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ALLOCHTHONOUS PALEOZOIC BLOCKS IN THE TERTIARY SAN LUIS–UPPER ARKANSAS GRABEN, COLORADO*

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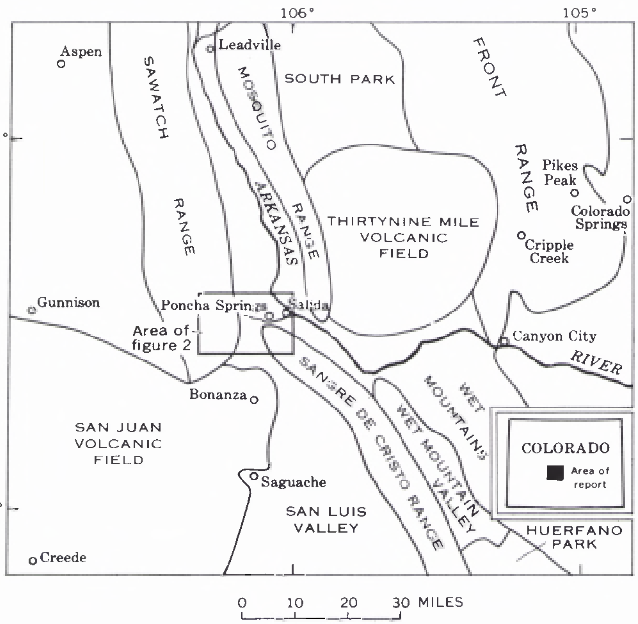

FIGURE 1.

Index map of south-central Colorado.

Geologic investigations, made in cooperation with the Colorado State Mining Industrial Development Board, southwest of Salida in the Southern Rocky Mountains of south-central Colorado (fig. 1), revealed more than 20 detached Paleozoic blocks within and adjacent to a Late Tertiary trough (Van Alstine, 1968). This narrow trough between the Sawatch and Sangre de Cristo ranges is part of the San Luis-Upper Arkansas graben (Tweto, 1968, p. 566, 582) and is the northward continuation of the Rio Grande depression (Bryan and McCann, 1938, p. 2-3; Kelley, 1956), a fault structure typical of the Basin and Range province. The detached blocks (fig. 2), composed mainly of brecciated carbonate rocks, are too large to have been transported by water. They were emplaced at several stratigraphic levels in the Dry Union Formation of Miocene and Pliocene age that fills the trough, evidently by gravitational sliding eastward from a structural high, the Sawatch Range (fig. 3). The trough deposits were derived largely from the same source area that shed the detached blocks. The Paleozoic blocks are now being exposed as the adjacent basin fill is removed by erosion.

Other interpretations have been given to several of the Paleozoic remnants. For example, from the presence of some of the brecciated Paleozoic masses, Russell (1950, pl. 1 and p. 17-18) inferred two steep fault zones and concluded that Paleozoic sedimentary rocks underlie the trough fill here.

DRY UNION FORMATION

The Dry Union Formation, named and defined by Tweto (1961) in the Leadville area about 45 miles north of Poncha Springs, records various geologic events that occurred in this area in Late Tertiary time. The formation is chiefly composed of unconsolidated gravel, sand, silt, clay, volcanic ash, and limestone deposited in alluvial-fan, mudflow, and pond environments, and it contains the detached Paleozoic blocks (fig. 4). The basal part is largely mudflow material consisting of unstratified gravel containing abundant clasts of vesicular basalt, andesite, and latite derived from Lower Oligocene lava flows at the eastern and southwestern edges of the trough. Especially conspicuous at many weathered outcrops are agates and blue-gray angular jasperoid fragments of intensely silicified volcanic rocks transported from the Bonanza volcanic center to the southwest (Burbank, 1932, p. 71-77; Cook, 1961, p. 289).

