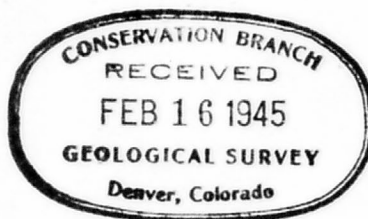
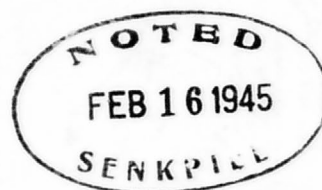


C O P Y

Geologic features of certain dam sites  
in the  
Bear River, Colorado River, and Rio Grande basins,  
1936-37  
by

Arthur M. Piper

45-43



## N O T E

The depth to bed rock as determined by resistivity measurements at the following named damsites is given in a report by H. Cecil Spicer filed in D-100, 9-E-13, and entitled Estimates of Depth to Bed Rock at Some Dam Sites in the Gunnison, Little Colorado, and Zuni River Basins, Colorado and Arizona, based on Resistivity Measurements 1938-1939:

### Lake Fork of Gunnison River

Independence Damsite  
The Gate           "  
Riverside School   "  
Medeira           "

### Little Colorado and Zuni Rivers, Arizona

Lower Zuni damsite  
Little Colorado River damsite  
Greer                   "



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Geologic features of certain dam sites in the  
Bear River, Colorado River, and  
Rio Grande basins, 1936-37

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By Arthur M. Piper

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Introduction

This report describes the pertinent geologic features at 24 potential dam sites in the basins of the Bear River in Utah and Wyoming, the Colorado River in Colorado and Arizona, and the Rio Grande in New Mexico. It is based on field examinations made in the periods November 2-24, 1936, and from April 20 to May 12, 1937. Previously, the topography of the dam sites and of the corresponding reservoir sites had been mapped under the supervision of W. C. G. Senkpiel through allocations of funds by the Public Works Administration to the Geological Survey for river-utilization surveys.

The field examinations have sought to evaluate the bearing power and watertightness of the rocks at each dam site, also to place broad limits on the types of structures for which each is best suited. Because no test pits have been dug nor exploratory holes drilled at any of the sites, the geologic features have been interpreted wholly from natural outcrops and from a few road cuts. Since the outcrops are fairly extensive, it is believed that the major features related to the construction and maintenance of dams are adequately known. However, minor features remain to be explored before construction could be undertaken. Though the reservoir sites were not examined in detail, passing attention was given to their broad features to which watertightness and volume of bank storage are related.



All the sites are in regions which have slight or moderate hazard of earthquake shocks, so that any dams should be designed to withstand stresses so created. This is true especially of the sites in New Mexico, for 19 earthquakes with intensities exceeding 5 on the Rossi-Forrel scale were recorded in that State in the period 1868-1927<sup>1</sup>. For most of these earthquakes the epicenters were in the vicinity of Socorro.

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<sup>1</sup>/ Heck, N. H., Earthquake history of the United States, exclusive of the Pacific region: U. S. Coast & Geodetic Survey, Spec. Pub. no. 149, pp. 49-50, 1928.

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The 24 dam sites are listed below:

#### Bear River Basin

##### Yellow Creek, Summit County, Utah

Yellow Creek site; secs. 33 and 34, T. 5 N., R. 8 E.; by road,  
13.1 miles southwest of the post office at Evanston, Wyoming

##### Bear River, Uinta County, Wyoming

Woodruff Narrows upper site; in the NW $\frac{1}{4}$  sec. 32, T. 18 N.,  
R. 120 W.; by highway (State 65), road, and lane, 19.8 miles  
north of the post office at Evanston

Woodruff Narrows lower site; in the S $\frac{1}{2}$  sec. 20, T. 18 N.,  
R. 120 W.; by highway, road, and trail, about 22 $\frac{1}{2}$  miles north  
of the post office at Evanston

#### Colorado River Basin, Gunnison and Hinsdale Counties, Colorado

##### East River (headwater fork of Gunnison River)

East River site (no. 40); in the W $\frac{1}{2}$  sec. 15, T. 51 N., R. 1 E.;  
by highway (State 135), 11.9 miles north of the post office  
at Gunnison

##### Gunnison River

Almont site (no. 50); in the NW $\frac{1}{4}$  sec. 27, T. 51 N., R. 1 E.; by  
highway (State 135), 9.8 miles north of the post office at  
Gunnison

North Beaver upper site (no. 3A); in the SW $\frac{1}{4}$  sec. 24, T. 49 N.,  
R. 2 W.; by highway (US 50), 7.5 miles west of the post office  
at Gunnison

North Beaver middle site (no. 2A); in the SE $\frac{1}{4}$  sec. 23 and the  
NE $\frac{1}{4}$  sec. 26, T. 49 N., R. 2 W.; by highway (US 50), 8.2 miles  
west of the post office at Gunnison

Colbrado River Basin, Gunnison and Hinsdale Counties, Colorado - Con.

Gunnison River - Continued

North Beaver lower site (no. 1A); in the SW $\frac{1}{4}$  sec. 23 and the NW $\frac{1}{4}$  sec. 26, T. 49 N., R. 2 W.; by highway (U S 50), 8.8 miles west of the post office at Gunnison

Lake Fork Junction site; in the SE $\frac{1}{4}$  sec. 31, T. 49 N., R. 4 W. and the NW $\frac{1}{4}$  sec. 4, T. 48 N., R. 4 W.; by highway (U S 50), 26.8 miles and 1.4 miles west of the post offices at Gunnison and Sapinero, respectively

Lake Fork of Gunnison River

Independence site; in the N $\frac{1}{2}$  sec. 2, T. 44 W.; by highways (U S 50 and State 149), 53.4 miles southwest of the post office at Gunnison and about 5 miles north of the post office at Lake City

The Gate site; in the SW $\frac{1}{4}$  sec. 7, T. 46 N., R. 3 W.; by highways, 40.8 miles southwest of the post office at Gunnison

Riverside School site; in the SW $\frac{1}{4}$  sec. 21, T. 47 N., R. 3 W.; by highways and road, 38.4 miles southwest of the post office at Gunnison

Madeira Siding site; in the NE $\frac{1}{4}$  sec. 17, T. 47 N., R. 3 W.; by highways, road, and railroad, 40.1 miles southwest of the post office at Gunnison and about 25 miles north of Lake City

Colorado River Basin, Apache and Navajo Counties, Arizona

Zuni River

Lower Zuni site; T. 14 N., R. 26 E., by road and wagon trail,  
21.1 miles northwest of the post office at St. Johns

Little Colorado River

Little Colorado site; secs. 20 and 21, T. 14 N., R. 27 E.; by  
road and wagon trail, 13.2 miles northwest of the post office  
at St. Johns

Greer site; sec. 5, T. 14 N., R. 25 E.; by highway (U S 260) and  
road, 29.8 miles and 15.2 miles northwest of the post offices  
at St. Johns and Concho, respectively

Forks site; sec. 19, T. 16 N., R. 22 E.; by highway (U S 260) and  
road, 14.5 miles south of the post office at Holbrook, 1.2 miles  
south of the post office at Woodruff

Woodruff site; sec. 36, T. 17 N., R. 21 E.; by highway and road,  
9.7 miles south of the post office at Holbrook

Holbrook site; sec. 14, T. 17 N., R. 21 E.; by highway and road,  
6.3 miles south of the post office at Holbrook

Rio Grande Basin, Tio Arriba County, New Mexico

Rio Chama

Cañon de Chama site; no public-land survey; by highway (U S 285)  
and lane, 22.0 miles and 44.8 miles northwest of the post  
offices at Abiquiu and Española, respectively

Abiquiu site; no public-land survey; by highway (U S 285), 7.4 miles  
and 30.2 miles northwest of the post offices at Abiquiu and  
Española, respectively

Rio Grande Basin - Continued.

Willow Creek

Willow Creek upper site (Rutherford site, after K. A. Heron); no public-land survey; by highway (U S 285) and roads, 17.0 miles southwest of the post office at Chama

Willow Creek middle site (Willow Creek site, after K. A. Heron); no public-land survey; by highway and roads, 19.0 miles southwest of the post office at Chama

Willow Creek lower site (Lower Rutherford site, after K. A. Heron); no public-land survey; by highway, road, and trail, 22.8 miles southwest of the post office at Chama

Bear River Basin, Utah-Wyoming

Yellow Creek dam site

As is indicated on plate 1, A, by the line marked "AB", the site on Yellow Creek affords only one position for a dam of economical size (pl. 2). At this position, a dam would rest wholly along the edge of a

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Plate 1.- A, Geologic map of the Yellow Creek dam site, Bear River basin; B, Explanation for geologic maps of dam sites in the Bear River basin, Utah-Wyoming.

Plate 2.- Yellow Creek dam site, viewed upstream.

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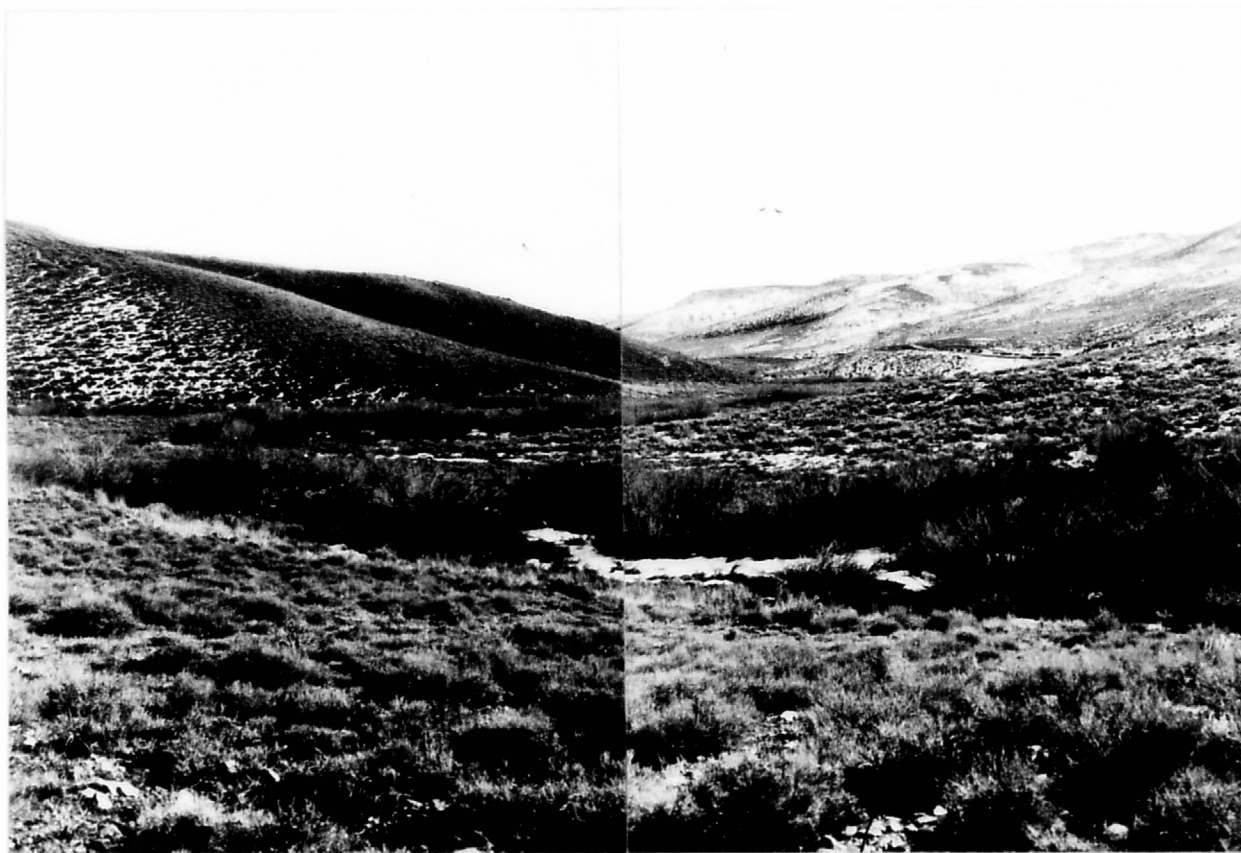
plate of the Beckwith formation thrust-faulted against the Almy formation. Thus the load-sustaining capacity and watertightness of the rocks in foundation and abutments depends in considerable part upon features caused by faulting. The fault, which is part of the great Medicine Butte overthrust mapped by Veatch \_\_/, has a stratigraphic displacement of several

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\_\_/ Veatch, A. C., Geography and geology of a portion of Southwestern Wyoming: U. S. Geol. Survey Prof. Paper 56, pl. 3, 1907.

---

thousand feet but has long been inactive. Its dip at the dam site cannot be determined satisfactorily from the discontinuous outcrops; the average dip in the vicinity appears to be about 70° NW. If this average holds at the site, the main fault plane either is warped or is offset along or near the stream by unrecognized secondary cross faults with the northern



Yellow Creek dam site, viewed upstream

block displaced eastward. (Two cross faults with such displacement occur just north of the area shown on plate 1, A.) The presence or absence of such secondary faults should be thoroughly explored by pits and trenches sunk through the alluvium of the flood plain and through the slope wash on the lower part of either abutment.



The Beckwith formation, which forms the upper or overthrust plate of the fault and is at the land surface over the downstream half of the area shown on plate 1, A, is composed of alternating members of sandstone, conglomerate, and shale. The sandstone members are gray or pinkish gray, massive or laminated, and commonly very dense owing to deposition of secondary silica in the fault zone. Some are nearly as dense as quartzite; others contain some gritty or pebbly lenses. These sandstone members are ledge-formers but are commonly only a few feet thick and so are not extensively exposed. The conglomerate members, which are few and thin at the dam site, are composed largely of chert pebbles no more than half an inch in diameter and embedded in a dense matrix. The shale members do not crop out at the site; from scant detritus and from remote outcrops they are inferred to be red in color, not laminated, and commonly not sandy. They are inferred further to make up half or two-thirds of the formation.

Along the line AB, which is from 200 to 500 feet downstream from the trace of the Medicine Butte fault, the Beckwith formation dips  $25^{\circ}$ - $50^{\circ}$  W. or NW. (downstream). Its inflexible members, sandstone and conglomerate, are closely fractured or even brecciated as a result of the faulting. Thus, although unfractured pieces doubtless have high crushing strength, these members are not rigid plates and add little or nothing to the strength of the relatively weak shale members.

The Almy formation, which forms the lower plate of the overthrust, crops out in the upstream half of the area shown on plate 1, A and passes beneath the Beckwith formation downstream. It is composed of alternating beds of conglomerate, sandstone, and shale, all unlike any members of the Beckwith formation. These are colored gray, yellow, yellowish brown, and red. The conglomerate is made up of pebbles and cobbles of which most are of quartzite and 4 inches or less in diameter; these are embedded in a scant matrix of moderately consolidated sand. The conglomerate encloses some thin lentils of cross-bedded sandstone. The sandstone members of the formation are thin-bedded and gritty or pebbly; the shale members are sandy. The conglomerate members are inferred to form a minor part of the formation, although residual pebbles and cobbles from them veneer most outcrop areas. These members probably interfinger with and grade laterally into the sandstone and shale members.

The load-sustaining capacity and perviousness of the Almy formation are judged to range widely. The conglomerate and sandstone members have moderate crushing strength, probably somewhat less than that of similar members in the Beckwith formation; they are moderately pervious, at least as pervious as the fractured members of the Beckwith. The shale members of the Almy formation have moderately low crushing strength but are not highly permeable. The least sandy of them might be somewhat plastic under load, if saturated with water.

The tongue of flood-plain and terrace deposits, about 325 feet wide at the site, is low in capacity to sustain load and includes some coarse pervious gravel. Thus, it does not afford a rigid foundation.

As has been stated, the load-sustaining power and perviousness of foundation and abutments depends upon features of the thrust faulting. Thus, if the main fault plane is as steep as has been suggested and if there are no cross faults, the foundation material along the line AB is all of the Beckwith formation and is essentially no stronger than shale to a depth of several hundred feet. Under load, this material might deform plastically if it became saturated by percolation through the fractured and brecciated sandstone members, which are pervious. To assure stability under these conditions, only a flexible and moderately broad dam should be constructed. Also, adequate provision should be made to prevent saturation of the foundation materials. If a zone of cross faulting passes along the creek, blocks or slices of the Almy formation may lie immediately beneath the flood-plain deposit along the line AB. These would neither increase nor decrease the bearing power of the foundation materially. However, they might increase the perviousness decidedly by more intense brecciation of the sandstone and conglomerate members in both bedrock formations.

As a basis for determining width of dam and depth of cut-off, it is recommended that a series of exploratory holes be drilled along the line AB for cores to be tested in compression, also for leakage tests under pressure. This exploration should be especially thorough across the flood plain and on the lowest part of each abutment.

Leakage in material volume may occur through layers of fractured and brecciated sandstone in the thin right abutment. However, intervening layers of shale would tend to confine percolation to the direction of the bedding, which is downstream and steeper than the flank of the abutment. Adequate pressure tests in drilled holes appear to be the only means of estimating this potential leakage. The opposite or left abutment is moderately broad; there the potential leakage is probably much less. It seems unlikely that an appreciable volume of water would percolate from the proposed reservoir along the Medicine Butte fault to the next creek valleys to the north and south, because the main fault is offset repeatedly by secondary faults and because the brittle fractured strata commonly are faulted against impervious shale.

Any spillway at the Yellow Creek site should embody a pavement or other protective works close to the dam, for no part of the Beckwith formation near the Medicine Butte fault would long resist scour by deep swift water.

## Dam sites in Woodruff Narrows

### General features

The two dam sites on Bear River in the Woodruff Narrows (pls. 3-6)

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Plate 3.- Geologic map of the Woodruff Narrows upper dam site,  
Bear River.

Plate 4.- A, Woodruff Narrows upper dam site, viewed downstream;  
B, Bear River basin viewed upstream from the entrance  
to Woodruff Narrows.

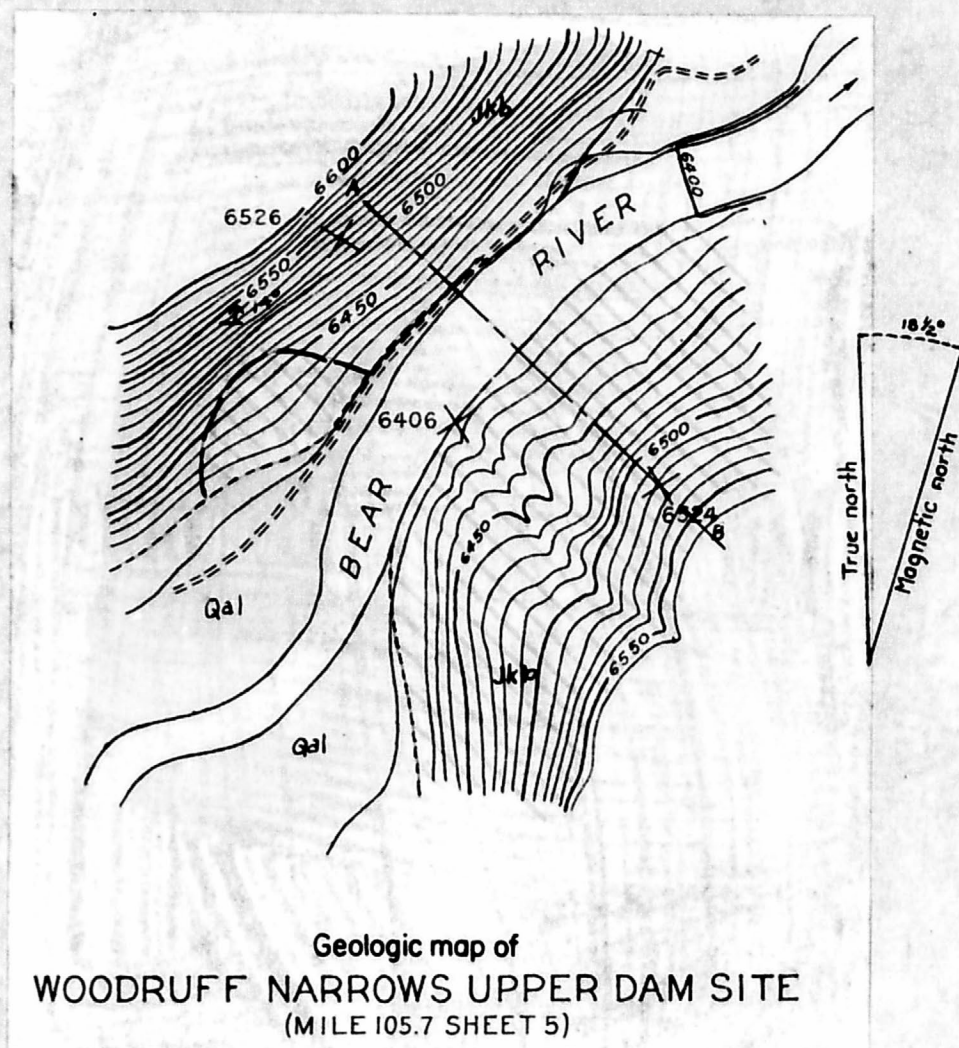
Plate 5.- Geologic map of the Woodruff Narrows lower dam site,  
Bear River.

Plate 6.- A, Woodruff Narrows lower dam site, viewed downstream;  
B, Outcrop of laminated sandstone low on the right abut-  
ment at the Woodruff Narrows lower dam site.

---

are alternative to one another in that they have a common reservoir site (pl. 4, B) and will impound water up to about the same altitude. As is to be brought out, geologic features of the two sites are nearly alike. Also, construction of a high dam at either site involves an auxiliary dam or spillway structure to close a saddle at altitude 6,460 feet about 0.7 mile northwest of the upper site.

No faults were found in the bedrock along or near the Narrows. Hence, neither the main sites nor the saddle site involve a major zone of rock fracture like that at the site on Yellow Creek.





A. Woodruff Narrows upper dam site, viewed downstream.



B. Bear River basin viewed upstream from the entrance to Woodruff Narrows





B. Outcrop of laminated sandstone low on the right  
abutment at the Woodruff Narrows lower dam site

## Upper site

According to the map by Veach \_/ the bedrock at the upper dam site

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\_/ Veach, A. C., op. cit., pl. 3.

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(pl.3) is the topmost part of the Beckwith formation. Fully two-thirds of this part of the formation, if not three-fourths, is sandy shale. The remainder consists largely of interbeds of sandstone which are from 1 foot to 3 feet thick, fine-grained, somewhat earthy, and moderately indurated. Debris in the slope wash suggests that a few layers of impure limestone are also interbedded with the shale; these are no more than a foot thick and are partly recrystallized. One such layer crops out just above the 6,600-foot contour beyond the western edge of the mapped area. All parts of the formation - sandstone, shale, and limestone alike - are traversed by many ramifying veinlets of calcite no more than 2 millimeters thick. In the left or west abutment these beds dip  $14^{\circ}$  N.  $11^{\circ}$  W. (diagonally downstream). On the opposite side of the river there are no outcrops within the area shown on plate 3 but outcrops farther upstream suggest that (1) the right abutment is also composed of alternating beds of sandstone and sandy shale of the Beckwith formation, though the sandstone beds may be fewer, (2) the inclination of the beds is nearly the same in both abutments and so no structural discontinuity intervenes, and (3) the dam site is underlain to a depth of several hundred feet by interbedded shale and sandstone similar to that in the two abutments.

In outcrops on the left abutment the sandstone members are parted by subvertical fractures that strike in all directions, commonly only a few feet apart. It is believed that most of these fractures have been caused by expansion and contraction of the sandstone with the variation in air temperature and by slump of the shale that intervenes between the sandstone members; consequently, that below the zone of weathering there are relatively few fractures and the sandstone members are essentially rigid and not highly pervious.

About 750 feet downstream from the line marked "AB" on plate 3 the Bechwith formation passes unconformably beneath thin-bedded fossiliferous limestone interbedded with dark carbonaceous shale. These fossiliferous strata are the lowest part of the Green River formation, which extends to and beyond the lower dam site in the Narrows and the 6,460-foot saddle mentioned above.

Because the bedrock in both the abutments and beneath the stream bed at the upper site dips diagonally downstream and is largely non-rigid shale with relatively thin interbeds of moderately rigid sandstone, it affords a foundation of fair but not high load-sustaining capacity. Accordingly, the site appears best suited to a flexible dam with moderately wide base resting wholly on the unweathered rock.

