INTRODUCTION

Ground water is the only source of supply in many parts of a 50,000-mi^2 area east of the Rocky Mountains of Colorado. The principal sources of ground water are the shallow aquifers in sediments of Tertiary and Quaternary age located on the High Plains along the eastern margin of the State and in the valleys of the principal rivers—the South Platte, the Arkansas, and some of their tributaries. Underlying these shallow and somewhat localized aquifers are potential water-yielding strata contained in extensive bedrock formations, of Pennsylvanian through Cretaceous age. The Cretaceous bedrock formations are extensively developed as water supplies in the southeastern part of Colorado and near Denver. Elsewhere, little use is made of the large volumes of water contained in the bedrock formations and little is known of the depth, thickness, and water-yielding character of the permeable strata. Such information is needed to properly evaluate the potential for developing new sources of potable water in this critically water-short area. Better knowledge of aquifers containing nonpotable water also is needed because these strata might serve as a source of water for industrial use, as a source of warm water for geothermal applications, or as a repository for disposal of liquid waste.

In 1981 the U.S. Geological Survey began a 5-yr study of the bedrock aquifers in the central midwestern region of the United States as part of an ongoing Regional Aquifer System Analysis (RASA) program. The study area includes Kansas, Nebraska, Oklahoma, eastern Colorado, southern Missouri, northern Arkansas, and small parts of South Dakota, Texas, New Mexico, and Wyoming. This report presents initial results of this study for the area of eastern Colorado extending eastward from the Precambrian outcrop along the Front Range of the Rocky Mountains (fig. 1). The purpose of the study is to evaluate the water resources of Cretaceous and older formations in the study area. This includes a description of the geohydrologic system and estimation of aquifer characteristics and ground-water quality. The aquifers investigated in the RASA program are defined on the basis of their regional hydrostratigraphic characteristics, and have designations as shown in figure 2.

In eastern Colorado, the formations investigated extend downward from the Cretaceous Laramie Formation to the Precambrian rocks and range in depth from 0 to 15,000 ft. Principal aquifers identified in this interval include the Laramie-Fox Hills, the Dakota-Cheyenne, and the Entrada-Dockum; minor aquifers include the Fort Hays-Codell, the Lyons, and the Fountain. These local aquifer names correlate with the regional hydrostratigraphic units as indicated in figure 2. Although water-yielding units were identified in Mississippian and older rocks, none were of sufficient hydraulic conductivity and areal extent in eastern Colorado to merit inclusion in this report.