Within the Tertiary sediments above the basal volcanic gravel, clasts of Paleozoic rocks are common among the debris. They have lithologies and ages similar to those of the adjacent detached Paleozoic blocks found at several stratigraphic horizons. On the ridge crest east of Little Cochetopa Creek, blocks of limestone (some fetid and containing black chert) and dolomite (without chert) probably are from the Leadville Limestone of Mississippian age; fossils in similar limestone clasts in the adjacent debris were identified as (1) fragments of *Ovtia* cf. *O. laevicosta* (White), known to occur in the Leadville Limestone, (2) echinoderm debris, and (3) fragments of a syringoporoid coral (J. T. Dutro, Jr., written commun., Feb. 7, 1969). Precambrian debris containing gneiss, granite, and pegmatite boulders as much as 12 feet in diameter is predominant in the upper part of the trough fill. Thus, the stratigraphy of the Dry Union Formation locally reflects, in reverse, the sequence of rocks in the adjoining source areas; debris, first from Tertiary volcanic rocks and then from progressively older Paleozoic and Precambrian formations, was stripped, carried into the trough, and deposited.

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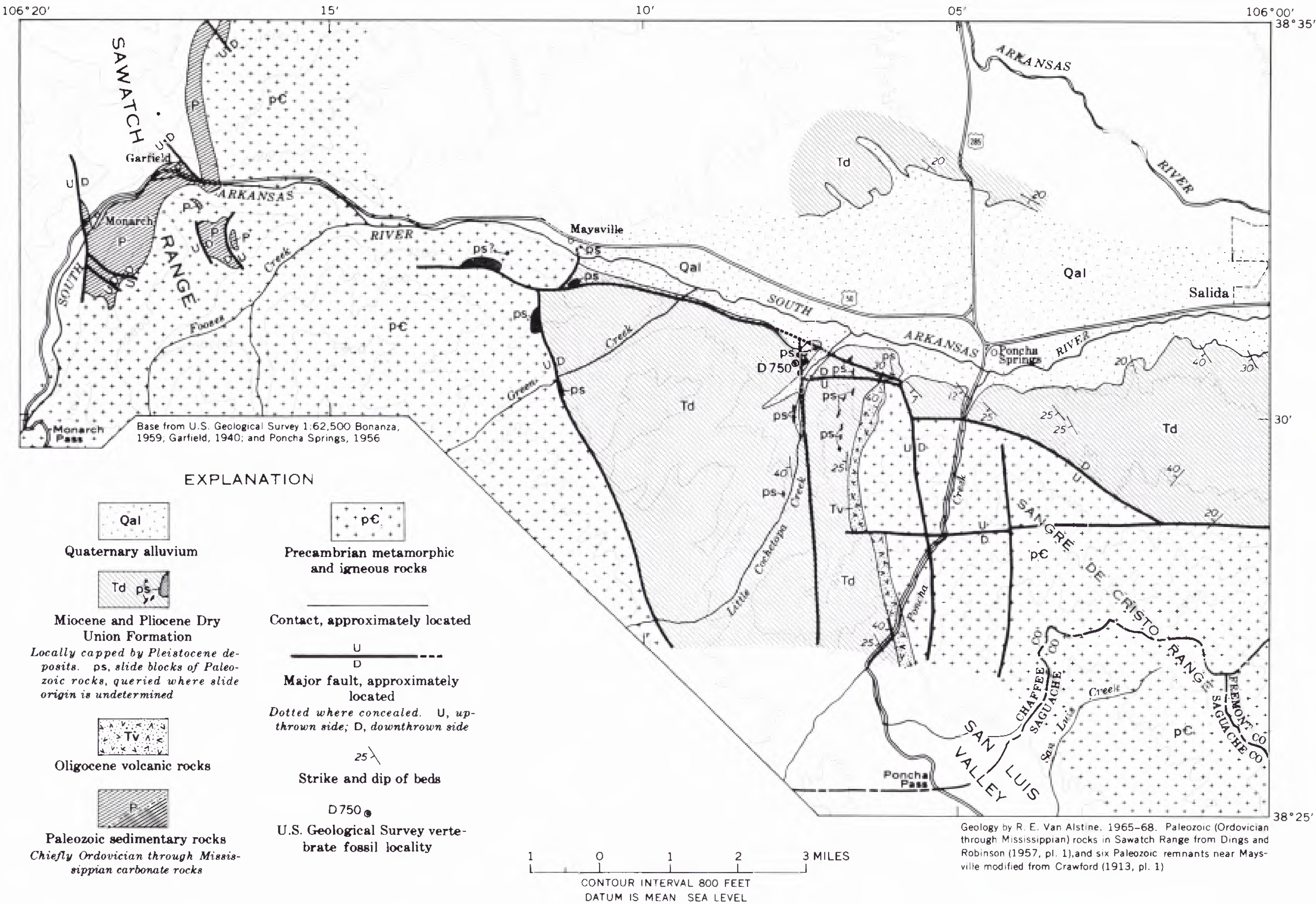

FIGURE 2.