The materials which would be unsatisfactory in the foundation of a dam include the flood-plain deposit along the river, the surficial slope wash, and unsound weathered bedrock. At the line marked "AB" on plate 3, the flood-plain deposit forms a tongue about 200 feet wide and presumably only a few tens of feet thick. This deposit is composed largely of silt but encloses some tongues of gravel and unsorted angular detritus from the adjacent slopes. This material is subplastic and highly unstable when saturated with water. Its capacity to retain water is believed to be so great that ordinary methods of drainage would not render it stable under a dam of the full height contemplated - up to the 6,560-foot contour - even though the dam should be very broad. Over all the right abutment and part of the left abutment the depth to sound bedrock may well be a few tens of feet. This is suggested by two features: the continuous mantle of slope wash on the right abutment with a form suggesting an alluvial fan and the small but probably shallow landslide on the left abutment (pl. 3). It is judged that the total volume of material to be stripped is not excessive; however, this judgment should be verified by means of test pits, borings, or drilled holes.

Leakage through the abutments would be facilitated by the downstream dip of the bedrock strata but, on the other hand, neither abutment is extremely thin and even the sandstone beds are not highly pervious except along fractures. It has been inferred that fractures are not extensive below the zone of weathering. Thus, leakage probably would not be excessive if the impervious membrane of the dam is seated everywhere in sound shale. If necessary, both abutments could be blanketed with fine material sluiced down from weathered carbonaceous shale that occurs on the slopes above either abutment.

With a high dam at the upper site, the most feasible place to waste water appears to be across the saddle - 6,460 feet in altitude - about 0.7 mile northwest of the site. Geologic features of this saddle are described on page 29. Even a low dam, with a crest at or below the level of the saddle, would require a pavement or other protective works in the spillway, for none of the bedrock or surficial material at and near the site would be highly resistant to scour and plucking by swiftly flowing water.

#### Lower site

At the lower dam site in the Woodruff Narrows, the Green River formation composes the bedrock in both abutments and beneath the stream bed to a depth of several hundred feet. Throughout the area shown on plate 5 it dips 90-100 eastward or directly upstream; the precise direction of dip ranges between N. 75° E. and S. 80° E.

In the right (north) abutment, where outcrops are fairly continuous the formation is composed wholly of interbedded sandstone and shale. The sandstone is fine-grained, earthy, and commonly laminated and ripple marked (pl. 6, B); its beds are from 1 to 5 feet thick. Much of the shale which intervenes between sandstone beds is carbonaceous; some is calcareous and little is sandy. To a height of about 65 feet above the river - that is, up to the 6,450-foot contour - sandstone makes up about half the thickness. Above, to the crest of the abutment spur at an altitude of 6,610 feet, the bedrock is largely shale: sandstone members sufficiently thick to form ledges are from 30 to 40 feet apart vertically. The same succession of strata probably occurs in the left or south abutment, as is suggested by the few small outcrops (pl. 5).

The character of the bedrock below stream level at the site is suggested by scattered outcrops downstream. From these it is inferred that to a depth of 100 feet or more relatively thin beds of sandstone and shale alternate as in the lower part of the right abutment, and that at a depth of about 250 feet there is a thick body of highly carbonaceous shale.

At most places the sandstone members are parted by subvertical fractures from 1 foot to 4 feet apart; the most extensive strike about N. 70° E. and N. 15° W., or parallel and transverse to the river, respectively. It is inferred that these and other fractures in the Green River formation are due to widespread shear and so extend throughout the rigid sandstone members but are discontinuous and widely spaced in the shale members, which are not rigid. In outcrops, these fractures commonly are open spaces as much as 4 inches wide owing largely to slump. Below the zone of weathering, however, they probably are fairly tight but none the less make the sandstone members moderately pervious.

Unconsolidated materials veneer nearly all the left (south) abutment (pl. 5). These include patches of coarse gravel remaining from a stream terrace below the 6,460-foot contour, also unstable slope wash that encloses some large blocks from concealed sandstone ledges. Above the 6,450-foot contour much of the abutment has a hummocky topography of a sort that suggests all the unconsolidated material is moving as a rock glacier, owing possibly to failure of weak shale beds in the bedrock. This feature suggests that sound bedrock is moderately deep below the land surface over the greater part of the abutment.

Like the upper site, the lower site in the Woodruff Narrows appears suited only to a broad flexible dam. Indeed, a high dam at the lower site should be materially wider, for much of the shale bedrock is judged to have less capacity to sustain load than any rock at the upper site. The lower site is also inferior in that it requires a longer dam and probably a greater average depth of stripping to expose sound bedrock. Thus, for any desired pool level, considerably more material would need to be placed at the lower site. Further, the rocks at the lower site would be even less resistant to abrasion and plucking and so would require more extensive protection in a spillway.

In two respects, the lower site is somewhat superior. First, the greater proportion of sandstone in the lower 65 feet of either abutment would afford a more rigid foundation beneath the center of a dam. For a low dam, therefore, the downstream site appears superior; for a dam 100 feet or more in height, the advantage of a more rigid foundation is offset by the weak shale above. Second, because impervious shale makes up about 85 percent of the rock in either abutment and dips upstream, there is little likelihood of excessive leakage, except possibly through the sandstone low in either abutment.

In a spillway, none of the rocks at the lower site would long resist abrasion and plucking. Least resistant of all would be the carbonaceous shale, which occurs at several levels in the abutments. Thus, if water is wasted over either abutment at pool level, protective works would be necessary.



### Saddle dam site

A dam about 55 feet high at the upstream site in Woodruff Narrows or about 75 feet high at the downstream site would raise water to the 6,460-foot contour, level with the saddle which is about 0.7 mile northwest of the upstream site and near the north quarter corner of sec. 31, T. 18 N., R. 120 W. Obviously, a higher dam requires closing the saddle. Further, with a dam at either site, the saddle is advantageously located for a remote spillway. However, the saddle is broad and so for a high pool level would require placing a large volume of material. Thus, for a pool level at the 6,560-foot contour, the structure in the saddle would be about 100 feet high and 3,400 feet long, or two-thirds the height and nearly three and a half times the length of the main-channel dam at the upstream site.

Slope wash and alluvium cover all the floor of the saddle and all the low ridge to the west for nearly half a mile. However, exposures to the east suggest that the whole area is underlain by carbonaceous shale and thin-bedded impure limestone, the lowest part of the Green River formation. As at the downstream site on the river, these rocks do not have a large capacity to sustain load and would not resist scour if exposed in a spillway. Hence a broad flexible dam and paved spillway would be essential. It appears feasible to construct an earth fill without stripping all the slope wash and alluvium, provided the impervious membrane of the structure is seated on sound bedrock.

## Colorado River Basin, Colorado

### East River and main fork of the Gunnison River

#### Character of the rocks

The rocks that occur at dam sites along the main fork of the Gunnison River are described below in descending stratigraphic order; the extent of each is shown on the respective maps (pls. 7 A, 9, 11, 14).

#### Unconsolidated materials:

Flood-plain and stream-bed deposit: Largely coarse gravel and boulders, fairly round, most particles between 2 and 6 inches in diameter but some 18 inches long; a minor porportion of coarse sand locally. Derived almost entirely from dense crystalline rocks. Extremely pervious. Thickness indeterminate.

Low-terrace deposit: Coarse sand, gravel, and cobbles; moderately assorted; particles well rounded, generally less than 4 inches in diameter but some 12 inches; largely from crystalline rocks. Little weathered and highly pervious. Forms discontinuous terrace remnants 40 to 60 feet above the river; maximum thickness not exposed.

Talus: Below cliffs of the crystalline rocks, fans and tongues of unassorted angular debris, particles commonly range in size from chips to blocks 5 feet long; larger blacks moderately numerous, the largest seen was about 30 feet long. Unstable and extremely pervious. Thickness probably exceed 50 feet in many fans.

High-terrace deposits: Largely an unassorted mixture of particles ranging in size from silt to subangular boulders 6 feet long, derived from all rocks exposed in the adjacent terrane; encloses or overlies some tongues of moderately assorted stream gravel. Commonly veneers a discontinuous bench 200 to 300 feet above the river but locally tongues descend to the flood plain. The deposit is torrential wash, probably related in origin to a past epoch of glaciation. On slopes it is highly unstable, especially if saturated with water.

Bedrock:

Dakota sandstone, Morrison formation, and older sedimentary rocks:

Largely fine-or medium-grained sandstone, beds from half an inch to 6 inches thick and commonly cross-laminated, somewhat friable in outcrops. Some is somewhat earthy, a little is tightly cemented with secondary silica. Subvertical fractures are common, strike in all directions, and are 3 to 10 feet apart; partings parallel to the bedding are less common. Moderately pervious both through interstices and fractures; low or moderate crushing strength.

These sedimentary rocks occur only in two of the areas shown on the several geologic maps of dam sites, in part of the right abutment at the East River site (pl. 7, A) and at the Lake Fork Junction site (pl. 14) beneath the high-terrace deposit.

Granite, schist, and related rocks: At all sites except that at Lake Fork junction, biotite granite and quartz monzonite or quartz diorite with irregular masses of biotite schist (inclusions) and of granite (intrusions); commonly plates of monzonite and schist alternate, each several tens of feet thick; schist commonly injected by dikelets and stringers of monzonite too numerous for separate mapping but at some places making half the rock. At the Lake Fork junction site, dense massive gneiss closely banded by injections of medium - or coarse-grained granite (pl. 15, A, p. 53). These crystalline rocks extend to extremely great depths.

Of the crystalline rocks just described \_/. all but the schist have

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\_/ For a full description of these rocks and others related thereto see; Hunter, J. F., Pre-Cambrian rocks of Gunnison River, Colorado: U. S. Geol. Survey Bull. 777, 94pp., 1925; Cross, Whitman, and Larsen, E. S., A Brief review of the geology of the San Juan region of southwestern Colorado: U. S. Geol. Survey Bull. 843, pp. 17-24, 1935.

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extremely high crushing strength and are quite impervious except as fractures afford secondary openings. Accordingly they are competent to sustain thin rigid dams.

All the crystalline rocks are parted by fractures (pl. 8, B; 12, B; 15, B) which may be grouped in four classes, as follows: (1) unpaired fractures dipping within  $30^{\circ}$  of the vertical, extending far along the strike, commonly with a pronounced selvage of crushed rock; (2) subvertical fractures of moderate extent, numerous and subparallel at any one site but taking many directions in the region as a whole, commonly but not always without selvages; (3) discontinuous fractures, random in direction of strike and dip, amount of dip  $60^{\circ}$  or more; (4) low-angle fractures dipping less than  $30^{\circ}$ , usually neither numerous nor extensive.

Where thick plates of granitoid rock alternate with equally thick plates of schist, each granitoid plate commonly has a distinct pattern of fractures that terminates in the adjacent schist. This is true at the Almont site (pl. 9). Thus, each granitoid plate is a structural unit.

Certain fractures in the two classes first described are, without doubt, faults along which there has been considerable displacement, although this displacement cannot be measured in the crystalline rocks themselves. None of the fractures at the several dam sites displace the relatively young volcanic rocks in the vicinity. Likewise, Hunter \_/ notes that those

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\_/ Hunter, J. F., op. cit. p. 86.

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faults in the region which extend beyond the crystalline rocks displace the Mesozoic sediments I which include the Dakota sandstone and Morrison formation of this report\_7 but not the overlying volcanic rocks L which are of Tertiary age\_7. Thus, even the major fractures along the Gunnison River have been inactive for a very long period. Accordingly, these fractures are not a hazard threatening the stability of an adequately constructed dam. They will influence construction only to the extent that they afford openings for the percolation of water or make certain crags and thin spurs insecure owing to undercutting.

### East River dam site

The dam site on East River (pls. 7, 8), one of the two headwater

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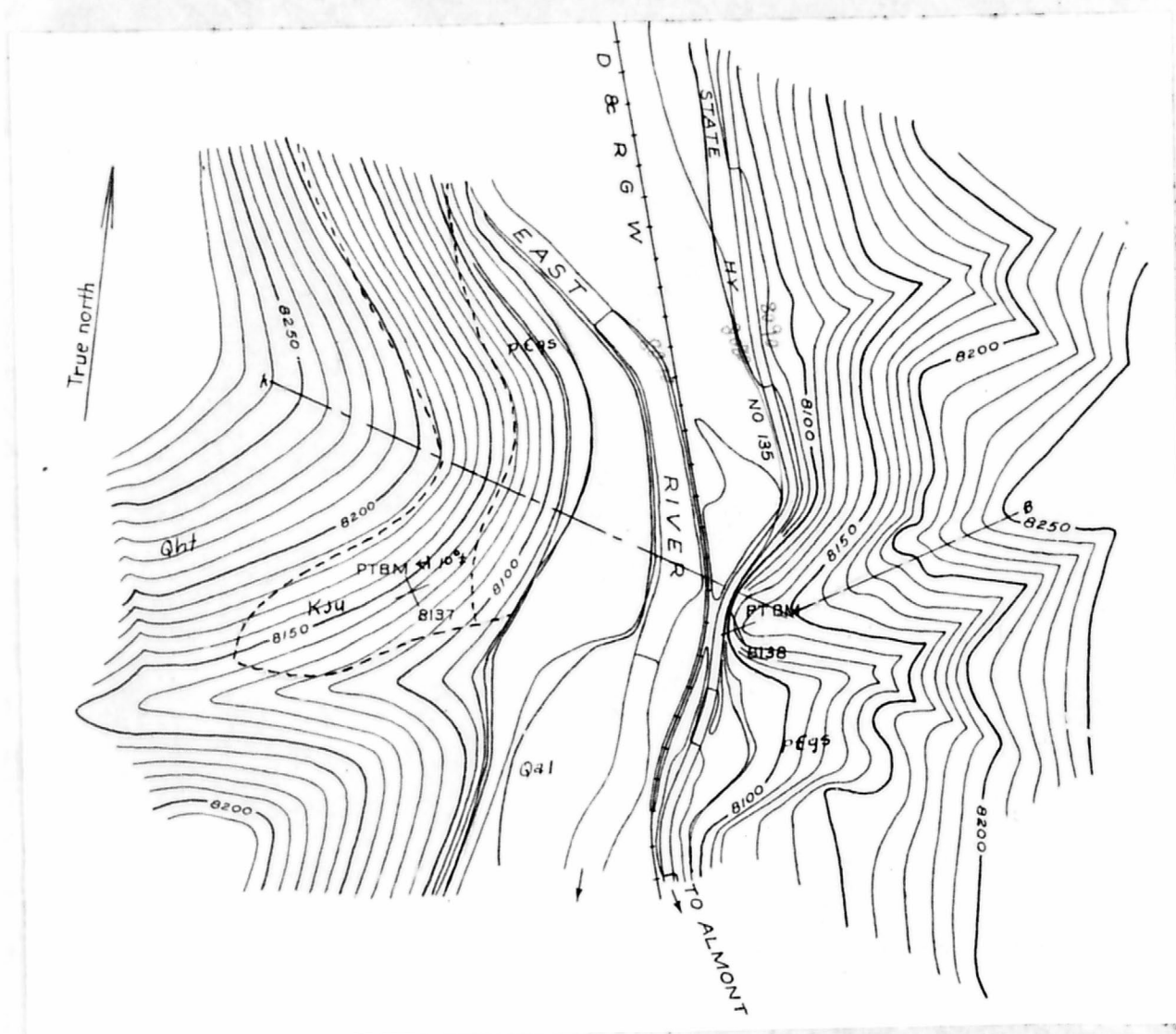
Plate 7. A, Geologic map of the East River dam site; B, Explanation for geologic maps of dam sites along the Gunnison River, Colorado.

Plate 8. A, Basin of East River from atop the ridge west of Almont; B, Fractures in granitoid rock that forms the left (east) abutment of the East River dam site.

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branches of the Gunnison River, involves materials that differ greatly in crushing strength, load-sustaining capacity, and perviousness. In addition to the stream-bed and flood-plain deposits, these materials include granitoid rock, sandstone (Dakota ?) and high-terrace deposits. The general character of all these has been described on pages 31-34.

The granitoid rock underlies the river bed and flood plain and forms all the left or east abutment up to and beyond the margin of the area that is shown on plate 7, A. In that abutment, this rock is medium-grained biotite granite or quartz monzonite with scattered inclusions of biotite schist no more than a few feet thick and a few tens of feet long. This rock is very little weathered at the land surface; it has extremely high crushing strength and is not pervious except through fractures.



Geologic map of the East River dam site

( Topographic base highly generalized; geologic boundaries are of sketch quality only )





A. Basin of East River from atop the ridge west of Almont. (The East River dam site is indicated in outline.)



B. Fractures in granitoid rock that forms the left  
(east) abutment of the East River dam site.

Throughout the abutment the granite is parted by fractures (pl. 8, B), of which the most extensive fall into two sets, as follows: (1) Dip subvertical, strike N.  $55^{\circ}$  E. or diagonally across the stream, subparallel, commonly from 1 to 5 feet apart, walls usually snug and without selvages of crushed rock. At a few places, fractures of this set are only a few inches apart and are closely braided into rude shear zones. (2) Strike N.  $80^{\circ}$  W., dip  $20^{\circ}$  -  $30^{\circ}$  S., or downstream. One prominent fracture in this direction passes through the lower part of the abutment just above the flood plain. Secondary fractures of slight extent and with various directions of strike and dip are common. Together, the fractures that have been described part all the granite into a mosaic of rhomboidal or wedge-shaped blocks that are imperfectly interlocked.

At the land surface these fractures commonly are open spaces 1 or 2 inches wide, owing largely to sag and creep in thin spurs and small pinnacles of the blocky granite. At moderate depth below the land surface, however, most fractures are probably fairly tight; nevertheless they render the granite somewhat pervious throughout. Being without selvages of crushed rock, however, they could be easily and thoroughly sealed by grouting or other appropriate measures.

The depth of stripping to expose unweathered granite probably averages less than 10 feet over most of the left abutment. However, in the tip of the spur that forms the lower part of the abutment there is considerable insecure rock which must be removed if a rigid foundation of uniform bearing power is to be made ready.

In contrast to the uniform load-sustaining capacity of the granite that forms all the left abutment, the materials in the right or west abutment are quite diverse. In the lowest part of the abutment - from the edge of the flood plain up to about the 8,140-foot contour or to a height of about 70 feet above the river - granite crops out discontinuously. In all its features this rock is a counterpart of that across the river. However, this mass of rigid rock probably is not extensive because its top is a near-plane erosion surface that dips about  $5^{\circ}$  -  $10^{\circ}$  W. or NW., and so descends to river level about 800 feet upstream from the line that is marked "AB" on plate 7, A and about an equal distance to the west of the flood plain.

Overlying the granite is cross-bedded somewhat friable sandstone which has only moderate capacity to sustain load and doubtless is pervious through interstices and fractures alike. This rock is inferred to have the shape of a wedge with a base resting everywhere on the granite and a top which is nearly horizontal within the area shown on plate 7, A. In the streamward face of the abutment this sandstone wedge is from 40 to 60 feet thick; to the west it thickens at an estimated rate of from 10 to 15 feet in each 100 feet.

Overlying the sandstone in turn - above the 8,190-foot contour - is a mass of the heterogeneous unstable material that has been termed the high-terrace deposit (p. 31). This material extends up to a flattish surface at an altitude of 8,290 feet; this surface is about 900 feet wide and is a remnant of a rude terrace, once more extensive. Over most of this remnant, the high-terrace deposit is estimated to be at least 100 feet thick. Near the southern edge of the area shown on plate 7, A a tongue of the deposit, possibly even thicker, descends to the margin of the flood plain.

So far as geologic features are concerned, the narrowest part of the valley at the East River site is as advantageous as any other for the construction of a dam. This is the position of the line AB. However, the height and type of dam depends primarily upon the features of the west or right abutment.

For a dam not more than 70 feet high, with pool level at the 8,140-foot contour, the site affords a foundation and two abutments all in rigid granite; to this height, the site appears suitable for a rigid dam of gravity cross-section provided the insecure rock low on the left bank is stripped and all fractures are thoroughly sealed against leakage. The low-angle fractures dipping downstream in the granite would require care in so preparing the foundation to resist the tendency of a dam to slide. Any dam at the site will raise water against the pervious sandstone in the right bank but there is believed to be little chance of excessive leakage if pool level is no more than 70 feet above the river bed.

A dam more than 70 feet but less than 120 feet high would rest on the weaker sandstone in the upper part of its right abutment and so should be moderately broad if rigid. Also, it should embody an impervious membrane extended a moderate distance into the abutment to restrain leakage through the sandstone.

A dam more than about 120 feet/<sup>high</sup>at the East River site would raise the pool above the sandstone and would saturate the unstable high-terrace deposit. To be secure, a dam so high would require a foundation excavated to the sandstone or granite bedrock, also a substantial cut-off structure seated in sound bedrock entirely across the high terrace - that is, to an estimated depth of about 100 feet below the land surface for a distance of some 900 feet.

An over-fall spillway on the left bank seems entirely feasible. There, the waste water would pass over resistant granite, so that a pavement or other works to prevent scour need not be extensive.

### Almont dam site

The dam site near Almont (pls. 9, 10) is within an upfaulted block

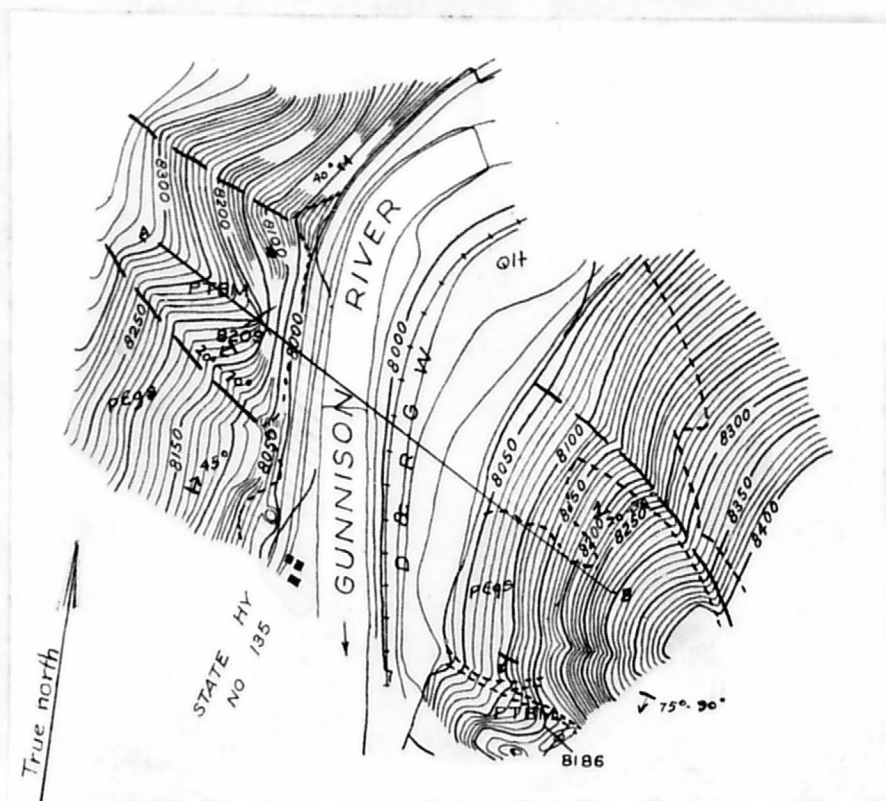
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Plate 9.- Geologic map of the Almont dam site, Gunnison River.

Plate 10.- Almont dam site on Gunnison River, viewed downstream.

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of crystalline rock about a mile across. Thus, except for the tongue of flood-plain and low-terrace deposits along the river, about 450 feet wide and probably at least 60 feet thick, all the foundation and both abutments are of rigid material high in crushing strength.



Geologic map of the Almont dam site on the  
Gunnison River





Almont dam site on Gunnison River, viewed downstream.

The crystalline rock is biotite granite or quartz monzonite of medium or coarse grain with many inclusions, large and small, of biotite schist. Discrimination of granite and schist on the geologic map is impossible, so closely are the two rocks intergrown over many parts of the site. However, in the central part of the area shown on plate 9 a zone formed largely of granite trends northwestward or diagonally across the river. This zone or plate is subvertical and from 250 to 500 feet thick; its axis is approximately along the line marked "AB". Both upstream and downstream this plate is enclosed <sup>by schist</sup> with many irregular injections of granite. The central thick plate of granite is essentially a structural unit and is the most suitable position for a dam. It appears to be sufficiently rigid and to have adequate mass to support a rigid dam.

