General and Engineering Geology of the Northern Part of Pueblo, Colorado

By GLENN R. SCOTT

GEOLOGICAL SURVEY BULLETIN 1262

Description of the geology of the bedrock and surficial deposits in and near Pueblo, Colo. Engineering behavior of the rocks is summarized at the end of report

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1969

UNITED STATES DEPARTMENT OF THE INTERIOR

WALTER J. HICKLE, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

Library of Congress catalog-card No. GS 68-379

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

CONTENTS

ILLUSTRATIONS

[Plate 1 in pocket; plate 2 follows index]

GENERAL AND ENGINEERING GEOLOGY OF THE NORTHERN PART OF PUEBLO, COLORADO

By Glenn R. Scott

ABSTRACT

Pueblo, Colo., lies on the Great Plains at the confluence of Fountain Creek and the Arkansas River about 30 miles east of the Wet Mountains of the Rocky Mountains. The low plains near Pueblo are dissected by deep arroyos and two broad valleys. Rising above the plains are low ridges of resistant sedimentary rock and low hills capped by gravel. The area has a semiarid climate; local cloudbursts are common and some result in disastrous floods.

Pueblo is built entirely on sedimentary deposits consisting partly of lithified sedimentary rocks and partly of surficial deposits. All lithified sedimentary rocks, of which about 3,000 feet is exposed, are marine and are Cretaceous in age. Shale, claystone, and siltstone are most abundant; but limestone, chalk, and sandstone make up a small part of the rock sequence. The exposed sedimentary rocks from oldest to youngest are: Dakota Sandstone, Graneros Shale, Greenhorn Limestone, Carlile Shale, Niobrara Formation, and Pierre Shale. The Niobrara Formation is divided into two members, the Fort Hays Limestone and the overlying Smoky Hill Shale. The Smoky Hill is further divided into seven lithologic units. The Pierre Shale is divided into five members or zones, in ascending order: transition member, Apache Creek Sandstone Member, Sharon Springs Member, Rusty zone of G.K. Gilbert, and Tepee zone of Gilbert.

All surficial deposits are nonmarine and are Quaternary in age. Surficial deposits are principally the product of stream action, but they include also material laid down by wind, slope wash, and the activities of man. The deposits are chiefly alluvium, but they include eolian sand, colluvium, and artificial fill. From oldest to youngest they are: Nussbaum, Rocky Flats, Verdos, Slocum, Louviers, and Broadway alluviums, eolian sand, Piney Creek Alluvium, colluvium, post-Piney Creek alluvium, and artificial fill. The formations at Pueblo have been subdivided in great detail so that each mapped unit will, as nearly as possible contain a single lithology and thus have a narrow range of engineering properties.

Engineering problems that result from the behavior of the rocks in the northern part of Pueblo are many and require correction before construction of most buildings and roads. The most troublesome conditions are those causing low bearing strength. Low bearing strength can be the result of high clay content of bedrock, swelling clays, collapse of structure of eolian sand under load, and lack of support given by some artificial fill. Other problems

are caused by frost susceptibility of the fine-grained deposits, seepage of ground water, drainage of surface water, erosion susceptibility of newly made cuts, and reaction of hardened concrete to sulfate waters.

The rocks at Pueblo are bent by two major anticlinal folds and are broken by many small faults. The Rock Canyon anticline west of town is a broad asymmetric doubly plunging extension of a larger fold, the Turkey Creek or Red Creek anticline, to the north. The Pueblo anticline is a low narrow northward-trending fold along which Fountain Creek is superimposed. Faults near Pueblo are short and have small stratigraphic throws.

The geologic history recorded in the outcropping rocks in the Pueblo area consists of only three major events. The earliest is submergence of the land and deposition of marine deposits under a broad, shallow Cretaceous sea. The second involves the uplift of the land, deposition of nonmarine deposits, and folding and faulting of the crust. The third includes the erosion of previously deposited sedimentary rocks, evolution of the modern drainage network, and deposition of the Quaternary surficial deposits.

INTRODUCTION

Pueblo, Colo., lies on the Great Plains at the confluence of Fountain Creek and the Arkansas River about 30 miles east of the Wet Mountains of the Rocky Mountains (fig. 1). The city is built on bedrock comprising marine shale, limestone, and chalk of Cretaceous age (70–110 m.y. old) and on surficial deposits comprising alluvium, colluvium, and eolian sand of Quaternary age (1½ m.y. ago to the present) that locally cover the Cretaceous bedrock.

Geologic mapping of the northern part of the Pueblo area was undertaken for several reasons. First, a detailed geologic map was needed; the only available geologic map of the Pueblo area was a generalized and outdated map at a scale of 1:125,000, the Pueblo Folio (Gilbert, 1897) mapped by G. K. Gilbert in 1893 as part of the Geologic Atlas of the United States. Second, foundation problems in the northern part of the city showed the need for a geologic map on which most lithologic variations and troublesome deposits could be identified; such a map would then allow the prediction that any formation causing an engineering problem would likely cause the same problem wherever the formation is exposed. Third, because of a lack of ground water of good quality, the area surrounding Pueblo was recommended in a list of places to be mapped geologically as part of the National Water Resources Policy Program. Fourth, a dam and powerplant to be built 6 miles west of Pueblo as part of the U.S. Bureau of Reclamation's Frying Pan-Arkansas reclamation project also required a detailed areal geologic map. In addition to these primarily engineering-geology needs, a purely scientific need existed to describe the character and the fossils of the Cretaceous sedimentary rocks and the folding and erosion of the area and to distinguish and map each of the Quaternary sur-

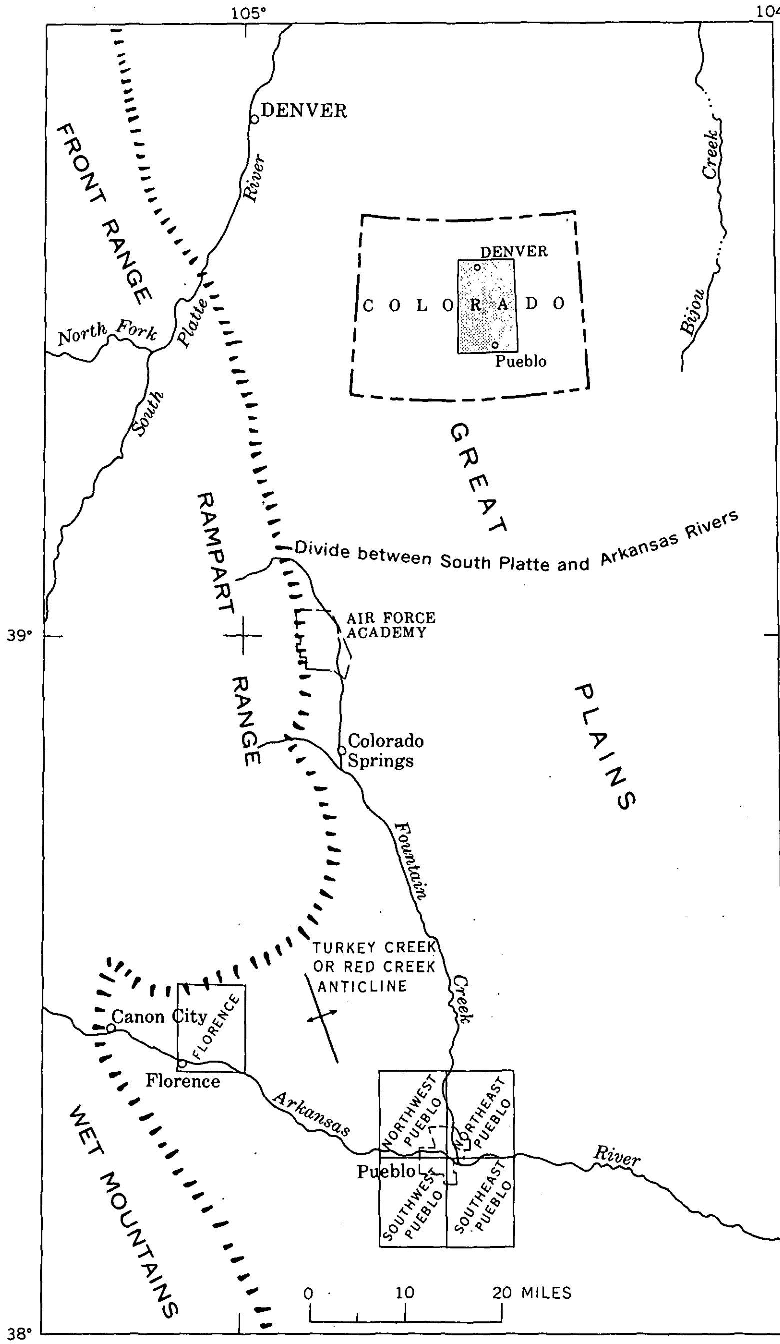


FIGURE 1.—Location of Pueblo and other places mentioned in text.

ficial deposits that contributed to the evolution of the hills and valleys lying around Pueblo.

The scientific needs have been partly satisfied by six reports, written since the beginning of the project, on the ammonites *Haresiceras* (Cobban and others, 1962) and *Clioscaphites saxitonianus* (Scott and Cobban, 1962), on the Apache Creek Sandstone Member of the Pierre Shale (Cobban and Scott, 1963), on the Nussbaum Alluvium (Scott, 1963a), on the geology of the Northwest and Northeast Pueblo quadrangles (a geologic map by Scott, 1964), on the stratigraphy and fossils of the Niobrara Formation (Scott and Cobban, 1964), and on some scaphitid cephalopods from the lower part of the Pierre Shale (Cobban and Scott, 1964). Answers to some of the broad engineering-geology problems are given in the present report, and it is hoped that the basic geologic information will expedite the work of site geologists, civil engineers, and city planners.

The earliest known use of engineering geology at Pueblo was in the selection of a foundation site for construction of Hinsdale School, which was built near the turn of the century. The building was planned to be at 5th and High (Grand) Streets; however, the site was changed to 7th and High Streets because the architect said that a good foundation could not be obtained at 5th and High without great cost. Now, in the crowded modern city, a site generally cannot be changed; therefore, a building design must be adapted to suit the foundation conditions. For this reason, foundation investigation precedes the construction of most new buildings in Pueblo.

SOURCES OF INFORMATION, AND ACKNOWLEDGMENTS

The engineering-geology study was facilitated and made more factual as a result of help given by the City Engineer, Dean M. Larrabee and his staff. From blueprints and maps showing boring logs and test data, the depth to the bedrock and the foundation characteristics of the geologic units were interpreted with the assistance of Eugene F. Johnson and John R. Sivils, of the Pueblo City Engineer's office. They also located on maps all the more recent rubbish dumps and areas of artificial fill. Some geologic problem areas in the city were visited with the City Soils Engineer, Ray M. Foster, and pavement failures and modern methods of overcoming them were studied in company with Louie Brauer, City Paving Engineer. The City Engineer also kept me informed of excavations in the built-up areas of town where deposits could be seen only at the time of an occasional excavation. The Chief City Building Inspector, J. D. Galloway, gave information on building failures and loaned photographs that show failures resulting from swelling clay beneath foundations.

The Colorado Department of Highways District 2 Materials Engineer, Kirk S. White, and his staff, Fred L. Amos, Albert N. Brown, and Garth T. Haigh, provided materials tests and performance records on all highways leading into and through Pueblo. John B. Gilmore, geologist, Colorado Department of Highways, Denver, provided records on Federal and State Highways that extend into Pueblo. Barney Cawlfield, Valuation Station Supervisor for the Federal Housing Authority, allowed the use of foundation information and evaluated different parts of the city according to the severity of their foundation problems. Harold W. Kirchen, U.S. Bureau of Reclamation, gave records of drill logs and performance characteristics of geologic units near the Rock Canyon Barrier Dam.

Laboratory analyses were made by Thomas C. Nichols, Jr., Robert A. Speirer, Joseph C. Thomas, Edward E. McGregor, George S. Erickson, and Michael P. Lane, in the engineering geology laboratory, U.S. Geological Survey, Denver, Colo.

Jeanne and James Scott assisted in the field during the 1961 and 1962 field seasons. In addition, they operated a meter in the field office to determine the potential volume change of the clayey soils.

Invertebrate Cretaceous fossils from Pueblo were prepared by Robert E. Burkholder and identified by W. A. Cobban, both of the U.S. Geological Survey. Cretaceous reptiles and Quaternary mammals were prepared by Robert W. O'Donnell and identified by Edward Lewis, both of the U.S. Geological Survey. Cretaceous fishes were identified by David H. Dunkle, U.S. National Museum. The fossils on plate 2 were drawn by John R. Stacy and Charles C. Capraro, both of the U.S. Geological Survey.

Acknowledgment is made to all those who, in September 1961, participated in the excavation of a large mosasaur from the Apache Creek Sandstone Member of the Pierre Shale north of Pueblo. The excavation took nearly 4 days; the digging crew consisted of Juanita, James, and Kathleen Scott, Edward and Jane Lewis, and Robert W. O'Donnell.

Many people gave access to their lands, gave information on mineral resources, and recounted the history of floods, river changes, and growth of the city as it was affected by the local geology. Others, including William H. Birechby, 1113 Ruppel St., Pueblo; Carl Jurie, Southern Colorado State College; and Carl K. Davidson and John R. Sivils, Pueblo City Engineer's office, told where to

collect fossils or made collections that were loaned or donated to the U.S. Geological Survey.

HOW TO INTERPRET THE GEOLOGIC MAP

The geologic map (pl. 1) shows by colors and symbols, printed on a topographic base, the distribution and shape of rock formations on the surface of the earth near Pueblo. The depth of each rock formation and the irregularity of its eroded upper surface as it projects back under the surface from the places where exposed are not shown on the geologic map. These features must be interpreted from the stratigraphic section on the left side of the geologic map and the cross sections at the bottom of the map. The cross sections show that the older rock formations near Pueblo are like the layers in a gently warped piece of plywood. The cross sections also show that erosion cut across and removed parts of these old warped layers and then the eroded surface was covered by thin layers of younger deposits.

Two categories of earth materials are shown on the geologic map (pl. 1) ; the older category is bedrock, which is both hard and soft, but is called bedrock because it is part of an evenly layered sequence of undisturbed marine beds of shale, limestone, and sandstone which bears the initial symbol [K] for Cretaceous. The bedrock that is shown on the map is exposed at the ground surface or is so thinly buried that any excavation below the depth of penetration of frost will be partly in bedrock. Where bedrock is not shown, it is buried by more than 3 feet of the younger category, surficial deposits. On the map the surficial deposits are mostly unconsolidated poorly bedded materials that were transported to their present position after the bedrock was eroded, and bear the initial symbol [Q] for Quaternary. Generally, by following the belts of bedrock (for example, Sharon Springs Member of the Pierre) across the map, the places along each belt where bedrock is buried by surficial deposits can readily be seen. Surficial deposits may also locally bury other surficial deposits. The buried surficial deposits were identified in the field in excavations or drill holes; they are shown on the geologic map by fractional logs that record the sequence and thickness of the exposed and buried deposits that would be penetrated if a hole were dug at that place. An example of a log showing a buried surficial deposit and buried bedrock is in the NE¼ sec. 3, T. 21 S., R. 65 W. Five feet of eolian sand overlies 10 feet of buried Slocum Alluvium which overlies the buried middle shale unit of the Smoky Hill Shale Member.

INVESTIGATION PROCEDURE AND ENGINEERING-GEOLOGY PRACTICE

During the first year of the project, fieldwork was devoted to mapping the Northwest Pueblo quadrangle and measuring stratigraphic sections of the older Cretaceous rocks in and near the Rock Canyon anticline. During the second year, the Northeast Pueblo quadrangle was mapped, younger Cretaceous rocks were measured, and a study of the engineering properties of most of the materials was started. In the third year the study of the engineering properties was completed.

Records showing engineering properties were collected from all agencies where available; where information was lacking, grab samples of soils and rocks were collected to be tested in the Engineering Geology laboratory, U.S. Geological Survey. For many of the geologic units, the tests by the U.S. Geological Survey were the only ones that could be regarded as characteristic of the geologic unit. Test results from other agencies had the disadvantage that the exact place and geologic horizon of collection were unknown; therefore, the sample could not be evaluated as to whether it was characteristic of the unit where its location plotted out. The test results that are shown, and which are called characteristic of a unit, probably can be duplicated by samples from two-thirds of that unit. The other one-third varies considerably, and the variation is described in general terms under each unit.

The Unified Soil Classification symbols (U.S. Army Corps Engineers, 1953; U.S. Bur. Reclamation, 1960) were determined for every part of the range of texture and clayiness for each unit, even though as many as four symbols are required to define some units. Tables showing the typical engineering performance expected from soils characterized by each of the symbols are included in several publications of the U.S. Army (1952) and U.S. Army and U.S. Air Force (1963).

The AASHO (American Association of State Highway Officials) classification (Allen, 1945) is used by the City of Pueblo and Colorado Department of Highways. This classification was devised by the U.S. Bureau of Public Roads and is widely used by roadbuilding agencies. The AASHO classification for each geologic unit, where known, is given in the text or tables.

CBR (California bearing ratio) is determined and used for the design of pavement by both the city of Pueblo and the Colorado Department of Highways for all fine-grained soils over which pave-

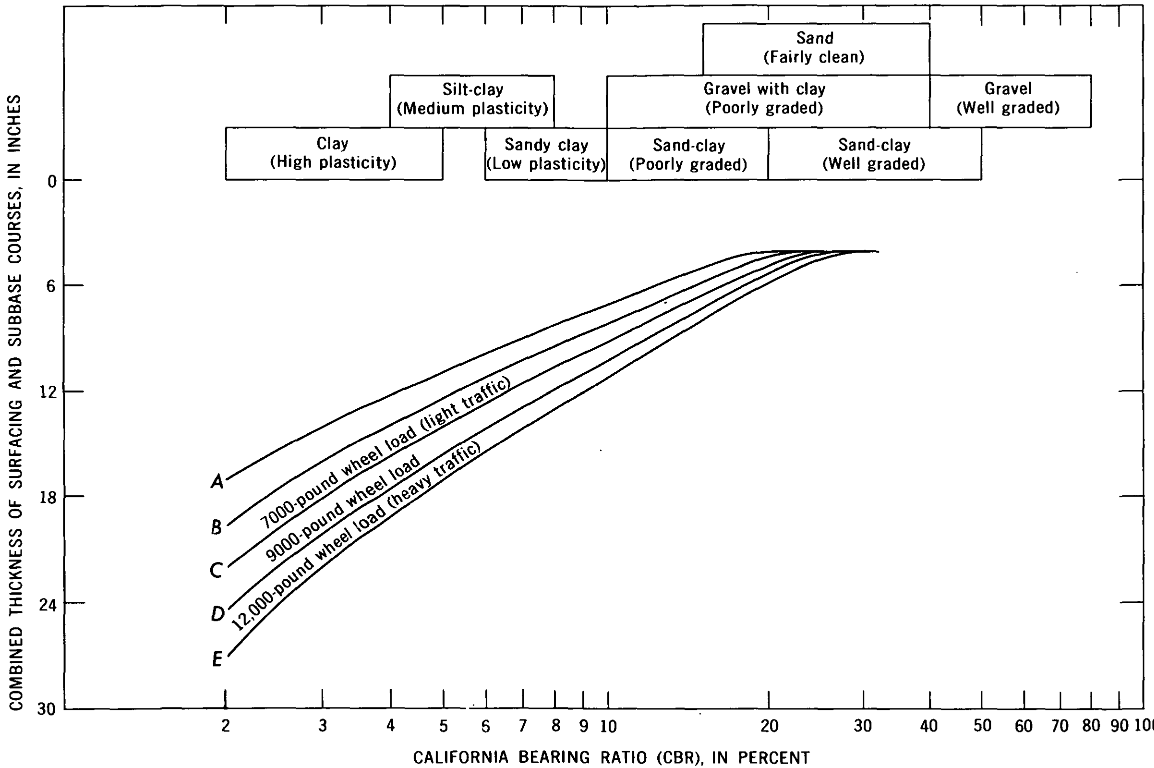


FIGURE 2.—Design curves used for determining thickness of surfacing and subbase courses, modified from Colorado Department of Highways "Field and Office Manual, January 1, 1952." Curves *A* and *B* are seldom used by the city.

ments are to be placed. The CBR is a penetration test giving a measure of the shearing resistance of a soil (Asphalt Inst., 1961, p. 95). By the use of curves (fig. 2), which are based partly on CBR and partly on experience from previous pavement performance, the combined thickness of surfacing and surface courses can be determined. To determine the combined thickness in inches of surfacing and subbase courses, both the CBR and the estimated wheel load of traffic in thousands of pounds must be known. A vertical line is drawn from the known CBR down to the curve that fits the wheel load of anticipated traffic. A horizontal line drawn from the point of intersection to the left side of the graph will show the necessary thickness of material. This method is generally used for the design of flexible pavement (other than concrete), but it can be used to design the combined thickness of concrete and subbase. For concrete, a slightly lower figure than shown by the curves can probably be used, owing to the greater ability of concrete to withstand high tensile stress (stretching). CBR values determined by the city of Pueblo and by the Colorado Department of Highways are given in the text or tables under each geologic unit for which they have been determined. Each geologic unit has a characteristic average CBR, which is inversely proportional to the plasticity index. Thus, Apache Creek Sandstone Member of the Pierre Shale, which has an average PI (plasticity index) of about 16, has an average CBR of 3.8; post-Piney Creek alluvium, which has an average PI of about 8, has an average CBR of 7.1; and eolian sand, which has an average PI of about 5, has an average CBR of 8.2. For most of the Cretaceous shale at Pueblo, neither flexible nor rigid pavement should be applied directly over the in-place shale, and the excavated shale should not be applied as a base or subbase material beneath pavement or other wearing course.

Size-analysis curves were plotted for most geologic units that contain material other than hard rock. The Wentworth (1922) classification is used throughout this report. For some units, only one analysis is available. In plotting the size-analysis curves that were made available from laboratories other than the Engineering Geology laboratory of the U.S. Geological Survey, I have assumed that all tests of samples whose locations are at bedrock outcrops shown on plate 1 were made of bedrock below any soil zone. A soil zone forms a thin layer of reworked material over most units shown as bedrock on the geologic map. This thin layer is not characteristic of the underlying bedrock unit, and the difference between it and bedrock cannot be predicted. Where, after plotting, a size-analysis curve was radically different from curves of known bedrock, the curve was assumed to be from a sample that was contaminated by the addition of colluvial soil material and the curve was discarded. Where the curve was similar to typical bedrock curves, the sample was assumed to be from bedrock and the curve was used.

Size analysis of shale was performed on relatively unweathered material, which consisted largely of flakes that were aggregates of individual particles. To disaggregate these flakes for hydrometer and sieve analysis, the shale first was leached in hydrochloric acid to remove calcium carbonate, then soaked in sodium polyphosphate overnight. Larger particles that had not disaggregated were broken by the action of a pestle in a wet mortar, then placed in an ultrasonic cleaner for 10 minutes.

The word "clay" as herein used has two meanings, clay mineral and clay size. Common clay minerals at Pueblo include montmorillonite, illite, and kaolinite. Bentonite is a rock composed principally of montmorillonite and is derived from the alteration of volcanic tuff or ash. Of the three clay minerals, montmorillonite has the greatest swelling potential because of its ability to take up water between the sheets of its internal molecular structure. Montmorillonite also exhibits extreme plasticity through a great range in water content. Illite is intermediate in physical properties and engineering behavior between montmorillonite and kaolinite. Kaolinite is less plastic and less inclined to swell than either montmorillonite or illite. Clay-sized material, as defined by Wentworth (1922), includes all particles that are smaller than 0.0039 mm (millimeters) in maximum size. Therefore, clay-sized material includes both clay minerals and nonclay minerals. The word "clay" also has a third definition not used in this report—plastic material smaller than 0.074 mm (nonplastic material is called silt).

The Atterberg limits—liquid limit, plastic limit, and plasticity index—are reported for every clayey unit. In the figures (12, 45, 51, 54, 58) showing plasticity index versus liquid limit, Casagrande's "A" line is an empirical boundary commonly drawn on plasticity charts. It generally separates cohesionless soils and inorganic clays of low to high plasticity in the region above the line from silty and organic soils below the line.

X-ray mineralogic analysis was performed on most materials containing a clay fraction. Figure 11 shows an example of the X-ray analysis as performed on the Graneros Shale. The mineralogy and approximate proportion of the constituents in each sample were estimated by Thomas C. Nichols, Jr., and Edward E. McGregor using a method developed by Schultz (1964). The proportions are reported in percent and are considered to be accurate to a factor of ±10 percent of the amount stated. Calcium carbonate in some samples varies more than 10 percent from the amount dissolved by dilute hydrochloric acid. Because all the samples reported were run in the same laboratory using the same method, they can be compared with each other confidently; but they cannot be compared accurately with samples run in a different laboratory, because the same samples run in a different laboratory using different methods could vary considerably more than 10 percent in the reported abundance of individual constituents.

Attainment of satisfactory bearing capacity under foundations is one of the significant engineering-geology problems in the northern part of Pueblo. The problem results primarily from high swelling pressure—potential volume change—of the clayey Cretaceous shale, and to a lesser degree, of Quaternary fine-grained deposits that have inherited a swelling potential by being derived from the Cretaceous shale. Damage is a result of both swelling and shrinkage. The volume change is caused by a change in water content of plastic clay containing platy particles having large surface areas. The settlement of dry soils, a problem characteristic of loess, is likely to be troublesome at Pueblo only in the eolian sand.

The Federal Housing Administration (Lambe, 1960) has recently studied the problem of expansive soils and devised a PVC (potential volume change) meter (fig. 3) with which to measure potential volume change of clay within a soil. This PVC meter was used to test one or more samples of the weathered zone of every geologic unit at Pueblo that contained enough fine-grained material to constitute a possible swelling hazard. All samples were remolded for this test. The evaluation of the samples tested is based on a numerical PVC classification system (Lambe, 1960, p. 28 and fig. 20) that embraces four broad categories: noncritical, 0–2,700 psf (pounds per square foot); marginal, 2,700–3,200 psf; critical, 3,200–4,700 psf; and very critical, above 4,700 psf. Most of the clayey geologic units at Pueblo have swelling pressures less than 3,000 psf and average about 2,200 psf. These pressures are relatively low and do not cause spectacular failures, but they are high enough to crack foundations and pavement and cause recurring trouble. Figure 4 shows a comparison of a sample having critical swelling pressure with one whose swelling pressure is noncritical. The two samples were photographed after removal from the PVC meter and are still resting on porous stones through which water is introduced. The expansion cracks and greater expansion of swelling shale are apparent in sample *A*. Difference in expansion amounts to more than the thickness of a quarter dollar. Swelling pressures greater than 3,000 psf are com-

327-617 O—69——2

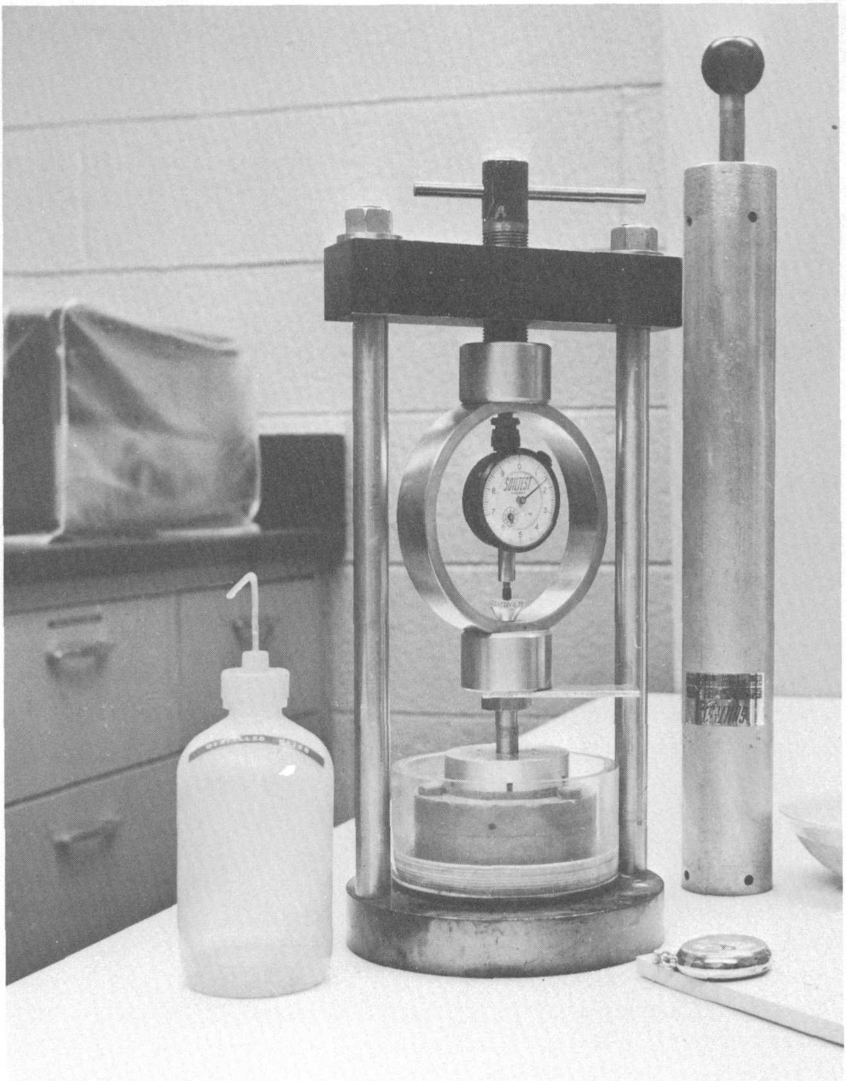


FIGURE 3.—PVC (potential volume change) meter and other equipment required for testing potential volume change of clay. From left to right are distilled-water bottle, meter, tablet for recording results, watch with second hand, compacting hammer, and bowl containing dried fraction of original sample that has passed the No. 10 U.S. standard sieve.

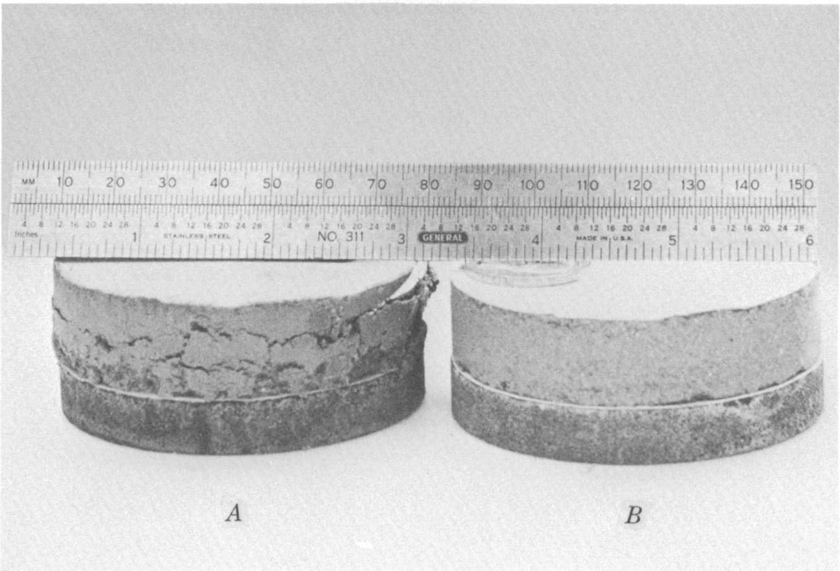


FIGURE 4.—Tablets of soil after removal from PVC (potential volume change) meter where they were tested for potential volume change of clay. Porous stones beneath tablets serve to introduce water to the samples at the beginning of test. *A*, Tablet shows cracks and great expansion as a result of critical swelling pressure. *B*, Tablet shows much less expansion as a result of noncritical swelling pressure (coin is a quarter dollar).

mon in noncalcareous Pierre Shale, where they are as high as 5,500 psf in the Rusty zone of Gilbert (1897). Bentonite beds are a potential hazard to foundations because of a propensity toward extreme expansion (more than 8,000 psf at Pueblo). No foundation should be placed directly on bentonite, and all caisson holes or other type foundations should be probed below their bottoms to assure that the foundation does not lie on, or too close to, any bentonite bed. The bentonite beds can be recognized by their yellowish-orange color and soft waxy or greasy feel. In natural slopes they commonly are concealed by slope wash but are readily recognized in artificial exposures. A typical bentonite bed is shown in figure 14.

To attain stable foundations it is necessary to load the soils with weight sufficient to offset their potential swelling pressures. The compensating weight, therefore, should be slightly more than the potential swelling pressure but less than the amount that would cause intolerable consolidation resulting from rearrangement of particles or driving out of pore water. These two figures, the optimum pressure owing to weight to offset potential swelling, and the

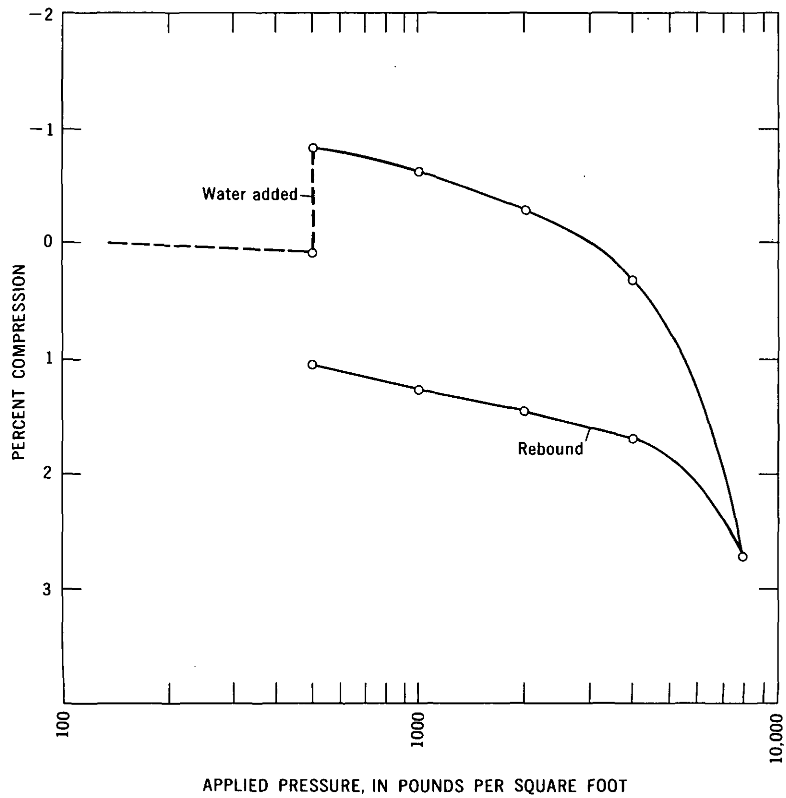


FIGURE 5.—Results of consolidation test of remolded Pierre Shale—probably transition member—from Mountair subdivision near Adrian Avenue and 29th Street, Pueblo, Colo. Initial moisture, 1.4 percent; final moisture, 16.2 percent; dry density, 109 lb per cu ft; wet density, 110 lb per cu ft. Tested by Harold E. Eyrich, Consulting Engineer, Denver, Colo.

allowable maximum soil pressure, generally are shown by a consolidation test such as figure 5. This consolidation test was run by Harold E. Eyrich, Consulting Engineer, Denver, Colo., on a remolded sample of weathered transition member of the Pierre Shale taken by the Federal Housing Administration from the basement of a completed house in Mountair subdivision in Pueblo. The test shows that when water was added, the soil immediately began to swell, and that the amount of mechanical compression needed to offset the soil swelling pressure was nearly 3,000 psf. Greater compression was then applied, and the sample reached a consolidation of 3 percent—the maximum generally allowed under a foundation—at 8,000 psf. On the basis of this test, the suggested dead-load soil pressure should exceed 3,000 psf and the maximum soil pressure should be 8,000 psf. According to Eyrich (oral commun., 1966), the maximum bearing capacity, which could be as high as 10,000 psf, was established not only from the results of this test but also from knowledge of behavior of similar soil types and construction.

Thus, the total weight of a structure on swelling soil must be distributed so that each pier will have its proper pressure in pounds per square foot. No non-load-bearing part of a structure should touch the soil unless it is free floating and unattached to the load-bearing parts. Grade beams and walls, for instance, generally are separated by a 3- to 6-inch air space from the underlying soil. This air space is achieved by pouring the concrete grade beams and walls over cardboard tubes that will readily disintegrate or over loose sand that is withdrawn after the concrete hardens. Basement slabs generally are poured on a cushion of gravel over the soil, or less preferably on the soil, and the slab is not tied to the load-bearing piers but floats freely. Similarly, all slablike concrete structures, such as sidewalks, driveways, patios, and curbs, should be poured over a cushion of permeable material, such as gravel, to avoid direct contact with swelling material and they should not be connected solidly to load-bearing members.