Generalized geologic map of area between the Sawatch and Sangre de Cristo ranges, Chaffee County, Colo.

FIGURE 3.

View west across Late Tertiary trough to source area of slide blocks in the Sawatch Range, showing Dry Union sediments (Td) faulted against Precambrian gneisses (p€).

Mesozoic rock fragments from the Morrison Formation, Dakota Sandstone and Mancos Shale were not observed among the clasts in the Dry Union Formation and evidently were not shed eastward into this trough. These three formations are exposed on the west edge of the Sawatch Range. Dings and Robinson (1957, p. 9, 18-19) suggested that possibly several thousand feet of Mesozoic sedimentary rock was removed from the range by erosion. The apparent lack of Mesozoic debris in the Tertiary trough deposits indicates that the three Mesozoic units may not have covered the base- and precious-metal district near Monarch and Garfield in Tertiary time when the mineralization occurred.

In the area near Little Cochetopa Creek, the Dry Union Formation may be more than 10,000 feet thick, if the moderate westward dip persists to the fault at the west edge of the trough. The westward tilting possibly is related to Late Pliocene uplift of the Sangre de Cristo Range to the east.

The Pliocene age of some of the trough deposits now assigned to the Dry Union Formation was determined from fossil horse teeth and camel bones found to the east and north in the Arkansas Valley (Powers, 1935, p. 189; Van Alstine and Lewis, 1960). The age, however, is now extended to Late Miocene, for at vertebrate fossil locality D750 (fig. 2) several identifiable horse teeth were collected from locally gypsiferous greenish clays and silts. G. E. Lewis (written commun., Dec. 17, 1968) reported the fossils to be cheek teeth of *Merychippus* cf. *M. calamarius* (Cope) and stated that this species is characteristic of the Upper Miocene part of the middle (?) Miocene to lower Pliocene Tesuque Formation of the Santa Fe Group of New Mexico in the southern part of the same structural trough (Spiegel and others, 1963, p. 39-43, 62-63). Possibly, older Miocene fossils could be found in the trough fill below the beds at fossil locality D750 or to the east, nearer the contact of the deposits with the Lower Oligocene volcanic rocks. Fossil charophytes, ostracodes, gastropods, and pelecypods were collected from the pond sediments immediately beneath the strata at the vertebrate fossil locality. Specimens of the genus *Chara* probably are late Tertiary in age (R. E. Peck, written commun., June 6, 1967). Some of the ostracodes were identified as *Candona* spp. and *Darwinula?* sp., smooth, fresh-water types common in Tertiary sediments (I. G. Sohn, written communs., May 10, 1967, and Mar. 5, 1968). The other invertebrate fossils have not yet been studied.

ALLOCHTHONOUS PALEOZOIC BLOCKS

Seventeen detached Paleozoic blocks of various sizes are exposed within the Dry Union Formation east and west of Little Cochetopa Creek; similar blocks, mostly larger, are found in Precambrian terrane and trough fill at higher altitudes about 4 miles farther west (fig. 2). The blocks near Little Cochetopa Creek crop out at altitudes between

FIGURE 4.

View south along Little Cochetopa Creek, showing faulted Miocene and Pliocene sediments (Dry Union Formation, Td) containing blocks of Paleozoic rocks (ps); underlying Oligocene volcanic rocks (Tv) rest on Precambrian gneiss (P€) of Sangre de Cristo Range.

7,830 and 8,880 feet. In outcrop they commonly are longer north-south, are arranged mainly in two north-trending belts, and are oriented approximately parallel to the attitude of the enclosing sediments at several stratigraphic horizons, calculated at 700 to 2,600 feet above the base of the Dry Union Formation. One of the belts of Paleozoic blocks sustains a prominent ridge east of Little Cochetopa Creek.

