robinson and others (1964) at the south end of the Cimarron Range, by Simms (1965) south of Rayado, by Schowalter (1969) in the Lucero area, by Ray and Smith (1941) and Petersen (1969) in and near the Moreno Valley, and by Johnson (1974, 1975) in the Rainsville and Fort Union areas (pl. 1). Radiometric age data have been reported by Stormer (1972), Hussey (1971), P. W. Lipman (written commun., 1978), and O'Neill and Mehnert (chapter A of this report). Geochemical analyses of samples collected along a northwest-southeast highway traverse across the volcanic field were published by Aoki and Kudo (1975). The physiography of the eastern part of the Sangre de Cristo Mountains has been described by Lee (1921), Fenneman (1931), Ray and Smith (1941), Smith and Ray (1943), and Levings (1951), but none have dealt directly with the Ocate area. This report is based on reconnaissance mapping of the volcanic rocks in the Ocate area by J. M. O'Neill during the summer of 1978.

INTRODUCTION

The Ocate volcanic field appears to cross the transition zone between the Southern Rocky Mountain and the Great Plains physiographic provinces (Fenneman, 1931). The structural boundary between the provinces is not clearly defined in north-central New Mexico. The boundary is here interpreted to follow the eastern edge of the Cimarron block which underlies the western part of the Ocate volcanic field (fig. B1). This differs from the boundaries proposed in earlier descriptions of the two physiographic provinces.

Lee (1921) drew the boundary between the two provinces in this area on structural grounds, along the Cretaceous hogbacks on the west side of the Raton Basin (fig. B1). Accordingly, the mountainous Raton Basin constitutes the highest, most severely dissected part of the Great Plains province, comprising lower Tertiary strata, gently inclined to the east, that rise to more than 3,000 m (10,000 ft) in elevation before the Cretaceous hogbacks are reached.

Fenneman (1931) continued this boundary between the provinces directly southward to the Moreno Valley; from the Moreno Valley he extended the boundary due south toward Las Vegas, N. Mex., along hogbacks formed in part by the Permian Glorieta Sandstone (figs. B1, B2). Smith and Ray (1943, p. 912–913) placed this boundary east of the Moreno Valley along the east side of the southeast-trending Cimarron Range, and suggested that the boundary then swing sharply southwestward to Coyote Creek (fig. B2).

Laramide structures in this area suggest instead that this boundary extends directly south from the east side of the Cimarron Range. In the Sangre de Cristo Mountains, Laramide-age structures consist of a series of west-tilted, north-trending basement blocks bounded on the east and west by high-angle reverse faults. From Las Vegas northward, the major frontal faults are marked by hogbacks that bound the east side of the Sangre de Cristo uplift and trend north towards the Moreno Valley (fig. B1); however, in the vicinity of La Cueva, this zone bifurcates. The main fault continues north to the Moreno Valley, whereas the second branch is marked by a gentle, northeast-trending monoclinal flexure. These two features enclose another gently west-tilted block lying on the east side of the Las Vegas-Moreno Valley fault zone. The southeast margin of this block is marked by gently to moderately upturned Paleozoic and Mesozoic sedimentary rocks. The margin thus defined trends north-northeast, is locally covered by the Ocate volcanic field, and takes on the character of a major fault where it merges with the high-angle faults that mark the eastern boundary of the Cimarron Range. This monoclinal flexure and the east fault boundary of the Cimarron Range represent a continuous lineament and define a natural structural unit, the Cimarron block. Ray and Smith (1941) restricted the name Cimarron block to the northern part of this uplift, where it is composed entirely of Precambrian igneous and metamorphic rocks; these rocks are separated from the southern, less strongly uplifted part, by a major northwest-trending high-angle fault.

The Cimarron block, defined here as a segmented but continuous structural entity, is crescent shaped, convex eastward, and widest in the central part, pinching out north and south where its frontal faults merge with the major frontal faults of the Sangre de Cristo Mountains proper (fig. B1). The Cimarron block is herein interpreted to belong to the Southern Rocky Mountain physiographic province. The western part of the Ocate volcanic field lies within the southern part of the Cimarron block; the western margin of the block roughly defines the westernmost extent of the volcanic field. The volcanic field crosses the eastern margin of the block and extends onto the Great Plains.

PHYSIOGRAPHIC EVOLUTION

The Ocate volcanic field consists of numerous basalt flows that cap the many mesas in the vicinity of Ocate. These flows cover three broad physiographic surfaces (figs. B3, B4) and several smaller buttes and mesas that range in elevation from more than 3,000 m (10,000 ft) in the Sangre de Cristo Mountains to less than 1,800 m (5,900 ft) on the Great Plains. The oldest flows erupted 8.3 to 5.7 m.y. ago (table B1) and cap the highest of the three broad surfaces. Flows of intermediate age (4.8 to 4.1 m.y.) cap the middle surface. Still younger flows, 3.3 m.y. old, cap the lowest of the three surfaces. Small flows, 2.2 m.y. old, cap the lowest mesas in the Ocate volcanic field. The youngest flows (1.4 and 0.8 m.y. old) cover surfaces at various elevations that have since been little eroded. For the purpose of this discussion, the flows are grouped by age (older than 5.0 m.y., 4.0 to 5.0 m.y., and younger than 4.0 m.y.) and are discussed by their corresponding surface—high, intermediate, and low, the highest surface having the oldest flows. The youngest age group includes flows on the lowest broad physiographic surface as well as still younger flows on smaller mesas and buttes. Some of the youngest flows, however, erupted at higher elevations and covered basalts of the older age groups.

HIGH-LEVEL SURFACES AND THEIR VOLCANIC CAPROCK

Basalts older than 5.0 m.y. cover the highest gravel-covered surfaces in the Ocate volcanic field (shown as Tv3 on pl. 1). The oldest basalts, dated at 8.3 m.y., cover about half of Sierra Montuosa Mesa in the northwestern part of the field (fig. B5).

Basalts dated between 5 and 6 m.y. erupted from widely separated vents. Near Wagon Mound, basal flows at Las Mesas del Conjelon (pl. 1; fig. B5) have been dated at 5.9 m.y. High flows along the west side of the field and at the present drainage divide of the Sangre de Cristo Mountains in the Cerro Vista quadrangle have been dated at 5.7 m.y.

Sierra Montuosa Mesa.—Sierra Montuosa Mesa is an elongate, northwest-trending mesa capped by basalt, reaching an elevation of 3,136 m (10,290 ft). The mesa stands above the slightly lower Ocate Mesa that is formed by the largely flat lying Permian Glorieta Sandstone (pl. 1). The base of the flows along the southwest side of Sierra Montuosa Mesa is about 100 m (300 ft) higher than on the northeast side, which suggests that the flows occupy, in part, a gentle depression. Well-rounded stream pebbles, cobbles, and boulders are exposed at the base of the flows along the southwest side of the mesa.

La Grulla Ridge.—High basalts east of Agua Fria Peak cap the 3,000 m (10,000 ft) high La Grulla Ridge

