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Middle Tertiary Volcanic Field in the Southern Rocky Mountains

THOMAS A. STEVEN

U.S. Geological Survey
Federal Center
Denver, Colorado 80225

ABSTRACT

A widespread volcanic field covered most of the Southern Rocky Mountains in middle Tertiary time, 40 to 25 m.y. ago (approximately Oligocene time). This field covered an erosion surface that beveled structures formed during the Laramide orogeny in Late Cretaceous and early Tertiary time. The source vents from which the volcanic rocks were derived were largely restricted to the deformed area. Recognized volcanic centers lie mostly within a broad triangular area bounded on the east by the Rocky Mountain front, on the northwest by the northeast-trending Colorado mineral belt lineament, and on the southwest by the southern margin of the recurrently active Uncompahgre-San Luis uplift. Local volcanic centers existed also in the Never Summer Mountains and Rabbit Ears Range north of the mineral belt lineament. The resulting volcanic field thus consisted of a major southern segment covering all of south-central Colorado and adjacent New Mexico and a northern segment extending into the mountain areas of north-central Colorado. The two segments were linked along the trend of the Colorado mineral belt.

Most of the volcanic field consisted of volcanic rock of intermediate composition derived from many widely scattered volcanoes. Extensive aprons of volcaniclastic rocks around these volcanoes coalesced to provide a virtually continuous cover of volcanic material. In places, the volcanic activity became more silicic with time, great ash-flow tuff sheets were erupted, and the source areas subsided to form calderas. The largest ash-flow field and most of the calderas formed in the San Juan Mountains. Other ash flows apparently were derived from areas in the Sawatch Range in central Colorado and the Never Summer Mountains in northern Colorado.

Large near-surface batholiths were emplaced beneath the San Juan Mountains and beneath the region that extends northeastward from the Elk Mountains and Sawatch Range along the trend of the Colorado mineral belt as far as the Rocky Mountain front. These batholiths are manifested by two large gravity lows and by many exposed epizonal plutons that represent cupolas on the larger underlying

bodies. The batholith in central Colorado probably consists of plutons of both Laramide (70 to 55 m.y.) and middle Tertiary (40 to 25 m.y.) ages.

INTRODUCTION

In a symposium a few years ago on volcanism in the Southern Rocky Mountains, Steven and Epis (1968, p. 241-258) suggested that south-central Colorado was covered by a widespread volcanic field in middle Tertiary time and that this field was fragmented by later Cenozoic block faulting and erosion. Other papers in that symposium (Corbett, 1968, p. 1-28; Taylor and others, 1968, p. 39-50; Epis and Chapin, 1968, p. 51-88; Siems, 1968, p. 89-124; Luedke and Burbank, 1968, p. 175-208) not only verified this conclusion but made it obvious that the middle Tertiary volcanic field also covered most of the remainder of the Southern Rocky Mountains. The purpose of this paper is to explore the nature and extent of this volcanic field more fully and to consider its relation to other geologic terranes in the Southern Rocky Mountain region.

The volcanic field formed largely in Oligocene time,[1] but evidence exists that related igneous activity began in latest Eocene time (about 40 m.y. ago) and persisted into early Miocene time (25 to 20 m.y. ago). The late Cenozoic basalts and associated high-silica rhyolites that were erupted widely throughout the Southern Rocky Mountains from early Miocene to Holocene time are believed to have evolved under a different tectonic regime (Lipman and others, 1970, p. 219; Christiansen and Lipman, 1972) and are not included in the assemblage of rocks that is the primary focus of this paper.

For the purpose of the present discussion, the volcanic field is limited to near-source lava and breccia and to the adjacent volcaniclastic mudflow and fluviatile outwash apron. A vast quantity of volcanic ash undoubtedly blanketed much of the surrounding area, particularly downwind to the east and southeast. Some of this material probably is represented by the large amounts of air-fall and reworked ash in the early Oligocene White River Group and other middle Tertiary sedimentary formations in the plains area to the east, but most of the blanketing ash was eroded and transported out of the region. It is beyond the scope of this paper to correlate any of the outlying ash-derived deposits with activity in the volcanic field itself.

GENERAL GEOLOGY

The middle Tertiary volcanic field (Figs. 1 and 2) consisted largely of intermediate-composition volcanic rocks that are typical of the continental interior of the western United States. Most are calc-alkalic or alkali-calcic andesitic, rhyodacitic, and quartz latitic lavas and breccias that formed many widespread central-vent volcanoes with coalescing aprons of volcaniclastic rocks. Rocks of more silicic composition, mostly somewhat younger ash-flow tuffs and associated quartz latitic and rhyolitic lavas, were erupted in large volume in parts of the field. A significant variant exists along the eastern fringe of the field where the more alkalic syenodiorites of the Spanish Peaks area, trachytes of the Rosita and Silver Cliff area, and phonolites of the Cripple Creek center occur. A fairly regular eastward increase in the K_2O/SiO_2 ratio at a given silica content across the field has been indicated by Lipman and others (1972, p. 236).

[1] The limits of the Oligocene used in this report, 38 to 26 m.y. ago, are from Harland and others (1964).

The middle Tertiary field developed in postorogenic time in an area that was strongly deformed during the Laramide orogeny in Late Cretaceous and early Tertiary time (Tweto, 1975) and during an earlier orogeny in late Paleozoic time that formed the Ancestral Rocky Mountains (Mallory, 1960). Structural trends resulting from both periods of prevolcanic deformation exercised major control over the distribution of middle Tertiary igneous activity, but individual volcanic centers generally show little relation to specific earlier structures. The volcanic field covered the late Eocene surface described by Epis and Chapin (1975) and is capped by widespread late Cenozoic basalt flows whose genesis and tectonic environment are interpreted in the accompanying papers by Lipman and Mehnert (1975) and Larson and others (1975).

Source Areas

The source areas from which the rocks of the middle Tertiary volcanic field were derived are largely confined within a large triangular-shaped area that covers most of the Southern Rocky Mountains in Colorado and northern New Mexico

