FIELD NOTES FROM THE ARIZONA BUREAU OF MINES

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GEOLOGIC CONDITIONS AND HIGHWAYS

Photo courtesy Arizona Highway Department

Fig. 1. View towards southwest from vicinity of station 820. (See figure 2.) In left middle ground rigs are set up on nose of ridge, drilling presplit blasting holes for channel relocation number 5.

Some of the effects of geology on highway planning and construction.

by
Richard T. Moore*

INTRODUCTION

In general, the modern car-borne citizen of the U.S.A. seems to take his fine, modern highways as a matter of coarse, not realizing, perhaps, that some of these roads are indeed engineering feats of great magnitude. One such piece of highway is the Arizona portion of Interstate 15. (See figure 1.) This highway, essentially a realignment of U.S. 91, which it will replace, ultimately will extend from Los Angeles, California, through the extreme northwestern corner of Arizona, on to Salt Lake City, Utah, and thence to Montana and the Canadian border.

The Arizona portion of Interstate 15 has a length of only about 30 miles (figure 2), but in that short distance it crosses an area of deeply incised stream channels, and then traverses a rugged mountain range by way of the narrow Virgin River Gorge.

Engineers have been intrigued with the possibility of building a major highway through the Virgin River Gorge for a number of years. The present alignment of U.S. 91 passes over the relatively high Shivwitz Summit in southwestern Utah where winter ice and show present serious hazards to traffic, and a continuing maintenance problem.

As early as 1946, the U.S. Bureau of Public Roads contemplated a highway through the Virgin River Gorge and made a reconnaissance study of such a project. Subsequently, the San Francisco office of the Bureau issued a report which included cost estimates for a two lane highway covering 21.75 miles of proposed road in Arizona and 8.12 in Utah, with a

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minimum design speed of 60 miles per hour. It was estimated that the Arizona portion would cost slightly in excess of $19 million. A supplement to the report was made in 1954 by the Bureau of Public Roads in which the cost of a four lane highway following the same alignment was determined. The revised total construction cost for the Arizona segment was approximately $25.5 million. With the passage of the Federal Aid Highway Act of 1956, which provided for approximately 41,000 miles of interstate highways in the United States, the Bureau of Public Roads pushed even harder for plans in initiate the construction of the Virgin River Gorge route, and in June, 1959, the Arizona State Highway Department retained consultants to undertake a detailed study and field survey of the contemplated route between Littlefield, Arizona, and the Utah line. The final recommended alignment was 21.5 miles in length with a maximum grade of 4.1 percent ascending and decending and a maximum horizontal curvature of 6 degrees. Approximately 85 percent of the route is designed for 70 mile per hour speeds and 15 percent for 60 miles per hour. The total cost for the segment of highway was estimated at $29.5 million.

By the time construction has been completed and the roadway opened to public usage, sometime within the next two years, the total cost probably will have exceeded $70 million. In 1968, it was estimated that the 3.8 mile section in the precipitous narrows region of the Virgin River Gorge would cost about $1,000 per foot making it the most expensive highway construction job, exclusive of tunnels, in all the 41,000 miles of interstate system. When completed, it may well be found that the actual cost has exceeded that preliminary figure by half again as much. A significant portion of these increases of actual cost over estimated cost, however, are not hard to account for when one considers the rate of inflation over the past 15-20 years, and, although these costs may seem excessive, a consideration of the geologic setting of the project, while not justifying the costs, does much to explain them.

It should be pointed out at this time that the Arizona Highway Department was in favor of an alternate route through a low pass to the north which, although about 3 miles longer, would have been considerably less expensive, and still would have conformed to the design specifications established for the interstate system. However, the Bureau of Public Roads, which is supplying 95 percent of the construction funds, endorsed the Virgin River Gorge alignment.