Failure to take precautions against swelling clay can result in continuing damage to buildings despite all measures taken to stop the destruction or to repair or conceal the cracks and displacements. Most of the damage in Pueblo seems to be in less expensive homes where the homeowner can least afford the disastrous results of foundation cracking, foundation shifting, breaking of pipes, upheaval of furnaces (fig. 34), and upheaval of concrete slabs. J. D. Galloway, Chief City Building Inspector (oral commun., 1967), described one basement slab lying only a few inches above a bentonite bed that rose 18 inches after the owner began to water his lawn. At another house, excessive water from the lawn ran into caisson holes, seeped to the bottoms of the piers, and caused heaving of the foundation.

To determine whether weathering increases the swelling potential of shale, samples were taken of an outcrop of the middle shale unit of the Smoky Hill Shale Member—from the weathered upper part and from a less weathered part 15 feet below. X-ray analysis shows that the two samples are nearly identical mineralogically. Their size-distribution curves plot out as a single line, indicating their similarity in grain size. The weathered sample, however, shows a plasticity index of 16, the less weathered sample, only 7. Furthermore, the weathered sample has a swelling pressure of 2,500 psf; the less weathered sample has a pressure of only 1,250 psf. This single test suggests the possibility that swelling pressures increase as a result of weathering. A large series of closely controlled tests should be run to test this possibility, which would have considerable importance in building at Pueblo.

Currently, if foundations are to be placed on swelling soils at Pueblo, the designs call for caisson or pier and grade-beam foundations. Deep foundations have an advantage over shallow spread footings because of the ability to confine laterally the shale at depth and because of the slight fluctuation of water content in shale at depth. The shale around spread footings is subject to sudden and great increases in water content, owing to rainfall and artificial watering. The exact depth, in each formation, where there is a steady state of moisture is unknown, but should be determined.

A different method of preparation of a foundation hole in material containing swelling clay was described by J. D. Galloway (oral commun., 1967). A contractor in Pueblo leaves a new foundation excavation open and keeps it saturated with water for 30 days, lets it dry out, and then pours the concrete for the foundation. In one especially clayey site he also bored holes 12 feet deep so as to saturate the soil to a greater depth. The contractor reportedly states that the continuous saturation allows the soil to swell as much as it is able to, after which no danger ensues from placing a spread-footing type foundation on it. According to Galloway, after as long as 10 years no foundation problems have resulted after this treatment.

Water is one of the chief causes of failure in the foundations of all engineering structures at Pueblo. Trouble can be largely avoided by the placement of peripheral drains in wet areas around foundations and of subdrains at seeps under highways and by channeling surface drainage away from all structures. Overabundant watering of plantings around foundations is a frequent cause of trouble, especially where backfill is not adequately compacted. Backfill should be compacted (not "puddled") to a density exceeding that of adjoining undisturbed soil. In order to avoid drying of the soil, excavations should not stand open for a long time before construction. Arroyos and swales that are buried during grading operations at a building site will still carry water even though buried. Therefore, tiles should be installed along the original water courses to provide for drainage.

The problem of changes in water content under pavement is particularly acute. To prevent volume changes under pavement, shale probably should be loosened and mixed by a scarifier, compacted to maximum density and optimum moisture, covered with a blanket of

FIGURE 6.—Alligator cracks in bituminous mat on 5th Avenue between 25th and 26th Streets. Cracks are caused by lack of subbase and resultant swelling and plasticity effects caused by moisture beneath pavement.

adequate thickness of subbase material, and then sealed with an impermeable material such as asphalt. Lack of adequate subbase and base-course material over clayey shale will cause failure in either concrete or bituminous pavement, owing chiefly to the swelling and plasticity effects caused by moisture trapped beneath the pavement. Figure 6 shows a failure of this type in bituminous mat on 5th Avenue between 25th and 26th Streets. The pavement is underlain by a thin layer of colluvium over Apache Creek Sandstone Member of the Pierre Shale. According to modern practice of the City Engineer, 12–20 inches of subbase would be placed over material of this sort; however, no subbase had been used under the old pavement shown in figure 6.

Deterioration of hardened concrete by sulfate-bearing water is a major problem at Pueblo. Most bedrock geologic units and some surficial units at Pueblo contain sulfate compounds that are readily dissolved and carried by ground water. The problem is avoided in most new construction by the use of sulfate-resistant cement. Therefore, concrete foundations, curbs, gutters, sidewalks, and slabs of all

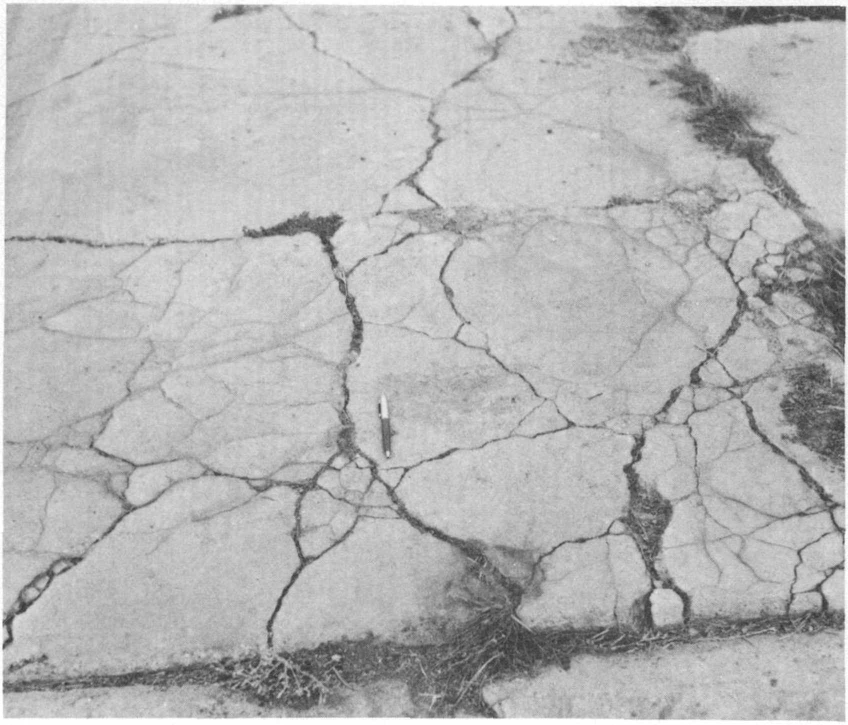


FIGURE 7.—Destruction of sidewalk by sulfate reaction at 1605 32d Street, Pueblo, Colo. The sidewalk is underlain by Apache Creek Sandstone Member of the Pierre Shale, from which seeps a strong sodium sulfate solution at many places in this neighborhood.

kinds that are to be placed against geologic units containing sulfate compounds should contain sulfate-resistant cement.

Reaction of hardened concrete to sulfate-bearing water results in corrosion, spalling, and eventual complete disintegration of the concrete (fig. 7). Corrosion is common where sulfate-bearing water from seeps flows across sidewalks. Channels as much as 2 inches wide and one-half inch deep are etched in the concrete. Spalling seems to be one of the early signs of disintegration; the outer surfaces of the concrete first flake off from the aggregate pebbles, then the concrete completely disintegrates.

A sample of efflorescence from a seep flowing out of Apache Creek Sandstone Member (fig. 8) was analyzed to determine its mineralogical and chemical composition. X-ray analysis shows a complex pattern made by quartz, hydrated ferrous sulfate, sodium sulfate, hydrated calcium aluminum silicate with a pattern like a

FIGURE 8.—Efflorescence of sodium sulfate along the channel of a seep from the Apache Creek Sandstone Member of the Pierre Shale on a vacant lot at 2925 Country Club Drive, Pueblo, Colo. Efflorescence is 1 inch thick on parts of this lot. Note the desiccation cracks at the surface of the shale. The seep corroded an adjoining concrete sidewalk.

synthetic zeolite ("calcium A zeolite"), and other minerals. Chemical examination by W. D. Goss and Wayne Mountjoy, U.S. Geological Survey, shows the sample to be for the most part sodium sulfate that contains minor impurities.

In a chemical engineering report, Hunter (1963), stated that

Deterioration of hardened concrete by sulfate waters is due to chemical reactions between dissolved sulfates and certain hydrated cement compounds in the concrete. The rate and severity of the attack depends on various factors such as the concentration and type of sulfate compounds in the water, porosity of the concrete, chemical composition of the cement, etc. In general, it appears that the order of severity of attack by pure sulfate solutions is $MgSO_4$ greater than Na_2SO_4 greater than $CaSO_4$.

Sulfate attack of concrete can be minimized in several ways, the most common of which is probably the use of Type II or Type V sulfate-resistant cement.

In order to avoid deterioration of concrete resulting from sulfate reaction, all suspected soils should be tested to detect the presence and determine the quantity of sulfates before the installation of concrete against the soil.

Frost susceptibility expresses the tendency of a soil to draw up rapidly capillary water from the water table. The water is fed to growing wedges of ice within the soil that cause surface heave equal to the thickness of the ice wedges. The intensity of the process depends on the availability of water and the frequency of the fluctuation of temperature about the freezing point. All building foundations should be placed below the depth of penetration of frost. Damage to pavement is caused by heaving during freezing and collapse during thaw. Susceptibility to frost damage can be reduced by using nonfrost-susceptible subbase and base, by lowering the water table, and by impermeable cutoff blankets between the subgrade and subbase or base (Asphalt Inst., 1961, p. 15). The evaluation of the frost susceptibility of each unit is inferred from the size analysis of the unit.

Users of this report are cautioned not to use in design the figures given here concerning bearing strength. Although the figures are considered to be reliable for the sample and the place where taken, they are unlikely to be adequately representative of every part of a geologic unit. For this reason, samples should be tested from each construction site, at least until enough samples have been tested to reveal the average and the range in characteristics for each geologic unit.

Foundation failures and overdesign are costly and can be avoided if the designer follows the recommendations of a competent soils engineer and engineering geologist. Where soil conditions are imperfectly known, many varieties of overdesign and faulty design are possible, for example: the use of a standard design for structures regardless of soil conditions; the use of broad spread footings over shale that is known to contain swelling clay; the use of piers in gravel; and the use of too few or too many piers to distribute properly the load in shale. These errors can be avoided, and a structure can be accurately designed if a detailed soil-exploration program is completed and the results interpreted for the designer.

As of 1964 the design of foundations in Pueblo was controlled by the Uniform Building Code (Internat. Conf. Bldg. Officials, 1964), a countrywide standard code that has been adopted by the city of Pueblo. The two regulatory chapters, 28 and 70, in this code that concern foundations, retaining walls, excavations, and grading, represent only a beginning toward the solution of engineering-geology problems at Pueblo. Concerning the problem of expansive soil, for example, the code is permissive and does not require tests for volume change because it is not written specifically for use at Pueblo. The many possible types of overdesign or faulty design cited previously suggest that a supplement to the Uniform Building Code written by local engineering geologists, soil engineers, and civil engineers providing for adequate treatment of local foundation problems would allow greater economy and safety in building. The supplement could specify that an engineering-geology or soils investigation would be required by the building official wherever foundations would lie upon certain geologic formations—and these would include most of the Cretaceous clayey shales. The supplement also could specify that sulfate-resistant cement would be used wherever concrete would directly overlie all named sulfate-bearing formations.

In addition to code supplements that concern foundation conditions, an additional zoning regulation apparently is needed so that buildings are not permitted on land that still contains recoverable gravel. When such areas are covered by buildings, the gravel is no longer available and hauling distance to available gravel increases (Roberts and others, 1965). Two reasons exist for keeping the principal source of gravel, the post-Piney Creek alluvium, relatively clear of buildings: (1) the flood plain (post-Piney Creek alluvium) is subject to floods, and (2) during floods new gravel is carried in and replaces gravel previously extracted. Some older deposits that could produce gravel are already largely covered by buildings—for instance, the broad terrace of Louviers Alluvium from Blue Ribbon Creek eastward to Interstate Highway 25. However, eastward from Interstate Highway 25 to the east edge of the mapped area are two large areas that still are only slightly built over and that contain large resources of gravel in both post-Piney Creek alluvium and Louviers Alluvium.

CLIMATE

The quadrangle is in an area of temperate continental climate characterized by low relative humidity, many sunny days, large daily range in temperature, and mild winters with little snow. Rainfall is slight and evaporation is high. Extended periods of subzeroweather or of temperature above 100°F are rare (see following table).

Precipitation average for 61 years and temperature average for 40 years at Pueblo, Colo.

[From records of U.S. Weather Bureau]

Period	Precipitation (inches)	Temperature (° F)	Period	Precipitation (inches)	Temperature (° F)
January	0.34	30.8	August	1.78	72.8
February	.55	33.1	September	.88	64.7
March	.67	41.2	October	.63	52.3
April	1.57	50.0	November	.42	40.4
May	1.60	59.2	December	.49	31.4
June	1.32	69.2			
July	2.01	74.1	Annual	12.26	51.6

The extreme maximum temperature for a 42-year period at Pueblo was 104°F, and the extreme minimum was —27°F. The average date of the last killing frost at Pueblo is April 24 and of the first, October 10—an average frost-free season of 169 days. According to E. Milton Payne, State Soil Scientist, U.S. Department of Agriculture (oral commun., 1964), the depth of average frost penetration at Pueblo is about 2 feet. Flowing water has been known to freeze in pipes at a depth of 4 feet. Precipitation averages just a little more than 12 inches (see table above), which is that of a semiarid climate, but is distributed mostly in the summer growing season. The area is subjected to sporadic intense summer rainfall, generally in the form of local thunderstorms. The track of most thunderstorms lies along the divide between the South Platte and the Arkansas Rivers (fig. 1) where the storms have produced as much as 24 inches of rainfall in 12 hours. Large amounts of rainfall such as this exceed the capacity of most stream channels, and flash floods result. The greatest 24-hour precipitation at Pueblo was 2.93 inches on June 3–4, 1921. Hail, commonly accompanied by strong wind, falls occasionally in early summer and creates a hazard to farm crops. The prevailing wind blows from the northwest and averages about 7.6 mph. Ancient deposits of windblown sand at Pueblo show that the area has been swept by winds from the northwest for thousands of years.

FLOODS

Many recorded and unrecorded floods have troubled Pueblo. Following a destructive flood of the Arkansas River in 1921 (Follansbee and Jones, 1922), the Rock Canyon Barrier Dam was built 6½ miles west of the center of Pueblo. It was designed to reduce a discharge of 175,000 cfs (cubic feet per second) of normal duration to a discharge of 100,000 cfs of water by passing it through two permanent gaps, one for the river and one for the Denver and Rio Grande Western Railroad. In addition, the course of the river through Pueblo was moved southward from the center of the valley to a new channel against the south valley wall where it was confined by a dike that extends from the west end of town to the east end. The new channel was designed to carry 125,000 cfs of water, thus providing for a flood flow of 25,000 cfs originating below the dam (Follansbee and Sawyer, 1948). A floodwall was built near Dry Creek at the west end of town to assure that all floodwater would be diverted into the new confined channel.

Complete impoundment of floodwater from the Arkansas River will be possible when the Pueblo Storage Reservoir unit of the Frying Pan–Arkansas Project is built. The dam of the Pueblo Storage Reservoir will have the same position as the Rock Canyon Barrier Dam. The reservoir is designed to hold 400,000 acre-feet of water.

The 1921 flood resulted from a series of local cloudbursts that increased the flow of most tributaries of the Arkansas River between Canon City and Pueblo and produced a peak discharge of 103,000 cfs at Pueblo. An example of the intensity of such local cloudbursts is shown by records from a disastrous storm of May 30, 1935, over the divide between the South Platte and Arkansas Rivers. An isohyetal map of this storm, prepared by the U.S. Forest Service (Rosa, 1954), shows that in a small area near the head of Bijou Creek 24 inches of rain fell between 6 a.m. and 6 p.m. Nearly as large amounts fell in other small areas and created widespread flood damage.

Four streams flow into the Arkansas River at Pueblo below the Rock Canyon Barrier Dam; these are Fountain, Dry, Salt, and Blue Ribbon Creeks. The drainage area of Fountain Creek is reported by Vaudrey (1960, p. 17) as 926 square miles. Estimates, in square miles, of the drainage areas of the other three streams are: Dry Creek, 100; Salt Creek, 14; and Blue Ribbon Creek, 5. The discharge of Fountain Creek in the May 30, 1935, flood was 35,000 cfs (Vaudrey, 1960). Discharges of the other streams in the 1921 flood (Follansbee and Jones, 1922) were, Dry Creek, 24,400 cfs; Salt Creek, 32,100 cfs (includes overflow from St. Charles River); and Blue Ribbon Creek, 9,130 cfs.

Residential, industrial, and civic developments are situated high on the flood plain of Fountain Creek about 12 feet above stream level; the flood plain in the area of Main and 20th Streets is mapped as post-Piney Creek alluvium. According to the high waterline shown on the north side of the Arkansas River and along Dry and Fountain Creeks on the geologic map (pl. 1), this area was not flooded in 1921 or in 1965, and a flood of large magnitude would be required to cover the area. As protection against stream erosion, four jetties (mapped as artificial fill) were constructed along the west side of Fountain Creek. A lower part of the flood plain between 8th and 4th Streets was covered by a flood in 1965 and considerable damage resulted.

A residential area lies on the flood plain of Dry Creek. Many of the houses are below the high waterline of the 1921 flood and are less than 10 feet above stream level. In their present position the houses would be subject to damage from any flood that overflowed the arroyo of Dry Creek. Salt and Blue Ribbon Creeks are in deep, narrow valleys along which few structures have been built that would be damaged by floods.

To avoid recurring flood hazards at Pueblo, flood-plain zoning or additional protective works may be necessary. An appraisal of flood risk from the four small streams cited previously, assuming that the Arkansas River is now controlled or soon will be controlled by Pueblo Reservoir of the Frying Pan-Arkansas Project, should show whether zoning or protective works are needed. To achieve perfect flood-plain zoning of areas that are already developed almost certainly would require some modification of existing usage of the flood plain. Over a period of many years flood-plain zoning is the only completely effective way to reduce or eliminate the damage potential (Wiitala and others, 1961). Effective flood-plain zoning should call for rules against new construction of homes, schools, and hospitals on most areas shown on plate 1 as post-Piney Creek alluvium. These areas are subject to seasonal or rarer floods and therefore may be used for parks, golf courses, parking lots, gravel pits, or other uses that are compatible with the river's need for increased waterway capacity during times of flood. If modifications of land usage are not possible, then conventional flood-control measures, few of which are 100 percent effective, provide the only means of reducing potential damage to the structures that already exist on the flood plain.

EXPLANATION OF THE USE OF TECHNICAL TERMS

(Adapted from Stokes and Varnes, 1955)

Albian. One of several European stage names used in this report. The others are: Cenomanian, Turonian, Santonian, Coniacian, and Campanian. They are particularly useful to paleontologists and stratigraphers for making correlation to Cretaceous rocks in Europe.

Alluvium. Material moved and laid down by perennial and ephemeral streams of all sizes.

Ammonite. A fossilized coiled or tubelike shell in which lived an animal like the squid. Scaphitid cephalopods and baculites are ammonites.

Anticline. An elongate fold in which the sides or limbs slope downward away from the crest.

Bedrock. The undisturbed rock at the surface or upon which transported surficial deposits lie.

Calcarenite. A limestone composed of sand-sized shell fragments or other calcareous detritus.

Colluvium. Material moved and laid down by gravity and slope wash.

Cone-in-cone. A series of interpenetrating cones, averaging 1–2 inches in height in two opposing sets with the apices of one set nesting between the bases of the other. Supposedly, pressure aided by crystallization and solution is necessary for their formation.

Consolidation. An effective decrease in volume of a soil in response to increased pressure and resulting from squeezing of water from the pores and a decrease in void ratio.

Dip. The angle between an inclined bedding or fault plane and a horizontal plane.

Eolian. Carried and laid down by the wind.

Fault. A fracture in rocks of the earth's crust along which one side has moved relative to the other.

Fold. A bend or wrinkle in layered rock. The anticline is an example.

Geologic unit. A body of rocks, loose or consolidated, shown by a single symbol on the geologic map.

Isohyetal map. A map containing lines that connect places having equal rainfall.

Limestone. A sedimentary rock composed mostly of calcium carbonate.

Liquid limit. The water content, expressed as a percentage of the weight of the oven-dried soil, at the boundary between the liquid and plastic states.

Lithology. Study of all the physical characters of rocks.

Plasticity index. The range of water content, expressed as a percentage of the weight of the oven-dried soil, through which the soil is plastic. It is defined as the liquid limit minus the plastic limit.

Plastic limit. The lowest moisture content, expressed as a percentage of the weight of the oven-dried soil, at which the soil can be rolled into threads one-eighth inch in diameter without the thread breaking into pieces.

Sandstone. A sedimentary rock composed of cemented grains of sand.

Scarify. To loosen and pulverize.

Septarian concretion. A concretion containing irregular polygonal cracks opened by shrinkage and later filled by material of a different composition.

Shale. Fine-grained sedimentary rock that is thinly laminated and splits parallel to the bedding. Claystone and siltstone are nonlaminated equivalents.

Stratigraphy. The study of the character, sequence, age, and distribution of stratified rocks and their correlation by the use of fossils or other methods.

Stratigraphic throw. The distance between the two parts of a disrupted bed measured at right angles to the plane of the bed.

Surficial deposits. Unconsolidated transported gravel, sand, silt, and clay at the earth's surface.

Swash marks. Wavy lines of sand left on the beach at the shoreward limit of the water after the breaking of a wave.

Unconformable. Showing evidence of being separated from the overlying or underlying formation by a surface representing erosion or lack of deposition of part of the local rock column.

DESCRIPTION AND ENGINEERING-GEOLOGY PROPERTIES OF OUTCROPPING ROCKS

Sedimentary rocks underlying the Pueblo area are 3,900 feet thick in the southwestern part where the Dakota Sandstone is exposed, and more than 6,800 feet thick in the northeast where younger Cretaceous rocks overlie the Dakota. Granitic rock of Precambrian age (more than 600 million years old) lies about 3,600 feet below the Arkansas River at the Rock Canyon anticline. Sedimentary rocks ranging in age from Ordovician to Jurassic overlie the crystalline rocks, but they are not exposed near Pueblo. All lithified sedimentary rocks exposed near Pueblo are of Cretaceous age (pl. 1). Over much of the area they are overlain by a thin mantle of Quarternary surficial deposits.

Each description of an individual formation includes a discussion of its appearance where exposed, its thickness, the size and composition of its grains, and the way the grains are grouped and cemented to make layers. Unusual features, such as concretions, markings, or characteristics resulting from weathering, also are described. The formations are described in order from oldest to youngest. Included also is a list of some of the animals and plants living at the time of deposition and which are now preserved as fossils.

The four most common and important types of fossils for dating the Cretaceous rocks in the Pueblo area are shown on plate 2.

Cephalopods and pelecypods make up more than 95 percent of the larger invertebrate fossils at Pueblo; nearly all the cephalopods are ammonites. Four kinds of ammonites are illustrated on plate 2, a normally coiled ammonite called *Metoicoceras whitei* and three differently formed ammonites or heteromorphs in various stages of being uncoiled. They include a completely uncoiled straight ammonite called *Baculites perplexus*, a flat coiled clock-springlike ammonite, *Exiteloceras jenneyi*, and a helically coiled ammonite, *Didymoceras nebrascense*. Other types of heteromorphs found at Pueblo include three other flat coiled ammonites, *Neocrioceras*, *Phlycticrioceras*, *Allocrioceras*; hairpinlike ammonites called *Oxybeloceras* and *Solenoceras*; and slightly uncoiled ammonites called *Scaphites*, *Trachyscaphites*, *Clioscaphites*, and *Hoploscaphites*. The pelecypods are chiefly clams such as *Inoceramus labiatus* shown on plate 2; but they include also some small, more symmetrical clams, such as *Lucina occidentalis*, and oysters, such as *Ostrea congesta*. Gastropods (snails) are uncommon; therefore they are not listed or illustrated. Photographs of some of these types of fossils from the Niobrara Formation and the Pierre Shale at Pueblo also are shown by Scott and Cobban (1964) and Cobban and Scott (1964).

Engineering-geology description of each formation includes a discussion of drainage and permeability, erosion susceptibility, excavation facility, natural and cut-slope stability, foundation stability, and materials use. The section on foundation stability generally contains information concerning ease of compaction, potential volume change or swelling potential of clayey material, and susceptibility to frost heave. Materials test data are added where available, in either narrative or tabular form. Major engineering-geology problems, such as swelling clay, sulfate reaction, and seepage, are given special attention under each formation.

A summary of the engineering behavior of geologic units at Pueblo is given in a table at the end of the report.

327-617 O—69——3

SEDIMENTARY ROCKS

All lithified sedimentary rocks at Pueblo are Cretaceous in age and range from the Early Cretaceous (Dakota Sandstone) to the Late Cretaceous (Pierre Shale). Probably more than 90 percent of these rocks are soft, nearly impermeable shale; the rest are bedded, hard, ridge-forming sandstone, limestone, and chalk. Twenty-two bedrock units are described in the present report as compared to only six in the Pueblo Folio (Gilbert, 1897). The units are now subdivided in such detail so that each rock unit on the geologic map has as nearly as possible a single lithology and thus a limited range of engineering properties. Some of the surficial units, for example, Slocum Alluvium, are too heterogeneous for this ideal to be realized. Nevertheless, the users of this report will find that many of the units are nearly monolithologic and that the engineering properties of different parts of each unit will not vary greatly. Variations in engineering properties due to different durations of exposure to weathering or to saturation by water are likely to be greater, within a geologic unit, than are the variations caused by original differences in composition.

DAKOTA SANDSTONE

The Dakota Sandstone (Meek and Hayden, 1862) of Early Cretaceous (Albian) age crops out only where the Arkansas River crosses the Rock Canyon anticline. The outcrop consists of rough massive beds of sandstone into which the river has cut a channel about 20 feet deep (fig. 9). Only 40 feet of sandstone is exposed here, and the next nearest outcrops where the whole 300 feet of the formation is exposed are nearly 10 miles to the west.

The sandstone is yellowish brown, friable, and tabular bedded in the upper 10–15 feet. Lower beds are yellowish gray and friable on a freshly broken face, but they become yellowish brown and hard upon exposure; the lower beds are massive and are composed of medium-grained poorly bonded to well-cemented sandstone. Much of the cement is silica; the coloring matter is iron oxide. The sandstone is composed of angular to subrounded quartz grains. According to petrographic examination by the U.S. Bureau of Reclamation (written commun., 1950), the sandstone also contains augite, biotite, chalcedony, and feldspar; the interstices between the grains contain clay minerals. The sandstone can be broken with the hands after immersion in water for 24 hours.

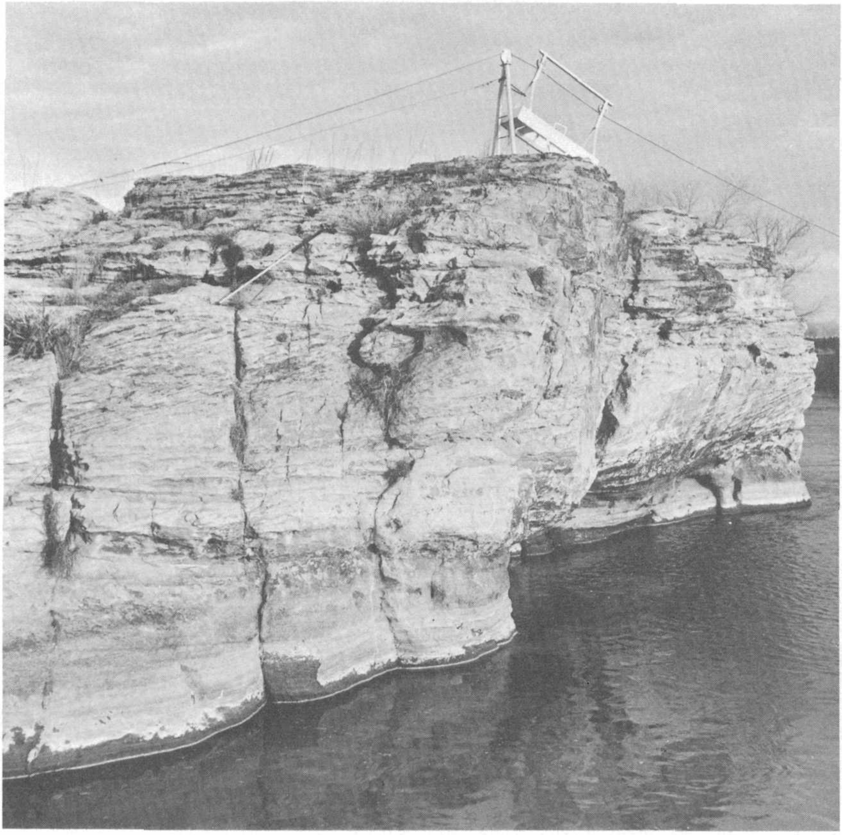


FIGURE 9.—Dakota Sandstone along Arkansas River in NE¼ sec. 36, T. 20 S., R. 66 W., Pueblo County, Colo. Notice cross-stratification below the 5-foot Jacob staff.

Engineering geology—No engineering problems are expected from the Dakota Sandstone. The Dakota is permeable and is a groundwater aquifier in the Pueblo area. Undoubtedly, the Rock Canyon anticline forms a minor recharge area for the Dakota. Excavation of the sandstone would have to be by quarrying methods or blasting. Foundation stability would be excellent. The Rock Canyon Barrier Dam built on the Dakota Sandstone more than 40 years ago is in excellent condition. This same site is to be the foundation of the Pueblo dam, an earthfill structure.

The Dakota Sandstone is known chiefly as an oil-producing formation and an artesian aquifer, but the stone also is used for building. At Pueblo, building stone from the Dakota Sandstone has been quarried and used in buildings and walls at City Park. The random blocks are in excellent condition after 25 years of service. The sandstone was tested by the U.S. Bureau of Reclamation (written commun., 1950) for use as riprap on the Pueblo dam. Results of the tests are as follows: Specific gravity, 2.37; 24-hour absorption, 2.7 percent; loss in the Los Angeles Abrasion test (A grading) after 500 revolutions, 97 percent; loss in soundness tests after 50 cycles of freezing and thawing, 0.01 percent, after 5 cycles of immersion in sodium sulfate, 35 percent. The rock was considered to be of poor quality for riprap, but it might be usable for that purpose if placed above the highest water level.

GRANEROS SHALE

The Graneros Shale (Gilbert, 1896) of Late Cretaceous (Cenomanian) age crops out in a circular pattern where the Arkansas River crosses the Rock Canyon anticline. The shale is well exposed only in freshly eroded steep slopes or arroyos, but a complete composite section can be put together by matching several good exposures. The Graneros is 108 feet thick and is marked by several layers of concretions and bentonite.

The formation is dark-gray fissile soft to medium-hard noncalcareous clayey shale and shaly siltstone. It contains much disseminated gypsum and crystals of selenite. The shale is well consolidated, but it weathers readily to soft light-gray clay to a depth of more than 5 feet.

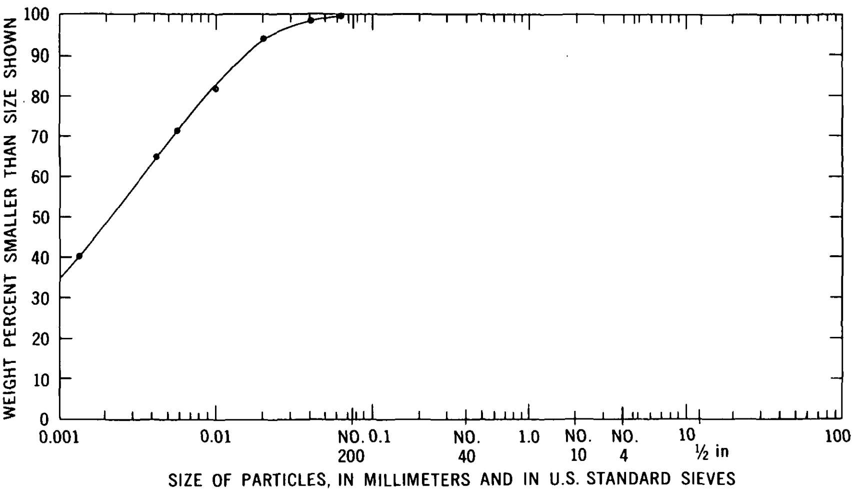


FIGURE 10.—General size-distribution characteristics of a typical sample of Graneros Shale.

Several layers of concretions form prominent ledges. About 18 feet above the base is hard platy siltstone in discontinuous layers. Six cone-in-cone limestone layers and concretions were observed between 44 and 60 feet above the base; the layer 60 feet above the base is the Thatcher Limestone Member. Thin limestone and ironstone concretions also lie 20–32 feet below the top. A size-distribution curve (fig. 10) using the Wentworth (1922) classification shows that the shale contains 64 percent clay-sized particles and 36 percent silt-sized particles.

A record of the X-ray diffraction of the Graneros Shale is shown in figure 11 to illustrate the method used to determine the minerals reported for each formation. Each mineral gives a characteristic X-ray pattern. The group of *d* spacings for each mineral, shown in

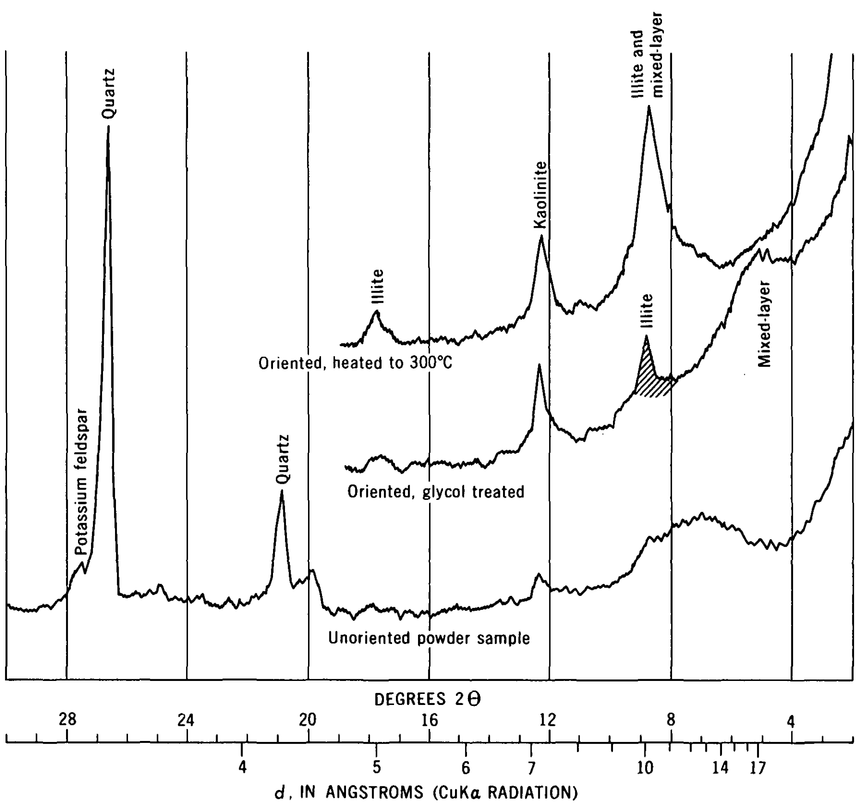


FIGURE 11.—X-ray diffractometer traces of Graneros Shale. The peaks are labeled to show the positions of the characteristic reflections of each mineral. Calculations of the amount of each mineral in the Graneros were made from these traces by measuring the heights or shaded areas of certain peaks.

angstroms on the horizontal scale, is indicative of atomic spacings within the crystal lattice. The vertical scale corresponds to the intensity of the X-ray reflection and is measured in counts per second. The intensity (height or shaded area) of a certain strong reflection from each mineral is used to measure the amount of that mineral in the sample. In figure 11, X-ray curves, which were made after different treatments, are spread vertically so that they do not overlap. Three traces are shown on the figure: (1) finely ground unoriented powder of the sample, (2) oriented, glycol treated, and (3) oriented, heated at 300°C for half an hour. Only the low-angle parts of the traces, which show the clay minerals present, are illustrated. Traces of the oriented air-dried sample and of the oriented sample heated to 550°C are not shown. The laboratory technique and interpretation are those devised by Schultz (1964) and will not be described here. X-ray analyses produce a rapid quantitative record of mineralogy and were run on most of the formations at Pueblo. The X-ray analysis of the Graneros Shale indicates that 70 percent is clay minerals, 30 percent is quartz, and a trace is potassium feldspar. Of the clay minerals, mixed-layer clay (consisting of illite and montmorillonite) is more abundant than illite, which is about equal in abundance to kaolinite.

