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GEOLOGY OF SOME DAM SITES ON LITTLE COLORADO RIVER AND ITS TRIBUTARIES, ARIZONA

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12 Tolchico site; right abutment, looking northeast. Shows differential weathering along sandy and limy beds in Kiabab limestone and weakness of northeasterly trending set of fractures.

13 Blackrock Mountain site on Cottonwood Wash, looking southeast toward Blackrock Mountain from lava-capped hill in center of valley. The hills in middle distance form left abutment of proposed dam. Their irregular surfaces are covered by a thin basaltic lava flow, underlain by soft shale.

14 Castle Mountain site on Cottonwood Wash; panoramic view looking upstream.

15 Castle Mountain site, looking west toward right abutment. The low gray hills in middle background are of soft Chinle Shale. The peak in background and 2 small black masses on edge of abutment are basaltic lava. Alluvial valley fill in foreground.

16 Castle Mountain site, left abutment looking east near right abutment. Arroyo in foreground shows character of valley fill. Castle Mountain is a volcanic plug of basaltic rock. All other rocks in abutment are shale (dark) and soft sandstone (white) of Chinle formation. Landslide mass outlined by dashed lines

17 Lower Leroux Wash site looking toward left abutment from near center of valley. Abutment consists of gypsum-bearing shale, capped by a layer of sandstone. The sandstone on forepart of abutment has slid slightly forward and down over underlying shale.

18 Lower Leroux Wash site, looking toward right abutment from center of valley. The cliffs are principally of sandstone, intervening slopes are of gypsum-bearing shale. Shinarump conglomerate caps the abutment.

19 Upper Leroux Wash site, looking toward left abutment. The cliff at top is moderately hard sandstone; the underlying rocks are alternating beds of shale and sandstone with a little limestone conglomerate.

20 Upper Leroux Wash site, showing landslide in right abutment, looking upstream. The sandstone and shale layers on left are in place; those in center and in foreground are jumbled and displaced by the slide.

21 Lower Big Carrizo Wash site, looking toward right abutment from near left abutment. The sandstone cliff, about 50 feet high, is underlain by soft shale. Note fractures in sandstone. Left abutment is almost exactly similar to thei except for presence of sand dunes between cliff and stream channel.

22 Oak Springs site, looking upstream toward head of Black Creek canyon. The ridges at head of canyon are of Coconino sandstone that dips steeply away from the observer. The rocks beneath this formation (left foreground and right middle ground) are red shaly and sandy beds of the Supai formation. Note deeply trenched alluvium along stream.

23 Left abutment of upper Oak Springs site. The cliff is Coconino sandstone that dips almost vertically. Slope on left of cliff is underlain by Moenkopi shales. A small seep spring issues from near top of alluvial bench in center of view.

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Introduction

This report contains descriptions of the geology of 10 dam and reservoir sites on the Little Colorado River and several of its larger tributaries in northern Arizona. All of the streams examined are intermittent in character and are dry during the greater part of every year. At times they all carry heavy floods, particularly in the early spring and late summer seasons. In addition to the periodic threat of damage to Holbrook, Joseph City and smaller communities, to the Santa Fe Railroad, and to other public and private property, the flood waters annually carry enormous quantities of silt. Most of this material eventually reaches the main Colorado River where it tends to fill the reservoir above Boulder Dam and is also undesirable for other reasons.

The principal purpose of any of the proposed dams whose sites are described herein is therefore for flood and silt control. Small irrigation projects might possibly be developed at some of them but they would be distinctly of secondary importance. Except for the Oak Springs site on Black Creek, none of the dam and reservoir sites is ideal from the standpoint of either a geologist or an engineer. Most of them will require very long dams and several require large auxiliary structures to close gaps in the reservoir walls. Except at Oak Springs and Tolchico all the dam sites are in soft shaly rocks that will necessitate broad base, flexible structures. All of the reservoir sites are broad and shallow and evaporation losses will therefore be high. This fact would spell failure for most irrigation or power projects but for the present purpose is not particularly disturbing except for the comparatively short life expectancy of the reservoir areas.

The field work on which this report is beased was done at intervals from April through September, 1939. Several of the sites were studied at the same time by H. C. Spicer of the Geological Survey, who used geophysical means to determine the thickness of alluvial valley fills and the shapes of the bedrock profiles. His results have not been incorporated herein.

General Geology

The following notes are intended to provide a background of knowledge concerning the general geologic relations in that part of northern Arizona that includes the dam sites. More detailed descriptions of the local character of the formations and of the geologic structures are given in the descriptions of individual sites.

The geology of this region is described by Gregory,[1/] Darton, Harrell and Eckel, and by other writers whose works are referred to in their reports. The general distribution of the formations is shown on the geologic map of Arizona, published in 1925 by the Arizona Bureau of mines, and on maps in the reports cited.

The rock units that occur within the area under discussion are shown in the following table:

1/ Gregory, H. E., Geology of the Navajo Country, U. S. Geol. Survey, Prof. Paper 93, 1917.

Darton, N. H., A resume of Arizona Geology, Arizona University, College of Mines and Engineering, Bull. 119, 1925.

Harrell, M. H., and Eckel, E. B., Ground-water resources of the Holbrook region, Arizona, U. S. Geol. Survey Water Supply Paper 836-B, 1939.

Generalized section of the geologic formations of the Holbrook region, Arizona

System	Formation	Thickness in region (feet)	Physical character	Engineering features
Quaternary Tertiary	Alluvium	0-150	Silt, clay, and sand along streams; sand dunes; thin deposits of unconsolidated sand, gravel, clay and limestone on benches and ridges.	Weak, easily eroded, and relatively permeable but will support broad base structures. Should be penetrated by impermeable membranes beneath dams. Principal source of material for earth dams.
	Lava		Basaltic lava rock as plugs, dikes, sills and flows	Strong and durable but commonly strongly fractured, hence permeable. Excellent source of riprap.
Triassic	Chinle formation	400-700	Variegated shales, with thin semi-consolidated sandstones and impure limestones; much volcanic ash locally.	Soft, weak, and easily eroded but will support broad base structures. Weathered shale should be removed from beneath dams.
	Shinarump Conglomerate	20-60	Coarse sandstone and conglomerate, commonly semi-consolidated.	Highly permeable in most places. Good source for clean sharp sand and for gravel.
	Moenkopi formation	200-400	Sandy shales and shaly sandstones, with much gypsum and a little limestone in places.	Like Chinle but somewhat stronger and more durable in general.
Permian	Kaibab limestone	0-250	Massive, thick bedded, cherty limestone, with many sandy and dolomitic beds.	Strong and durable but brittle, hence marked by many fractures, some of which are apt to be open. Good source for quarried or crushed rock.
	Coconino sandstone	450-865±	Massive fine-grained, white to buff, cross-bedded sandstone.	Strong and durable but brittle like Kaibab. Permeable to ground water but in general should form good dam foundations.
	Supai formation	1000+	Red sandstone, shale, mudstone and siltstone with a little impure limestone.	See description of Oak Springs site for character there.

In general the sedimentary rocks dip toward the north at very low angles. Minor structures occur in a few places and result in reversals of the regional dip or in local exposures of older rocks that are elsewhere covered by younger beds. There are no known faults near any of the sites.

The only structural feature of any importance to the engineer is the fracture system. Throughout almost the entire region the rocks are broken along 2 sets of fractures, or joints. One of these, the stronger in most places, trends northwest. The other trends northeast. The fractures are tight and scarcely noticeable in soft rocks like the Chinle and Moenkopi formations. They are very strongly developed in the brittle rocks like the Coconino sandstone and Kaibab limestone, however. The courses of nearly all the streams in the region are controlled almost entirely by these fracture systems. In most places the fractures are relatively tight in unweathered rock and offer no cause for serious concern. On the Holbrook dome and farther south, however, many of them are continuous and open to great depths. One irrigation project has failed in its purpose because of loss of reservoir water through these openings. This is the Lone Pine reservoir, near Show Low.

Fortunately the Kaibab and Coconino formations occur at the surface at only two of the sites described here. At the Oak Springs site on Black Creek there are relatively open

Figure 10

Tolchico site on Little Colorado River, looking downstream.

fractures in the sandstone that forms the abutments but local structural conditions are such that possible loss of water does not appear to be serious. Fractures are well developed at the Tolchico site but, as is pointed out below, much further exploration is necessary in order to determine whether any of them are open to considerable depths.

Little Colorado River

Tolchico Site

<u>Introduction</u>. - The Tolchico dam site is situated in T. 24 N., R. 11 E., on the Little Colorado River, 3 miles west of the abandoned settlement of Tolchico and 11 miles west of the Leupp trading post. It is in a steep-walled canyon that is about 1½ miles long, 400 to 500 feet wide, and 50 to 100 feet deep. With the aid of low but comparatively long dikes in 2 gaps north of the canyon a 30 to 100 foot dam could be built that would back water over a large basin between the site and Leupp. The dam would serve to control floods on the Little Colorado and the wide, flat reservoir would provide an excellent desilting basin. In addition, it is probable that stored water could be used for irrigation of large Indian-inhabited areas below the dam.

<u>Geology</u>. -

<u>Rocks</u>. - With the exception of 2 small bodies of Quaternary lava that have no direct bearing on the availability

Figure 11

Little Colorado River near Tolchico site, looking northwest.

of the site, the rocks near Tolchico are all nearly horizontal sediments. The general character and distribution of the formations, which range from the Coconino sandstone through the Chinle formation, are described in the general part of this report. The local character of the rocks is described below and their distribution near the site is shown on figures 1a and 1b.

Coconino sandstone. - The Coconino sandstone certainly underlies the dam and reservoir site but as it is not exposed at the surface and as the thickness of the overlying Kaibab limestone is not known the position of its top is not known. It is at least 450 feet thick in this area, and as elsewhere is a massive, moderately hard, cross-bedded sandstone. Composed in large part of fine- to medium-sized rounded grains of quartz, with a little limy cement, it is permeable to ground water. It is brittle and most fractures in it are open.

Kaibab limestone. - As shown in figures 1b, 11 and 12 the Kaibab limestone forms the canyon walls at the dam site. Several small masses of limestone are also exposed within the reservoir area. The thickness of the formation is not known. Records of wells near Leupp indicate that the Kaibab there ranges from 29 to nearly 200 feet.[1/] A little more than 100 feet of limestone is exposed in the canyon at the site, but whether the canyon floor is cut in limestone or in Coconino sandstone can be determined only by drilling.

1/ Harrell, M.A., and Exkel, E.B., Groundwater resources of the Holbrook region, Arizona, U.S. Geol. Survey Water Supply Paper 836-B, wells 1,2,3, 393, 394, pp. 75,80, and 91, 1939

The formation is made up of white to light gray or cream massive beds of limestone in beds 1 to 20 feet thick. The top 5 to 10 feet of beds are commonly yellow or pink. Much of the limestone is sandy and some of it closely resembles the Coconino sandstone. Some of the beds are of comparatively pure limestone, however. All of them, whether sandy or not, are very dense.