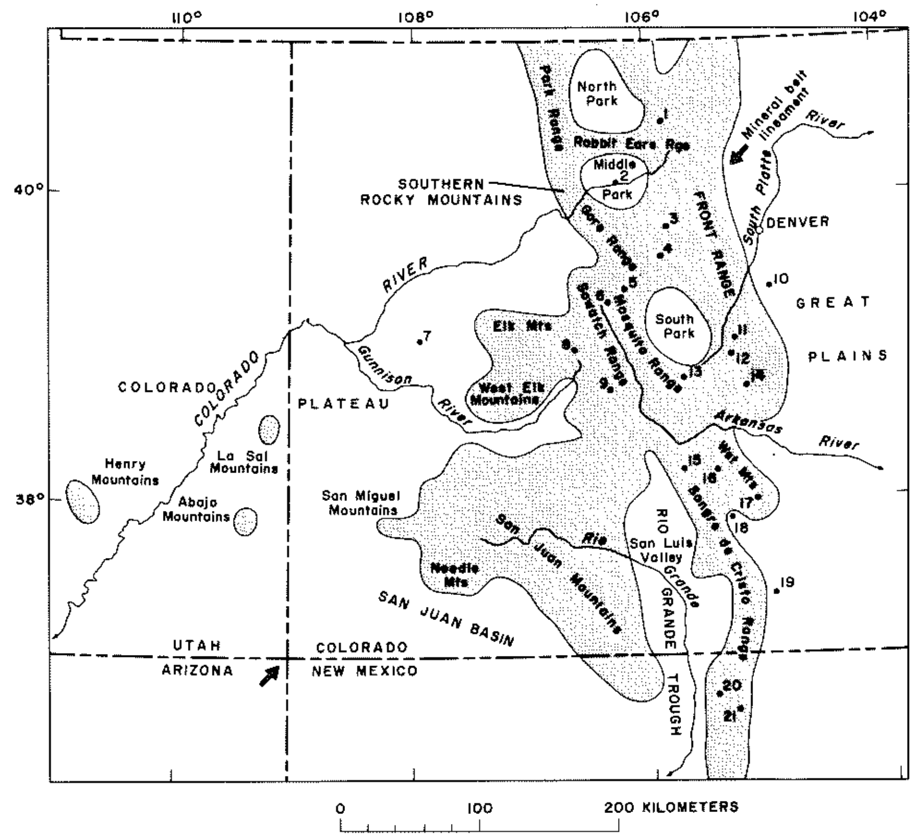

Figure 1. Geographic reference map of Southern Rocky Mountains. Points of reference: 1, Never Summer Mountains, Specimen Mountain, Lulu Mountain, Mount Richthofen; 2, Hot Sulphur Springs; 3, Red Mountain stock; 4, Montezuma batholith; 5, Climax, Chalk Mountain stock; 6, Leadville; 7, Grand Mesa; 8, Grizzly Peak caldera, Twin Lakes stock; 9, Mount Princeton batholith; 10, Castle Rock; 11, Signal Butte; 12, Florissant; 13, Thirtynine Mile volcanic field; 14, Cripple Creek; 15, Cottonwood (Rito Alto) stock; 16, Westcliffe, Silver Cliff, Rosita Hills; 17, Deer Peak; 18, Huerfano Park, Devils Hole; 19, Spanish Peaks; 20, Red River; 21, Eagles Nest.

(Figs. 1 and 2). Igneous centers extend south of this triangle along the trend of the Southern Rocky Mountains to join with areas of major middle Tertiary volcanism in central New Mexico. Scattered laccolithic centers were formed in the Colorado Plateau west of the composite middle Tertiary field, and some of these may have vented to form local volcanic accumulations.

In the southern segment of the composite volcanic field, the northwest margin of the source area is broadly limited by the well-known Colorado mineral belt lineament (Fig. 2). This lineament follows the trend of a major shear zone of Precambrian age (Tweto and Sims, 1963) and is marked by a belt of Laramide intrusions that extends from northeast Arizona to the eastern front of the Southern Rocky Mountains northwest of Denver (Steven and others, 1972). Middle Tertiary plutons in the Elk and West Elk Mountains extend at least 50 km northwest of the mineral belt lineament in west-central Colorado, and intrusions in the core of the San Miguel Mountains extend 20 to 22 km west of the Laramide intrusions at Rico in southwest Colorado. However, on a regional scale (Fig. 2), the mineral belt lineament appears to have had a definite limiting effect on middle Tertiary igneous activity.

The southwest margin of the source area, in the southern segment of the composite volcanic field, extends from the San Miguel Mountains southeastward along the margin of the San Juan basin into New Mexico, where it crosses younger fault-block mountains and basins to terminate finally at the eastern front of the Southern Rocky Mountains. The southwest boundary closely parallels the southwest margin of the recurrently active Uncompahgre-San Luis highland, a structural element

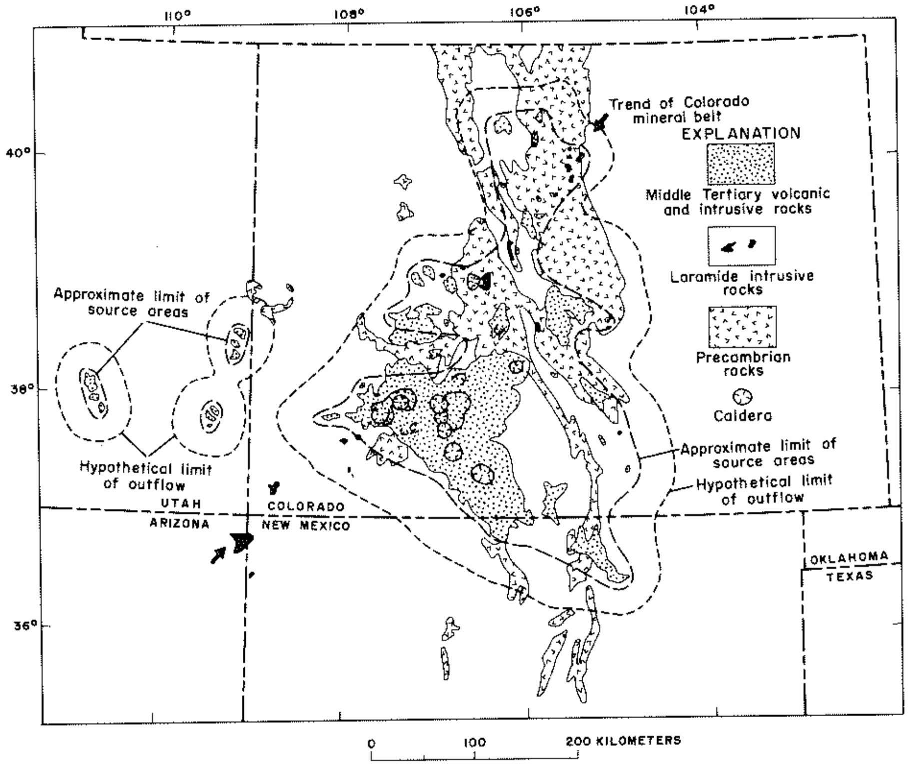

Figure 2. Map of Southern Rocky Mountains showing extent of middle Tertiary volcanic field (geology modified from Steven and others, 1972).

first uplifted in late Paleozoic time as part of the so-called Ancestral Rockies (Tweto, 1975; Mallory, 1960, p. 27, Fig. 2). This uplift, extending from eastern Utah across southwestern Colorado to northern New Mexico, was reactivated in Laramide time; several subsidiary folds, such as the Needle Mountains uplift, then formed along its borders.

The eastern boundary of the source area in the southern segment of the volcanic field virtually coincides with the eastern front of the Southern Rocky Mountains and, thus, with the edge of major Laramide deformation. Neglecting the minor Signal Butte center in the southern Front Range, the eastern margin extends from a southern laccolithic intrusive center near Eagles Nest on the east side of the Sangre de Cristo Range northward to the Cripple Creek center near the south end of the Front Range. From here, the limit of the source area swings northwestward in a broad arc to the Colorado mineral belt in the vicinity of Climax in central Colorado.