Bentonite beds are abundant throughout the Graneros. More than 20 dark-yellowish-orange to light-gray beds ½–4 inches thick were measured. The bentonite is soft, plastic, and generally unlayered, but some beds are well stratified. A bed near the base contains abundant selenite crystals.

Fossils are uncommon in the lower part of the Graneros Shale, which contains only Foraminifera, fish parts, and worm burrows. Ammonites, mostly of the genus *Acanthoceras*, are common in the upper 45 feet of the formation.

Engineering geology.—The formation may cause engineering problems because of its clayiness. The shale is nearly impermeable. Water flows on the surface of the shale or through joints to seeps; the flow is good, except under surficial materials and in depressions. Seeps along arroyos generally are marked by prolific stands of saltcedar. Water from the shale is charged with sulfate. Erosion check dams are needed because the shale erodes readily to deep arroyos. Excavation to a depth of 8 feet is easy with small power tools, such as a backhoe.

Natural slopes in the Graneros are as steep as 20° where protected by overlying resistant rocks, but as low as 5° where only shale is exposed. The average stable slope probably is 5°–10°. Slumps and landslides were not observed and probably will not take place, except in nearly vertical slopes.

Foundation stability is fair to poor. All foundations should be placed below the weathered part of the shale in sound material, which lies 5–10 feet below the surface. All holes prepared for foundations should be probed beyond the drilled depth to assure that bentonite beds do not lie close to the bottoms of the holes. The presence of more than 20 separate bentonite beds increases the need to explore to greater depth before concrete is poured for foundations.

Swelling pressure of a shale sample from 10 feet above the base of the Graneros Shale is 1,000 psf, or noncritical. The bentonite beds have high swelling pressures and are numerous and so closely spaced through the formation that they will be difficult to avoid beneath foundations. Frost susceptibility, based on size analysis, is medium to high. The Unified Soil Classification symbol is CL. Plasticity index versus liquid limit for the shale is shown in figure 12.

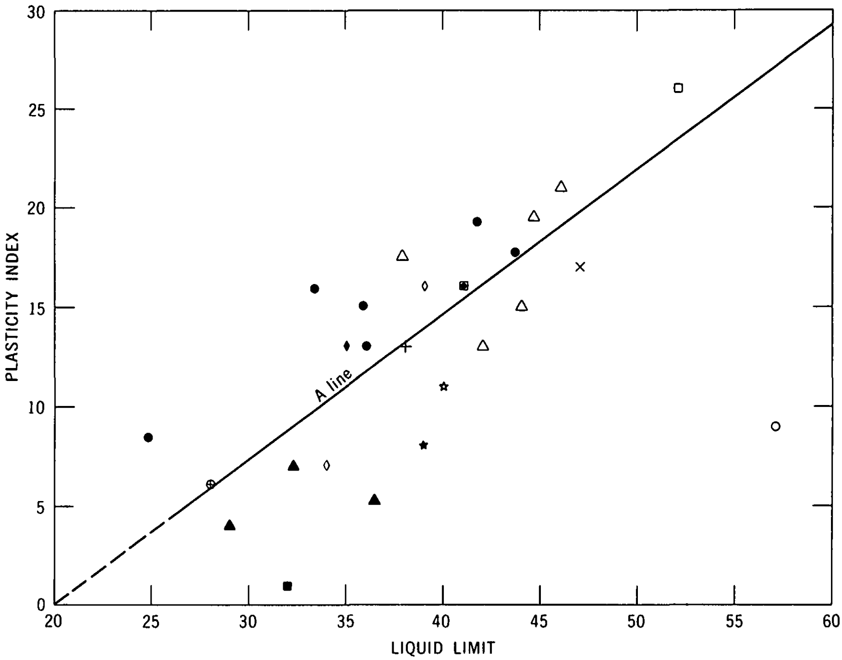


FIGURE 12.—Plasticity index versus liquid limit for shale units of Cretaceous age: ■ Tepee zone of Gilbert (1897); □ Rusty zone of Gilbert (1897); ○ Sharon Springs Member; ● Apache Creek Sandstone Member; △ transition member; ▲ upper chalky shale unit; ◇ middle shale unit; ⊕ lower shale unit; ◆ Blue Hill Shale Member; × Fairport Chalky Shale Member; ☆ Hartland Shale Member; ★ Lincoln Limestone Member; + Graneros Shale.

GREENHORN LIMESTONE

The Greenhorn Limestone (Gilbert, 1896) of Cenomanian and Turonian age contains, in ascending order, the Lincoln Limestone, Hartland Shale, and Bridge Creek Limestone Members. The members (unmapped) crop out on the lower of two scarps that circle Rock Canyon anticline where it is breached by the Arkansas River.

LINCOLN LIMESTONE MEMBER

The Lincoln Limestone Member (Cragin, 1896; Logan, 1897; Rubey and Bass, 1925) of Cenomanian age crops out where the

FIGURE 13.—Ledge of hard platy calcarenite composed of fragments of fossil shells at top of Lincoln Limestone Member of Greenhorn Limestone in the NE¼SE¼ sec. 25, T. 20 S., R. 66 W., Pueblo County, Colo. Slabs in foreground show fossils and flow casts.

Arkansas River crosses the Rock Canyon anticline. The member forms a minor ledge and the lower part of the steep slope composed of the Greenhorn Limestone. The Lincoln Limestone Member, which is 38 feet thick, is composed of calcareous shale containing thin calcarenite beds (fig. 13).

The shale is dark gray, soft, and fissile. It consists largely of sand- and silt-sized material which is composed of fragments of mollusk shells and Foraminifera. The shale weathers to soft chips, then to clayey calcareous silt to a depth of several feet. The calcarenite beds are dark gray, stratified, and locally limonitic; they weather to hard thin platy layers commonly showing swash marks and fossil impressions on their upper and lower surfaces. Several layers of calcarenite are continuous and as much as 1.6 feet thick, but some are lenticular and very thin. The thickest bed forms a ledge near the top of the member. Three white or yellowish-gray bentonite beds, ranging in thickness from 1 inch to 2 feet, were observed. The thickest bed, called the marker, or "X," bentonite, lies a little more than 1 foot above the base (fig. 14). This key correlation bed has been traced in outcrops and in the subsurface for hundreds of miles. X-ray analysis

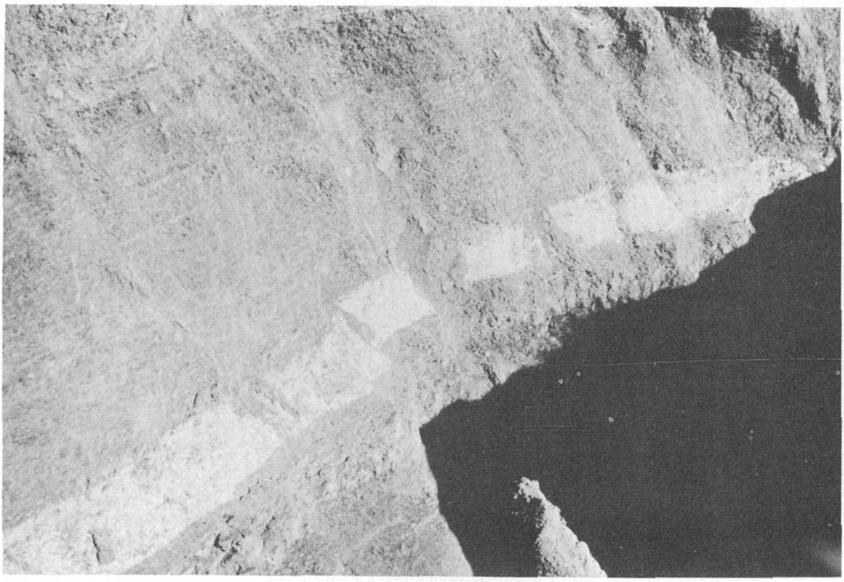


FIGURE 14.—Freshly exposed 2-foot-thick marker, or "X," bentonite (light-colored layer), 1.5 feet above base of Lincoln Limestone Member. This is the thickest bentonite bed in the area. Graneros Shale lies in bottom of arroyo. A sample of bentonite from this outcrop, in the SE¼NW¼ sec. 25, T. 20 S., R. 66 W., Pueblo County, Colo., had a swelling pressure of 8,000 psf.

shows that the bed contains 40 percent clay, 5 percent quartz, 55 percent gypsum, and a trace of feldspar. Of the clay minerals, mixed-layer clay (composed of illite and montmorillonite) is more abundant than kaolinite. The bentonite has a liquid limit of 61, plastic limit of 40, and a plasticity index of 21.

A size-distribution curve (fig. 15) shows that the noncalcareous fraction of a sample of shale contains about 57 percent clay, 37 percent silt, and 6 percent sand-sized particles. X-ray analysis shows that the shale contains 55 percent clay minerals, 15 percent quartz, 5 percent feldspar (plagioclase equals potassium feldspar in abundance), 20 percent calcite, and 5 percent dolomite. Of the clay, illite is equal in abundance to kaolinite, which is more abundant than mixed-layer clay (consisting of illite and montmorillonite). Sixty-three percent of the shale is insoluble in hydrochloric acid.

Two faunal zones in the Lincoln Limestone Member contain abundant fossils. Concretions at the base contain the clams *Inoceramus rutherfordi* Warren and *Ostrea beloiti* Logan and the ammonites *Acanthoceras amphibolum* Morrow, *Tarrantoceras* sp., and *Turrilites* sp. Associated with the concretions is a coquina bed composed of fragments of *O. beloiti*. A calcarenite bed near the top contains *Inoceramus pictus* Sowerby and an ammonite *Calycoceras canitaurinum* (Haas). The fossil shells of microscopic one-celled animals called Foraminifera are extremely abundant.

Engineering geology.—No major engineering problems are anticipated from the Lincoln Limestone Member. Because of its out-

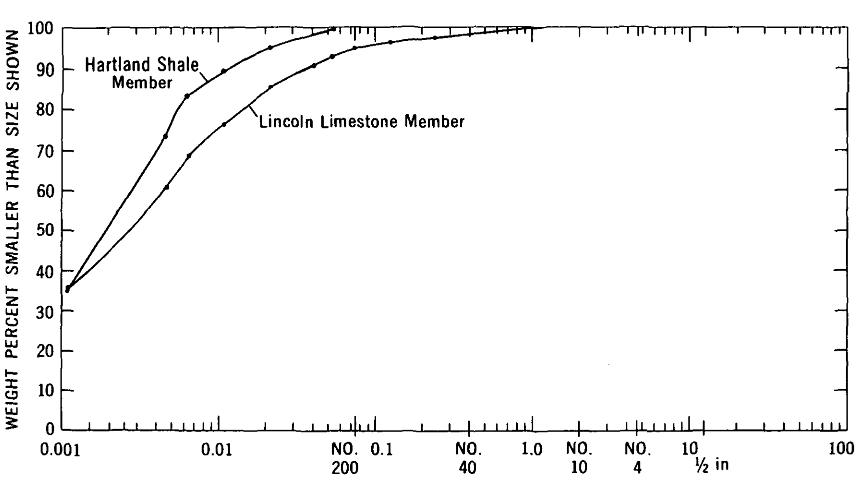


FIGURE 15.—General size-distribution characteristics of typical shale samples of Lincoln Limestone and Hartland Shale Members of Greenhorn Limestone.

crop position on steep slopes, the Lincoln has no surface drainage problems, but seeps were observed above some bentonite beds. The member is easily eroded and in diversion ditchs would require installations to check erosion. Excavation to a depth of 8 feet is easy with small power tools.

The Lincoln lies in 35° slopes where freshly eroded. Weathered slopes, where the shale is stripped of its cover, have a more stable slope of 5°–10°. The member is not likely to be used for foundations because of its steep slopes. Foundation stability is fair to poor. Foundations should be placed below the clayey weathered zone.

Swelling pressure of one sample from the shale is 1,600 psf, or noncritical. One of the three bentonite beds, the marker bentonite, has a swelling pressure as high as 8,000 psf, and the other two probably have swelling values higher than that of the shale. Frost susceptibility of the shale is inferred to be medium to very high. The Unified Soil Classification symbol is ML. Plasticity index versus liquid limit is shown in figure 12.

HARTLAND SHALE MEMBER

The Hartland Shale Member (Bass, 1926) of Cenomanian age crops out on the Rock Canyon anticline where it forms the middle of a steep slope composed of Greenhorn Limestone. The member is 59 feet thick and consists of calcareous shale and thin calcarenite lentils.

The shale is gray to dark gray, calcareous, soft and friable, and it contains thin, lenticular, shaly beds of calcarenite that are composed of prisms of *Inoceramus* shells and Foraminifera. Soft light-gray chalky limestone concretions as much as 3 feet long and 6 inches thick lie near the middle of the member, and limonite beds and nodules are scattered throughout the member. Twenty-four light-gray, gray, or yellowish-orange bentonite beds, ¼–6 inches thick, were measured.

A size-distribution curve (fig. 15) of the noncalcareous part of a sample of shale of the Hartland shows that it contains 69 percent clay and 31 percent silt-sized particles. X-ray analysis of the shale shows that clay minerals constitute 50 percent, quartz 10 percent, gypsum 10 percent, calcite 25 percent, and dolomite 5 percent. Of the clay, illite is equal in abundance to kaolinite, which is more abundant than mixed-layer clay (composed of illite and montmorillonite). Forty-six percent of the shale is insoluble in dilute hydrochloric acid.

Fossil fragments are abundant, but well-preserved fossils are uncommon. The most diagnostic species is *Inoceramus pictus* Sowerby;

with it are scraps of ammonites including *Calycoceras* sp. Foraminifera are very abundant.

Engineering geology.—Because of the position of the Hartland on a steep slope, there is little chance that it will become the site of foundations. Some seeps were observed along the bedding planes, especially above bentonite beds. The shale erodes to deep gullies that are filled with chunks of limestone from the Bridge Creek Member. Excavation to a depth of 10 feet is easy with small power tools. Natural slopes are about 30°, but certainly would not be stable at that angle if unprotected by the overlying Bridge Creek Limestone Member. A stable slope probably would be about 5°–10° if not overlain by Bridge Creek. Foundation stability, as interpreted from the Unified Soil Classification symbol, ML, is fair to poor. Swelling pressure of one sample from the shale is 1,700 psf, or noncritical. The 24 bentonite beds undoubtedly have higher swelling pressures. Frost susceptibility of the Hartland is medium to very high. Plasticity index versus liquid limit is shown in figure 12.

BRIDGE CREEK LIMESTONE MEMBER

The Bridge Creek Limestone Member (Bass, 1926) of Turonian age crops out on the Rock Canyon anticline. The limestone forms the lower of two strong persistent tree-lined ledges on the north side of the Arkansas River, but it is mantled by gravelly alluvium on the south side. The member, which is 52 feet thick, consists of many thin beds of limestone separated by thick beds of shale (fig. 16).

The limestone is gray, hard, and massive and is intersected by two good joint sets nearly at right angles to each other. Where weathered, the limestone is light gray, shaly, platy, or nodular. Most of the massive beds weather to irregular conchoidal-shaped chips that armor the slopes. Limestone beds in the member are thinner than the shale beds. Limestone beds range in thickness from 1 inch to 1.5 feet and average about 5.5 inches. Shale beds in the member range from 2 inches to 5 feet and average 1 foot. The shale is gray, calcareous, and hard; it weathers to soft clayey calcareous silt. Eleven bentonite beds, ranging in thickness from ½ to 7 inches, were measured. According to petrographic examination by the U.S. Bureau of Reclamation (written commun., 1950), the limestone is composed predominantly of calcareous oolite, calcite, some pyrite, illitic clay, quartz, chalcedony, feldspar, and magnetite in a fine-grained clayey calcareous matrix. Thin continuous calcite veinlets form a network in the limestone. Constituents insoluble in hydrochloric acid make up about 6 percent of the limestone.

FIGURE 16.—Bridge Creek Limestone Member of Greenhorn Limestone in NE¼NW¼ sec. 31, T. 20 S., R. 65 W., Pueblo County, Colo. Upper beds show tendency to weather shaly after prolonged exposure which is typical of all beds in this member. The Jacob staff is 5 feet long.

Fossils are abundant and diverse in the limestone beds. They are present in the shale but are not easily recovered. Three zones are recognized, each characterized by a distinctive suite of mollusks. The lower zone, only a little more than 3 feet thick, contains *Inoceramus pictus* and the ammonites *Sciponoceras gracile* (Shumard), *Allocrioceras pariense* (White), *Kanabiceras septemseriatum* (Cragin), and *Metoicoceras whitei* Hyatt. In addition, a remarkably well-preserved fish was collected by Wally Latimer, a student at Southern Colorado State College, from the lower part of the Bridge Creek. The specimen, cast in limestone, retains its original form including the head, gill plates, and scales; it lacks only the tail and fins from being perfectly preserved. It is described by David H. Dunkle, U.S. National Museum, as an example of an elopid fish best referred to as *Apsopelix sauriformis* Cope, 1871. The middle zone, about 12 feet thick, contains *I. pictus* and *Kanabiceras* sp. The upper zone, about 37 feet thick, contains *I. labiatus* (Schlotheim) and the ammonites *Mammites nodosoides* (Schlotheim) and *Baculites* sp. The upper 10 feet of the Bridge Creek and the lower 7 feet of the overlying Fairport Chalky Shale Member of the Carlile Shale contain a mixed fauna of the upper part of the zone of *I. labiatus* and the lower part of the zone of the ammonite *Collignoniceras woollgari.*

Engineering geology.—The Bridge Creek has a few engineering problems related to permeability, drainage, and erosion. Some seeps occur along the bedding, showing that the member has slight permeability and that channelways form through the limestone beds. The limestone beds prevent erosion; on vertical slopes, however, limestone blocks loosen and fall after the shale between the limestone beds is washed out.

Slopes stand at 20° where the member is much weathered, at 35° where less weathered, and vertically where freshly exposed. (fig 16). Foundation stability probably is excellent on the limestone beds, but the shale partings and bentonite beds could be troublesome. Excavation to any great depth is difficult if not impossible with small power equipment. Frost susceptibility is medium to very high.

Laboratory tests by the U.S. Bureau of Reclamation (written commun., 1950) to determine the suitability of the limestone for use as riprap show the following properties. The limestone has a specific gravity of 2.59, 24-hour absorption of 2.7 percent, and a loss of 25 percent after 500 revolutions of the Los Angeles Abrasion test (A grading). In soundness tests, a limestone sample showed a loss of 75–100 percent after 50 cycles of freezing and thawing and a loss of 20 percent after 5 cycles of immersion in sodium sulfate. The conclusion was reached that the sample of limestone was of poor quality for use as riprap, particularly in locations that will be exposed to severe weathering.

CARLILE SHALE

The Carlile Shale (Gilbert, 1896) of Turonian age contains, in ascending order, the Fairport Chalky Shale Member, Blue Hill Shale Member, Codell Sandstone Member, and the Juana Lopez Member. These members (unmapped) crop out on the flanks of the Rock Canyon anticline between the circling cliffs of the Bridge Creek and the Fort Hays Limestone Members.

FAIRPORT CHALKY SHALE MEMBER

The Fairport Chalky Shale Member (Rubey and Bass, 1925) crops out in most places in a gently sloped bench at the base of the cliff below the Codell Sandstone Member. It generally is poorly exposed, owing to an accumulation of slope wash. The best exposures are in the NW¼ sec. 30, T. 20 S., R. 65 W., and the NW¼ sec. 25, T. 20 S., R. 66 W. Here, the member is 99 feet thick and consists of calcareous shale; in the lower part are thin calcarenite beds (fig. 17).

The shale is pale yellowish brown, light olive gray, or gray, fissile to platy, calcareous or chalky. It weathers to soft clayey calcareous silt. The lower 10 feet is characterized by thin layers and lenses of gray platy calcarenite and limestone. A layer 8 feet above the base is marked by V-shaped impressions called flow casts. A size-distribution curve (fig. 18) shows the noncalcareous part of a sample of shale to contain 53 percent clay, 42 percent silt, and 5 percent sand-sized particles. X-ray analysis indicates that 50 percent is clay minerals, 15 percent is quartz, 5 percent is feldspar (plagioclase is more abundant than potassium feldspar), 5 percent is gypsum, 20 percent is calcite, and 5 percent is dolomite. Of the clay minerals, illite is more abundant than kaolinite, which is more abundant than mixed-layer clay (consisting of illite and montmorillonite). Sixty-five percent of the shale is insoluble in dilute hydrochloric acid. Twenty-one light-gray or yellowish-orange soft plastic bentonite beds, ranging in thickness from 1½ to 3 inches, were observed. Several of these are limonitic, and some contain selenite crystals.

Fossils in the Fairport are abundant, but they are preserved only as delicate impressions in the shale and calcarenite beds. *Inoceramus labiatus* (Schlotheim) and *Collignoniceras woollgari* (Mantell) occur together in the lower 7 feet, and *C. woollgari* extends to within 22 feet of the top. Foraminifera are abundant in the shale.

FIGURE 17.—Fairport Chalky Shale Member of Carlile Shale in the NW¼NW¼ sec. 30, T. 20 S., R. 65 W., Pueblo County, Colo. The shale weathers rapidly from hard platy beds like those in the gully to soft clayey shale like that near the head of the 5-foot Jacob staff.

Engineering geology.—Clayiness and deep weathering may cause the Fairport to be troublesome in foundations. The Fairport is relatively impermeable, but it absorbs enough water to be sticky after a rain. Water drains off the shale rapidly, except in depressions or beneath surficial deposits. Artificial drains would be necessary in low places. The shale is easily eroded, and check dams are necessary along roadside ditches. Freshly eroded shale slopes 20°–30°; weathered shale slopes 5°–10°, and the gentler slope would be preferable for artificial cuts. The shale can be excavated easily with small power tools to a depth of 10 feet.

Foundation stability of the shale is fair to poor. Foundations should be deep, and the bottoms of borings for piers should be probed to avoid placing the piers or other type foundations too close to bentonite beds. Foundations should be placed below the weathered

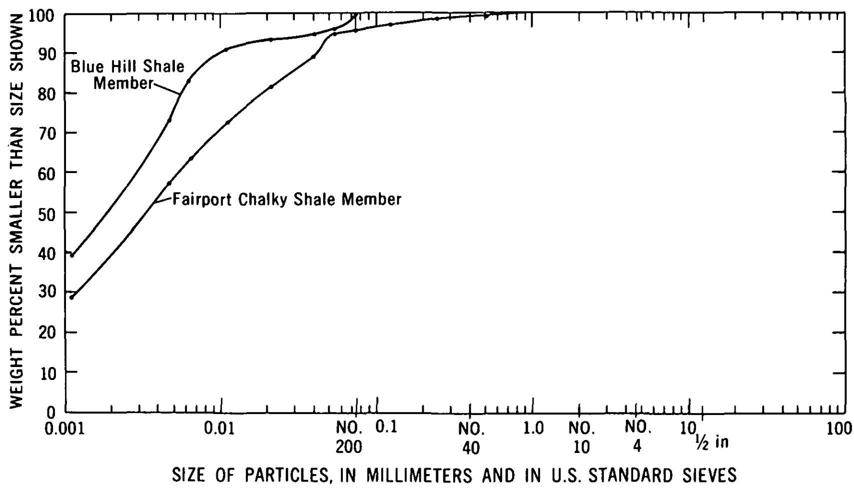


FIGURE 18.—General size-distribution characteristics of typical samples of Fairport Chalky Shale and Blue Hill Shale Members of Carlile Shale.

zone, which ranges in depth from 3 to 10 feet. Swelling pressure of a sample from the lower part of the shale is 3,000 psf, or marginal. The 21 bentonite beds surely will give higher swelling pressures and are so widely spread through the shale that they will be difficult to avoid beneath foundations. Frost susceptibility inferred from the size analysis is medium to very high. The Unified Soil Classification symbol is ML. Plasticity index versus liquid limit for the shale is shown in figure 12.

BLUE HILL SHALE MEMBER

The Blue Hill Shale Member (Logan, 1897) crops out as dark places on the steepest part of the slope below the cliff made by the Codell Sandstone Member. The shale is well exposed in few places because of a cover of colluvium, but giant concretions from the shale are exposed almost continuously along the slope or are tumbled down at its base. The best exposure is in the NW¼ sec. 25, T. 20 S., R. 66 W. The member, which is 101 feet thick, is composed of clayey shale in the lower half and sandy siltstone containing septarian concretions in the upper half.

The lower half of the member contains dark-gray hard fissile noncalcareous clayey shale and dark-gray hard blocky noncalcareous claystone. The lowest 18 feet of the member forms the nearly black clayey shale outcrop spots on the slope (fig. 19); the surfaces of the clayey shale chips from this part of the section are smooth and shiny. The chips from overlying silty beds are rough textured. The lowest sandstone bed lies 35 feet above the base, but sandstone beds

FIGURE 19.—Lower part of Blue Hill Shale Member of Carlile Shale in NW¼ NW¼ sec. 25, T. 20 S., R. 66 W., Pueblo County, Colo., showing drab black noncalcareous flat-lying clayey shale that characterizes lower part of member. Pick lies on a layer of bentonite. Note how effectively rainfall erodes the soft Cretaceous shale.

and sandy shale predominate at 50 feet above the base. The upper half of the member contains dark-gray blocky sandy friable micaceous siltstone and concretions (fig. 20). Sandstone increases in abundance toward the top, and the topmost 10 feet is yellowish-gray shaly to nodular sandstone. Only two bentonite beds, each 1 inch thick, were observed in the lower part. Concretions are abundant in the upper part. The lowest, a single septarian concretion 4 feet in diameter, lies 42 feet above the base. Other giant round septarian concretions, 4 feet thick and 6 feet in diameter, lie in two prominent layers 50 and 64 feet above the base (figs. 20, 21). These concretions are composed of yellowish-gray hard sandy limestone penetrated by ramifying veins of brown and white calcite crystals; they also contain some masses of barite. Other smaller septarian concretions and some shaped like 20-inch cannonballs lie in the upper 17 feet of the member.

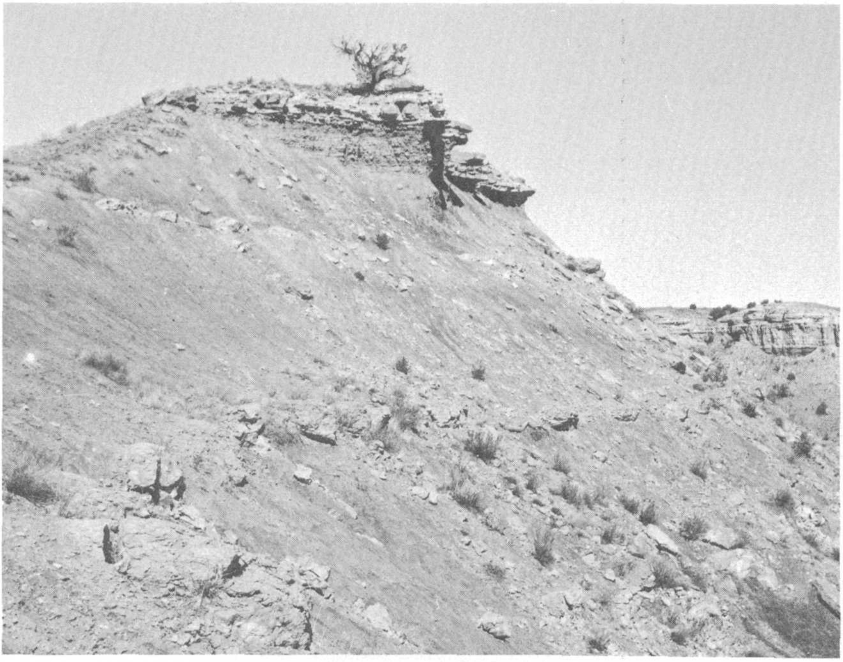


FIGURE 20.—Upper part of Blue Hill Shale Member of Carlile Shale showing three layers of concretions—in lower right, middle, and upper left of photograph. Concretions in middle layer are 4 feet thick. Codell Sandstone Member of Carlile forms cliff at top of exposure. NW¼NW¼ sec. 25, T. 20 S., R. 66 W., Pueblo County, Colo.

FIGURE 21.—Septarian, concretion, 4 feet thick, in upper of two prominent layers in Blue Hill Shale Member in the NW¼NW¼ sec. 25, T. 20 S., R. 66 W., Pueblo County, Colo.

A size-distribution chart (fig. 18) shows that the noncalcareous fraction of a sample of shale from about 40 feet above the base contains 68 percent clay, 29 percent silt, and 3 percent sand-sized particles. X-ray analysis of the Blue Hill shows that it contains 65 percent clay minerals, 25 percent quartz, 5 percent feldspar (plagioclase is equal to potassium feldspar in abundance), and 5 percent calcite. Illite is equal in abundance to kaolinite, which is more abundant than mixed-layer clay (consisting of illite and montmorillonite). Of the shale sample tested, 91 percent was insoluble in dilute hydrochloric acid.

Fossils are uncommon and poorly preserved in the Blue Hill. The only fossils collected were from the upper of the two prominent layers of concretions. They contain the ammonite *Collignoniceras hyatti* (Stanton), many gastropods, and a large species of oyster.

Engineering geology.—The steep slopes formed by the Blue Hill shale member suggest that it is unlikely to be the site of any building foundations. Permeability is negligible, and no seeps were observed. Surface water drains away rapidly. The shale is eroded readily (fig. 19), except where it is covered by stony colluvium. Steep slopes gradually erode to about 30° where they remain. Rockslides that affect the Blue Hill were seen in the southwest corner of the area along Colorado Highway 96 and elsewhere. The slump blocks include parts of the Fort Hays Limestone and Blue Hill Shale Members and a complete section of the Codell Sandstone Member. Generally, the blocks rotate so that the ultimate dip is downward toward the slip plane. The shale can be excavated easily with small power tools to a depth of 5 feet.

Foundation stability is fair to poor. The upper half of the Blue Hill apparently would cause no problems and is not discussed here. In the lower half, deep foundations are preferable to shallow foundations. The shale possibly is deeply weathered beneath its colluvial cover; foundations should extend below this weathered zone. Swelling pressure of one sample of the clayey lower part of the shale is noncritical at 2,400 psf. The two bentonite beds would give higher pressures. Frost susceptibility of the shale is medium to high. The Unified Soil Classification symbol is CL. Plasticity index versus liquid limit is shown in figure 12.

CODELL SANDSTONE MEMBER

The Codell Sandstone Member (Bass, 1926; Dane and Pierce, 1933) crops out for the most part as a vertical cliff circling the Rock Canyon anticline (fig. 22). It generally is very well exposed, but some parts locally are inaccessible owing to their position on the cliff. The member is 30 feet thick and is entirely sandstone.

The sandstone, which is composed of well-cemented rounded quartz grains, is divisible into three parts—a lower platy part, a middle massive cliff-forming part, and an upper massive ledge-forming part. The lower 5 feet is yellowish gray, crossbedded, lenticular, and platy, and the bedding surfaces are marked by worm borings and trails. The middle 18 feet is light-gray massive very fine grained cross-stratified worm-bored noncalcareous sandstone that weathers yellowish gray. The upper 7 feet is yellowish-gray to moderate-yellowish-brown massive or thick-bedded worm-bored sandstone. On weathered slopes the upper part makes two ledges; on unweathered slopes it makes a vertical cliff in combination with the middle part. Common thin lenticular sandstone concretions lie in the lower platy part of the member, and 16-inch cannonball-like concretions lie in the middle.

Fossils are abundant and diverse in the lenticular sandstone concretions near the base. Diagnostic forms are *Collignoniceras hyatti*,

FIGURE 22.—Codell Sandstone Member of Carlile Shale near crest of Rock Canyon anticline in the SE¼SW¼ sec. 24, T. 20 S., R. 66 W., Pueblo County, Colo. The Jacob staff is 5 feet long. Lower platy part, middle massive part, and upper ledge-forming part are well shown.

Inoceramus howelli White, and *Ostrea malachitensis* Stanton. *O. malachitensis* also occurs in sandy lenses at the base of the upper ledge-forming bed.

Engineering geology.—Few foundations are likely to penetrate to the Codell Sandstone Member because of the widespread cover of

Fort Hays Limestone Member. The sandstone is permeable and is the source of several seeps. Erosion is very slow, except where the sandstone forms the lip of a waterfall of a perennial or intermittent stream. Blasting or quarrying techniques are necessary for the removal of the sandstone. The sandstone stands in vertical slopes that are stable except where undercut by erosion or by slides in the underlying Blue Hill Shale Member. Rockslide blocks involving also Blue Hill and Fort Hays are as large as 100 feet long, 20 feet wide, and 50 feet high. They generally rotate as they slide so that the bottom moves outward and the top inward toward the slide surface.

Foundation stability is excellent, except near the edges of the high cliffs where the sandstone is not laterally confined. The sandstone is nonswelling and nonsusceptible to frost.

Codell Sandstone Member was widely used for dimension stone in retaining walls, foundations, buildings, stone arch bridges, and aprons. Its performance over a period exceeding 65 years is excellent. Examples of the use of Codell are as a retaining wall on Joplin Street at 2d Street, and in the Minnequa Bank building at Evans and Northern Avenues. Most of the pits that supplied the stone are southwest of town at the south end of the Rock Canyon anticline west of Columbia Heights Subdivision in the Southwest Pueblo quadrangle. Potential value of the stone as riprap is unknown, and it should be tested.

JUANA LOPEZ MEMBER

The Juana Lopez Member (Rankin, 1944) crops out as shaly sandstone containing thin, discontinuous lenses of calcarenite between the Codell Sandstone Member and the Fort Hays Member of the Niobrara Formation. The shaly sandstone is light gray, very fine grained, calcareous, soft, slightly glauconitic, and somewhat shaly; it weathers light yellowish gray. Few of the lenses are larger than 3 feet in diameter or 6 inches thick. They are composed of dark-brownish-gray hard petroliferous-smelling fine-grained calcarenite containing patches of light-gray fine-grained glauconitic calcarenite. They are scattered at 10- to 20-foot intervals. The calcarenite is extremely resistant to weathering; fragments, intermingled with resistant igneous rocks, are common many miles from their source. Total thickness of the member is 2.5 feet.

The calcarenite lenses rarely contain fossils. Diagnostic fossils in the calcarenite include *Inoceramus dimidius* White, the ammonites *Scaphites warreni* Meek and Hayden and *Prionocyclus wyomingensis* Meek, and an oyster, *Lopha lugubris* (Conrad).

NIOBRARA FORMATION

The Niobrara Formation (Meek and Hayden, 1862) is of Late Cretaceous age. Most of the western part of the area has Niobrara Formation at the surface or underlying a thin mantle of surficial deposits. The formation is composed of the Fort Hays Limestone Member and the overlying Smoky Hill Shale Member. The names Timpas Limestone and Apishapa Shale applied by Gilbert (1896) to rocks of Niobrara age in this area were recently abandoned by the U.S. Geological Survey (Scott and Cobban, 1964).

FORT HAYS LIMESTONE MEMBER

The Fort Hays Limestone Member (Mudge, 1877; Williston, 1893) of late Turonian and early Coniacian age crops out over the southwest corner of the area, where it forms a prominent scarp that circles the Rock Canyon anticline (pl. 1). Individual beds of the member, because of their weathering habit, are poorly exposed despite the fact that the limestone lies at the surface over many square miles. The member, where it is well exposed in cliffs and quarry faces, is 40 feet thick and consists of about 82 percent limestone and 18 percent shale (fig. 23).

At Pueblo the member contains about 40 limestone beds separated by thin shale partings. The limestone beds, which are 1–26 inches thick, are gray, dense, and hard, and weather to yellowish-gray thinner layers or flakes. The shale partings are yellowish gray, soft, fissile to platy or blocky, and calcareous. One thin bentonite bed lies 34 feet above the base. Petrographic examination by the U.S. Bureau of Reclamation (written commun., 1950) showed the limestone to be composed of calcareous oolites, calcite, and minor amounts of pyrite, illite, quartz, chalcedony, feldspar, and magnetite in a fine-grained calcareous matrix. Three fossil zones based on the clam *Inoceramus* are known (Scott and Cobban, 1964). The lowest 1 foot of the member contains a small species that resembles *I. perplexus* Whitfield. *I. erectus* Meek lies 19–24 feet above the base; with it are the ammonites *Barroisiceras* (*Forresteria*) *hobsoni* Reeside and *Prionocycloceras*? sp. *I. deformis* Meek lies in the upper 13 feet of the member.