In its unweathered condition the formation is massive and bedding planes are tight. Fractures are likely to be open even in fresh rock. The Kaibab forms many steepwalled canyons in this part of Arizona. Incipient fractures are opened and small caves are formed along canyon walls. Near Tolchico the sandy beds are more deeply etched by erosion than the limy ones. This indicates that most of the erosion is carried on by mechanical rather than chemical means.

Moenkopi formation. - The Moenkopi formation, which overlies the Kaibab limestone, has been eroded in the vicinity of the dam site, but it forms much of the reservoir floor and is also extensively exposed north of the site, in and near "Gap 1". Local variations in dip of the beds prevents accurate determination of its thickness but the formation is probably between 50 and 100 feet thick in this area. The lower part of the formation is made up of dull red to chocolate brown, micaceous, shaly sandstone and sandy shale. Thin lenses of gypsum and conglomerate occur in places. The uppermost few feet are variagated soft shale, indistinguishable from the younger Chinle beds.

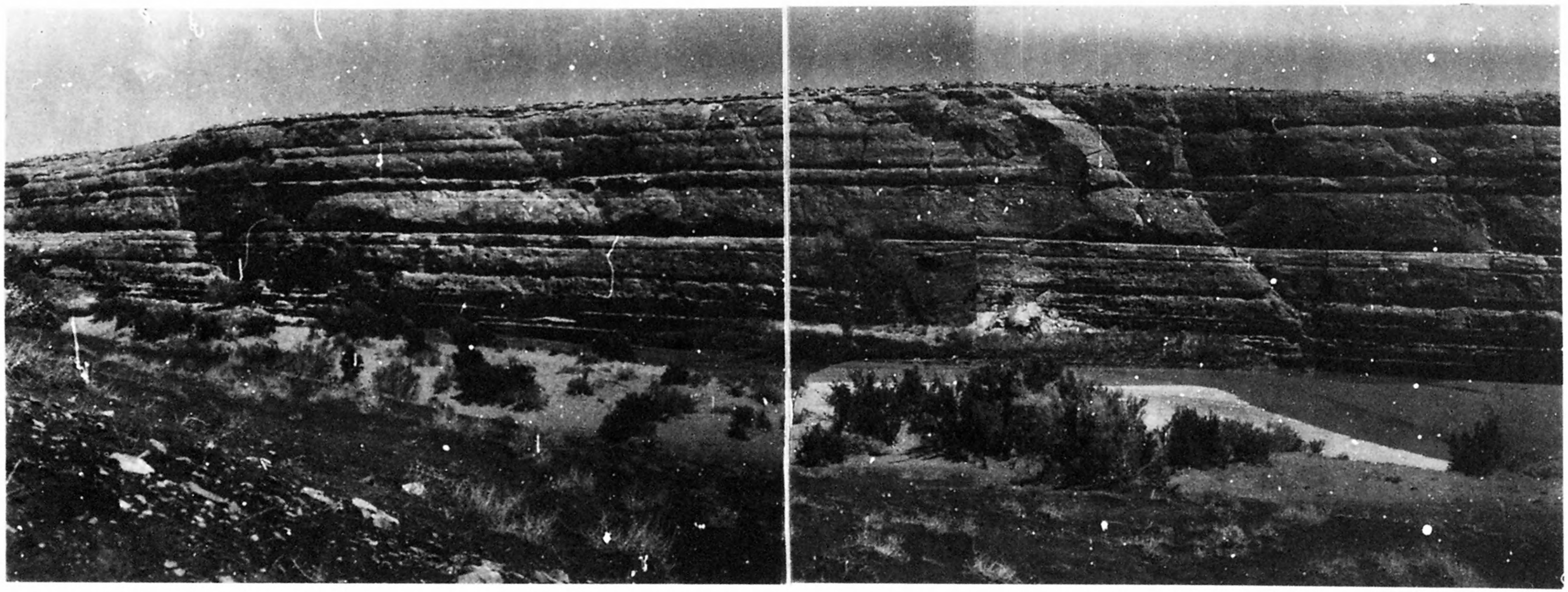

Figure 12

Tolchico site; right abutment, looking northeast.

Except for the sandstone beds, which are thickest and most numerous toward the base, the formation is easily eroded by running water. The shales are virtually impermeable and even the sandstone layers rarely yield water to wells.

Shinarump conglomerate. - The Shinarump conglomerate crops out in a narrow band on the ridge 3 miles north of the Tolchico site and is also exposed in a chain of small knobs and hills that cross the northeastern part of the reservoir area. The formation ranges from 20 to 60 feet thick and is composed in most places of coarse-grained, loosely cemented sandstone, light gray to red in color. Lenses of conglomerate are characteristic. Most of the pebbles are composed of chert or quartzite and range from less than $\frac{1}{2}$ inch to 4 inches in diameter but a few are a foot or more in size. Fragments of petrified wood are locally abundant. The pebbles from this formation tend to spread out on surfaces of the underlying Moenkopi and thus give an erroneous impression as to the distribution and thickness of the Shinarump. The rocks are very permeable in most places.

Chinle formation.- The Chinle formation is widely distributed north and east of the site and forms bedrock beneath "Gap 2" and along the entire northeastern side of the reservoir. It is composed in large part of soft varicolored shale but locally it contains some thin sandstones and conglomerates. The most prominent conglomeratic horizon is exposed along the top of the ridge between the saddles of "Gap ". A few large petrified logs are exposed just east of "Gap 2". Altered volcanic ash, or bentonite, is widely distributed, but nowhere abundant. The formation is readily eroded by running water but it is impermeable to ground water and seldom yields water to wells.

Recent lava. - A basaltic lava flow that spread northward from one of the volcanic centers near Flagstaff after the present topography was well defined, approached but did not reach, the Little Colorado River. One lobe of this flow ends about 1 mile southwest of old Tolchico; another partly fills the end of a side canyon $1\frac{1}{2}$ miles southeast of the dam site. Only the first-mentioned lobe occurs within the area shown on figure 1a. The lava has no direct bearing on the dam site.

Alluvium. - The bed of the Little Colorado River is filled with fine sand and silt. The depth of the material has been investigated by geophysical means by H. C. Spicer. From river level to the floor of the rock channel this material is saturated with water and much of it has quicksand characteristics at times. Great blocks of limestone have dropped from the canyon walls in places. Some of these are exposed but probably many others are concealed by sand. Large sand dunes have been built up along the left abutment.

Most of the knolls and hills are barren of soil or alluvial material but flat areas, especially those on the north side of the river, are covered by variable thicknesses of alluvium. This consists largely of clay and silt, with a little sand and gravel. Shifting sand dunes characterize parts of the reservoir area.

Structure. - The rocks dip in general toward the northeast at angles of 3 degrees or less. At the dam site itself the limestone has been raised up in a small asymetric dome, which pitches northeast. Even within the dome the dips are very low. Several smaller domes account for other Kaibab exposures in the reservoir area. No faults are present near the site.

The most important structural features are factures in the limestone. These are all nearly vertical and all fall into 2 sets, which trend N. 60° - 70° W. and N. 30° - 42° E. Most of the fractures, which range from a few inches to 10 feet apart, are weak and tight. Strong fractures are 30 to several hundreds of feet apart. The northeasterly trending fractures are discontinuous, both vertically and horizontally and most of them end abruptly against bedding planes or against the stronger northwesterly trending fractures. Members of the latter set can be traced for several hundred feet horizontally and most of them traverse the entire exposed thickness of the limestone. The photographs reveal the relative strengths of the 2 sets of fractures and of their effect on erosion of the rocks. It is clear that at the dam site the river follows the northwesterly set, which are probably more strongly developed here than elsewhere.

The underlying Coconino sandstone is doubtless broken by fractures similar to those in the limestone but whether any of the fractures in either rock type are open more than 10 to 20 feet beneath the surface is not known. Since similar fractures are known to be open to great depths in other parts of the Holbrook region the possibility that they are open here must be recognized.

Engineering Geology

<u>Dam site</u>. - So far as the strength and durability of the foundations and abutments are concerned, a gravity or earth dam of the proposed height could be built anywhere within the Tolchico canyon. The section however is not well adapted to an earth dam because of the nearly vertical walls. An arch dam would appear inadvisable because of the presence of strong fractures parallel to the canyon walls. The slightest seismic disturbances or even the pressure of stored water against the arches might set up slight but destructive movements in the abutments.

The fractures in the limestone and underlying sandstone constitute the chief cause for concern. If any of these are open, they would provide easy channels for leakage beneath the dam and through its abutments. There would be a slight tendency toward enlargement of these channelways by solution of the limestone but the enlargement during any reasonably expectable life of the dam will probably be extremely small. If the dam is to be used for control of silt and flood waters only, the possible presence of open fractures offers no serious problems. Those fractures in the immediate abutments should of course be sealed by grouting to increase the strength of the rocks. If it is proposed to conserve water for irrigation uses, losses of water through the abutments or into the foundation rocks might easily be so large as to endanger the success of the project. For this reason, a fairly extensive program of drilling should be undertaken to determine the character of the fractures. The exposures of Kaibab limestone in the reservoir area are also potential leakage areas but as they are comparatively small the possiblity of notable water losses is not particularly disturbing.

As shown in the photographs the canyon walls are slabby. All loose slabs should of course be removed before the dam is built. This will necessitate removal of 5 to 25 feet of rock in most places. Regardless of the type of dam that is selected, it should penetrate the dune sand and river alluvium with its included limestone blocks and be securely tied into bedrock.

Auxiliary dikes. - Unless the main dam is very low, it will be necessary to construct auxiliary dikes in Gaps 1 and 2 north of the river. Since both dikes will be comparatively low and long, they will presumably be built of earth. Gap 1 is cut in Moenkopi sandstone and shale. Both types of rock are essentially impervious and no preparation of the site other than removal of the thin cover of sandy alluvium should be necessary. Gap 2 is underlain by the lower part of the Chinle formation. Most of the beds are shale that is even more impervious than the Moenkopi rocks in Gap 1. The higher parts of the ridge in the central part of Gap 2 contain conglomeratic material. This is relatively porous, but as the reservoir water would rest against it for only short, infrequent periods, no danger of serious leakage is indicated. It will doubtless be found necessary to excavate 2 to 8 feet of alluvium and weathered shale along the axis of the dike in order to rest the structure on firm material.

Spillway. - An overflow spillway at the main site seems to be the most feasible since the limestone in the canyon walls and floor is resistant to erosion by running water. Either of the gaps could be used as emergency spillways but the shales beneath them are easily eroded. For this reason, it will be necessary to line any spillway structure that is expected to see constant or repeated use.