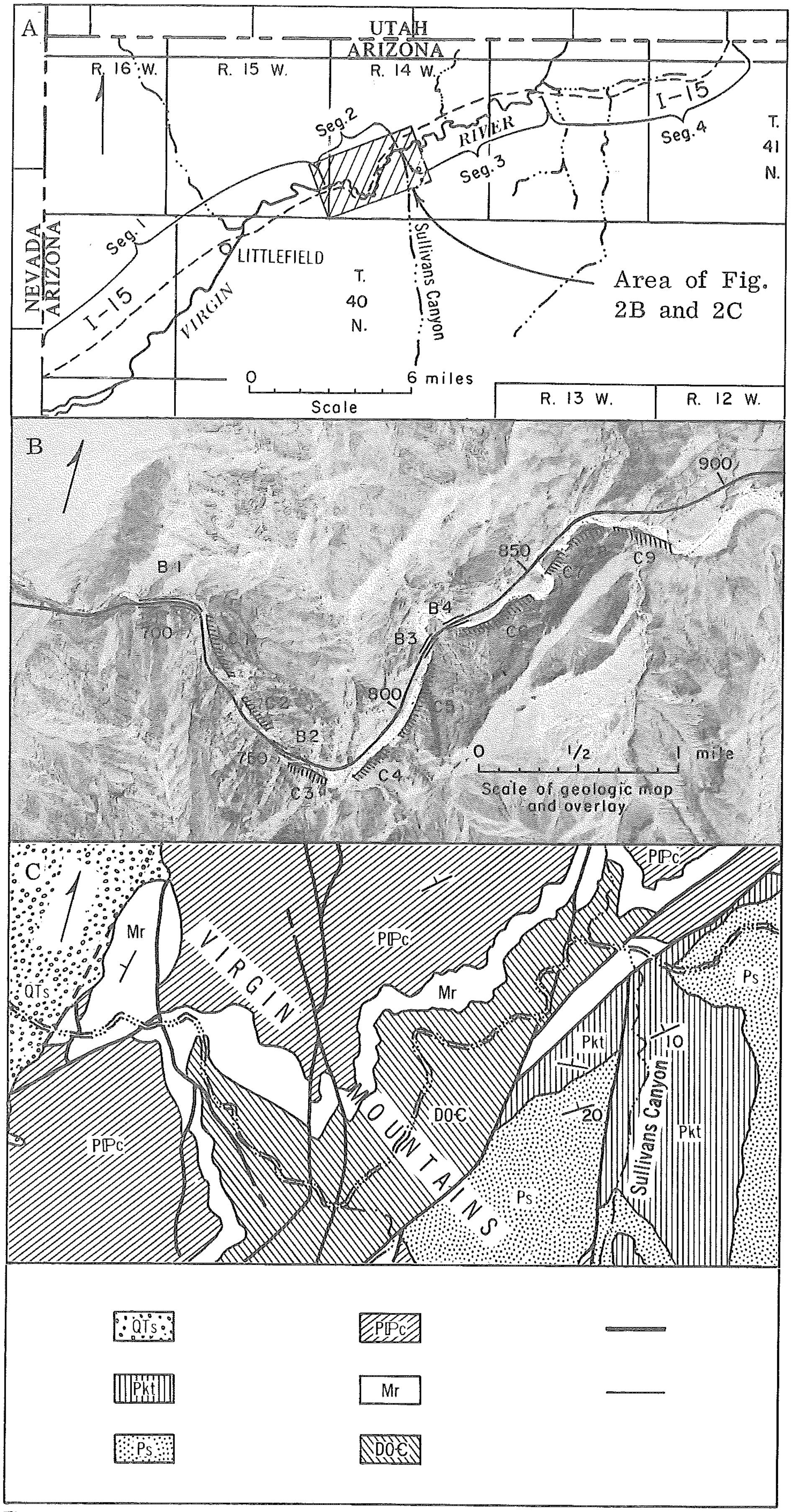

Fig. 2. Map of a portion of northwestern Arizona showing general location of Interstate 15 and aerial photograph showing details of the narrows portion of the Virgin River Gorge.

Photo courtesy Arizona Highway Department

Fig. 3. Excavation of road cut near west end of Virgin River Gorge. More than 1.2 million cubic yards of rock was removed in a 2,000-foot section of roadway by presplit blasting.