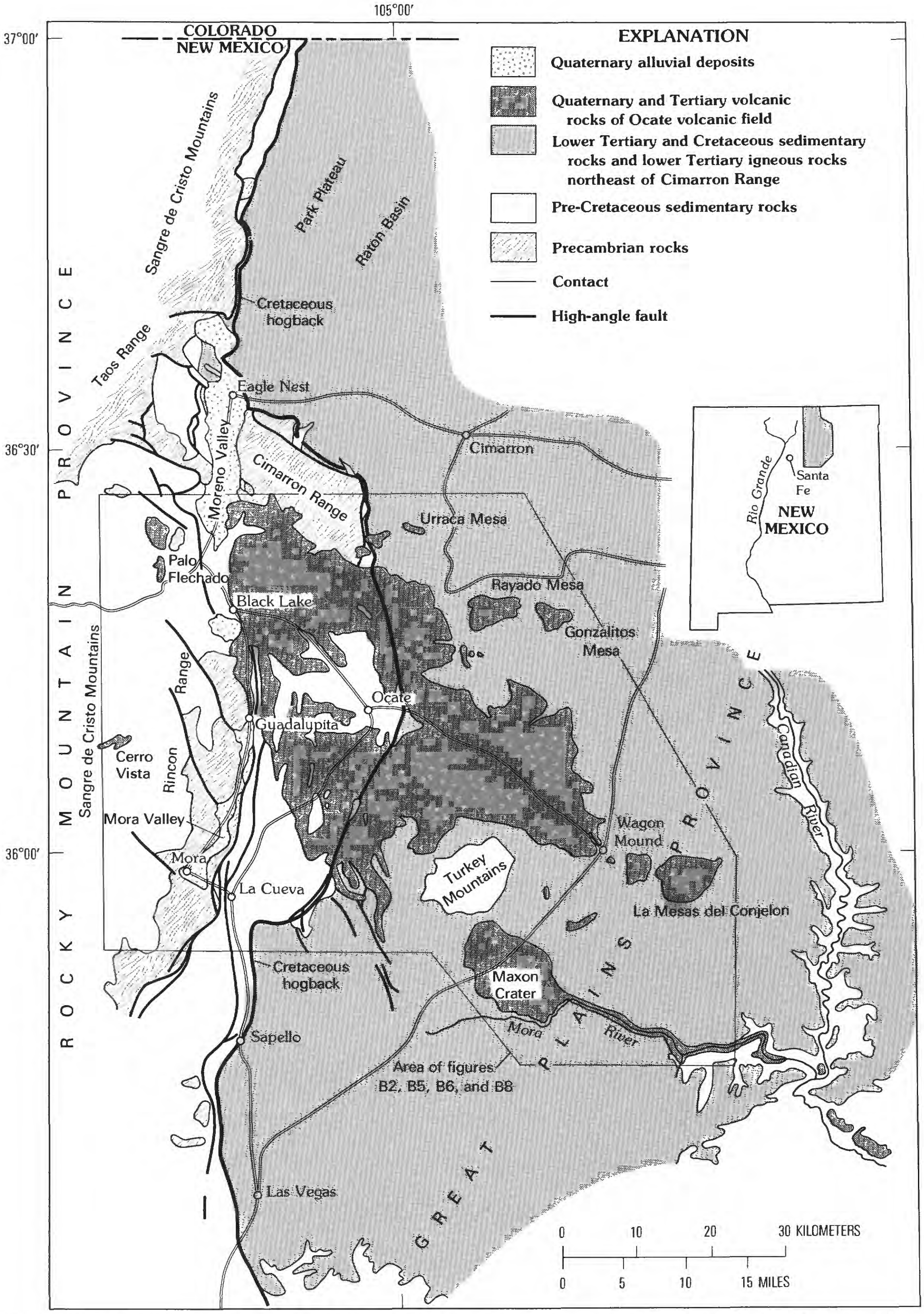


FIGURE B1.—Generalized geologic map of the Ocate volcanic field (Quaternary and Tertiary volcanic rocks) and vicinity, N. Mex. (modified from Dane and Bachman, 1965). Area shown in block diagrams (figs. B2, B5, B6, and B8) indicated by dashed line.

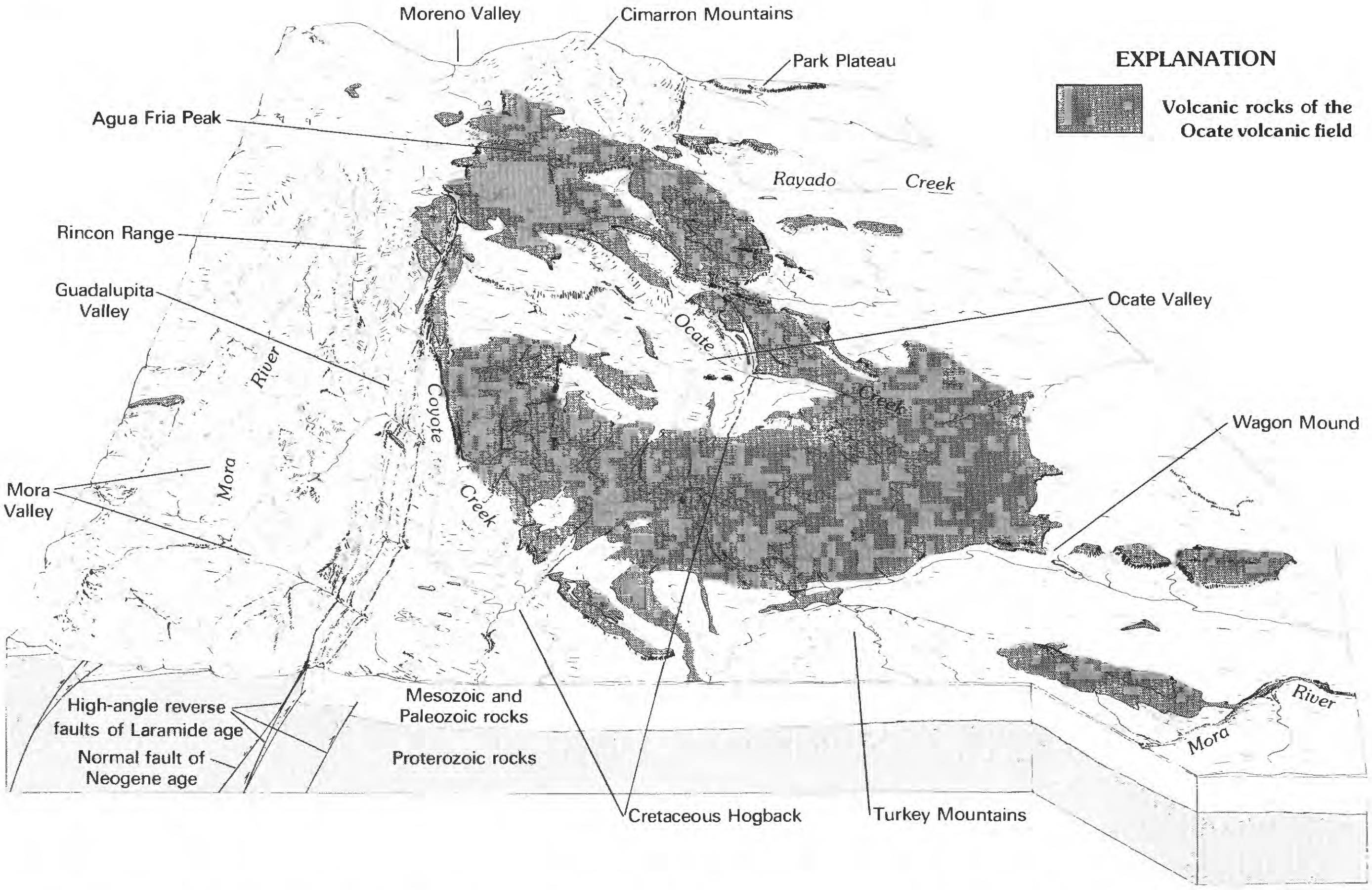


FIGURE B2.—Block diagram of the Ocate volcanic field showing major geographical features. Area shown in diagram is indicated on figure B1. View is to north.

(pl. 1; fig. B5). The basalts overlie abundant, rounded pebbles of Precambrian granite, quartz-feldspar-muscovite gneiss, and pegmatite that are well exposed on the southeast. The underlying sedimentary rocks and gravels are not exposed along the northwest side of the ridge where younger basalt flows have covered this contact. The base of the basalts is about the same elevation as those on the northeast side of Sierra Montuosa Mesa. The similarity in elevation of the basalts on Sierra Montuosa Mesa and La Grulla Ridge suggests that the basalts are roughly equivalent in age. The source of the basalts on La Grulla Ridge is not known; however, because they lie at a slightly lower elevation than the basalts of Sierra Montuosa Mesa, they may represent the more distal parts of the same flow system.

Cerro Vista area.—Olivine basalts in the Cerro Vista area, dated at 5.7 m.y., consist of a northeast-trending flow-capped ridge about 3 km (2 mi) in length. The base of the basalts ranges in elevation from about 3,017 m (9,895 ft) at the divide to near 2,895 m (9,500 ft) at the southwesternmost exposure; maximum elevation of the basalts is 3,060 m (10,036 ft). The base of the basalts is higher southeast of the axial part of the exposure, which suggests that the flows occupy a southwesterly inclined paleovalley. The basalts were deposited on the Pennsylvanian Sandia Formation. Locally, pebbles and cobbles of well-rounded Precambrian igneous and metamorphic rocks underlie basalts present at this contact. These gravels are separated from the nearest Precambrian outcrops in the Rincon Range to the east by the Mora River valley (pl. 1). The present valley floor is nearly 600 m (1,950 ft) below the base of the basalts and the underlying gravels. The crest of the Rincon Range rises nearly 900 m (3,000 ft) above the valley floor.