Construction materials. - The Kaibab limestone would form excellent material for concrete aggregate or for rip rap. Most of the sand near the site is too fine and contains too much silt to be of use for concrete but it is likely that good, coarse sharp sand can be recovered from outcrops of the Shinarump conglomerate. There is a great abundance of material suitable for earth-fill construction.

Further exploration. - Aside from a few test pits to determine the depth of weathering in the gaps north of the dam, the only further exploration that seems to be necessary is determination of the character of the fractures in the abutments and foundations of the main dam. Since nearly all of the fractures are vertical, inclined or forizontal holes will be necessary. Figure 1b shows a suggested plan of drilling. The thoroughness of the drilling program will depend in large part on the objectives of the project - whether it is to be used for flood control or for irrigation.

Cottonwood Wash

Four dam sites have been studied on Cottonwood Wash, one of the larger tributaries to the Little Colorado River. This wash drains a large part of the Navajo Reservation and carries great quantities of silt during flood seasons. Two sites, Blackrock Mountain and Castle Mountain, in sec. 21, T. 21 N., R. 19 E., and secs. 22 and 23, T. 21 N., R. 20 E., have been surveyed. The other two, in T. 22 N., R. 21 E., and in T. 22 N., R. 22 E., respectively, have not been mapped but cursory inspection indicates that they present good sections for dams and large reservoir capacities. All four of the sites will require long, comparatively low, earth dams. Soft shale is the predominant foundation rock in all of them, a fact which will necessitate the construction of broad base flexible structures. There is abundant sandy and clayey silt near each of the sites which should form good material for earth dams.

The Blackrock and Castle Mountain sites are somewhat complicated by the presence of volcanic rocks and of landslide masses, but there is little actual choice between the four sites so far as the geology is concerned. Instead, the choice should rest on further engineering studies with particular attention to comparative costs, available storage capacity and drainage area affected by the projects.

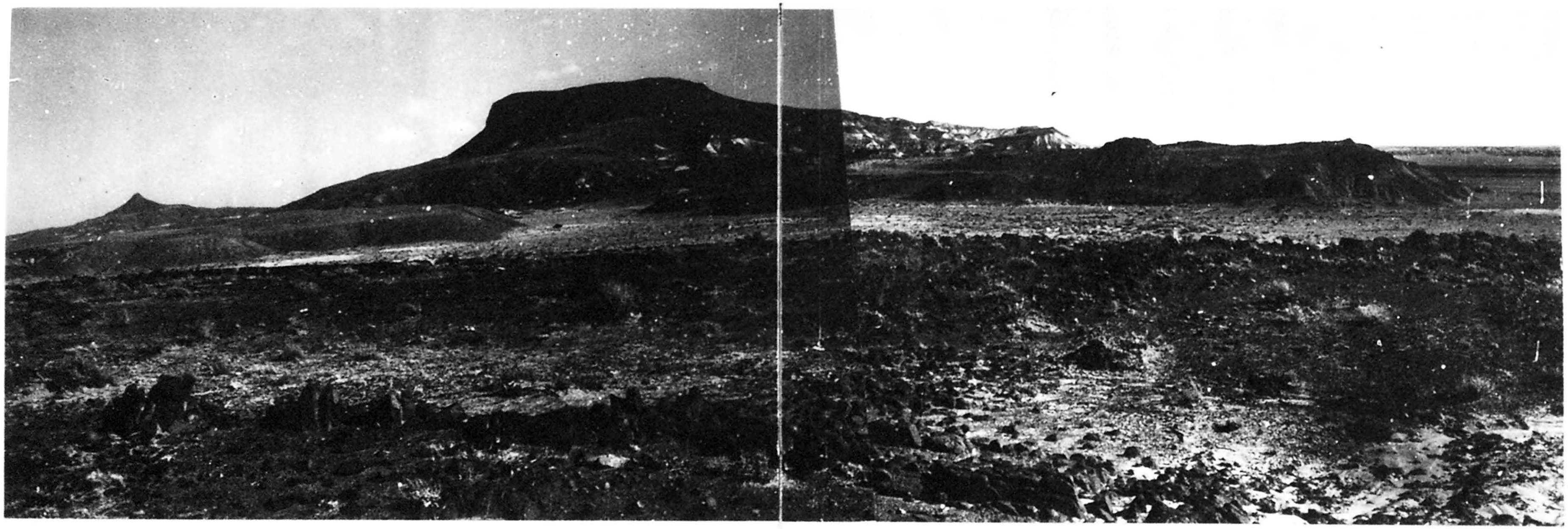

Figure 13
Blackrock Mountain site on Cottonwood Wash, looking southeast toward Blackrock Mountain from lava capped hill in center of valley.

Blackrock Mountain Site

The Blackrock Mountain site lies principally within sec. 11, T. 21 N., R. 19 E. Because of the presence of low gaps on each side of the main channel, any dam more than 20 feet high would require two auxiliary dams; figure 2. Furthermore, it will be necessary to build the dam at least 40 feet high to obtain adequate storage capacity in the reservoir. The aggregate length of the 3 structures would range from about 2,700 feet for a 40-foot dam to more than 6,000 feet for one 100 feet high.

General Geology

General statement. - Bedrock consists in the main of horizontally bedded Chinle shale, overlain in the main stream channel and in the northwesterly saddle by silty alluvium. The 3 hills in the central part of the valley are capped by thin layers of basaltic lava with highly irregular surfaces. One narroa dike of lava is exposed and others may be present. The higher parts of two of the hills are covered by deposits of soft limestone, unconsolidated sand and gravel. There are several small landslide masses.

Chinle shale. - The Chinle beds exposed near the dam site are light red to pink in color and are made up almost exclusively of soft shale. Sandy beds are present, but they are few and thin. The beds are essentially horizontal. No faults are observable and it is probable that none are present but because of the lack of distinctive marker beds, faults with small displacements could be easily overlooked.

Shale is exposed in both of the main abutments and in the small hills in the central part of the valley (see figures 2, 4b, and 13). Similar shale certainly underlies Cottonwood Wash and the saddle northwest of the stream. Where exposed at the surface the shale is weathered and extremely soft. This weathered zone is probably not more than 15 feet thick at any place and is doubtless very thin beneath the valley floor.

Basaltic lava. - The shale in the 3 hills in the central part of the valley is capped by thin layers of dark green, dense, basaltic lava. The rock is rather strongly altered everywhere and is much fractured. The layers range from 2 to 10 feet in thickness and have highly irregular surfaces, as shown in the illustrations (figures 2 and 13). One narrow dike of similar rock is exposed near the road on the left, or southeast, abutment. Other dikes or plugs may possibly exist beneath the lava-capped hills. Blackrock Mountain itself is carved from a large volcanic plug and the mountain northwest of the site is covered by a thick lava flow.

The thin layers of lava mentioned above were certainly formed as surface flows rather than as intrusive sheets. They rest on Chinle shale and two of them are capped by unconsolidated sediments that have been classed as "Tertiary sand" in other parts of northern Arizona. They are certainly younger than the lava. The irregularity of the lava surface is somewhat puzzling. It cannot be due to folding or faulting, for the underlying beds of shale are horizontal and continuous. Except for the 3 small bodies shown on figure 2 there are no landslide masses. The only plausible explanation seems to be that the lava flowed out over an irregular erosion surface, of which the present lava-capped hills are remnants. The lava may possibly have been fluid enough to flow freely, yet viscous enough to transmit pressures that pushed it over obstructions without notable thickening in the intervening depressions. It is also possible that the flows were originally thick in depressions but thin on ridges. After crusts had formed on the flows, still-molten lava in the depressions found local exits, allowing the crusts to subside.

Study of figure 2 will show that there must have been several centers of eruption. Three possible centers are known - the dike on the left abutment, the plug in Blackrock Mountain, and the flow on the mountain to the north - and other smaller centers may well exist beneath the lava caps.

Landslide masses. - Three small landslide masses that have formed rather recently are shown on the geologic map (figure 2). They were formed by oversteepening of the hill slopes, which allowed blocks of shale capped by lava to slump. No great importance can be attached to them.

Tertiary deposits. - Two of the hills in the center of the valley are capped by unconsolidated Tertiary deposits. A 1 to 3-foot layer of soft, light-colored, impure nodular limestone occurs at the base, immediately above the lava flow described above. The limestone is iverlain by loose sand that contains much gravel. Most of the pebbles are of chert or of limestone derived from the basal bed.

Alluvium. - The lower parts of the dam site and most of the reservoir basin are covered by alluvium. It is made up largely of silt but contains much clay and some sand. The thickness of the alluvial deposits is not known. They may be relatively thick along Cottonwood Wash but are believed to be very thin - probably no more than 10 feet at most - in the saddle northwest of the stream.

Engineering Geology

The Chinle shale which underlies nearly the whole of this site is similar to that exposed over large areas in northern Arizona and at several other dam sites described in this report. The weathered shale is untrustworthy and should be removed from beneath the dam. The fresh shale, though weak, is believed to be sufficiently strong to support a broad base flexible dam. It would be impermeable to water.

The altered and fractured lava that caps the hills in the central part of the valley should be removed along the impermeable part of the dam, since it would transmit water freely and would furthermore prevent equal distribution of the load on the shale foundations. If any dikes are discovered during the removal of this material, they should be grouted.

The Tertiary sediments that overlie the lava and the landslide masses on the hill slopes should be avoided or removed from beneath the dam. The silty alluvium in the lower parts of the site will probably support a dam but the impermeable part of the structure should penetrate it and tie into fresh shale.

Either of the saddles near the abutments could be used as spillways. Both are underlain by shale which should be protected from erosion by running water even though the spillway is to be used only occasionally.

The following studies are believed to be necessary:

1. Check depth to bedrock across the stream channel and the righthand saddle by drilling or test-pitting, possibly supplemented by geophysical surveys.

2. Determine thickness and character of weathered zone in abutments and on hills in central part of site by drilling or test pitting.