As might be expected, considering the costs, the most difficult section, from the point of view of construction, is the nearly four-mile piece starting at the western end of the Virgin River Gorge and extending to the east, to the vicinity of Cedar Pocket Wash. In this stretch the Virgin River cuts a deep, sinuous canyon through the spine of the Virgin Mountains and in places the canyon walls are as much as 750 feet high and the bottom of the canyon is no more than 70 feet wide. In this, the narrows section of the gorge, 4 bridges and 2.5 miles of channel relocation were required. Cuts of as much as 350 feet in height were excavated in solid limestone. Among the unique, situations encountered along this roadway is a bridge (figures 6 and 7) which starts out across the river bed but, because of bends in the river, ends up on the same side that it started. An idea of the magnitude of the construction job can be seen in figure 1 and 8, and the scale of the country is well examplied in figure 10. Because of the severity of the terrain and the critical effect it would have on the design and construction of the highway, an important part of the consultant's investigation was involved in a study of the geology of the Virgin River Gorge.

I wish to express my appreciation to personnel of the Arizona Highway Department for their cooperation in furnishing data for this report and also for the excellent photographs that have aided immeasurably to the discussion of this project.

GEOLOGY

The geologic conditions that prevail along the Arizona portion of Interstate 15 can be described most concisely by dividing the alignment into four segments (figure 2A), based on the relative diversity of rock units encountered and the structural complexity characteristic of each segment.

Along the first segment, extending from the Nevada line to the mouth of the Virgin River Gorge at the west flank of the Virgin Mountains, the geology is relatively simple and structural relations are uncomplicated. Throughout this segment, the roadway is founded on essentially flat-lying Cenozoic basin-fill deposits consisting of, in ascending order, the "Littlefield Conglomerate," "Littlefield Limestone," and a thin veneer of alluvium. The "Littlefield Conglomerate" is a semi-consolidated unit containing fragments of a vareity of rock types, including limestone, sandstone, and crystalline metamorphic rocks, all derived from the Virgin Mountains. Sorting within the conglomerate varies widely, with layers of predominantly cobblesized particles being randomly interbedded with thin layers of siltstone and sandstone. The thickness of

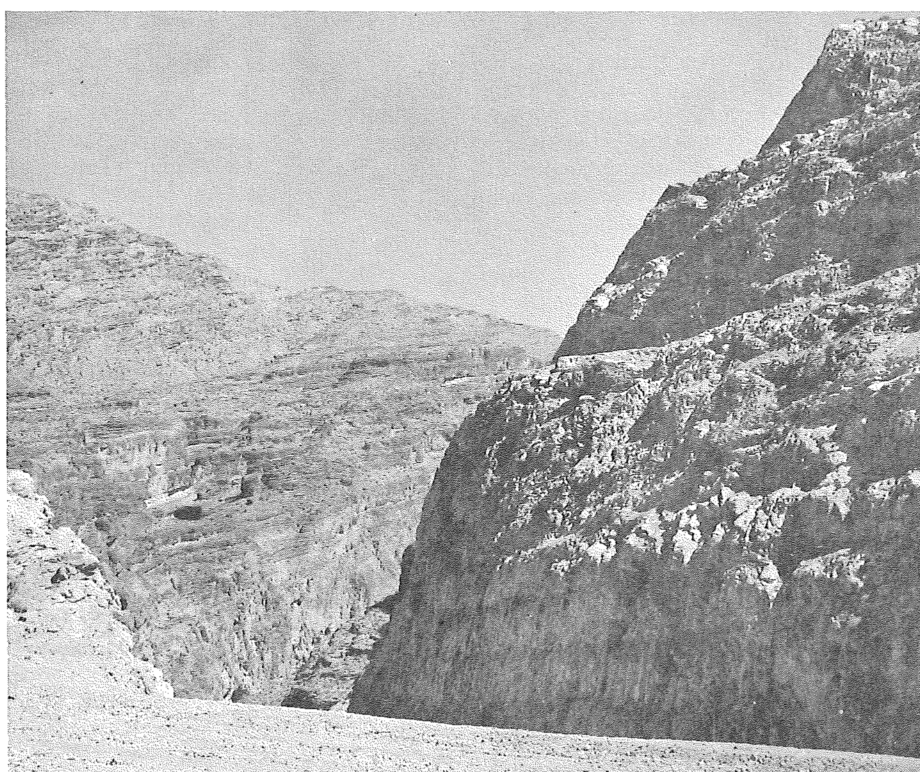

Photo courtesy Arizona Highway Department

Fig. 4. View east (upstream) from near station 691. The cut to the right is 340 feet high.