The Paleozoic formations found in the detached blocks are the Manitou Dolomite, Harding Quartzite, and Fremont Dolomite of Early, Middle, and Late Ordovician ages, respectively; the Chaffee Formation of Late Devonian age; and the Leadville Limestone of Mississippian age. Especially distinctive among the predominantly carbonate rocks are the Harding Quartzite containing conspicuous fossil fish plates, the fossiliferous Fremont Dolomite, and the basal argillaceous part of the Chaffee Formation. Criteria for the recognition of the various Paleozoic formations, as found at higher altitudes in the Sawatch Range to the west, were given by Johnson (1944) and by Dings and Robinson (1957, p. 11-18). Litsey (1958, p. 1150-1161) has also described these units at a locality a few miles to the east at lower altitudes on the northeast flank of the Sangre de Cristo Range.

Although most detached blocks are composed of one or two of the Paleozoic formation, some contain as many as four. Near the west edge of Little Cochetopa Creek Valley just below an altitude of 8,000 feet, the largest and most accessible allochthonous block here is exposed in an area of about 400 by 800 feet and for a height of about 150 feet (fig. 5). Remnants of the Manitou, Harding, and Fremont Formations appear along the cliffed east face,

FIGURE 5.

Allochthonous Paleozoic block in the Dry Union Formation near the west edge of Little Cochetopa Creek Valley. View north.

and the crest and west slope are occupied by the Chaffee Formation. These brecciated Paleozoic units make up about 300 feet of strata in the exposure; the four units total approximately 540-700 feet in thickness where they are completely exposed in the Sawatch Range about 8 miles to the west (Dings and Robinson, 1957, p. 11-15) and in the Sangre de Cristo Range at a locality about 9½ miles to the east (Litsey, 1958, p. 1149). The bedding, still recognizable locally in this detached block, dips 25°-50° W., approximately parallel to the dip of the enclosing Tertiary beds; the steeper dips are near Late Tertiary faults.

The Paleozoic blocks are made up predominantly of crackled and brecciated dolomite and limestone. Much of the material, especially that near the base, consists of breccia fragments less than 2 inches in diameter. Sharply angular fragments and others rounded by abrasion are set in a highly indurated matrix of crushed carbonate rock cemented by calcite, generally fine grained but locally coarsely crystalline. Bedding is no longer evident in this type of breccia but is discernible in less brecciated parts of blocks. Irregularities of adjacent breccia fragments generally do not correspond in shape, which further suggests relative movement following brecciation. Brecciation occurred before the Paleozoic blocks came to rest within the Tertiary sediments, for fragments of brecciated Paleozoic rocks commonly occur in the immediately overlying and surrounding beds. Miocene ostracodal limestone beds of the Dry Union Formation above the largest Paleozoic block immediately west of Little Cochetopa Creek Valley contain small angular and rounded clasts of brecciated Paleozoic rocks (fig. 6).

Three and one-half to 5 miles west of Little Cochetopa Creek (fig. 2), Crawford (1913, pl. 2) mapped six patches of Paleozoic carbonate rocks, ranging in age from Ordovician to Mississippian. Some of these remnants of Paleozoic rock were shown in areas underlain by Precambrian gneiss; others were in areas underlain by unconsolidated fill. The remnants are at altitudes of 8,200 to 9,600 feet, about 3½ miles east of a large faulted synclinal mass composed of the same formations (fig. 2), which is exposed

FIGURE 6.

Angular and rounded clasts of brecciated Paleozoic limestone, dolomite, and chert in Miocene ostracodal limestone of the Dry Union Formation.