3. Determine bearing power and permeability of shale and of alluvium by field and laboratory tests.

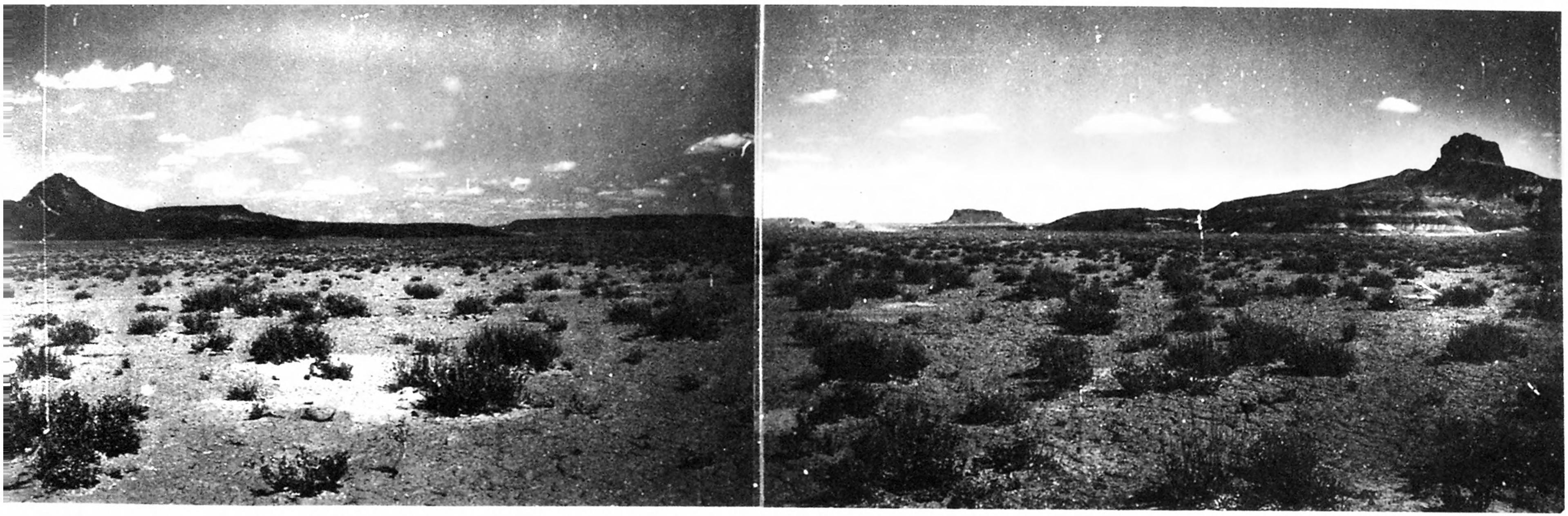

Figure 14

Castle Mountain site on Cottonwood Wash; panoramic view looking upstream.

Castle Mountain Site

The Castle Mountain site on Cottonwood Wash in secs. 22 and 23, T. 21 N., R. 20 E. The reservoir area has not been surveyed but it is evident from field inspection that its capacity would be very large for any dam 40 or more feet in height. Depending on its height the proposed dam would range from 4,000 to more than 5,000 feet in length. Unless the gap north of the main dam (figure 3) were used as a spillway, an auxiliary dike from 250 to 750 feet would be necessary.

General Geology

General statement. - Bedrock consists of nearly jorizontal beds of Chinle shale that have been intruded by plugs, dikes and sills of basaltic lava. The valley bottom is filled with silty alluvium. The only other geologic feature of interest is a moderate-sized landslide mass on the slope of Castle Mountain.

Chinle shale. - The Chinle beds exposed at the surface consist of red and greenish-gray soft shale in large part. Many of the beds contain some bentonite, a clay mineral that swells when wet. Several 5 to 20 foot beds of light-colored semi- consolidated sandstone are inter-bedded with the shales. One of these contains many small pebbles in places. Shale and sandstone are not separated on the map (figure 3), but they can be distinguished in figure 16. Thin lenses and layers of shaly limestone and of sandy shale occur in places and small concretions of ferruginous lime carbonate are widely distributed. A 6 to 12-inch layer that consists of cauliflower-like concretions of brown, impure aragonite is exposed at altitude 5,270, 750 feet south of BM 5263. It is apparently continuous for only a few hundred feet. Good exposures about $\frac{1}{2}$ mile north of the left abutment, where the beds dip south, show that the rocks beneath the alluvium in the valley floor are similar to those described above. The shale in the upper parts of both abutments is weathered and very soft to depths of 10 to 20 feet below the surface. Elsewhere it is relatively fresh.

The Chinle beds dip in general toward the southwest at a low angle. A minor syscline, apparently due to slight settlement that followed the intrusion of the Castle Mountain plug is present on the left abutment and can be seen in figure 16.

Basalt. - Castle Mountain and the sharp pointed hill on the right (west) abutment have been carved from volcanic necks or plugs of basaltic lava. The basalt is dense in most places, particularly near the central parts of the plugs. Elsewhere it is vesicular or scoriaceous. Both of the plugs contain numerous fragments and blocks of shale and sandstone that were torn from the walls and carried upward during intrusion. Several smaller plugs, dikes, and sills of basalt are exposed in the vicinity of the western plug. All of them are doubtless connected with the limestone and of sandy shale occur in places and small concretions of ferruginous lime carbonate are widely distributed. A 6 to 12-inch layer that consists of cauliflower-like concretions of brown, impure aragonite is exposed at altitude 5,270, 750 feet south of BM 5263. It is apparently continuous for only a few hundred feet. Good exposures about $\frac{1}{2}$ mile north of the left abutment, where the beds dip south, show that the rocks beneath the alluvium in the valley floor are similar to those described above. The shale in the upper parts of both abutments is weathered and very soft to depths of 10 to 20 feet below the surface. Elsewhere it is relatively fresh.

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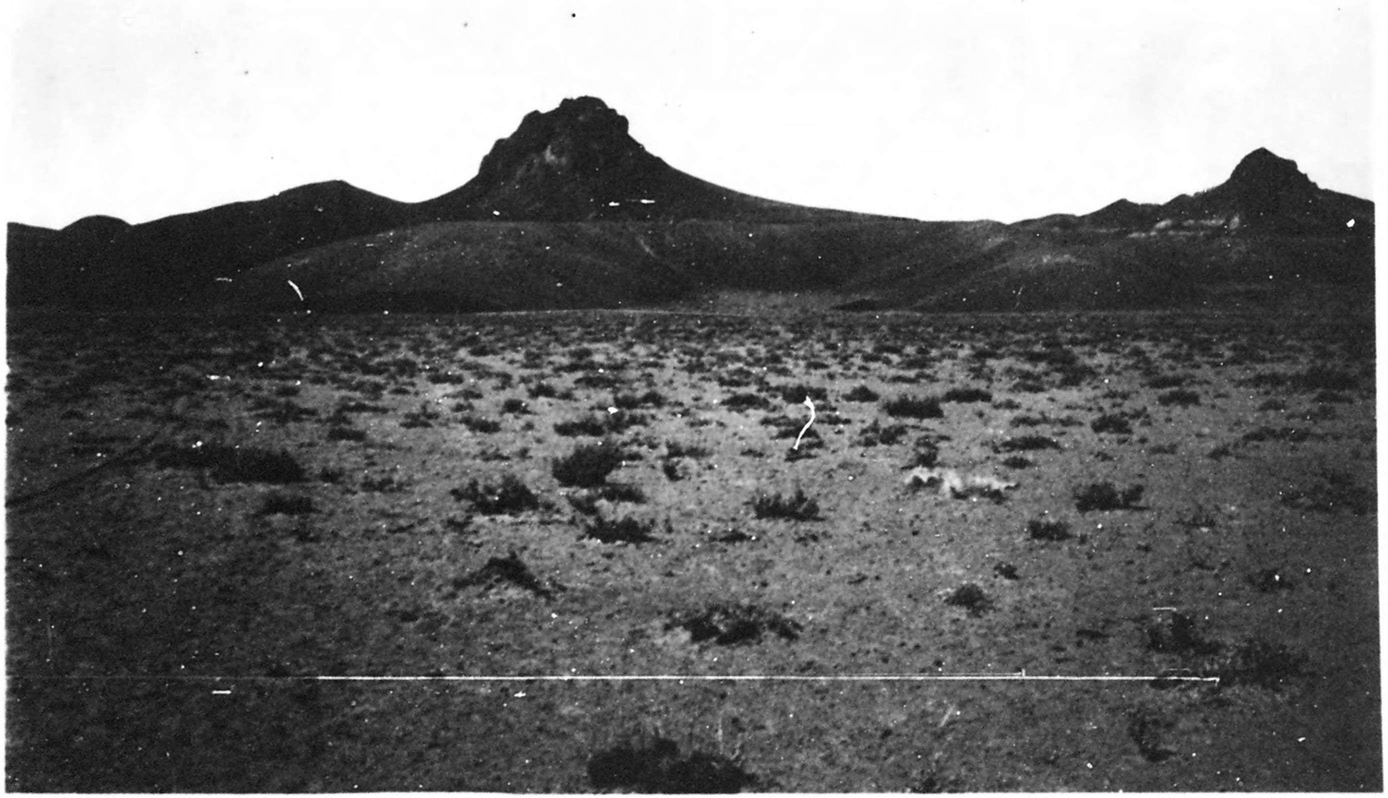

Figure 15
Castle Mountain site, looking west toward right abutment.

main plug in depth. The basalt is strongly fractured in most places.

Landslide. - A landslide mass of moderate size exists on the west slope of Castle Mountain. It has little direct bearing on the suitability of the site but it provides an example of one of the methods by which the Chinle shale erodes. Within the landslide area the shale dips at angles as high as 40 degrees to the east, or toward Castle Mountain. Instead of the smooth erosion surface that slopes gently away from the volcanic plug in other places, the surface of this mass is uneven and hummocky. It is evidently underlain by a somewhat jumbled mass of small landslide blocks. The shape of the slide mass is known only in general but its base is probably concave upward.

Apparently Castle Mountain acts as a focus for local storms. Water falling on or near the top of the peak has entered the ground along the steep contact between shale and basalt, saturated the shale and finally casued it to slide. This belief is based on the following observations. Recent gullies in the coarse talus on the southwest side of the peak are marked by levees 3 to 4 feet high made up of angular blocks of basalt 6 to 10 inches in diameter. These levees indicate strong flows of water, although the drainage area is very small. The landslide is on the southwest side of the peak, facing the direction of prevailing storms. Erosion on this side of the peak is much more advanced than elsewhere.

Alluvium. - The alluvial fill in the floor of the valley is composed of silt and fine sand with a few layers of coarser sand

and a little gravel. Most of it contains enough clay to give it an adobe-like consistency when wet. Figure 16 shows its general character. The fill is doubtless very thin near the abutment and probably reaches its maximum thickness near the center of the valley. The shape of the bedrock profile has been investigated by Mr. Spicer.

The tops of both abutments are actually old erosion surfaces that slope downward from the two main volcanic necks. These surfaces, which can be easily reconstructed from study of the topographic map and the photographs (figures 15,16), are covered by a layer of loose sand, gravel, and fragments of basalt. On the mesa at altitude 5,330 on the right abutment this material is 5 to 20 feet thick but elsewhere it is less than 5 feet thick.