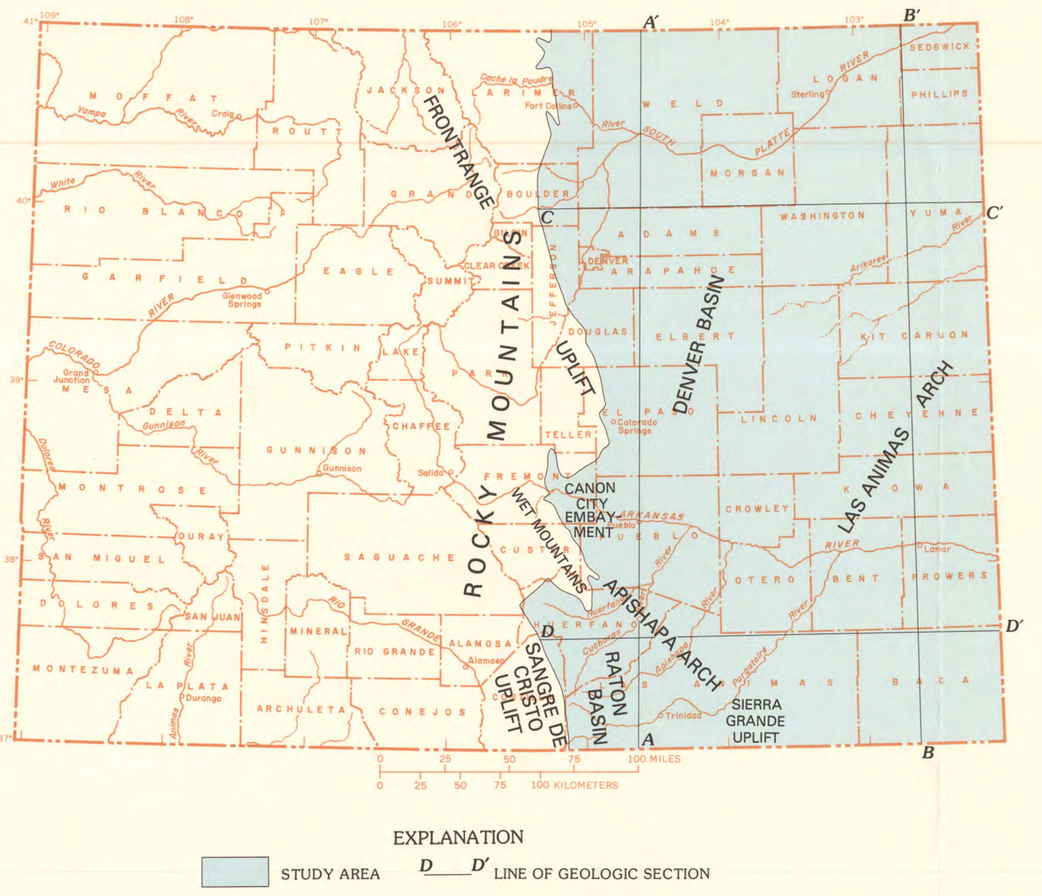

Figure 1.—Location of principal structural features of eastern Colorado.

GEOLOGIC HISTORY AND STRUCTURAL FEATURES OF EASTERN COLORADO

Bedrock aquifers identified in this study primarily are contained in coarse clastic sedimentary rocks of continental or shallow marine origin. The geologic processes involved in the deposition, deformation, and alteration of these sediments have been discussed in varying detail by numerous authors. The following discussion summarizes the findings of some of these studies and is based primarily on work published by Maher (1953a, 1953b), McCoy (1953), Wilson (1958), Haun and Weimer (1960), Oriel and Craig (1960), Martin (1965), Howard (1966), Garbarini and Veal (1968), Young (1970), Rocky Mountain Association of Geologists (1972), Levandowski and others (1973), Weimer (1973), Berman and others (1980), De Voto (1980a, 1980b), Maughan (1980), Ross and Tweto (1980), Tweto (1980a), and Nibbelink (1983).

Paleozoic units of eastern Colorado rest unconformably on a weathered Precambrian surface of complex sedimentary, metasedimentary, volcanic, and granitic rocks. Although some permeability exists in Precambrian regolith in the outcrop, and to a lesser extent in the paleoregolith at depth, the Precambrian rocks are considered to be an impermeable base for the bedrock aquifer system in the subsurface of eastern Colorado.

Cambrian through Mississippian sedimentation in eastern Colorado was generally associated with erosion of two structurally positive areas located northeast and southeast of Colorado. Deposition during this time was concentrated in an east-west trending trough located between the two positive areas. Recurrent tectonic uplift affected the sedimentary facies patterns in the trough, and erosion removed younger sediments from emergent areas. A complex sequence of nondeposition and erosion resulted in an incomplete geologic record of early Paleozoic time. Only sedimentary rocks of Late Cambrian, Ordovician, Late Devonian, and Mississippian age are preserved in eastern Colorado; these strata are present in a roughly triangular area with vertices in Pueblo, Yuma, and Baca Counties. The Cambrian and Mississippian rocks consist primarily of marine carbonates interlayered with minor amounts of sandstone and shale. The aggregate carbonate thickness for this interval exceeds 1,000 ft in the southeast; the aggregate sandstone thickness rarely exceeds 100 ft. During the Cambrian through Mississippian Periods, eastern Colorado remained a tectonically stable area of only moderate broad-scale structural movement. Such movements caused episodic transgressions of seas from the north and west.