Engineering geology.—The Fort Hays Limestone Member causes no great engineering problems. Permeability is poor, but some water flows in the shale between limestone beds. Seeps issue from channelways at the bases of the limestone beds and along joints; solution of the limestone takes place along the channelways. Shale partings are frost susceptible. Limestone is not subject to rapid weathering

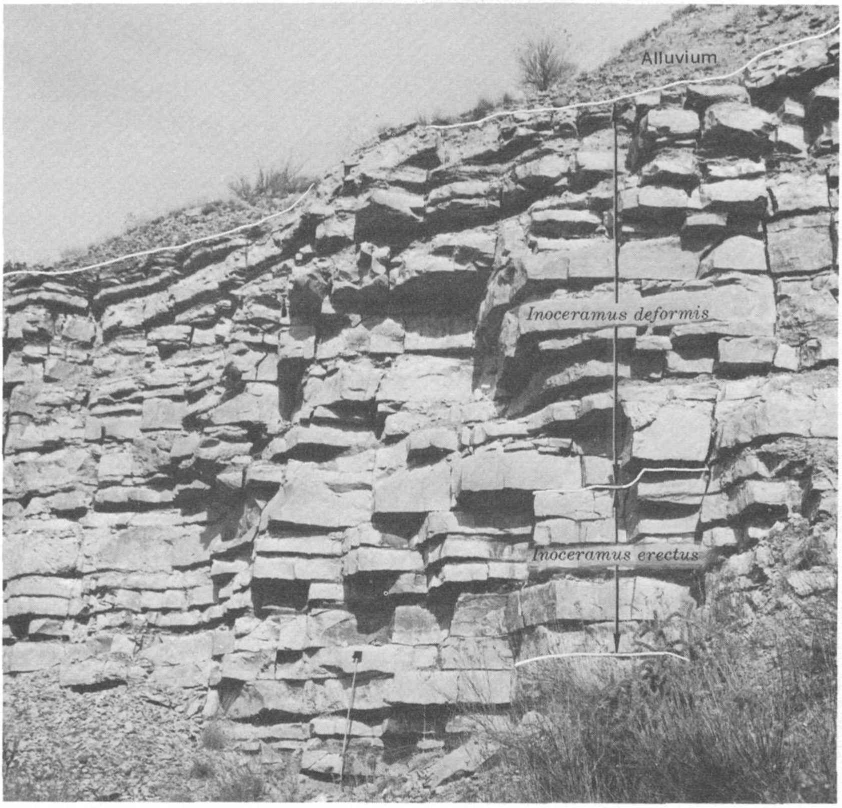


FIGURE 23.—Fort Hays Limestone Member of the Niobrara Formation in a slightly weathered quarry face in the SE¼NE¼ sec. 32, T. 20 S. R. 65 W., Pueblo County, Colo. The uppermost and lowermost parts are not exposed, and only two faunal zones are visible. Limestone predominates over shale. The Jacob staff is 5 feet long.

in a semiarid climate, but is removed mostly by erosion and solution. Stable slopes in nature are 25°–30°, but steeper slopes probably would cause little trouble along highways. Rockslides and rockfalls are fairly common along the cliffs circling Rock Canyon anticline, and nearly all of them involve some Fort Hays Limestone Member.

Foundation stability of the Fort Hays is excellent. Shallow foundations and spread footings would be suitable under most buildings. Excavation below a depth of 3 feet is difficult except with large power equipment, or unless the limestone is broken by blasting.

The stone is a fairly good source of construction material. Laboratory tests by the U.S. Bureau of Reclamation (written commun., 1950) to determine the suitability of the limestone for use as riprap showed it to have the following properties. Specific gravity is 2.57;

24-hour absorption is 2.9 percent. Los Angeles Abrasion loss (A grading) after 500 revolutions is 25 percent. In soundness tests the limestone sample tested showed a loss of 90 percent after 50 cycles of freezing and thawing and a loss of 18 percent after 5 cycles of immersion in sodium sulfate. As a result of the tests the Fort Hays Limestone Member was concluded to be a poor source of rock for riprap. The limestone has been used as a source of smelter and foundry limestone, mineral filler, agricultural limestone, cement, structural, and dimension stone, and road metal. Cut stone has been used as walls at El Pueblo Museum, which originally was built as an airport hangar, and as walls at Mineral Palace Park, both built about 1936. The performance of the stone at the museum is good, except for some spalling along bedding planes and at iron-stained spots. At Mineral Palace Park the stones are splitting, slaking, and spalling somewhat near ground level, but they are in good shape above ground level. In service as road metal the limestone dusts very badly.

SMOKY HILL SHALE MEMBER

The Smoky Hill Shale Member (Cragin, 1896) of Coniacian, Santonian, and early Campanian age crops out in the western half of the area. The member is 700 feet thick and consists of shale, chalk, and some limestone. Several hard beds form low hogbacks. The member has been divided (Scott and Cobban, 1964) into seven lithologically distinct units, in ascending order, as follows: shale and limestone, lower shale, lower limestone, middle shale, middle chalk, upper chalky shale, and upper chalk.

SHALE AND LIMESTONE UNIT

The shale and limestone unit of early and middle Coniacian age crops out on the downslope end of the dip slope made by the Fort Hays. The unit is 21 feet thick and consists of less than 50 percent Fort Hays-type of limestone and more than 50 percent soft calcareous shale.

Eighteen layers of limestone were measured. The limestone is gray and massive and weathers yellowish gray and shaly (fig. 24). Individual beds range in thickness from 3 to 19 inches and average 6 inches. The shale is gray, calcareous, hard, and blocky; it weathers yellowish gray and soft. Shale layers average 7 inches in thickness. Beds near the base and top are gypsiferous. Two bentonite beds lie 4–5 feet below the top. Fossils are abundant, but only a few species are known. *Inoceramus deformis* occurs throughout the shale, *I. inconstans* Woods is 2 feet above the base, and *I.* (*Volviceramus*) *involutus* Sowerby is in only the top bed.

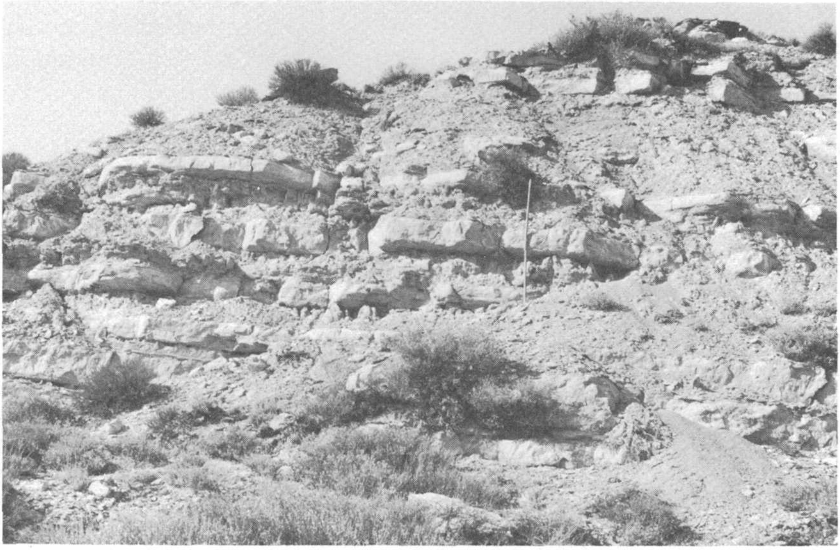


FIGURE 24.—Shale and limestone unit of Smoky Hill Shale Member along north valley wall of Arkansas River in the SE¼NE¼ sec. 32, T. 20 S., R. 65 W., Pueblo County, Colo. Shale predominates over limestone. The Jacob staff is 5 feet long.

Engineering geology.—The shale and limestone unit presents a few engineering problems; the major one is a potential swelling hazard. Permeability is very slight, but seeps were seen at the base of limestone beds. Surface water drains quickly, but the thick limestone beds prevent rapid erosion. The unit stands in vertical faces, but will gradually erode back to a more stable angle approaching 25°. Blocks fall from cliffs where undercut by streams.

Foundation stability is fairly good. Bearing-strength tests of the shale partings, should be performed as the shale very likely contains some swelling clay. Frost susceptibility is medium to high in the shale partings. Excavation is difficult; the limestone can be shattered and removed with difficulty to a depth of 8 feet by dropping a steel ball or chisel and digging with a backhoe. Dynamite shatters the limestone more readily, but it might cause damage to houses or other property. The unit is being used for the manufacture of cement and was previously used for smelter limestone.

LOWER SHALE UNIT

The lower shale unit of middle Coniacian age forms a low swale between the shale and limestone unit and the overlying lower limestone unit (fig. 26). The unit is 56 feet thick and consists of shale and platy limestone.

The shale is dark gray and weathers to pale-, moderate-, or dark-yellowish-brown fissile to platy fragments or to soft crumbly calcareous flakes. The limestone layers are dark or light gray, platy, and very even splitting. Selenite crystals, fibrous selenite, and granular gypsum form limonite-stained lenses in the lower part and coatings on fossils near the middle. Two bentonite beds lie 20 and 25 feet above the base. A size-distribution curve (fig. 25) of the noncalcareous part of a sample of lower shale shows that it contains 50 percent clay, 47 percent silt, and 3 percent sand. X-ray analysis indicates that 40 percent is clay minerals, 15 percent is quartz, and 45 percent is calcite. Of the clay minerals, mixed-layer clay (consisting of illite and montmorillonite) is more abundant than illite, which is more abundant than kaolinite. Forty-six percent of the shale tested is insoluble in dilute hydrochloric acid.

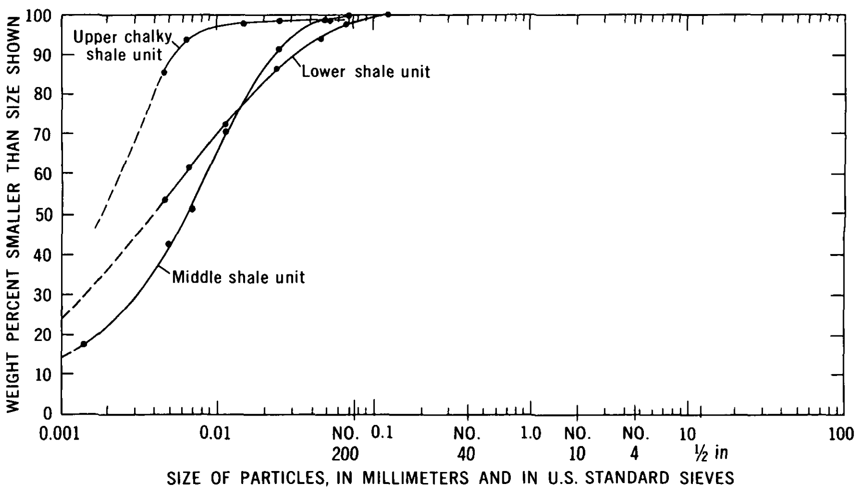


FIGURE 25.—General size-distribution characteristics of typical samples of lower and middle shale units and upper chalky shale unit of Smoky Hill Shale Member of the Niobrara Formation.

Fossils occur abundantly as flattened impressions. Diagnostic species are *Inoceramus* (*Volviceramus*) *involutus*, *I. stantoni* Sokolow, *Baculites asper* Morton, and *B. codyensis* Reeside.

Engineering geology.—The calcareous hard shale in this unit is unlikely to cause major engineering problems. The shale is somewhat permeable, and water seeps locally from bedding planes. Surface water drains readily; the unit seems to erode slowly and does not need erosion check dams, except where weathered. The upper 6 feet commonly is much weathered. A fresh slope stands vertical, and a weathered slope stands at 25°.

Foundation stability of the shale depends largely on its swelling potential. Swelling pressure of a sample from the lower part of the shale is only 500 psf, or noncritical. The bentonites would have higher swelling pressures. Frost susceptibility is medium to very high. The shale probably is most highly susceptible to frost in the upper 6-foot weathered zone. The Unified Soil Classification symbol is ML. Plasticity index versus liquid limit for the shale is shown in figure 12. Excavation is fairly easy with power equipment, such as a backhoe, to a depth of 10 feet. The shale is used for manufacture of cement and for dumped fill.

LOWER LIMESTONE UNIT

The lower limestone unit of middle and late Coniacian age forms one or more low white ridges of gently dipping limestone (fig. 26). The unit is 38 feet thick and consists of cyclically bedded limestone and shale (Scott and Cobban, 1964).

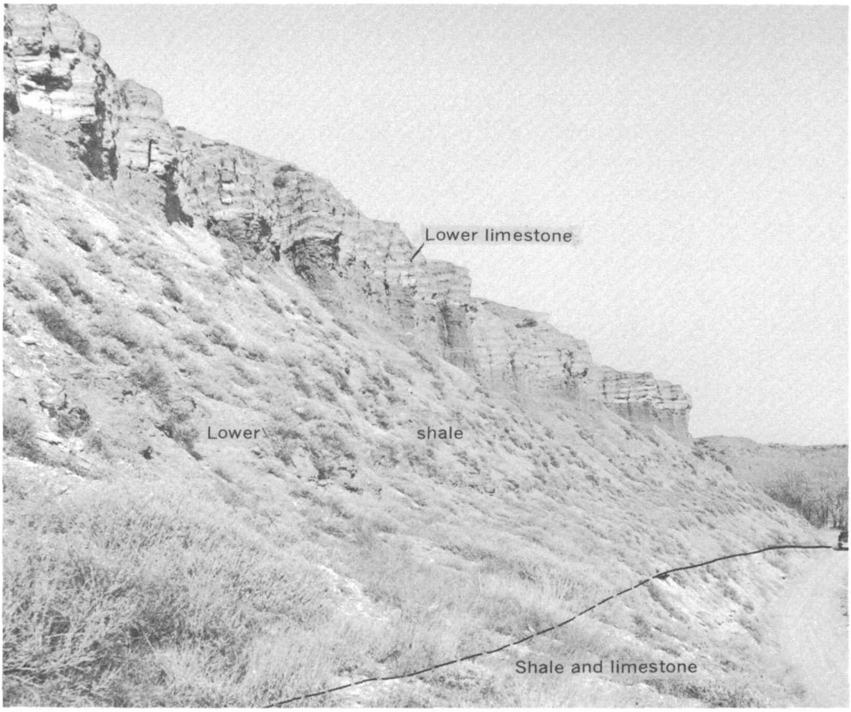


FIGURE 26.—Lower limestone unit of Smoky Hill Shale Member overlying lower shale unit and shale and limestone unit in cliff along north valley wall of Arkansas River in the NW¼ sec. 33, T. 20 S., R. 65 W., Pueblo County, Colo. Cyclic repetition of the limestone beds is well shown.

Sixteen limestone beds 3 inches to 6 feet thick separated by shale were measured. The limestone is gray, hard, slightly chalky, and platy, and it forms ledges. The shale is light olive gray, medium gray, or grayish brown, calcareous, hard, and fissile to platy. Lenses and nodules of limonite-stained gypsum are common in the unit. Two bentonite beds lie 4 inches and 6 feet below the top.

Fossils are abundant and include several species. The clams *Inoceramus* (*Volviceramus*) *involutus* and *I. stantoni* and the ammonites *Neocrioceras* n. sp., *Pseudobaculites* sp., *Baculites asper*, and *Phlycticrioceras oregonense* Reeside are the diagnostic species.

Engineering geology.—The lower limestone is not expected to cause any engineering problems, except for difficulty in excavation and the swelling of clays in shale partings. Seeps from bedding planes were observed along some arroyos. Surface water drains readily; the limestone is not easily eroded and requires no erosion check dams. Slopes are 35° to vertical where the underlying lower shale unit is being eroded; small blocks slump where erosion has removed support. Weathered slopes stand at 20°.

Foundation stability is good. Shallow foundations on spread footings below the depth of frozen ground probably can be used if placed on limestone and if water is kept out of the underlying shale. Probably very little subbase would be needed for a road across the lower limestone. Shale partings, and especially the two bentonite beds, will have a potential swelling pressure for which allowance should be made in foundation design. Weathered limestone and the shale partings are susceptible to frost heave. Excavation to a depth of 10 feet is possible but difficult with a backhoe; deeper excavation is possible with larger equipment or with breakage by dynamite. The lower limestone has a potential use for the manufacture of cement.

MIDDLE SHALE UNIT

The middle shale unit of late Coniacian to middle Santonian age forms a valley between the subdued ridges of the lower limestone and middle chalk units. The unit is about 280 feet thick and consists of shale and some sandstone.

The shale is dark gray, hard, platy, and calcareous; it weathers to light-olive-gray, pale-yellowish-brown, or yellowish-gray soft fissile silty clay. Silty platy limestone beds occur in the lower and upper parts. Light-olive-gray platy sandy shale containing thin lenses of sandstone lies 150–190 feet above the base. The only limestone concretions in the Niobrara Formation lie 30 feet below the top of the middle shale (fig. 27). Generally, there are four layers of concretions 2–14 inches in diameter in a shale interval 11 feet

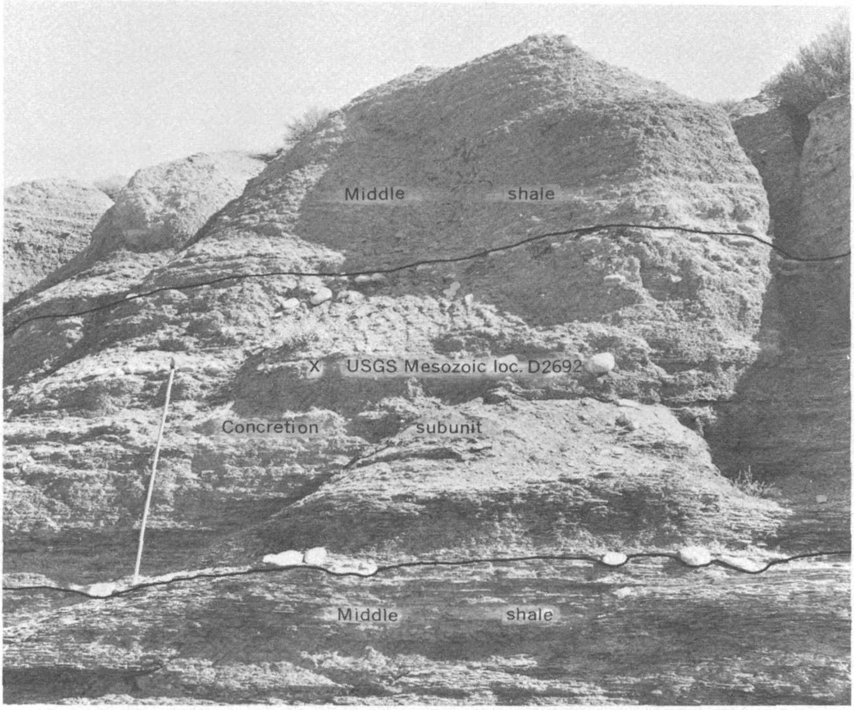


FIGURE 27.—Concretion subunit of middle shale unit of Smoky Hill Shale Member in valley of Dry Creek in the SW¼ sec. 3, T. 20 S., R. 65 W., Pueblo County, Colo. Concretions are more abundant but smaller at top of subunit. The Jacob staff is 5 feet long.

thick. Limonite-stained gypsum nodules or lenses of selenite crystals occur along with beds of limonite. Seven layers of bentonite ½–2 inches thick were measured.

A size-distribution curve of the noncalcareous part of a sample of shale (fig. 25) shows that it contains 36 percent clay and 64 percent silt. X-ray analysis shows that the shale contains 40 percent clay minerals, 20 percent quartz, 5 percent feldspar (plagioclase is equal to or exceeds potassium feldspar in abundance), 25–30 percent calcite, 5 percent dolomite, and minor amounts of gypsum. Of the clay minerals, mixed-layer clay (illite and montmorillonite) is more abundant than illite, which is more abundant than kaolinite. About 90 percent of the shale is insoluble in dilute hydrochloric acid.

Fossils are abundant and varied in the middle shale (Scott and Cobban, 1964). Four scaphitid ammonite zones, in ascending order, include *Scaphites depressus* var. *stantoni* Reeside, *Clioscaphites saxitonianus* (McLearn), *C. vermiformis* (Meek and Hayden), and *C.*

choteauensis Cobban. The ranges of the scaphites overlap those of three inoceramid zones, in ascending order, *Inoceramus undulatoplicatus* Roemer, *I. cordiformis* Sowerby, and *I. platinus* Logan. In addition, three diagnostic ammonites, *Protexanites shoshonensis* (Meek), *Texanites americanus* (Lasswitz), and *Stantonoceras pseudocostatum* Johnson, were found at or near Pueblo.

Engineering geology.—Problems in the middle shale are expected from the swelling potential and low bearing capacity of weathered shale. Permeability is very poor in the shale, and seeps are uncommon, occurring only on the floors of arroyos cut in the shale. Surface water draining off the shale is charged with sulfate minerals. The unweathered shale erodes slowly; however, erosion check dams should be used where roadside ditches cross the weathered zone. Where the shale is capped by resistant material, such as gravel, it stands in 30° slopes; but where it is uncovered, it forms more gentle slopes. A 12° slope was measured, for example, in a place where the shale was weathered to a depth of 20 feet.

Foundation stability is fair to poor, and foundations should extend below the depth of weathering. The excavated shale is unsuitable for highway base material directly beneath pavement or other wearing course. The weathered zone commonly is 10 feet thick and was observed as deep as 20 feet beneath the surface. Where the shale is weathered, excavation to a depth of 10 feet is easy with small power equipment.

Swelling pressures of a weathered and a less weathered sample of the lower part of the shale gave, respectively, 2,500 and 1,250 psf. These shale samples were bentonitic, but they would not have so high swelling pressures as the seven bentonite beds. Susceptibility to frost action is medium to very high. The Unified Soil Classification symbols are CL, and ML. Plasticity index versus liquid limit is shown in figure 12.

MIDDLE CHALK UNIT

The middle chalk unit of late middle Santonian age forms a low broad light-colored hogback that parallels Dry Creek for 5 miles north of the Arkansas River (fig. 28). The unit, which is 28 feet thick, consists of chalk beds and a layer of shale.

The chalk is moderate yellowish orange or yellowish gray, hard, clayey, and platy to fissile. Five discrete layers 10 inches to 12 feet thick, were recognized; each forms a minor crest on the hogback. Weathered chalk forms small yellowish-gray chips a few inches in length. A single layer of shale, 7 feet thick, is light olive gray, chalky, fissile, earthy, and softer than the chalk. A bentonite bed and

FIGURE 28.—Hogback ridge formed by middle chalk unit of Smoky Hill Shale Member along valley of Dry Creek in the SE¼ sec. 16, T. 20 S., R. 65 W., Pueblo County, Colo. Middle bed of middle chalk is shown in foreground. Ridge of upper chalk lies east of Dry Creek; upper chalky shale underlies valley of Dry Creek between the two ridges. The Jacob staff is 5 feet long.

a bentonitic limonite bed lie near the middle of the unit. Limonite-stained gypsum nodules are common in the upper part.

Fossils of a few species are abundant. The unit is characterized by *Inoceramus platinus* Logan, a giant clam more than 3 feet in diameter. Shells of a small oyster, *Ostrea congesta* Conrad, are abundant, especially attached to the large clam shells. The unit lies within the zone of *Clioscaphites choteauensis.*

Engineering geology.—The only engineering problem expected from the middle chalk is slight difficulty of excavation. No seeps were observed, but permeability probably is fairly good along bedding planes. Surface water drains readily, but the chalk erodes slowly and needs no erosion protection. Slopes are vertical or even overhanging along streams; but where weathered, they erode back to 5°–13°.

327-617 O—69——5

Foundation stability is excellent. Foundation piers in a unit that contains alternating hard and soft beds, such as the middle chalk, should all be founded on the same type bed, preferably hard chalk beds. Differential settlement otherwise would be almost unavoidable. In addition, foundations should not be placed on the bentonite or on the bentonitic limonite bed. Frost susceptibility probably is slight, except where the shale is weathered. Excavation to a depth of 10 feet, even where the chalk is weathered, is difficult with a backhoe. Deeper excavation probably would require larger equipment or breaking before removal. The chalk has a potential use in the manufacture of cement.

UPPER CHALKY SHALE UNIT

The upper chalky shale unit of late Santonian and early Campanian age crops out along the valley of Dry Creek. It forms a nonresistant and easily eroded strip between the hogbacks of the middle and upper chalk units. The unit is about 265 feet thick and consists of shale and some chalk beds.

The shale is dark yellowish orange, grayish orange, or pale yellowish brown, hard, platy, and chalky; it weathers soft, fissile, and earthy. The chalk layers are dark gray, hard, and platy where fresh; but they are yellowish gray, earthy to fissile, and readily eroded where weathered. Soft dark-yellowish-orange beds of limonite containing gypsum or selenite crystals are abundant in the lower 65 feet. Seventeen beds of dark-yellowish-orange granular soft plastic bentonite, ½–3½ inches thick, lie chiefly between 180 and 240 feet above the base. Concretionary disklike masses of dark-gray hard speckled shaly limestone, 3 feet in diameter and 2 feet thick, lie in the shale between 180 and 205 feet above the base (fig. 29). They are more resistant to erosion than the shale and project from banks and floors of arroyos.

Size-distribution analysis of shale from the lower part of the unit was difficult because the shale flocculated so badly that a hydrometer analysis could not be completed. An approximation of a true size-distribution curve (fig. 25) shows that the noncalcareous part of a sample of shale contains 80 percent clay-sized material and about 20 percent silt. X-ray analysis shows that the shale contains 21 percent clay minerals, 10 percent quartz, 26 percent calcite, and 43 percent gypsum. Mixed-layer clay (consisting of illite and montmorillonite) is more abundant than kaolinite. Of the shale tested, 76 percent is insoluble in dilute hydrochloric acid.

Fossils probably are abundant in the upper chalky shale unit, but are not readily found or well preserved. They occur as flattened impressions in the shale. Fish scales and bones are more abundant

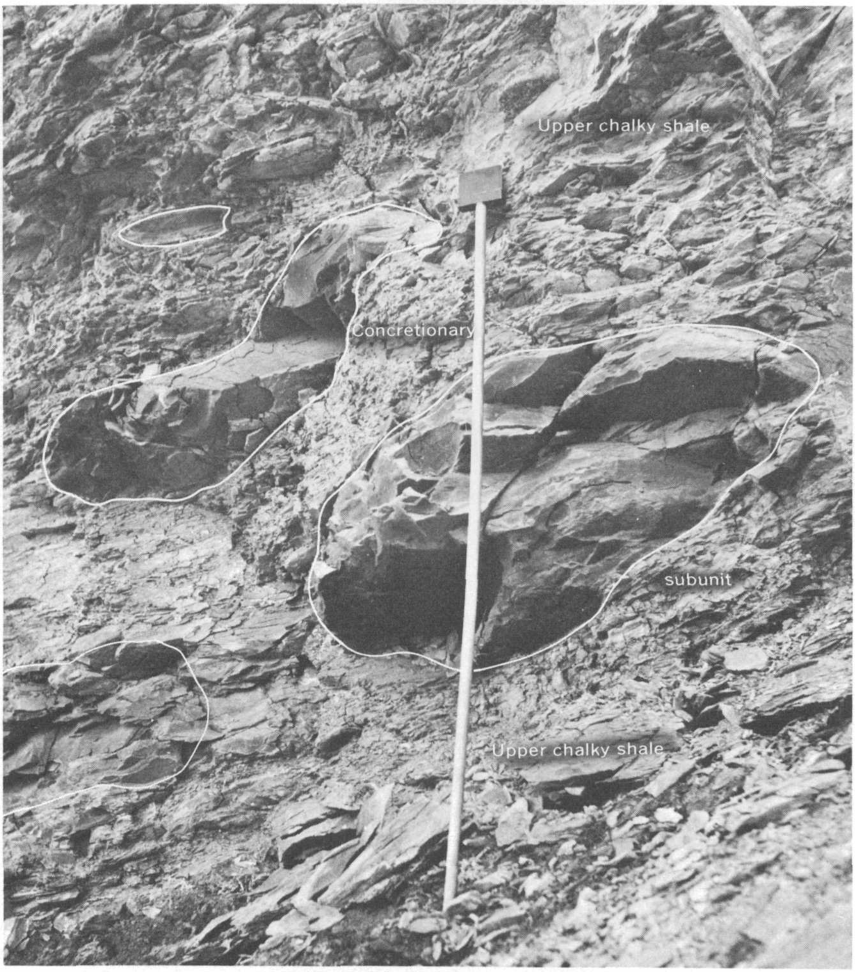


FIGURE 29.—Concretionary submit of upper chalky shale of Smoky Hill Shale Member in valley wall of Arkansas River in the NE¼ sec. 35, T. 20 S., R. 65 W., Pueblo County, Colo. The Jacob staff is 5 feet long.

in this unit than in any other part of the Niobrara. The fish genera *Enchodus*, sp., *Ichthyodectes* or *Gillicus* sp., and *Xiphactinus* sp. were found at several localities ranging through the unit. The unit contains three species of *Inoceramus* including *I. simpsoni* Meek, whose range extends above the top of the unit, a fragment that resembles *I. patootensis* de Loriol, and *I. platinus*, which lies in the lower 180 feet of the member. A faunal zone in the upper part of the unit along the Apishapa River south of Fowler, Colo., contains the ammonites *Haresiceras placentiforme* Reeside, *Scaphites* cf. *S. hippocrepis* (DeKay), and *Baculites* cf. *B. haresi* Reeside. Light-colored specks in the shale are aggregates of coccospheres—microscopic, calcareous, flagellate, unicellular organisms generally classed as algae—most of which are marine in habitat. These coccospheres make up more than half of the calcareous beds in the upper part of the Niobrara Formation and the transition member of the Pierre Shale.

Engineering geology.—The upper chalky shale seems to offer severe problems in its swelling clay and impregnation with sulfate minerals. The shale is nearly impermeable except in the weathered zone. Surface drainage is poor, and water stands on the shale, making it muddy even after adjoining formations have dried. Water flowing on the surface of the shale is highly charged with sulfates. The soft shale is easily eroded, and check dams are needed. Vertical slopes were seen where the shale is freshly eroded, and weathered slopes as steep as 15° were observed, but stable slopes probably are gentler.

Foundation stability is fair to poor. Deep foundations are preferable to shallow ones because of the swelling clays and probable lesser bearing strength of shallow weathered clayey shale. Swelling clay in the upper chalky shale has caused cracking and heaving of a facing along 2d Street beneath the Interstate 25 Freeway (fig. 30); the sloped facing is bowed outward more than 1 foot and has slid downward several inches, owing to its own weight. The excavated shale is not suitable as base material directly under the pavement or other wearing course of a road. Swelling pressure of a sample of the shale in the lower part of the unit is noncritical at 2,050 psf. This probably is lower than the more bentonitic shale near the middle, and certainly is lower than the swelling potential of the 17 bentonite beds. No foundation should be placed very close to any of the bentonite beds. Susceptibility to frost action is medium to very high.

Laboratory tests on the upper chalky shale show that in the laboratory modified AASHO compaction test the maximum density is 114.4 pcf and the optimum moisture is 14.7 percent. The laboratory CBR at 90 percent maximum density is 5.2. The AASHO classification is A–4, and the Unified Soil Classification symbol is ML. Plasticity index versus liquid limit is shown in figure 12. The upper chalky shale has a potential use in the manufacture of cement. It now is used only as dumped fill.

UPPER CHALK UNIT

The upper chalk unit of early Campanian age crops out as a sharp hogback as much as 30 feet high parallel to and east of Dry Creek (fig. 31) and in a smaller area east of Fountain Creek. Fautling

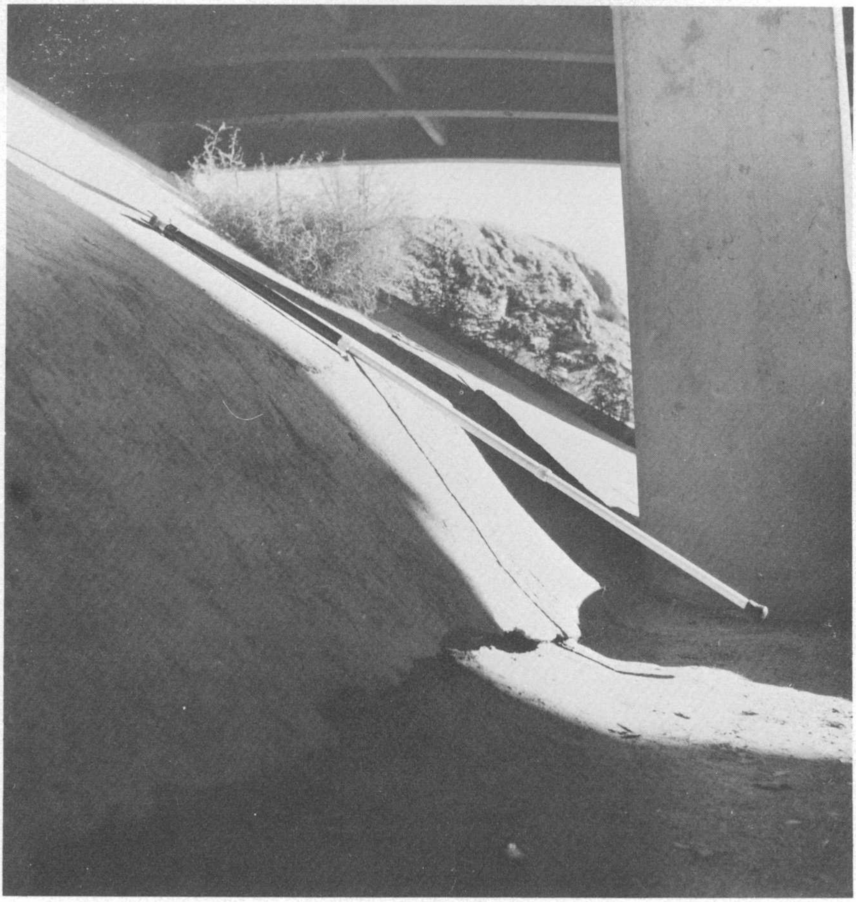


FIGURE 30.—Crack and heave in facing beneath the Interstate 25 Freeway bridge over 2d Street, Pueblo, Colo., caused by swelling clay in the upper chalky shale unit of the Niobrara Formation. The Jacob staff is 5 feet long.

and folding parallel to the Pueblo anticline has caused the hogback to be repeated as two or three ridges at several places. The unit is 8 feet thick and consists entirely of chalk.

The chalk is olive black, blocky, platy to even bedded, and weathers dark yellowish orange. In a fresh exposure the chalk is difficult to differentiate from underlying and overlying chalky layers. Where weathered, however, the chalky layers below and above are shaly, and only the 8-foot-thick upper chalk bed forms a hogback. The chalk is a weakly cohesive rock composed of small light-colored specks of calcium carbonate, clay, and tests of Foraminifera.

FIGURE 31.—Ridge formed by upper chalk unit of Smoky Hill Shale Member along east side of Dry Creek in the NE¼ sec. 22, T. 20 S., R. 65 W., Pueblo County, Colo. Weathered upper chalk is shown in foreground. The Jacob staff is 5 feet long.

Fossils possibly are abundant but are difficult to collect because they are soft impressions on bedding planes. The most common and diagnostic fossils are smooth baculites, the clam *Inoceramus simpsoni*, and a barnacle, *Stramentum haworthi* Williston. The specks mentioned above are aggregates of coccospheres.

Engineering geology.—The upper chalk unit poses only the problem of difficult excavation. Erosion due to surface drainage is negligible, and erosion control is unnecessary. The chalk will stand in vertical banks for many years. The slope opposite the dip slope is generally about 35°. Rockslides have broken away along joints from some steep slopes; these slides generally also include the upper part of the upper chalky shale unit.

Foundation stability is excellent. The unit is weathered to shallow depths particularly along bedding planes and joints. The chalk is susceptible to frost action where weathered. Unless the shale is deeply weathered, excavation to a depth of 5 feet is difficult with a backhoe. Deeper excavation probably would require larger equipment or breaking the chalk before removal. The chalk has no probable use except for the manufacture of cement. It probably would be suitable for dumped fill but not for compacted embankment because the large blocks would create voids in the fill.

PIERRE SHALE

The lower half of the Pierre Shale (Meek and Hayden, 1862) of Late Cretaceous age underlies the eastern part of the area as part of a broad belt of nonresistant shale. The formation contains, in ascending order, a transition member, Apache Creek Sandstone Member, Sharon Springs Member, and the Rusty and Tepee zones of Gilbert (1897).

TRANSITION MEMBER

Owing to the Pueblo anticline, the transition member of early Campanian age of the Pierre Shale forms a double belt of outcrops paralleling Dry and Fountain Creeks. The member crops out only locally between the upper chalk unit of the Niobrara Formation and the Apache Creek Sandstone Member of the Pierre Shale and generally forms a low colluvium-covered slope. The transition member is 228 feet thick and consists of shale that is mostly calcareous.