2-4 miles east of the Continental Divide and at altitudes of 10,500 to 12,000 feet (Dings and Robinson, 1957, pl. 1). Recent examination of the four Paleozoic remnants along the west edge of the Tertiary trough suggests that they are detached blocks; they are composed of thoroughly brecciated and calcite-cemented material typical of the other slide blocks farther east. Crawford (1913, p. 88, 101, and pl. 3, sec. *E-E'*) regarded two of the six Paleozoic remnants as synclines. Gabelman (1952, p. 1594) similarly interpreted the patches of east-dipping to nearly horizontal Paleozoic rocks as evidence for a synclinal area between the uplifted Sawatch and Sangre de Cristo ranges. Evidence for the east limb of this proposed syncline, however, is even less convincing, because on the west flank of the Sangre de Cristo Range, at its north end, the rocks that underlie the fill in the trough and overlie the Precambrian basement are not Paleozoic sedimentary rocks but volcanic rocks of Oligocene age (fig. 2).

TERTIARY FAULTING RELATED TO DETACHED BLOCKS

In this region near the junction of the San Luis and Arkansas valleys, Tertiary faulting probably occurred before, during, and after emplacement of the detached Paleozoic blocks in the Tertiary sediments. The continuity of the faults in many places is evident on aerial photographs but is not obvious in the field; this is especially true of the faults in the unconsolidated Dry Union Formation. The dip of the fault and the amount and direction of displacement commonly are not determinable.

Laramide faults

Possibly Early Tertiary faulting and associated folding initiated the conditions favorable for detachment and transport of the allochthonous Paleozoic blocks in later Tertiary time. In the adjoining quadrangle west of the area of detached breccia blocks, Dings and Robinson (1957, p. 36-40) described various types of Laramide faults, some mineralized with base metals. Their Tincup-Morning Glim fault (1957, p. 36), the mineralized Chester fault of the Marshall Pass uranium district about 10 miles south of Garfield (Wright and Everhart, 1960, p. 357-359), and the Eocene faults in the Bonanza mining district (Burbank, 1932, p. 38-41) about 15 miles south-southwest of Poncha Springs are all reported as thrust faults that displaced Precambrian rocks chiefly northward or westward over Paleozoic rocks. To the north near Aspen, Colo., the Elk Range thrust sheet may have formed in Early Tertiary time by gravity sliding of a thick section of Upper Paleozoic and Mesozoic sedimentary rocks off the steep western flank of the Sawatch Range uplift (Bryant, 1966).

Miocene north-trending border faults

The north end of the San Luis Valley, structurally part of the Rio Grande depression, is bordered on the east by a steep fault that formed chiefly from Late Oligocene to the end of Tertiary time, according to Burbank and Goddard (1937, p. 965). More recently, others have reported that downfaulting of this depression began in Miocene time (Gabelman, 1952, p. 1606; Kelley, 1956; Lipman and Mehnert, 1968; Steven and Epis, 1968, p. 248-249). Recent fieldwork in the Poncha Springs and Bonanza quadrangles similarly shows that faults bordering the trough formed at some time between the eruption of Oligocene volcanic rocks and the deposition of sediments of Late Miocene age. As suggested below, recurrent movement of the fault at the west border of the trough (fig. 2) may have helped the eastward transfer of the detached Paleozoic blocks along their underlying slide surfaces and over the Tertiary sediments.

Post-Pliocene faults

Steep north-trending and east-trending faults cut some of the detached Paleozoic blocks and the adjacent Dry Union sediments of Miocene age near Little Cochetopa Creek (fig. 2), as well as the fossiliferous Pliocene part of the Dry Union Formation farther north and east. West of the creek, a north-trending fault zone dips about 70° W.; argillaceous beds near the base of the Chaffee Formation of Late Devonian age that are normally pink are locally green and sheared along this fault zone. The east-trending fault cutting the Dry Union Formation south of the South Arkansas River (fig. 2) dips steeply north and offsets the linear belts of detached Paleozoic blocks near Little Cochetopa Creek. Along the fault, the north side has been displaced downward and to the east. The Arkansas Valley is about 1,000 feet lower than the San Luis Valley as a result of downfaulting along the east-trending and north-trending Late Tertiary structures and also because of more active erosion in the Arkansas drainage during Pleistocene and Holocene time (Van Alstine, 1970). About 3 miles east of Salida, Rold (1961, p. 116 and fig. 4) also reported right-lateral movement on a probably related east-trending fault zone on the northeast flank of the Sangre de Cristo Range.