Engineering Geology

Despite the presence of sandy and limy layers as described above, the Chinle beds can all be characterized as weak and soft, with moderately low resistance to erosion by running water. Most of the beds will become plastic when saturated. The presence of bentonite would add to the plasticity of the foundations but I believe its net effect should be beneficial. That is, the bentonitic material on and near exposed surfaces would swell when wet, thus forming a watertight

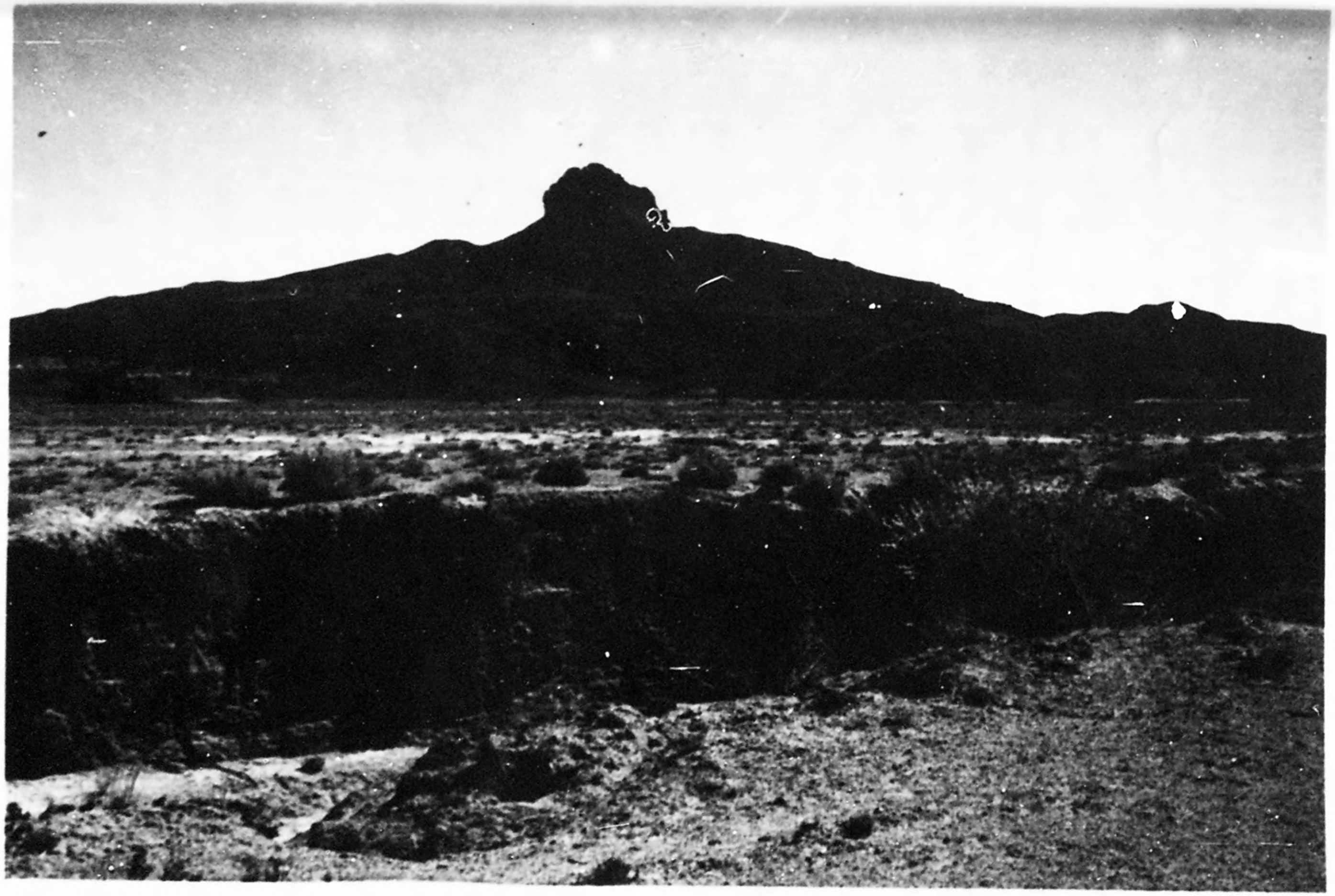

Figure 16

Castle Mountain site, left abutment looking east near right abutment.

layer that would prevent or hinder further saturation of the rock mass.

With the exception of the weathered shale in the upper parts of the abutments, which should be removed, it is believed that the shale is strong enough to support a dam of the proposed size. An earth dam or other equally flexible structure is indicated and it will be necessary to provide a broad base so as to distribute the load as much as possible. Saturation by reservoir water will probably cause renewed movement of the lower part of the landslide mass but as no part of the dam will rest on the slide, this should have no ill effect on the structure.

Tests should be made of the valley fill to determine its suitability for foundations or construction material. I believe it will prove satisfactory for these purposes but that an impervious core, set in bedrock, will be found necessary.

The fractures in the basaltic lava will render bodies of this rock permeable to water. Since only very small areas of lava will be exposed to reservoir water, since the leaks would not increase with time and since the project is designed for flood and silt control, rather than for storage, it is not believed that the lava need cause serious concern. Complete protection from leaks would call for grouting of all lava bodies exposed along the axis of the dam. The basalt will form excellent, durable, material for concrete aggregate or for riprap.

The best spillway site is in the saddle west of the main valley. Bedrock here is soft shale and even if the spillway is to be used only at rare intervals, it should be lined to prevent erosion.

The following studies are believed to be necessary:

1. Check depth to bedrock along dam axis by drilling.

2. Determine thickness and character of weathered zone in abutments by drilling or test-pitting.

3. Perform physical tests to determine character and bearing power of shale and of valley fill.

4. Study effect of spillway water on toe of dam.

Cottonwood Wash

Unsurveyed site in T. 22 N., R. 21 E.

A brief examination was made of an unsurveyed site on Cottonwood Wash, in T. 22 N., R. 21 E. It is about $2\frac{1}{2}$ miles east of the point where the Holbrook-Indian Wells road crosses the wash. A poor road that follows the north side of the wash leads directly to the site. A dam 50 to 60 feet high and about 2,500 feet long could be built at this site and the reservoir area is comparatively large.

The sketch cross-section (figure 4c) shows the geologic relations along what appears from casual inspection to be the shortest axis for a dam. It is evident from the sketch that most of the site is underlain by valley-fill alluvium which has been trenched by the main wash and by one of its tributaries to a depth of approximately 25 feet. The depth of this fill is not known but it is probably not more than 25 to 50 feet below the present stream bed (50 to 75 feet below the general surface). The alluvium consists of silt and fine sand in large part but contains enough clay to be slightly plactic when wet. Thin lenses of gravel and sand occur locally. The alluvium is unconsolidated, weak, and as is shown by the trenches in it, is eroded rapidly by running water.

The abutments consist of soft, dull red shale of the Chinle formation. Similar shale, with perhaps a few thin beds of sandstone, forms the valley floor beneath the alluvium. The beds dip northward at a low angle. A 4 to 5½-foot bed of hard, impure limestone that contains a layer of soft shale in its central part in places, caps the north abutment and is exposed in the slope on the south abutment. Several limy layers are exposed above this bed in the upper part of the south abutment.

Conclusions. - Because of the soft and relatively weak nature of the shale foundations, a flexible dam, preferably of rolled-earth or hydraulic fill, will be advisable. An impervious core, keyed into the bedrock shale, should be provided. Field and laboratory tests by competent soils engineers seem necessary to determine whether the valley fill is sufficiently strong and impermeable to support a dam or whether the entire foundation should be stripped to bedrock. The limestone cap on the north abutment should serve as a fair foundation for a side-channel spillway but it is too thin and is probably too much fractured to serve without lining. The bedrock shale and the alluvium must be protected from erosion by running water along the spillway.

This site is as good geologically as those farther downstream and I would recommend that it be mapped topographically and studied by the engineers before a final choice is made. The depth to bedrock along the axis should be determined by means of drilling or geophysical exploration. Mechanical tests should be made of both the shale and the alluvium to determine their suitability for foundations and for construction purposes.

Pueblo Colorado Wash

Unsurveyed Site in T. 22 N., R. 22 E.

An unsurveyed dam site exists on Pueblo Colorado Wash (the upper part of Cottonwood Wash) a short distance below the mouth of Creosote (?) Wash in T. 22 N., R. 22 E. The site is 14 miles downstream from the Greasewood trading post and 8.3 miles below the poor Indian Wells-Greasewood-Ganado road, from which it can be reached over very poor Indian roads. The valley is 2,000 to 3,000 feet wide at this place and a 50 to 75-foot dam would back water over a very large area. It should be noted that most of the Pueblo Colorado valley is rather thickly inhabited by Indians who would have to be moved to other and probably less desirable land if a reservoir were created.

Bedrock consists of soft red shale of the Chinle formation and is similar to that exposed at several other sites described in this report. Hard and moderately hard beds of sandstone and limy shale are present but they are few and very thin. The shale dips toward the north, or directly across the site, at an angle of about 2 degrees. This slight dip has led to the development of broad, low steps on the left (south) abutment, along which the shale is exposed at the surface. The right abutment is capped by a thin layer of Tertiary sand, some of which has been reworked and now appears as sand dunes. The flat valley floor, intrenched by the stream is underlain by alluvial material that consists of fine sand and silt with some clay. The depth to the shale that forms bedrock and the shape of the bedrock profile are not known.

The shale at this site would doubtless support a broad base earth dam satisfactorily. A cutoff wall or impervious core that penetrates the valley-fill and is securely tied to bedrock will very probably be found necessary. There is no site for a side-channel spillway, in which respect the site is somewhat less desirable than the one in T. 22 N., R. 21 E. The valley fill should prove to be usable for construction but it will probably require comparatively flat slopes. Abundant basaltic lava for use as riprap can be obtained within 2 to 3 miles of the site.