Marked changes in the geologic structure of eastern Colorado occurred during Pennsylvanian time. These strata record a history of marine encroachment from the southeast over the eroded surface of Mississippian and older rocks. Carbonate deposition predominated in most of eastern Colorado; however, tectonic movement rapidly elevated the ancestral Rocky Mountains so that coarse-grained fluvial sediments were deposited on alluvial fans, bajadas, and braided alluvial plains near the mountain fronts along the entire western margin of the study area. The black marine shale and carbonates of the eastern part of the study area change facies and intertongue to the west with nonmarine siltstone and arkosic sandstone which in turn change facies to the coarse-grained arkosic sandstone and conglomerate of the Fountain Formation and related formations. The ancestral Rocky Mountains were composed of several discrete uplifted areas, each of which was fringed by Pennsylvanian aprons of arkosic detritus; these areas include the Front Range uplift, Apishapa Arch, Sangre De Cristo uplift, and Sierra Grande uplift in eastern Colorado (fig. 1). Displacement across several northwest-trending faults accounts for some of the estimated 10,000 ft of structural relief produced by Pennsylvanian tectonism. Lesser uplift initiated the development of the Las Animas Arch. Marine and continental sedimentation continued through Pennsylvanian time. Today as much as 1,500 ft of Pennsylvanian carbonates occur along the axis of the depositional basin in central eastern Colorado, and more than 1,200 ft of coarse clastics occur along the northern flank of the Apishapa Arch and north along the western margin of the present Denver Basin to west of Greeley. The Fountain Formation thickens toward the outcrop and is more then 4,500 ft thick at the type locality on Fountain Creek near Colorado Springs. By the end of the Pennsylvanian age, sediments had covered all of eastern Colorado with the exception of the crest of the Apishapa Arch.

Sedimentary rocks of Permian age in eastern Colorado record a period of relatively stable tectonism during which continued erosional reduction of uplifts coupled with sedimentation of basins led to the general leveling of Colorado terrain. Deposition in shallow transgressive and regressive seas and on bordering areas produced today's lithology which ranges from eolian and littoral clastics to marine siltstone and evaporites. In northeastern Colorado near the basin depocenter, regressive seas produced an evaporite sequence as much as 500 ft in aggregate thickness. The anhydrite, gypsum, and halite deposits in this area are the most significant evaporites in eastern Colorado. Near the western margin of the depositional basin ("Front Range" in fig. 2), eolian, fluvial, and littoral deposits formed the Lyons Sandstone, which thins eastward and changes facies from sandstone to the interlayered siltstone and evaporites of the central part of the depositional basin. The Lyons Sandstone crops out along most of the eastern margin of the Front Range, is thick near Lyons, Colo., and in the south-central part of the study area, and pinches out in the northeastern part of the area. Permian sedimentation buried the Apishapa Arch for the first time and was the final stage of a more or less continuous process of deposition begun during Pennsylvanian time. The ancestral Rocky Mountains, located to the west of the present mountain front, were relatively low-lying land masses by the end of the Permian age.

During Triassic and Jurassic time, eastern Colorado remained a tectonically stable area of moderately low relief. Major structural elements that existed from late Paleozoic time still influenced Triassic and Jurassic sedimentation, although the substantially subdued relief and modified shape of the topography limited the generation of detritus. Southerly encroachment of seas into Utah and western Colorado was accompanied by intermittent marine encroachment from the north and south into eastern Colorado. Continental and marine sedimentation occurred during Early and Late Triassic time and Middle to Late Jurassic time, but no geologic record of part of the early Mesozoic era was left because of nondeposition or subsequent erosion.