The granite at the Almont site is everywhere parted by fractures, of which the most extensive sets are indicated on plate 9 and are about as follows: (1) In the left or east abutment, a parting into plates from half a foot to 6 feet thick by subvertical fractures that strike N. 70°-85°W. or across the stream and parallel to the axis of the central plate of granite. These fractures are most conspicuous in a zone about 300 feet wide and extending the full height of the abutment just south of the line AB; commonly the individual fractures are not extensive and are arranged en echelon. On the opposite bank, fractures in this direction are common in the thin spur along the line AB at an altitude of 8,200 feet. (2) Strike N. 70° E., dip 20°-30° N, or diagonally upstream and downward into the right abutment, a few extensive fractures high on both banks of the river forming several rock plates from 30 to about 75 feet thick. The fractures in this direction and those first described appear most likely to be extensive beneath the surficial zone in which the rock is exposed to frost and to the seasonal variation in temperature. (3) Dip subvertical, strike N. 50° W., or diagonally across the river, forming a zone of platy parting about 50 feet wide along the upstream face of the thin spur in the right abutment. With depth, the fractures tend to die out but the dip flattens to as little as 40° S. at an altitude of 8,060 feet in the streamward face of the spur. (4) In the downstream half of the spur in a zone about 40 feet thick, curved fractures forming spheroidal shells from 3 to 10 feet thick; at the crest of the spur, at an altitude of 8,200 feet, these fractures dip 20° S. 55° -90°W., then steepen downward and dip about 70° SW. or W. at an altitude of 8,050 feet. The two sets of curved fractures just described are peculiar in form. Although they may have been accentuated by the agents of weathering, they are believed to be due primarily to regional stresses, resolved locally about inclusions of schist within the more rigid granite. Thus, it is concluded that they do not indicate any serious weakness in the right abutment.

Owing to the fractures that have been described and to many secondary fractures in various directions, practically all outcrops of the crystalline rocks at the Almont site are parted into slices or blocks from  $1\frac{1}{2}$  to 6 feet across. Rock so closely parted has sagged where crags and pinnacles are undercut; accordingly, at the land surface some fractures are open an inch or two. However, at moderate depth beneath the land surface many of the secondary fractures probably die out and the remainder become rather tight. Thus, it is believed that even in the thin right abutment the mass of the rock is quite stable, for selvages of crushed rock are lacking and many of the blocks and plates are random in shape and so are securely interlocked. Nevertheless, many fractures probably are extensive and make the rock somewhat pervious.

It is believed that the mantle of unsound rock at the Almont site is not more than a few tens of feet thick on the average and that the sound rock is adequate to sustain a rigid dam of any height that is topographically feasible. However, foundation and abutments are perhaps too closely fractured to justify a dam thinner than gravity cross-section. Also, grouting or other appropriate measures to prevent percolation would be essential, especially across the thin right abutment.

A fault, doubtless long inactive, is inferred to pass behind the left abutment outside the area shown on plate 9. It strikes about N.  $60^{\circ}$  E. and dips about  $70^{\circ}$  NW. Its hanging-wall plate, from 600 to 1,000 feet thick, is the abutment. There is only a remote chance that the fault zone is sufficiently pervious to cause excessive leakage, even with a high dam, or so weak as to jeopardize the stability of a rigid dam with gravity cross-section.

## Dam sites near North Beaver Creek

### General features

The upper, middle, and lower dam sites near North Beaver Creek (pls. 11-13) are located in a sinuous reach of the Gunnison River that is

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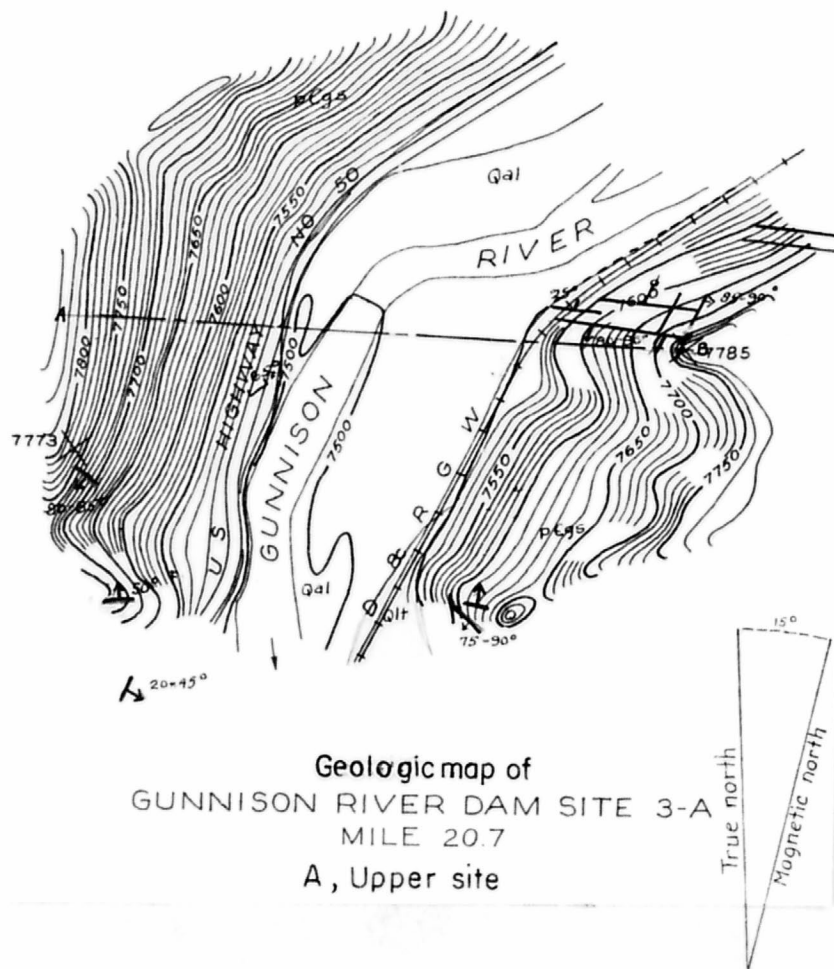
Plate 11. Geologic maps of dam sites on the Gunnison River  
near North Beaver Creek.

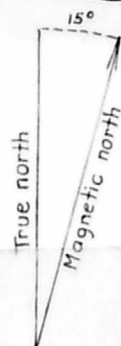
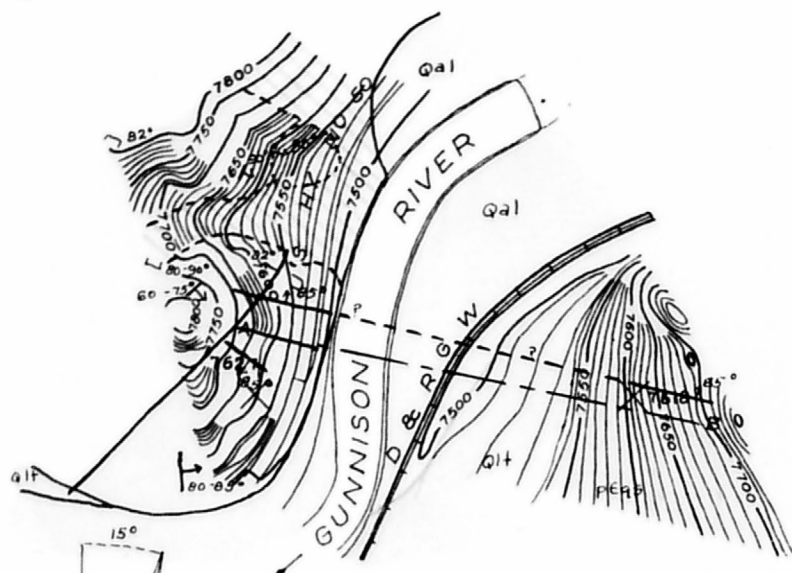
Plate 12. A, Left (east) abutment of the North Beaver upper site,  
viewed along the axis of the proposed dam; B, Fractured  
granitoid rock forming the right (west) abutment of  
the North Beaver middle dam site.

Plate 13. North Beaver lower dam site, viewed downstream.

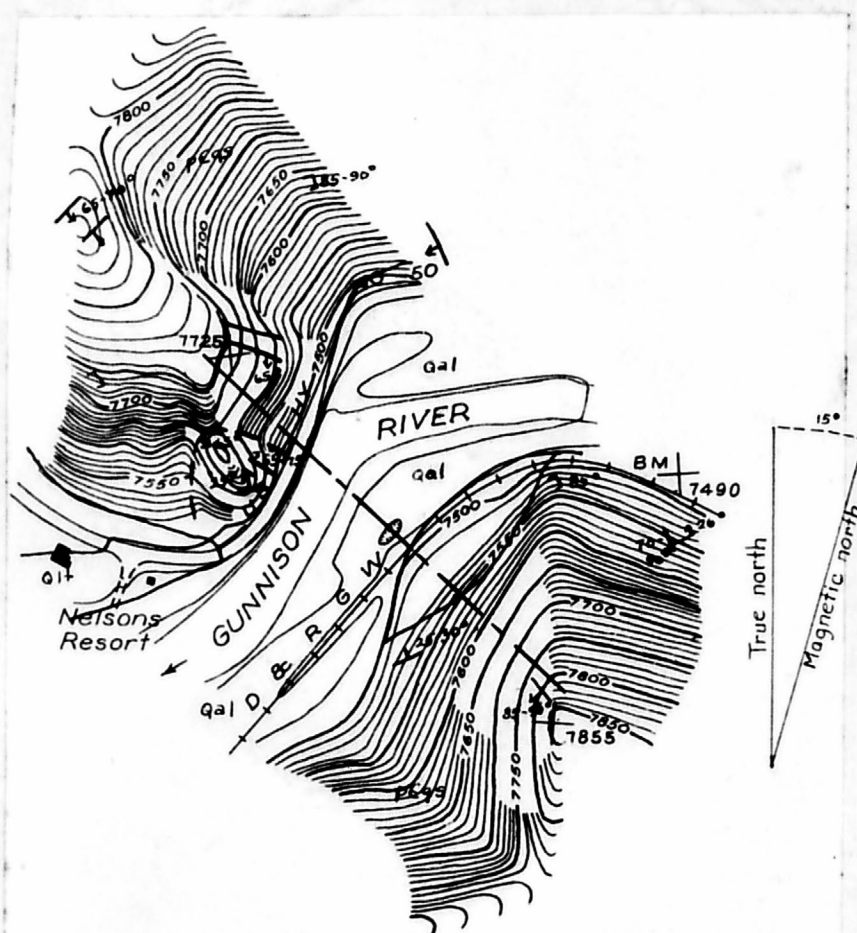
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about a mile long and that falls about 20 feet. The three sites are alternative to one another, although topographically the lower site is especially advantageous for a dam rising above the 7,700-foot contour. All three sites are in a common upraised block of the crystalline rocks and in general features each seems adapted to a non-flexible dam. A choice between the three depends primarily upon detailed characteristics of the crystalline bedrock and the character and extent of fractures.





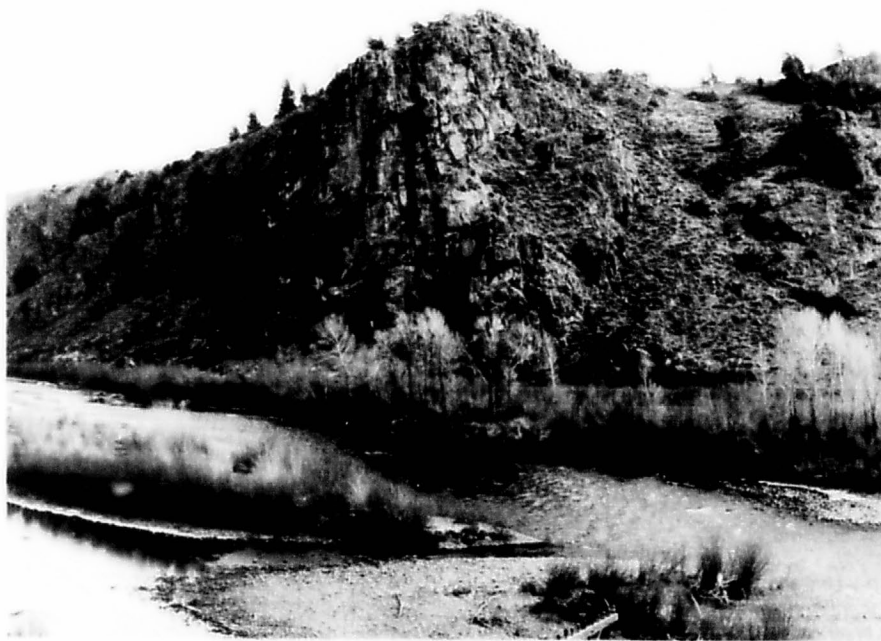
Geologic map of  
GUNNISON RIVER DAM SITE NO. 2-A  
MILE 20  
B, Middle site



Geologic map of  
GUNNISON RIVER DAM SITE I-A  
MILE 19.5

C, Lower site





A. Left (east) abutment of the North Beaver upper site,  
viewed along the axis of the proposed dam.



B. Fractured granitoid rock forming the  
right (west) abutment of the  
North Beaver middle dam site.



North Beaver lower dam site, viewed downstream.

### Comparison of the three sites

Flood-plain and low-terrace deposits.- At each of the three sites the Gunnison River is bordered by a flood plain and remnants of a low stream terrace; plain and terrace are underlain by a tongue of the unconsolidated material that has been described on page 30. At the upper and middle sites this tongue is about 500 feet wide; at the lower site, 400 feet wide. Its thickness is not known but probably is not less than 60 feet at the middle and lower sites. All along the reach that contains the three dam sites, the river cut its valley largely by plucking along extensive fractures. It is not unlikely, therefore, that it fluted the bedrock deeply along certain fractures before the low-terrace and flood-plain deposits were laid down. Thus, the maximum thickness of these unconsolidated deposits may be considerably more than 60 feet at all three sites. Because the grade of the river was probably fairly uniform through the mile-long reach before the low terrace was built, it seems likely that the unconsolidated deposits are about equally thick at the three sites. Thus, the lower site probably would require considerably less excavation to expose the crystalline bedrock for the foundation of a dam.

Bedrock.- At each of the three sites the bedrock includes biolite schist, medium-grained quartz monzonite or biotite granite, and granite in varying proportions. Since the two granitoid rocks are somewhat superior foundation materials, their distribution and extent is perhaps the most critical geologic feature in the comparison of the three sites.

At the upper site nearly all the rock that crops out is quartz monzonite. In the central part of the area the monzonite encloses a few small blocks and plates of schist in which the planes of schistosity locally dip about  $65^{\circ}$  N.  $20^{\circ}$  W., or steeply upstream. Schist is not known to be present in extensive or thick masses but commonly this rock is blanketed with talus. Thus, it is inferred from an extensive area of talus and from zones of discontinuity between sets of fractures that at least one thick plate of schist extends across the river immediately downstream from the spur that forms the left abutment for the proposed dam (pl. 12, A). This plate would trend acutely across the suggested axis; if present, it would form a zone somewhat inferior to either abutment in bearing power.

At the middle site the bedrock includes siliceous biotite schist quartz monzonite, and dikes of coarse-grained granite cutting the other two rocks. These dikes generally strike northward; the widest are about 8 feet across. Even if the dikes are disregarded no large part of the mapped area is wholly schist or wholly monzonite. Rather, there is every gradation between schist enclosing a few monzonite injections along the planes of schistosity and monzonite enclosing discontinuous masses and plates of schist in all sizes up to several tens of feet thick and several hundred feet long. One zone that is largely schist is about 150 feet thick, dips  $80^{\circ}$  -  $90^{\circ}$ , and strikes about N.  $70^{\circ}$  W. through a shallow talus-floored notch across the right abutment. (See pls. 11, B and 12, B.) Nevertheless, schist and monzonite are closely intergrown all through the zone. Immediately to the south, the prominent pinnacle in the angle of the river is largely monzonite but includes masses of schist far too numerous and far too varied in shape and extent to be discriminated in detail on the geologic map. This pinnacle is the most feasible abutment for a dam.

At the lower site a subvertical rib of coarse-grained monzonite from 300 to 400 feet wide strikes directly across the river along the line that is marked "AB" on plate 11, C. This rib forms the prominent spur in the northwest angle of the river and affords the right abutment for a dam (pl. 13). Within this rib the monzonite contains a few relatively small inclusions of schist; even these inclusions are injected by numerous stringers of monzonite. Dikes of the young granite as much as 12 feet thick cut through the monzonite at several places. This thick rib of monzonite and granite offers the most rigid foundation and abutments among the three sites. To either side of the monzonite rib just described there are zones from 250 to 400 feet wide formed largely of schist with many injected bands of monzonite a few inches or a few feet thick. The schist zone upstream accounts for the band of talus that crosses the right abutment.

Fractures.- As at the sites upstream already described, the crystalline rocks at the dam sites near North Beaver Creek are everywhere parted by closely spaced fractures. Most of these fractures lack selvages of crushed rock and probably are fairly tight at moderate depth beneath the land surface. On the other hand, a few relatively extensive fractures have selvages of crushed or sheared rock a few feet thick; these are zones of appreciable weakness. The upper site is characterized by subvertical fractures transverse and parallel to the river, respectively, also a fairly extensive set of low-angle fractures that dip  $25^{\circ}$   <sup>$15^{\circ}$  E.,</sup>  $-50^{\circ}$  N. <sup>three</sup> or or upstream. Together these fracture sets part the bedrock into rhomboidal blocks. (See pl. 12, A) Because the low-angle fractures are so extensive there has been considerable sag and creep in craggy outcrops; altogether a fairly large volume of insecure rock exists.

At the middle dam site the most prominent fracture strikes south-westward entirely through the spur that affords the right abutment (pl. 12, B). This fracture dips  $82^{\circ}$  N.  $57^{\circ}$  W.; it is a zone of shearing from  $1\frac{1}{2}$  to 4 feet wide, and appears to be a master fracture of the region. However, it has long been inactive and probably does not constitute a hazard with respect to the construction of a dam except as it forms a crushed zone to be bridged and plugged for prevention of excessive leakage and as it makes some small crags insecure by undercutting them. Thus, along this fracture, part of the pinnacle that forms the tip of the spur appears to have sagged outward as much as half a foot. The block to the west, the hanging wall, is parted into <sup>five</sup> S-shaped plates whose average thickness is about 35 feet, by fractures that dip  $60^{\circ}$  -  $75^{\circ}$  S.  $50^{\circ}$  E. These also are shear zones in which the rock is somewhat brecciated from 1 to 3 feet in width. In the foot-wall or east block of the master fracture there are moderately extensive subvertical fractures that strike about N,  $80^{\circ}$  W. - that is, parallel to the planes of schistosity - and divide the rock into plates from 1 to 3 feet thick. A few of these fractures are shear zones; the one projected across the river on plate 11, B has a crushed selvage from 3 to 5 feet thick. Cross flaws of slight extent strike and dip in many directions.



At the lower site extensive subparallel master fractures strike about N.  $50^{\circ}$  E. and dip  $65^{\circ}$  -  $70^{\circ}$  SE., or downward toward the left bank. These form a zone of bold rock plates that is at least 600 feet wide, passes across the right abutment, and extends into the opposite bank of the river downstream from the site. The most conspicuous fracture in this set passes beneath the small pinnacle at the tip of the right abutment (pl. 13); it is a zone of shearing and crushing from 6 to 8 feet wide. At least four other fractures in this direction and from 50 to 200 feet apart cross the right abutment to the northwest (pl. 11, C). In both abutments less extensive fractures dip  $25^{\circ}$  -  $30^{\circ}$  N.  $20^{\circ}$  W., or diagonally upstream and downward into the right abutment, or are subvertical and strike about N.  $40^{\circ}$  W. parallel to the planes of schistosity.

If any fractures in the bedrock at the three sites near North Beaver Creek are faults they have long been inactive. With respect to the construction of a dam, therefore, the master fractures are a hazard only so far as they undercut small spurs and crags and so create a moderate volume of insecure rock, or form pervious zones of low bearing-power which must be bridged/ and sealed against percolation. Some of these master fractures have selvages of crushed or sheared rock that might not accept grout readily. The secondary fractures, by far the more numerous, make all the bedrock somewhat pervious but probably do not greatly lessen the load-sustaining capacity. Doubtless they could be readily and effectively sealed by grouting or other appropriate means.

There is no reason to believe that fractures such as have been described are more numerous at one of the three sites than another. With respect to the stress that would be imposed on the abutments by a high dam, the fractures are judged to be least serious at the lower site.

Spillway.- None of the three sites near North Beaver Creek presents any serious problem of spillway construction. All the bedrock would have a high resistance to abrasion and, except in the relatively few shear zones, to plucking. The schist is somewhat less resistant than the monzonite, but even this rock would not require extensive protective works.

Summary.- Considering all known geologic features, the lower site near North Beaver Creek appears to be superior for the construction of a high dam, especially a dam rising above the 7,700-foot contour. It affords a thick rigid plate of monzonite and granite in both abutments and beneath the river all along the suggested axis. The master fractures strike at right angles to the axis of the monzonite plate and dip into the left bank. It is believed that this site is especially well suited for a rigid arch dam of gravity cross-section. At the lower site, as at the two alternative sites upstream, one abutment is a rather narrow spur through which material leakage might take place. Accordingly, particular care should be taken to seal all fractures with grout, an impervious blanket over the face of the abutment, or some other appropriate means.

This inferred superiority of the lower site is contingent largely on the character of the rocks in the master fracture zone which crosses the right abutment and probably passes also between the two abutments. Accordingly, the adequacy of the foundation beneath the river and of the right abutment should be explored thoroughly by pits and trenches along exposures of the fractures, also by drilled holes for cores and leakage tests. Further, the presence or absence of a thick plate of schist at the upper site striking acutely across the suggested axis for a dam should be verified likewise. If schist is not extensive there and if the master fracture zone of the lower site proves to be a cause of serious weakness, the upper site would be superior. The middle site is judged to be the least satisfactory.

#### Lake Fork Junction dam site

In geologic features, the dam site just below the mouth of the Lake Fork (pl. 14) is unique among the sites along the Gunnison River. It is

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Plate 14.- Geologic map of the Lake Fork Junction dam site,  
Gunnison River.

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located at the upstream end of the so-called Black Canyon described by Hunter \_/. There, the canyon is very narrow and its walls rise precipitously

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\_/ Hunter, J. F., op. cit.

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about 200 feet from the river, then ascend more gently to a narrow bench on either side of the stream.

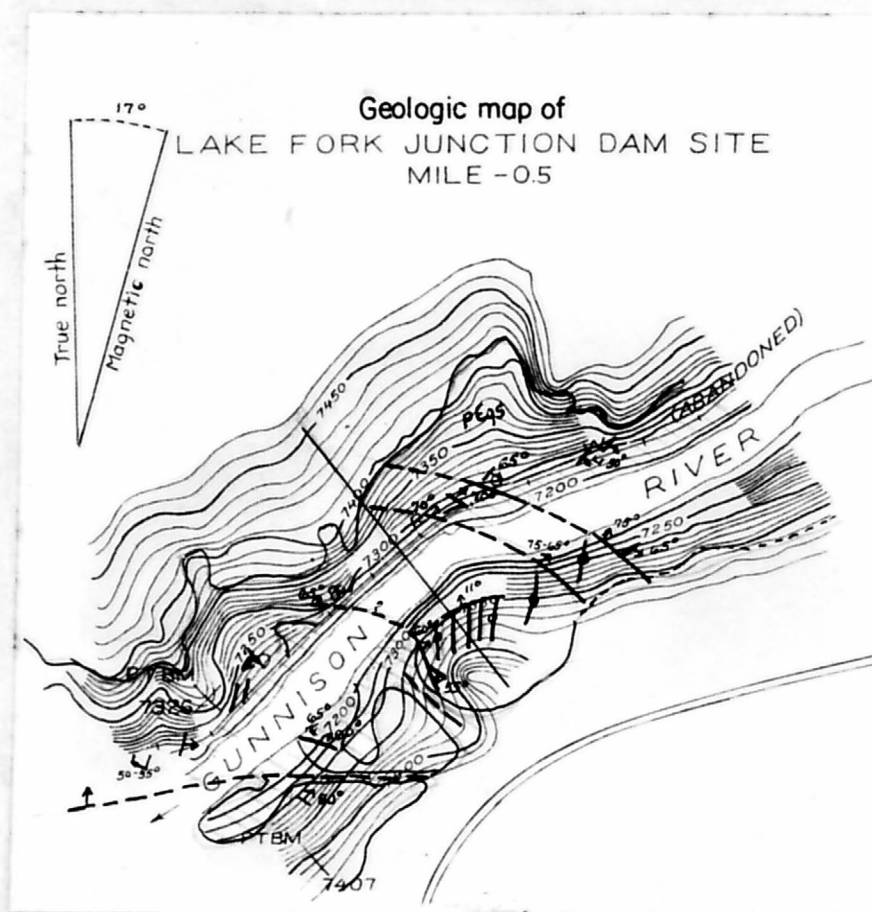
All the exposed bedrock at the Lake Fork Junction site is massive gneiss injected by many stringers of coarse-grained granitoid material (pl. 15, A). Schistosity and injections dip  $50^{\circ}$  -  $55^{\circ}$  N.  $10^{\circ}$  -  $20^{\circ}$  E., or

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Plate 15.- A, Typical gneiss with injections of granitoid material,  
Lake Fork Junction dam site.