The member appears to be uniform in lithology, but is composed of several types of sedimentary rock, principally drab calcareous clayey shale (fig. 32). The lower 50 feet contains beds of dark-gray chalk that weathers yellowish gray to light brown and shows small lighter colored speckles. The chalk is soft and platy to shaly, and upon weathering, resembles the upper chalk unit of the Smoky Hill Shale Member; but it is differentiated by its shaliness compared to the massive chalk beds in the upper chalk unit. These shaly chalk beds overlie the hogback-forming beds of the upper chalk and locally contain hard limestone lenses.

FIGURE 32.—Horizontally bedded transition member of Pierre Shale in clay pit of brick plant in NE¼NE¼ sec. 30, T. 20 S., R. 64 W., Pueblo County, Colo. Heavyweight equipment, such as this large dragline, can excavate weathered shale to a depth of 25 feet.

The middle 100 feet of the member consists of olive-gray calcareous blocky to platy shale that shows speckles. The upper 78 feet consists of olive-gray noncalcareous silty blocky shale containing a thin siltstone bed and siltstone concretions. Seventeen beds of dark-yellowish-orange soft plastic bentonite were seen in the member and others probably are present, for not all the shale was seen where the stratigraphic section was measured. The bentonite beds range in thickness from 0.05 to 0.5 feet, and when saturated, most swell to twice their thickness when dry.

A size-distribution curve of the noncalcareous part of a sample from the transition member (fig. 33) shows it to contain about 56 percent clay, 26 percent silt, 14 percent sand, and 4 percent granules and pebbles. The granules and pebbles probably are particles of shale that were not disaggregated. Between 89 and 96 percent of the shale in the samples tested is insoluble in dilute hydrochloric acid.

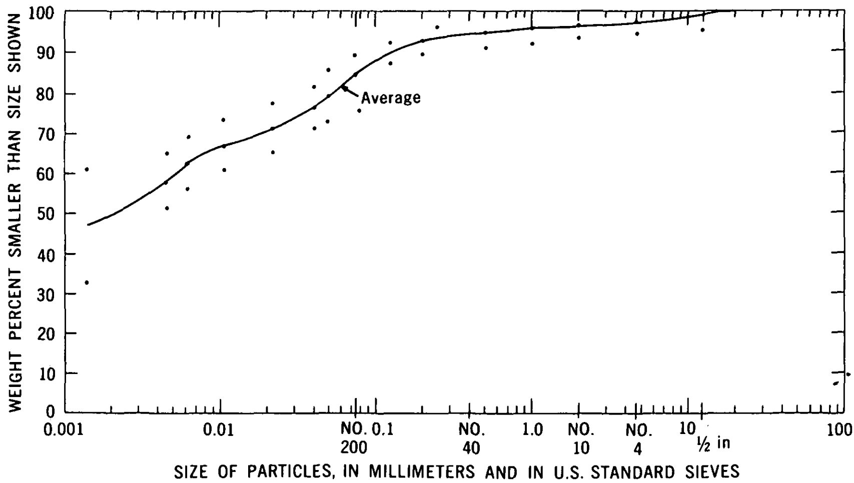


FIGURE 33.—General size-distribution characteristics of typical samples of transition member of Pierre Shale.

X-ray analysis of two samples from the lower and middle parts of the transition member show the major constituents to be similar in abundance. In the sample near the base, 40 percent is clay minerals, 25 percent is quartz, 5 percent is feldspar (potassium feldspar is more abundant than plagioclase), 13 percent is calcite, 4 percent is dolomite, and 13 percent is gypsum. Of the clay, illite is equal in abundance to mixed-layer clay (illite and montmorillonite), which equals kaolinite. In the sample near the middle, 43 percent is clay minerals, 25 percent is quartz, 5 percent is calcite, 27 percent is gypsum, and a trace is hematite. Of the clay, mixed-layer clay (illite and montmorillonite) is more abundant than illite, which equals kaolinite. The principal changes from bottom to middle are a doubling of gypsum and a sharp decrease in the carbonates, calcite, and dolomite.

Fossils occur as impressions on bedding planes, and in the upper part of the member, as casts in a siltstone bed. The member is characterized in the lower part by fish scales, smooth baculites, and *Inoceramus simpsoni* Meek; in the upper part by noded *Baculites* aff. *B. obtusus* Meek, *I.* aff. *I. cycloides* Wegner, parts of the chirocentrid fish, *Ichthyodectes* sp., and plant fragments. The speckes mentioned earlier are aggregates of coccospheres.

Engineering geology.—The transition member is expected to cause some major problems, owing to swelling clays and sulfate reaction. Permeability is very poor in the transition member, yet some large seeps were observed. A seep north of the State Hospital in the SE¼ sec. 23, T. 20 S., R. 65 W., flows at a rate large enough to fill a ½- to 1-inch pipe. Most seeps produce less water than this, but they flow in both wet and dry seasons. Water in the seeps and flowing along the interface between the shale and overlying material is highly charged with sulfate. Artificial drainage is difficult. All depressions at building sites should be artificially drained to avoid collection of water and to prevent cyclic wetting of clay minerals. Erosion control is required along roadside ditches because the shale becomes soft where weathered and contains very few hard beds to resist erosion. Where exposed in a flat surface, as many as four channels in 10 feet were observed. Excavation of the transition members to a depth of about 15 feet is easy with small power tools, and the member can be dug to greater depths with large equipment (fig. 32).

Few of the slopes formed by the transition member are steeper than 5°, except where the shale is capped by gravel or by the Apache Creek Sandstone Member. The slope is 25° along the south bank of the Arkansas where the shale is capped by gravel and where the toe of the slope was cut by the river less than 100 years ago. No slumps or landslides were observed along these steep slopes, but steep slopes that are not stabilized will erode back. A probable maximum stable cut slope is 5°.

Foundation stability is fair to poor. Stability is best for deep foundations where the water content can be held steady. The excavated shale is not suitable for base material directly under pavement or other wearing course. The amount of subbase required on top of the in-place shale in the upper part of the member, using a CBR of 4.7, is 11–18 inches, depending on wheel load of the traffic to be imposed (fig. 2). Sound material in the transition member is generally found at 5–20 feet beneath the surface of the shale, or deeper, according to the amount of overburden on the shale. Swelling clay has caused foundation failures wherever the transition member crops out. For example, under one house (fig. 34) swelling clay uplifted

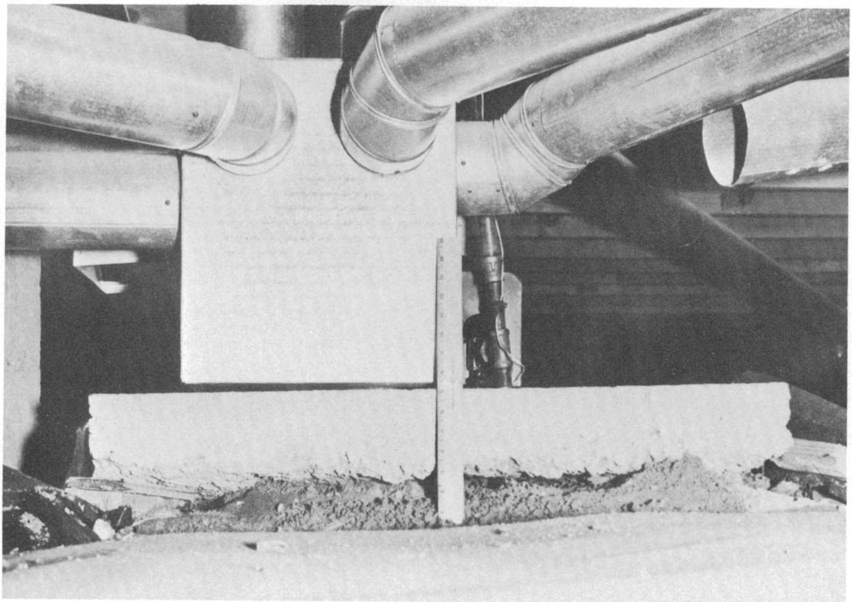


FIGURE 34.—Uplift of concrete pad beneath furnace under house in Mountair subdivision, 2100 block 27th Street, Pueblo, Colo., caused by swelling clay in transition member of the Pierre Shale. Pipes attached to furnace are bent where they were forced upward against floor joists. Uplift exceeds 3 inches. Pad formerly sat at level of impermeable paper in foreground. Scale is 15 inches long. Photograph from inspection Division, Pueblo Department of Public Works.

the concrete pad beneath the furnace and forced attached pipes up against the floor joists. Possibly the uplift would not have been so severe if the moisture barrier paper had not been laid over the weathered shale in the entire crawl space. Relatively unweathered shale commonly requires 40–75 blows per foot for penetration by the split-tube sampler driven by a 140-pound hammer freely dropping 30 inches.

Swelling pressures recorded for three samples of the shale are marginal, ranging from 2,600 to 3,000 psf. Seventeen bentonite beds, 0.05–0.5 inch thick, were observed, any one of which could cause foundation trouble. Frost susceptibility of the transition member is medium to very high.

Very little information is available concerning the physical properties of the transition member. Plasticity index versus liquid limit is shown in figure 12. In the laboratory-modified AASHO compaction test the maximum density is 113.7 pcf; the optimum moisture is 14.9 percent. The laboratory CBR at 90 percent maximum density is 4.7. The pH is 7.88–8.02. The insoluble residue for the lower chalky part of the member is 89 percent; for the middle calcareous part it is 96 percent. The AASHO classification is A-6. The Unified Soil Classification symbols are CL and ML. The shale is used for fill and the manufacture of brick and tile. For the latter use, it is mixed with eolian sand.

APACHE CREEK SANDSTONE MEMBER

The Apache Creek Sandstone Member (Lavington, 1933; Scott and Cobban, 1963) of early Campanian age of the Pierre Shale dips eastward and forms a strip extending southward along Fountain Creek and across the northeastern part of town. The member locally is exposed as low ridges strewn with sandstone chips; in most places, however, it weathers to gentle slopes covered by alkali (fig. 35) or is obscured by surficial deposits. At Pueblo the member is 200 feet thick and consists of shale containing concretions and thin lenses of fine-grained sandstone.

The shale is dark gray where fresh and light olive gray where weathered. Sandstone layers range from irregular-shaped plates one-fourth inch thick and 3 inches across to tabular beds 5 feet thick. A size-distribution curve of the Apache Creek Member (fig. 36) shows

FIGURE 35.—Apache Creek Sandstone Member of Pierre Shale in the NW¼SE¼ sec. 12, T. 20 S., R. 65 W., Pueblo County, Colo. This member is characterized at Pueblo by its soft shaly aspect and strong efflorescence of the alkali, sodium sulfate (white patches). The Jacob staff is 5 feet long.

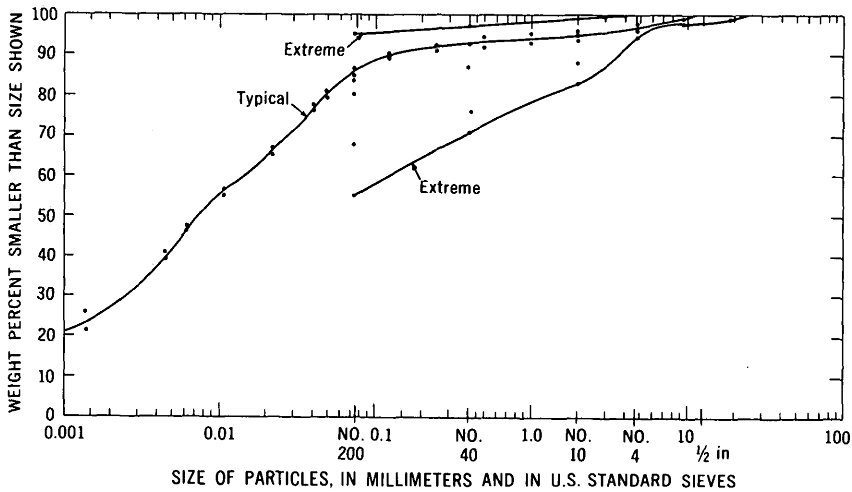


FIGURE 36.—General size-distribution characteristics of Apache Creek Sandstone Member of Pierre Shale. Centerline is typical of two samples of known Apache Creek. Other samples are from areas mapped as Apache Creek, but they probably are contaminated by surficial material.

it to contain about 37 percent clay, 46 percent silt, 12 percent sand, and 5 percent granules and pebbles. The granules and pebbles probably are particles of shale that would not readily disaggregate.

The proportion of the mineralogic material in the shale was estimated from X-ray analysis of two samples, one near the base and one near the top of the member. In the sample near the base, 40 percent is clay minerals, 35 percent is quartz, 7 percent is feldspar (plagioclase is more abundant than potassium feldspar), 3 percent is gypsum, and 15 percent is unknown amorphous material. Of the clay minerals, illite is equal in abundance to mixed-layer clay (consisting of illite and montmorillonite), which is nearly equal to kaolinite. In the sample from near the top, 35 percent is clay minerals, 20 percent is quartz, 5 percent is feldspar (plagioclase is more abundant than potassium feldspar), 28 percent is gypsum, and about 12 percent is dolomite. Mixed-layer clay (illite and montmorillonite) is more abundant than kaolinite, which is more abundant than illite. The principal changes from bottom to top are a decrease in clay, quartz, and feldspar and an increase in gypsum.

Concretions are abundant in at least nine layers in the Apache Creek. Five of the concretion layers form persistent ledges that are easily traced or correlated from place to place where outcrops are good. The concretions average 1 foot in diameter and 4 inches in thickness; five layers are composed of yellowish-gray sandstone, three of yellowish-orange limestone, and one of dark-gray siltstone.

Sandy layers are everywhere marked by borings, excreta of worms, and tracks of crustaceans. Impressions of mollusks were found in several layers, and carbonaceous woody fragments are abundant in one siltstone concretion layer.

Well-preserved fossils are uncommon; however, *Inoceramus agdjakendensis* Aliev and a weakly ribbed species of *Baculites* that is earlier than *B. obtusus* Meek seem to characterize the member. In addition, a partial mosasaur skeleton, identified as *Platecarpus* cf. *P. crassartus* (Cope) by Edward Lewis, U.S. Geological Survey, was found in the middle of the member about 6 miles north of town. After mounting by Robert W. O'Donnell and art work by John R. Stacy, the mosasaur was placed on display in the U.S. Geological Survey offices in the Federal Center, Denver, Colo. Later, another small specimen of ?*Platecarpus* sp. was found by Ray M. Foster at Normandy Lane and Gamble Drive in Belmont.

Engineering geology.—Engineering problems in the Apache Creek result principally from its clayiness. Subsurface waterflow from the member has been seen at small seeps along arroyo walls where the water issues from bedding planes or joints. The water contains sulfate minerals; therefore, sulfate-resistant cement should be used in concrete to be placed against the shale. The relative impermeability of the member indicates that artificial drainage would be difficult. All depressions at building sites should be artificially drained to avoid collection of water and prevent cyclic moistening of clay minerals. Leakage would not be expected from open canals cut in the member. Erosion would be a problem in roadside ditches; therefore, erosion control should be provided. In several parts of the city the ground-water table is so high in the Apache Creek Member that sump pumps must be installed in some basements. Unlined water reservoirs in the member probably would contribute some effluent to the ground-water table. A lined reservoir in the SE¼ sec. 14, T. 20 S., R. 65 W., shows evidence of some leakage into the shale.

Excavation of the Apache Creek Sandstone Member can be done with small power tools to a depth of 7 feet. Below that depth blasting may be necessary. Some of the larger deeply buried unweathered concretions probably would require breaking or blasting before removal.

The Apache Creek Sandstone Member forms the most stable slopes of any part of the Pierre Shale at Pueblo. Nevertheless, few natural slopes in the member are steeper than 5° except where capped by a ledge of resistant concretions or gravel. Some artificial slopes near Eden are steeper than 25°; landslides or slumps are not expected, but the steep slopes probably will slowly erode to a lower angle. The probable maximum stable cut slope is 10°.

Foundation stability is only fair to poor, but it can be improved where water content can be kept steady in the load-bearing shale. Thus, caissons and piers have an advantage over spread footings because of the slight fluctuation of water content at depth. The excavated shale is not suitable for base material directly beneath pavement or other wearing course. According to an average CBR of 3.8 given in the table below summarizing some physical tests of the Apache Creek Member, 12–20 inches of granular subbase will be required on top of the in-place shale, depending on wheel load of the traffic (fig. 2).

Nearly all specifications for foundations in Pueblo call for excavation to sound material. Sound material in the Apache Creek Sandstone Member, generally about 15 feet below the surface of the shale, is called hard blue shale and commonly requires 100–200 blows per foot for penetration by the split tube sampler driven by a 140-pound hammer freely dropping 30 inches.

Swelling pressures of 1,800–2,700 psf recorded for two samples of the shale are marginal. Too few samples were tested to indicate whether these values are average or unusual. No bentonite beds were seen in the member; there is little likelihood, therefore, of any extremely high swelling pressures. Nevertheless, pressures in the critical range (3,200–4,700 psf) probably can be anticipated. Frost susceptibility of the Apache Creek Member is medium to high depending on the availability of water. Some physical properties and soil classifications of the Apache Creek are given in the following table. Plasticity index versus liquid limit is shown in figure 12. The shale has no construction material uses except as fill. A potential future use is as lightweight aggregate made by bloating the shale.

Summary of some physical tests of Apache Creek Sandstone Member of the Pierre Shale

	Number of tests	Average	Range
Specific gravity g/cc	3	2. 75	2. 74–2. 76
Maximum density, AASHO modified compaction lb per cu ft	3	111. 0	106. 2–116. 1
Optimum moisture percent	3	16. 5	13. 9–18. 9
Laboratory California Bearing Ratio at 90 percent maximum density	4	3. 8	3. 0–6. 7
pH	2	7. 65	7. 4–7. 9
AASHO Classification		A–6	A–4, A–6, A–7
Unified Soil Classification		CL	------------

SHARON SPRINGS MEMBER

The Sharon Springs Member (Elias, 1931) of early and late Campanian age crops out in the trough of a syncline west of Fountain Creek northwest of Eden and along the east flank of the Pueblo anticline east of Fountain Creek. Hard flat shale slopes of the member crop out downslope from orange ironstone-littered knobs of the Rusty zone. The Sharon Springs, which is 113 feet thick, is composed of hard black shale containing many septarian concretions.

The shale in the lower few feet is olive gray and sandy and nearly identical to shale of the underlying Apache Creek. Overlying beds are nonsandy olive-gray, dark-gray, or medium-light-gray silty hard carbonaceous, gypsiferous fissile shale. The shale weathers very slowly and generally remains hard enough on an exposed surface that it crunches when walked upon. Shale typical of the organic-rich Sharon Springs Member lies between 12 and 62 feet above the base (fig. 37).

A sample of the Sharon Springs contained 63 percent clay-sized material and 37 percent silt-sized material (fig. 38). X-ray analysis shows that 30 percent is mixed-layer clay of unknown composition, 5 percent is quartz, 45 percent is gypsum, 10 percent is jarosite, and 10 percent is siderite.

The member is characterized by large and abundant concretions. The base of the member was placed at the lowermost concretions because they formed a better mapping horizon than the top of the Apache Creek-type of sandy shale which lies a few feet above the basal bed of concretions. The basal bed is composed of ledge-forming platy moderate-yellowish-orange limestone concretions as much as 6 feet in diameter and 1 foot thick. Light-gray septarian limestone concretions as large as 12 feet in diameter and 3 feet thick are scattered through the Sharon Springs, but they are most abundant in the upper 25 feet. Cone-in-cone concretions are found 60–75 feet below the top. A bed of dark-greenish-gray ovoid phosphatic nodules ½–1 inch in diameter in a granular gypsum matrix occurs locally 75 feet below the top.

Six bentonite beds, ½–5 inches thick, were measured. Four are grouped between 30 and 40 feet above the base and may be equivalent to the Ardmore Bentonite Bed (Spivey, 1940). In addition, a layer of carbonaceous, micaceous volcanic ash was seen near the top in the NW¼ sec. 17, T. 20 S., R. 64 W.

Fossils are abundant in the Sharon Springs Member and include five baculite zones. An early weakly ribbed form of *Baculites obtusus* Meek was found in the basal 12 feet along with the ammonites *Trachyscaphites praespiniger* Cobban and Scott, *Delawarella danei*

FIGURE 37.—Sharon Springs Member of Pierre Shale along Steele Hollow in the NE¼SE¼ sec. 12, T. 19 S., R. 65 W., Pueblo County, Colo. The lower part of the member contains hard silty buttress-forming black shale that is typical of the Sharon Springs Member. The Jacob staff is 5 feet long.

Young, and the clam *Inoceramus agdjakendensis* Aliev. A more strongly ribbed form (the typical form) of *B. obtusus* was found in large septarian limestone concretions 18 feet above the base. Flattened gypsiferous baculites that may be *B. mclearni* Landes were found about 30 feet above the base. *B.* aff. *B. asperiformis* Meek was

327-617 O—69——6

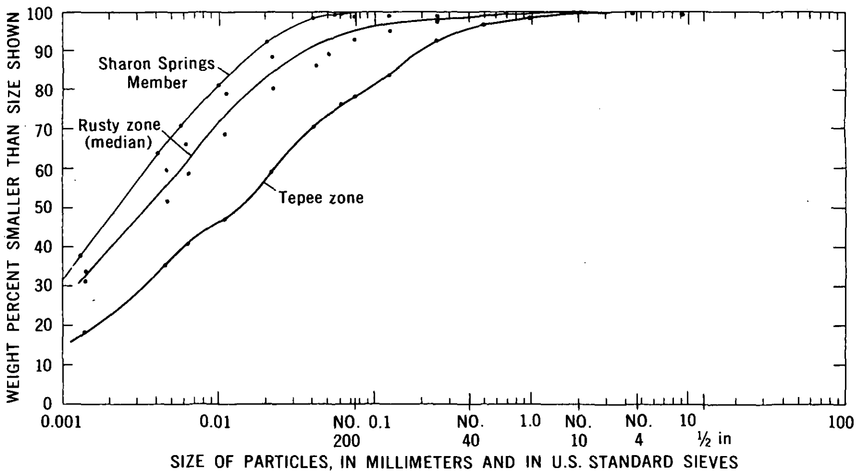


FIGURE 38.—General size-distribution characteristics of typical samples of Sharon Springs Member (single line), Rusty zone, and Tepee zone (single line) of Pierre Shale.

found 57 feet above the base and *B.* aff. *B. perplexus* Cobban and *Inoceramus subcompressus* Meek and Hayden were found 91 feet above the base in large septarian limestone concretions. Vertebrate fossils include parts of a mosasaur and a plesiosaur, *Polycotylus latipinnis* Cope, collected from the lower part of the member in the NE¼SW¼ sec. 17, T. 20 S., R. 64 W., by Carl K. Davidson and John R. Sivils, Pueblo City Engineer's office.

Engineering geology.—Minor engineering problems are anticipated in the Sharon Springs, owing to its high clay content. Permeability of the member is very poor. Surface water flows across the shale with almost no infiltration. Bentonite beds are saturated, and water seeps from some; but seeps were not seen in the shale. The shale is hard and more resistant to erosion than other parts of the Pierre Shale. Erosion control probably is needed only along steep roadside ditches that are subject to torrents of runoff. Artificial drainage is difficult. Depressions should be drained, especially if any bentonite beds are near the surface.

Excavation of the Sharon Springs is easy to a depth of 10 feet by use of small power tools, except for the large concretions that may require blasting before removal.

Slopes are low in angle regardless of the hardness of the shale. The shale stands in vertical banks where freshly cut, but most natural slopes are gentler than 5°. The maximum stable slope probably is between 5° and 10°. Slumps and slides were not seen and are not anticipated.

Foundation stability of a shale having a Unified Soil Classification symbol MH is considered to be poor; however, although the Sharon Springs is classified as MH, it may be better than average because of its hardness. No foundation should be placed just above any of the bentonite beds. The shale weathers slowly to a depth of 3–8 feet. Foundations should be placed in hard shale below the weathered zone.

Swelling pressure of two samples of Sharon Springs shale is noncritical to critical at 2,450–4,500 psf. The six bentonite beds undoubtedly would have higher swelling pressures. Frost susceptibility of the member is medium to very high in the weathered zone, but probably is slight in the hard unweathered shale. Only in swales or valleys would there be enough water to cause frost heave. The Unified Soil Classification symbol is MH. The plasticity index versus liquid limit for the shale is shown in figure 12.

RUSTY ZONE

The Rusty zone of Gilbert (1897) of late Campanian age crops out in a syncline west of Fountain Creek at the north edge of the area and in a broad southeast-trending belt across the Northeast Pueblo quadrangle. This outcrop belt is marked by low ridges paved with fragments of ironstone (siderite?) concretions. The Rusty zone, which is 440 feet thick, consists of shale containing ironstone and limestone concretions and beds of bentonite.

The shale is dark gray, blocky to fissile, and weathers olive gray. Sixty-five feet above the base is a bed of shale almost 25 feet thick containing gray limestone concretions and a thick bed of platy limestone but no ironstone concretions. Ironstone concretions are most abundant in the lower part of the zone (fig. 39), but, except as noted, occur throughout the member.

According to a size-distribution curve (fig. 38), shale in the Rusty zone contains about 52 percent clay-sized, 42 percent silt-sized, and 6 percent sand-sized particles. The proportion of the mineralogic material in the shale was estimated from X-ray analysis of two samples, one near the base and one near the middle of the member. In the sample near the base, 67 percent is clay minerals, 20 percent is quartz, 5 percent is plagioclase feldspar, 4 percent is siderite, and 4 percent is dolomite. Of the clay, mixed-layer clay (consisting of illite and montmorillonite) equals illite, which equals kaolinite in abundance. In the sample near the middle of the member, 51 percent is clay minerals, 20 percent is quartz, 10 percent is feldspar (plagioclase is more abundant than potassium feldspar), 4 percent is gypsum, and 15 percent is unknown amorphous material. Of the clay, mixed-layer

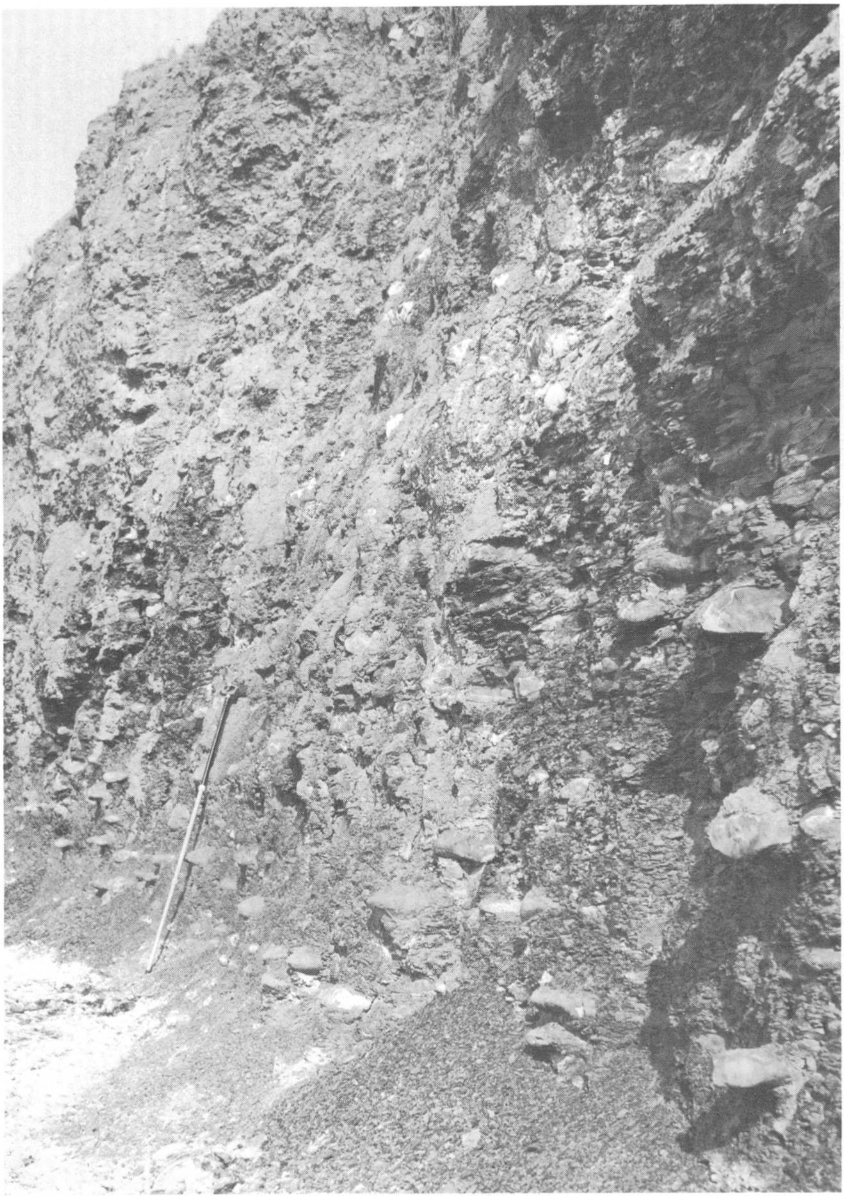


FIGURE 39.—Rusty zone of Gilbert of the Pierre Shale in a stream cut in the NE¼SW¼ sec. 21, T. 20 S., R. 64 W., Pueblo County, Colo. Note the blockiness of the relatively unweathered shale and abundance of ironstone concretions. The Jacob staff is 5 feet long.

clay (consisting of illite and montmorillonite) is more abundant than illite, which is equal to kaolinite. Thus, clay apparently decreases in abundance from the base to the middle of the unit. X-ray analysis of a bentonite bed at the base of the limestone concretion unit 65 feet above the base shows 40 percent clay (mixed-layer clay of unknown composition is more abundant than kaolinite), 5 percent quartz, 55 percent gypsum, and a trace of feldspar.

Concretions are composed mainly of reddish-brown-weathering ironstone (siderite?) and gray limestone. Some ironstone concretions have limestone centers; others have pyrite centers, but during weathering, the pyrite alters to limonite. The concretions range in diameter from a few inches to 3 feet and in thickness from 1 to 8 inches. The average size is 8 inches in diameter by 3 inches thick. They possibly constitute, at the most, 10 percent of the volume of the shale.

Three yellowish-orange or light-gray bentonite beds were observed in the lower 75 feet of the member. Other beds may be present in the overlying shale, which was poorly exposed owing to very gentle shale-covered slopes.

Fossils are uncommon in the lower part of the Rusty zone, but are abundant in the upper part. Three baculite zones are known, and the upper zone can be further subdivided into four subzones based on other ammonites. The zone of *Baculites perplexus* Cobban occupies the lower 170 feet and contains *Inoceramus convexus* Hall and Meek and *I.* aff. *I. cycloides* Wegner. The zone of *B. gregoryensis* Cobban apparently occupies the overlying 120 feet and contains *I.* cf. *I. tenuilineatus* Hall and Meek and *I.* aff. *I. cycloides.* The zone of *B. scotti* Cobban occupies the upper 150 feet and contains the ammonite *Oxybeloceras* sp. Four ammonite subzones in the lower part of the zone of *B. scotti* are, in ascending order, *Didymoceras* n. sp., *Anapachydiscus? complexus*, (Hall and Meek) *Didymoceras* n. sp. (loosely coiled), and *D.* n. sp. (tightly coiled).

Engineering geology.—Swelling clays and low bearing capacity of the Rusty zone are expected to cause foundation problems. Permeability is very poor in the Rusty zone. Seeps were not seen, yet the alluvium-covered arroyo floors have wet and dry segments suggesting that the wet segments are watered by seeps. Infiltration is very slight, and surface runoff is good except in depressions, which should be drained at building sites. Water in seeps and flowing across the top of the shale is charged with sulfate. Erosion check dams should be provided because the shale is readily eroded despite a nearly continuous pavement of ironstone pieces. Excavation is easy with small power tools to a depth of about 15 feet.

The Rusty zone forms gentle slopes, except where it is undergoing erosion. The lowest beds commonly form a sharp bluff above the Sharon Springs Member. Other steep slopes along actively eroding arroyos have slopes as steep as 20°. The average stable slope is 5°. No slumps or landslides were observed, but they would be anticipated if large areas of shale were excavated and left as steep slopes.

Foundation stability is fair to very poor. No shallow foundations should be used, especially for large structures. The excavated shale is not suitable for base material directly beneath pavement or other wearing course. Sound material beneath the weathered zone generally is more than 6 feet below the shale surface or deeper by the amount of surficial overburden. In the weathered zone the ironstone concretions alter from siderite(?) to limonite, and the shale softens and expands.

Swelling pressures for two samples of shale are marginal to very critical at 3,500 and 6,100 psf. A gypsiferous bentonite bed at the base of the limestone concretion unit 65 feet above the base has swelling pressure of 2,600 psf. Other bentonite beds may have higher pressures. Frost susceptibility of the Rusty zone is medium to high. The Unified Soil Classification symbols are CL and CH. Plasticity index versus liquid limit is shown in figure 12.

TEPEE ZONE

The Tepee zone of Gilbert (1897) of late Campanian age crops out in the northeast corner of the area. The outcrop area consists of gentle slopes and low rounded ridges studded by small sharp pointed hills shaped like cones and called tepee buttes (fig. 40). The Tepee zone is more than 635 feet thick and is composed of shale containing many ironstone concretions, limestone concretions, and large masses of limestone.

The shale is olive gray or gray, silty, micaceous, and resistant to weathering, or clayey, fissile, and readily weathered. Some beds are gypsiferous, carbonaceous, or bentonitic. Bentonitic shale becomes puffy on its surface, but the expanded surface collapses when weight is put on it. A typical bed of bentonitic shale lies about halfway up the south slope of Baculite Mesa near U.S.G.S. Mesozoic locality D3936 (pl. 1). The shale from 400–450 feet above the base tends to be light gray and contains more limestone concretions and less ironstone concretions than the underlying and overlying beds.

A size-distribution curve (fig. 38) shows that the shale contains 33 percent clay, 43 percent silt, and 24 percent sand-sized particles. Some of the sand-sized material may be particles of shale that did not completely disaggregate.

FIGURE 40.—Tepee zone of Gilbert showing soft bentonitic gypsiferous shale and tepee buttes at south end of Baculite Mesa in the NE¼NW¼ sec. 10, T. 20 S., R. 64 W., Pueblo County, Colo. Ironstone concretions here contain abundant *Baculites scotti* (type locality).

X-ray mineralogy indicates that a sample from the bentonitic shale on the south slope of Baculite Mesa contains 55 percent clay minerals, 25 percent quartz, 10 percent feldspar (plagioclase is more abundant than potassium feldspar), 5 percent dolomite, and 5 percent gypsum. Of the clay, mixed-layer clay (consisting of montmorillonite and illite) is more abundant than kaolin, which equals illite in abundance.

The Tepee zone is characterized by ironstone and limestone concretions and masses of tepee butte limestone. Ironstone concretions are reddish brown, brownish black, or grayish red, and are composed of siderite, calcite or pyrite, and clay or silt. Some have cone-in-cone limestone cores more than 1 foot in diameter. Some are concentrically banded. They are as large as 3 feet in diameter and 6 inches thick. Limestone concretions are dark gray and weather yellowish gray or gray. They range in diameter from 2 inches to 1 foot, and some are shaped like dumbbells. Cone-in-cone limestone beds also were observed. Large masses of rough, irregular nodular, vuggy, fossilferous gray limestone called tepee butte limestone (fig. 41) are scattered through the tepee zone, but are somewhat less abundant in the faunal zone of the ammonite *Didymoceras stevensoni*. The tepee butte limestone masses are ovoid bodies that are higher than they are wide. Most seem to be 15 feet high and 10 feet wide, but they range in height from 2 to 40 feet. The buttes, composed entirely of the limestone masses, stand as high as 60 feet above the surrounding shale (fig. 42).

Much of the shale is bentonitic, but only three discrete bentonite beds were seen. These lie about 160, 245, and 265 feet above the base. Other beds may be present, but if so, they are masked by shaly colluvium.