The northern segment of the composite volcanic field is linked to the southern segment along the trend of the Colorado mineral belt. The linkage area contains most of the intrusions with well-established middle Tertiary ages in central Colorado. Few Tertiary plutons of any kind have been mapped in the central Front Range southeast of the Colorado mineral belt, and therefore this zone almost certainly marks the southern limit of sources in the northern segment of the middle Tertiary volcanic field. Other igneous centers of middle Tertiary age are known north of the mineral belt as far as the Never Summer Mountains and Rabbit Ears Range in north-central Colorado (Fig. 2).

Tectonic Setting

The source vents for the southern segment of the composite field are not only limited by pre-existing trends but also appear to be confined largely to an area of recurrent tectonic activity. The San Juan and West Elk Mountains were built largely on top of the recurrently active Uncompahgre-San Luis uplift. To the northeast, the plutons in the Elk Mountains and Sawatch and Sangre de Cristo Ranges and the volcanic rocks in the Thirtynine Mile volcanic field and Wet Mountains were emplaced largely in the Central Colorado trough, a feature that formed in late Paleozoic time when it was filled with a thick accumulation of sediments. Parts of the trough were extensively compressed and thrust faulted during the Laramide orogeny (Burbank and Goddard, 1937; Tweto, 1975).

The volcanic centers of middle Tertiary age in the Leadville-Climax area in central Colorado were emplaced near the eastern margin of the Central Colorado trough and along the eastern flank of the Sawatch anticline of Laramide age. To the northeast, the eruptive vents follow the mineral belt lineament onto the top of the Front Range highland element of the late Paleozoic Ancestral Rockies (Tweto, 1968b, p. 561). This ancestral structural element trends northwest and embraces the area that now includes the igneous centers in the Never Summer Mountains and Rabbit Ears Range. The middle Tertiary igneous centers in this segment of the field show no obvious control by Laramide structural features, however, because the Never Summer centers are along the west flank of the Front Range anticline, and the Rabbit Ears centers extend west across the trend of the North Park-Middle Park synclinal basin.

Despite the earlier history of recurrent tectonic activity, the area covered by the composite volcanic field appears to have been structurally stable when the field was emplaced. The Laramide structures were widely beveled by Eocene erosion. A regional surface of low relief was developed in the southern part of Colorado (Epis and Chapin, 1975), but the Rabbit Ears Volcanics in north-central Colorado accumulated on irregular topography (Izett, 1968, p. 36). Most of the structural features developed during Oligocene volcanism were of volcano-tectonic origin, were of limited extent, and were related to eruptions or movements of magmas at local centers. Regional block faulting that began in early Miocene time (Lipman and Mehnert, 1975; Izett, 1975; Taylor, 1975) heralded the end of the middle Tertiary volcanism.

San Juan Mountains

The San Juan Mountains in the southwestern part of Colorado consist largely of a dissected volcanic plateau and form the largest remnant of the middle Tertiary volcanic field. Volcanic eruptions in this portion of the field took place largely between 35 and 26 m.y. ago, although locally they persisted for another several million years (Lipman and others, 1970). Numerous igneous centers are associated with the volcanic rocks throughout the San Juan Mountains, but they are notably sparse in adjacent areas to the west and southwest (Steven and others, 1974), except for the intrusions in the core of the San Miguel Mountains that extend nearly 30 km west of the San Juan volcanic pile. Erosion evidently has removed nearly all of the outflow apron of volcanic and volcaniclastic rocks in the area west and southwest of the San Juans; the thick near-source accumulations associated with the core volcanoes are all that remain.

Early intermediate-composition lavas and breccias constitute about two-thirds of the volcanic pile of the San Juan Mountains (Lipman and others, 1970, p. 2331). These rocks are largely andesite, rhyodacite, and mafic quartz latite, and they formed numerous widely scattered central-vent volcanoes whose volcaniclastic aprons coalesced to form an unbroken volcanic field much wider than the present area of exposure. Volcanic activity in the San Juans culminated in more silicic, commonly explosive eruptions, and great ash-flow tuff sheets were emplaced. The thick sequence of welded ash-flow tuffs that covers a large part of the San Juan Mountains was erupted from numerous vents in the central and western San Juans, and major calderas have been identified at the sources of all major individual sheets (Fig. 2).

The full extent of volcanic cover that once existed over the flat-lying sedimentary rocks south and west of the San Juan Mountains cannot be established. The Needle Mountains (Figs. 1 and 2), which lie along the south side of the western San Juan Mountains, are the remains of a Laramide uplift. This uplift had an eroded core of Precambrian rocks and stood as a knot of hills (30 to 35 km across) that may never have been completely covered by the middle Tertiary volcanic accumulations. No comparable barrier existed east or west of the Needle Mountains, however, and a coalescing outflow apron of volcaniclastic rocks from the San Juan Mountains probably spread around this local uplift and extended many kilometers to the south, southwest, and west.

The San Juan volcanic plateau is bounded on the east by the San Luis Valley segment of the Rio Grande trough, a late Cenozoic rift zone that extends northward from southern New Mexico along the trend of the Southern Rocky Mountains at least as far as central Colorado. Along the eastern edge of the San Juan Mountains, the volcanic formations dip eastward beneath alluvial fill of the San Luis Valley, and no fault is evident along the margin. However, gravity studies (Gaca and Karig, 1965) have indicated that rough fault-block topography beneath the alluvial fill in the Rio Grande trough cuts off the San Juan volcanic rocks. In southernmost Colorado and northern New Mexico, the Rio Grande trough is filled with 3.5- to 4.5-m.y.-old basalt flows (Ozima and others, 1967) that obscure the bounding faults. Intermediate-composition volcanic rocks that probably represent the eastern flank of the San Juan volcanic accumulation are exposed in the San Luis Hills in the southern part of the San Luis Valley (Burroughs, 1971, p. 280) and are exposed in places on the Sangre de Cristo mountain block east of the Rio Grande trough. These patches extend from a point northwest of the Spanish Peaks in Colorado (Johnson, 1969) to the Red River in New Mexico. Some of these rocks just south of the Colorado-New Mexico border have been dated as 35.6 m.y. old (Pillmore and others, 1973), and Burroughs (1971, p. 280) reported ages of 27.4 and 27.9 m.y. for intrusive rock cutting the volcanic rocks in the San Luis Hills.