Palo Flechado area.—Several basalt flows near Palo Flechado Pass (pl. 1; fig. B5), west of the Moreno Valley (Petersen, 1969), are described as thin local flows resting on lag gravels interpreted to represent the Miocene Carson Conglomerate (Just, 1937). The flows aggregate less

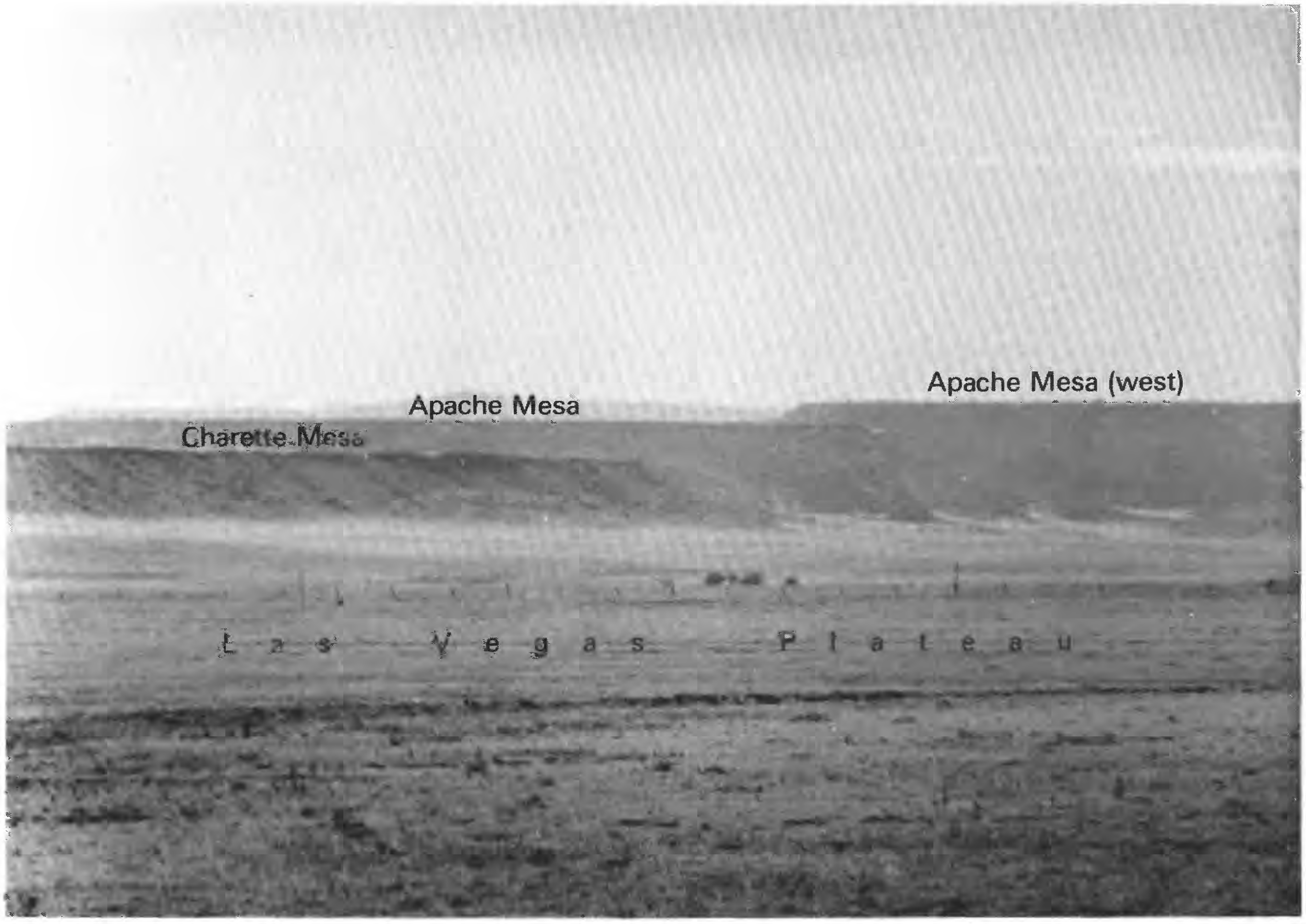


FIGURE B3.—Part of Ocate volcanic field in Great Plains province, north-central New Mexico. View to the southwest; snow-capped Sangre de Cristo Mountains in background. Four major physiographic levels are shown, from highest to lowest: Apache Mesa (west), Apache Mesa, Charette Mesa, and Las Vegas Plateau.

than 15 m (50 ft) in thickness. Their geomorphic expression is similar to that of the 5.7–m.y.-old basalts located in the Cerro Vista quadrangle to the south.

Apache Mesa (west), Encinosa Mesa, and Black Mesa.—Three basalt-capped mesas lie on a surface which is 60 m (200 ft) above the widespread surface on which the 4- to 5-m.y.-old flows lie (pl. 1); therefore, these mesa basalts are interpreted to be older than 5 m.y. Apache Mesa (west) is northeast of the town of Ocate, and Encinosa and Black Mesas are to the south of the town of Ocate (fig. B5). The source for these older basalts is not known. All flows are sinuous in plan and trend northwest; the surface on which they flowed dips gently southeast. At least one flow, Apache Mesa (west), is underlain by a thin veneer of gravel composed mainly of Precambrian pebbles and cobbles. Although these flows are widely separated, they all lie close to the eastern margin of the Laramide-age Cimarron block (fig. B1). These basalts appear to be about the same age and are older than the 4- to 5-m.y.-old volcanic sequence. They were derived from individual centers probably located near the east edge of the Cimarron block, and they may have been confined to broad, southeasterly inclined stream valleys.

Las Mesas del Conjelon.—Olivine basalts near Wagon Mound cap a series of east-west trending buttes and mesas, collectively called Las Mesas del Conjelon. They consist of volcanic necks and basalt-capped mesas (pl. 1; fig. B2). Santa Clara Mesa and the Wagon Mound are two highly dissected volcanic necks west of the main sequence of basalts that cap Las Mesas del Conjelon. These basalts lie on the Dakota Sandstone, Niobrara, Carlile, and Greenhorn Formations; the basalts are separated from the underlying sedimentary rocks by thin gravels composed principally of Precambrian cobbles and pebbles. The base of the basalts is

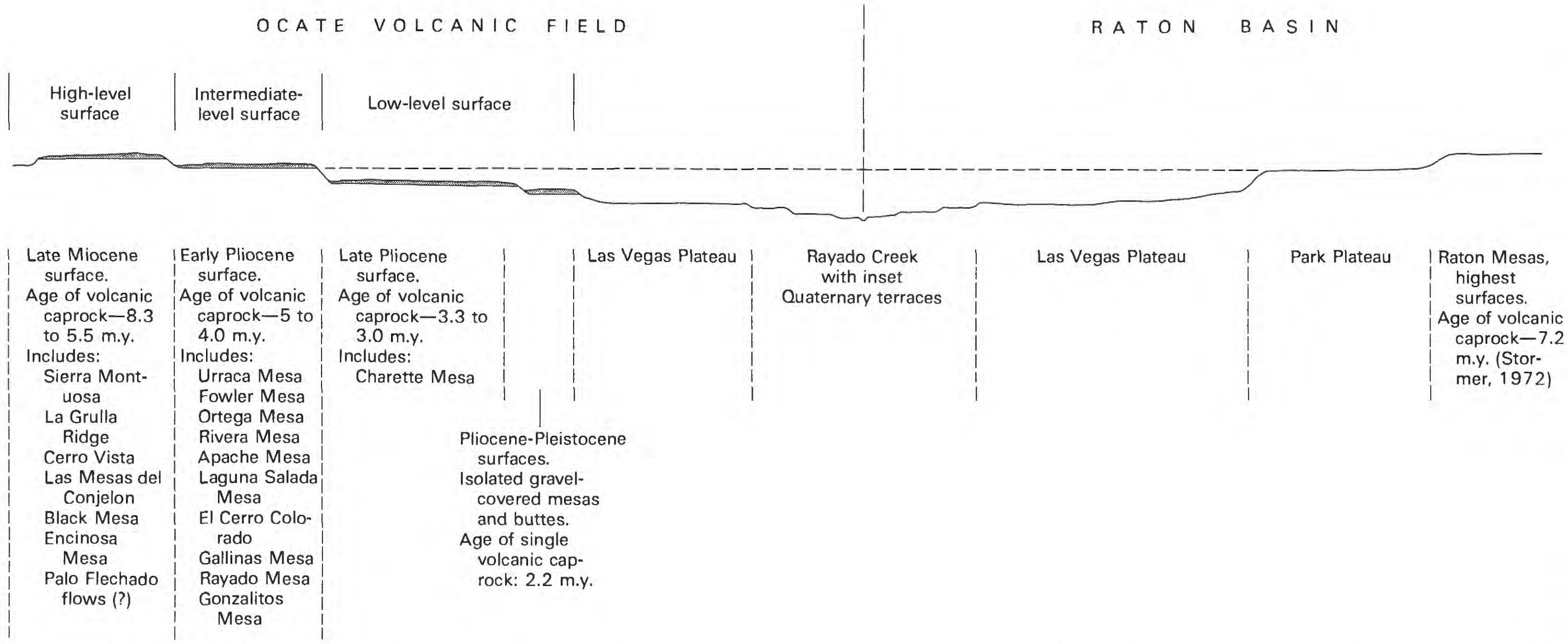


FIGURE B4.—Schematic topographic profile showing physiographic relations between various erosion surfaces and overlying basaltic rocks in the Ocate volcanic field and the Raton Basin. Dashed lines connect correlative surfaces.