Photo courtesy Arizona Highway Department

Fig. 5. Preconstruction view of Virgin River Gorge near site of Bridge One.

the formation is unknown; observations along the Virgin River channel, however, indicate a minimum thickness of 80 feet, and judging from the surrounding land forms, it is probable that it is considerably thicker. Surficially the unit appears to be quite weak, however, this is probably the result of weathering of the exposed surfaces, and at depth the material has proven to be more competent.

The "Littlefield Limestone," which overlies the "Littlefield Conglomerate," outcrops along the banks of the Virgin River, downstream from the mouth of the Lower Gorge, and probably lies slightly below ground surface throughout the area of the alignment west of the Virgin Mountains. Where exposed, it is between 50 and 75 feet thick, and throughout the area it is essentially comformable with the ground surface. The formation is comprised of isolated cobbles and pebbles of limestone, quartzite, and crystalline metamorphic rocks imbedded in a competent matrix of calcium carbonate. Although termed a limestone, the unit probably was formed as a very dense deposit of caliche.

Segment 2, the narrows section, or Lower Gorge of the Virgin River, extends from the west flank of the Virgin Mountains to the vicinity of Sullivan's Canyon (figures 2A, B, and C). It is by far the most complicated segment in the geologic sense and the most rugged from the viewpoint of topography. (See figures 1, 5, and 8.) Rocks exposed in this segment of the alignment consist of extensively faulted, fractured, and tilted Paleozoic limestones. These are, in ascending order, undifferentiated limestones of Ordovician and Devonian age, the Redwall Limestone of Mississippian age, and the Callville Limestone of Pennsylvanian and Permian age.

The undifferentiated limestones are probably correlative with the Devonian Muddy Peak and Ordovician Pogonip limestones of Nevada. From an engineering point of view the unit can be subdivided into five members on the basis of competency; these include three, massive, hard limestone units separated respectively by two zones of thinly bedded limestone, sandstone, and siltstone. Whereas the three, hard, massive members are very competent and form cliffs that stand in near vertical faces, the two, interbedded units, because of their thin bedding and siltstone-interbeds, are less competent, more susceptible to erosion, and consequently, form slopes rather than cliffs. Also, because of their relatively softer character, the thin bedded units tend to waste away, undercutting the massive beds, and thus, landslide conditions exist locally in this unit.

The Redwall Limestone outcrops only in the western segment of the Lower Virgin River Gorge, where it has a westerly to northwesterly dip of between 20° and 30°. The upper portion of the unit is composed entirely of hard, massive, cherty limestone. The rock is highly competent and stands in vertical faces in excess of 300 feet in height. A number of caves occur in the face of the member and some of the openings are as much as five feet in diameter (figure 3). They occur along fractures and bedding planes and undoubtedly represent solution caverns. The lower 200 feet of the formation is comprised of thinly bedded alternating layers of dense limestone and chert. Locally this unit stands vertically but in other areas is has a marked tendency toward slabbing. As a whole, however, the Redwall Limestone is a very stable, competent rock.

The Callville Limestone, which overlies the Redwall, consists of alternating bands of massive to thinly bedded limestone, and occasional sandstone layers. Overall, the Callville is a hard, moderately competent unit, but locally, as where a preponderance of thinly bedded units occur, it tends to form slopes. Where encountered in the narrows segment of the Virgin River Gorge, it dips from 20° to 30° in a west to northwesterly direction.

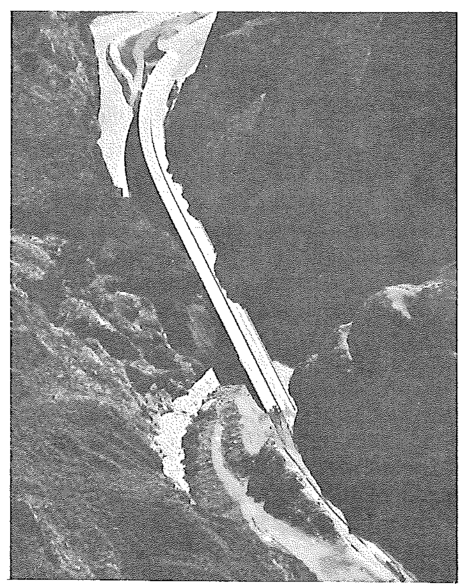

Photo courtesy Arizona Highway Department

Fig. 6. Aerial view of Bridge One. This bridge is perhaps unique in that both abutments are on the same bank of the river which here flows essentially parallel to the bridge. Note that the gorge is so narrow along this stretch that the bridge nearly fills it.