Triassic sedimentation extended over all but the northeastern part of eastern Colorado and deposited the thickest section west of, and parallel with, the present axis of the Denver Basin. This pattern of deposition may have been affected by the initial downwarping of the present Denver structural basin. Triassic sediments primarily consist of fluvial, medium- to fine-grained clastics and evaporite beds. Sandstones of the Triassic Dockum Group (fig. 2) exceed 500 ft in aggregate thickness and extend into southeastern Colorado from more extensive deposits in Texas, northern New Mexico, western Oklahoma, and western Kansas. Sandstone of the Triassic Jelm Formation unconformably underlies the Jurassic Sundance Formation and Entrada Sandstone in the northern part of the study area; differentiation of these Triassic and Jurassic units is difficult. Middle to Late Jurassic sedimentation covered all of eastern Colorado; these sedimentary rocks are in unconformable contact with underlying Permian and Triassic sedimentary rocks. In the south-central part of the study area, the Entrada Sandstone overlies lithologically similar sandstone in the Dockum Group, and the Triassic-Jurassic contact is not easily discernible. These eolian, lacustrine, and littoral clastics extend into eastern Colorado from the north and south, attain an aggregate thickness of 150 ft or more in much of the area, and grade into overlying marine sedimentary rocks. Marine deposition extended over all of Colorado in Late Jurassic time. Regressive seas and subsequent erosion of emergent areas produced coarser sedimentary rocks near the unconformity at the top of the Jurassic section.

The Cretaceous Period was typified by deposition associated with repeated transgressive and regressive movements of seas through a downwarping inland basin that extended over Colorado and much of the central United States. Deposits in excess of 10,000 ft thick were laid down in the area formerly occupied by the ancestral Rocky Mountains. The present Rocky Mountains west of Denver occupy part of this area and were uplifted (figs. 1 and 3, sections C-C′, D-D′) from the bottom of this Cretaceous basin.

In Early Cretaceous time, erosion of source areas to the west, east, and southeast of Colorado led to the deposition of fluvial sediments in eastern Colorado. Subsequent basinal subsidence caused submergence and the deposition of marine-transitional clastics overlain by marine shale. Renewed uplift of eastern and western source areas produced additional influx of detritus and caused a northward regression of the sea; however, downwarping ultimately predominated and led to another transgressive stage. This sequence of alternating continental and marine deposition produced the interlayered coarse clastics and marine shale of the Dakota Group (fig. 2). The sandstone units of the Dakota Group are variously known as, or are equivalent to, the Cheyenne Sandstone Member of the Purgatoire Formation, the Dakota Sandstone, and the "J" and "D" sandstones of the Dakota Sandstone. Aggregate thickness of these sandstone units exceeds 300 ft at scattered locations in eastern Colorado.

Deposition of carbonates and fine clastics predominated during Upper Cretaceous time, although at least three regressive intervals during this period produced minor amounts of interedded terrestrial sandstone in these otherwise marine strata. As much as 8,000 ft of marine shale and carbonate rock are present today in strata that thicken from east to west. Basinal subsidence prevalent in Early Cretaceous time was replaced by uplift in south-central Wyoming and Colorado during Late Cretaceous time. The resulting regression produced up to 200 ft of littoral sandstone of the Fox Hills Sandstone interbedded with, and underlain by, offshore marine sedimentary rocks and overlain by deltaic sedimentary rocks of the Laramie Formation (fig. 2). The close of the Cretaceous Period in eastern Colorado was characterized by a distinct change from a pattern of marine deposition to a pattern of deposition in fluvial, piedmont, and braided alluvial plains environments often extending into freshwater lake or swamp environments.

The dominant geologic event of the Tertiary Period in Colorado was the uplift of the Rocky Mountains, which began in the Cretaceous age and continued as episodic movements into the Eocene Epoch. Major downwarping of the Denver Basin into its present asymmetrical north-south trend also occurred during this period. As much as 20,000 ft of structural relief was produced between Precambrian rocks in the trough of the Denver Basin and rocks exposed in the mountains to the west. Abrupt deformation of Paleozoic and Mesozoic strata along the margin of the uplift has produced steeply dipping to overturned beds and hogback topography in some areas. In other areas, low-angle reverse or thrust faulting has been the principal displacement mechanism, and Paleozoic and Mesozoic strata are truncated by, and in lateral contact with, Precambrian rocks of the Rocky Mountains. Extensive volcanism occurred along the western margin of the Raton Basin during the Tertiary Period. The stocks of present day Spanish Peaks and Silver Mountain extend through Cretaceous and lower Tertiary strata and are surrounded by hundreds of radial dikes that extend to a distance of 40 mi or more to the east and northeast. To the west, the dikes extend only a few miles and generally do not cut the north-trending outcrop of the Dakota Sandstone.