Spanish Peaks and Wet Mountains

The Spanish Peaks intrusive center (Johnson, 1969) just east of the Sangre de Cristo Range in southern Colorado is believed to represent the roots of former volcanoes of middle Tertiary age (J. D. Vine, 1972, written commun.). K-Ar ages reported by Stormer (1972, p. 2445) indicate that igneous activity at this center was largely in early Miocene time, 26 to 22 m.y. ago, and fission-track ages reported by Smith (1973, p. 513-514) range from 28.5 to 19.8 m.y. in confirmation. Any volcanic edifice that existed above this center has been removed by erosion, and its former extent can only be conjectured. On the other hand, one of the patches of volcanic rock that has been mapped along the southern Sangre de Cristo Range (Johnson, 1969) is only 19 km west of the Spanish Peaks center, and it seems likely that volcanic rocks covered the intervening area. If so, a virtually continuous cover of volcanic rocks may have existed between the San Juan Mountains and the eastern edge of the volcanic pile that accumulated above the Spanish Peaks intrusive center.

Middle Tertiary volcanic rocks form a discontinuous cap on the Wet Mountains from the vicinity of Westcliffe southward. The Rosita and Silver Cliff volcanic centers (Siems, 1968) near the northern part of this assemblage of volcanic rocks are the remnants of former central-vent volcanoes that erupted lavas and breccias ranging from andesite to rhyolite in composition. Pyroclastic rocks form only a minor part of either volcano. An age of 31.7 m.y. has been reported for pumice from the Rosita center (Scott and Taylor, 1974). Equivalent mudflow and conglomeratic outflow debris is found in the Devils Hole area in Huerfano Park to the south (Scott and Taylor, 1974). The Deer Peak center in the southern Wet Mountains (Scott and Taylor, 1974) exposes the root of another volcano of intermediate composition; related volcanic rocks are still preserved in adjacent parts of the Wet Mountains, and outflow debris has been recognized in the Devils Hole area to the southwest.

The eastern flank of the Wet Mountains volcanic pile has been eroded, and the original position of the eastern margin of the pile cannot be established. Some of the volcanic rocks pass beneath younger alluvial fill in the Wet Mountain Valley west of the Silver Cliff and Rosita Hills volcanic centers. Similar rocks that reappear on the west side of the valley and volcanic rocks that belong to the Thirtynine Mile volcanic field farther north are in fault contact with deformed sedimentary rocks in the Sangre de Cristo mountain block (Scott and Taylor, 1974). Evidently the volcanic rocks of the Wet Mountains extended much farther west prior to late Cenozoic block faulting, and they may have been continuous with those in the San Juan Mountains.

Dikes, sills, plugs, and stocks of intermediate to silicic composition have been mapped in the Sangre de Cristo Range and adjacent parts of Huerfano Park northwest of the Spanish Peaks. These intrusive bodies extend beyond Cottonwood (Rito Alto) Peak (Toulmin, 1953) in the northern part of the Sangre de Cristo Range.

The age of most of these intrusions has not been established, but some of the more southerly ones cut or deform Eocene sedimentary rocks and probably were emplaced in middle Tertiary time. Preliminary fission-track ages on the Cottonwood (Rito Alto) stock indicate a middle Oligocene age (R. B. Taylor and C. W. Naeser, 1973, oral commun.). Some of these intrusions may have vented at the surface and contributed to the volcanic cover between the San Juan and Wet Mountains.

Thirtynine Mile Volcanic Field and Southern Front Range

The Thirtynine Mile volcanic field (Epis and Chapin, 1968) consists largely of andesitic lavas and breccias derived from a cluster of central-vent volcanoes. The field was built largely in Oligocene time in the southern part of the South Park intermontane basin. The Wall Mountain Tuff at the base of the succession has been dated as 35 to 36 m.y. old (Van Alstine, 1969, p. 15). K-Ar ages obtained on the overlying Antero Formation of Johnson (1937) and the Gribbles Park Tuff are, respectively, 33 m.y. and 29 m.y. Most of the outflow apron of volcanic and volcaniclastic rocks around the margins of this field has been removed by erosion, and a complex of near-source lavas and breccias that accumulated around clustered volcanic centers in the heart of the field are all that remain. Rock units that can be correlated with some of those in the Thirtynine Mile field have been recognized (1) along the east side of the Sangre de Cristo Range south of the Arkansas River (Scott and Taylor, 1974) within 10 to 20 km of the volcanic centers at Silver Cliff and Rosita (Fig. 1), and (2) near the northern end of the San Luis Valley associated with locally derived volcanic rocks in the northeast part of the San Juan volcanic field (Lowell, 1971, p. 216). It thus seems a certainty that the Thirtynine Mile volcanic field was once connected with the accumulation of volcanic rocks in the Wet Mountains and San Juan Mountains.

R. C. Epis and C. E. Chapin (1973, written commun.) have mapped a series of ash-flow units in the Thirtynine Mile volcanic field that appear to have had sources to the west of the upper Arkansas River valley, possibly in the Sawatch Range. Two of these units, the Wall Mountain Tuff and the Gribbles Park Tuff, are sheets of sufficient volume that caldera subsidence probably took place at their sources. These sources are being actively sought by the combined efforts of several workers, and speculations here as to their locations would be premature.

The Cripple Creek mining district (Loughlin and Koschmann, 1935; Koschmann, 1949), 15 to 18 km east of the Thirtynine Mile volcanic field, is largely within a deeply eroded remnant of a middle Tertiary volcano. Most of the volcanic rocks at Cripple Creek are within a subsided block enclosed within walls of Precambrian granite, but Tobey (1969) has mapped patches of volcanic rock that are related to the rocks at Cripple Creek and overlie Precambrian rocks in adjoining areas. Rocks derived from the Cripple Creek center overlie one of the ash-flow tuff sheets from the Sawatch Range, and phonolite typical of that at Cripple Creek forms plugs that cut andesitic breccias derived from centers in the Thirtynine Mile field. The phonolite at Cripple Creek has been dated as 28 m.y. old (R. C. Epis and C. E. Chapin 1973, written commun.).

Other localities in the southern Front Range where there are small volcanic accumulations of Oligocene age are Florissant and Signal Butte. At Florissant (MacGinitie, 1953), tuffaceous lake sediments containing Oligocene plant fossils were deposited during the period of volcanism that produced the Thirtynine Mile volcanic field (Niesen, 1969). The lake at Florissant formed behind a barrier of andesitic volcanic rocks derived from the Thirtynine Mile volcanic field, and the tuffaceous sediments deposited in the lake were subsequently covered by additional

volcanic rocks from the same source. At Signal Butte, about 13 km north of Florissant, a deeply eroded remnant of a volcanic dome of intermediate composition rests on the late Eocene erosion surface. The vent that fed the dome is probably beneath the existing remnant. The volcanic materials at Signal Butte appear to be locally derived, and no continuous cover of volcanic materials between this locality and the Thirtynine Mile field is required by the evidence.