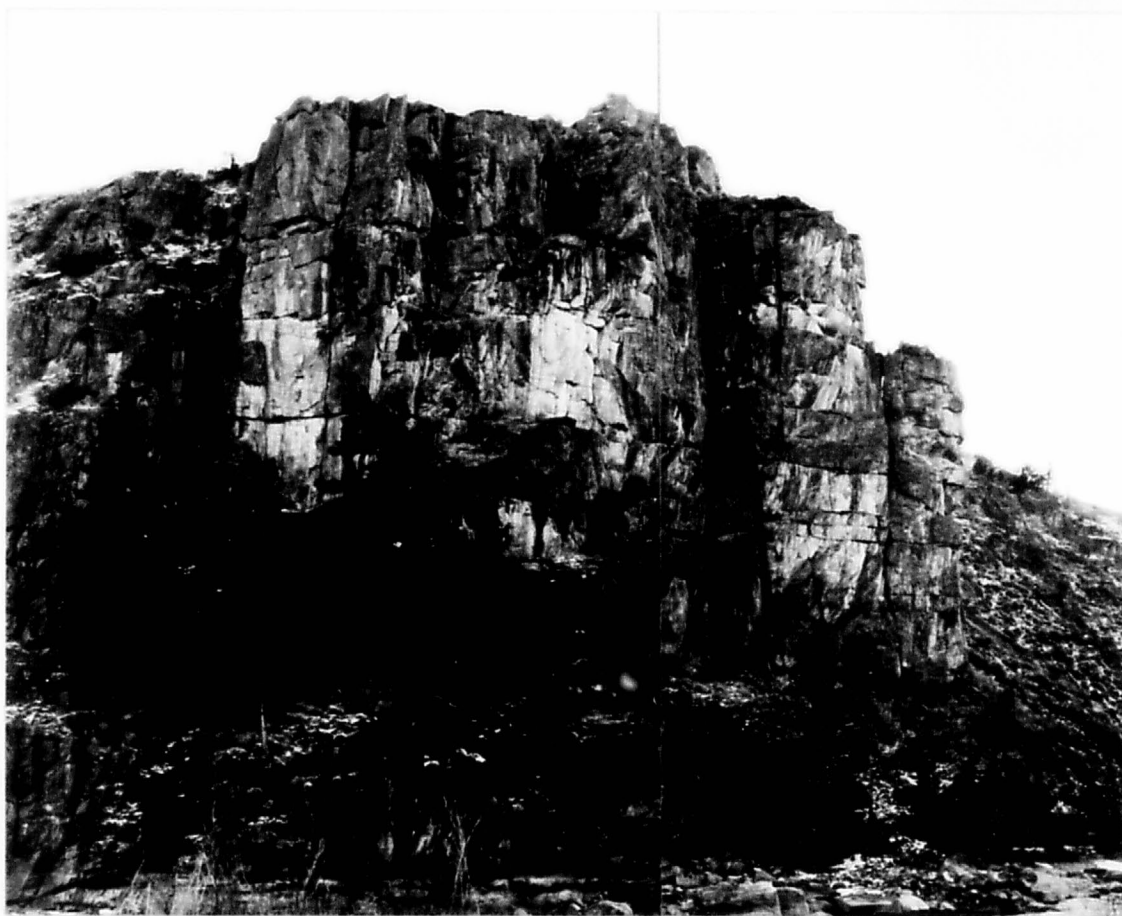
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diagonally upstream. The rock has extremely high crushing strength, doubtless greater than that of the foundation material of any other dam site in the region.





A. Typical gneiss with injections of granitoid material, Lake Fork Junction dam site.



B. Left (south) abutment at the Lake Fork Junction dam site, viewed  
directly across the Gunnison River.

As in other areas of the crystalline rocks, fractures are numerous. Chief among these are three fractures that strike between N.  $80^{\circ}$  E. and S.  $60^{\circ}$  E. and dip  $60^{\circ}$  -  $75^{\circ}$  northward, or upstream and acutely across the schistosity. Four such fractures are shown on plate 14, one crossing the river obliquely near the downstream edge of the mapped area and the others within a distance of 1,000 feet upstream. These fractures have extensive selvages of comminuted or coarsely brecciated rock; they are probably the most serious source of weakness in any part of the site.

The most feasible position for a dam appears to be along the line marked "AB" on plate 14, midway in the zone of master fractures just described; and abutting against the thin spur that is conspicuous on the left bank.



Secondary fractures in this spur (pl. 15, B) are the most critical

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Plate 15. -B, Left (south) abutment at the Lake Fork Junction dam site, viewed directly across the Gunnison River.

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feature of the site with respect to construction of a dam. Near its base, the upstream flank of the spur is undercut by a low-angle fracture that dips about  $11^{\circ}$  northward - that is, diagonally upstream. This low-angle fracture constitutes a potential sole along which any insecure rock would tend to slide. Possibly the sole passes downstream into one of the four master fractures (pl. 14) and so extends beneath all the spur. Above, the rock is parted by a succession of subvertical fractures/<sup>from</sup> about 10 to 35 feet apart, also by subhorizontal fractures about equally far apart. Thus, the spur is essentially a mosaic of fairly large rectangular blocks resting, at least in part, on a sole inclined diagonally upstream. There is a considerable amount of insecure rock in the streamward tip and upstream flank of the spur; all this should be stripped to prepare a sound abutment. Only thorough exploration by drilled holes will determine whether the core of the spur is adequately stable.

The fractures already described and many others that are slight in extent and common over all the site doubtless make the gneiss somewhat pervious. Thorough measures to prevent leakage through these openings would be essential, especially in the thin left abutment.

The gneiss that has been described forms the stream bed and both banks to a height of from 150 to about 250 feet above the river. Its upper surface is a near-plane erosion surface that slopes about  $3^{\circ}$  N.  $20^{\circ}$  W. in the central part of the mapped area and so descends from an altitude of 7,450 feet at the crest of the left-abutment spur to about 7,410 feet on the opposite bank. Thus, to a height of about 200 feet above the river, the site affords a foundation and abutments all in gneiss. Provided the thin spur that forms the left abutment is stable, the site appears wholly suitable for a rigid dam of this height.

Outcrops upstream and downstream from the site indicate that the gneiss is overlain immediately by earthy sandstone and sandy shale (Dakota ? and Morrison ?, respectively). As at the East River site upstream, these sedimentary rocks are much inferior to the gneiss in load-sustaining capacity and are moderately pervious. Within the area shown on plate 14 they are mantled by the incoherent high-terrace deposit (p. 31). Together the sandstone, shale, and terrace deposit are from 75 to 100 feet thick along the right rim of the canyon. A dam more than 200 feet high would abut against these materials on the right bank and so would require deep excavation to uncover a rigid foundation, also extensive cut-off works to restrain seepage. (See p. 39.)

Lake Fork of Gunnison River

Independence dam site

Bedrock.-- All the bedrock at the dam site near the mouth of Independence Creek (pls. 16, 17) belongs to the Lake Fork andesite as discriminated by

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Plate 16.-- A, Geologic map of the Independence dam site, Lake Fork of Gunnison River; B, Explanation for geologic maps of dam sites along Lake Fork of the Gunnison River, Colorado.

Plate 17.-- A, Independence dam site on Lake Fork of the Gunnison River, viewed downstream; B, Basin of Lake Fork of the Gunnison River, viewed upstream from the right abutment of the Independence dam site.

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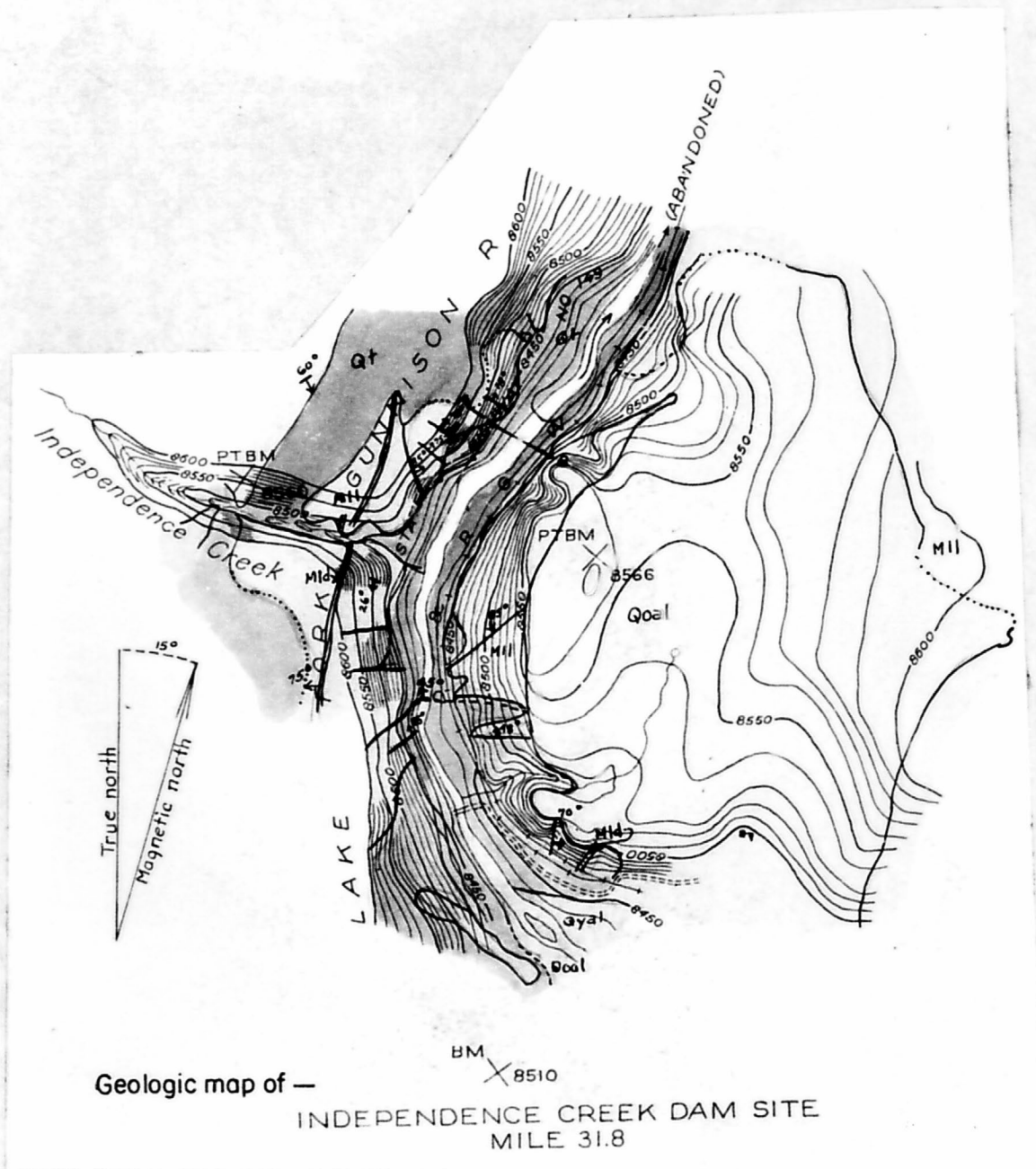
Cross and Larsen \_/. Three types exist: massive non-fragmental lava rock,

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\_/. Cross, Whitman and Larsen, E. S., A brief review of the geology of San Juan region of southwestern Colorado: U. S. Geol. Survey Bull. 843, pp. 55-56, 1935.

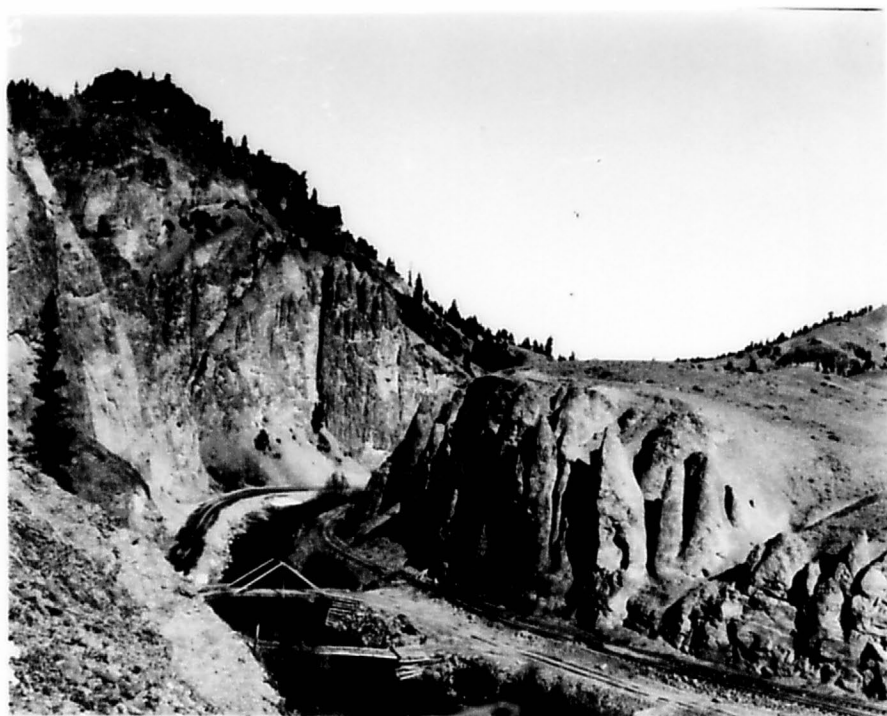
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agglomeratic lava rock, and dike rocks.



Geologic map of —

INDEPENDENCE CREEK DAM SITE  
MILE 31.8



A. Independence dam site on Lake Fork of the Gunnison  
River, viewed downstream



B. Basin of Lake Fork of the Gunnison River, viewed  
upstream from the right abutment of the  
Independence dam site.

In petrographic composition the non-fragmental lava rock is quartz latite. It contains a moderate number of small phenocrysts of feldspar and a few of hornblend (?) in a fine-grained matrix which at some places is somewhat glassy and inflated. This rock forms a single massive layer which in stratigraphic sequence dips about  $26^{\circ}$  SW., or upstream and is the lowest exposed at the site. The top of this layer is about 125 feet above the stream near the downstream edge of the area shown on plate 16, A but descends to stream level about 100 yards upstream from the mouth of Independence Creek.

Overlying the non-fragmental rock is a layer of massive agglomeratic latite which is composed of dense fragments as much as 5 feet long embedded in<sup>a</sup> matrix that ranges from dense fine-grained lava rock to inflated glass or moderately consolidated ash. The contact of this layer on the underlying non-fragmental rock is not sharp; the two layers grade one into another. The agglomerate commonly weathers cavernous, especially where its matrix is ashy.

Two dikes cut the latite in the dam-site area. One on the right bank near the upstream edge of the area is andesitic (?) and from  $2\frac{1}{2}$  to 4 feet thick; its dip is somewhat uneven but averages about  $70^{\circ}$  S.  $65^{\circ}$  E. The other dike is roughly parallel to Lake Fork and from 200 to 300 feet to the west; it is rhyolitic (?), from 8 to 12 feet thick, and dips about  $75^{\circ}$  W. Either face of this dike has a fissile selvage about a foot thick which weathers away to form a niche as much as 15 feet deep. The material in this selvage has been rather thoroughly decomposed by the hot solutions rising with the dike-forming material; it probably would be plastic if saturated with water. Other dikes with similar selvages may be concealed by incoherent materials elsewhere in the area.

Fractures.— The chief elements in the pattern of fractures that cut through all the latite of the dam-site area are as follows: (1) About 250 feet upstream from the mouth of Independence Creek, two parallel fractures strike N.  $78^{\circ}$  W. or across Lake Fork and dip  $45^{\circ}$  N. or downstream. The main fracture of the pair is a shear zone about 2 feet wide; its hanging wall is commonly brecciated. This fracture is a normal fault along which the downstream block has been thrown down about 150 feet. (2) Trending across the pair just described, three subvertical fractures from 5 to 10 feet apart strike N.  $45^{\circ}$  E. in both banks of the river. In the right bank the intervening rock plates are somewhat brecciated; they are marked by talus-floored chutes extending the full height of the bluff. (3) About 400 feet west of and parallel to the Lake Fork a band of talus from 100 to 200 feet wide strikes NE. across the canyon of Independence Creek between subvertical rock walls at least 50 feet high. Possibly the talus conceals a major fracture zone parallel to the zone just described. (4) Passing through the mouth of Independence Creek and prolonging the course of Lake Fork upstream, a subvertical fracture strikes N.  $10^{\circ}$  W., or diagonally across the rock plate that intervenes between the second and third fracture zones thus far described. This diagonal fracture is a zone of brecciation which has weathered away in a niche from 2 to 5 feet wide and as much as 25 feet deep. Discontinuous fractures parallel to the breccia zone occur in either wall.



Less extensive fractures strike in several directions but commonly are subparallel in any one block between two major fractures. Thus, the fracture pattern that is exposed along Lake Fork changes decidedly about at the mouth of Independence Creek, downstream from which the rocks lie in the acute angle between two of the major subvertical fractures. In this acute angle, the latite is divided into plates from 30 to 100 feet thick by subvertical fractures that strike about N. 50° W., or directly across Lake Fork. Some of these are shear zones as much as 18 inches wide. Other subvertical fractures divide the intervening rock plates into rude prismatic columns that extend the full height of the bluff (pl. 18).

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Plate 18. Fractured volcanic rock forming the left (west) bank  
of the Lake Fork at the Independence dam site.

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Incoherent deposits.— The two incoherent deposits to be considered at the Independence dam site are talus and stream-laid terrace gravel. Talus forms a continuous fringe at the base of the bluffs along either side of Lake Fork. From this fringe tongues extend up either bluff and floor successive niches (which may indicate concealed fractures). The thickness of the talus is difficult to estimate since its base is below stream level everywhere in the vicinity of the site. The terrace deposit is composed chiefly of unassorted sand and gravel mingled with rounded cobbles and boulders in all sizes up to those 18 inches in diameter. Mingled with this material are some angular and subangular blocks as much as 6 feet long. This deposit is clearly the outwash from an alpine glacier that formerly occupied the Lake Fork valley farther south.



Fractured volcanic rock forming the left  
(west) bank of the Lake Fork at the In-  
dependence dam site. (The canyon of  
Independence Creek is at the left of the  
view.

This terrace deposit is highly pervious. It is most extensive on the right bank where it forms a terrace which is about 8,560 feet above sea level and 500 feet wide. To the east, it merges into an alluvial fan which rises to an altitude of about 8,625 feet. To the west the deposit thins to a feather edge at the crest of the bluff along Lake Fork, (pl. 19).

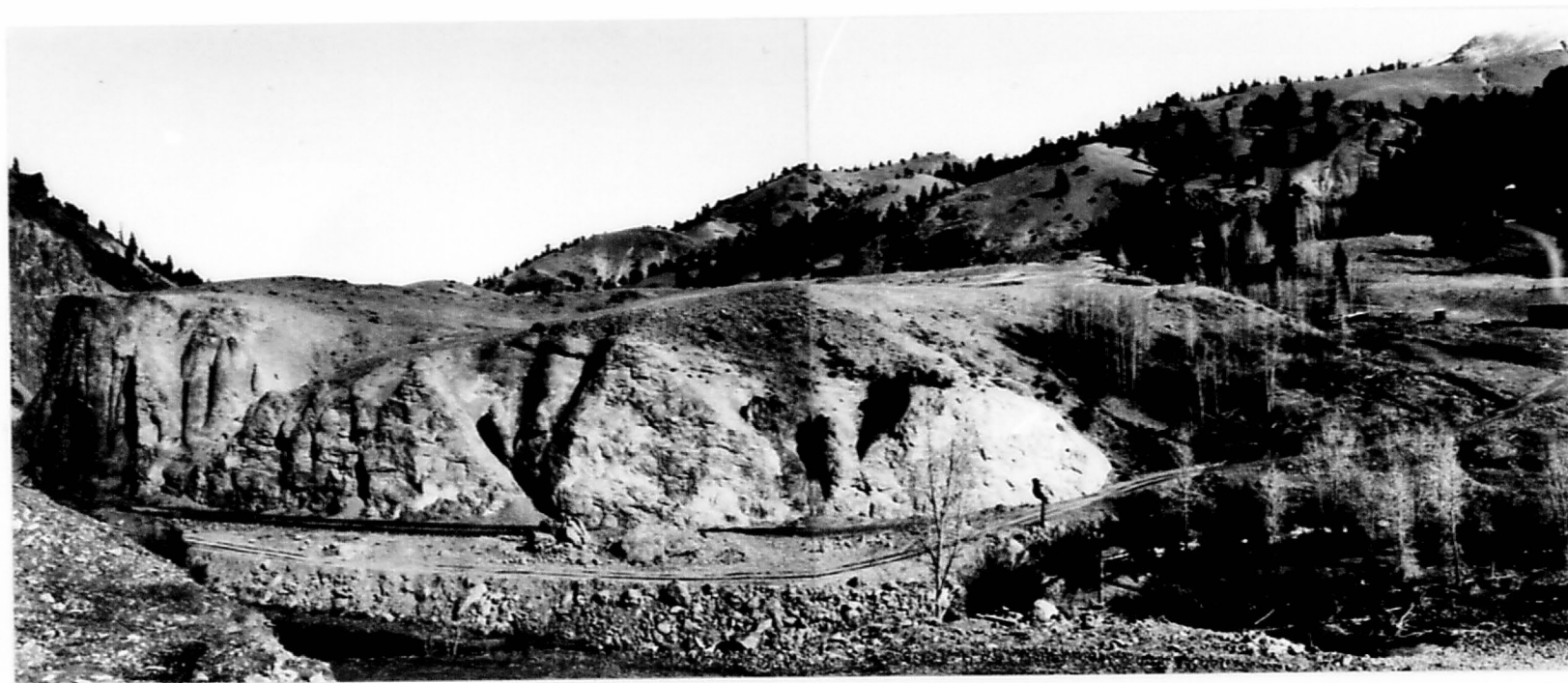
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Plate 19.- Right (east) abutment of the Independence dam site; a gravel-capped terrace.

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The thickness of the deposit is not known precisely. At the upstream edge of the dam-site area, the greatest thickness appears to be near the eastern edge of the terrace. At the downstream edge of the area, the few scattered outcrops of latite suggest that the base of the deposit may be as low as 8,510 feet in altitude or 50 feet below the terrace.

Summary.- With respect to the construction of a dam, the most critical two geologic features of the Independence site are the thickness and perviousness of the terrace deposit on the right bank and the load-sustaining capacity of the latite. The terrace deposit doubtless has a relatively high permeability. If, as has been suggested, the downstream lip of the underlying bedrock floor is 8,510 feet in altitude a dam with pool level at the 8,550-foot contour would require the deposit to withstand a percolation coefficient of about 18 to 1. It seems likely, therefore, that leakage would ensue unless an impervious cut-off is sunk through the terrace deposit and seated in bedrock.



Right (east) abutment of the Independence dam site; a gravel-capped terrace.

The most advantageous position for a dam appears to be about 400 feet downstream from Independence Creek, along the line marked "AB" on Plate 16, A. In this position a dam would not cross any of the known major fractures and would be parallel to the principal secondary fractures. Also, the massive nonfragmental latite would form either abutment for the full height of any dam that is feasible. Below the zone of weathering, this rock probably has moderately high crushing strength. However, because it is parted by closely spaced fractures parallel to the axis of the suggested dam, only a flexible structure of moderate width appears feasible.

To assure watertightness the foundation and abutments should be made ready with particular care for many of the fracture zones contain selvages of crushed rock and so would be difficult to seal effectively by grouting.

In a spillway the massive nonfragmental latite would be fairly resistant to abrasion and to plucking except in the brecciated zones along certain fractures. Some protective works to prevent scour would doubtless be advisable.

### The Gate dam site

Incoherent materials.- At The Gate dam site (pls. 20, 21) incoherent

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Plate 20.- Geologic map of dam site at The Gate, Lake Fork  
of Gunnison River.