Tertiary and Quaternary headward erosion of the South Platte River and the Arkansas River systems extended northward and southward near the mountain front and captured the smaller streams that had formerly flowed to the east from the mountains. The reduced discharge of the beheaded eastward drainages, coupled with the downcutting of new northerly and southerly drainages, led to the establishment of new drainage patterns in much of eastern Colorado. More easterly tributaries to the South Platte and the Arkansas Rivers were gradually added to the drainage systems as the scarp of the eroding Tertiary sediments retreated farther east, and the valleys of the South Platte and the Arkansas Rivers deepened and widened. Tertiary strata were removed from much of eastern Colorado leaving the present remnants on the High Plains and in the Denver and the Raton Basins. Downcutting of the Purgatoire River and other tributaries to the Arkansas River has exposed Lower Cretaceous through Permian strata along the crests of the Apishapa Arch and Sierra Grande uplift. Cretaceous strata outcrop or subcrop in most of central eastern Colorado.

The present structural features of eastern Colorado (fig. 3) resulted from the tectonic and depositional history of the area. Many of the major faults or fault zones originated in Precambrian time and have been repeatedly reactivated in more recent time. Patterns of movement on the reactivated faults sometimes have been radically different from the Precambrian movement due to subsequent changes in stress. In some cases, changes in stress have produced fault zones in which a complex series of movements have occurred as indicated by numerous fault surfaces of varied dip and direction of displacement.

Large-displacement faulting associated with the uplift of the Rocky Mountains generally is confined to a 5- to 10-mi-wide zone paralleling the mountain front (fig. 4). Vertical displacements on some of these faults exceed 10,000 ft and are principally associated with dip-slip movement. Westward-dipping reverse or thrust faults predominate in the interval from Boulder to Pueblo, and Precambrian rocks of the hanging walls have overridden younger rocks of the footwalls. The Sangre de Cristo uplift produced a zone of complex thrust faulting along the western flank of the Raton Basin. Subsequent faulting associated with intrusion of Tertiary volcanics has increased the complexity of faulting in this area, and vertical displacements exceed 10,000 ft across this fault zone. Large-displacement faults are less common along the mountain front north of Boulder; in this area folding and associated transverse faulting is the principal deformational mechanism. East of Boulder, a zone of complex growth faulting exists in the Upper Cretaceous sedimentary rocks. These northeast-trending faults have vertical displacements ranging from about 50 to 500 ft and generally do not extend below the upper part of the Pierre Shale.

Concealed faults in the buried Precambrian surface are primarily associated with deformation of the Apishapa Arch or with other more widespread adjustments in the Precambrian structure. Total vertical displacements on Precambrian faults are not known, due in part to the regional nonconformity at the top of the Precambrian; present-day offsets in the buried Precambrian surface indicate as much as 3,000 ft of vertical displacement on some faults (fig. 4). Faults in northeastern Colorado generally have an east or northeasterly trend and apparent vertical displacements of less than 100 ft. Near the Apishapa Arch a more complex pattern of movement has developed in response to differential elevation of the Arch, and apparent displacements commonly exceed 500 ft.

The following discussion of aquifers in eastern Colorado is presented in order of youngest to oldest rocks to facilitate discussion of the interconnected ground-water flow systems in some units. Although the Laramie-Fox Hills aquifer is the uppermost aquifer considered, it is overlain by other bedrock aquifers in sedimentary rocks of Cretaceous and Tertiary age. These aquifers have been studied by Romero (1976), Robson and Romero (1981a, 1981b), Robson, Romero, and Zawistowski (1981), and Geldon (1984), and are not discussed in this report.