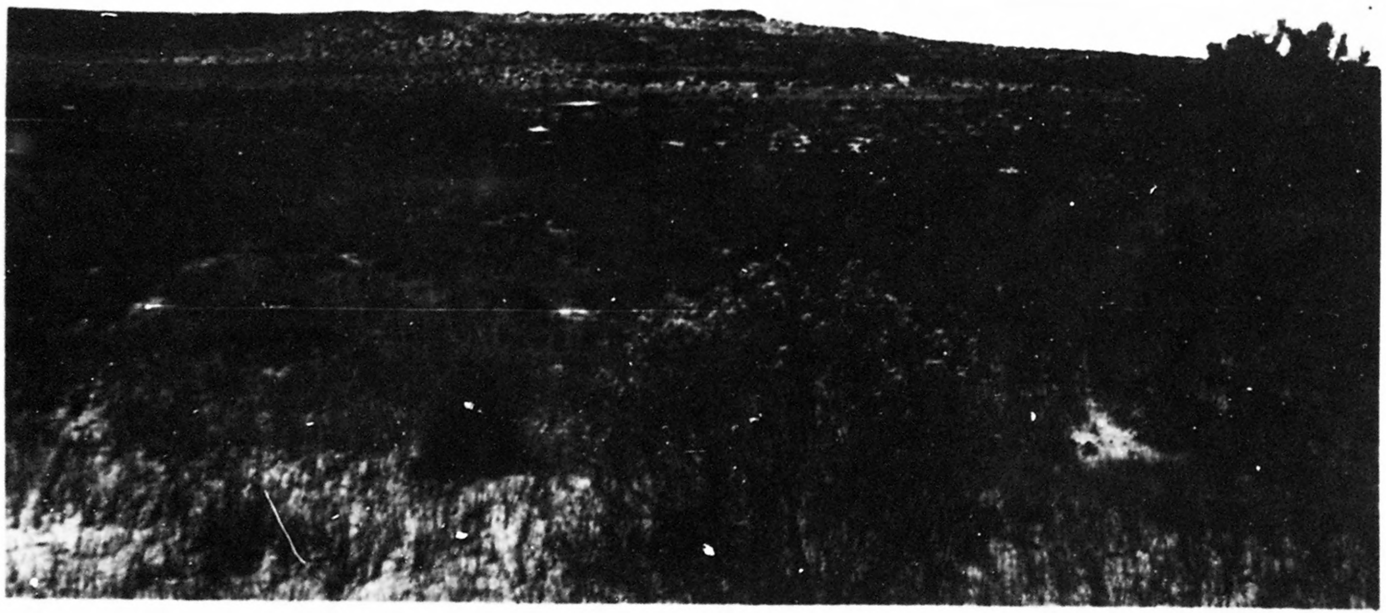

Figure 17

Lower Leroux Wash site looking toward left abutment from near center of valley

Leroux Wash

Two dam and reservoir sites exist on Leroux Wash, a large southwesterly flowing tributary of the Little Colorado River. The lower site is just west of Holbrook, in T. 18 N., R. 20 E., about 1 mile above the mouth of Leroux Wash. The upper site is 25 miles upstream, in T. 21 N., R. 23 E. The reservoir areas are large and of comparable extent. A 75-foot dam with a crest length of about 4,000 feet could be built at either site but the lower one would require a long, comparatively low, auxilary dike in a broad saddle 3 miles west of the main dam. The geologic conditions are similar at the 2 sites. Abutments and alluvium-covered foundations consist of flat-lying beds of sandstone and shale. One abutment of each site contains a landslide mass that would require special treatment or removal. The shales at the lower site contain much gypsum. Geologically, the upper site seems to be slightly superior to the lower one but choice of site must depend almost entirely on engineering factors. The greater accessibility of the lower site, and the fact that it controls a much larger watershed may well make it far more desirable than the upper site.

Lower Site

General-Geology

As shown in figures 5, 17, and 18, bedrock at the lower site consists of alternating beds of sandstone and gypsiferous shale that belong to the upper part of the Moenkopi formation. The gentle northwestward dip of the rocks serves to expose slightly older beds on the left abutment than on the right and accounts in part for the preservation of the overlying Shinarump conglomerate on the right abutment.

Left abutment. - The entire hill that forms the left abutment (figure 17) is capped by a 7 to 10-foot bed of soft to moderately hard, reddish brown, fine to medium grained sandstone that contains much shaly material intersticial to the sand grains. Irregular and discontinuous partings of soft red shale occur in places and a few thin layers flakes and modules of shale and small pebbles of chert.

This sandstone bed is underlain by 60 feet of dark red shale that contains a few dull green streaks. The shale is in turn underlain by a 15-foot zone of sandstone, shale and gypsum. In some places it consists of shale and soft, cross-bedded sandstone in irregular layers and lenses with a little shaly gypsum at the base. Elsewhere the entire zone is made up of a semi-consolidated mixture of gypsum and sand with veins and thin layers of relatively pure gypsum throughout. The lowest beds exposed on the left abutment consist of shale which probably contains considerable quantities of gypsum.

There is strong reason to suppose that the shape of the left abutment is due in part to landslide movement. The sandstone cap of this abutment slopes irregularly downward toward the

Figure 18

Lower Leroux Wash site, looking toward right abutment from center of valley.

Wash at an angle slightly greater than the regional dip of the rocks. Cursory examination suggests that there are 3 distinct layers of sandstone, separated by beds of shale but more detailed obserations show that the exposed masses all belong to the same bed. It must be concluded that during the erosional development of the valley large parts of the sandstone cap broke off and slid forward and downward over the soft underlying shale beds; which were probably relatively undisturbed.

Right abutment. - The right abutment is capped by 5 to 8 feet of loose to semi-consolidated gravel that represents remnants of the Shinarump conglomerate. The uppermost 70 feet of the abutment is made up of dull red, moderately hard shaly sandstone that contains extensive but irregular lenses of soft shale. These lenses range from 6 inches to 5 feet in thickness and make up about one-fourth of the total thickness. The thick sandstone layer with its included lnese of shale is underlain by 10 feet of gypsiferous shale. The lower part is sandy and hard enough in places to form benches. This layer is underlain by 10 to 15 feet of light reddish brown highly gypsiferous sandstone. The bed is massive, moderately hard, and sufficiently erosion-resistant to form a steep cliff along the lower part of the abutment. The lowest beds exposed are a series of red and green shales and mudstones with a 1 to 2-foot bed of relatively pure gypsum at the top. The shales probably contain many thin layers and veinlets of gypsum throughout.

Valley fill. - The greater part of the proposed dam will rest on the broad flat flood plain of Leroux Wash. The alluvial material in this plain consists of silt with some clay and sand and probably a few small lenses of gravel. Large sand dune levees have been built up along both banks of the stream channel. The depth of the valley fill has been investigated by H. C. Spicer, who used geophysical methods. The character of bedrock beneath the valley fill is not known, but it is doubtless composed largely of gypsiferous shale like that in the lower parts of the abutments.

Auxiliary saddle. - A low broad saddle, which forms part of the divide between Leroux Wash and Manila Wash, exists about 3 miles northwest of the dam site and would have to be closed by an auxiliary dike or used as a spillway. Soft, varicolored shales that belong to the lower part of the Chinle formation are exposed across the entire saddle. The hills at its north end are capped by a thin layer of bright-colored chert. The Chinle shales are underlain by the Shinarump conglomerate but because of the northwesterly dip of the sediments this formation is at least 100 feet beneath the surface in the saddle.

Structure. - The beds dip at angles of 2 to 4 degrees toward the northwest. The effect of this slight dip is to expose slightly older rocks on the left abutment than on the right. The harder sandstone beds are fractured along 2 sets of joints that trend N. 40-55 W. and N. 30-45 E. The northwesterly trending set is much the stronger. The fractures are 2 to 10 feet apart and many of them are open at the surface, particularly where they are close to the cliffs. The same fractures must also cut the interbedded shaly layers but they are certainly tight there and are probably tight even in the sandstones except within 10 to 15 feet of the surface.

Engineering Geology

The lower site is not particularly suirable for a dam, but if proper precautions are taken a safe structure can be built. The presence of soluble gypsum throughout most of the foundation rocks raises the question of leakage. All of the gypsiferous masses seen are so thin and so impure that there is little likelihood of developing large solution channels. Long-continued saturation by reservoir water might well lead to removal of enough gypsum to allow settlement of the foundations and abutments, however. This possibility is so strong that a flexible structure is imperative. The alternating layers of sandstone and shale will be stronger than would shale alone but even so the foundations are not capable of supporting heavy, concentrated loads and a broad base dam should be provided. The low slopes on the surface and the nearly horizontal attitude of the bedrock layers should inhibit any tendency toward sliding if the rocks remain moderately dry. If they become saturated, however, the tendency to slide would be greatly increased, particularly on the left abutment. For this reason, a good, impermeable cut-off

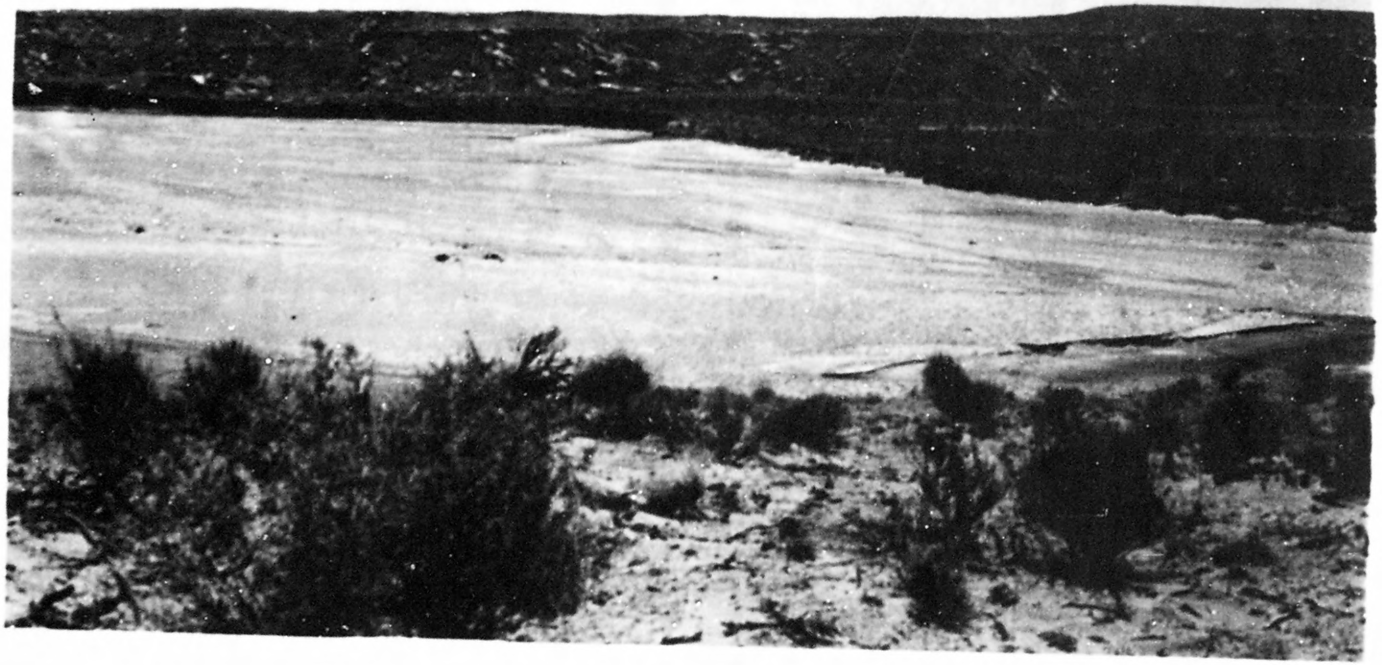

Figure 19
Upper Leroux Wash site, looking toward left abutment

should be built in both abutments. The landslide conditions on the left abutment offer some cause for concern, but the movement was so slight and the sandstone cap has been so little broken that removal of any material except that in the shallow weathered zone and along the cut-off trench should not be necessary.

The valley fill is probably strong enough to support a broad base dam but it is permeable and subject to erosion by running water. It should therefore be penetrated by an impermeable membrane that is securely set in the underlying bedrock.