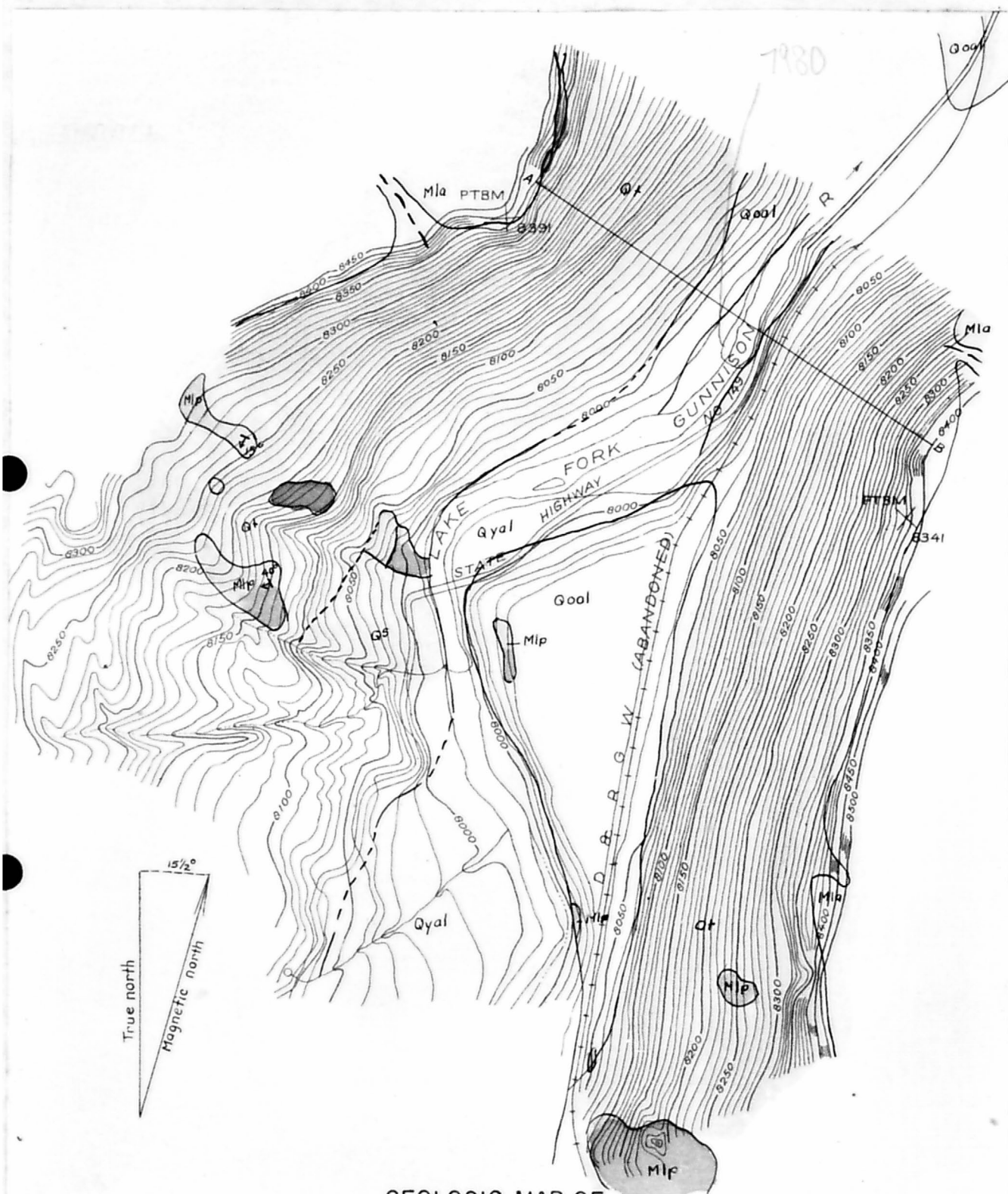
Plate 21.- A, The Gate, viewed upstream along the Lake Fork;  
B, Basin of Lake Fork of the Gunnison River, viewed  
upstream from the left buttress of The Gate.

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materials cover the greater part of the land surface. These include stream deposits of two ages low in the valley, talus, slope wash, and glacial debris (?).

The youngest of the incoherent materials underlies the river bed and forms a flood plain that is generally not more than 10 feet above the stream. This deposit is composed of sand and gravel with cobbles and boulders reworked from the terrace deposit above. It forms a tongue from 75 to 200 feet wide.

The terrace deposit is composed largely of sand and gravel with rounded cobbles and boulders as much as 18 inches through. There are a few sub-angular blocks several feet long but apparently no silt. Thus, the material doubtless is highly pervious. The terraces formed by this material is about 60 feet above the stream; its most extensive remnant, on the right bank, is about 500 feet wide and 1,700 feet long. On the left bank the terrace is not sharply defined and appears to be not more than 100 feet wide.



GEOLOGIC MAP OF  
THE GATES DAM SITE  
MILE 194





A. The Gate, viewed upstream along the Lake Fork.



B. Basin of Lake Fork of the Gunnison River, viewed upstream from the left buttress of The Gate.



Together, the flood-plain and terrace deposits form a tongue of highly pervious material that fills all the lower part of the Lake Fork valley where it passes through The Gate. As has been stated the thickness of this tongue above stream level is about 60 feet. Its thickness below stream level may well be several tens of feet in addition. Talus forms a continuous mantle on either buttress of The Gate to a height of about 370 feet above the stream and about 310 feet above remnants of the stream terrace. This material comprises the angular debris from cliffs above; its particles range in size from small chips to blocks 10 feet long.

Slope wash occurs chiefly on the left bank in the upstream half of the area that is represented by plate 20. There, to a height of at least 110 feet above the river, some of the material mapped as slope wash contains angular and subangular blocks which in petrographic character are unlike any on or adjacent to the dam-site area. These pieces of distant origin are inferred tentatively to indicate glacial origin.

Bedrock.— The most conspicuous bedrock unit in the dam-site area is a single cliff-forming layer of lava rock capping either buttress of The Gate. This layer is about 250 feet thick and nearly horizontal. It is composed of dense massive andesite, in part porphyritic. In a zone 25 feet thick at the base of the layer and another zone from 50 to 75 feet thick at the top the andesite commonly is distinctly banded owing to flowage after it was partly cooled. At a few places its lowest part is somewhat vesicular. The base of this andesite layer is exposed at a few places on the left bank at altitudes between 8,350 and 8,390 feet; there it rests on andesitic or basaltic breccia.

Below the cliff-forming andesite, all the bedrock to and below stream level appears to be of pyroclastic origin, although only a discontinuous section is exposed through the talus. At least three distinct types are exposed: light gray to white pumiceous beds, chiefly above the 8,250-foot contour on the left bank; moderately dense scoria between the 8,250- and 8,200-foot contours; and below, unstratified agglomerate composed of andesite blocks as much as 6 feet long embedded in a matrix whose texture ranges from friable to vitreous. These types and others of similar character probably form irregular beds or layers that interfinger or grade into one another in complex fashion. Several outcrops suggest that the individual layers are cross-bedded at many places.

High on the left bank in the west-central part of the area shown on plate 20, there are several outcrops of agglomerate that has been rather thoroughly decomposed by hot solutions. This altered rock is grayish green in color; doubtless it has little load-sustaining capacity, especially if saturated with water.

Summary.— Pyroclastic rocks such as those described are inferred to form all of either abutment to and above the crest of any dam that is likely to be constructed at The Gate. None of these rocks has extremely high crushing strength and some doubtless are very weak. Because the extent, thickness, and succession of their beds are not known in any detail, the bearing power of the foundation and abutments to various heights above the river cannot be estimated. It is believed that only a flexible dam with moderately wide base would be suitable.

Any dam at The Gate should embody an impervious cut-off extending entirely through the talus, terrace deposit, and flood-plain deposit, and seated in sound bedrock beneath. Together, these incoherent deposits are so thick and extensive that this cut-off would necessarily be both long and deep.

On the average the pyroclastic rocks probably are not highly pervious but contain some beds through which water might percolate beneath or around a dam. Thus, adequate provision should be made to restrain leakage through the abutments, possibly by depositing a blanket of impermeable material upstream from the dam.

None of the pyroclastic materials would long resist scour in a spillway. Accordingly, all would require a pavement of other protective works wherever exposed to deep swiftly flowing water near the dam.

#### Riverside School dam site

At the dam site just below Riverside School (pls. 22, 23) only inco-

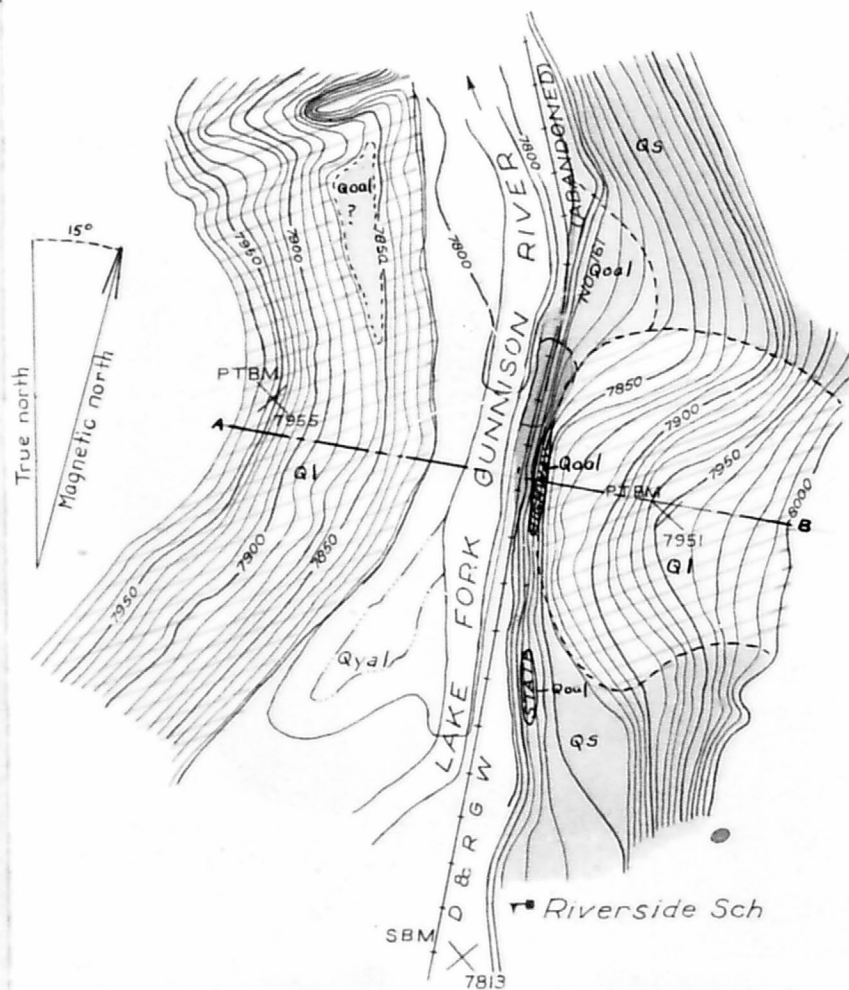
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Plate 22. Geologic map of the Riverside School dam site, Lake  
Fork of Gunnison River.

Plate 23. A, Riverside School dam site, viewed downstream; B, Basin  
of Lake Fork of the Gunnison River, viewed downstream  
from the left buttress of The Gate.

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herent materials are exposed at the land surface and no bedrock appears to be available for the foundation and abutments of a dam. These incoherent materials include a young gravel deposit in the stream bed and flood plain, an older terrace deposit at a few places, slope wash, and landslide rubble. The two stream deposits are quite like the corresponding deposits at the two sites upstream.



Geologic map of  
RIVERSIDE SCHOOL DAM SITE  
MILE 14.1



A. Riverside School dam site, viewed downstream. (The site is indicated in outline.)



B. Basin of Lake Fork of the Gunnison River, viewed downstream from the left buttress of The Gate. (The Riverside School site occupies the narrows at the far end of the open valley.)

The right or east abutment at the site has been formed by a slide of slope wash which entered the dam-site area from the east and overrode the stream-laid terrace deposit on the right bank. The material includes angular rock fragments in all sizes up to 6 feet in length embedded in a reddish brown earthy matrix. The slide is relatively young, its surface is moderately steep, and its matrix includes considerable material that probably would be plastic if saturated with water. Thus, although there is no obvious evidence that the slide has been in motion recently, it may not be wholly stable under natural conditions and, if its toe were saturated by raising the water level, it quite likely would be unstable.



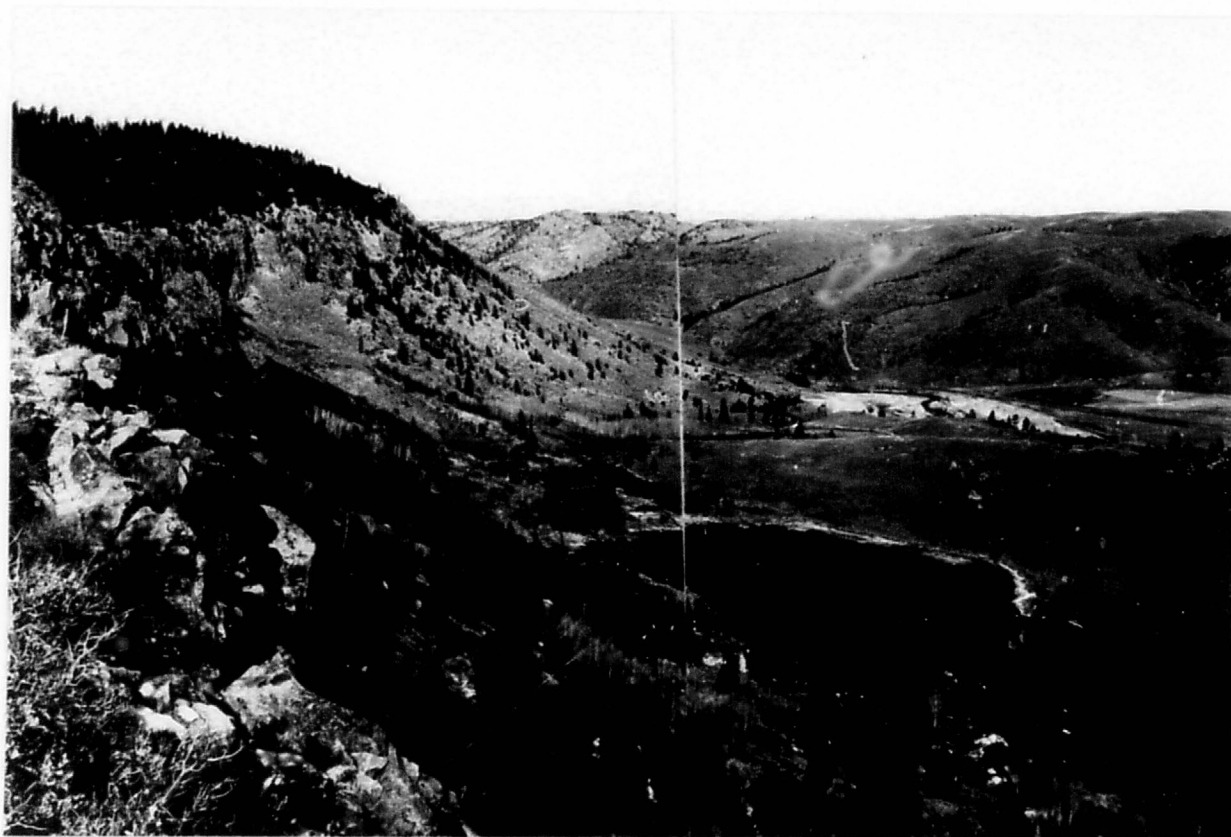
The left abutment is afforded by the toe of an old landslide which is about 0.8 mile long by 0.6 mile wide and which rises to a crescentic ridge about 525 feet above the river and half a mile to the west. From this ridge a gentle back slope descends to a crescentic depression which is partly occupied by two small ponds (pl. 24). The bulk of the material in

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Plate 24. Landslide alcove high on the left (east) bank of the  
Lake Fork opposite the Riverside School dam site.

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the landslide mass is composed of fragments of andesite such as form the cliff high above the site. These fragments range from small chips to blocks 10 feet long and are embedded in a fine-grained earthy matrix. This landslide on the left bank of the stream appears to be decidedly older than that on the east bank and to have been stable for a relatively long time, even where the Lake Fork is now cutting back its toe. The material of which it is composed appears not to be highly pervious, for no springs break out along its margins below the two high-level ponds in spite of the steep hydraulic gradient. Nevertheless, it is quite likely that some of the material would become unstable if it were saturated with water above stream level.



Landslide alcove high on the left (east) bank of the Lake Fork opposite the Riverside School dam site. (Viewed from flank of the ridge about 1,000 feet above the stream; the toe of the slide, whose top lies to the right of the two small lakes, forms one abutment of the dam site.)



Obviously, the site near Riverside School is feasible only for a flexible dam with a base of considerable width. Stability of a structure would require that both abutments be kept unsaturated. Thus, a satisfactory dam would necessarily embody an impervious membrane extending downward and laterally so far into the incoherent landslide materials as to make the percolation coefficient very small. As an alternative, the parts of the two landslide masses within the proposed reservoir site might be blanketed with impervious material.

A spillway at the site would require protection of all the materials from swiftly flowing water, for all would scour very easily.

#### Madeira Siding dam site

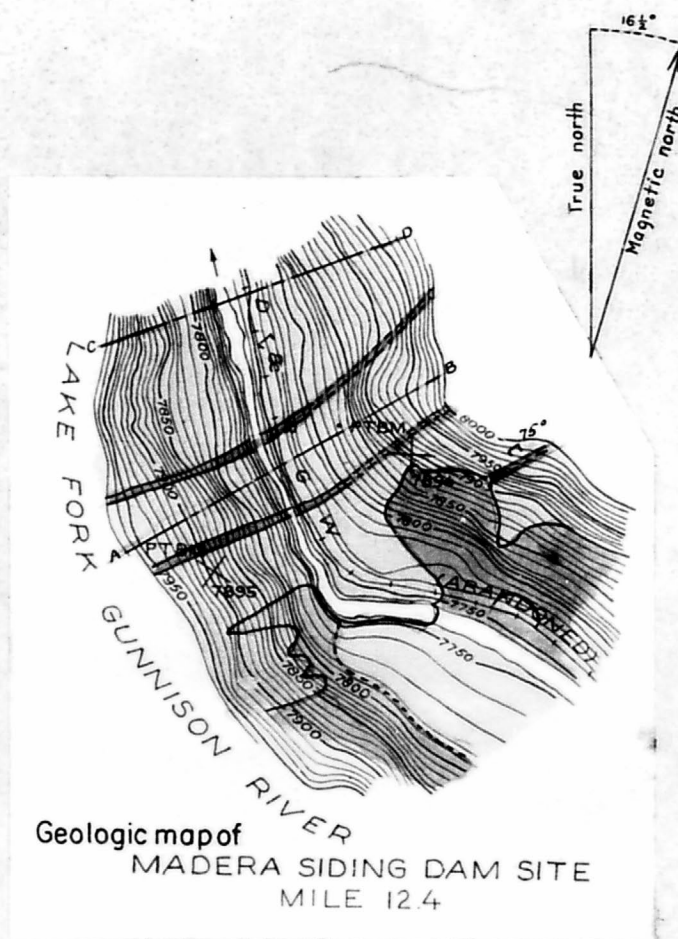
At the Madeira Siding dam site (pl. 25) the Lake Fork has cut a pre-

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Plate 25. Geologic map of the Madeira Siding dam site, Lake Fork  
of Gunnison River.

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cipitous-walled canyon into siliceous amphibolite schist. Very little incoherent material exists other than a thin discontinuous blanket of talus and one remnant of stream-laid terrace material on the left bank at the upstream edge of the area.



The schist is fine-grained, very dense, and doubtless has extremely high crushing strength. Throughout the area its planes of schistosity strike N.  $60^{\circ}$  -  $65^{\circ}$  E. or across the stream and dip  $70^{\circ}$  -  $75^{\circ}$  SE., or upstream. In general the schist becomes progressively thicker bedded and more siliceous downstream. Its beds are especially thick and dense near the downstream edge of the mapped area.

Fractures are closely spaced throughout the schist but none appear to be zones of serious weakness and none are active faults. The principal fractures appear to be as follows: (1) Strike N.  $40^{\circ}$  -  $50^{\circ}$  W., dip  $80^{\circ}$  SW., parting the schist into plates from 4 to 10 feet thick and at a few places as little as 1 foot thick. (2) Strike N.  $65^{\circ}$  E., dip  $65^{\circ}$  -  $70^{\circ}$  NE., or downstream, locally a direction of platy parting. (3) Strike N.  $45^{\circ}$  W., dip  $45^{\circ}$  SW. or diagonally upstream and downward into the left bank; at the downstream edge of the mapped area one fracture in this direction <sup>spur at an alti-</sup> undercuts a thin / tude of 8,100 feet on the right bank. Secondary fractures of slight extent and various directions of strike and dip are rather closely spaced throughout the schist. Accordingly, nearly all small crags and pinnacles are insecure. At moderate depth below the land surface many of the secondary fractures doubtless die out and most probably are tight so that only a moderate volume of rock need be stripped to expose a sound foundation and abutments.

In the central part of the mapped area two distinct bands of talus a few yards wide and from 150 to 200 feet apart extend the full height of either abutment (see pl.25). A third such zone occurs on the right bank <sup>upstream?</sup> another 150 feet downstream and above the 7,900-foot contour. These talus bands floor shallow notches in the schist and so suggest either a crushed zone or a non-resistant bed that is easily eroded. A decision between these alternatives cannot be made in the absence of exploratory drill holes.

The Madeira Siding dam site is believed to be ideally suited for a thin arched dam. Two alternative positions for a dam of this sort are indicated on plate 25 by the lines marked "AB" and "CD". At the downstream position the schist is most thickly bedded, is very siliceous, and appears to afford a foundation of superior strength. The upstream position is slightly more economical but might not be suitable for an arched dam if exploration should show that the talus bands close upstream and downstream conceal extensive fracture zones in the schist.

The many fractures doubtless render the schist slightly pervious. However, virtually all these lack selvages of crushed rock and so should be easily grouted or otherwise sealed to restrain percolation.

A spillway presents no difficult problems for the siliceous schist is extremely resistant to abrasion and, at a depth of a few feet below the land surface probably would not be plucked. Thus, only a nominal amount of paving would be required to assure a stable spillway structure.

Little Colorado and Zuni Rivers, Arizona

Features common to the  
upstream three sites

The upstream three dam sites in the basin of the Little Colorado River - the Lower Zuni, Little Colorado, and Greer sites (pls. 26-28) - are much

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Plate 26.- A, Geologic map of the Lower Zuni dam site, Zuni River;

B, Explanation for geologic maps of the Lower Zuni,  
Little Colorado, and Greer dam sites, Arizona.

Plate 27.- Geologic map of the Little Colorado dam site, Little  
Colorado River.

Plate 28.- Geologic map of the Greer dam site, Little Colorado  
River.

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alike in the rocks of which they are composed and in features that will determine the stability and watertightness of the foundation and abutments of a dam. The character of the rocks, in descending stratigraphic order, is described in the following section; the extent of each is shown on the several geologic maps.

Rocks that compose the Lower Zuni,  
Little Colorado, and Greer dam sites

<u>Unconsolidated materials:</u>	Feet
<p>Flood plain deposit: Clayey silt, maroon and pinkish gray, rude beds and interfingering lentils from 1 to 5 feet thick; tongues of unassorted sand and gravel or of angular slope wash crop out here and there in lower part of deposit. The clayey silt probably is nearly impervious but plastic when wet; the tongues of gravel and slope wash are pervious but somewhat more stable - - - - -</p>	20+
<p>Terrace deposit: Sand and gravel, unassorted and inco- its herent; even/finest particles are not decomposed and so the deposit doubtless is pervious. Veneers a bedrock shelf from 25 to 95 feet above river level. If not saturated, probably would be stable under a light load - -</p>	0-50 <sup>+</sup>
<u>Bedrock:</u>	
<p>Chinle formation (?): Limestone, earthy, thin-bedded; light-gray, yellowish-gray, and yellowish-brown colors; commonly cellular owing to many small solution passages. only Occurs in place/at the Lower Zuni site on the right bank of the river above the crest of any practicable dam but yields abundant talus and coarse land-slide rubble that covers nearly all the slope below - - -</p>	55+

Chinle formation: Largely shale, thick-bedded; maroon, greenish-gray, bluish-purple, and dark-green colors. Contains at least one member of coarse-grained friable sandstone (calcareous?). The Chinle formation commonly contains gypsum, \_/ which dissolves readily

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\_/ Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 42-49, 1917.

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in water. Such beds were not seen during the dam-site surveys but may exist beneath the slope wash; their presence would explain the extensive landslide in the overlying limestone at the Lower Zuni site. Thickness about - - - - -

270

Shinarump conglomerate: Sandstone, white or light buff; beds from 2 to 8 feet thick; in part earthy, in part even-grained and somewhat friable. Locally the top-most bed is conglomerate comprising a dense sandstone matrix with pebbles of chert, quartzite, and other rocks as much as 2 inches in diameter. Has moderate bearing power but probably is somewhat pervious - - -

16-30

Moenkopi formation: Largely shale of maroon or, in a few beds, of dark-green color. Contains many beds of sandstone which are either (1) earthy, maroon, very discontinuous, and from a few inches to 10 feet thick (see pl. 29); or (2) even-grained, light gray, somewhat friable, and fairly continuous. On slopes, the shale commonly erodes rapidly, leaving a pavement of large sandstone blocks (pl. 30). Certain shale members may be somewhat plastic if wet but the sandstone members have moderate bearing power. As a whole, the formation probably is slightly pervious along the contacts between shale and sandstone members and through the coarser sandstone members. In the region about the dam sites the Moenkopi formation is as much as 700 feet thick and is largely of red shale and sandstone with some beds of gypsum and "marl". \_/ At the dam sites

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\_/ Gregory, H. E., op. cit., pp. 23-31.