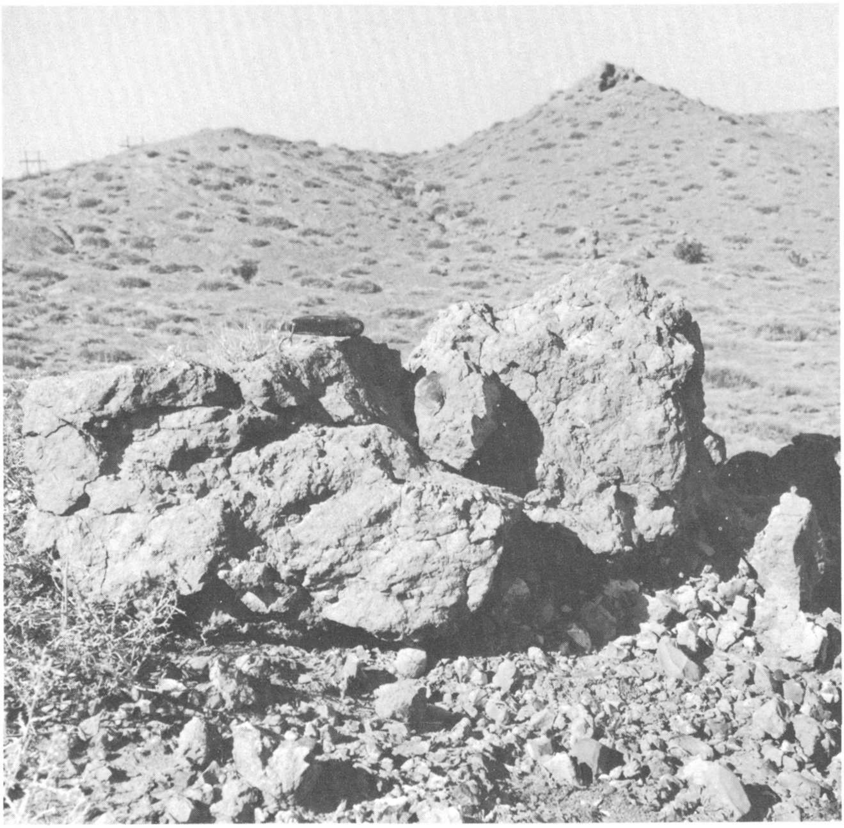


FIGURE 41.—Tepee butte limestone in zone of *Baculites scotti*, Tepee zone of Gilbert in the Pierre Shale, in NE¼SW¼ sec. 10, T. 20 S., R. 64 W., Pueblo County, Colo. Limestone is typically cracked and vuggy, and contains abundant fossils. Knife is 3 inches long.

FIGURE 42.—Tepee buttes—large masses of limestone—rising out of the Tepee zone of Gilbert in the Pierre Shale near Pueblo Ordnance Depot east of Pueblo, Colo. Buttes shown are 20–30 feet high, but some others are higher than 60 feet. Photograph courtesy of Pueblo Ordnance Depot.

Fossils are abundant and diverse in the Tepee zone. Four ammonite zones are known in the Tepee zone within the map area. The zone of *Baculites scotti* Cobban continues up into the Tepee zone another 285 feet above the Rusty zone for a total range of 435 feet. *Inoceramus saskatchewanensis* Warren and the ammonite *Hoploscaphites* n. sp. are common associates. The subzone of the tightly coiled *Didymoceras* n. sp. occupies the lower 20 feet of the Tepee zone. In tepee buttes 240 feet below the top of the zone of *B. scotti* is a new species of *Didymoceras* that appears to be ancestral to *D. nebrascense*. The zone of *D. nebrascense* (Meek and Hayden) is 95 feet thick and is composed of light-gray-weathering shale containing many tepee butte limestone masses. The ammonites *Solenoceras* cf. *S. mortoni* (Meek and Hayden) and *Baculites crickmayi* Williams and the clam *Inoceramus saskatchewanensis* Warren are associates of *D. nebrascense*. Only 100 feet of the zone of *D. stevensoni* Whitfield was measured; the zone probably is not much thicker. Common associated fossils are *I. pertenuis* Meek and Hayden, *B. crickmayi* Williams, and *Oxybeloceras crassum* (Whitfield). The zone of the ammonite *Exiteloceras jenneyi* (Whitfield) was not measured, but it probably is about 50 feet thick. This zone is characterized by abundant *Baculites rugosus* Cobban, *Solenoceras* cf. *S. mortoni*, and *I. pertenuis*.

Engineering geology.—Engineering problems are anticipated as a result of the extreme clayiness of the Tepee zone. Permeability is poor, and seeps were observed along arroyo walls where the water percolates slowly from joints. Infiltration is negligible, and surface waterflow is rapid except from depressions or swales, which tend to become boggy. Water from seeps and across the surface is charged with sulfate and is acid in reaction. The shale is easily eroded, and erosion check dams are required along roadside ditches. Excavation to a depth of 15 feet is easy for small power equipment.

The Tepee zone forms gentle slopes, except along the steep flanks of Baculite Mesa. The shale not only is relatively unweathered there, but also is protected by a cover of alluvium. The average stable slope probably is 5°; erosion will rapidly lower any steep slope. Landslides or slumps were not observed on any slope, but loads placed on steep slopes probably would cause creep.

Foundation stability is fair to poor. Caisson or pier foundations should be used, especially for large structures. The shale should not be applied as a base material directly below pavement or other wearing surface of a road. Foundations of large structures should be extended down into unweathered material that lies 10 or more feet below the shale surface. Swelling pressure of the bentonitic shale on the south flank of Baculite Mesa is noncritical at 1,650 psf. Some beds in the Tepee zone probably will give much higher swelling pressures. Frost susceptibility is medium to very high. The Unified Soil Classification symbol is ML. Plasticity index versus liquid limit is shown in figure 12.

SURFICIAL DEPOSITS

Overlying bedrock unconformably in more than half of the Pueblo area is a cover of unconsolidated clay, silt, sand, and gravel, locally more than 100 feet thick. Most of this cover was deposited by streams as they flowed across the area during hundreds of thousands of years of Quaternary time. A small part was laid down by sheet flow and rill wash as colluvium. A small part also was blown out of the valleys up onto the highlands by wind. An even smaller part (probably no more than 1 sq. mi.) was placed by man.

The stream deposits, called alluvium, range in age from earliest Pleistocene to Holocene and include sand and gravel that is being transported by the streams today. The alluvium lies on broad flat terraces, as at City Park, parallel to the streams, or on flat pediments, as at the site of Southern Colorado State College southwest of Baculite Mesa, sloping away from high areas such as Baculite Mesa. The highest terrace, more than 100 feet above modern stream level, is the oldest, and each younger terrace is progressively lower so that the youngest is only a few feet above modern stream level. Similarly, the highest pediment, between 320 and 360 feet as projected above the Arkansas River, is the oldest; but the youngest pediment, which is the same age as the oldest terrace, is also more than 100 feet above modern stream level.

The alluvial deposits from oldest to youngest are the Nussbaum Alluvium, Rocky Flats Alluvium, Verdos Alluvium, Slocum Alluvium, Louviers Alluvium, Broadway Alluvium, Piney Creek Alluvium, and post-Piney Creek alluvium. All but the first of these deposits were first named and mapped near Denver, Colo. The same names are applied to deposits at Pueblo because all the characteristics that are commonly used for correlation—such as physical geology, geomorphology, soil stratigraphy, fossils, and artifacts—show that the deposits in the two areas constitute nearly identical sequences. To erect new names for the deposits at Pueblo, because they lie in the drainage basin of the Arkansas River rather than in that of the South Platte River, would result in an unnecessary proliferation of geologic names. The names used at Denver have now been used also at Florence and at Fort Morgan, Colo. The wind-deposited material at Pueblo is called eolian sand. The material deposited by sheet flow and rill wash is mapped as colluvium. The rubbish, waste, and embankment placed by man is called artificial fill.

Ancient soils are developed in the upper parts of the surficial deposits, but the degree of development is anomalously weak compared to soils in deposits of the same age and similar texture near Denver, Colo. All soils at Pueblo are Brown soils characterized by a brown surface (B) horizon and an accumulation of calcium carbonate (C_{ca}) in the parent material. Where soils are normally developed, they are valuable aids in the identification and correlation of surficial deposits; the pre-Bull Lake soil at Pueblo has served this purpose by providing a way to divide the pre-Bull Lake Slocum Alluvium from younger deposits that do not contain pre-Bull Lake soils. The pre-Bull Lake soils differ from the post-Bull Lake soils by having thicker B and C_{ca} horizons; the B horizon is more reddish, contains more clay, and has a stronger, coarser, columnar structure, and the C_{ca} horizon contains a much denser concentration of calcium carbonate. A detailed discussion of soils in eastern Colorado can be read in Professional Paper 421–A (Scott, 1963b).

Fossils are scarce and nondiagnostic in the surficial deposits. Bones were found in two deposits and mollusks in one. Diagnostic fossils are needed to assure further the correctness of the correlations with the surficial deposits near Denver. Correlations now are based on height of deposit above stream level, position of a deposit over or under another deposit, and degree of development of soils.

NUSSBAUM ALLUVIUM

The Nussbaum Alluvium (Gilbert, 1897; Scott, 1963a) of Pleistocene age crops out only on Baculite Mesa, the type locality, where it covers an ancient cut surface that slopes gently to the southeast and projects to a height about 320–360 feet above modern streams. The alluvium is deeply dissected because of its great age, exposed position, and ease of erosion of the underlying shale. The formation is more than 100 feet thick and consists of stream-deposited coarse sand containing pebbles (fig. 43).

The alluvium is light-brownish-gray well sorted flat-bedded to slightly cross-stratified subrounded nonsticky nonplastic loose or slightly cemented sand and subangular pebbles. Cobbles as large as 4 inches in diameter were seen. A layer 6 feet thick of light-yellowish-brown to pale-brown sticky plastic clayey pebbly silt lies 20 inches above the base (not near the top, as stated by Scott (1963a)) of the alluvium at the south end of Baculite Mesa. The silt contains nodules of calcium carbonate. The lower 20 inches of the alluvium is gravel containing some clay balls from the underlying Pierre Shale. The sand about 20 feet above the base is torrentially crossbedded, and measurements of the dips of cross sets show that the current direction probably was from the northwest.

The composition of the alluvium indicates that it was deposited by a stream that flowed across sedimentary rocks on its way from a granite terrane. A count of 100 pebbles ¾–2 inches in diameter showed 71 pegmatite, 8 quartz, 5 clayey ironstone, 5 sandstone, 3 granitic, 3 devitrified chert, 2 sandy ironstone, 1 aragonite, 1 petrified wood, and 1 quartzite. The ½-inch grain size probably contains less of the unusual stones and more pegmatite and quartz. The sand-sized material appears to be more than 90 percent quartz. A size-distribution curve (fig. 44) shows that the alluvium is composed of 1 percent clay, 6 percent silt, 50 percent sand, 25 percent granules, and 18 percent pebbles. None of the pebbles in the sample was larger than three-eighths inch. About 3 percent of the sample was composed of calcium carbonate that dissolved in dilute hydrochloric acid.

The alluvium is slightly consolidated and loosely cemented by clay. Clayey cement forms films between the grains and helps to hold the alluvium in vertical banks during dry times. The cement is weakened when wetted, and as a result, the banks collapsed. At the base, calcium carbonate, derived from ground water flowing across the Pierre Shale, has firmly cemented a 2- to 3-foot-thick conglomerate

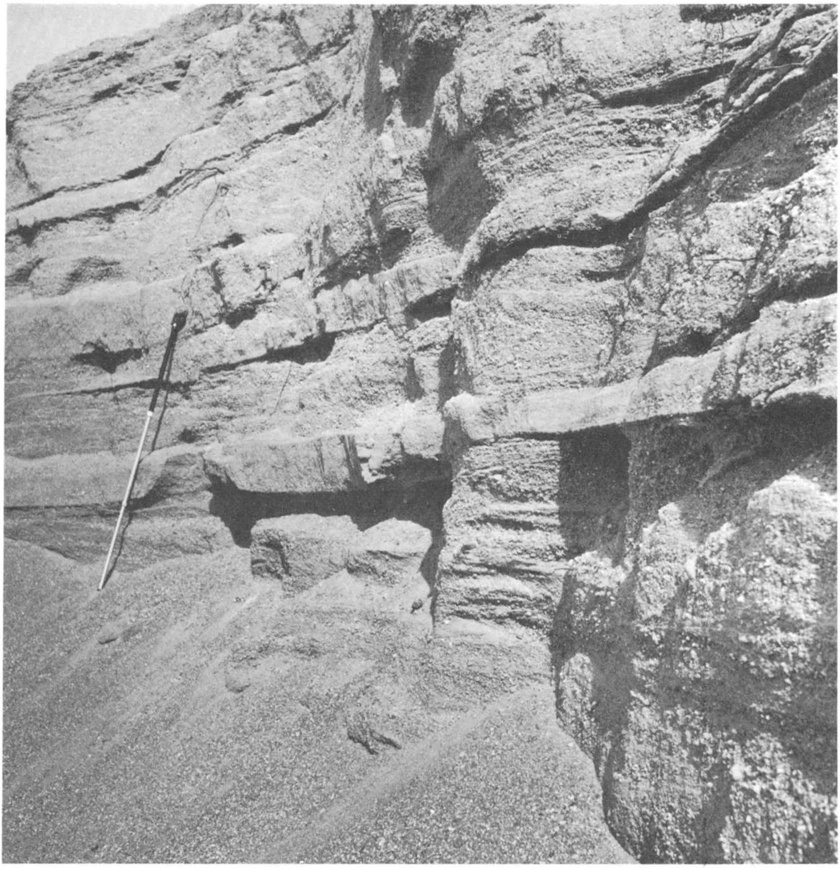


FIGURE 43.—Nussbaum Alluvium in gravel pit at south end of Baculite Mesa in the NW¼NW¼ sec. 10, T. 20 S., R. 64 W., Pueblo County, Colo. The alluvium is composed largely of cross-stratified coarse sand varying in amount of cementation. The Jacob staff is 5 feet long.

that armors the slopes of Pierre Shale with slabs 2 by 3 by 6 feet in dimension.

Weathering is not severe, but is shown by a soil zone and slight kaolinization of feldspar grains. At no place was an original soil observed on the Nussbaum. Perhaps this soil is preserved on the higher parts of Baculite Mesa where there are no cuts in the alluvium, but the soil that was observed is a younger pre-Bull Lake soil containing a diffuse layer of calcium carbonate and a reddish-brown clay-enriched horizon.

Fossil bones have been found; all but one were lost or destroyed before they could be identified (Scott, 1963a). A bone recovered in

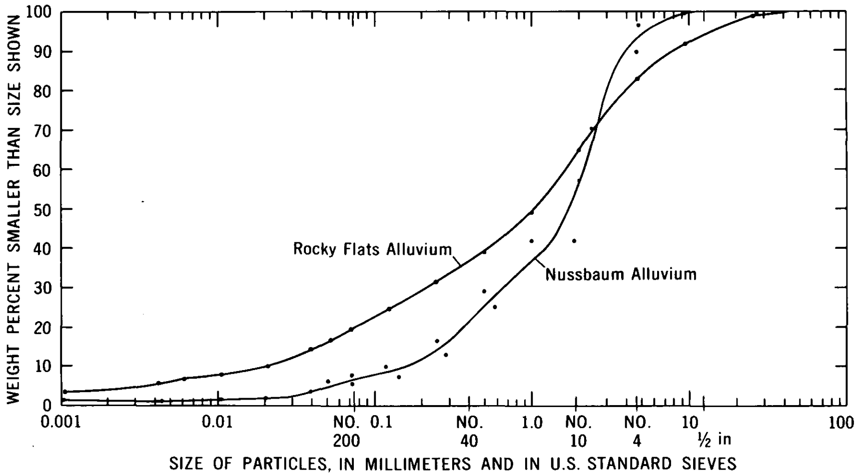


FIGURE 44.—General size-distribution characteristics of typical samples of Nussbaum and Rocky Flats (single line) Alluviums.

several pieces by Herman Schlegel, equipment operator for the city of Pueblo, and by me, was identified by Edward Lewis as a tibia of an immature individual of ?*Camelops* sp. The need for identifiable fossils is more critical for the Nussbaum than for any other formation in the area.

Engineering geology.—The Nussbaum Alluvium presents no engineering problems with the possible exception that wetting under foundations might weaken the clay bond between the particles. Permeability is excellent, and springs are plentiful at the base of the alluvium all around the south end of Baculite Mesa. The spring water carries calcium carbonate that cements the lower part of the alluvium. Slope of the alluvium is vertical in a fresh cut where clay forms a weak bond between the particles. A stable slope in nature is about 20°. Erosion is rapid, and erosion check dams are necessary. Excavation is easy by hand or power tools.

Foundation stability probably is good where shallow spread footings are used. The lack of firm consolidation and the presence of clay films at the point contacts of grains pose a potential problem. If a heavy load is imposed on the alluvium where it is not laterally confined, wetting may cause further consolidation of the grain structure. Such a problem was encountered in the Douglass Mesa Gravel at the Air Force Academy, Colorado Springs, Colo. (Varnes and Scott, 1967). There, the Douglass Mesa Gravel is a fine gravel bonded by clay. To determine the foundation stability of the gravel, four load tests were performed by the use of test caissons and hydraulic jacks. Even without the addition of water (such as might be added during the watering of landscape plantings), the gravel consolidated so much that, in the final buildings, foundations were placed in the underlying bedrock rather than in the Douglass Mesa Gravel.

Foundation stability certainly will be better where the alluvium is laterally confined and not wetted excessively. The Nussbaum Alluvium is nonplastic, and its swelling potential, if any, is noncritical. Frost susceptibility is slight to high depending on the amount of fine material present. The Unified Soil Classification symbol is SM. The excavated material is poor for use as base material directly beneath pavement or other wearing surface. It was being removed in 1965 from a pit on the south end of Baculite Mesa and used as road metal, subbase, and in bituminous hot mix. It probably is unsuitable for use in concrete aggregate.

ROCKY FLATS ALLUVIUM

The Rocky Flats Alluvium (Scott, 1960) of Nebraskan or Aftonian age crops out only in the northeast corner of the area. Dissection has removed most of the formation, and the remnants lie on low benches cut along the east side of Baculite Mesa. The surface at the base of the alluvium projects to a height about 250–260 feet above modern streams. The formation is about 10 feet thick and consists of stream-deposited sand and gravel.

The alluvium is dark-grayish-brown coarse sand and pebble gravel containing subrounded sand grains and subangular pebbles. Because the alluvium is derived from Nussbaum Alluvium mixed with reworked Pierre Shale, it is not as well sorted as the Nussbaum. The matrix is clayey silt, and the alluvium is noncemented but well compacted. Composition was determined by a count of 100 pebbles ¾–2 inches in maximum dimension. Pebbles include 43 concretionary limestone, 24 pegmatite, 12 quartz, 8 aragonite, 4 chert, 3 granite, 3 sandstone, 2 clayey ironstone, and 1 sandy ironstone. The composition of the half-inch grain-size material appears to be similar to the above. A size-distribution curve (fig. 44) shows that the alluvium contains 5 percent clay, 13 percent silt, 46 percent sand, 16 percent granules, and 20 percent pebbles. Boulders as large as 10 inches in length were seen. X-ray analysis of the minus-200-mesh fraction of the alluvium shows 30 percent clay minerals, 40 percent quartz, 10 percent feldspar (potassium feldspar is more abundant than plagioclase), and 20 percent calcite. Of the clay minerals, illite is more abundant than kaolinite, which equals mixed-layer clay (consisting of illite and montmorillonite) in abundance. About 14 percent of the material in the alluvium is soluble in dilute hydrochloric acid.

A soil zone on the alluvium is characterized by a slightly sticky slightly plastic dark-brown blocky B horizon more than 1 foot thick and a pale-brown calcium carbonate zone in the upper part of the parent material. The soil profile is calcareous throughout, probably owing to later enrichment by calcium carbonate. No fossils were found.

Engineering geology.—The Rocky Flats Alluvium is not likely to make excellent foundation material because of its clayiness. Infiltration and permeability probably are very poor in the alluvium. At least one spring issues from the base of the gravel, and drinking water is collected for livestock. Drains may be needed where highways cross the base of the alluvium. Surface waterflow is excellent because of the low infiltration and steep slopes. Erosion is slow, owing to hard compaction and an armor of pebbles; however, check dams probably are needed. Slopes in nature are stable at 15°. Excavation is easy with hand or power tools.

Foundation stability is fair to good. The formation probably would make satisfactory foundations for small buildings, but for large structures, caissons into the underlying Tepee zone of the Pierre Shale might be preferable. The excavated alluvium should not be applied as base material directly under pavement or other wearing surface of a road. Swelling pressure of one sample of the clay minerals in the alluvium is noncritical at 600 psf. Frost susceptibility is slight to high. Plasticity index versus liquid limit is shown in figure 45. Unified Soil Classification symbol is SC. The alluvium possibly is suitable for road metal, but probably not for subbase because of its clayiness. No prospect pits have been opened in the material.

VERDOS ALLUVIUM

The Verdos Alluvium (Scott, 1960) of Kansan or Yarmouth age crops out in the northeast corner of the area. It forms a thin cover on pediments sloping gently eastward from Baculite Mesa. The pediments project to a height of about 200–220 feet above modern streams. The formation is about 20 feet thick and consists of stream-deposited sand and silt.

The alluvium is dark-yellowish-brown fairly well sorted calcareous coarse sand and small pebbles in a clayey silt matrix. Pebbles and cobbles are subrounded to subangular and as large as 4 inches. Grain size becomes finer toward the toe of the pediment. A size-distribution curve (fig. 46) of material from the head of the Verdos pediment inside the area shows 2 percent clay, 2 percent silt, 39 percent sand, 37 percent granules, and 20 percent pebble-sized material. A size-

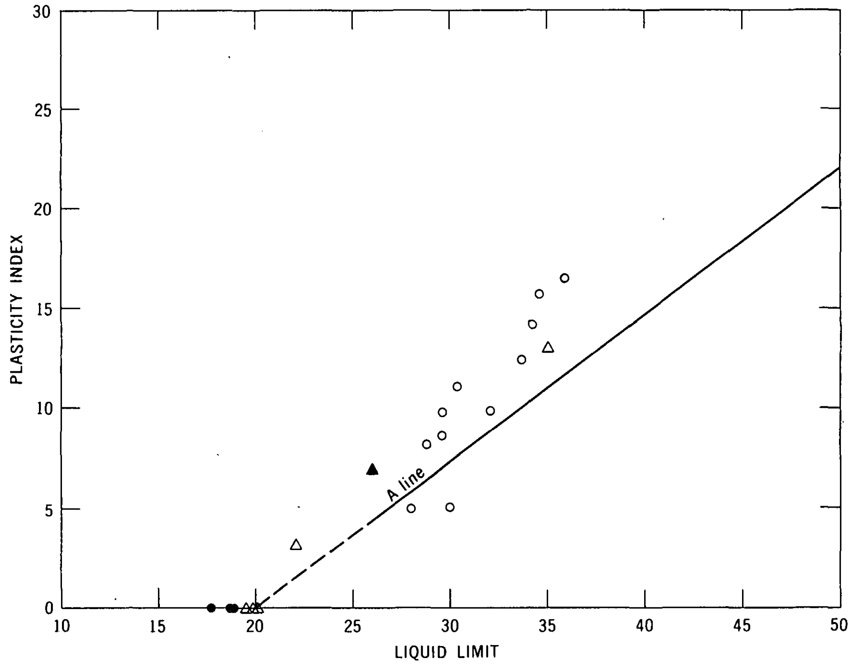


FIGURE 45.—Plasticity index versus liquid limit for pre-Bull Lake alluvium: ○ Slocum Alluvium, local facies; ● Slocum Alluvium, facies of Arkansas River origin; △ Verdos Alluvium; ▲ Rocky Flats Alluvium.

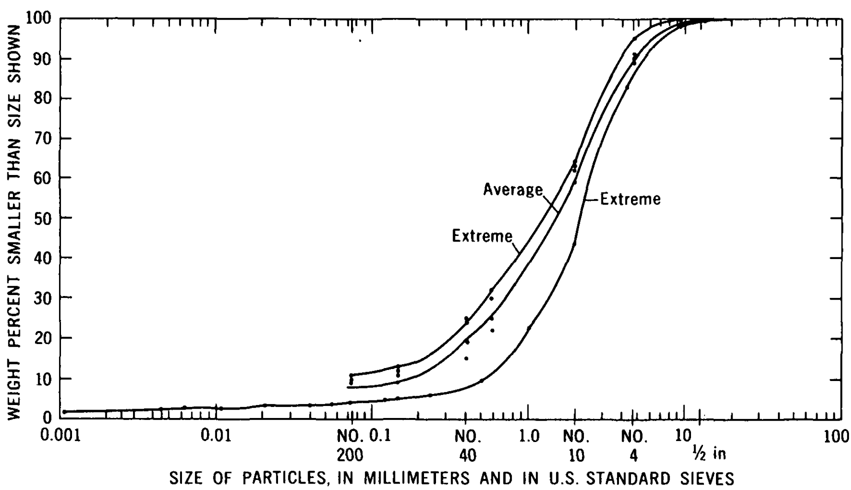


FIGURE 46.—General size-distribution characteristics of Verdos Alluvium. Lower extreme line represents sample of deposit near source on Baculite Mesa; other lines are of deposits near Arkansas River but not containing rocks originating from the river.

distribution curve showing an average of all material sampled, including material from the toe of the pediment east of the area in the NE¼ sec. 18, T. 20 S., R. 63 W., shows 8 percent clay and silt, 52 percent sand, 26 percent granules, and 14 percent pebbles. The extremes of each grain size also are shown in figure 46. Composition of the alluvium was determined by a count of 100 pebbles ¾–2 inches in diameter. They include 40 concretionary limestone, 25 pegmatite, 20 quartz, 5 chert, 4 aragonite, 1 granite, 1 basic igneous dike rock, 1 ironstone, 1 quartzite (possibly from a sandstone dike), 1 quartz fault breccia, 1 sandstone. The pebble count is similar to that of the Rocky Flats because both are derived from Nussbaum Alluvium. Two percent of the alluvium is soluble in dilute hydrochloric acid. No fossils were found. A soil was not observed on Verdos Alluvium.

Engineering geology.—The Verdos Alluvium probably is satisfactory foundation material unless films of clay between the grains cause it to have poor bearing capacity. The formation has medium permeability, and seeps flow from its base. Drains may be needed where a highway crosses the base of the alluvium. Infiltration of rainfall is fairly slow because of a clayey soil, but surface waterflow is good. The alluvium erodes readily and requires erosion control. Slopes are as steep as 25° on the ends of spurs where the underlying Pierre Shale is undercut; more normal and stable slopes average about 10°.

Foundation stability is good for light structures. For heavy structures, attention should be given to the effect that wetting and loading of the alluvium has on the weak clay bonds between grains. The alluvium is well compacted but not so firmly consolidated as underlying bedrock. The excavated alluvium should not be applied as base material directly beneath pavement or other wearing course. Swelling potential of the alluvium probably is noncritical, but it was not tested because of its porosity and small amount of clay. Potential frost action is slight to high. Plasticity index versus liquid limit is shown in figure 45. The Unified Soil Classification symbol is SM. The material is easily excavated by hand or power tools. The alluvium is suitable for use as dumped fill, road metal, and subbase. No pits are opened in the area, but gravel has been taken from pits north of Pueblo Municipal Airport in the NE¼ sec. 18, T. 20 S., R. 63 W.

SLOCUM ALLUVIUM

The Slocum Alluvium (Scott, 1960) of Illinoian or Sangamon age crops out over most of the area as a thin veneer on high terraces or on pediments sloping away from high areas. The Pediment cover slopes about 70 feet per mile; the terrace alluvium slopes 20–40 feet per mile and lies about 110–120 feet above modern streams. The alluvium consists of gravel, sand, or silt (fig. 47), and is about 25 feet thick along the Arkansas River; elsewhere, it is thinner.

The Slocum has a highly variable composition, and to a lesser extent, texture, owing to difference in local source material. Two extremes of variation are separated on the geologic map as silty alluvium of local origin and coarse gravel of Arkansas River origin. Variations in the alluvium of local origin include clayey, silty, coarse sand near Baculite Mesa, derived from Nussbaum Alluvium and Pierre Shale and containing quartz grains and ironstone fragments; coarse sand and pebble gravel along Fountain Creek in large part derived from granitic terrane west of Colorado Springs, Colo., but also containing sandstone, ironstone, and chert; and calcareous silt containing pieces of limestone and coarse sand, in the northwest corner of the area, derived from Niobrara Formation and old surficial deposits outside the map area.

FIGURE 47.—Coarse-grained Slocum Alluvium of Arkansas River origin in gravel pit in the SW¼SW¼ sec. 5, T. 21 S., R. 64 W., Pueblo County, Colo. Fine-grained alluvium of local origin and of Bull Lake(?) age overlies the Slocum. Boulders, cobbles, and pebbles in gravel are only slightly weathered despite great age. The Jacob staff is 5 feet long.

The locally derived alluvium can be described in a general way as containing yellowish-brown clayey silty sand and pebble gravel. The alluvium is loosely consolidated in the upper part, but is cemented by calcium carbonate to a hard conglomerate in the lower 1–2 feet. Stratification is good in the terraces along Fountain Creek, but crude in the upland areas. Small grains are better rounded than the large ones. Grain sorting is fairly good in the Fountain Creek terraces but poor elsewhere. A size-distribution curve on the noncalcareous fraction of a sample from local alluvium in the NE¼NE¼ sec. 17, T. 20 S., R. 64 W., shows 23 percent clay, 15 percent silt, 49 percent sand, 9 percent granules, and 4 percent pebbles. This material is about average in size; extreme size ranges are shown on figure 48. X-ray analysis of the minus-200-mesh fraction of this same sample showed 30 percent clay minerals, 20 percent quartz, 25 percent potassium feldspar, 20 percent gypsum, and about 5 percent calcite. Mixed-layer clay (consisting of illite and montmorillonite) is more abundant than kaolinite, which is equal in abundance to illite. Only 2.6 percent of the total sample is soluble in dilute hydrochloric acid.

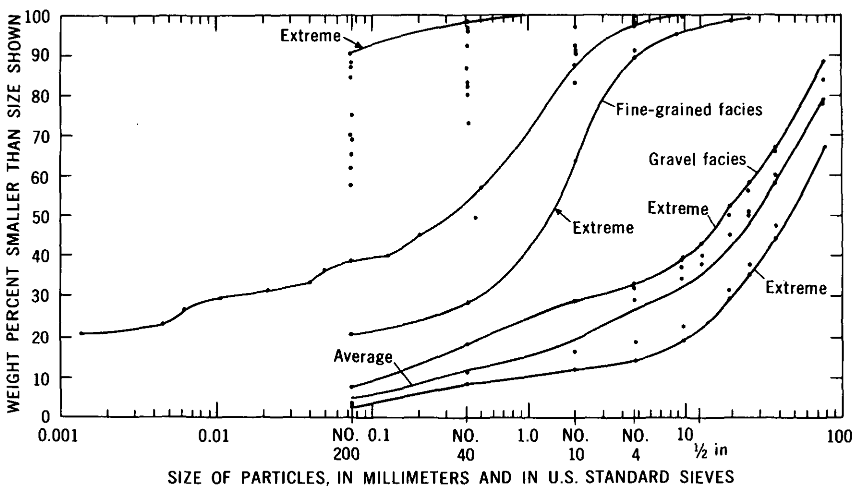


Figure 48.—General size-distribution characteristics of fine-grained and gravel facies of Slocum Alluvium. Fine-grained facies (Qs on pl. 1)—centerline is typical sample from NE. cor. sec. 17, T. 20 S., R. 64 W. Other samples may be contaminated by addition of shale. Gravel facies ((Qsa on pl. 1)—centerline is a calculated average.

An interfingering relationship of the fine-grained local alluvium to the coarse-grained alluvium of Arkansas River origin was observed in gravel pits that lie along the north edge of the ancient valley occupied by the Arkansas River in Slocum time. The ancient valley is entrenched a few feet deeper than the pedimentlike slopes that flank it. The best place to see the ancient valley is in the NW¼ sec. 32, T. 20 S., R. 65 W., where a knob of Fort Hays Limestone Member of the Niobrara Formation at locality D3991 forms the south wall of the ancient valley. Tongues of fine-grained alluvium tail out in, and are overlapped by, the coarse alluvium within a few feet from the side of the ancient river channel. Coarse alluvium at the edge of the channel is cemented to hard conglomerate. Locally, overlying the coarse alluvium is local fine-grained alluvium (fig. 47) that was attributed, at the time the preliminary Pueblo map (I–408) was published (Scott, 1964), to a late influx of Slocum Alluvium.

In 1963, evidence indicating a younger age for the fine-grained alluvium was shown to me in the Florence area by Henry Kane, Ball State University. An outcrop of coarse-grained Slocum Alluvium of Arkansas River origin in the SE¼ sec. 9, T. 19 S., R. 69 W., Florence quadrangle, Colorado, has a very strong pre-Bull Lake soil developed in its upper part. Overlying the pre-Bull Lake soil is a fine-grained local alluvium on which a strong post-Bull Lake soil has formed; therefore, the conclusion is unavoidable that the fine-grained alluvium at this outcrop is one stage younger than the coarse alluvium. Most likely, a similar age relationship applies to the coarse- and fine-grained alluviums near Pueblo. Mollusks from an outcrop of the fine-grained alluvium that overlies coarse Slocum Alluvium in a gravel pit in the NE. cor. sec. 7, T. 21 S., R. 64 W., Southeast Pueblo quadrangle, are the same as those found in the Louviers Alluvium near Denver (Scott, 1963b). No change has been made on the geologic map as a result of these implications; but wherever Slocum gravel of Arkansas River origin is shown on the geologic map (pl. 1), the upper fine-grained alluvium possibly is Bull Lake in age.

Coarse-grained alluvium of Arkansas River origin is composed of dark-yellowish-brown cobble gravel containing boulders as large as 18 inches in diameter. Stratification is good only in thin lenses of sand- and pebble-sized material. Most stones are well rounded and ovate or flattened. Composition was determined by a count of 119 pebbles, 1–2 inches in maximum size, which showed 44 fine and coarsely crystalline quartz monzonite of both igneous and metamorphic origin, 13 quartzite, 11 pegmatite, 11 dark-gray finely crystalline porphyry, 9 granite, 8 dark-gray medium-crystalline porphyry, 8 medium-gray coarsely crystalline porphyry, 5 biotite quartz gneiss, 4 granite gneiss, 4 quartz, and 2 black dike rock. Some fragments of yellowish-brown jasper were seen. The fragments of porphyry probably are from igneous dikes or flows in the mountainous upstream area. Size-distribution curves (fig. 48) of the coarse alluvium show that it contains an average of 4 percent combined silt- and clay-sized material, 15 percent sand, 5 percent granules, 49 percent pebbles, and 27 percent cobbles. Some boulders are 18 inches in diameter. Extreme size range is shown in figure 48.

The pre-Bull Lake Sangamon soil contains a brown or reddish-brown B horizon about 4 feet thick characterized by an intense accumulation of clay minerals and a strong columnar structure; in the parent material below the B horizon is a dense accumulation of calcium carbonate. The soil is fairly well preserved in sec. 7, T. 21 S., R. 64 W., Southeast Pueblo quadrangle.

Engineering geology.—Engineering properties of the Slocum Alluvium are expected to be as variable as the alluvium itself. Infiltration and permeability are poor in the fine-grained alluvium but are excellent in the coarse. Water flows at the base of the alluvium where it overlies impermeable bedrock; springs and seeps issue locally from the base. Drains may be needed where foundations intersect the base of the gravel. For erosion to affect the formation, it must actually cut away the underlying shale that supports the Slocum; erosion of the Slocum is slow and erosion check dams are required only where the alluvium is silty, as in the northwestern part of the area. Slopes as steep as 25° were seen, but a stable slope apparently never is steeper than 18°. No slumps or slides were observed, except on drastically steep slopes. Excavation is easy by hand or power equipment, except in the basal conglomeratic layer.

Foundation stability of the fine-grained local alluvium is poor to good; of the coarse-grained alluvium of Arkansas River origin it is good to excellent. Much of the fine-grained local alluvium is very clayey and probably unsuitable for foundations of large structures; the alluvium is thin enough that foundations can be extended into unweathered bedrock. Foundations of small structures in Slocum should be placed back away from the edge of each deposit to assure that the material is laterally confined. Swelling pressure of one sample of the clay in the fine-grained alluvium is noncritical at 1,550 psf. Frost susceptibility is slight to high depending on grain size and availability of water. Plasticity index versus liquid limit for the fine- and coarse-grained alluvium is shown in figure 45. Some physical properties of the fine- and coarse-grained alluvium are given in the following tables.