TABLE B1.—*Late Cenozoic K-Ar ages of basaltic flows of the Ocate volcanic field*

[Source of age dates: Chapter A, table A1, except as noted]

Locality	Age (m.y.)
Lower-level flows	
Cerro del Oro	0.81±0.14
Maxon Crater[1]	1.37±0.15
Wagon Mound (lower mesa)[1]	2.20±0.17
Charette Mesa[1]	3.07±0.34
Charette Mesa[2]	3.3±0.3
White Peak	3.53±1.20
Intermediate-level flows	
Urraca Mesa[3]	4.3±0.1
Guadalupita Valley	3.83±0.46
Guadalupita Valley	4.53±0.18
El Cerro Colorado	4.12±0.24
La Mesa (south end)	4.19±0.25
Guadalupita Valley	4.32±0.44
Black Lake	4.97±0.23
Gonzalitos Mesa	4.52±0.34
Cerro Montoso	4.67±0.32
Coyote Cr.[2]	4.7±0.3
Upper-level flows	
Cerro Vista	5.74±0.34
Las Mesas del Conjelon[1]	5.94±0.40
Sierra Montuosa	8.34±0.50

[1]Samples collected by P.W. Lipman.
[2]Stormer (1972).
[3]Hussey (1971).

approximately 225 m (740 ft) above the lowlands to the south and about 100 m (330 ft) above the younger Charette Mesa flows to the northwest (pl. 1; fig. B5). The flows of Las Mesas del Conjelon were erupted from a series of vents and fissures that are aligned with or parallel to the east-trending line defined by the two dissected vents that lie to the west of the mesa (pl. 1). These flows probably did not extend far beyond their present limits. Thickness of the flows is variable: as much as 75 m (230 ft) thick near vents, decreasing to about 20 m (75 ft) at the present margins of the mesa.

Conclusions.—The nearly equivalent elevations—near 3,000 m (9,850 ft)—of the highest basalts at Sierra Montuosa, La Grulla, Cerro Vista, and perhaps the Palo Flechado area (fig. B5), and their underlying gravels, suggest that these basalts were erupted onto the same surface or a series of surfaces of nearly the same elevation. This surface extended across major topographic depressions of today, as the source of gravels underlying these basalts could only have been rocks exposed in the central parts of the Sangre de Cristo Mountains on the west. The numerous accordant ridge tops, subsummits and parks (Ray and Smith, 1941; Smith and Ray, 1943) in the adjacent Taos and Cimarron Ranges are probably remnants of this widespread surface.

The surface beneath the basalts on Las Mesas del Conjelon appears to be an eastward extension of the surface beneath the physiographically highest basalts to the west. The basalts of Encinosa Mesa, Black Mesa, and Apache Mesa (west) rest on a surface that is physiographically equivalent to and apparently approximately coeval with those segments to the east and west. The surface beneath Las Mesas del Conjelon rises 9.5 m/km (50.2 ft/mi) to Apache Mesa (west); the slope then increases to 32 m/km (169 ft/mi) to the base of the basalts capping Sierra Montuosa Mesa. The change in gradient occurs at the eastern margin of the Cimarron block.

This surface cuts across sandstone, shale, and sharp monoclinal folds, which suggests that late Miocene time was marked by major erosion and pediplanation without tectonic activity. This surface is probably coextensive with the widespread late Miocene erosion surface in the front ranges of Colorado and Wyoming (Scott, 1963, 1975; Knight, 1953; Moore, 1959). Moreover, this surface probably represents the upland erosional area from which sediment was supplied for the Miocene Ogallala Formation. The Ogallala Formation is believed to have been deposited during a period of major crustal stability that was characterized by pediplanation in the mountain interior and by thin, sheetlike deposition in the adjacent plains (Scott, 1975; Frye and Leonard, 1957, 1959).

INTERMEDIATE-LEVEL SURFACES AND THEIR VOLCANIC CAPROCK

Basalts and interlayered andesites and minor dacites of the second age group (4 to 5 m.y. old—shown as Tv2 on pl. 1) are most abundant in the northwestern part of the Ocate volcanic field (fig. B6). These rocks cap Urraca (4.3 m.y. old (Hussey, 1971)), Fowler, Rayado, and Gonzalitos (4.5 m.y. old) Mesas located east-southeast of the Cimarron Range and are the lowermost basalts of Ortega and Rivera Mesas northeast of Ocate. Rocks of this age group apparently constitute the majority of flows on and around Agua Fria Peak and interfinger with 4.5-m.y.-old volcanic rocks at Black Lakes. Flows erupted from the north end of La Mesa and from Cerro Montoso (4.7 m.y. old) flooded the southern part of La Mesa (4.2 m.y. old) and parts of Le Febres Mesa. The basalt-capped Gallinas Mesa, directly north of Ocate, is at equivalent elevation and distance above the present-day streams and is interpreted to belong to this period of volcanism. Basalts that are 4 to 5 m.y. old are present in Guadalupita Valley (4.3 m.y. old), to the north along Coyote Creek (4.7 m.y. old (Stormer, 1972)) and cap El Cerro Colorado (4.1 m.y. old) (pl. 1; figs. B2, B6).

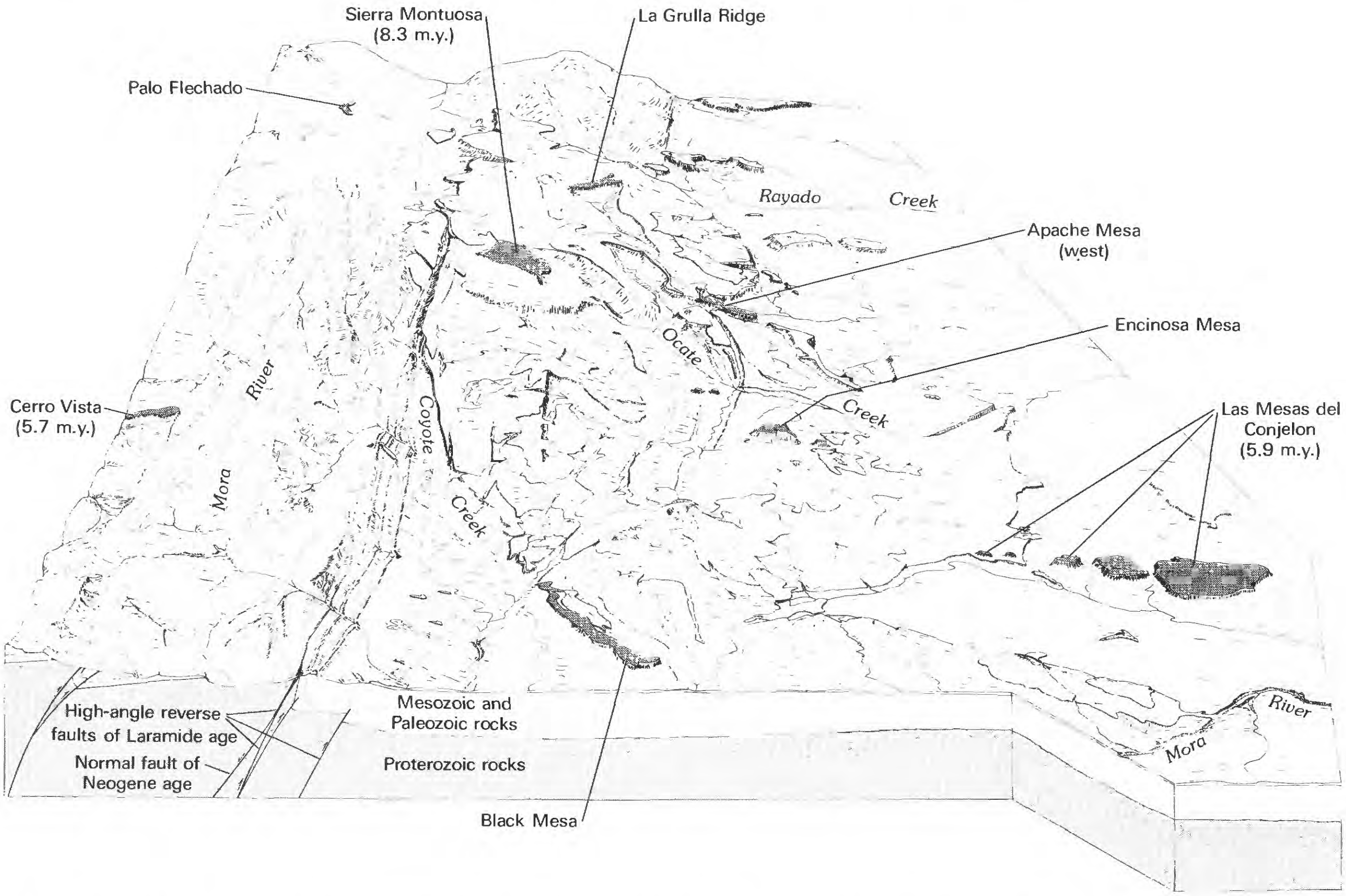


FIGURE B5.—Distribution of volcanic rocks in the Ocate volcanic field erupted prior to 5 m.y. ago (named and patterned areas). K–Ar dates given in parentheses.

Basalts in the northwestern part of the volcanic field (pl. 1; fig. B6) rest on a southeasterly inclined surface covered by gravels composed largely of Precambrian metamorphic and igneous rocks—an extension of the Urraca surface of Smith and Ray (1943). It is apparently a compound surface formed in the early Pliocene by lateral corrasion of the ancestral Rayado Creek. Smith and Ray defined the Urraca surface for the northeastern part of the Ocate volcanic field as including the erosion surface overlain by the basalts of Rayado, Gonzalitos, and Urraca Mesas, which are east of the frontal faults bounding the Cimarron Range (pl. 1; fig. B1), and including the more westerly Fowler, Ortega, and Rivera Mesas. Smith and Ray tentatively correlated this surface with the erosional surface of the Park Plateau to the north, a correlation that appears reasonable (fig. B4). Basalts from Urraca Mesa were dated at 4.3 m.y. (Hussey, 1971) and those from Gonzalitos Mesa at 4.5 m.y. (table B1). The Urraca surface formed at some time between 5.7 m.y. ago (the age of the youngest basalts that preserve beneath their cover the highest gravel-capped surfaces) and 4.3 m.y. ago (the age of the basalts on Urraca Mesa).