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only the uppermost part of the formation is exposed and no gypsum was seen; thickness of exposed beds           

70



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Plate 29.-A, Interbedded shale and sandstone of the Moenkopi formation exposed in right abutment of the Little Colorado dam site; B, Lenticular sandstone and shale of the Moenkopi formation exposed in highway cut 0.65 mile upstream from the Greer dam site.

Plate 30.- Pavement of sandstone blocks overlying shale of the Moenkopi formation on the left abutment of the Greer dam site.

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The rock units just described range rather widely in load-sustaining power and in perviousness; thus, they place critical limits on the type of dam for which the three sites are suited. Of the bedrock units only the Moenkopi formation and the Shinarump conglomerate offer dependable foundations and abutments; even these are non-rigid and are inconstant in bearing power. Only flexible dams of wide base seem feasible, such as fills of earth. Of the two incoherent materials, the terrace deposit, if dry, probably is fairly stable and competent to sustain a dam that imposes only a moderately light load; however, to assure stability it is essential that the dam embody a substantial impervious membrane extending through the deposit into tight bedrock beneath. The flood-plain deposit probably can sustain a light, highly flexible dam but the perviousness of its coarse tongues also requires that the dam embody a substantial cut-off structure seated in tight bedrock beneath.



A. Interbedded shale and sandstone of the  
Moenkopi formation exposed in right  
abutment of the Little Colorado dam site



3. Lenticular sandstone and shale of the Moenkopi formation exposed in highway cut 0.65 mile upstream from the Greer dam site



Pavement of sandstone blocks overlying shale of the  
Moenkopi formation on the left abutment of the Greer  
dam site

At each of the upstream three sites, the topography favors a spillway across one of the abutments a short distance from the dam. Spillway structures can have sound foundations on either the coarse sandstone of the Shinarump conglomerate or the interbedded shale and sandstone of the Moenkopi formation but should embody a cut-off adequately seated in impervious rock at a moderate depth below pool level. In part, the spillway channels would pass over the terrace deposit and the flood-plain deposit; both these incoherent materials would be scoured rapidly by swiftly flowing water and so would require protective works wherever erosion would tend to undermine the dam. On the other hand, erosion is not likely to be excessive where the spillway channel passes over bedrock, both because the rock would be abraded somewhat more slowly than the incoherent materials and because the reservoir capacities are so large that the rate of spillway discharge can be kept moderate. Thus, the initial construction need not include a pavement on the bedrock except immediately below the spillway crest; maintenance may involve later extension of the initial pavement.

General features of the corresponding three reservoir sites suggest that none is likely to leak seriously, except possibly near their downstream ends where tongues of pervious terrance gravel or other incoherent material may extend below pool level and pass around a dam-site abutment. Otherwise, bodies of incoherent material that lie below pool level are advantageous in that they can hold considerable water in temporary "bank storage". The floors of the several reservoirs are formed by the flood-plain deposit, which is judged to be so thick and so impervious as effectively to prevent downward percolation under the moderate heads that would be created by the proposed dams. Leakage laterally into the bedrock probably would not be material, both because the relatively impermeable Moenkopi formation underlies all or nearly all of each reservoir and because the water table appears to be above river level, except possibly at the Little Colorado site.

## Critical features of the upstream three sites

### Lower Zuni dam site

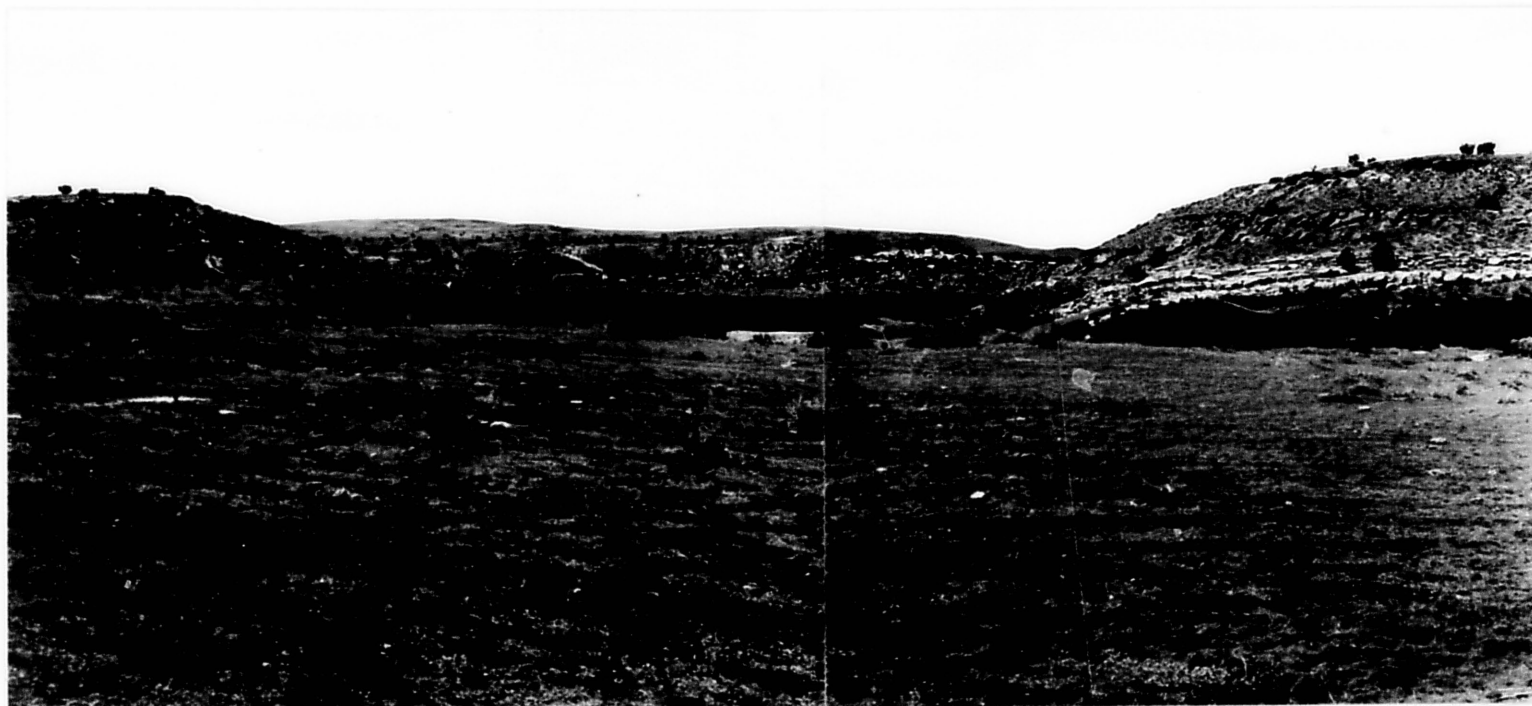
On plate 26, A three possible positions for a dam at the Lower Zuni site are indicated by the lines marked "AB", "CD", and "EF", respectively. Each position appears to afford sound bedrock abutments up to about the 5,520-foot contour - that is, 60 feet above the flood plain or 75 feet above the river. The relative advantage of these positions depends largely upon two critical features of the site: first, the thickness of the landslide rubble on the right bank and second, on the contour of the bedrock beneath the flood plain. The thickness of the rubble is critical because that material is very unstable and so should be stripped completely from the foundation of any dam, / <sup>also</sup> because it probably is pervious and may conceal a channel in the bedrock passing around the abutment below the proposed pool level. The contour of the bedrock beneath the flood plain is critical because it determines the extent of the cut-off structure that would be needed to prevent leakage under a dam. Both features should be explored thoroughly by pits or drill holes before a position is chosen.

The downstream position, AB, exposes bedrock (Moenkopi formation overlain by Shinarump conglomerate) to the greatest height above the stream on the right (north) bank. Thus, it suggests that a suitable abutment can be prepared with the least excavation in the landslide rubble. Its two disadvantages are: first, the right abutment is rather narrow and so may leak unless extensively grouted or blanketed with silt; second, the flood plain is widest and so may require the most extensive cut-off structure. The middle position, CD, offers the narrowest flood-plain section between outcrops of bedrock in place and possibly the dam of least volume. However, it may require the greatest volume of excavation/<sup>on</sup>the right bank and, with the landslide rubble removed, may lose the seeming advantage of the broadest right abutment. The upstream position, EF, is perhaps the least advantageous for it requires the longest dam and considerable excavation on the right bank. However, it is slightly superior to the downstream position in that the flood plain is narrower and the right abutment wider.



One minor feature of geologic structure suggests a possibility of leakage around a dam. Thus, on the left (south) bank, the shale and sandstone of the Moenkopi formation are sharply downfolded, but apparently are not faulted, along an axis that is roughly parallel to the stream. (See pl. 26,A) In the downstream half of the area the fold is sharpest and along its axis the sandstone members are fractured and so are probably somewhat pervious. However, this pervious zone has a relatively long path around the abutment of the downstream position so that the potential leakage is not likely to be serious. Upstream, the fold is less sharp and the rocks less fractured so that the possibility of leakage at the upstream two positions probably is no greater even though the abutments are narrower. Except for this feature just described, the three suggested positions seem to be equal with respect to the possibility of leakage through the bedrock at the dam.

At all three positions, the most advantageous place for a spillway is on the left abutment because the unstable landslide rubble is so extensive on the opposite bank. For an adequate spillway channel, the downstream position appears to require the most excavation.



Little Colorado dam site viewed downstream; the most advantageous abutments are at either edge  
of the field

### Little Colorado dam site

At the Little Colorado dam site (pls. 27, 41) all the bedrock is of

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Plate 31.- Little Colorado dam site viewed downstream; the most advantageous abutments are at either edge of the field.

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the Moenkopi formation (p. 76), which has fairly low bearing power and probably is slightly pervious along the contacts between its shale and sandstone members. With respect to the stability and watertightness of a dam, the most critical geologic features of the site are: (1) certain small folds in the bedrock, the form of which is shown on plate 27 by symbols that show the direction and amount of dip, also the outcrops of certain sandstone members; and (2) the thickness of the pervious terrace deposit, which is extensive on either side of the stream. Another feature, the cross-sectional area of the flood-plain deposit, determines the extent of the cut-off structure that would be necessary beneath a dam (see p. 84) and so determines one large item of construction cost. In following paragraphs, these three features are discussed in relation to the erection of a dam at either of two positions, which are indicated on plate 27 by the lines marked "AB" and "CD", respectively.

In all the area shown on plate 27, the position AB requires the least material for a dam and seems to call for the least extensive cut-off through the flood-plain deposit. Thus, it involves the least expenditure for construction of the main dam. The feasibility of a dam in this position depends chiefly on conditions in the left abutment, which is a relatively narrow spur. Of the rock that forms this spur, fully two thirds is impervious shale and the remainder comprises several sandstone interbeds which are largely earthy and only moderately or slightly pervious. These beds are folded into a small anticline whose axis follows the line AB and whose flanks are parallel to the two side slopes of the spur (which are dip slopes on a single sandstone member). The width of the spur is about 10 times the head that would be imposed by the dam that is contemplated. It is believed that this head is too small to cause material leakage through the spur - that is, across the anticlinal fold in rocks that are not highly pervious. Further, that owing to its anticlinal form the spur would be adequately stable even if its shale beds were saturated. Thus, the economical position AB appears to be feasible, although the critical features just described should be explored thoroughly by pits and drilled holes before construction is undertaken. Above an altitude of 5,550 feet, the crest of the spur just described is formed in part by the pervious terrace deposit. The thickness of this deposit along the line AB is estimated to be 10 feet or less, so that no great expense would be involved in removing it completely or in sinking a cut-off structure through it to the underlying bedrock.

The position CD is superior in that it permits a dam of shorter crest and affords a left abutment of greater stability and less potential leakage. It is decidedly inferior in that its flood-plain section is nearly twice as long, so that a dam would require much more material and a more extensive cut-off. However, it is a feasible alternative for the upstream position, AB, in case unforeseen conditions in the left abutment there prove to be unfavorable for a stable watertight dam.

The pervious terrace deposit is extensive on the right bank, where it may be so thick as to extend below the contemplated pool level and so to permit leakage around the abutment of the dam. To assure watertightness, the contour of the top of the bedrock should be established by pits and appropriate cut-off works provided.

For a spillway, a cut on the right bank through the small saddle that is marked "E" on plate 27 would be advantageous in that neither the abutment nor the toe of the dam would be exposed to scour. That saddle is about 5,598 feet above sea level, little above the contemplated pool level. However, it is formed in part by the incoherent terrace deposit, which may extend below pool level and so require extensive paving and a substantial cut-off.

To spill water across the opposite or left abutment, with a dam at the upstream position AB, would require rather extensive works to prevent scour along the abutment and toe. With a dam at the downstream position CD, neither its abutment nor its toe would be exposed to scour but a relatively long cur would be required.

### Greer dam site

The Greer dam site affords one practicable position for a dam, along the line marked "AB" on plate 28. The geologic features of the site are closely analogous to those of the Little Colorado site just described, except that the bedrock strata (Moenkopi formation) are very nearly horizontal and include relatively coarse clean sandstone near the base of either abutment. This sandstone probably is moderately pervious, both through the interstices between its grains and through its few fractures. Accordingly, the right (north) abutment, whose width is only about 10 times the head that would be created by the proposed dam, is liable to leak unless extensively grouted or blanketed with silt. The left abutment may require similar treatment although it is relatively broad and so less liable to leak.

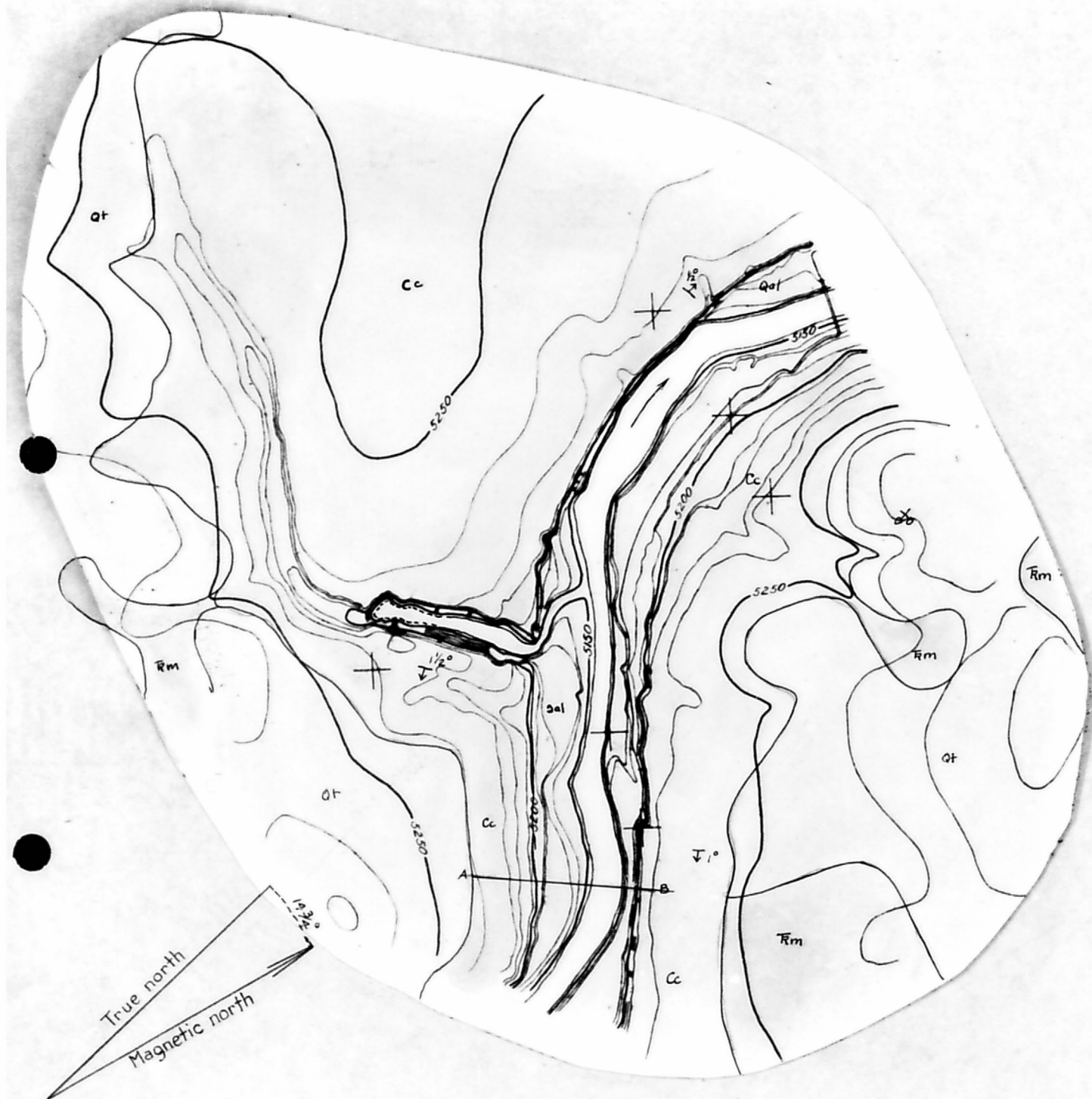
Character of the rocks at the downstream three dam sites

The following section describes, in descending stratigraphic order, the rocks that form the downstream three dam sites on the Little Colorado River: the Forks, Woodruff, and Holbrook sites (pls. 32-37).

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Plate 32.- A, Geologic map of the Forks dam site, Little Colorado River; B, Explanation for geologic maps of the Forks, Woodruff, and Holbrook dam sites, Arizona.

- 33.- Little Colorado River: Forks dam site viewed downstream.
  - 34.- Geologic map of the Woodruff dam site, Little Colorado River.
  - 35.- Little Colorado River: Woodruff dam site viewed downstream.
  - 36.- Geologic map of the Holbrook dam site, Little Colorado River.
  - 37.- Little Colorado River: Holbrook dam site viewed downstream.
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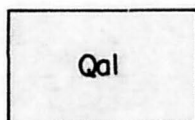


Geologic map of the Forks dam site, Little Colorado River

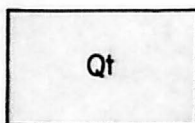


# EXPLANATION

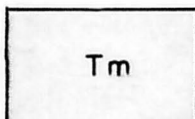
For geologic maps of the Forks, Woodruff, and  
Holbrook dam sites, Arizona



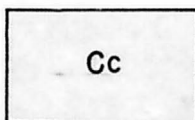
Stream-bed and flood-plain deposit  
*(silt and fine sand with a few local talus blocks)*



Terrace deposit  
*(gravel and sand)*



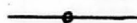
Moenkopi formation  
*(maroon shale enclosing thin discontinuous beds of  
maroon earthy sandstone)*



Coconino sandstone  
*(thick-bedded white sandstone in part cross-bedded)*



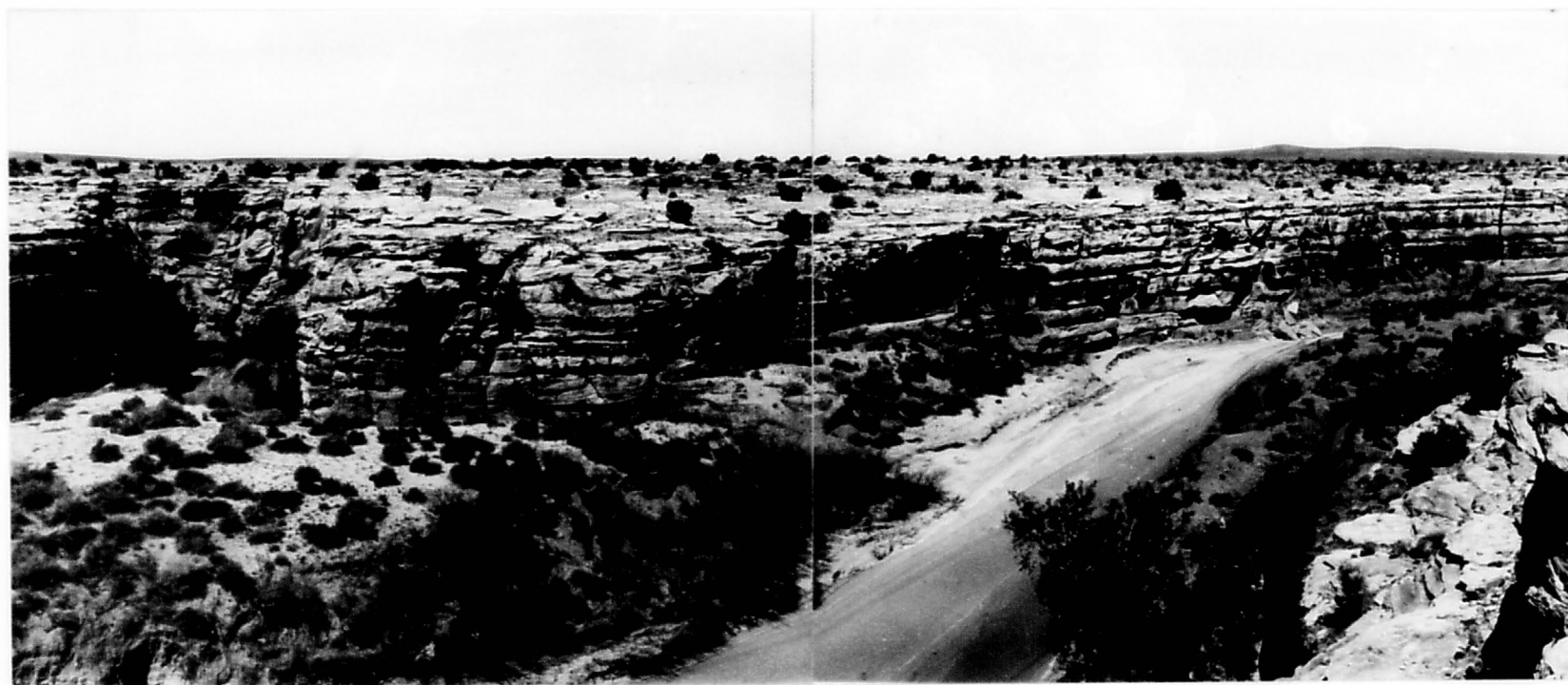
Direction and amount of dip



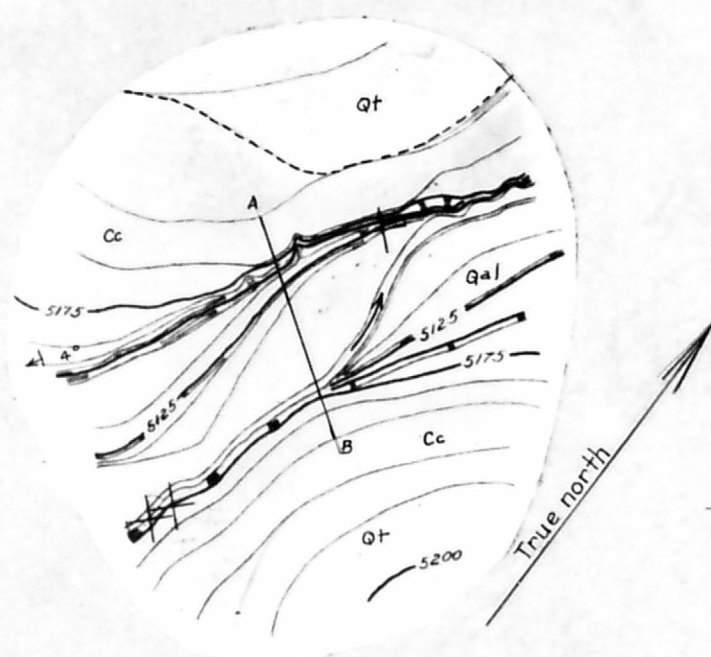
Strike of subvertical fracture



Suggested position for dam



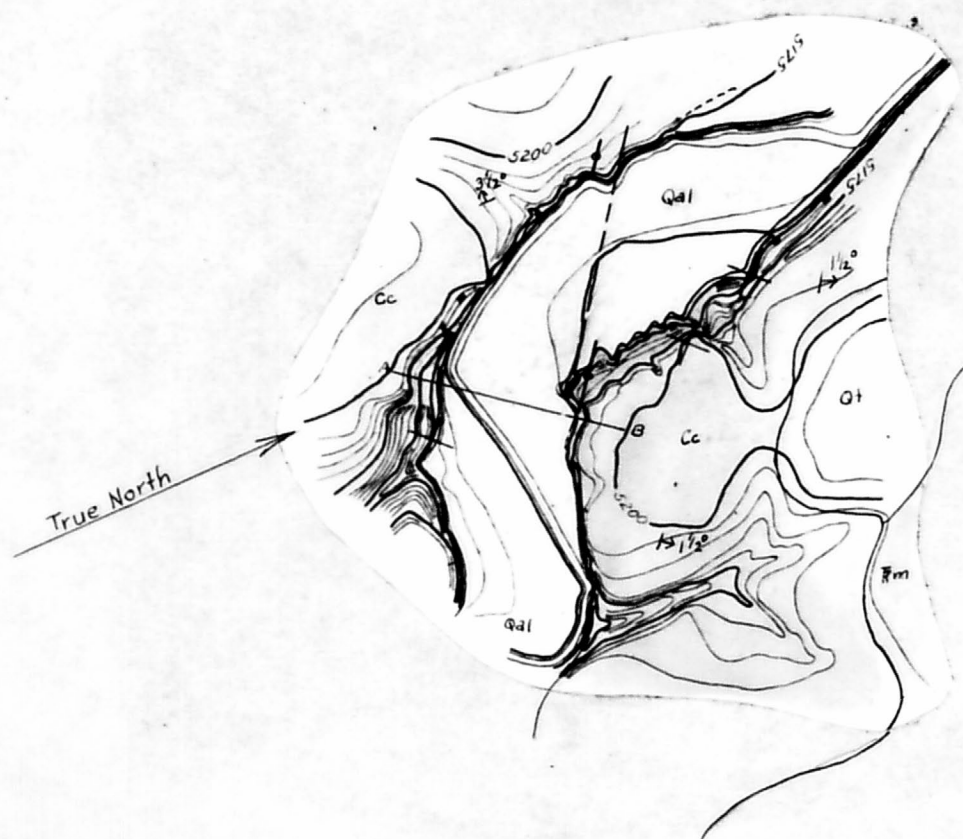
Little Colorado River: Forks dam site viewed downstream