The saddle northwest of the site offers no special problems. If it is closed by a dike it should only be necessary to remove a thin layer of soil and weathered shale along the axis of the dike. This saddle seems to offer the best site for a spillway. The shales that underlie it are soft and easily eroded by running water. Lining of the spillway channel will therefore be necessary unless it is to be used only at rare intervals.

The valley-fill alluvium will doubtless be found suirable for earthfill construction. Excellent gravel and clean, sharp sand for concrete structures can be obtained from the Shinarump beds on and near the right abutment.

Upper Site

<u>General geology</u>. - As indicated on the map and cross-section (figure 6) bedrock at the upper Leroux Wash site consists

of shale and sandstone of the Chinle formation. The rocks dip toward the northeast at angles of 2 to 5 degrees so that the sections exposed in the 2 abutments are almost identical.

Both abutments are capped by thin layers of unconsolidated fine sand that contains a few pebbles of chert. This is underlain by a 3 to 12-foot zone of interbedded sandstone and shale that forms a prominent cliff in most places (figures 6 and 19). Locally this zone is entirely made up of massive, moderately soft, chocolate brown sandstone, but elsewhere it consists of thin alternating layers of sandstone and soft shale. The zone is underlain by 4 to 15 feet of soft, dull red shale. Since the upper sandy zone thickens in places where the shale thins, and vice versa, the combined thickness of the two members ranges from 12 to 18 feet. These members are underlain by a 10 to 15-foot bed of massive, moderately soft brown sandstone. Locally it contains up to 5 thin partings of shale. A bed of limestone conglomerate from 2 to 5 feet thick forms the base. It consists of pebbles and fragments of dark gray limestone in a shaly matrix. The two beds together form cliffs in most places, and are underlain by soft, dull red shale which forms slopes. Similar shale probably underlies the valley floor although some layers of sandstone may be present.

The sandstone layers contain numerous strong fractures, or joints, most of which fall into 2 sets that trend N. 50-65 W. and N. 30-40 E. Many of these are open to depths of at least 10

Figure 20

Upper Leroux Wash site, showing landslide in right abutment looking upstream feet from the present surface but probably they are all fairly tight in unweathered rock.

A moderate-sized landslide mass characterizes the right abutment. All of the beds in the abutment are involved and the mass is a confused jumble of blocks of sandstone and shale. Figure 20 shows its character. The slide was doubtless caused by oversteepening of the slope by stream erosion. Its shape was controlled in part by fractures in the brittle rocks and in part by slippage of these rocks over the layers of soft shale.

The alluvial fill in the valley floor, like that at the lower site, consists of silt, sand and clay. Its thickness has been determined by H. C. Spicer, who used geophysical methods.

Engineering geology. - The shales and sandstone beds that make up the abutments and underlie the foundations should be strong enough to support a broad base dam and unless the factures in the sandstones are open in unweathered rock they are essentially impermeable. As is evidenced by the landslide mass noted above there is a strong tendency for the hard sandstone layers to slide over wet shale surfaces. This tendency would be increased by the load of the dam. For this reason, percolating water must be prevented from entering the immediate abutments by means of deep cutoff walls. As a further precaution, a broad base structure, with widely distributed loads, should be provided. The disturbed rock in the landslide mass should be avoided or removed. A cutoff wall or impervious core to bedrock beneath the valley fill seems to be highly advisable. It will be difficult to provide adequate side-channel spillway capacity but there are several low saddles in the right abutment that can probably be used without excessive excavation. The thicker sandstone beds would doubtless be sufficiently durable to serve for intermittent use without lining. If, as is probable, the spillway cut exposes layers of shale, they should be protected from erosion by concrete lining or heavy rip-rap.

There is abundant material for earth-fill construction near the dam and adequate search will probably lead to the discovery of usable deposits of sand and gravel. None of the rock at the site could be used as concrete aggregate and none of it can be highly recommended for use as durable rip-rap.

Rio Puerco

Adamana Site

The Adamana site on the Rio Puerco is in T. 18 N., R. 24 E., about 3 miles east of Adamana. The dam axis would follow approximately the course of the main Petrified Forest highway. The site is unattractive physically, since a dam only 50 feet in height would have a crest length of $1\frac{1}{2}$ miles and since it would be necessary to relocate the Santa Fe railroad tracks throughout the length of the reservoir. It is nevertheless the only site on the Rio Puerco, a stream that often empties large silt-laden floods into the Little Colorado River at Holbrook. The necessary relocation of the railroad would have some advantages in that the tracks are now below stream level in several places, being protected from flood waters only by natural levees of dune sand.

Geology. -

Rocks. - Except for the alluvium that fills the Rio Puerco valley all the rocks exposed at the Adamana site belong to the Chinle formation. The mesa south of the river that is crossed by the Petrified Forest highway is held up by a cap of brown, massive, fine to medium grained sandstone, covered on the higher parts of the mesa by deposits of unconsolidated sand and gravel. This sandstone, which is one of the hardest and most durable rocks in the region, is 25 to 60 or more feet thick on the main part of the mesa but it thins rapidly toward the north and on the narrow ridge immediately south of the Puerco it is not more than 10 feet thick. The sandstone layer is underlain by soft varicolored shales of the typical Painted Desert type. They contain highly colored petrified logs in places but there are no hard beds of any kind.

Thin deposits of sand and grovel cover nearly all of the bedrock on the right, or north abutment. A few scattered outcrops, together with the general shape of the land surface, make it seem quite certain that the entire abutment is underlain by soft Chinle shale like that in the lower part of the left abutment.

If there are any hard beds they are very thin for otherwise they would crop out at the surface somewhere in the vicinity.

Alluvial sand, silt and clay fills the valley floor. In general material is courser than that in most of the washes that drain the Navajo country but a large part of it will probably be found to range from fine sand to coarse silt in grain size. Extensive levees of dune sand have been built up along the banks of the Rio Puerco by the action of wind on the alluvial valley fill. Several prominent dunes are situated on the north side of the river at the site. The depth of the valley fill has been determined by geophysical means by H. C. Spicer. The character of bedrock beneath the valley floor is not certainly known, but it is believed to consist of soft Chinle shales with few if any hard beds. There is some possibility that the sandstone layer that caps the south abutment continues northward beneath the stream. Since it is clearly thinning toward the north, however, it seems more likely that it dies out completely in this direction.

The rocks dip toward the north at angles of 2 to 4 degrees. This northward dip accounts for the fact that the sandstone cap drops gradually from the level of the high mesa south of the site down to stream level. The sandstone cap is fractured in many places. The strongest fractures, or joints, parallel the edges of the mesa and many of them are open. These relations indicate that most of the fractures are due to undermining of the shale by erosive processes, followed by slight settling of the more brittle sandstone cap.

Engineering features. - The shale that forms the predominant bedrock at this site is essentially impermeable to water. It is weak, however and would be unable to withstand concentrated loads. For this reason a broad base, flexible structure, is indicated. The sandstone cap on the left abutment is strong and durable in itself but it would have a strong tendency to slide on the underlying shale, particularly if the latter were wet. Furthermore, the sandstone is so much fractured that it would transmit water freely, resulting in weakening of the foundation rocksand of the dam itself. It would seem best to remove the sandstone completely from beneath the structure, using the rock for rip-rap or other purposes. If this is not done an impermeable core should be constructed to tie the dam into the tight shales beneath the sandstone.

Neither of the abutments seems to be adapted to construction of a side channel spillway. Regardless of the type of spillway that is used, it must be remembered that the Chinle shale is readily eroded by running water and that any channel that is to be used often must be lined.

No further exploration of the site seems necessary except determination of the depth to bedrock by drilling and studies of available construction materials.

Big Carrizo Wash Sites

Two possible sites for flood - or silt-control dams exist on Big Carrizo Wash in T. 19 N., R. 23 E. They are 3 and 5

Figure 21

Lower Big Carrizo Wash site, looking toward right abutment from near left abutment miles, respectively, above the place where the highway crosses the wash. Auxiliary dams would be necessary to close side channels at both sites. The sites are similar in that the abutments consist of massive sandstone that rests on soft shale. The lower site is much more suitable than the upper because the sandstone layer is much thicker there and because the combined length of the main and auxiliary dams would be only about half as great as at the upper site.

Geology. -

Rocks. - Bedrock along this part of Big Carrizo Wash consists of shales and sandstones of the Chinle formation. The low benches that form the abutments of both sites are capped by an extensive bed of massive sandstone that contains flakes and small lenses of shale in a few places. The lowest part of the bed consists of white, coarse grained sandstone that is locally only semi-consolidated. The remainder of the bed is light brown, fine to medium grained, and medium hard. A few fragments of petrified wood occur near the top and bottom of the sandstone. The bed is about 50 feet thick at the lower site, where it forms nearly vertical cliffs (figures 8, 21) but it thins toward the north and at the upper site is less than 15 feet thick. It is everywhere underlain by soft, dull gray shale. This material makes up the greater part of the abutments at the upper site but the sandstone cliffs extend almost down to stream level at the lower site, where shale is exposed at only a few places.

Both the main valley and the side channels are filled with alluvium that contains much silt and some clay, sand, and gravel.

The depth of this material and the shape of the bedrock profile has been studied by geophysical means by H. C. Spicer. The alluvium is undoubtedly underlain by soft shale like that exposed in the base of the abutments.

The rocks are slightly warped in several places but in general they dip northward at a very low angle. There are no faults near the sites. Two sets of fractures, or joints, cut the heavy sandstone bed. The stronger and more continuous of these trends N. 65-80 W., or parallel to the dam axis in general. The other set trends N. 10-20 E. The westerly trending fractures have been opened by erosion and by the settling of blocks to depths of 10-15 feet from the cliff faces (figure 21) but most of those exposed on the mesa surfaces are tight. All of the fractures are probably tight in unweathered rock.

Engineering features. - In addition to the fact that it calls for much shorter dams, the lower site is the more attractive of the two by reason of the presence of strong hard sandstone in the abutments and the comparative lack of talus. The shale foundations at both sites are essentially impermeable but relatively weak. Broad base, flexible structures are therefore advisable. The massive snadstone is sufficiently impermeable to prevent notable leakage except along open fractures. Since most of these trend across the stream rather than parallel to it, the chances of material leakage are diminished. Nevertheless, it will be necessary to search out and seal all open fractures and it may also be found advisable to remove 15-20 feet of partly weathered rock from each abutment. There will doubtless be some tendency for the massive sandstone to slide on its soft shale foundations. Since the beds are nearly or quite horizontal this tendency will be slight and unless very concentrated loads are to be imposed can probably be ignored in large measure. It offers a second good reason for sealing all fractures in the sandstone, however. That is, all available means should be taken to prevent percolation of water to and along the sandstone-shale contact.