Summary of some physical tests of local fine-grained Slocum Alluvium

	Number of tests	Average	Range
Specific gravity g/cc	4	2. 68	2. 66–2. 71
Maximum density, AASHO modified compaction lb per cu ft	4	115. 8	108. 8–123. 7
Optimum moisture percent	4	14. 8	12. 0–17. 7
Laboratory California Bearing Ratio at 90 percent maximum density	19	5. 4	3. 2–8. 6
pH			7. 52
AASHO classification		A–4	A–2, A–4, A–6
Unified Soil Classification symbol		SC, CL	

Summary of some physical tests of coarse-grained Slocum Alluvium of Arkansas River origin

	Number of tests	Average	Range
Specific gravity g/cc	1		2. 63
Maximum density, AASHO modified compaction lb per cu ft	4	123. 5	102–132
Optimum moisture percent	3	5. 6	4–7. 7
Los Angeles abrasion percent wear			30. 2
Stabilometer, R value [1]	3	81. 7	81–82
AASHO classification		A–1–A	
Unified Soil Classification symbol		GP	

[1] Asphalt Institute, 1961, p. 164.

The coarse-grained alluvium possibly is suitable for concrete and bituminous aggregate where not too weathered or coated by calcium carbonate; it is also suitable for road metal, subbase, and base course material. The fine-grained alluvium is suitable for road metal, possibly for subbase or soil cement. The conglomerate layer at the base of the fine-grained alluvium was used for dimension stone in a decorative gate at the south end of Mineral Palace Park at Main and 15th Streets. The stone was laid up before 1894 in random blocks of various lengths and thicknesses, and the performance is excellent. The same stone also was used on the corners of the Mineral Palace, which was dismantled in the late 1930's.

LOUVIERS ALLUVIUM

The Louviers Alluvium (Scott, 1960) of early Bull Lake age crops out on terraces 70–80 feet above Fountain Creek and the Arkansas River, as local channel-fill deposits west of Baculite Mesa, and within the Fort Hays rimrock at Rock Canyon anticline. The alluvium slopes downstream about 15 feet per mile along the Arkansas River and 30 feet per mile along Fountain Creek. The formation is about 20 feet thick and consists of coarse and fine gravel (fig. 49) and pebbly silt.

FIGURE 49.—Coarse-grained Louviers Alluvium of Arkansas River origin in gravel pit south of the Arkansas River in the NE¼SE¼ sec. 5, T. 21 S., R. 64 W., Pueblo County, Colo. Boulders, cobbles, and pebbles in upper part of deposit are nearly unweathered but are coated by calcium carbonate. Note the torrential cross-stratification of the sand layer. The Jacob staff is 5 feet long.

Coarse gravel lies in a terrace along the Arkansas River. The alluvium is yellowish-brown poorly stratified sandy pebbly cobble gravel that contains some boulders. Particles in the gravel are well rounded but poorly sorted; finer grained particles occur in stringers and lenses. A size-distribution curve of the gravel (fig. 50) shows 3 percent combined clay and silt, 24 percent sand, 4 percent granules, 54 percent pebbles, and 15 percent cobbles. Extremes of size range are shown in figure 50: In composition the gravel is similar to the Slocum Alluvium. The lower few inches of the Louviers is firmly cemented by calcium carbonate. The distal part of a large bovid meta-

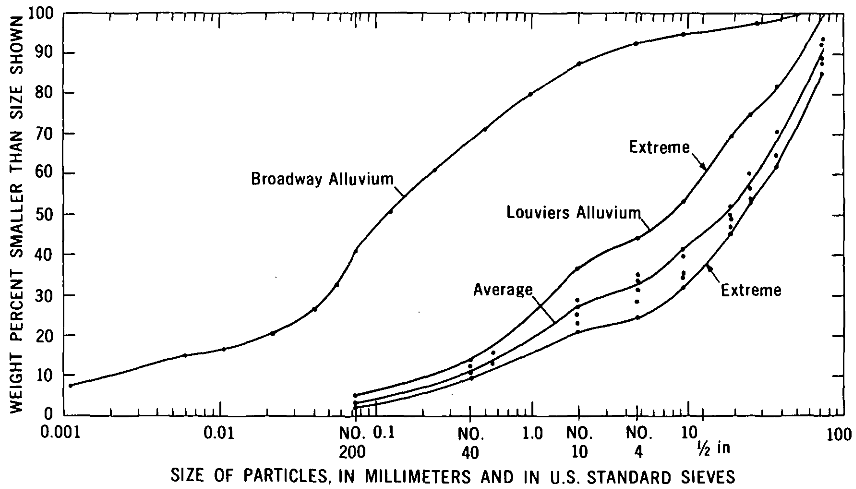


FIGURE 50.—General size-distribution characteristics of typical samples of coarse-grained facies of Louviers Alluvium (Qla on pl. 1) from various localities and of fine-grained facies of Broadway Alluvium (Qb on pl. 1) from Dry Creek.

carpal bone found by Carl K. Davidson in the gravel at the Crisman pit in the W½ sec. 4, T. 21 S., R. 64 W., is described by Edward Lewis as *Bison* (*Bison*) sp.

Louviers Alluvium along Fountain Creek is moderate-brown crudely stratified poorly sorted pebble gravel containing cobbles and boulders as much as 12 inches in length. The average size is 1 inch. Fragments derived from granitic rocks compose more than 90 percent of the alluvium and include granite, granite gneiss, pegmatite, feldspar, and quartz. Other fragments are ironstone and chert and sandstone from the Dakota Sandstone and from the Apache Creek Sandstone Member. In the lower few inches the gravel is cemented by calcium carbonate.

Louviers Alluvium in upland areas between Fountain Creek and Baculite Mesa and north and south of the Arkansas River at Rock Canyon anticline is finer grained than Louviers Alluvium in any of the terrace deposits and consists of clay or silt containing ironstone or limestone fragments. This fine-grained alluvium is of local origin and overlies the coarse terrace alluvium that was deposited by the Arkansas River. Assuming that the fine- and coarse-grained alluvium bear the same relationship to each other as do fine- and coarse-grained Slocum, then the fine-grained alluvium may be one stage younger than the coarse—that is, equivalent to the Broadway Alluvium of Pinedale age.

A post-Bull Lake Brown soil formed on Louviers Alluvium contains a dark-yellowish-brown B horizon about 18 inches thick characterized by a moderate accumulation of clay minerals and a moderate prismatic structure; in the parent material just below the B horizon, spots or streaks of calcium carbonate have accumulated. The soil is fairly well preserved on Louviers Alluvium along the west side of Fountain Creek and the south side of the Arkansas River.

Engineering geology.—No major engineering problems are expected from the Louviers Alluvium. Permeability is excellent, and seepage can be expected at the base. Drains may be needed where roads cross the base of the gravel. The fine-grained local alluvium erodes readily and probably would require erosion control. Slopes as steep as 30° were seen below resistant beds, but an average stable slope is about 15°. Excavation of Louviers is easy with small power equipment.

Foundation stability of the coarse-grained terrace alluvium is good to excellent; of the fine-grained local alluvium, it is poor to good. The fine-grained alluvium is clayey and probably is unsuitable for shallow foundations of large structures; the alluvium is thin enough that foundations can be extended through it into unweathered bedrock. Frost susceptibility is slight to high depending on grain size and availability of water. Plasticity index versus liquid limit for the coarse-grained alluvium of Arkansas River origin is shown in figure 51, and some of the physical properties are given in the following table.

Summary of some physical tests of Louviers Alluvium facies of Arkansas River origin

	Number of tests	Average	Range
Maximum density, AASHO modified compaction lb per cu ft	2	120	113–127
Optimum moisture percent	2	13.2	6.6–19.8
Stabilometer, R value	2	75	70, 80
Los Angeles abrasion percent wear			36.4
AASHO classification		A–1–a	
Unified Soil Classification symbol		GP	

BROADWAY ALLUVIUM

Broadway Alluvium (Scott, 1960) of Pinedale age crops out in small deposits scattered over much of the area. The alluvium was laid down on terraces about 40 feet above modern streams, and it slopes downstream about 20 feet per mile. The formation is 10–25 feet thick and consists of sand and gravel.

Two facies of the Broadway are mapped, a fine-grained facies along small streams and a cobble-gravel facies along the Arkansas River. The fine-grained facies consists of coarse pebbly granitic sand along Fountain Creek; clayey pebbly coarse sand along streams flowing

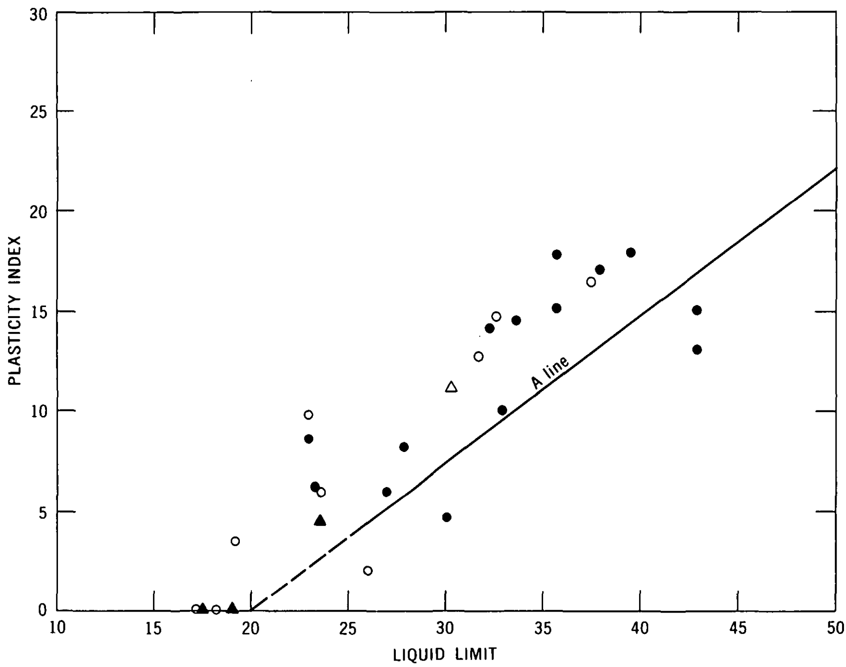


FIGURE 51.—Plasticity index versus liquid limit for Bull Lake and later alluvium: ○ post-Piney Creek alluvium; ● Piney Creek Alluvium; △ Broadway Alluvium, local facies; ▲ Louviers Alluvium facies of Arkansas River origin.

south from Baculite Mesa; and silty clayey pebbly calcareous sand along Dry Creek.

In general, the local alluvium is yellowish-gray or moderate-brown silty, pebbly, and fine or coarse sand that is slightly compacted, poorly sorted, and well stratified. The pebbles along Fountain Creek are composed of fragments of granite, those along streams south of Baculite Mesa are chiefly ironstone, and those along Dry Creek are chiefly limestone fragments from the Niobrara Formation. A size-distribution curve (fig. 50) on nonplastic local alluvium along Dry Creek in the NE¼NW¼ sec. 15, T. 20 S., R. 65 W., shows 13 percent clay, 23 percent silt, 51 percent sand, and 13 percent pebbles. Another sample, probably from the soil horizon of the same deposit, showed that 70 percent passed the No. 200 U.S. Standard sieve. X-ray analysis of the minus-200-mesh fraction of this same deposit showed 35 percent clay minerals, 15 percent quartz, 20 percent feldspar (potassium feldspar exceeds plagioclase in abundance), and 25 percent calcite. Of the clay, illite is equal in abundance to kaolinite, which is more abundant than mixed-layer clay (consisting of illite and montmorillonite). Thirty-nine percent of the sample is soluble in dilute hydrochloric acid.

Coarse-grained alluvium along the Arkansas River consists of sandy cobble gravel. Only three small areas of this alluvium were mapped. Composition and size probably are similar to that of the Slocum Alluvium.

A mass of Broadway Alluvium in the SW¼ sec. 32, T. 20 S., R. 64 W., appears to be the vestigial deposit of a large ancient flood of Fountain Creek. The alluvium is a yellowish-gray nearly uniform sand. Cross-stratification slopes steeply southeastward, indicating that the sand was deposited by water flowing from the northwest across a ridge of the upper chalk unit of the Niobrara Formation. The top of the deposit lies 55 feet above modern Fountain Creek and about 15 feet higher than the tops of most deposits of Broadway Alluvium in the area.

Engineering geology.—No major engineering problems are anticipated from the Broadway Alluvium. Permeability is good in the alluvium. Water flows at the base of the alluvium where it overlies impermeable bedrock. The average stable slope of the alluvium is about 15°. The fine-grained local facies is readily eroded and requires erosion checkdams. No slumps were observed or anticipated. Excavation is easy to a depth of 10 feet with small power tools.

Foundation stability of the fine-grained alluvium is fair to good where not subject to frost action; of the coarse-grained alluvium of Arkansas River origin, it is good to excellent. The fine-grained material should not be applied as base material directly under pavement or other wearing course of a road. Some of the fine-grained alluvium is slightly sticky and slightly plastic but has little or no swelling potential. Potential frost action in the fine-grained alluvium is slight to high. Plasticity index versus liquid limit of one sample possibly taken from the clay-enriched horizon of a soil is shown in figure 51. The laboratory CBR at 90 percent maximum density is 3.5. The Unified Soil Classification symbol of the fine-grained alluvium is SC. The coarse alluvium is suitable for concrete aggregate, and the fine alluvium, for dumped fill.

EOLIAN SAND

Eolian sand of early Holocene age crops out east of Fountain Creek, south of the Arkansas River, and east of Dry Creek at the north edge of the area. The sand was blown chiefly from loose deposits of Broadway Alluvium lying along valleys, carried downwind, and deposited as gently rounded mounds of sand that conform grossly to the topography of underlying deposits. The formation locally is more than 20 feet thick and consists chiefly of sand.

The eolian sand is yellowish gray or yellowish brown, fine to coarse, slightly compacted, and weakly cemented. Cross-stratification is present but not readily apparent. An average size-distribution curve (fig. 52) of the sand shows 40 percent combined silt- and clay-sized material, 57 percent sand, 2 percent granules, and 1 percent pebbles. The amount of combined silt and clay in samples tested ranges from 14 to 68 percent. A sample that is considered typical of the deeper part of the eolian sand below a soil was collected from a roadside pit in the 1700 block of Hudson Avenue; a test result from the U.S. Geological Survey laboratory, curve labeled coarse-grained sample on figure 52, shows 3 percent clay, 6 percent silt, and 91 percent sand. Sand grains are well rounded and frosted. The deposit is nonsticky and nonplastic. In the upper part is a moderately well developed "Altithermal" Brown soil (fig. 53). Clay enrichment extends through about 1 foot, and calcium carbonate extends 4 more feet down into the parent material.

An "Altithermal" Brown soil formed on the Broadway Alluvium and eolian sand contains a pale-yellowish-brown B horizon, 8 or more inches thick, characterized by a slight accumulation of clay minerals and a weak prismatic structure; in the parent material just below the B horizon is a weak concentration of calcium carbonate. The soil was observed on the Broadway Alluvium along the east side of Fountain Creek.

Engineering geology.—Eolian sand is a homogeneous material that is not expected to cause major engineering problems. Permeability is very good, and the sand is not readily eroded if it has a plant cover. Where exposed, it is eroded by either wind or water. The common

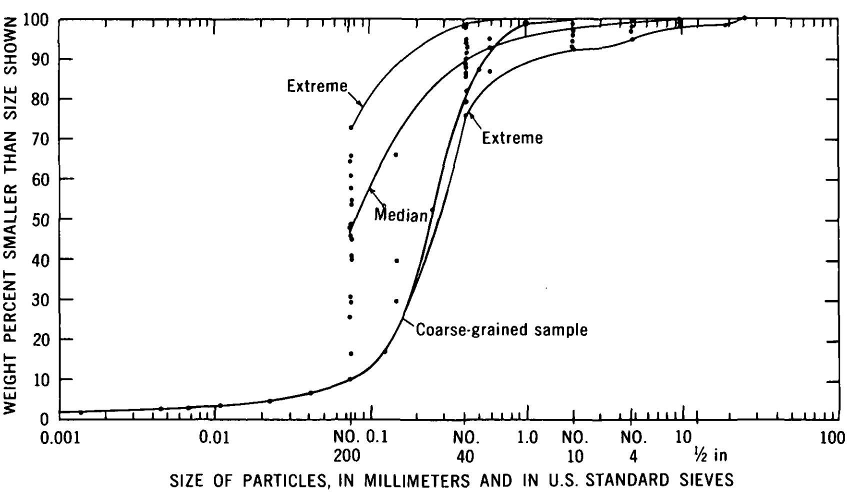


FIGURE 52.—General size-distribution characteristics of a broad range of textures of eolian sand.

FIGURE 53.—Eolian sand in pit in the SE¼NE¼ sec. 30, T. 20 S., R. 64 W., Pueblo County, Colo. An "Altithermal" clay-enriched Brown soil is well developed at the top; below the soil is a white accumulation of calcium carbonate in the upper part of the parent material. The Jacob staff is 5 feet long.

native plants that stabilize the sand are fringed sagebrush, yucca, and grass. Drains probably will be needed at the base of the sand because of the large amount and speed of movement of water. Locally, for example on the hill west of East High School, water in the sand is under hydrostatic head. Dry sand is stable in vertical slopes where freshly cut, but as rainwater dissolves the cementing material, the sand quickly slumps or weathers back to a stable 10° slope. Excavation is easy by either hand or power tools.

Foundation stability of the eolian sand is good to poor where not subject to frost action. Bearing capacity is unknown; however, the dry sand is known to compact under the pressure of a static load. The formation should not be applied as base material directly under pavement or other wearing course of a road. According to Louis Brauer, City Paving Engineer (oral commun., 1963), the sand becomes quaky when wet and needs nearly as much subbase beneath a wearing course as do the clayey Cretaceous shale units. The reason for the poor performance is not clear, for the CBR of the eolian sand averages 8.2, whereas the CBR of the Cretaceous shale is only about 4. Perhaps the poor performance is the result of poor original consolidation of the sand. The sand has little or no swelling potential. Frost susceptibility is slight to very high. Plasticity index versus liquid limit is shown in figure 54. The following table gives some of the physical properties of the eolian sand. The sand is used in combination with

Summary of some physical tests of eolian sand

	Number of tests	Average	Range
Specific gravity..................g/cc..	2	2. 66	2. 66–2. 67
Maximum density, AASHO modified compaction............lb per cu ft........	11	116. 4	113. 7–123. 1
Optimum moisture.............percent..	11	13. 1	10. 6–14. 4
Laboratory California Bearing Ratio at 90 percent maximum density..........	19	8. 2	2. 8–12. 5
AASHO classification..........................		A–4	A–2, A–3, A–4, A–6
Unified Soil Classification symbol.........................			SC, SM, CL, ML

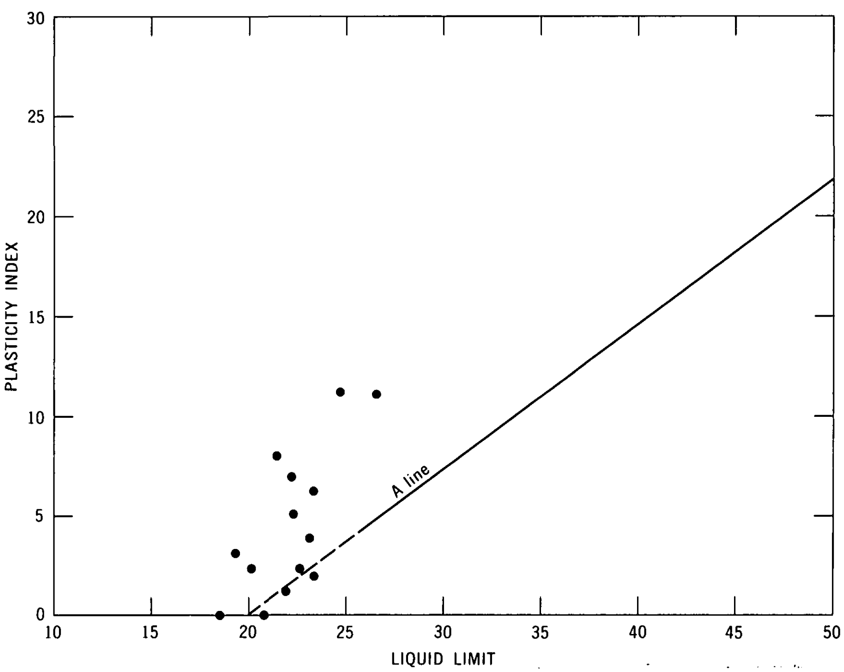


FIGURE 54.—Plasticity index versus liquid limit for 14 samples of eolian sand.

Pierre Shale for the manufacture of bricks. It has a potential use as plaster sand.

PINEY CREEK ALLUVIUM

The Piney Creek Alluvium (Hunt, 1954) of late Holocene age crops out along most streams in the area. It occupies the second or third lowest terrace about 20 feet above modern streams and slopes 20 feet per mile downstream. The formation is locally 25 feet thick and consists of stream-deposited silt and clay (fig. 55).

The alluvium is yellowish-gray blocky firm clayey silt. The lower part is well stratified and contains layers of sand and shingled pebbles; the upper part is poorly stratified. The silt is firmly compacted

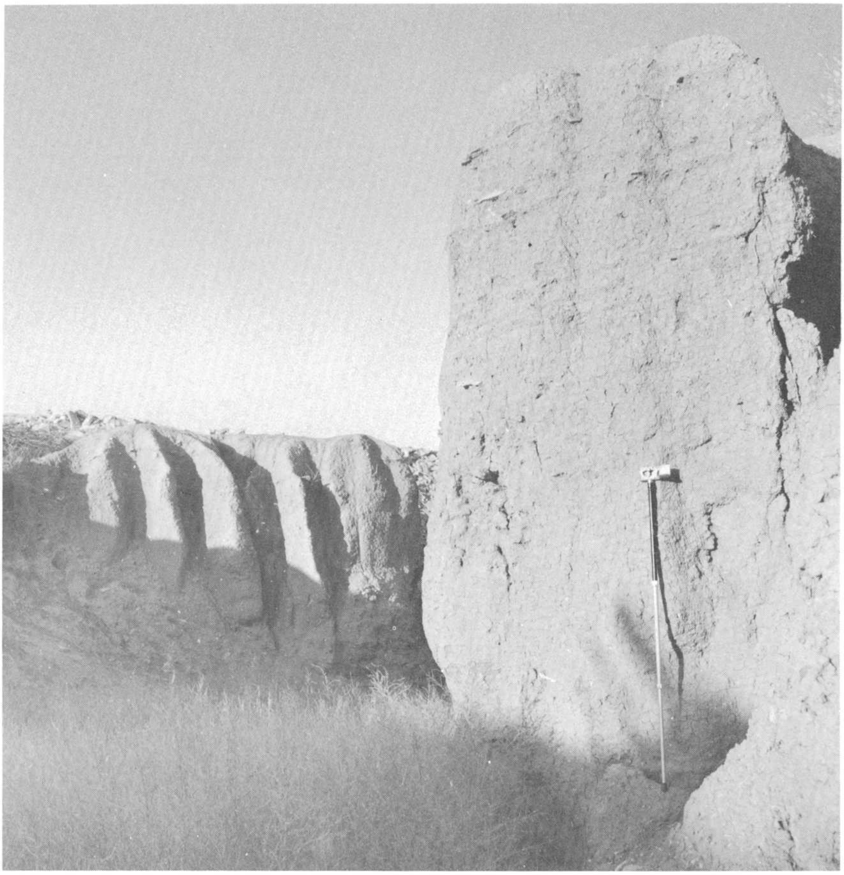


FIGURE 55.—Piney Creek Alluvium exposed by arroyo north of Rock Canyon in the NE¼ sec. 31, T. 20 S., R. 65 W., Pueblo County, Colo. The alluvium is chiefly stratified pebbly silt characterized by steep arroyo walls. The Jacob staff is 5 feet long.

and its consistence when wet is slightly sticky and plastic; when dry, it is very hard. Probably coarse alluvium in the lower part of the channel of the Arkansas River and Fountain Creek was deposited at the same time as Piney Creek Alluvium elsewhere; however, there is no way now to distinguish it on the map from the overlying post-Piney Creek alluvium, except in abbreviated columnar sections such as those at Rock Canyon Barrier Dam. An upper Holocene Brown soil is weakly developed in the upper part of the alluvium. The B horizon of the soil is enriched by clay and is characterized by a strong coarse columnar structure. Columns average 2 feet in diameter and extend down through the parent material to the floors of the arroyos. They are stable until wetted or undercut, when they fall over and dam arroyos.

A size-distribution curve on average material shows that the noncalcareous part of a sample of alluvium contains 23 percent clay, 49 percent silt, 25 percent sand, 1 percent granules, and 2 percent pebbles. Extremes of range in size are shown on figure 56. Four X-ray analyses given in the following table show that the mineralogic composition of the alluvium is extremely variable, but is similar to the composition of the rocks from which it is derived. Locally, as much as 17 percent of the alluvium derived from Niobrara Formation and as much as 5 percent derived from Pierre Shale are soluble in dilute hydrochloric acid.

X-ray analyses, in percent, of the minus 0.074 mm fraction (200-mesh sieve) of four samples of Piney Creek Alluvium

[Relative abundances of mixed-layer (ML), illite (I), and kaolinite (K) clay minerals, and plagioclase (P) and potassium (KF) feldspar]

No., locality, and member or formation from which alluvium is derived	Clay	Quartz	Feldspar	Calcite	Gypsum	Hornblende	Dolomite	Amorphous mineral
2-1144; arroyo in SE¼SW¼ sec. 28, T. 20 S., R. 65 W.; Niobrara Formation.	33 ML>I=K	22	5 KF>P	35	3	2	----	----
2-1149; NW¼SW¼ sec. 17, T. 20 S., R. 64 W.; Apache Creek Sandstone Member.	55 ML>K>I	30	10 KF=P	5	----	----	----	----
2-1156; NE¼SW¼ sec. 17, T. 20 S., R. 64 W.; Sharon Springs Member.	25 ML>I>K	10	5 KF>P	----	60	----	----	----
2-1056; NW¼NW¼ sec. 26, T. 20 S., R. 64 W.; Rusty zone.	46 ML=I=K	30	10 All P	4	----	----	5	5

327-617 O—69——8

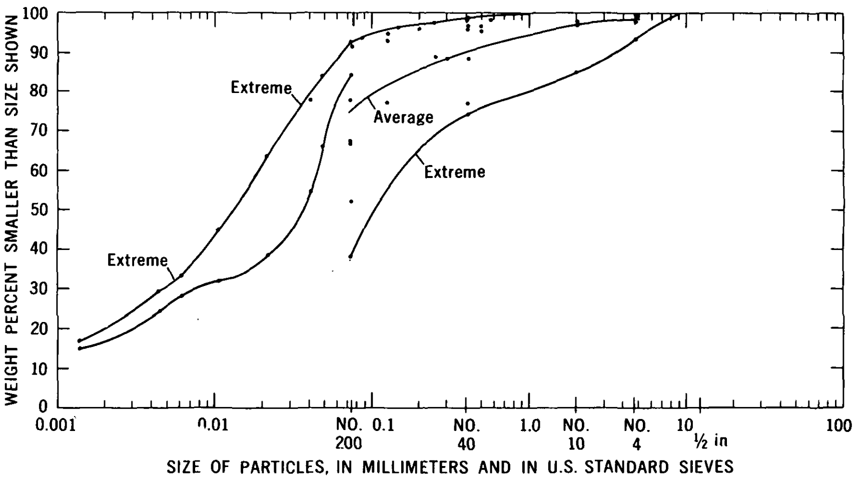


FIGURE 56.—General size-distribution characteristics of Piney Creek Alluvium. The lower extreme in the range from No. 200 to ⅜-inch sieves shows the influence of a source in the eolian sand. Normal Piney Creek probably is finer grained than the average shown here.

An upper Holocene Brown soil developed in the Piney Creek Alluvium contains a grayish-brown B horizon 10 inches or more thick characterized by a very slight accumulation of clay and a weak columnar structure; developed in the parent material below the B horizon is a very weak accumulation of calcium carbonate. The soil is preserved on Piney Creek Alluvium along Dry Creek.

Engineering geology.—The Piney Creek Alluvium is likely to cause many engineering problems because of its expansive clays, potential settlement, and low topographic position in relation to streams and arroyos. Permeability probably is poor, but seeps are common at the base of the alluvium where it overlies impermeable bedrock. That the alluvium is readily eroded is shown by many deep vertical-walled arroyos. Check dams along these arroyos are required at intervals close enough to prevent further headward cutting and to allow sediment to fill behind the dams. The dams must have adequate spillways and be wider and deeper than the potential width and depth of arroyo cutting or they will be removed during the flash floods that characterize the Pueblo area. Many shallow check dams that had been breached, including some made of concrete, were observed. Slopes will sand vertical where freshly cut, but gradually erode to 10°–20°. Excavation is easy by hand or power equipment.

Foundation stability is poor to good depending on clayiness, content of organic matter (which causes the alluvium to be locally compressible), and susceptibility to frost action. The alluvium probably is suitable as foundation only for small buildings, unless special consideration is given to design to offset potential swelling or settlement of the alluvium. No foundation should be placed close to an arroyo because of lack of lateral confinement, continuance of subsurface drainage even after filling, and possible flood damage. Swelling potential of four samples of the alluvium ranges from 2,000 to 3,000 psf in the noncritical and marginal categories. Frost susceptibility is slight to high depending on grain size and availability of water. Plasticity index versus liquid limit is shown in figure 51. Some physical properties of the alluvium are given in the following table. The material has been used as dumped fill and has a potential use as soil binder.

Summary of some physical tests of Piney Creek Alluvium

	Number of tests	Average	Range
Maximum density, AASHO modified compaction ---lb per cu ft--	1	--------	116. 9
Optimum moisture ---percent--	1	--------	13. 7
Laboratory California Bearing Ratio at 90 percent maximum density	8	5. 4	2. 0–11. 3
pH	5	7. 67	7. 58–7. 81
AASHO classification		A–4	A–4, A–6, A–7
Unified Soil Classification symbol			CL, OL, SM

COLLUVIUM

Colluvium of late Holocene age crops out on gentle slopes over much of the area. It generally overlies soft bedrock that was readily eroded and then covered by colluvium as a result of gravity and slope wash. Most of the colluvium overlies areas of the middle shale unit and upper chalky shale unit of the Smoky Hill Shale Member and the transition member and Apache Creek Sandstone Member of the Pierre Shale. Most colluvium is older than post-Piney Creek alluvium, but some is younger. The formation probably is generally no more than 10 feet thick and consists of variable but generally fine grained deposits.

The colluvium has a highly variable composition and texture owing to its derivation from many kinds of deposits. Where derived from the Niobrara Formation, the colluvium is loose gypsiferous calcareous clayey silt containing fragments of limestone; from the Pierre Shale the colluvium is compact silty clay containing fragments of sandstone and ironstone. Size-distribution curves (fig. 57) show that

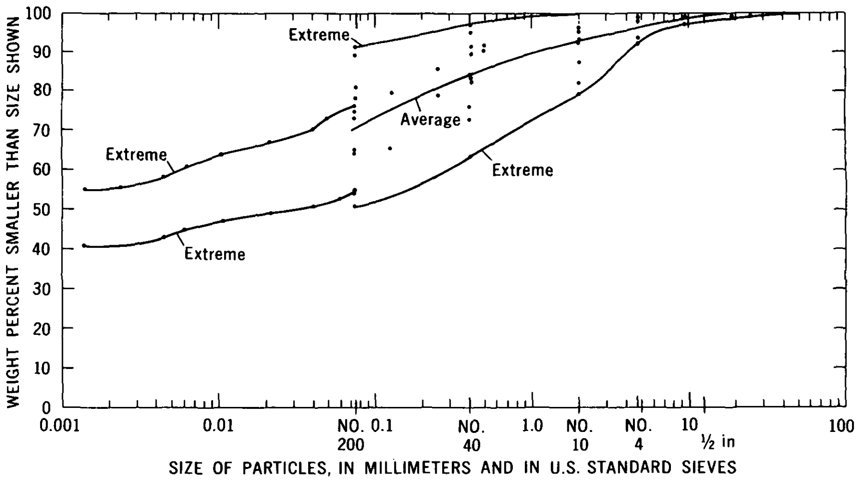


FIGURE 57.—General size-distribution characteristics of a broad range of textures of colluvium. Because only two analyses of material smaller than No. 200 sieve were available, extent of extreme variation is less, causing a break in the curves.

the noncalcareous part of an average sample contains about 50 percent clay, 14 percent silt, 29 percent sand, 2 percent granules, and 5 percent pebbles. Also shown in figure 57 are extremes in size range. X-ray analysis of the minus-200 U.S. Sieve fraction of the colluvium indicates that, where derived from the upper chalk unit, it contains 35 percent clay (mixed-layer clay is more abundant than illite, which equals kaolinite), 15 percent quartz, 5 percent plagioclase feldspar, 5 percent calcite, and 40 percent gypsum. Where derived from Apache Creek Sandstone Member, it contains 35 percent clay (mixed-layer clay is more abundant than illite, which equals kaolinite), 30 percent quartz, 15 percent feldspar (potassium feldspar equals plagioclase in abundance), and 20 percent calcite. Only 5–6 percent of the colluvium is soluble in dilute hydrochloric acid.

Engineering geology.—Engineering problems are not anticipated in the colluvium because it is so thin that most foundations are likely to be placed below it. Foundations placed in colluvium will be subject to some of the problems described below. Permeability is very poor, but water flows at the base of the colluvium above impermeable bedrock. Both this subsurface seepage and surface waterflow have a strong concentration of sulfates. The colluvium erodes readily and requires erosion control. Natural slopes range from 1° to 25°; the steepest colluvial slope lies below the Fort Hays-Codell cliff and is mapped as Carlile Shale, but it contains much colluvium. A stable slope probably is not greater than 10°. Excavation is easy with hand or power tools.

Foundation stability is fair to poor and is worse in the upper part where the colluvium is subject to frost action. The excavated colluvium should not be applied as base material directly beneath pavement or other wearing course. Colluvium underlies a large part of the city, and many houses and small structures have been built on it. Nearly all foundations of large structures have been extended through the colluvium and into bedrock. Expansive clay is one of the most serious problems in the colluvium; noncritical to marginal pressures of 1,500 and 3,100 psf were recorded for two samples, and cracks that show the effects of greater pressure were observed in many buildings. Another problem is seepage; sump pumps are installed in the basements of some houses. The large amount of sulfate in the seepage has necessitated the use of type 2 or type 5 sulfate-resistant cement in the concrete used over colluvium. Susceptibility to frost action is medium to very high. Plasticity index versus liquid limit is shown in figure 58. Some physical properties of the colluvium are given in the following table.

Summary of some physical tests of colluvium

	Number of tests	Average	Range
Specific gravity g/cc			2. 77
Maximum density, AASHO modified compaction lb per cu ft	5	111. 5	108. 4–113. 7
Optimum moisture percent	5	16. 1	14. 9–17. 8
Laboratory California Bearing Ratio at 90 percent maximum density	12	4. 0	3. 1–5. 6
pH	2	7. 67	7. 59–7. 75
AASHO classification		A–6	A–4, A–6, A–7
Unified Soil Classification symbol			CL, ML

POST-PINEY CREEK ALLUVIUM

Post-Piney Creek alluvium of late Holocene age crops out only along Fountain Creek and the Arkansas River. It forms two terraces as much as 20 feet above modern streams, both of which could be covered by larger floods. How much of the 30-foot thickness of alluvium in the Arkansas River channel is post-Piney Creek in age is unknown; but the upper part has been rearranged by modern stream scour, and only the lower half or so can possibly be of Piney Creek age. The alluvium consists of silt, sand, and gravel.

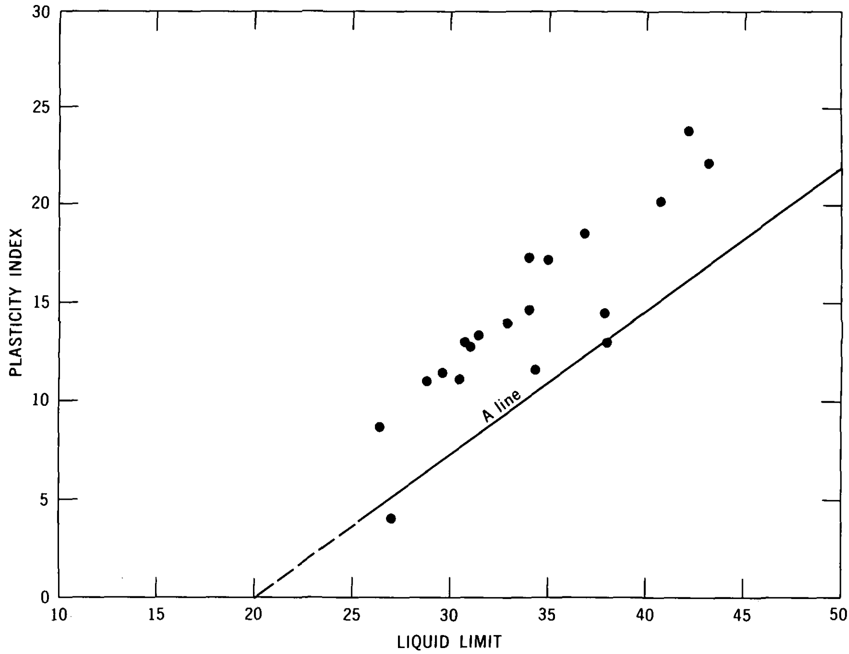


FIGURE 58.—Plasticity index versus liquid limit for 20 samples of colluvium.