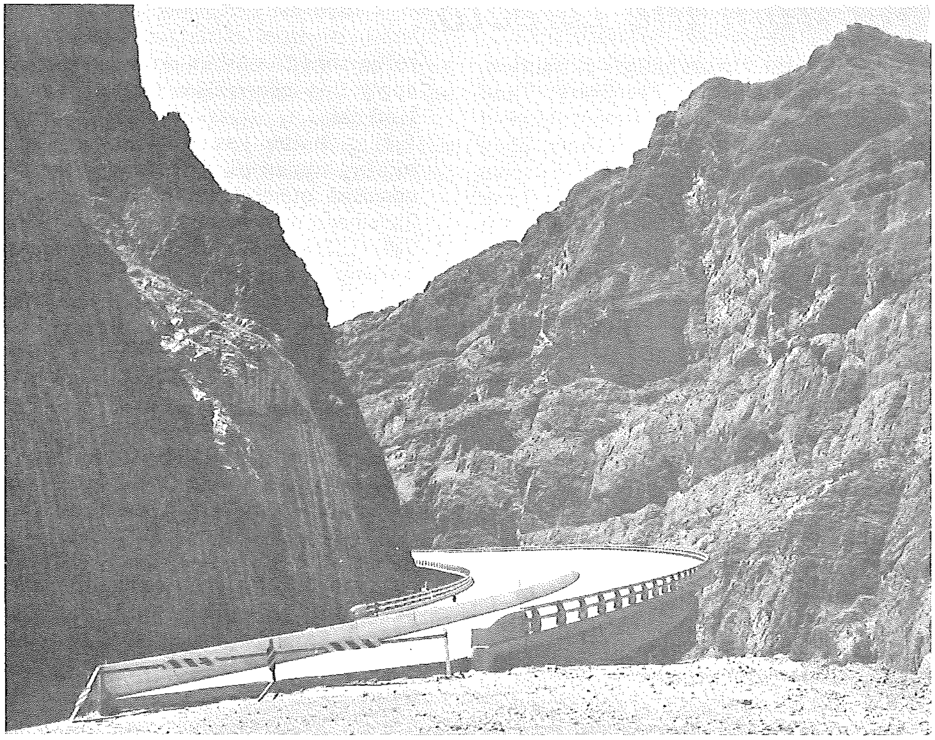

Photo courtesy Arizona Highway Department

Fig. 7. East abutment of Bridge One showing rock-cut at left excavated by presplit blasting.

The rocks within this segment have been subjected to relatively severe faulting and two major classes of faults predominate; one with a strike essentially north-south, and a second striking north 20°-25° east. The direction and amount of dip in both classes varies along strike but in general the dip is in excess of 50° and usually between 70° and vertical. Faults of the north-south class are the more abundant, and vertical displacement on them ranges from a few inches to several hundred feet. The faults of the northeast striking variety, while certainly in the minority, are by far the more important structural features in the Lower Gorge. Only three faults of this class are present, but each has a vertical displacement in excess of 500 feet and each is accompanied by severe brecciation. Intense fracturing occurs locally in the vicinity of major faults and two sets of fractures are represented; one strikes essentially north-south and the other east-west. Within the Redwall Limestone, the fractures are from 20 to 50 feet apart and in the undifferentiated limestone the spacing in on the order of from 15 to 20 feet. Healing, or recementing along fractures, has progressed to a marked degree within the Redwall Limestone but is only slight to moderate within the undifferentiated limestone. Where the fractures tend to parallel the canyon walls, massive slabs of rock have broken off and fallen down the slopes.

The third segment of the alignment, that following the Middle Gorge of the Virgin River, extending from Sullivan's Canyon, east to the mouth of Black Rock Canyon (figures 2A, 13, and 14), is marked by only relatively mild deformation and the surficial rocks are almost exclusively sandstones of the Supai Formation locally overlain by thin gravels, remnants of once more extensive terrace deposits.