Figure B7 depicts the early Pliocene topography of the Urraca surface. The Park Plateau has a gentle southeast slope with a concave-upward profile; the slope is steepest near the Sangre de Cristo Mountains. To the south, around Ocate, the Urraca surface contains areas of variable slope, and profiles are locally both concave upward and downward. From the Moreno Valley on the west to La Grulla Ridge, the elevation of the Urraca surface decreases from nearly 3,000 m (9,800 ft) to about 2,850 m (9,350 ft). East of La Grulla Ridge, the surface and the base of the overlying basaltic rocks become more steeply inclined before again assuming a gentle southeast-dipping gradient to the east (figs. B2, B7). Contours in this area (fig. B7) suggest that streams locally dissected the surface east of La Grulla Ridge before it was covered by volcanic rocks. These contours define a surface that cuts evenly across highly resistant

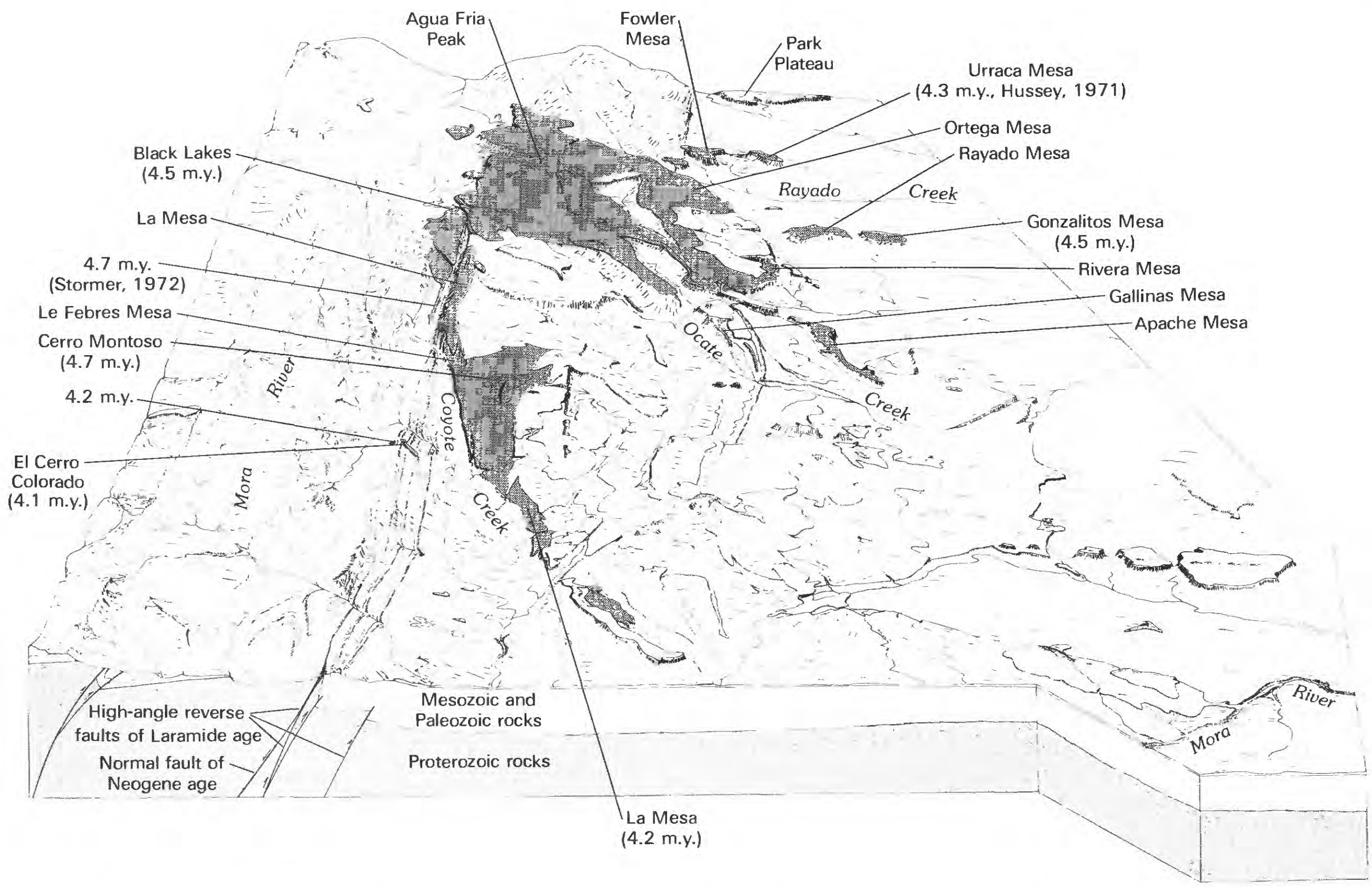


FIGURE B6.—Distribution of volcanic rocks in the Ocate volcanic field erupted between 4 and 5 m.y. ago (named and patterned areas). K-Ar dates in parentheses.

Permian Glorieta Sandstone as well as across easily eroded Pennsylvanian shales. The surface also truncates the zone of strongly upturned Paleozoic and Mesozoic sedimentary rocks that extends southward from the east side of the Cimarron Mountains. This zone defines the eastern margin of the Cimarron block.

The gentle east-west upward concavity of the Urraca surface, and its truncation of various lithologies and major structural zones, are characteristic of topographic planation by the lateral corrasive action of streams. The convex-upward profile of this surface east of La Grulla Ridge is opposite the concave-upward profile characteristic of pediment surfaces and cannot be considered to have been present when this surface was formed. The convex-upward aspect observed on the Urraca surface must represent warping of that surface. The warping probably represents differential uplift between the Sangre de Cristo Mountains, including the Cimarron block, and the Great Plains; this warping may have occurred before volcanism, as well as after.

Basalts erupted from the Agua Fria Peak area lie on the Urraca surface, and are continuous with the basalts in the Moreno Valley at Black Lake. But the Black Lake flows lie some 100 m (300 ft) below this surface. The youngest flows, which have not been dated, appear to have cascaded over an arcuate west-facing scarp held up by steeply dipping Paleozoic sedimentary rocks that now separates the two levels (fig. B2). The basalts on both levels appear to be essentially the same age; radiometric age data indicate that their lateral equivalents were erupted between 4.8 and 4.1 m.y. ago.

The ancestral Rayado Creek, a major drainage system in early Pliocene time, cut a large, east-southeast-trending plain on predominantly gently folded Glorieta Sandstone and older sandstone and shale prior to 4.8 m.y. ago. This drainage appears to have been captured by Coyote Creek, which followed the less resistant Laramide structural zone, parallel to the mountain front (fig. B2). The Laramide zone is marked by