Geologic map of the Woodruff dam site, Little Colorado River



Little Colorado River: Woodruff dam site viewed  
downstream



Geologic map of the Holbrook dam site Little Colorado River



Little Colorado River: Holbrook dam site viewed downstream

Composite section of rocks at the Forks, Woodruff,  
and Holbrook dam sites

<u>Unconsolidated materials:</u>	Feet
Stream-bed and flood-plain deposit: Unassorted silt and fine sand enclosing a few talus blocks of local origin; somewhat pervious and extremely unstable if saturated with water - - - - -	40+
Terrace deposit: Unassorted sand, pebbles, and cobbles of quartzite, chert, and other dense rocks; few cobbles more than 3 inches in diameter. To a depth of about 3 feet, the deposit has been reworked and mingled with silt; at greater depth it is fresh, incoherent, and highly pervious. The deposit is discontinuous and veneers a rock shelf from 80 to 105 feet above the river - - - - -	0-30+
<u>Bedrock:</u>	
Moenkopi formation: Maroon shale enclosing discontinuous beds of maroon earthy sandstone; probably nearly impervious. Forms patches high on either bank of the river at the Forks and Holbrook dam sites; extensive in all three reservoir sites. The beds exposed form the lowest part of the formation; thickness about - -	75
Coconino sandstone: Even-grained white sandstone, slightly friable; beds from 2 to 20 feet thick; in part cross-bedded. Inferred to have moderate crushing strength but to be highly pervious through interstices, between beds, and along fractures. From 90 to about 1,000 feet thick in the region about the dam sites; exposed, at and near the sites - - - - -	85-110

The incoherent stream-bed and flood-plain deposit is not suitable to remain beneath a dam of any type. The depth to which it extends below river level is not known but may well be several tens of feet all along the downstream reach of the river.

Only the Coconino sandstone occurs in the abutments of the three sites; in general, this rock is sound and has uniform moderate bearing power. Its principal fractures are as follows:

1. Strike N.  $45^{\circ}$  -  $50^{\circ}$  W. (acute to the general course of the river), dip  $80^{\circ}$  -  $90^{\circ}$  SW. Ordinarily these extend vertically the full height of the river bluffs and horizontally for several hundred feet; they are from 20 to 60 feet apart, somewhat wavy, and without crushed selvages. A few are zones, several feet wide, of discontinuous en echelon partings.

2. Strike about N.  $40^{\circ}$  E., dip  $75^{\circ}$  -  $90^{\circ}$  NW. or SE. These also extend the full height of the bluffs, are wavy, and lack crushed selvages; however, along the strike they commonly terminate against fractures of the set first described.

3. Strike about N.  $30^{\circ}$  W. and in various other directions, dip various in amount and direction. These are minor cross fractures within single beds of the sandstone; commonly they are no more than 5 feet apart.



Among the three dam sites, the fractures just described are most closely spaced at the Woodruff site; they are most extensive at the Holbrook site. None of the fractures are faults of appreciable displacement and so probably do not seriously weaken the abutments or foundations of the sites. However, they afford a moderate number of extensive openings through the abutments, and so will require extensive grouting or other suitable measures to restrain leakage. Further, they loosen a considerable volume of rock along the bluffs, where the outermost rock plate commonly is detached and leans toward the river as much as 18 inches. For example, at the Holbrook site all the small spur on the right bank immediately downstream from the suggested position for a dam (line AB on plate 36) is so insecure.

The rock that lies below the river does not crop out at or near the sites, so that its character is unknown. Because plates of the Coconino sandstone commonly lean outward along the river bluffs, as just described, it is inferred that the underlying rock may be inferior in bearing power.

## Comparison of the Forks, Woodruff, and

### Holbrook sites in critical features

The Coconino sandstone affords stable abutments for a dam at each of the downstream three sites along the Little Colorado River, provided all insecure plates along the bluffs are completely removed. If rock of equal or superior bearing power is moderately thick beneath the river bed, each of the sites appears to be suitable for a rigid dam of gravity cross-section and about 90 feet high, but probably not suitable for a thin arched dam. However, if rock weaker than the exposed Coconino sandstone lies at or just below river level, as has been suggested, flexible dams may be necessary. Fills of rock quarried from the Coconino sandstone at the several sites would be feasible. As a basis for determining the feasible type of dam, exploratory drilling in the river bed is desirable.

On the geologic maps of the several sites (pls 32, A; 34,36), the lines marked "AB" suggest positions for dams involving (1) the minimum volume of scaling to prepare sound abutments, (2) the least volume of material in the structure, and (3) a minimum leakage through abutments or foundation. In all three respects, the Forks dam site appears superior to the Woodruff or Holbrook sites, which are downstream. The Woodruff site is inferior in that its abutments are much more closely fractured and so would require more extensive works to restrain leakage. The Holbrook site requires a greater volume of material for a dam and probably the greatest amount of scaling.

In a spillway, the Coconino sandstone would be moderately but not highly resistant to abrasion and would yield somewhat by the plucking and undercutting of blocks. Accordingly some pavement or other protective works would be required. All other rock formations at the three sites would be eroded more rapidly.

## Watertightness of the downstream three

### reservoir sites

The relative watertightness of the reservoir sites that correspond to the three dam sites just described is suggested by folds in the bedrock and by the relative extent of the pervious Coconino sandstone and of the impervious Moenkopi formation that overlies the sandstone. However, a close estimate of potential reservoir leakage is impossible because neither the form of the water table nor the head of the ground water with respect to the proposed reservoir levels is known.

From the Forks dam site, the Coconino sandstone dips  $2^{\circ}$  -  $4^{\circ}$  NE. and plunges under the Moenkopi formation; this condition favors infiltration along the right bank of the reservoir and percolation through the sandstone toward the town of Woodruff. Between  $1\frac{1}{2}$  and 2 miles from the dam site, however, the sandstone conduit is inferred to be dammed, at least in part, by igneous rocks related to those of Woodruff Mountain and other smaller volcanic vents along the west side of Woodruff Lake. Together, all these features suggest that the reservoir may leak moderately but probably not excessively.

On the other hand, the Woodruff reservoir site is a structural basin whose floor and lower slopes are underlain by the impervious shale of the Moenkopi formation. Thus, it is believed that most of the reservoir is watertight. Only close to the dam, where the bedrock is flexed upward rather sharply, could impounded water reach the pervious sandstone. Even there, a considerable part of the water that entered the sandstone probably would return as the reservoir was emptied. This seeming advantage of the Woodruff site is largely, if not wholly, offset by the fact that the reservoir is many times more extensive than at the Forks or Holbrook sites and so would lose much more water by evaporation.

The Holbrookreservoir site is formed by bluffs of the Coconino sandstone; in the vicinity, this pervious formation is nearly horizontal. Thus, the potential leakage is limited by the height of the impounded water above the ground-water level and by the form of the water table; neither of these limiting factors is known. It is believed that leakage would be moderate, probably somewhat more than at the Woodruff reservoir site but less than at the Forks site.

Rio Grande Basin, New Mexico

Rio Chama

Character of the rocks at the Canon de Chama  
and Abiquiu dam sites

The following table describes the rock formations of the Canon de Chama and Abiquiu dam sites in descending stratigraphic order; the geologic maps that accompany the descriptions of the sites (pls. 40-42) show the extent of each formation.

Rock formations at the Cañon de Chama  
and Abiquiu dam sites

Unconsolidated materials:

Feet

Stream-bed deposit: unassorted sand, pebbles, and  
 cobbles of crystalline rocks, commonly as much as  
 6 inches in diameter; also sparse blocks of local  
 sedimentary rocks, of which many are as much as  
 5 feet long and a few 20 feet long. Unweathered  
 and highly pervious - - - - - Unknown

Flood-plain deposit: rude strata of pebbly sand and  
 silt, also of coarse gravel derived largely from  
 crystalline rocks. Highly pervious - - - - - do

Low-terrace deposit: largely unassorted pebbles and  
 cobbles of crystalline rocks in all sizes up to  
 12 inches in diameter; uppermost part pebbly sand;  
 all particles somewhat iron-stained but not decom-  
 posed. Probably formed by reworking of the inter-  
 mediate-terrace deposit, to be described, and sepa-  
 rable from that deposit only by land forms. Inco-  
 herent and highly pervious.

Intermediate-terrace deposit: physical character  
 identical with that of the low-terrace deposit.  
 Veneers bedrock shelves from 50 to 350 feet above  
 river level (in considerable part, this wide range  
 in altitude probably is due to subsequent faulting - - - - 0-60+

High-terrace deposit (Cañon de Chama site only): coarse gravel derived from crystalline rocks; similar in composition to the intermediate-terrace deposit but more weathered. Veneers bedrock shelf about 175 feet above river level, but commonly reworked and washed far down the slopes. Overridden by and mingled with old talus, next described - - - - -

0-40+

Old talus: earthy matrix enclosing blocks in all sizes up to 10 feet long from the denser rocks that underlie the adjacent high mesas (sandstone, conglomerate, and gypsum at the Cañon de Chama site; largely basalt at the Abiquiu site). Probably very unstable if wet. Initial thickness unknown but may well exceed 100 feet; locally reworked and washed far down the slopes - - - - -

Bedrock:

Chinle (?) formation \_/: largely shale; red, purple, and

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\_/ Correlation of bedrock formations after Darton, H. H., "Red beds" and associated formations in New Mexico: U. S. Geol. Survey Bull. 794, pp. 8, 20-21, 31-32, 1928.

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greenish gray in color; contains near the base a few beds of earthy sandstone from 1 to 2 feet thick. The lower part of the formation composes the upper part of the abutments at the Cañon de Chama site. Perviousness very low; bearing power moderate or low, because some beds probably would be somewhat plastic if wet. Thickness in the region about the sites - - - - -

250-950+

Poleo sandstone (pl. 38): sandstone, light gray to drab,

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Plate 38.--A, Upper part of the Poleo sandstone at  
base of left abutment, Cañon de Chama  
dam site; B, Poleo sandstone overly-  
ing Abo sandstone in left bank at the  
Abiquiu dam site.

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weathers chocolate brown; largely even-grained, dense  
(somewhat friable if weathered), massive, strata from  
2 to 30 feet thick and in part cross-bedded. Lower  
half of the formation contains many bands of grit and  
conglomerate. The upper 75 feet of the formation in-  
cludes relatively thin beds of somewhat earthy sandstone  
separated by layers of sandy shale as much as 18 inches  
thick; this zone may grade into or interfinger with the  
Chinle (?) formation. The base of the Poleo sandstone  
is an unconformity, which at most places is inclined  
5° or less. The formation has moderate bearing power;  
it probably is moderately pervious through interstices,  
between beds, and along fractures. Thickness at the  
Abiquiu dam site - - - - - 220-290





A. Upper part of the Poleo sandstone at base of left abutment, Cañon de Chama dam site



B. Poleo sandstone (Tr p) overlying Abo sandstone (Ca) in left bank at the Abiquiu dam site

Bedrock - Continued.

Feet

Abo sandstone: comprises alternate members of

(1) shale, in part sandy, red to pinkish or greenish gray, from 10 to 50 feet thick, enclosing discontinuous seams of coarse earthy sandstone a few inches thick; and (2) coarse sandstone (arkosic) containing streaks of conglomerate, greenish gray when fresh, weathers brownish red, beds from 15 to 25 feet thick. At the Abiquiu site the sandstone members compose about a third of the exposed section and in general thicken upstream. The bearing power of the sandstone members is equal to that of the Poleo sandstone; of the shale members, slight. As a whole the formation probably is only slightly pervious. Thickness of the formation in the region, 600-800 feet; of the part exposed at the Abiquiu site - - - - -

150+

### Cañon de Chama dam site

At the site in the Cañon de Chama (pls. 39, 40), a dam as much as

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Plate 39.- Rio Chama, Cañon de Chama dam site viewed upstream  
from the left abutment.

40.- A, Geologic map of the Cañon de Chama dam site,  
Rio Chama; B, Explanation for geologic maps of the  
Cañon de Chama and Abiquiu dam sites, New Mexico.

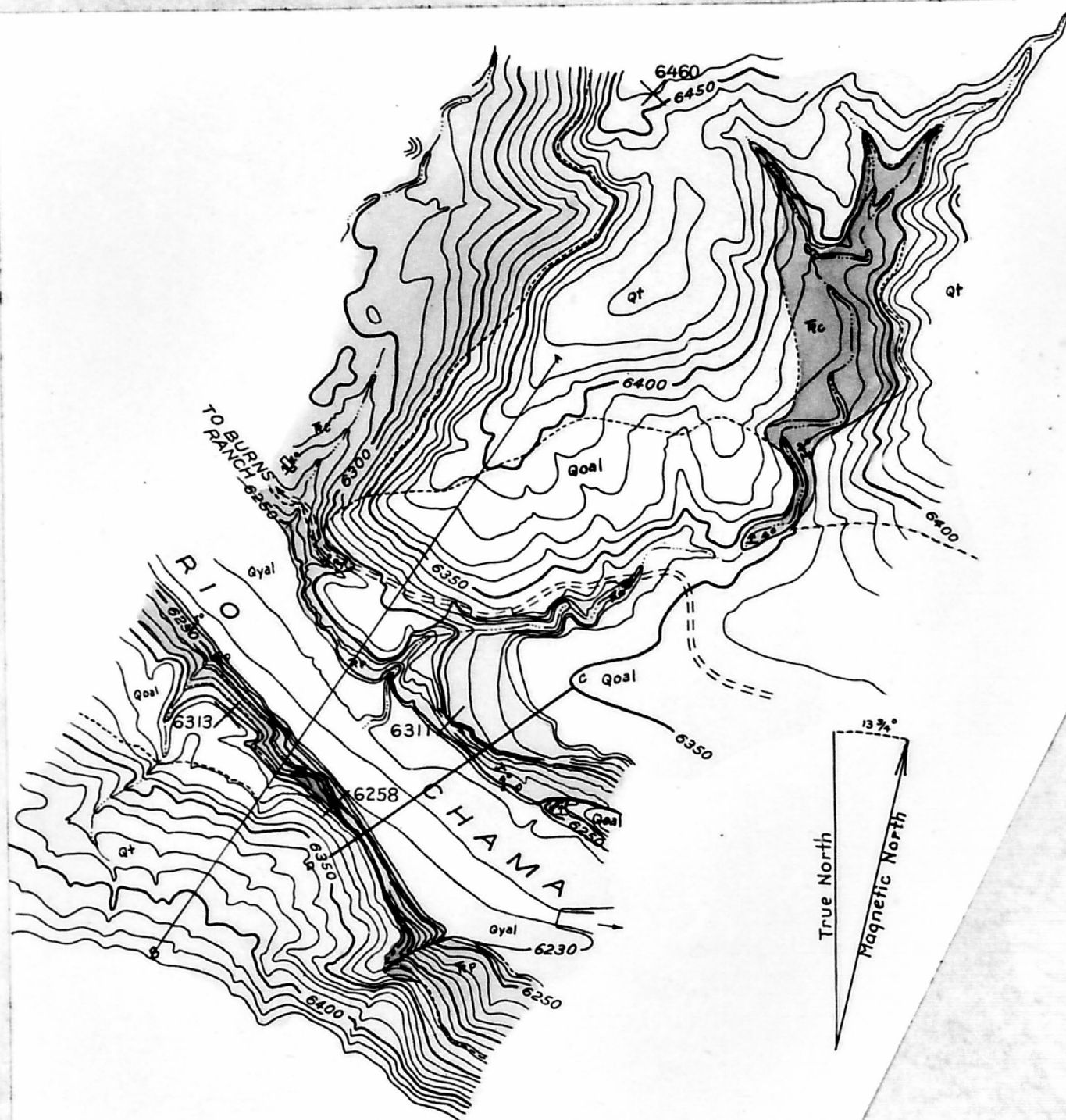
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200 feet high is contemplated. For a dam so high only one economical position exists, as indicated on plate 39, A by the line marked "AB". Also, only a structure of moderate width is permitted by the narrow spur that affords the left (north) abutment, so that a fill of earth or rock seems infeasible. For a lower dam, not more than 120 feet high, there is a more advantageous position about 350 feet downstream, indicated by the line marked "CD".

With reference to the high dam, the most critical features of the site are: (1) the depth of excavation necessary in the several incoherent deposits, which are extensive on either bank; (2) the extent and relative bearing power of the two bedrock formations, Poleo sandstone and Chinle (?) formation; (3) the watertightness of the bedrock in the narrow spur that affords the left (north) abutment and (4) the local earthquake hazard. These four features are treated in order by following paragraphs.



Rio Chama, Cañon de Chama dam site viewed upstream from the left abutment



GEOLOGIC MAP OF  
CANYON DE CHAMA DAM SITE  
(MILE 45.9-SHEET 4)

Neither the several terrace deposits nor the old talus affords a stable foundation for the high dam. These incoherent deposits are continuous above the 6,295-foot contour on the right bank and the 6,280-foot contour on the left bank - that is, beneath all the proposed dam except the lower 50 to 60 feet of either abutment. On the left bank, their average thickness is estimated as 40 feet; on the right bank somewhat more, possibly not less than 50 feet. Thus, a large volume of material must be excavated to prepare a satisfactory foundation; also, a dam more than 170 feet high (above the 6,400-foot contour) would require a long wing or a substantial cut-off structure on the crest of the left abutment.

The incoherent materials that form the stream bed and flood plain likewise should be removed completely. Their thickness may well be several tens of feet.

The two bedrock formations are very gently folded but in general dip  $2^{\circ}$  -  $5^{\circ}$  upstream. The lower formation, the Poleo sandstone, is fairly rigid and has moderately high bearing power. Along the line AB, its base is probably at least 100 feet below the river; its top is between 40 and 75 feet above the river and is inclined upstream parallel to the dip. This rock probably would sustain a rigid dam of gravity cross-section but not a thin dam arched for stability. Above the Poleo sandstone, is the Chinle (?) formation, which would underlie the upper two-thirds of the 200-foot dam. This formation is decidedly inferior to the Poleo sandstone in bearing power and may be too weak to sustain so high a rigid dam of gravity cross-section. Thorough exploration of this weak formation by drilled holes and loading tests seems essential as a basis for determining the ratio between height and width of a dam that would be stable. This ratio having been determined, the maximum feasible height will be limited by the width of the left abutment.



With a dam 200 feet high, the hydraulic gradients across the relatively thin left abutment would be about 25 percent or less for the shale of the Chinle (?) formation and from 25 to at least 60 percent for the Poleo sandstone. Under hydraulic pressure of this magnitude the potential leakage is moderately large for the sandstone but probably not excessive for the shale. It seems essential that the high dam embody either an impervious curtain extending to considerable depth in the sandstone and to moderate depth in the shale, or a blanket of impervious material over the upstream face of the abutment to a minimum height of 100 feet above the river.

The hazard of an earthquake with an epicenter near the Cañon de Chama site is not negligible, owing to faults that are potentially active. One fault of small displacement is exposed at the base of the right abutment about 600 feet downstream from the line AB. About a mile downstream the river crosses two more faults of small displacement and then is sharply deflected southward along a fault scarp about 100 feet high. That these faults are not inactive is suggested by the fact that others in the vicinity have displaced terrace deposits which are young in the geologic time scale. (See p. 106) Accordingly, any dam at the site should be designed to withstand a strong earth motion.



The geologic features of the position suggested for the low dam (indicated by the line marked "CD" on plate 40, A) are analogous in all respects to those just described. For the height proposed, not more than 120 feet above the river, the principal advantages of the position are as follows: (1) a dam would require about one fourth less material; (2) considerably less excavation would be needed to remove incoherent materials, especially on the right bank; (3) neither abutment is critically thin; and (4) the relatively strong Poleo sandstone would form all the left abutment and the lower 60 feet of the right abutment. An inflexible dam of gravity cross-section probably would be stable but, on the other hand, the abutments are wide enough for a fill of earth or rock. Works of moderate extent would suffice to restrain leakage through the abutments.

### Abiquiu dam site

At the Abiquiu site a dam as much as 350 feet high is contemplated. For a dam so high, the most advantageous position seems to be downstream from the conspicuous hanging valley on the left bank, as indicated by the line marked "AB" on plate 41. That position minimizes the potential leakage

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#### Plate 41.- Geologic map of the Abiquiu dam site, Rio Chama

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without a material increase in the volume of the dam or loss in stability of foundation and abutments. General features of the rock formations at the site have been described on pages 94 to 98; of these, only the bedrock can sustain a high dam.

Stability and watertightness of a dam.- The stability of a dam at the Abiquiu site depends both on the bearing power and distribution of the bedrock formations (Abo and Loleo sandstones), also on the local earthquake hazard. Following paragraphs discuss these features in order.

The Abo sandstone underlies the river bed to a depth of several hundred feet and forms the lower part of either abutment, to a height of about 55 feet above the river on the right bank and 145 feet on the left bank. Along the line AB, the top of this formation dips  $4^{\circ}$  -  $5\frac{1}{2}^{\circ}$  S.  $20^{\circ}$  W. - that is, downward from the left bank and directly across the river. Commonly the topmost member of the formation is gritty clayey shale from 30 to 50 feet thick; it has moderate or low bearing power and probably would be non-rigid if wet. Its inclination is not opposed to the tendency of a dam to slide downstream. Thus, the member is a cause of weakness low in either abutment. The remainder of the formation exposed in the river banks comprises alternate strata of sandstone and shale whose average bearing power is moderate or low. Rock of similar character presumably underlies the stream bed. Because rocks so weak underlie its lower part, the Abiquiu site appears unsuited for an extremely thin<sup>dam</sup> and possibly is suited only for a non-rigid dam. With respect to this feature of the site a final judgment can not be made without exploratory drill holes and suitable loading or crushing tests.

The Poleo sandstone, which overlies the Abo sandstone and forms all the upper part of either abutment (see pl. 38, B) has somewhat greater bearing power. Its strata are very nearly horizontal (dip less than  $1^{\circ}$ ) and so neither oppose nor favor the tendency of a dam to slide downstream. This sandstone probably would sustain a rigid dam of moderate width but not an arched dam thinner than "gravity" cross-section; it affords abutments sufficiently rigid for any type and height of dam that would not overload the Abo sandstone beneath.

There seems to be a considerable hazard of earthquakes with epicenters near the Abiquiu dam site which, as Erdmann \_/ has pointed out, is located

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\_/ Erdmann, C. E., Geologic reconnaissance of the Abiquiu dam site, Rio Arriba County, New Mexico: U. S. Geol. Survey, official memorandum, May 27, 1935.

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in an upfaulted block or horst about 1.5 miles wide along the river. (See pl. 42). The two faults that bound this horst have displaced both terrace

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Plate 42.- Geologic map showing faults near the Abiquiu dam site.