Izett and others (1969) dated a rhyolite ash-flow tuff near Castle Rock, Colorado, as early Oligocene (34.8 m.y.) by the K-Ar method. This tuff overlies the Dawson Arkose of Late Cretaceous and Paleocene age and underlies the Castle Rock Conglomerate of early Oligocene age. The source of the tuff was postulated to lie in the mountain area to the southwest, and the unit may correlate with one of the ash-flow tuff sheets mapped in the Thirtynine Mile volcanic field (Epis and Chapin, 1968). Subsequent microprobe analytical work on minerals from the tuff at Castle Rock by George Desborough of the U.S. Geological Survey (1973, written commun.) suggests that the tuff may be the distal end of a major sheet at the base of the Thirtynine Mile volcanic succession that has been mapped widely in and adjacent to the southern part of South Park. If this correlation proves valid, Oligocene volcanic rocks must have been widely distributed over the southern Front Range, although perhaps largely confined to topographically lower portions of the area.

Elk and West Elk Mountains

The West Elk Mountains consist largely of a great mass of volcanic breccia called the West Elk Breccia. This rock probably was derived from volcanoes that may have existed above granodiorite plutons exposed in the northern West Elk Mountains (Olson and others, 1968; Lipman and others, 1969), where stocks and related dikes, laccoliths, and sills cut both the West Elk Breccia of Oligocene age and lower Eocene sedimentary rocks of the Wasatch Formation (Godwin and Gaskill, 1964). In addition, Gaskill and others (1973) identified a volcano source for some of the West Elk Breccia in this area. To the south, near the Gunnison River, the West Elk Breccia coalesces with similar volcanic breccias (35 to 30 m.y. old) derived from volcanoes in the northern and western San Juan Mountains, and great ash-flow sheets (29 to 27 m.y. old) from caldera sources in the San Juans overlie breccias from both areas (Olson and others, 1968; Hansen, 1965; Lipman and others, 1970).

The core of the Elk Mountains (which extend northwest from the Sawatch Range in central Colorado) contains many epizonal plutons of Oligocene age that are between 34 and 29 m.y. old (Obradovich and others, 1969, p. 1749-1756). These rocks are largely granodiorite and are closely similar to the intrusive rocks in the West Elk Mountains to the south. No volcanic rocks are preserved in the Elk Mountains proper, but the nearby Grizzly Peak caldera in the vicinity of Independence Pass in the central Sawatch Range (Cruson, 1972; Obradovich and others, 1969, p. 1854) contains volcanic rocks, including ash-flow tuff. These rocks are more than a kilometer thick and are preserved in a downdropped block about 8.5 km across. Some of the Elk Mountains plutons may have vented to form significant volcanic accumulations similar to those in the West Elk Mountains. Lipman and others (1969) called attention to the close similarity in age and composition of the intrusive rocks in the Elk Mountains and the intrusive and extrusive rocks in the West Elk and San Juan Mountains. However, the original extent of any volcanic pile that might have existed above the Elk Mountains is unknown.

Mount Princeton Batholith

The Mount Princeton batholith in the southern Sawatch Range was largely mapped by Dings and Robinson (1957) and has been studied intensively in recent years by P. Toulmin III of the U.S. Geological Survey. According to Toulmin (1973, written commun.), K-Ar age determinations by C. Hedge of the U.S. Geological Survey indicate that intrusion of the batholith took place in latest Eocene and early Oligocene time. Toulmin (in U.S. Geol. Survey, 1963, p. A88) suggested that the roots of a Tertiary volcano may be preserved in the Mount Aetna area in the southern part of the batholith and that the deeply eroded remnant of a caldera may be represented. A similar conclusion was reached by Lipman and others (1969, p. D38) by interpreting the geological map of Dings and Robinson (1957, p. 1). Brock and Barker (1965, p. 320) described a dike of welded tuff more than 1.5 km long and 9 to 17 m thick near the north margin of the Mount Princeton batholith. Chapin and others (1970) and Lowell (1971, p. 216) described paleovalleys filled with volcanic rocks derived in part from the Sawatch Range along the east side of the upper Arkansas River valley across from the Mount Princeton batholith. These relations all suggest that a major volcano or cluster of volcanoes was present above the Mount Princeton batholith in Oligocene time.

Colorado Mineral Belt

Intrusive igneous rocks in north-central Colorado are concentrated along the northeast-trending Colorado mineral belt (Fig. 2). Two distinct episodes of igneous activity are represented: (1) a Late Cretaceous-early Tertiary (Laramide) episode in which abundant intrusions were emplaced between 70 and 55 m.y. ago from the west side of the Sawatch Range to the northeast end of the mineral belt, and (2) an Oligocene episode in which intrusions were emplaced 39 to 26 m.y. ago in the Climax-Chalk Mountain area in the Tenmile and southern Gore Ranges, on the west side of the Front Range (Montezuma batholith), and in the Red Mountain area. Reworked volcanic rocks formed during the first episode were deposited in sedimentary basins that flank the mountains on either side of the mineral belt (Tweto, 1975). Volcanic rocks produced during the second episode occur in Middle Park (Izett and others, 1969; Naeser and others, 1973).

Wallace and others (1968) described the complex sequence of intrusive and hydrothermal events leading to the development of the highly mineralized igneous center at Climax, Colorado. The last thermal event in that sequence, probably related to hydrothermal activity, has a K-Ar age of about 30 m.y. The Chalk Mountain stock, 3 to 5 km west of Climax, and a rhyolite plug a few kilometers north of Climax were reported by V. E. Surface (Tweto and Case, 1972, p. C7) to be about 27 and 35 m.y. old, respectively. Tweto (1968a, p. 693-694) and Tweto and Case (1972, p. C7) pointed out that other intrusive bodies in the Leadville-Climax area also might have been emplaced in post-Laramide (middle Tertiary?) time. No volcanic rocks related to the Leadville-Climax intrusive rocks have been identified, and no evidence has been cited to indicate that volcanic venting took place. However, the intrusives clearly indicate that magmatism occurred in the mineral belt of central Colorado in Oligocene time, and the possibility of concurrent volcanic activity cannot be ruled out.

The Montezuma batholith is a major intrusive body on the west side of the Front Range along the trend of the Colorado mineral belt. The Montezuma pluton has been described as a stock, but a recent study of underground exposures in the H. D. Roberts water diversion tunnel and geophysical evidence indicate that the body is of batholithic proportions. Before the advent of isotopic dating techniques, this pluton was believed to belong to the Laramide sequence of igneous intrusions in the Colorado mineral belt (Lovering, 1935, p. 32; Lovering and Goddard, 1938, 1950, p. 44-47) and was placed near the middle of that sequence. K-Ar dates by McDowell (1966) and Hedge and others (in U.S. Geol. Survey, 1970, p. A34) show, however, that the batholith was emplaced about 39 m.y. ago, roughly at the end of Eocene time, and that it is decidedly younger than the numerous bodies of Laramide age (summarized by Tweto, 1968b, p. 565) that exist throughout the mineral belt. Geological maps and sections of the H. D. Roberts water diversion tunnel that traverses the batholith (Wahlstrom and Hornback, 1962, Pl. 7; Warner and Robinson, 1967, Pl. 1) show that the west margin of the batholith approximately underlies the edge of outcrop, but that the east margin is nearly 3 km east of the exposed edge of the batholith. Gravity studies by Brinkworth (1970) indicate that the pronounced gravity low produced by the batholith extends at least 19 km north of its surface outcrop; the gravity low includes the Red Mountain igneous center that has been dated as 27 to 26 m.y. and is therefore of latest Oligocene age (Taylor and others, 1968, p. 42; Naeser and others, 1973).