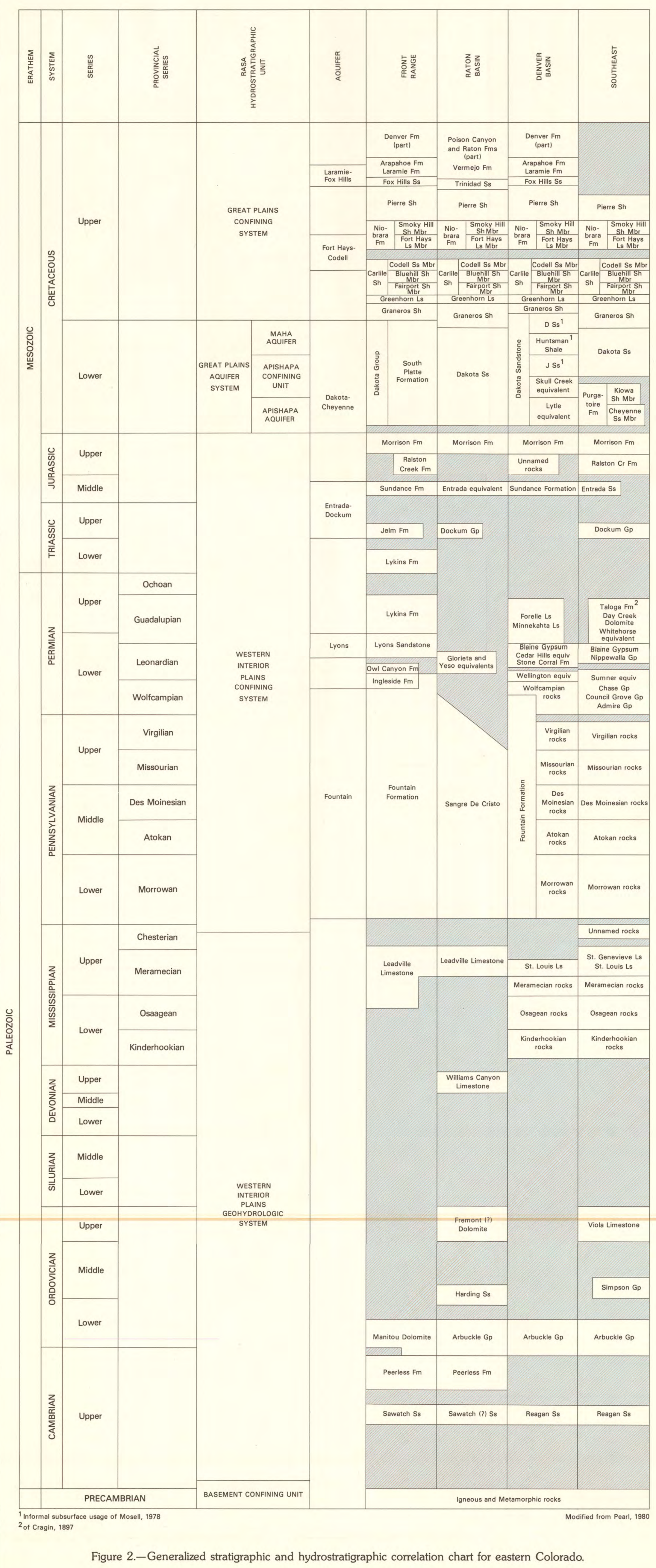

Figure 2.—Generalized stratigraphic and hydrostratigraphic correlation chart for eastern Colorado.