The alluvial fill in the valley floors is probably strong enough to support an earth dam but it is relatively permeable and offers little resistance to erosion by running water. It will be highly advisable therefore to extend the impermeable part of the dam downward through the alluvium and to tie it into firm shale bedrock.

Either of the 2 channels that are to be dammed could be used as sites for overflow spillways. The most acceptable side-channel spillway is about 1 mile northwest of the lower site. Since it is underlain by massive durable sandstone and will only be used occasionally, there seems to be no necessity for lining it.

Further exploration. - The thickness of the alluvial fill should be checked by means of drilling. It may also seem worthwhile to drill the abutments and to test the permeability of the sandstone by means of pressure tests. No other exploration except detailed studies of available construction materials seems to be necessary.

Figure 22
Oak Springs site looking upstream toward head of Black Creek canyon

Black Creek

Oak Springs site

The Oak Springs site in T. 24 N., R. 30 E., is near the head of the canyon of Black Creek, about 20 miles above the confluence of that stream with the Rio Puerco. A short dam in this canyon would back water over a large area in the wide valley of Black Creek. Much of the land that would be flooded is relatively fertile and is extensively cultivated by Navajo Indians.

The narrow place at the very head of the canyon presents the shortest cross-section for a low dam. If the structure is to be more than about 75 feet high almost any place in the upper 2 miles of the canyon is equally suitable. Bedrock is hard, strong, and durable and would support any type of dam satisfactorily.

Geology. -

Rocks. - The canyon of Black Creek is a deep, narrow, steep walled gorge, about 1 mile wide and 700 feet deep. Through the greater part of the canyon the exposed rocks lie horizontal and consist of about 500 feet of red shales, mudstones and sandstones of the Supai formation, surmounted by 200 feet of Coconino sandstone. Just upstream from river mile 20 (figure 9), the beds bend over sharply, bringing the Coconino sandstone down to stream level at the head of the canyon in almost vertical position. The wide valley above the canyon is cut in the comparatively soft Moenkopi, Shinarump and Chinle beds that overlie the Coconino sandstone.

The following section was measured on the northwest canyon wall, along the line between bench marks 7172 and 6472, where the rocks are horizontal. Unless the site finally chosen is in the uppermost half mile of the canyon only the lower beds in the section will be of immediate interest:

Character. -

Bed	Top of plateau. -	Thickness, feet
1.	Typical Coconino sandstone; massive, crossed bedded, white to buff hard sandstone composed of fine to medium sized quarts grains with a little limy cement.	67
2.	Coconino (?) sandstone; red to pink, massive, strongly cross-bedded, fine to medium grained, and moderately hard. Like typical Coconino sandstone except for color and almost certainly represents the lower part of this formation. Thickness of beds 1 and 2 calculated by difference between measured section below and total depth of canyon.	133
3.	Dull red, silty and shaly, fine grained, medium soft, sandstone in massive beds. Probably represents top of Supai formation.	20
4.	Dull red limy siltstone, sandy in part.	37
5.	White to buff, moderately soft, fine to medium grained sandstone alternating with layers of pink sandy shale.	72
6.	Soft red shale, sandy in part.	16
7.	Light gray, slabby, impure limestone.	7
8.	White to cream fine grained sandstone, locally streaked with pink.	30
9.	Brick red shaly siltstone.	22
10.	Light brownish red, sugary, fine grained sandstone.	10
11.	Brick red siltstone becoming shaly toward top. Contains 2 thin beds of white fine grained sandstone in upper 15 feet and a 3 to 5 foot bed of maroon mudstone at top.	134
12.	Brick red, very shaly siltstone.	49
13.	Brick red siltstone in massive beds. A few thin layers are shaly. Moderately hard.	146
	Bed of stream; lower Supai rocks not exposed. Total thickness measured, feet.	743

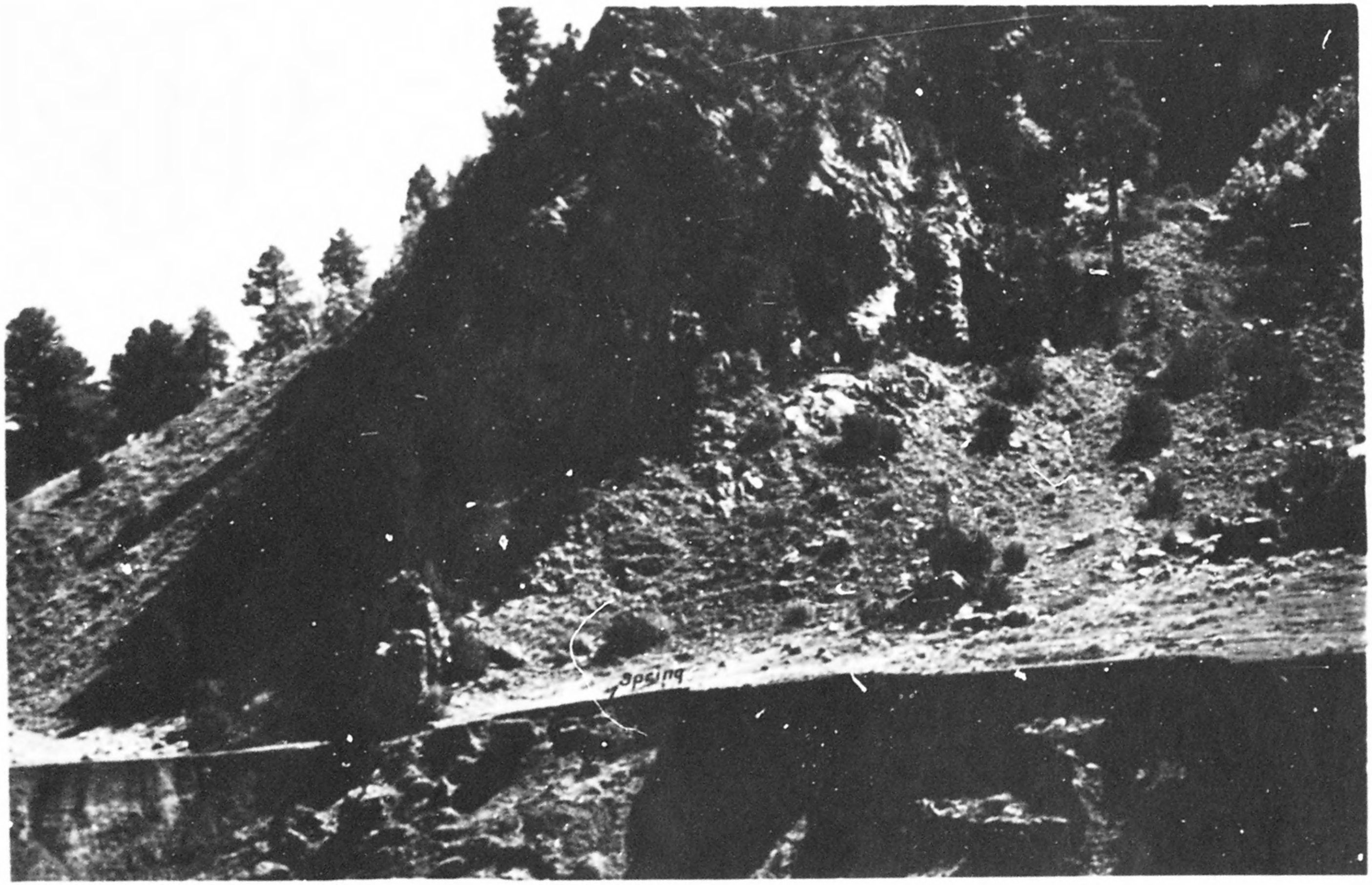

Figure 23
Left abutment of upper Oak Springs site

The Coconino sandstone is the hardest and most durable rock in the exposed section. Where the beds are horizontal it forms nearly vertical cliffs. Where the beds are downturned it is almost equally resistant to erosion and forms a prominent ridge on each side of the canyon at its head. The Supai rocks, though in general somewhat softer and weaker than the Coconino are never-the less well compacted and durable and are believed capable of withstanding the loads that would be imposed by a dam up to 200 feet or so in height.

Where the rocks are horizontal they contain a few widely distributed irregular fractures, most of which are sealed with narrow veins of calcite. None of them offer any cause for concern with regard to possible leakage. Where the rocks are bent over, fractures are much more numerous and stronger than elsewhere. They resulted from tensional forces set up during the folding process and nearly all of them are normal to the bedding planes. Near the head of the canyon, several small seep springs emerge from the lower part of the sandstone a few feet above the stream bed (figures 9, 23). They are undoubtedly fed by surface water that has entered the sandstone on the plateau, penetrated the Coçonino beds, and then followed down the Supai-Coconino contact to the points of emergence. Their presence is a clear indication of the relative permeability of the two formations.

The canyon floor is filled with silty alluvium which has been intrenched by the present stream to a depth of more than 30 feet. In a few places, bedrock is exposed down to stream level and the alluvial fill is only as wide as the actual stream channel. Elsewhere there is an alluvial bench on one or both sides of the stream. The course of the bedrock valley beneath the alluvium can be traced only where bedrock is exposed at stream level. H. C. Spicer's geophysical studies indicate that the deepest part of the bedrock floor is nearly 100 feet lower than the stream and that in some places it is beneath the benches rather than directly beneath the present stream.

Engineering features. - The downturned Coconino sandstone beds that form the constriction at the head of the canyon would serve admirably as durable, strong abutments for an earth or concrete dam. Since this rock is relatively resistant to erosion it seems likely that the depth to bedrock is less here than farther downstream but this possibility can be proved only by further exploration. The fractured condition of the sandstones renders them permeable to water but it would be a comparatively simple matter to seal the openings by grouting.

The chief advantage of the site at the head of the canyon lies in the shorter cross section it offers for a dam less than 75 feet in height and in the somewhat greater strength of the foundation rocks. These advantages must be weighed against the relative impermeability of the Supai rocks farther downstream. All the rocks are strong enough for the purpose and in my opinion the choice of site should rest on estimates of comparative costs. In these estimates, the depth to bedrock and the shape of the valley floor as determined by drilling will probably be a decisive factor. If a concrete dam is built, all of the silty alluvium should be removed from beneath it but if an earth dam is chosen, it will probably only be necessary to penetrate the alluvium with an impermeable core.

The only possible site for a side channel spillway exists on the right-hand sandstone ridge at the head of the canyon. If a spillway is cut there, the fractures in the sandstone should be sealed to prevent seepage of water into the rocks and against the dam. No other protection of the spillway channel seems to be necessary.

Further exploration. - Since the choice of site seems to depend on location of the shortest cross section for the height of dam chosen and on the depth to bedrock, the studies most necessary seem to be detailed, large scale topographic surveys and an extensive drilling campaign in the valley bottom. If the site at the head of the canyon is to receive further consideration, pressure tests of drill holes in the abutments will be advisable in order to determine the permeability of the sandstone and the likelihood of extensive leakage.