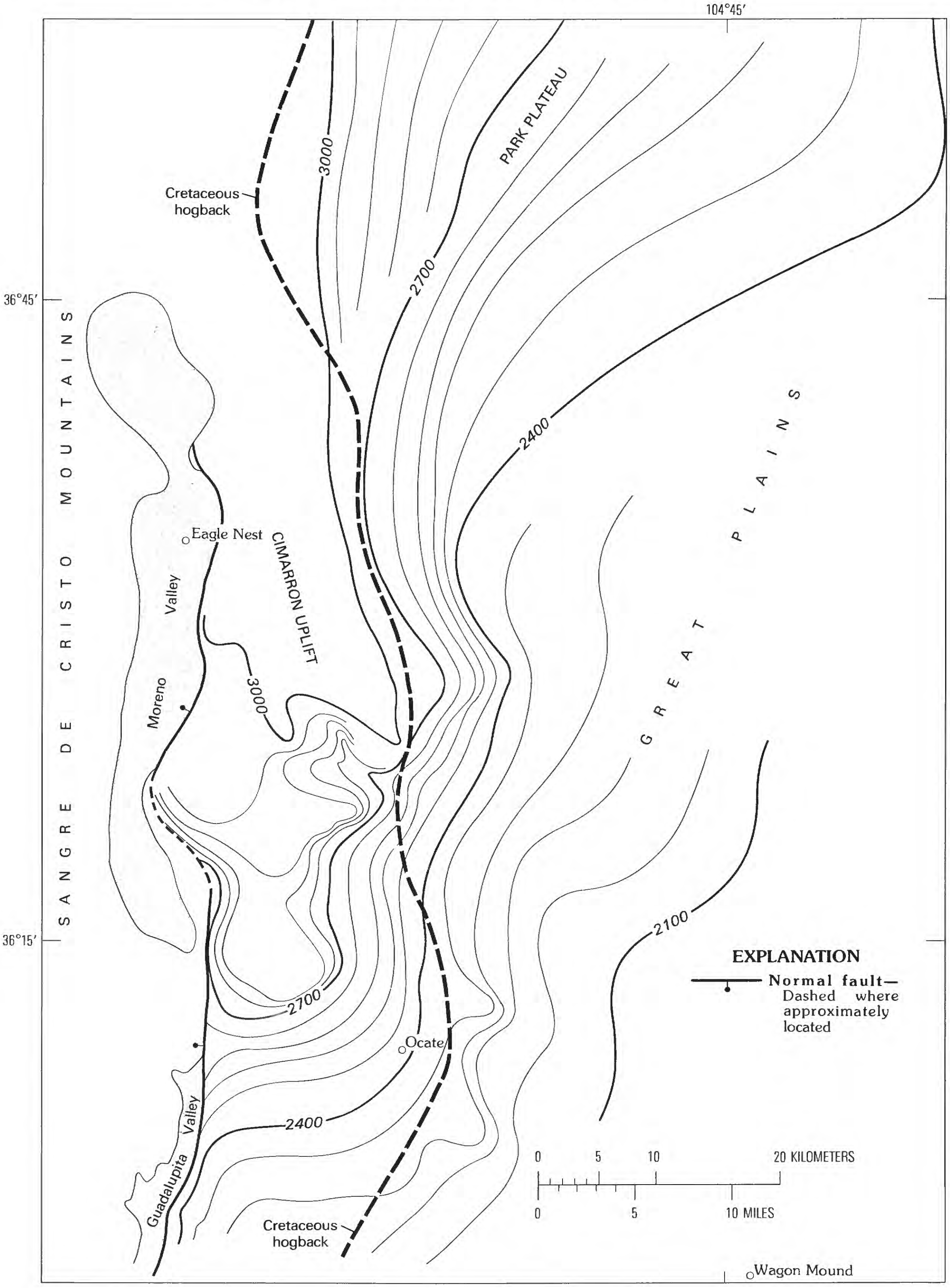


FIGURE B7.—Structure contour map drawn on 4- to 5-m.y.-old Urraca surface in the Ocate volcanic field and on the Park Plateau in the Raton Basin. Contour interval is 60 m (200 ft). Contour lines are approximately located. Contours are defined by accordant ridge tops in the Park Plateau area and were drawn at the base of the basalt flows resting on the Urraca surface in the Ocate area.

high-angle reverse faults and nearly vertical sandstone and shale, and the zone is much less resistant to erosion than the gently inclined Glorieta Sandstone in the upper reaches of the Rayado Creek drainage. The capture of the headwaters of the ancestral Rayado Creek by Coyote Creek stopped pediplanation along the remaining course of the ancestral Rayado Creek. The plain cut by the headwaters of the ancestral Rayado Creek is perched above the surface carved by the ancestral Coyote Creek.

Erosion along the ancestral Coyote Creek lowered the westernmost part of the original pediplain several tens of meters before volcanism occurred; flows of this period of volcanism—dated at 4.7 m.y. (Stormer, 1972)—appear to be confined to an ancestral shallow valley on the west side of the volcanic field, and the flows now present in the northern part of Guadalupita Valley. The pediplain cut by the ancestral Coyote Creek apparently extended over much of La Mesa and Le Febres Mesa and may have extended over the area now occupied by the Ocate Valley. Small streams flowing east out of the Rincon Range were apparently graded to the Coyote Creek drainage, as indicated by perched, basalt-covered gravels on El Cerro Colorado whose overlying basalts were dated at 4.1 m.y. Coplanar pediments, not capped by basalts but preserved between El Cerro Colorado and La Mesa, appear to be remnants of this surface. The Guadalupita Valley did not exist at this time. Rather, the basalts in this valley, downdropped along a major, north-trending normal fault, were probably coextensive with the volcanic rocks on La Mesa.

Down-to-the-west normal faulting may have initiated the Coyote Creek erosion cycle. This is reflected in the lower level of the Black Lakes basalts that flowed across the scarp. North-trending, down-to-the-west normal faults are present directly north of the Black Lakes area and mark the east boundary of the Neogene Moreno Valley (Clark and Read, 1972; Ray and Smith, 1941) and offset some of the Agua Fria flows (pl. 1). To the south, the basalts that cap El Cerro Colorado—dated at 4.1 m.y.—end abruptly at the valley that contains the village of Guadalupita and Los Chupaderos Valley on the west. In this valley, directly west of the basalts and 275 m (900 ft) below, are flows interpreted to be the down-faulted extension of the El Cerro Colorado flows. Farther south, faults cut older alluvium on the east side of the valley (Baltz and O'Neill, 1980, 1984). Geophysical data of Mercer and Lapalla (1970) show an eastward thickening wedge of valley fill in the Mora Valley to the south. The north-trending valley that contains the town of Mora and the continuation of that valley to the north toward Guadalupita appears to be a half graben, bounded on the east by normal faults.

LOW-LEVEL SURFACES AND THEIR VOLCANIC CAPROCK

Basalts of the third age group (less than 4 m.y. old—shown as Tv1, QTv, and Qv on pl. 1) make up most of the field by volume in the Ocate volcanic field. They comprise most of the flows of the Ocate volcanic field that are in the Great Plains province and also cover a large part of the southern Cimarron block. Some volcanic centers that expelled these flows are aligned along the structural boundary between the Great Plains province and the Cimarron block. Age relations among these basalts are known largely from superposition and physiographic expression; however, five K–Ar age dates from these flows indicate that they range in age from 3.5 to 0.8 m.y. (table B1).

Charette Mesa.—In this report, the name Charette Mesa is applied to the surface that extends westward from Wagon Mound to Cerro Pelon and the Ocate Valley. Flows that cap Charette Mesa are the oldest dated flows in the third age group and define the highest surface below the Urraca surface (fig. B8). Charette Mesa is a broad, flat feature, named for Charette Lakes.

Basalt-capped mesas and buttes directly east of Rivera Mesa and south of Rayado Mesa are at the same elevation as the Charette Mesa flows, and lie 60 m (200 ft) lower than the 4- to 5-m.y.-old Urraca surface. Flows on Charette Mesa are also 60 m (200 ft) below the 4- to 5-m.y.-old flows that cap Apache Mesa.

The oldest volcanic rocks on Charette Mesa are multiple olivine flood basalt flows which form the lowest flows of this age group. Near Wagon Mound, they have been dated at 3.3 m.y. by Stormer (1972), and 3.1 m.y. from samples submitted by P. W. Lipman (written commun., 1978). Westward, these basalts are overlain by successively younger, less voluminous flows erupted from small vents that stand as rounded knobs and mounds with about 30–100 m (100–300 ft) of relief. These vents form three major groups: an older series which may have expelled the basalts to the east; an intermediate age-group which expelled subdued basalt flows; and moderately eroded cinder cones associated with a youthful-looking series of flows showing well-preserved flow morphology.

Flanks of the older vents generally slope between 5° and 10°. Dikes and small plugs that intruded these cones form locally steep cone flanks. Volcanic breccia, scoriaceous material, and oxidized vesicular basalt compose these vent structures; most of these rocks occur as thin layers that dip gently toward the center of the vent. Radial dikes are common, and some vents are capped by dishlike sheets of coherent basalt that may have formed as small intra-crater lava lakes.