EMPLACEMENT OF THE DETACHED BLOCKS

Detachment of the Paleozoic blocks evidently resulted from recurrent gravitational sliding off the flank of the Sawatch anticline and off the upthrown side of the fault at the margin of the Late Tertiary trough. Emplacement of the blocks within the Dry Union Formation near Little Cochetopa Creek is dated fairly closely, for it occurred after Oligocene volcanism, during Dry Union sedimentation, and before deposition of the beds containing the vertebrate fossils of Late Miocene age. At this time the Paleozoic rocks to the west were being very actively eroded, as shown by the abundant clasts from Lower, Middle, and Upper Paleozoic carbonate rocks, Lower Paleozoic quartzite, and Upper Paleozoic arkosic sandstones found within the Tertiary sediments immediately above and below the blocks. Mudflows associated with the blocks in the Dry Union Formation further indicate that landslides were very active at this time.

The blocks are not overturned, suggesting that the sliding was not accompanied by toppling that occurs during rockfall or flow; the normal stratigraphic section of Paleozoic rocks can be recognized in less brecciated parts of some blocks, as previously described. The brittle carbonate rocks and quartzite were broken into many detached blocks that moved independently and were emplaced without markedly disturbing the underlying Tertiary sediments. Near the northeast crest of the ridge east of Little Cochetopa Creek, the lower surfaces of two blocks strike about N. 20° E. and dip about 20° W.; this attitude is approximately parallel to that of the enclosing Tertiary sediments, as shown locally by stratification and by the orientation of boulders and cobbles in the underlying mudflow. The material immediately beneath these Paleozoic blocks is made up of unbrecciated clasts consisting largely of Tertiary volcanic and Paleozoic carbonate rocks in a clayey gouge. The contacts between the underlying sediments and the bases of the breccia blocks obviously were the surfaces along which the blocks slid.

Intrusion of a batholith and stocks northwest of the area and local differential movement may have increased the gravitational potential for sliding. Doming probably accompanied emplacement of the Mount Princeton batholith and other intrusive bodies (Dings and Robinson, 1957, p. 25-27, 31-32); these Tertiary intrusives have not yet been precisely dated. Differential movement caused by uplift of the Sawatch Range or lowering of the Rio Grande trough in Miocene time probably triggered the eastward transfer of Paleozoic blocks over the Precambrian terrane and down the flank of the Sawatch anticline, the major Laramide structure. Some detached blocks came to rest on Precambrian gneiss and on trough fill near the fault at the west edge of the Tertiary depression. Other blocks slid farther east over the well-lubricated mudflows and other unconsolidated sediments of Late Tertiary age.

Although a highland source area for the detached blocks is available to the west in the Sawatch Range, the actual bedrock structure or structures that furnished the slide blocks are not definitely known. The downfolded and downfaulted masses of Lower and Middle Paleozoic bedrock near Monarch and Garfield (fig. 2) are the most probable sources now remaining in this extensively eroded, largely Precambrian terrane. These masses in the Monarch district were locally mineralized with base-metal sulfide minerals in Early Tertiary time (Crawford, 1913, p. 195-283; Dings and Robinson, 1957, p. 81-95), but sulfide minerals were not seen in the detached breccia blocks in the trough.

The magnitude of slope of the surface of transport is not definitely known. If the blocks now at an altitude of about 8,800 feet near the fault along the west border of the Tertiary trough slid eastward about 3½ miles from the nearest large synclinal mass, which is at an altitude of about 10,500 feet (fig. 2), the inclined slide surface would slope east at about 5°; such a slope is well within the range in which mudflows respond to gravity and twice the slope angle of the Wyoming Heart Mountain detachment fault along which Paleozoic masses slid (Pierce, 1963, p. 1234). One cannot estimate the slope angle of the similar inclined surface of transport from the possible source area in the Sawatch Range eastward for 9½ miles to the Paleozoic blocks beyond Little Cochetopa Creek; this surface would cross the border fault of the Tertiary trough, which probably was active during and has been active since the time of gravitational sliding. A further complication is the fact that the Paleozoic blocks and enclosing Tertiary beds have been tilted westward since emplacement.