Post-Piney Creek alluvium is grayish-brown well-stratified loose humic silt and sand in the upper part and yellowish-gray or yellowish-brown pebble or cobble gravel in the lower part. The gravel along Fountain Creek is finer grained than that along the Arkansas River. A size-distribution curve (fig. 59) of sandy silt shows that it contains 61 percent combined clay and silt, 34 percent sand, 2 percent granules, and 3 percent pebbles. A sample of the overbank silty sand along the Arkansas River is labeled "Coarse-grained sample" in figure 59 and shows about 4 percent clay, 20 percent silt, 75 percent sand, and 1 percent granules. A size-distribution curve (fig. 59) of gravel from the Arkansas River valley shows that it contains 3 percent combined clay and silt, 44 percent sand, 17 percent granules, 31 percent pebbles, and 5 percent cobbles. Gravel from the Arkansas River that was examined by the U.S. Bureau of Reclamation (written commun., 1950) contains 30 percent particles coated by firmly bonded calcium carbonate. About 12 percent is unsound particles; 9 percent is composed of dacite, latite, rhyolite, andesite, and opaline and chalcedonic sandstone.

Engineering geology.—The only engineering problem expected in the post-Piney Creek alluvium is flood hazard. In the great flood of 1921, water was 10–20 feet deep over post-Piney Creek alluvium

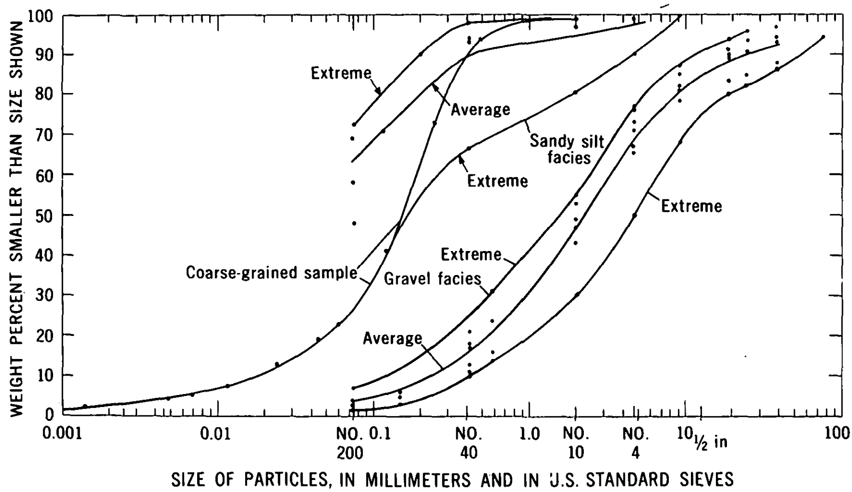


FIGURE 59.—General size-distribution characteristics of typical samples of sandy silt and gravel facies of post-Piney Creek alluvium. Coarse-grained sample is overbank silty sand from Arkansas River valley. Samples of gravel facies also are from Arkansas River valley.

along most of the Arkansas River valley, and new sediment now mapped as post-Piney Creek alluvium was deposited on the terraces. An accurate measurement of the depth of scour and the amount of reworking of older deposits by floodwater of the Arkansas River was reported by Herbert Snow (oral commun., 1963) of the Fountain Sand & Gravel Co. Mr. Snow stated that, in the gravel pit south of the river in sec. 6, T. 21 S., R. 64 W., a bed of silt 3–5 feet thick overlies the gravel, which has a nearly uniform thickness of 22 feet and at its base shows no marked channels into bedrock. The silt and the upper part of the gravel are younger than the 1921 flood, for two 9-foot-high flatbed coal cars that had been swept away and buried by the flood were excavated later from beneath the silt. The depth of burial indicates that the river scoured more than 14 feet and probably almost 20 feet during the flood. Thus, the river scoured about one-half the depth of its present channel, which is inferred from nearby boreholes to be about 30 feet deep.

Excavation of the alluvium is easy with either hand or power tools. Steep slopes will fail after a short time but stabilize at about 10°–20°. The water table is shallow over much of the flood plain and might locally prevent the use of deep basements.

Foundation stability is poor to good on the sandy silt, for which the Unified Soil Classification symbols are SC, CL, and ML. Foundation stability is good on the gravel. The excavated sandy silt should not be applied as base material directly below pavement or other wearing course. Beneath the streets along the west side of Fountain Creek some trouble was caused by the silt, owing partly to poor drainage. Frost susceptibility is slight to very high. Plasticity index versus liquid limit is shown in figure 51. Some physical properties of the gravel are given in the following table.

Summary of some physical tests of post-Piney Creek alluvium-gravel facies

	Number of tests	Average	Range
Specific gravity g/cc	2	2. 61	
Maximum density, AASHO modified compaction lb per cu ft	2	120. 2	115. 5–125. 0
Optimum moisture percent	2	10. 5	6. 9–14. 1
Laboratory California Bearing Ratio at 90 percent maximum density	8	7. 1	2. 7–11. 0
Los Angeles abrasion percent wear	4	34. 6	33. 6–35. 9
Absorption percent	6	0. 6	0. 4–0. 8
Freeze and thaw soundness, 5 cycles percent loss	3	4. 97	2. 3–6. 86
Stabilometer, R value		77	
AASHO classification		A–4	A–4, A–6
Unified Soil Classification symbol			SW, SM

The gravel from the Arkansas River is suitable for concrete or bituminous aggregate, road metal, subbase, and base course material. Owing to the presence of unsound and possibly deleterious particles for use as concrete aggregate, the U.S. Bureau of Reclamation (written commun., 1950) recommends the addition of low-alkali cement and proper amounts of entrained air. The gravel from Fountain Creek possibly is unsuitable as concrete aggregate because it is too fine grained, but it is satisfactory for other uses.

ARTIFICIAL FILL

Artificial fill underlies many manmade structures, and it fills low areas as waste. The greatest amount of fill (called embankment) is used in grades of railroads and roads. Many small patches of fill are old trash dumps.

Most of the embankment is compacted or noncompacted material excavated from deposits that surround construction sites. The excavated material generally consists of sand, silt, and clay, which under highways is compacted to maximum density under conditions of optimum moisture. Embankment contains no large stones, timbers, or trash and thus makes stable foundations for railroads or roads. Great care must be taken to prepare special design for any building that is founded partly on embankment and partly on natural ground. If proper precautions are not taken, differential settlement can take place.

Trash dumps were mapped wherever the locations were known to me or to the City Engineer; undoubtedly, some were missed and will not be found until building excavations are made. Dumps are uncompacted; therefore, great amounts of settlement are expected. The best way to avoid engineering problems is to place foundation piers in stable material below the trash.

STRUCTURAL GEOLOGY

The principal local structural features in the Pueblo area are the Rock Canyon and Pueblo anticlines, which are separated by a broad asymmetric syncline (pl. 1). Minor structural bends and breaks in the rocks include a postulated gentle fold southeast of Baculite Mesa and several faults on Rock Canyon anticline where the rocks have shifted 20 feet or so. The regional dip of rocks in this area is 70–300 feet per mile to the northeast. Folds such as the Rock Canyon anticline are minor flexures on this broad regional trend. Subsurface segments of the above structures are shown in the cross sections on the geologic map (pl. 1).

The Rock Canyon anticline is a broad asymmetric gentle doubly plunging fold that raises the rocks several hundred feet above the height they would be if affected only by the regional dip. The west flank is steeper than the east flank. Only part of the anticline is exposed in the Northwest Pueblo quadrangle; the anticline is about 4 miles wide and 14 miles long and extends north and south of the mapped area. To the north it joins the Turkey Creek or Red Creek anticline. To the south an extension of the Rock Canyon anticline has been called the Columbia Heights anticline. Several test holes have penetrated the Rock Canyon anticline, but none has produced oil or gas.

The Pueblo anticline is a low, narrow northward-plunging fold along which Fountain Creek is superimposed. This anticline raises the rocks more than 100 feet above where they would be if affected only by the regional dip. The fold extends several miles north and south of the area mapped; its exact extent is unknown because these areas have not been mapped in detail. The high hills along Fountain Creek east of the center of town are erosional remnants of the upper chalk unit of the Niobrara Formation uplifted by the Pueblo anticline. No information concerning the potential value of this anticline for oil and gas is available; also, no test holes are known.

A minor anticline was postulated in sec. 11, T. 20 S., R. 64 W., as a result of mapping the faunal zones in the Pierre Shale. The zones of a tightly coiled *Didymoceras* n. sp. and of *D. nebrascense* suggested a flattening of dip; subsequent examination of the shale revealed reversals of dip that coincide with the outcrop patterns of the faunal zones. The rocks appear to be uplifted more than 100 feet by the fold. A dry hole of the Berry Hollow 1 lies just east of the fold, but no test holes are known at the crest of the surface expression of the fold.

About 20 minor faults are mapped; none has more than 50 feet of stratigraphic throw or extends much more than 1 mile. Three northeastward-trending faults, in secs. 25, 35, and 36, T. 20 S., R. 66 W., at Rock Canyon anticline, possibly are three segments of a single fault, but they cannot be confidently connected because of a cover of surficial deposits. Faults are most common along the middle and upper chalk units of the Niobrara Formation. North of U.S. Highway 50 the middle chalk is repeatedly faulted (faults not mapped); but each fault has small displacement, and the faults tend to cancel each other in net stratigraphic throw.

The age of the folds and faults is considered to be Laramide (Late Cretaceous and early Tertiary), the same as the age of major uplift of the Wet Mountains and the Rampart Range.

GEOLOGIC HISTORY

The geologic history of the Pueblo area is simple because most of the events that complicated the history of the adjacent mountains did not substantially affect the Pueblo area. At Pueblo three major events took place: (1) deposition of sediments in a large shallow interior ocean; (2) uplift of the land surface, deposition of nonmarine sediments, and folding and faulting coincident with formation of the Rocky Mountains; (3) erosion of previously deposited sedimentary rocks, formation of modern drainage network, and deposition of a thin veneer of stream and windblown deposits.

The earliest event represented by deposits near Pueblo is the widespread submergence of the area beneath a Cretaceous sea. A variety of creatures that are now extinct lived in this sea. It covered the area during deposition of the Dakota Sandstone through deposition of the Trinidad Sandstone, which overlies the Pierre Shale elsewhere but is no longer present at Pueblo. The Rocky Mountains began to rise far to the west in latest Cretaceous time, probably during deposition of the youngest part of the Pierre Shale; after the Trinidad Sandstone was deposited, the sea gradually drained away to the south and the mountains began to rise nearby. All the folds and faults were formed in

Late Cretaceous and early Tertiary time as the Wet Mountains and Rampart Range were rising to the west. Probably in early Tertiary time the Trinidad Sandstone was removed by erosion, and then Tertiary rocks, including at least the Ogallala Formation of Miocene(?) and Pliocene age, were deposited on a surface cut across the Pierre Shale. During late Pliocene time and earliest Pleistocene (pre-Nussbaum) time about 500 feet of sedimentary rocks was removed from the Pueblo area. The nearest outcrop of Ogallala Formation east of Pueblo is 120 miles away on the east side of Big Sandy Creek. The area northeast of Pueblo shown as Ogallala on the geologic map of Colorado (Burbank and others, 1935) is mostly alluvium of early Pleistocene age (Scott, 1963a, p. C50).

At the onset of Pleistocene (Ice Age) time the Arkansas River was flowing through the area a few miles south of its present course, as indicated by ancient stream gravel in the Southeast Pueblo quadrangle. Ancestral Fountain Creek was depositing the Nussbaum Alluvium on Baculite Mesa or was flowing nearby. During subsequent stages of the Pleistocene, the Arkansas River gradually moved northward and cut downward. Fountain Creek flowed in virtually its present position throughout the Pleistocene. Pediments of four ages were cut across bedrock in pre-Bull Lake time by small streams as they shifted laterally in their channels. During each of the four stages of pedimentation, alluvium was deposited on the gently sloping pediment surfaces and on broad flood plains along the major streams. Because of a progressive but cyclic lowering of base level resulting from regional climatic change, each successive pediment and terrace (remnant of flood plain) is lower than the preceding one. In Bull Lake time and later, five more flood plains formed, and again each flood plain remnant or terrace is lower than the preceding one. In early Holocene time, the wind blew sand out of the flood plains and up onto the upland.

The landscape that resulted from the foregoing events is gently rolling where underlain by soft rocks and marked by sharp bluffs where underlain by hard rocks. Steep bluffs are formed by the gravel mantle on dissected terraces and pediments. Most valleys are broad and shallow.

ECONOMIC GEOLOGY

Economic resources in the bedrock near Pueblo include limestone, clay, riprap, ornamental stone, and structural and dimension stone. The surficial deposits contain gravel, sand, and ornamental stone. Oil and gas have not been found, but perhaps the favorable anticlines near Pueblo have not been thoroughly tested.

LIMESTONE

Three limestone beds are potential sources for agricultural lime, foundry lime, flux for the manufacture of steel, and cement rock. The Fort Hays Limestone Member of the Niobrara Formation has been used for all these purposes, and great reserves are available very close to the railroad at Pueblo. An analysis of the limestone is given by Gilbert (1897, p. 7, No. 1 in table). The Bridge Creek Limestone Member of the Greenhorn Limestone is harder than the Fort Hays Limestone and contains more shale partings; but it also contains large reserves, although not so great as the Fort Hays, owing to smaller area of outcrop. The lower limestone unit of the Smoky Hill Shale Member of the Niobrara Formation is a large potential source of rock for the manufacture of portland cement. At Portland the lower limestone and the underlying lower shale, shale and limestone units, and the Fort Hays Limestone Member have all been used for the manufacture of portland cement. An additional source of limestone, the large masses of tepee butte limestone in the Tepee zone of the Pierre Shale, might be usable as crushed stone for road metal. An analysis of tepee butte limestone is given by Gilbert (1897, p. 7, No. 7 in table).

CLAY

Clayey shale at Pueblo has been used for many years as raw material for the manufacture of brick and tile. All the brick plants at Pueblo use shale from the transition member of the Pierre Shale, which has a large area of outcrop along Fountain Creek. Other parts of the Pierre Shale and probably of the Graneros Shale would be suitable for low-grade refractory products. Another potential use of the Pierre and Graneros Shales is in the manufacture of lightweight aggregate from expanded shale.

RIPRAP

Riprap is defined as any material that will protect artificial earthen fills from erosion. The material for this use must be relatively sound and free from impurities, cracks, and other structural defects that would cause it to disintegrate through erosion, slaking, or freeze-and-thaw. Blocks of riprap should have approximately rectangular faces, 7 inches or more in width.

Potential sources of riprap near Pueblo are Dakota Sandstone, Bridge Creek Limestone Member, Fort Hays Limestone Member, and conglomerate beds in the surficial deposits. Certain parts of the Dakota, Bridge Creek, and Fort Hays were tested by the U.S. Bureau of Reclamation (written commun., 1950); (see details under each formation) and were found to be unsuitable as riprap. Whether the layers tested are representative of the whole of each formation is unknown. Conglomerate layers at the base of the Slocum and Nussbaum Alluviums are available in small quantities and possibly are usable as riprap.

ORNAMENTAL STONE

Any stone that can be used for decoration such as facing, for planters, or for rock gardens is here called ornamental stone. For this purpose, angularity and an antique appearance including a coating of moss or lichens is advantageous. Potential sources are the Dakota Sandstone and blocks of conglomerate in the Nussbaum Alluvium. At the south end of Baculite Mesa, blocks of conglomerate several feet in maximum dimension are common on the slope below the base of the Nussbaum.

STRUCTURAL AND DIMENSION STONE

Structural stone is any hard dense rock that can be quarried and cut to a desired size and shape. Among stones used for this purpose are Dakota Sandstone, Codell Sandstone Member, Fort Hays Limestone Member, and blocks of conglomerate from the Slocum Alluvium. The use and performance of these stones are described under each formation. Apparently, no naturally occurring dimension stone has been used in construction at Pueblo since the 1930's.

GRAVEL AND SAND

Gravel and sand probably are the most valuable economic resources at Pueblo. They are used for concrete aggregate, bituminous aggregate, road metal, base, subbase, mortar and plaster sand, and for many other purposes. Potential sources of gravel are the Nussbaum, Rocky Flats, Verdos, Slocum, Louviers, Broadway, Piney Creek, and post-Piney Creek Alluviums. Sand is available in the eolian sand. As a general rule, all Nussbaum, Rocky Flats, Verdos, and other alluvium along or derived from Fountain Creek are finer grained (coarse sand size containing some pebbles) than alluvium derived from the Arkansas River. Also, alluvial deposits of Louviers and younger age are composed of harder less weathered stones and contain less clay and calcium carbonate cement than the pre-Bull Lake deposits; hence, they are more suitable for use as concrete aggregate. Size-distribution graphs, pebble counts showing composition, and the results of other physical tests are listed under each formation.

SUMMARY OF ENGINEERING BEHAVIOR OF GEOLOGIC UNITS AT PUEBLO

The following table gives the geologic units at Pueblo and summarizes the excavation and foundation characteristics that could cause engineering problems.

Summary of engineering behavior of geologic units at Pueblo

Rock name	Rock type	Characteristics that could cause engineering problems	
		Excavation	Foundation
Artificial fill.	Sand, silt, and clay; also trash.	None.	Potential settlement in noncompacted fill and trash; frost susceptibility.
Post-Piney Creek alluvium.	Silt and sand; gravel.	Partly below water table.	Slight clayiness; slight to high frost susceptibility; widespread flood hazard.
Colluvium.	Clay and silt.	None.	Clayiness; frost susceptibility; seeps swell potential; sulfate reaction.
Piney Creek Alluvium.	Clayey silt; gravel in trenches of major streams.	Partly below water table.	Clayiness; frost susceptibility; seeps; swell potential; potential settlement; sulfate reaction; local flood hazard.
Eolian sand.	Silty sand.	None.	Apparent poor bearing capacity owing to partial collapse under load; slight frost susceptibility; seeps; erosiveness.
Broadway Alluvium.	Silty pebbly sand; gravel.	None.	Fine-grained facies; Slight clayiness; slight frost susceptibility; seeps. Coarse-grained facies: None.
Louviers Alluvium.	Pebbly clay and silt; gravel.	None.	Fine-grained facies: Clayiness; frost susceptibility; seeps; sulfate reaction. Coarse-grained facies: None.
Slocum Alluvium.	Pebbly clay and silt; gravel.	Contains local hard conglomerate at base.	Fine-grained facies; Clayiness; frost susceptibility; seeps; sulfate reaction; erosiveness. Coarse-grained facies: None.
Verdos Alluvium.	Clayey coarse sand.	None.	Clayiness; frost susceptibility; seeps; sulfate reaction; erosiveness.
Rocky Flats Alluvium.	Clayey coarse sand.	None.	Clayiness; frost susceptibility; seeps; sulfate reaction; erosiveness.
Nussbaum Alluvium.	Coarse sand.	Contains local hard conglomerate at base.	Clay bond between particles; frost susceptibility; seeps; erosiveness.
Tepee zone.	Silty and clayey shale.	Clayiness; tepee butte limestone masses may require blasting.	Clayiness; frost susceptibility; low permeability; seeps; sulfate reaction; erosiveness; swelling shale.
Rusty zone.	Silty and clayey shale.	Clayiness.	Clayiness; frost susceptibility; low permeability; seeps; sulfate reaction; erosiveness; swelling shale and bentonite beds.
Sharon Springs Member.	Silty shale.	Contains large hard concretions.	Frost susceptibility; low permeability; sulfate reaction; swelling bentonite beds.
Apache Creek Sandstone Member.	Sandy shale.	Contains large concretions and hard layers.	Frost susceptibility; low permeability; seeps; strong sulfate reaction; erosiveness; swelling shale.

Summary of engineering behavior of geologic units at Pueblo—Continued

Rock name	Rock type	Characteristics that could cause engineering problems	
		Excavation	Foundation
Transition member.	Clayey and silty calcareous shale.	None.	Frost susceptibility; low permeability; seeps; sulfate reaction; erosiveness; swelling shale and bentonite beds.
Upper chalk unit.	Clayey chalk.	Hardness may necessitate ripping or breaking.	Frost susceptibility where weathered.
Upper chalky shale unit.	Clayey chalky shale.	Local hard layers.	Frost susceptibility; low permeability; seeps; sulfate reaction; erosiveness; swelling shale and bentonite beds.
Middle chalk unit.	Slightly clayey chalk.	Hardness may necessitate ripping or breaking below depth of 10 ft.	Frost susceptibility where weathered.
Middle shale unit.	Silty calcareous shale.	Local hard beds.	Frost susceptibility; low permeability; seeps; sulfate reaction; erosiveness; swelling shale and bentonite beds.
Lower limestone unit.	Limestone and shale.	Hardness probably will necessitate ripping or breaking below depth of 10 ft.	Frost susceptibility in weathered zone; seeps; sulfate reaction; swelling shale and bentonite beds.
Lower shale unit.	Hard shale.	Hardness may necessitate ripping or breaking below depth of 10 ft.	Frost susceptible in weathered zone; low permeability; seeps; sulfate reaction; swelling shale and bentonite beds.
Shale and limestone unit.	Shale and limestone.	Hardness necessitates breaking and blasting of entire unit.	Frost susceptible in shale partings; seeps; sulfate reaction; swelling shale and bentonite beds.
Fort Hays Limestone Member.	Hard limestone.	Hardness necessitates breaking and blasting of entire member.	Seeps; rockfalls.
Codell Sandstone Member.	Sandstone.	Hardness necessitates breaking and blasting of entire member.	Seeps; rockslides.
Blue Hill Shale Member.	Silty shale.	Deep cuts may require ripping or blasting. Contains large hard concretions.	Frost susceptibility; low permeability; sulfate reaction; swelling shale and bentonite beds; rockslides.
Fairport Chalky Shale Member.	Chalky clayey shale.	Deep cuts may require ripping or blasting. Contains hard beds near base.	Frost susceptibility; low permeability; sulfate reaction; erosiveness; swelling shale and bentonite beds.
Bridge Creek Limestone Member.	Hard limestone and shale.	Hardness necessitates breaking and blasting of limestone beds.	Frost susceptibility of shaly beds; swelling shale and bentonite beds.
Hartland Shale Member.	Silty shale.	Deep cuts may require ripping or blasting.	Frost susceptibility; seeps; sulfate reaction; erosiveness; swelling shale and bentonite beds.
Lincoln Limestone Member.	Silty shale and thin limestone beds.	Deep cuts may require ripping or blasting. Contains some thin hard beds.	Frost susceptibility; seeps; sulfate reaction; erosiveness; swelling shale and bentonite beds.

Summary of engineering behavior of geologic units at Pueblo—Continued

Rock name	Rock type	Characteristics that could cause engineering problems	
		Excavation	Foundation
Graneros Shale.	Shale.	Deep cuts may require ripping or blasting. Contains large hard concretions.	Frost susceptibility; low permeability; seeps; sulfate reaction; erosiveness; swelling shale and bentonite beds.
Dakota Sandstone.	Sandstone.	Hardness necessitates breaking and blasting.	None.

REFERENCES CITED

Allen, Harold, chm., 1945, Report of committee on classification of materials for subgrades and granular type roads: Natl. Research Council, Highway Research Board 25th Ann. Mtg. Proc., p. 375–388.

Asphalt Institute, 1961, Soils manual for design of asphalt pavement structures, 1st ed.: College Park, Md., Asphalt Inst., Manual Ser. 10, 176 p.

Bass, N. W., 1926, Geologic investigations in western Kansas, with special reference to oil and gas possibilities; pt. 2, Geology of Hamilton County: Kansas Geol. Survey Bull. 11, 95 p.

Burbank, W. S., Lovering, T. S., Goddard, E. N., and Eckel, E. B., 1935, Geologic map of Colorado: U.S. Geol. Survey, scale 1:500,000; repr., 1959.

Cobban, W. A., and Scott, G. R., 1964, Multinodose scaphitid cephalopods from the lower part of the Pierre Shale and equivalent rocks in the conterminous United States: U.S. Geol. Survey Prof. Paper 483–E, 13 p.

Cobban, W. A., Scott, G. R., and Gill, J. R., 1962, Recent discoveries of the Cretaceous ammonite *Haresiceras* and their stratigraphic significance, *in* Geological Survey research 1962: U.S. Geol. Survey Prof. Paper 450–B, p. B58–B60.

Cragin, F. W., 1896, On the stratigraphy of the Platte series, or Upper Cretaceous of the plains: Colorado Coll. Studies, v. 6, p. 49–52.

Dane, C. H., and Pierce, W. G., 1933, Geology and oil and gas prospects in part of eastern Colorado: U.S. Dept. Interior Press Memo. 72215, 8 p.

Elias, M. K., 1931, The geology of Wallace County, Kansas: Kansas Geol. Survey Bull. 18, 254 p.

Follansbee, Robert, and Jones, E. E., 1922, The Arkansas River flood of June 3–5, 1921: U.S. Geol. Survey Water-Supply Paper 487, 44 p.

Follansbee, Robert, and Sawyer, L. R., 1948, Floods in Colorado: U.S. Geol. Survey Water-Supply Paper 997, 151 p.

Gilbert, G. K., 1896, The underground water of the Arkansas Valley in eastern Colorado: U.S. Geol. Survey 17th Ann. Rept. pt. 2, p. 551–601.

——— 1897, Description of the Pueblo quadrangle [Colorado]: U.S. Geol. Survey Geol. Atlas, Folio 36.

Hunt, C. B., 1954, Pleistocene and Recent deposits in the Denver area, Colorado: U.S. Geol. Survey Bull. 996–C, p. 91–140.

Hunter, H. M., 1963, Deterioration of hardened concrete by sulfate waters: U.S. Bur. Reclamation, Chem. Eng. Rept. CH–109, 11 p.

International Conference of Building Officials, 1964, Uniform building code, 1964 ed.: v. 1, 503 p.

Lambe, T. W., 1960, The character and identification of expansive soils: Washington, Federal Housing Adm. Tech. Studies Rept. FHA-701, 51 p.

Lavington, C. S., 1933, Montana group in eastern Colorado: Am. Assoc. Petroleum Geologists Bull., v. 17, no. 4, p. 397-410.

Logan, W. N., 1897, The upper Cretaceous of Kansas: Kansas Geol. Survey, v. 2, p. 195-234.

McGovern, H. E., Gregg, D. O., and Brennan, Robert, 1964, Hydrogeologic data of the alluvial deposits in Pueblo and Fremont Counties, Colorado: Colorado Water Conserv. Board Basic-Data Release 18, 27 p.

Meek, F. B., and Hayden, F. V., 1862, Descriptions of new Lower Silurian (Primordial), Jurassic, Cretaceous, and Tertiary fossils, collected in Nebraska Territory, with some remarks on the rocks from which they were obtained: Acad. Nat. Sci. Philadelphia Proc., 1861, p. 415-447.

Mudge, B. F., 1877, Notes on the Tertiary and Cretaceous periods of Kansas: U.S. Geol. Geog. Survey Terr. (Hayden) 9th Ann. Rept., p. 277-294.

Rankin, C. H., Jr., 1944, Stratigraphy of the Colorado group, Upper Cretaceous, in northern New Mexico: New Mexico School Mines Bull. 20, 27 p.

Roberts, D. V., Schroter, G. A, Seeman, Roy, and Baumann, Paul, 1965, The urban threat to the sand and gravel industry: Los Angeles, Calif., Dames and Moore, Eng. Bull. 29, 17 p.

Rosa, J. M., 1954, The hydrology of upstream flood prevention, upper Arkansas River, Colorado: U.S. Forest Service [unpub. mimeo. rept. available at U.S. Geol. Survey, Denver, Colo.].

Rubey, W. W., and Bass, N. W., 1925, The geology of Russell County, Kansas, with special reference to oil and gas resources: Kansas Geol. Survey Bull. 10, p. 1-86.

Schultz, L. G., 1964, Quantitative interpretation of mineralogical composition from X-ray and chemical data for the Pierre Shale: U.S. Geol. Survey Prof. Paper 391-C, 31 p.

Scott, G. R., 1960, Subdivision of the Quaternary alluvium east of the Front Range near Denver, Colorado: Geol. Soc. America Bull., v. 71, no. 10, p. 1541-1543.

——— 1963a, Nussbaum Alluvium of Pleistocene(?) age at Pueblo, Colorado, *in* Geological Survey research 1963: U.S. Geol. Survey. Prof. Paper 475-C, p. C49-C52.

——— 1963b, Quaternary geology and geomorphic history of the Kassler quadrangle, Colorado: U.S. Geol. Survey Prof. Paper 421-A, p. 1-70.

——— 1964, Geology of the Northwest and Northeast Pueblo quadrangles, Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I-408.

Scott, G. R., and Cobban, W. A., 1962, *Clioscaphites saxitonianus* (McLearn), a discrete ammonite zone in the Niobrara Formation at Pueblo, Colorado, *in* Geological Survey research 1962: U.S. Geol. Survey Prof. Paper 450-C, p. C85.

——— 1963, Apache Creek Sandstone Member of the Pierre Shale of southeastern Colorado, *in* Geological Survey research 1963: U.S. Geol. Survey Prof. Paper 475-B, p. B99-B101.

——— 1964, Stratigraphy of the Niobrara Formation at Pueblo, Colorado: U.S. Geol. Survey Prof. Paper 454-L, 30 p.

327-617 O—69——9

Spivey, R. S., 1940, Bentonite in southwestern South Dakota: South Dakota Geol. Survey Rept. Inv. 36, 56 p.

Stanton, T. W., 1893, The Colorado formation and its invertebrate fauna: U.S. Geol. Survey Bull. 106, 288 p. [1894].

Stokes, W. L., and Varnes, D. J., 1955, Glossary of selected geologic terms with special reference to their use in engineering: Colorado Sci. Soc. Proc., v. 16, 165 p.

U.S. Army, 1952, Geology and its military applications: Tech. Manual 5-545, 356 p.

U.S. Army and U.S. Air Force, 1963, Control of soils in military construction: Tech. Manual 5-541 (Air Force Manual 88-52), 74 p.

U.S. Army Corps of Engineers, 1953, The unified soil classification system: Tech. Memo. 3-357, v. 1 and 3, 30 p.

U.S. Bureau of Reclamation, 1960, Earth manual—A guide to the use of soils as foundations and as construction materials for hydraulic structures: Denver, Colo., U.S. Bur. Reclamation, 751 p.

Varnes, D. J., and Scott, G. R., 1967, General and engineering geology of the United States Air Force Academy Site, Colorado, *with a section on* Ground water, by W. D. E. Cardwell and E. D. Jenkins: U.S. Geol. Survey Prof. Paper 551, 93 p.

Vaudrey, W. C., 1960, Floods of May 1955 in Colorado and New Mexico: U.S. Geol. Survey Water-Supply Paper 1455-A, p. 1-68.

Wentworth, C. K., 1922, A scale of grade and class terms for clastic sediments: Jour. Geology, v. 30, no. 5, p. 377-392.

Wiitala, S. W., Jetter, K. R., and Sommerville, A. J., 1961, Hydraulic and hydrologic aspects of flood-plain planning: U.S. Geol. Survey Water-Supply Paper 1526, 69 p.

Williston, S. W., 1893, The Niobrara Cretaceous of western Kansas: Kansas Acad. Sci. Trans., v. 13, p. 107-111.

INDEX

[Italic page numbers indicate major references]

PLATE 2

PLATE 2

Types of fossils that are characteristic of the Cretaceous rocks at Pueblo, Colo. All fossils illustrated are one-half their actual size.

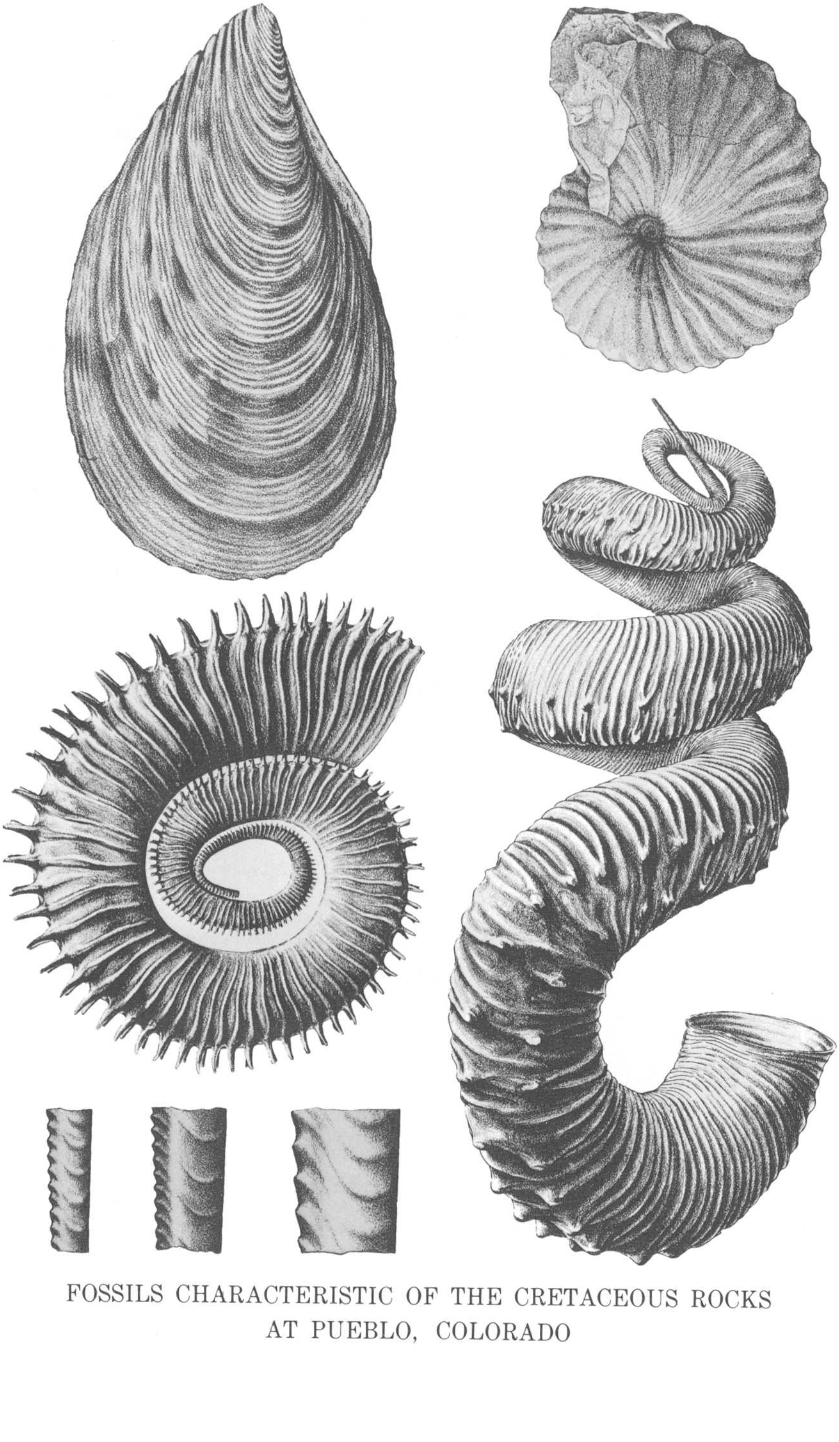
Upper Left: A clam, *Inoceramus labiatus* (Schlotheim), from the upper part of the Bridge Creek Limestone Member (drawing by C. C. Capraro).

Upper right: A normally coiled ammonite, *Metoicoceras whitei* Hyatt, from the lower part of the Bridge Creek Limestone Member (copied from Stanton, 1893, pl. 38, fig. 2).

Middle left: A flat coiled clock-springlike ammonite, *Exiteloceras jenneyi* (Whitfield), from the middle part of the Pierre Shale (drawing by J. R. Stacy).

Lower left: A completely uncoiled straight ammonite, *Baculites perplexus* Cobban, from the lower part of the Pierre Shale (drawing by C. C. Capraro).

Lower right: A helically coiled ammonite, *Didymoceras nebrascense* (Meek and Hayden), from the middle part of the Pierre Shale (drawing by J. R. Stacy).



FOSSILS CHARACTERISTIC OF THE CRETACEOUS ROCKS
AT PUEBLO, COLORADO