Intermediate-age vents are present south of Apache

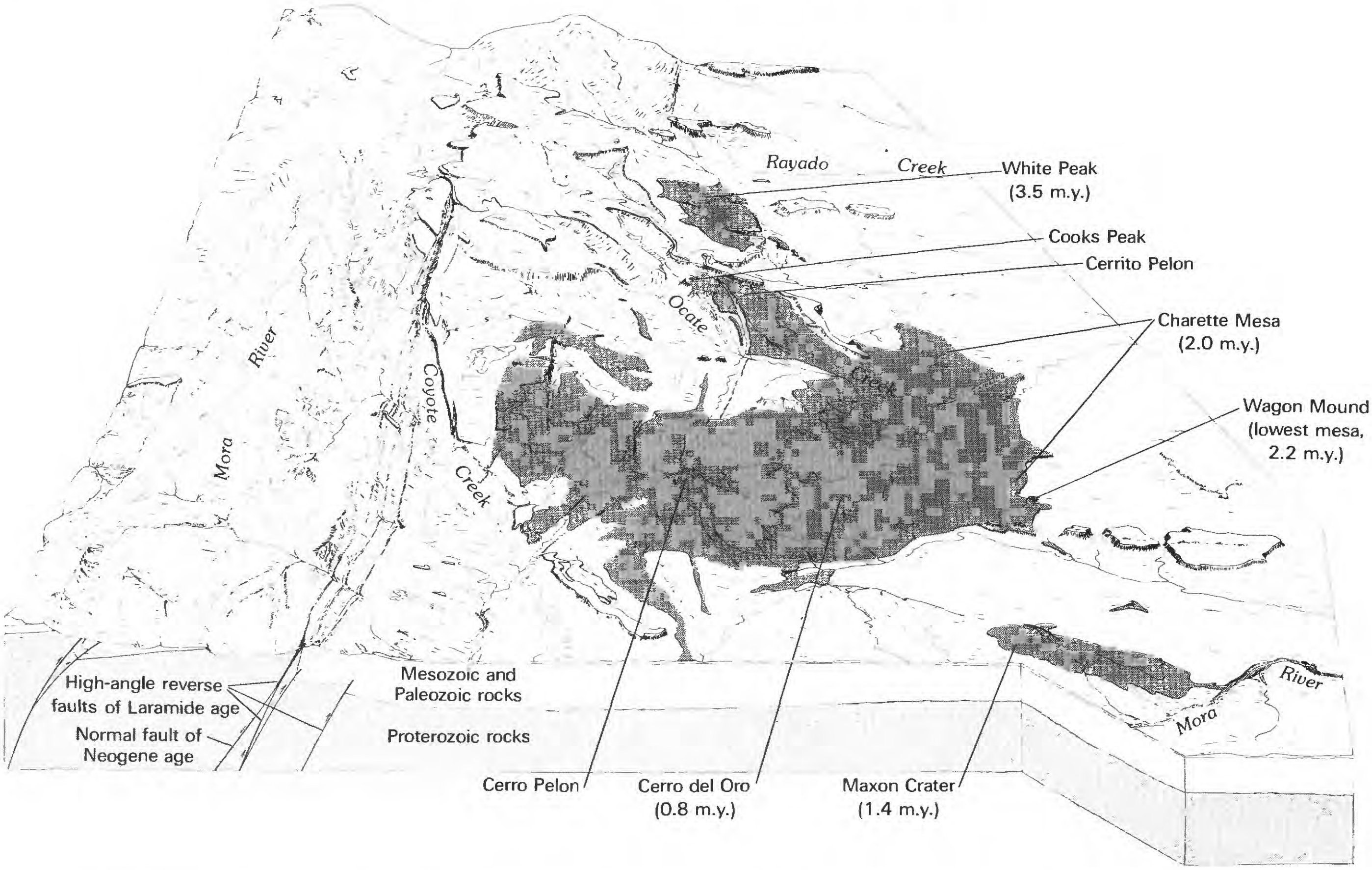


FIGURE B8.—Distribution of volcanic rocks in the Ocate volcanic field erupted since 4 m.y. ago (named and patterned areas). K–Ar dates in parentheses.

Mesa (pl. 1), on either side of State Highway 120. These vents expelled the majority of basalts that cover the central part of Charette Mesa. Cerrito Pelon and Cooks Peak northeast of Ocate expelled basalts that also flooded the area between Apache Mesa and Encinosa Mesa (pl. 1). These basalts interfinger with each other and hence are contemporaneous.

Basalts on Charette Mesa are underlain by coarse stream gravels composed of Precambrian metasedimentary and igneous rocks, Paleozoic sedimentary rocks, and minor Tertiary basaltic rocks. These gravels and the flat surface on which they rest appear to represent a broad surface formed by an east-flowing stream that headed in the vicinity of Ocate and coalesced with streams flowing south and southeast from the Cimarron Range. These streams formed an erosion surface about 60 m (200 ft) lower than the base of the 4- to 5-m.y.-old volcanic flows that cap the Urraca surface. The younger surface was subsequently buried by the 3.3- to 3.1-m.y.-old basal basalts on Charette Mesa.

Ocate valley.—The basalts within Ocate valley were not dated; hence, neither the age of the basalts nor the minimum age of underlying fluviatile deposits known as Las Feveras Formation (Bachman, 1953) is known. That the Ocate Valley did not exist during the 4- to 5-m.y.-old volcanism but had essentially assumed its present physiographic expression by the beginning of the intermediate period of volcanism, 3.3 to 3.1 m.y. ago, is indicated by the following evidence.

First, it appears that the Ocate Valley began to form after the 4- to 5-m.y.-old period of volcanism. Ocate Valley is a large, roughly elliptical depression that is drained by Ocate Creek. The valley is bounded on the east by upturned and beveled sedimentary rocks that mark the eastern margin of the Cimarron block. The north and west sides of the valley are bordered by high mesas capped by 4.8- to 4.1-m.y.-old basalts that do not spill into the depression.

Second, the basaltic flows directly east and southeast of Ocate, which make up Charette Mesa, rest on a beveled surface. The plan of these flows and the surface on which they lie broadens to the east, toward

Wagon Mound (pl. 1; fig. B8). The surface and the overlying flows are bounded by Apache Mesa and Apache Mesa (west) on the north and by the Turkey Mountains on the south (pl. 1). However, remnants of this surface are present north of Apache Mesa and adjacent to Rivera Mesa (pl. 1, fig. B6), and its presence suggests that several streams coalesced near Wagon Mound to form a broad surface over much of this region. This surface rises to the west toward Ocate along a gradient of 10 m/km (50 ft/mi). The steepest gradient along Ocate Creek is north and west of Ocate Valley, but the gradient becomes noticeably flat in and east of the valley (pl. 1). The flattest part of the stream is coincident with the surface on which the Charette Mesa volcanic rocks rest so as to suggest that Ocate Creek was graded to this surface prior to 3.0- to 3.1-m.y.-old volcanism. Hence, this surface may be interpreted to represent a broad pediplain developed in part along the ancestral Ocate Creek.

Third, Cerro Pelon volcanic flows present in Ocate Valley represent some of the older flows erupted during this period of volcanism. These flows are laterally continuous with the basalts on Charette Mesa near Wagon Mound, dated at 3.3 and 3.1 m.y. They also have a poorly preserved flow morphology. Thus, Ocate Valley appears to have been present during the earlier stages of the third period of volcanism.

The gravels below the basalts that cover Charette Mesa and the flat surface on which the gravels lie probably represent the ancestral Ocate Creek pediplain as it existed prior to about 3 m.y. ago. The approximately equivalent elevation of basalts above the creek, both within the valley and 5 km (3.1 mi) east of the valley, and the fact that these flows appear to be only slightly younger than the oldest flows on Charette Mesa, suggest that the Ocate Valley was a significant physiographic depression when this period of volcanism began.

Fourth, distribution and age of the Las Feveras Formation, a fine-grained fluvial valley-fill deposit that covers much of the floor of Ocate Valley, is consistent with development of the valley before the Charette Mesa period of volcanism. In contrast to the pervasive erosion and denudation that characterizes the Pliocene-Pleistocene history of the front ranges of the southern Rocky Mountains (Ray and Smith, 1941; Smith and Ray, 1943; Levings, 1951; Scott, 1963, 1975), this deposit records a period of deposition. Infilling of the valley must have been produced by blockage of the Ocate drainage system. That the Las Feveras Formation is restricted to the Ocate Valley (Bachman, 1953) suggests that this blockage occurred very near the present stream outlet to the valley. The cause of the blockage is unknown, but damming of the drainage either by lava or by faulting prior to volcanism is a reasonable possibility. Flows lacking distinct flow morphology that belong to the third period of volcanism (younger than 4 m.y.) rest directly on the Las Feveras Formation, which indicates that this valley had formed by late Pliocene time. Thus, the age of the Las Feveras Formation can be more specifically designated as Pliocene, rather than late Tertiary or early Quaternary, the age assigned originally by Bachman in 1953.

Youngest basalt-capped mesa.—One or two periods of incipient pediplanation after the Charette Mesa period of volcanism are recorded by scattered erosional remnants in the form of small buttes and mesas (pl. 1). Most of these are capped by gravel, but a small mesa 4.5 km (2.8 mi) north of Wagon Mound is capped by basalt. The basalt cap lies 20 m (65 ft) below the Charette Mesa flows and about 15 m (50 ft) above the adjacent lowlands. Basalts on this mesa, dated at 2.2 m.y., were erupted from a low shield vent directly west on Charette Mesa. Gravel-covered surfaces similar in their physiographic expression to the 2.2-m.y.-old basalt-capped mesa are preserved as isolated buttes extending from Rayado Creek southward toward Rivera Mesa. These small buttes define the lowest surface preserved in this area except for those stream terraces preserved adjacent to Rayado Creek.

Buttes near El Cerro Colorado.—Gravel-covered buttes are also preserved southeast of El Cerro Colorado in the large valley drained by Coyote Creek (pl. 1). These small buttes define the lowest gravel covered pediment surface in this valley, rising some 40 m (130 ft) above the valley floor. Their age is not known, but their physiographic position indicates that they are younger than the Charette Mesa surface.

Maxon Crater.—This large basaltic shield volcano is located about 12 km (7.5 mi) south of Wagon Mound and directly west of Interstate 25. The main vent is located near the west side of the shield and is marked by a large east-trending depression more than 1 km (0.6 mi) long. Basalts expelled from Maxon Crater flowed about 90 km (55 mi) eastward, through the canyon carved by the Mora River, and then a short distance beyond the confluence of the Mora and Canadian Rivers. At the confluence of the two rivers the flows lie 100 m (300 ft) below the rim of the canyon, and 125 m (400 ft) above the present level of the rivers. A basalt specimen collected from the Maxon Crater flows exposed in the roadcut along Interstate 25 gave a K–Ar date of 1.4 m.y.