It is unknown if any volcanic accumulation existed above the Montezuma batholith. However, Taylor and others (1968, p. 46) believed that at Red Mountain, intrusion breccias, the shattering of wall rock, and the appearance of pumice fragments and glass shards in the upper part of the intrusion indicate volcanic venting. They suggested (p. 43) that the rhyolitic pyroclastic rocks of approximately the same age as the Red Mountain intrusion (29 m.y.) in the Fraser basin a few kilometers to the north are probably derived from nearby centers. Other rhyolite intrusions at Cabin Creek and Leavenworth Creek, 8 km northeast of the exposed part of the Montezuma batholith and within the gravity low shown by Brinkworth (1970), have been assigned a middle Tertiary age by R. B. Taylor and R. U. King on the basis of geologic evidence (in U.S. Geol. Survey, 1968, p. A30).

Never Summer Mountains

Wahlstrom (1944) described the eroded roots of a silicic volcano at Specimen Mountain in the northwestern part of Rocky Mountain National Park, and Corbett (1968) mapped contiguous remnants of a related volcanic field northwest of Specimen Mountain in the Never Summer Mountains. Corbett separated the volcanic rocks into two units: (1) an older assemblage of relatively mafic volcanic rocks, the Cameron Pass Volcanic Group, that probably forms part of a volcano centered above an andesite porphyry plug on Mount Richthofen (Corbett, 1968, p. 2-3), and (2) a younger assemblage of silicic volcanic rocks, the Specimen Mountain Group of Corbett (1968), derived from central vents at Specimen and Lulu Mountains. The older sequence was postulated to be Eocene in age, based on its compositional similarity to andesitic rocks interlayered with sedimentary rocks of Cretaceous to Eocene age in the nearby North Park basin. It seems equally plausible that some of the older rocks mapped by Corbett are generally equivalent to andesitic volcanic rocks in the Rabbit Ears Range to the west, which Izett (1966) has shown to be Oligocene in age. The younger silicic volcanic rocks in the Never Summer Mountains are largely pyroclastic rocks and local lava flows. A remnant of one formerly widespread sheet of ash-flow tuff has been preserved. The younger rocks were dated by Corbett (1968, p. 8) as 27 to 28 m.y. old.

The Never Summer stock of granodiorite and quartz monzonite cuts the older volcanic units along the west side of the area mapped by Corbett (1968, p. 28, Pl. 1). A K-Ar age of 28 m.y. obtained on the stock accords closely with the 27- to 28-m.y. ages obtained on the silicic volcanic rocks of the Specimen Mountain Group of Corbett.

The remnant of volcanic rocks preserved in the Never Summer Mountains appears to be only a small, near-source part of the original accumulation. Little detailed geological mapping is available on adjacent areas to the north, east, or south, and there is little evidence to indicate the former extent of the volcanic field in these directions. To the northwest, however, a wedge of volcanic rocks in the southeast part of North Park is considered by Kinney (1970a) as probably contemporaneous with the Rabbit Ears Volcanics that lie to the south and southwest. The volcanic rocks in southeast North Park are only 8 to 20 km northwest of volcanic centers in the Specimen Mountain area and probably were derived from them.

Intrusive plugs cut older sedimentary rocks in several places southwest of the Never Summer Mountains in the eastern part of the Rabbit Ears Range (Kinney, 1970b). Some of these intrusions probably mark the roots of volcanoes that may have produced a coalescing pile of volcanic rocks extending from the Never Summer Mountains to the large mass of volcanic rocks in the western part of the Rabbit Ears Range.

Rabbit Ears Range

The Rabbit Ears Range between North and Middle Parks, Colorado, is capped by an extensive sequence of mafic, intermediate, and silicic volcanic rocks that are cut by a series of volcanic necks and pluglike intrusive bodies that mark the roots of ancient volcanoes (Kinney and others, 1968, p. 3-6). Most of these volcanic rocks are included in the Rabbit Ears Volcanics (Izett, 1966, p. B42; 1968, p. 29-40) of Oligocene and Miocene(?) age. A sample of rhyolite obtained near the middle of this volcanic sequence was dated by K-Ar methods as about 33 m.y. old (Izett, 1966, p. B45), and a silicic ash-flow tuff at Troublesome Creek (on the south slope of the range) was dated by the fission-track method as 30 m.y. old (Naeser and others, 1973). Other fission-track ages from rocks in the Rabbit Ears Range (Naeser and others, 1973) are about 28 m.y. for a stock at Haystack Mountain and about 23 m.y. for a stock at Poison Ridge. The Rabbit Ears Volcanics rest unconformably on Upper Cretaceous and lower Tertiary sedimentary rocks and are overlain by, and perhaps interfinger with, Miocene basin-fill sediments of the Troublesome Formation (Izett, 1968, p. 36).

Volcanic breccia of the Rabbit Ears Volcanics has been mapped as far west as the crest of the Park Range near Rabbit Ears Peak (Hail, 1968, Pl. 2) and north into the southern part of North Park (Hail, 1968, Pls. 2 and 3; Kinney and Hail, 1970). Izett (1966, Fig. 1; 1968, p. 29) traced the same unit south to the Colorado River near Hot Sulphur Springs.

Tweto (1957, p. 24) described an intrusive center surrounded by patches of volcanic rocks at Green Mountain in the Blue River valley 28 km southwest of Hot Sulphur Springs. On the basis of geologic evidence, Tweto favored a late Tertiary age for the igneous activity of this locality, but a recent fission-track age on a sill at Green Mountain (Naeser and others, 1973) indicates emplacement about 30 m.y. ago. Other intrusive bodies and a rhyolite flow that occur along the west side of the Front Range 20 to 30 km northeast of Hot Sulphur Springs and south of the Never Summer Mountains have fission-track ages (Naeser and others, 1973) of generally 25 to 27.5 m.y.

Colorado Plateau

Numerous laccolithic intrusive centers have been emplaced in the flat-lying sedimentary rocks of the Colorado Plateau, and as summarized by Witkind (1964, p. 79), all these centers were originally believed to have been intruded at about the same time. Hunt (1956, p. 42) postulated that this was during the late Tertiary, but Witkind (1964, p. 79-81) concluded that the preponderance of available evidence favored Late Cretaceous-early Tertiary intrusion. More recently, isotopic age determinations (Armstrong, 1969; Dickinson and others, 1968; Damon, 1968) have shown clearly that two general episodes of intrusion were involved: (1) an older Laramide episode during which laccoliths were emplaced in the linear belt extending from the western San Juan Mountains southwestward to northeast Arizona, and (2) a middle Tertiary episode during which more widely scattered laccoliths were emplaced in southwest Colorado and southeast Utah (Armstrong, 1969, Fig. 1; Steven and others, 1972, Fig. 1). The Laramide intrusions are limited to a regional northeast-trending belt that includes numerous intrusions in the Colorado mineral belt of central Colorado, whereas the middle Tertiary laccoliths are widely dispersed, as are most other middle Tertiary igneous centers.