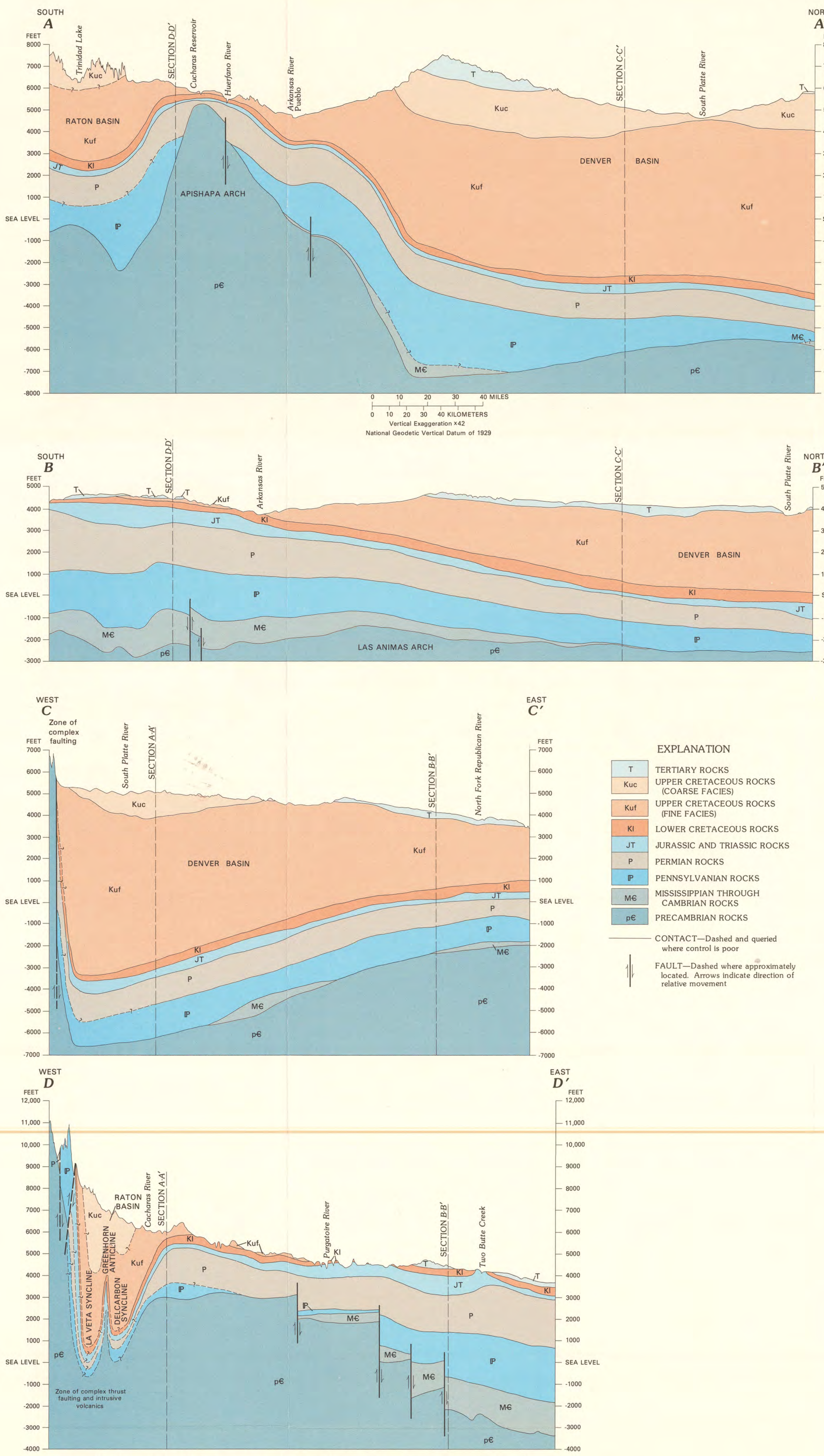

Figure 3.—Generalized geologic sections through eastern Colorado (trace of sections located in figure 1).