Cerro del Oro.—The youngest volcanic rocks in the the area were erupted from the central part of Charette Mesa, south of New Mexico Highway 21. The basalts consist of two thick, viscous flow systems, each erupted from one major and at least one minor vent and covering about 16 km^2 (6.25 mi^2). The surfaces of the flows are hummocky and are scattered with volcanic bombs and scoriaceous material. Numerous pressure ridges and flow ramparts are present, standing as elliptical knobs 7–10 m (23–33 ft) above the surrounding basalts. The cores of these structures show blocky, oxidized lava overlain by dense, aphanitic, nonvesicular, and somewhat platy basalt. The flows that show these features best were erupted from the Cerro del Oro cinder cone. The flanks of this cone consist of outward dipping cinders, ash, bombs, volcanic breccia, and agglomerate. The original crater has been partly eroded by a south-draining gully. Basalts flowed southward from this cone. A specimen collected from basalt interlayered in the cinder cone was dated at 0.8 m.y.

SUMMARY

Volcanic flows 8.3 to 5.7 m.y. old preserve beneath their cover the physiographically highest gravel-covered surfaces in the Ocate volcanic field. The flows appear to rest on a surface or series of nearly equivalent surfaces that slope gently southeast from a drainage divide, which in this part of the Sangre de Cristo Mountains was located east of the present divide, probably near the Rincon Range (pl. 1). This paleosurface cuts across diverse rock types and sharp structural breaks, which suggests that late Miocene time was marked by erosion and pediplanation without tectonic activity.

About 5.5 m.y. ago, the crustal stability of the southern Rocky Mountains during the late Miocene ended. Uplift caused moderate dissection of the late Miocene surface and development of a younger, lower surface which was several tens of meters lower. This intermediate-level surface, which is equivalent to the Urraca surface of Smith and Ray (1943), wraps around the mesas capped by the older basalts and around the Cimarron Range and is continuous with the vast, broad surface of the Park Plateau in the Raton Basin. This surface truncates diverse rock types and structures. In the vicinity of the Ocate volcanic field, it is represented by a southeast-sloping erosion surface, largely carved by the ancestral Rayado and Coyote Creeks. Much of the upper reaches of this surface was covered by volcanic rocks erupted between 4 and 5 m.y. ago.

Profiles drawn on the Urraca surface and the older surface nearly parallel to it are locally warped, showing concave upward and downward deflections. The concave downward aspect of the surfaces is roughly coincident with the eastern margin of the Cimarron block. Warping is due to uplift of the Cimarron block with respect to the adjacent Great Plains. This surface is also cut by significant down-to-the-west normal faults on the west side of the field. These faults extend from the Moreno Valley south at least to the Mora Valley; displacement is as great as 275 m (900 ft).

After this period of broad uplift and volcanism, major erosion was confined to the southeast side of Sierra Montuosa Mesa and resulted in the formation of Ocate Valley. The ancestral Ocate Creek cut this valley to about its present size and elevation; the present floor of the valley is graded to the surface beneath the lowest-level basalts, 3.3–3.1 m.y. old, that cap Charette Mesa. These flows or contemporaneous faulting apparently dammed Ocate Creek and raised the base level, causing deposition of the alluvial-fluvial Las Feveras Formation in Ocate valley.

This volcanism was followed by continued uplift; associated denudation is marked by the formation of the lowest paleoerosion surfaces and overlying gravels in the area, now preserved as isolated gravel-capped buttes and locally basalt-capped mesas standing slightly below the Charette Mesa surface. Basalts on one of these surfaces present near Wagon Mound were dated at 2.2 m.y.

By the time of the Maxon Crater eruption, 1.4 m.y. ago, the present major drainages were well established.

The youngest flows in the field were erupted from several small vents on Charette Mesa, northwest of Wagon Mound. This youngest volcanic episode is characterized by hummocky flows of limited extent that are surmounted by cinder cones.

REFERENCES CITED

Aoki, Ken-Ichiro, and Kudo, A.M., 1975, Major element variations of late Cenozoic basalts of New Mexico: New Mexico Geological Society, Special Publication no. 5, p. 82–88.

Bachman, G.O., 1953, Geology of a part of northwestern Mora County, New Mexico: U.S. Geological Survey Oil and Gas Investigations Map OM–137.

Baltz, E.H., and O'Neill, J.M., 1980, Preliminary geologic map of the Sapello River area, Sangre de Cristo Mountains, Mora and San Miguel Counties, New Mexico: U.S. Geological Survey Open-File Report 80–389, 22 p.

______1984, Geologic map of the Mora River area, Sangre de Cristo Mountains, Mora County, New Mexico: U.S. Geological Survey Miscellaneous Investigations Series Map I–1456, scale 1:24,000.

Clark, K.F., and Read, C.B., 1972, Geology and ore deposits of Eagle Nest area, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 94, 134 p.

Dane, C.H., and Bachman, G.O., 1965, Geologic map of New Mexico: U.S. Geological Survey, scale 1:500,000.

Darton, N.H., 1928, Geologic map of New Mexico: U.S. Geological Survey, scale 1:500,000.

Fenneman, N.M., 1931, Physiography of western United States: New York, McGraw-Hill, 534 p.

Frye, J.C., and Leonard, A.B., 1957, Ecological interpretations of Pliocene and Pleistocene stratigraphy in the Great Plains region: American Journal of Science, v. 255, no. 1, p. 1–11.

______1959, Correlation of the Ogallala Formation (Neogene) in western Texas with type localities in Nebraska: Bureau of Economic Geology, Texas University, Report of investigations no. 39, 116 p.

Hussey, K.M., 1971, A K-Ar date on the Rocky Mountain pediment sequence, north-central New Mexico: Isochron/West, no. 2, p. 45.

Johnson, R.B., 1974, Geologic map of the Fort Union quadrangle, Mora County, New Mexico: U.S. Geological Survey Geologic Quadrangle Map GQ-1164, scale 1:24,000.

______1975, Geologic map of the Rainsville quadrangle, Mora County, New Mexico: U.S. Geological Survey Geologic Quadrangle Map GQ-1276, scale 1:24,000.

Just, Evan, 1937, Geology and economic features of the pegmatites of Taos and Rio Arriba Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 13, 73 p.

Knight, S.H., 1953, Summary of the Cenozoic history of the Medicine Bow Mountains, Wyoming: Wyoming Geological Association Guidebook, 8th Annual Field Conference, Laramie Basin and North Park, p. 65-76.

Lee, W.T., 1921, Description of the Raton, Brilliant, and Koehler quadrangles [New Mexico-Colorado]: U.S. Geological Survey, Geologic Atlas, Folio 214.

Levings, W.S., 1951, Late Cenozoic erosional history of the Raton Mesa region: Colorado School of Mines Quarterly, v. 46, no. 3, 111 p.

Mercer, J.W., and Lapalla, E.G., 1970, A geophysical study of alluvial valleys in western Mora County, New Mexico: U.S. Geological Survey Open-File Report, 69 p.

Moore, F.E., 1959, The geomorphic evolution of the east flank of the Laramie Range, Colorado and Wyoming: University of Wyoming Ph.D. thesis, 132 p.

Petersen, J.W., 1969, Geology of the Tienditas Creek-La Junta Canyon area, Taos and Colfax Counties, New Mexico: University of New Mexico M.S. thesis, 79 p.

Ray, L.L., and Smith, J.F., 1941, Geology of the Moreno Valley, New Mexico: Geological Society of America Bulletin, v. 52, no. 2, p. 177-210.

Robinson, G.D., Wanek, A.A., Hays, W.H., and McCallum, M.E., 1964, Philmont Country: The rocks and landscape of a famous New Mexico ranch: U.S. Geological Survey Professional Paper 505, 152 p.

Schowalter, T.T., 1969, Geology of part of the Creston Range, Mora County, New Mexico: University of New Mexico M.S. thesis, 84 p.

Scott, G.R., 1963, Quaternary geology and geomorphic history of the Kassler quadrangle, Colorado: U.S. Geological Survey Professional Paper 421-A, 70 p.

______1975, Cenozoic surfaces and deposits in the southern Rocky Mountains: Geological Society of America Memoir 144, p. 227-248.

Simms, R.W., 1965, Geology of the Rayado area, Colfax County, New Mexico: University of New Mexico M.S. thesis, 90 p.

Smith, J.F., and Ray, L.L., 1943, Geology of the Cimarron Range, New Mexico: Geological Society of America Bulletin, v. 54, no. 7, p. 891-924.

Stevenson, J.J., 1881, Report upon geological examinations in southern Colorado and northern New Mexico during the years 1878 and 1879: U.S. Geographical Survey West of the 100th Meridian (Wheeler), 3rd Supplement, 420 p.

Stormer, J.C., Jr., 1972, Ages and nature of volcanic activity on the southern High Plains, New Mexico and Colorado: Geological Society of America Bulletin, v. 83, no. 8, p. 2443-2448.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1989—673-047/86,078 REGION NO. 8