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deposits and old talus, and so have been active late in the geologic time scale. Probably they should be considered as still potentially active, although they have been at rest so long that the river is roughly graded across them. A third fault, about 1.6 miles downstream from the site, has much greater displacement but shows no obvious evidence of late activity. Owing to nearness of the two potentially active faults, any dam at the Abiquiu site should be designed to withstand a strong earthquake shock.

Moderate leakage is to be expected through abutments and foundation close to the proposed high dam unless suitable measures are taken to seal interstices in the Poleo sandstone and pervious zones along bedding planes and fractures in both the Poleo and Abo formations. A substantial cut-off seated well into the Abo formation also seems essential so that shale members close below the dam will not become saturated and so non-rigid.

Some leakage through the Poleo sandstone to the fault scarp half a mile downstream from the dam is likely, because the hydraulic gradient favoring such leakage would be as much as 10 percent. Deep percolation to the fractured zone along the fault and thence to the river may also be appreciable, because the hydraulic gradient would be as much as 15 percent and the zone probably is highly pervious at some places. Leakage of this sort would not threaten the stability of the dam; if it proves to be excessive, probably it could be reduced materially by sluicing an impervious blanket of silt over the upstream faces of the two abutments. There seems to be no possibility of reducing this slight potential leakage by placing the dam farther upstream, for the potential leakage into the hanging valley on the left bank is even greater.

Spillway problems.- Swiftly flowing water of considerable depth would abrade the massive thick-bedded sandstone slowly, accordingly this rock would not require extensive pavement or other protective works in a spillway. On the other hand, the earthy partings in the thin-bedded upper part of the Poleo sandstone and the shale members of the Abo sandstone would be cut easily. In this manner, large masses of the massive sandstone might be undermined and so made insecure. Accordingly, these partings and members would need substantial protective works wherever excessive erosion would endanger the stability of the dam or spillway structure.

Watertightness of the reservoir.- Nearly all the reservoir above the Abiquiu dam site is veneered with the incoherent terrace deposits. These deposits are highly pervious and would absorb considerable water as the reservoir was filled; on the other hand, they have little capacity to retain water and so would drain freely as the reservoir was drawn down. Thus, they would increase the nominal capacity by temporary "bank storage". Immediately beneath these pervious deposits, most of the reservoir is underlain by impervious shale of the Chinle (?) formation. The moderately pervious Poles sandstone forms the reservoir floor only near the dam site and discontinuously along the river farther upstream. These general features suggest that leakage is not at all likely to be material.

As plate 42 shows, the lower end of the reservoir is crossed by one of the major faults that have been described, also by at least one minor fault. Along the major fault the thick-bedded sandstone is somewhat brecciated but in considerable part abuts against impervious shale. Accordingly, even the brecciated zones probably will not cause an excessive volume of water to percolate from the reservoir.

## Willow Creek

### Features common to the three sites

Character and succession of the rocks.— The following table describes, in descending stratigraphic order, the rocks that form the upper, middle, and lower dam sites on Willow Creek (also designated by K. A. Heron as the Rutherford, Willow Creek, and Lower Rutherford sites, respectively), also the corresponding reservoir sites. The areal extent and inclination of these rocks are shown by the geologic maps of the several sites (pls. 43-45)

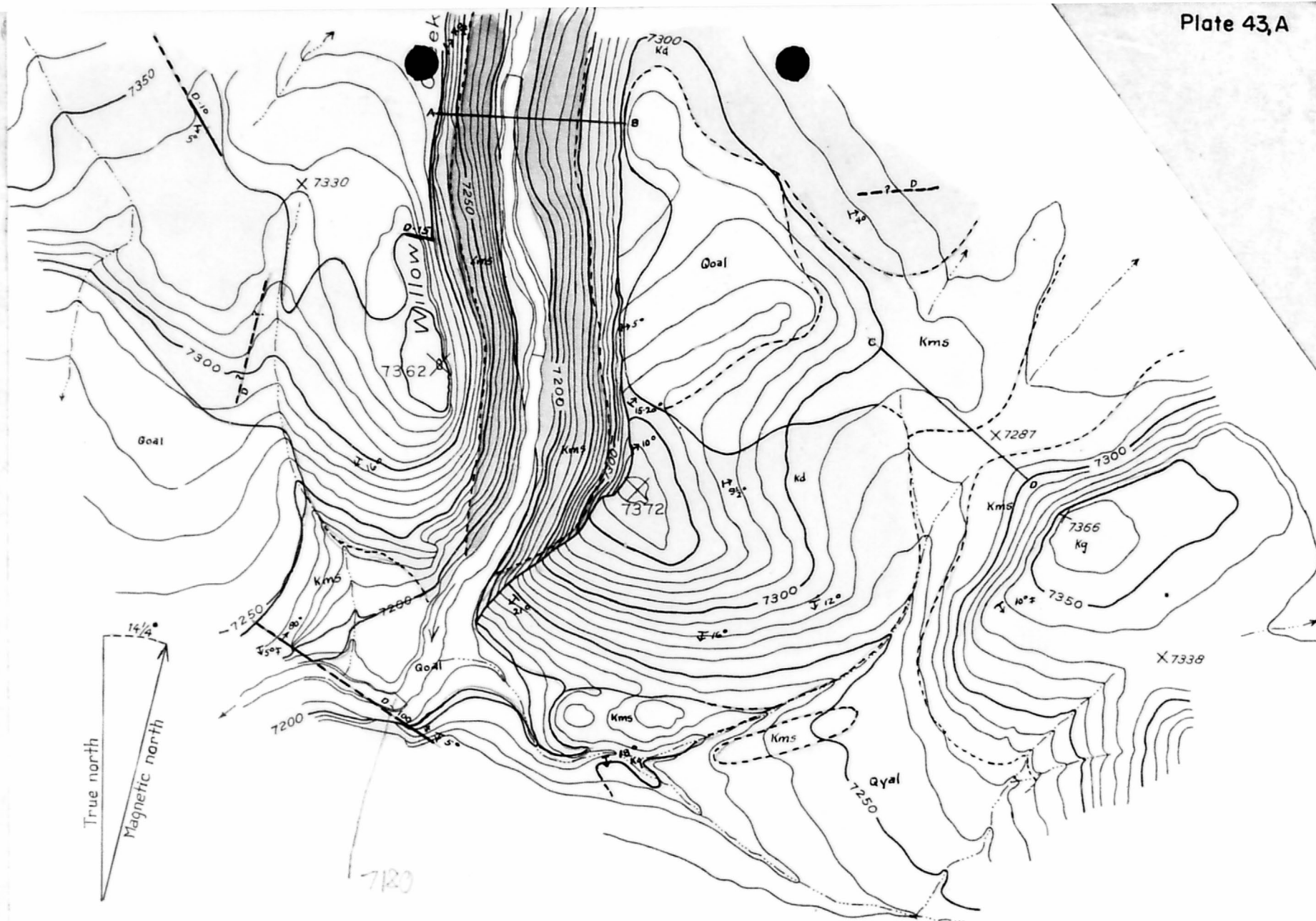
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Plate 43.— A, Geologic map of the Willow Creek upper (Rutherford) dam site, Rio Chama basin; B, Explanation for geologic maps of dam sites along Willow Creek, New Mexico.

44.— Geologic map of the Willow Creek middle dam site, Rio Chama basin.

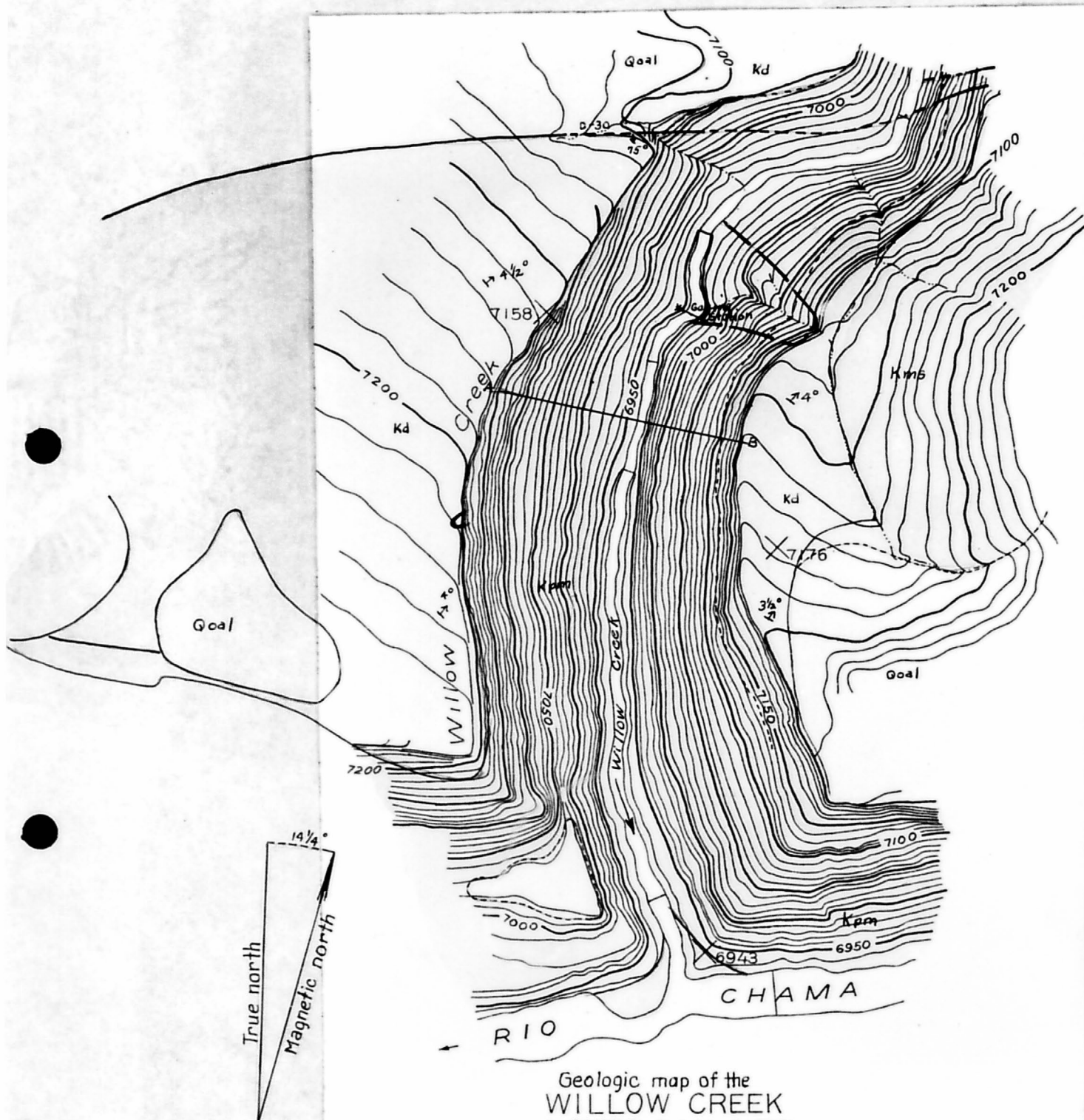
45.— Geologic map of the Willow Creek lower (Lower Rutherford) dam site, Rio Chama basin.

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GEOLOGIC MAP OF  
WILLOW CREEK  
UPPER DAM SITE  
(MILE 8.9-SHEET 6)





Geologic map of the  
WILLOW CREEK  
LOWER DAM SITE  
(MILE 0.4-SHEET 6)  
(Rio Chama basin)

Rocks that form the three dam sites along

Willow Creek

Feet

Incoherent materials:

Stream-bed and flood-plain deposit: Unassorted silt  
and sand mingled locally with coarse angular material  
transported from talus. Moderately permeable; plastic  
and unstable if saturated with water - - - - - 0-20+

Reworked slope wash: Fine calcareous silt derived from the  
Mancos shale and transported far down the slopes; merges  
with the flood-plain deposit at a few places. Plastic  
and unstable if wet - - - - - 0-10

Terrace deposit: Fairly rounded particles in all sizes from  
coarse sand to boulders a foot through; derived largely  
from dense crystalline rocks; somewhat oxidized through-  
out, non-crystalline particles decomposed to gritty earth.  
Veneers rock shelves from 20 to 270 feet above the stream.  
Highly pervious, non-plastic if wet - - - - - 0-60

Bedrock:

Timpas (?) limestone \_/: Brown and bluish-brown limestone,

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\_/ Correlation of bedrock formations after Darton,  
N. H., op. cit., pp. 37-42.

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in part concretionary. Scattered small outcrops, most of  
which are above the pool levels of the proposed dams - - - - 60+

## Mancos shale:

Upper shale member (Carlile shale?): Dark  
 bluish-gray shale, laminated; forms a minor  
 portion of the reservoir sites. Impervious but  
 probably somewhat plastic if wet - - - - - 60

Limestone member (Greenhorn limestone?): Dense  
 bluish-gray limestone in beds from 3 to 15 inches  
 thick separated by laminated dark calcareous shale  
 as much as 2 feet thick. (See pl. 46, A). Moder-

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Plate 46.- A, Greenhorn (?) limestone member in the  
 Mancos shale, Willow Creek middle  
 dam site.

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ately extensive in the higher parts of the reservoirs.  
 May be slightly pervious along bedding planes - - - - 20+

Lower shale member (Graneros shale?): Similar to  
 upper shale member in physical character. Forms the  
 greater part of the reservoir sites and low saddles  
 near the upper and middle sites. Impervious, low in  
 bearing power (in part probably plastic if wet), and  
 not resistant to erosion - - - - - 90



A. Greenhorn (?) limestone member in the Mancos shale, Willow Creek middle dam site.



B. Cliff-forming Dakota sandstone, Willow Creek lower dam site.

Dakota sandstone: Thick-bedded massive sandstone, grains about a millimeter in diameter, slightly friable, light buff and light gray in color; a prominent cliff-maker. (See pl. 46, B.) Forms the upper part of either

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Plate 46.- B, Cliff-forming Dakota sandstone, Willow Creek lower dam site.

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abutment at each of the dam sites. Moderate bearing power; moderately pervious through interstices, fractures, and fault zones; fairly resistant to erosion - - - - - 60-80

Purgatoire and Morrison (?) formations: Gritty shale and thin-bedded earthy sandstone alternating with beds of massive sandstone which are of uneven grain, enclose pebbly lentils, are in part earthy, and are as much as 20 feet thick. Forms the lower part of either abutment and the foundation at each of the three sites. Bearing power of the massive sandstone beds is equal to that of the Dakota sandstone; of the most earthy beds (especially the gritty shale that forms the topmost member), slight or moderate. Probably only slightly pervious. Somewhat less resistant to erosion than the Dakota Sandstone - - - - - 270+

Geologic structure and earthquake hazard.- Throughout the lower part of the Willow Creek basin, which contains the three dam sites, the rocks are deformed by broad shallow folds and by steeply inclined faults of moderate displacement. In general, the lower parts of the land surface are areas of downfolding or downfaulting. Also, the height of the topographic features commonly is less than the height of the corresponding features of geologic structure. Thus, the reservoir sites are structural basins floored by the youngest rocks (largely by the impervious Mancos shale), whereas the dam sites occur in upfolded or upfaulted areas of the older rocks (Dakota sandstone and underlying formations). Some of these features of geologic structure are shown by plates 47 and 48.

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Plate 47.- Sharp dome in the Dakota sandstone at the upper  
dam site on Willow Creek, viewed upstream.

48.- A, Downstream reach of the middle dam site on Willow  
Creek, viewed upstream; B, Lower dam site on  
Willow Creek, viewed upstream.

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The structural features just described are very young in the geologic time scale because the terrace deposit is folded with the bedrock and at several places is faulted against bedrock, also because fault scarps little modified by erosion are common. Although Willow Creek is roughly graded across them, both folds and faults are believed to be unstable in part and the faults to be potentially active. Thus, there is a real hazard of an earthquake with its epicenter near the three prospective dam sites. Any dam erected in the Willow Creek basin should embody features that assure it stability against such earth motions.



Sharp dome in the Dakota sandstone at the upper dam site  
on Willow Creek, viewed upstream



A. Downstream reach of the middle dam site on Willow  
Creek, viewed upstream.  
(The upfaulted block in the mid-distant part of the field  
is the right abutment for the most feasible dam.)





B. Lower dam site on Willow Creek, viewed upstream.  
(The site is on the flank of an asymmetric dome in the  
Dakota sandstone.)

Watertightness of reservoirs.- As has been stated, the three reservoir sites on Willow Creek are structural basins floored almost everywhere by the impervious Mancos shale or by clayey silt derived from that formation. In these materials, neither "bank storage" nor leakage is likely to be appreciable. Even the fault zones in the shale seem not to comprise extensive openings through which water would percolate. On the other hand, there is a potentiality from some leakage near the several dams, where the pervious and fractured Dakota sandstone crops out. Measures to control leakage through this formation are treated under following discussions of the critical features of each dam site.

## Critical features of the three sites

### Upper (Rutheron) dam site

The upper dam site on Willow Creek is afforded by a small gorge across a narrow ridge whose flanks are dip slopes on the Dakota sandstone. (See pls. 43, A; 47.) The topography of the gorge permits a dam about 160 feet high - that is, up to the 7,350-foot contour. However, so high a dam in the main gorge would require an auxiliary dam - about 80 feet high and 1,000 feet long - to close an adjacent saddle on the left bank. Also, owing to features described in the next paragraph, it would involve very extensive works to prevent excessive leakage through the upper part of either abutment. Only for a lower dam has the site any advantage over the two alternative sites downstream.

Being sharply folded, the rigid Dakota sandstone is parted by closely spaced shear fractures, a few of which are faults with displacements of a few feet. Thus, all the sandstone probably is highly pervious. The underlying Purgatoire and Morrison (?) formations are concealed by talus but are inferred to contain beds of shale alternating with earthy sandstone, and so to have fewer fractures and to be decidedly less pervious. To minimize leakage under these conditions, it is suggested that (1) the pool level of a dam be no higher than the base of the Dakota sandstone at the crest of the fold - that is, no higher than the 7,300-foot contour; and (2) the dam be placed as far upstream as possible so as to afford the minimum hydraulic gradient across the two abutments. The position indicated by the line marked "AB" on plate 43, A seems most advantageous.

At the position just suggested the lower half of the proposed dam would rest on the Purgatoire formation, the upper half on the Dakota sandstone. A rigid structure appears feasible only if its base is moderately wide so as to distribute the load adequately onto the weakest shale members of the Purgatoire formation. (See p. 112.) Exploratory pits and drilled holes in the bedrock are essential to afford a basis for judgment with respect to this feature of the dam. If a flexible structure proves to be desirable, a quarry in the Dakota sandstone on the crest of the fold would yield material suitable for a rock fill. Either type of dam should embody an impervious curtain extending into impervious rock in the Purgatoire formation and a moderate distance laterally into the Dakota sandstone.

With a dam of the height suggested, about 110 feet, excess water can be wasted across the saddle on the left bank. The line marked "CD" on plate 43,A indicates an advantageous location for a spillway structure. At that location the structure probably would rest for its full length on the impervious Mancos shale although beneath its western half the shale is thin, possibly so thin that a cut-off curtain should be extended down into the Dakota sandstone.

It is concluded tentatively that leakage will not be excessive in the vicinity of the spillway with pool level at or below the 7,300-foot contour. However, if this conclusion proves to be ill-founded, leakage probably can be effectively reduced by washing a blanket of silt over the Dakota sandstone upstream from the spillway and opposite the dam.

Below the spillway structure, the wasted water would follow the contact between the Dakota sandstone and the Mancos shale. Because the shale would erode easily, adequate protective works would be essential lest the east bank be undermined.

### Middle (Willow Creek) dam site

At the middle dam site on Willow Creek (pl. 44) two locations for a dam have been proposed, one upstream from the prominent S-bend of the creek and the other downstream from that bend. The upstream location appears altogether infeasible for reasons as follows: (1) All the right (north) bank to a height of 175 feet above the creek (altitude 7,300 feet) is a landslide (pls. 44, 49) which comprises blocks of the Dakota sandstone in all sizes up

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Plate 49.- Central part of landslide on the right bank of

Willow Creek at the middle dam site.

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to 600 feet long. No secure abutment exists. To prevent excessive percolation through the slide appears wholly impracticable. (2) A dam more than 50 feet high would require an auxiliary structure on the left bank about 500 feet long to stop percolation through a remnant of the terrace deposit and to close a narrow saddle. A dam more than 80 feet high would require an additional dike at least 500 feet long to close a second saddle.

The reach downstream from the S-bend affords a somewhat inferior site for a dam as much as 150 feet high - that is, up to the 7,250-foot contour. The line marked "AB" on plate 44 indicates the position that appears most advantageous. As at the upper site, the lower half of a dam in that position would rest on sandy shale and sandstone of the Purgatoire formation, the upper half on the Dakota sandstone. These two formations dip upstream; the dip is slight but sufficient to oppose the tendency of a dam to slide. Their crushing strength probably is adequate to support a rigid dam with a base of moderate width. To prepare a sound foundation for such a dam would entail scaling a moderately large volume of insecure rock from the two bluffs of Dakota sandstone, which is parted by many subvertical fractures. (See pl. 48, A.)



Central part of landslide on the right bank of Willow Creek at the  
middle dam site.

The chief deficiencies of the dam site are a considerable earthquake hazard (see p. ) and potential excessive leakage. Both deficiencies are related to the fault which is close downstream and which is one of numerous faults in a zone of relatively intense deformation about a mile wide. The earthquake hazard perhaps is sufficient to require a flexible dam. In the Dakota sandstone, at least, the fault is a pervious crushed zone several feet wide; to minimize leakage through the abutments to the fault zone and thence to the stream would require an extensive cut-off curtain the full thickness of the sandstone. A less extensive curtain may suffice in the underlying Purgatoire formation, whose shale beds are inferred to seal some parts of the fault zone.

For an over-fall spillway the most advantageous place appears to be at a saddle which is about half a mile southeast of the proposed dam and about 7,230 feet in altitude. The saddle and the drainage way below it are formed of the Mancos shale, which would require protective works to prevent scouring.

#### Lower (Lower Rutheron) dam site

The lower dam site on Willow Creek (see pls. 45; 46,B; 48,B) is similar to the two alternative sites upstream in that the Dakota sandstone and Purgatoire formation probably afford a foundation and abutments sufficiently superior, particularly for a high dam, in that leakage probably would be nominal.

The minimum height of dam is proposed to be 210 feet above the creek; with a dam of that height, the pool surface would be at the 7,150-foot contour and level with the base of the Dakota sandstone in the escarpment along the Rio Chama. To that height, the gritty shale that forms the topmost member of the Purgatoire formation is a barrier that will effectively prevent lateral percolation southward through the Dakota sandstone to the escarpment. For a dam so high, the most advantageous position appears to be along the line marked "AB" on plate 45. The chief advantages of that position are as follows: (1) relatively little loose rock exists in the bluffs of Dakota sandstone at either end of the proposed dam; (2) the lower part of the dam will rest on one of the thicker and more massive sandstone members of the Purgatoire formation; and (3) the greater part of the dam will be below the gritty shale member which is the top of the Purgatoire formation and which is the weakest rock in either abutment.



With a dam of the height just proposed, the one possible cause of leakage appears to be the fault that crosses Willow Creek near the upstream edge of the area shown on plate 45. That fault was traced westward in the Dakota sandstone for about 2 miles; farther west, also east of Willow Creek, its land-surface trace passes into the Mancos shale and is concealed. In the Dakota sandstone, the hanging (south) wall of the fault is so crushed as to form a pervious zone about 5 feet wide. The nature of the fault zone in the underlying Purgatoire formation is not shown by outcrops; however, that formation includes considerable shale that would tend to seal the fault. To escape at the land surface, water would be forced to percolate about  $1\frac{1}{2}$  miles along the fault under a maximum hydraulic gradient of about 0.8 percent. Accordingly, it seems unlikely that leakage would be excessive. If necessary, however, the fault zone can readily be plugged, grouted, or otherwise sealed where it crosses Willow Creek.

If a dam more than 210 feet high is desired, a position downstream from the line AB will be necessary to secure abutments of adequate height. The greater height would raise the pool surface above the base of the pervious Dakota sandstone in the escarpment of the Rio Chama. The shift in position would steepen the hydraulic gradient between the pool and the escarpment. Thus, the higher dam would require an extensive impervious curtain in either abutment to prevent leakage through the sandstone to the Rio Chama.

Excess water can be spilled into the Rio Chama across a saddle which is about  $1\frac{1}{2}$  miles west of the dam site and which is about 7,125 feet in altitude - that is, about 185 feet above Willow Creek and 25 feet below the pool level that has been proposed. The saddle and the drainage way below it lie along the contact between Dakota sandstone to the east and Mancos shale to the west. A spillway structure in that saddle would have a firm foundation on the Dakota sandstone. It should include an impervious curtain of moderate depth in the sandstone and adequate works to prevent excessive scour of the weak shale in the west bank.

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