In the area adjacent to the alignment of Interstate 15, the Supai Formation can be differentiated into three units. The upper and lower members are quite similar, consisting predominantly of massive, hard sandstone with interbedded thin layers of softer sandstone and siltstone. Crossbedding is common, particularly in the upper member. Both units stand vertically in natural faces, the only exception being in areas where severe fracturing has occurred.

The middle member of the Supai is composed of interbedded medium-hard sandstone and soft, sandy, red shale. The shale is platy and weathers rather rapidly to moderately gentle slopes. The amount of shale present in the member, and consequently its hardness, varies considerably throughout the area.

Along this segment, although some tilting and locally strong flexures in the strata are apparent, the only major structure is Grand Wash fault. Throughout much of the area, however, the Supai Formation displays a marked fracture pattern in which one set strikes north-south and a second set strikes east-west. The fractures of both sets are near vertical in dip, and spacing between the fractures is as close as 1 to 2 feet for those striking north-south and slightly greater for those striking east-west. Intense shattering of the sandstone, as marked by the fracture pattern, is most pronounced in the extreme western portion of the segment and in the vicinity of Grand Wash fault. Healing of the fractures is practically nonexistent.

The fourth and final segment of the alignment, that extending from the mouth of Black Rock Canyon east and

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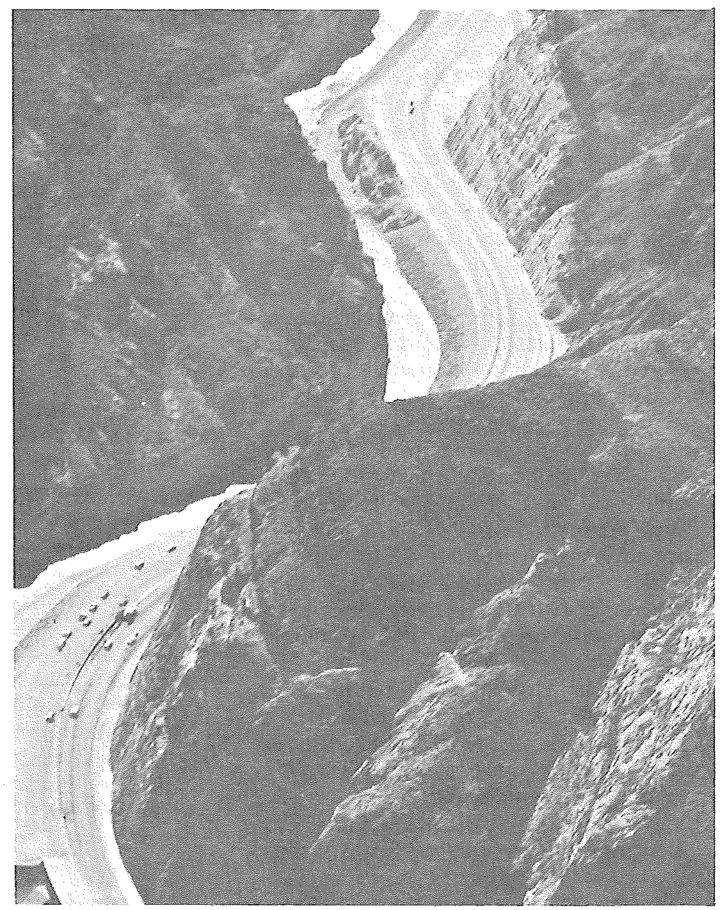

Photo courtesy Arizona Highway Department

Fig. 8. Aerial view of channel relocations and high side-hill cuts between stations 710 and 750. The channel has been relocated to the east (left of picture) and in the vicinity of station 745 (top of picture) the roadway has been constructed on fill placed out through the old channel. The vehicles give a measure of the scale of the cuts and channel relocations.

sulfide deposits in Arizona is discussed and areas considered favorable for regional study are outlined. The circular includes a selected reference section in which are listed numerous reports that describe in greater detail strata-bound massive sulfide deposits, Arizona Precambrian stratigraphy, and some Arizona massive sulfide deposits.

The Circular, illustrated with several figures and photographs, will be priced at a nominal charge to non-residents of Arizona and is free to residents of the State.