Furthermore, no estimate can be made of the attenuation that occurred in individual blocks during gravity sliding, because examination of the detached blocks fails to show precisely when brecciation and thinning of the stratigraphic section took place; an unknown amount perhaps occurred before the masses were freed from the bedrock to slide as isolated blocks. In the probable source area to the west, all Paleozoic formations are separated by erosional unconformities, and reduced thicknesses of the Lower Paleozoic rocks also resulted from Laramide faulting and squeezing of the beds (Dings and Robinson, 1957, p. 9, 11).

OTHER EXAMPLES OF GRAVITATIONAL SLIDES IN THE WESTERN UNITED STATES

Other areas of the Western United States contain excellent, well-documented examples of localities where gravitational sliding is the suggested mechanism for the formation of detached and brecciated blocks. About 50 miles east of the area under investigation, in the Milsap Creek area of Fremont County, Colorado, blocks of Lower Paleozoic carbonate and Precambrian rocks slid westward, probably in Late Cenozoic time, down the flank of the Cripple Creek arch and onto Upper Paleozoic rocks in a graben (Gerhard and Wahlstedt, 1965). Along the Front Range west of Fort Collins, Colorado, blocks of standstone of the Dakota Group slid down the dip slopes of hogbacks in Pleistocene time and overrode younger Cretaceous strata (Braddock and Eicher, 1962). South of the Owl Creek Range, Wyoming, brecciated Paleozoic blocks moved during Early Tertiary time by gravity sliding across a frontal fault zone and onto Triassic redbeds in the Wind River Basin (Wise, 1963).

Even more analogous to the detached blocks southwest of Salida, Colorado, are various structures formed when gravity sliding occurred during deposition within Tertiary basins and when the blocks became incorporated within the sediments. Pierce (1957, 1960, 1963) has given detailed accounts of detachment faults on the west side of the Bighorn Basin, Wyoming, along which allochthonous blocks of brecciated Paleozoic rocks moved 5 to 30 miles basinward; some finally came to rest within Eocene sediments (Pierce and Nelson, 1968).

The Basin and Range province of the southwest similarly contains many gravity slide blocks formed in Cenozoic time. In the Shadow Mountains area, San Bernardino County, California, beds or large lenses of brecciated carbonate rocks of Early Paleozoic age occur at several horizons in sediments of Middle Tertiary age; detached blocks moved laterally and evidently were emplaced under the influence of gravity (Hewett, 1956, p. 88-90, 96, 99). About

100 miles southwest of there, large blocks of brecciated Paleozoic limestone slid northward, possibly on a cushion of trapped air (Shreve, 1968), for several miles beyond the San Bernardino Mountains and onto Upper Tertiary sediments of the Mojave Desert (Woodford and Harriss, 1928, p. 279-283, 287-290). Gravity sliding attenuated the stratigraphic section to one-fourth the normal thickness in allochthonous Paleozoic masses in Miocene-Pliocene sediments in the Horse Range of east-central Nevada (Moores, 1968, p. 94-96; Moores and others, 1968, p. 1716, 1719). In the San Manuel area, Pinal County, Arizona, a large lens about 500 feet thick and 4,500 feet long, composed chiefly of blocks of Paleozoic limestone and Precambrian diabase, slid laterally about 8 miles from the probable source area to the resting place within Upper Tertiary sediments of the basin (Creasey, 1965, p. 20-22). Sheets of Upper Cretaceous sandstone in the Jicarilla Mountains of central New Mexico moved under the influence of gravity from an area domed by intrusion; the blocks rest on the eroded surface of Triassic and Permian rocks and are partly covered by the Ogallala Formation of Pliocene age (Budding, 1963).

Gravity slide blocks may also occur near the east edge of the Rio Grande trough in the Santa Fe area, New Mexico. Large detached blocks of Pennsylvanian (?) quartzite are arranged in a linear belt parallel to the strike of adjacent strata in the Tesuque Formation (Miocene and Pliocene) of the Santa Fe Group (Spiegel and others, 1963, p. 63, 76-78). The authors suggested that the blocks may represent ancient talus from basement rocks raised to the surface along a fault not yet recognized; the possible origin of the blocks by gravity sliding from reported exposures at greater altitudes several miles to the east seems worthy of further consideration.

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