The three largest middle Tertiary laccolithic centers, the Henry, La Sal, and Abajo Mountains, have all been studied in detail. In the Henry Mountains, Hunt and others (1953, p. 147-148) concluded that the overburden at the time of intrusion was sufficiently thin so that volcanic venting probably took place, although no definite supporting evidence was found. The La Sal Mountains (Hunt, 1958, p. 319) contain pipelike masses of intrusion breccia that very likely indicate concurrent volcanic venting. Witkind (1964) cited no comparable evidence in the Abajo Mountains, although the logic applied to the Henry Mountains (Hunt and others, 1953, p. 147) would seemingly apply here as well. Although unproven, it thus is possible that scattered middle Tertiary volcanoes were active in the Colorado Plateau area west of the main composite volcanic field in the Southern Rocky Mountains.

RELATIONS TO BATHOLITHS

The area occupied by the composite volcanic field of middle Tertiary age is in part coincident with two large gravity lows (Fig. 3) that have been interpreted as reflecting the presence of shallow batholiths (Plouff and Pakiser, 1972, p. B186; Case, 1965; Tweto and Case, 1972, p. C18). The outlines of batholiths shown on Figure 3 were drawn along the trends of steepest gravity gradients bordering the gravity lows shown by Behrent and Bajwa (1972). The southern gravity low covers much of the San Juan Mountains and is nearly coincident with the distribution of calderas that mark the sources of major ash-flow deposits. The northern gravity low extends northeastward from the Elk Mountains and southern Sawatch Range along the trend of the Colorado mineral belt, encompasses the Montezuma batholith, and terminates at the east side of the central Front Range. This gravity low embraces the source areas of igneous rocks of both Laramide and middle Tertiary age.

Whereas the gravity low in the San Juan Mountains is almost coincident with the area of ash-flow-related calderas, it shows little relation to the distribution of early intermediate-composition central-vent volcanoes. This can be interpreted to indicate that the early central-vent volcanoes were fed from deep-seated, relatively mafic magma chambers, and that the high-level silicic batholith that fed the ash-flow eruptions and produced the gravity low did not rise to shallow depths until the middle of the volcanic episode. The silicic ash flows that were erupted indicate that the upper parts of the batholith were significantly more differentiated than the deeper magma chambers that fed the early intermediate-composition volcanoes. The less dense silicic rocks of the batholith have sufficient density contrast with the Precambrian host rocks to produce a clear-cut gravity low (Tweto and Case, 1972, p. C12-C13). The compositional zoning displayed by many major ash-flow sheets, which range from crystal-poor rhyolites at the base to crystal-rich quartz latites at the top, indicates a layered aspect of the differentiated magma chamber. This conclusion is further substantiated by the eruption of andesitic to rhyodacitic lavas from local centers during the general period of ash-flow eruptions; these centers presumably tapped the batholith at lower, less differentiated levels (Lipman and others, 1970, p. 2347).

The gravity low underlying central Colorado (Behrent and Bajwa, 1972; Tweto and Case, 1972, p. C17; Brinkworth, 1970) is a composite of several individual gravity lows produced by intrusions of two distinct ages. A gravity low underlying the southern Sawatch Range is centered on the Mount Princeton batholith and seems clearly related to this major middle Tertiary pluton. This gravity low is separated from a broad gravity low that extends west from the Sawatch Range

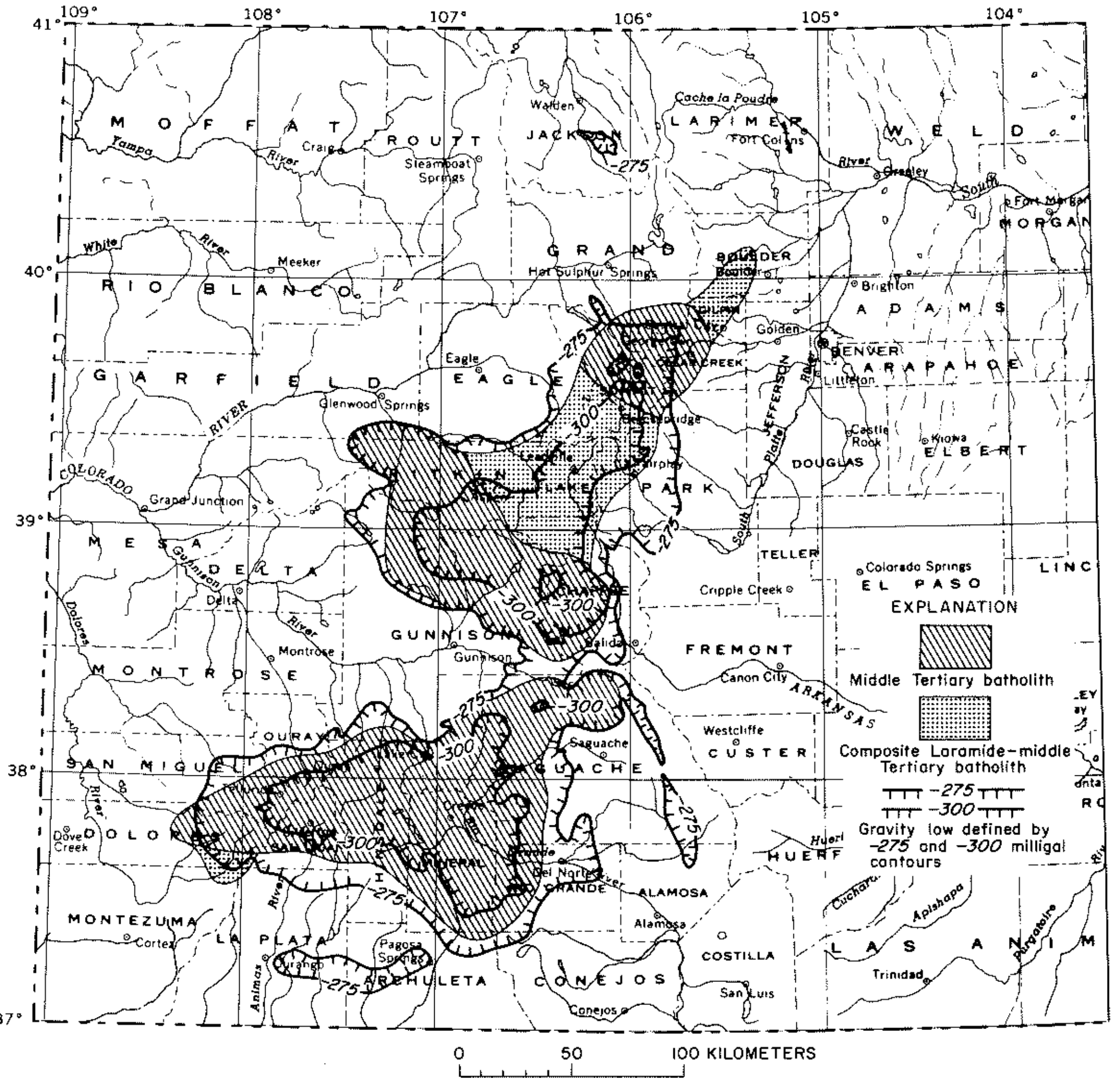

Figure 3. Map showing relation of postulated batholith to gravity lows (modified from Behrent and Bajwa, 1972; Tweto and Case, 1972; and Plouff and Pakiser, 1972).