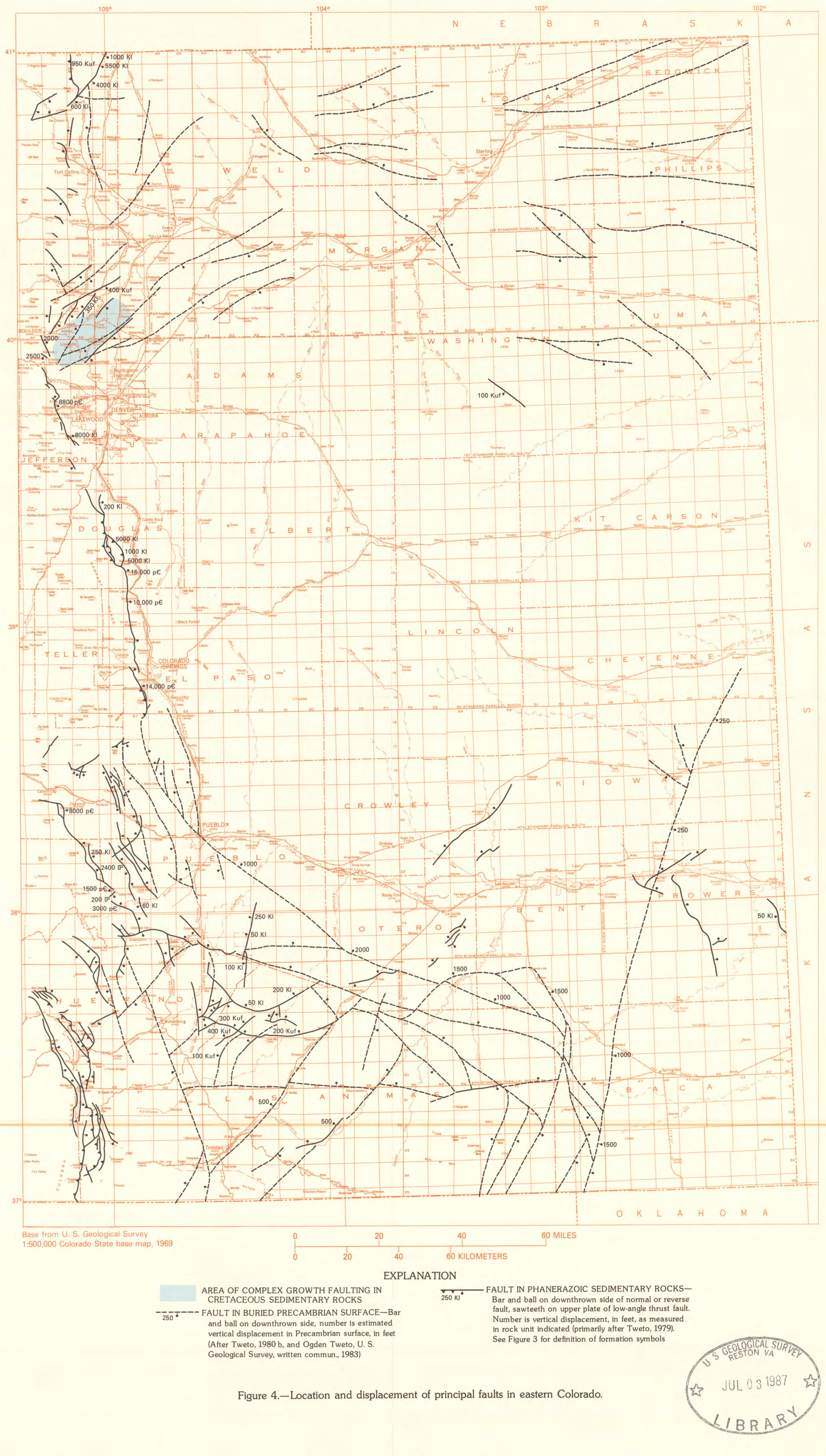

Figure 4.—Location and displacement of principal faults in eastern Colorado.

GEOLOGY AND HYDROLOGY OF THE DEEP BEDROCK AQUIFERS IN EASTERN COLORADO

By
S. G. Robson and E. R. Banta
1987