under the Elk Mountains and the northern part of the West Elk Mountains by a low gravity divide. The broad gravity low coincides with an area of abundant middle Tertiary epizonal plutons (Obradovich and others, 1969) and probably reflects the presence of a large underlying batholith. The east end of this broad gravity low merges into a narrower northeast-trending low that extends from the Sawatch Range to the east side of the Front Range. In the Sawatch Range, the Grizzly Peak caldera of middle Tertiary age (Cruson, 1972; Obradovich and others, 1969) cuts the Twin Lakes stock of probable Laramide age. To the northeast—across the Sawatch Range, the upper Arkansas River valley, and the Gore and Mosquito Ranges—most of the hypabyssal intrusions are Laramide in age, but middle Tertiary intrusive bodies have been documented in places, and these may be more numerous than are presently known. The postulated batholith underlying this segment of the gravity low in central Colorado is very likely a composite of numerous plutons of both Laramide and middle Tertiary age. To the northeast, the deeper parts of the gravity low in central Colorado embrace the Montezuma batholith and seem largely to correspond to this major middle Tertiary intrusion. A shallower gravity trough extends northeast from the Montezuma batholith along the trend of the mineral belt to the eastern Rocky Mountain front. Numerous shallow intrusions are exposed along this trend. Most of those dated are of Laramide age, but some may have been emplaced in middle Tertiary time.

The parts of the composite middle Tertiary volcanic fields in the Rabbit Ears Range and Never Summer Mountains, in the Thirtynine Mile volcanic field-Cripple Creek area, in the Wet Mountains-Spanish Peaks area, and in the West Elk Mountains lack a clear-cut gravity expression. Like the andesitic rocks in the San Juan Mountains, the rocks of intermediate composition in these areas were probably derived from deep and relatively undifferentiated bodies of magma that did not contrast markedly in density with the adjacent wall rocks.

RELATION TO EARLIER IGNEOUS ROCKS

Most Laramide and middle Tertiary igneous rocks of equivalent silica content in the Southern Rocky Mountains are virtually identical in general composition and lithology. Both are predominantly intermediate-composition calc-alkalic rocks or somewhat more silicic differentiates. Some middle Tertiary rocks along the eastern fringe of the volcanic field are distinctly more alkalic, in common with many igneous areas along the cordillera of western North and South America. Although the distributions of the igneous rocks of the two ages differ greatly, both are strongly limited in one way or another by the Colorado mineral belt lineament. The batholith that probably underlies the mineral belt in central Colorado seems likely to be a composite of plutons of both ages. It thus seems likely that the two periods of igneous activity were related magmatic pulses generated by recurrent geologic processes.

Lipman and others (1972, p. 234–240) have proposed a genetic scheme that fits the broad requirements concerning composition, distribution, and tectonic setting of the rocks under discussion. In general, they proposed that an imbricate subduction system underlay western North America in Laramide and middle Tertiary time, with one zone dipping eastward under the Great Basin area of Nevada and western Utah and a parallel one descending under the eastern Colorado Plateau and Southern Rocky Mountains. These zones apparently were joined along a zone of horizontal shear within the low-velocity zone of the mantle. Using the method devised by Dickinson and Hatherton (1967) and Hatherton and Dickinson (1969), which related the K_2O/SiO_2 ratios of andesitic rocks to the depth of the underlying Benioff zone, they determined that these imbricate subduction zones dipped 15° to 20° E., a dip similar to those of modern continental-margin Benioff zones, although considerably more gentle than most intraoceanic Benioff zones.

Whereas this scheme provides a general mechanism for generating magmas of appropriate compositions in the proper gross tectonic settings, many detailed questions remain to be answered. Especially, why should the mineral belt lineament, which trends diagonally northeastward across the more north-trending Laramide uplifts and basins, have had such a profound influence in localizing igneous activity during both Laramide and middle Tertiary time? Except for deflecting the eastern margin of the Front Range somewhat, this lineament had little apparent effect on major Laramide structural blocks, and detailed accounts of the geology of many parts of the belt give no hint of localized stress fields or regional dislocations that might have influenced the recurrent generation and upward migration of magma. The lineament broadly follows the trend of a Precambrian shear zone (Tweto and Sims, 1963), but this shear zone is only one of several in the Southern Rocky Mountains and seems subordinate to the major Mullens Creek-Nash Fork shear zone in southern Wyoming that separates Precambrian terranes of greatly differing ages (Houston and others, 1968, p. 140-141). An adequate answer to this question would contribute greatly to an understanding of both the igneous rocks and the related ore deposits in the Southern Rocky Mountains.

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Controls of Sedimentation and Provenance of Sediments in the Oligocene of the Central Rocky Mountains

JOHN CLARK

Field Museum of Natural History
Roosevelt Road and Lake Shore Drive
Chicago, Illinois 60605

ABSTRACT

Oligocene rocks on the eastern side of the central Rocky Mountains are part of a broad expanse of such deposits extending from central Colorado to Saskatchewan. Resting unconformably on older rocks, they record renewal of sedimentation following an erosional episode. Only in western South Dakota and Nebraska and southeastern Wyoming do the succeeding Miocene beds lie conformably on the Oligocene; however, with few exceptions, the Oligocene strata have not been disturbed from their original attitude. Heavy mineral suites of the early Oligocene beds indicate derivation from local sedimentary rocks, from volcanic sources, and from the Black Hills, the Laramie Range, the Front Range, and perhaps other mountain uplifts. Late Oligocene strata in mapped channels were derived from about the same sources, whereas finer sediments of this age are mostly of pyroclastic origin.

Consideration of these beds and others previously mapped in central and western Wyoming permits reconstruction of the major elements of a probable Oligocene drainage system. Most of the streams flowed generally eastward, but local exceptions are indicated, and the drainage pattern differed in details from the present-day network.

The development of an aggrading fluvial regime, extending from central Colorado to Saskatchewan in Oligocene time, can scarcely have resulted from simple transgressive overlap, from basin downwarping near source mountains, from downwarp along a regional hinge, nor solely from overloading of the streams by volcanic ash. Instead, the evidence points to progressively drying climate with increased erosion as the major factor causing widespread fluvial deposition.