I - 15 *Continued*

north to the Utah line, is founded on essentially flat-lying shales, sandstones, and limestones of the Supai, Kaibab, and Moenkopi formations.

The Supai Formation, described previously, is overlain by the Kaibab Formation which in the vicinity of Interstate 15 is comprised of four distinct members. The basal member consists of generally thin bedded, relatively soft, buff sandstone and drab, silty limestone. It is not continuous in the area but forms lenses and pockets at the contact of the Kaibab Formation with the underlying Supai Sandstone. The member, where present, is a slope-former and is generally covered with talus debris.

Overlying the basal unit is a massive, competent, gray limestone containing a high percentage of chert. Numerous cleavage planes, which to a large degree have been healed, dissect the member. It forms vertical cliffs and is quite resistant to erosion.

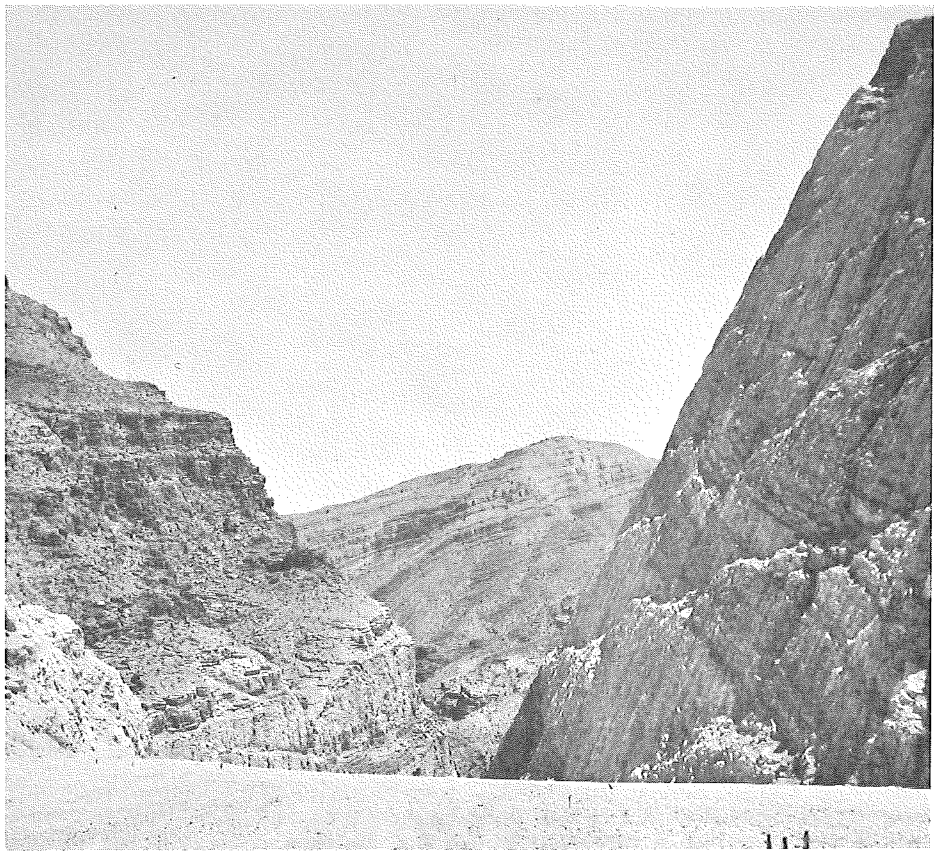

Photo courtesy Arizona Highway Department

Fig. 9. Details of cut in vicinity of station 737. This side-hill cut is approximately 300 feet high. The attitude and fractured nature of the limestone necessitated the cutting of five benches as catchments for falling rock.

Photo courtesy Arizona Highway Department

Fig. 10. Aerial view of Bidge Two and channel relocation south of roadfill. An impression of the scale of the river gorge and the construction project can be obtained from the relative size of the tractor trailer rig on the roadway (view looking north).

A second soft member separates the lower hard member from the upper hard member. It tends to form a natural slope of about 30° and generally has a moderately thick talus cover. It consists of gray, medium-hard to soft, silty limestone containing considerable chert as bands and nodules.

The upper hard member is comprised entirely of competent, massive, gray, cherty limestone which stands in vertical cliffs and is quite resistant to erosion.

Overlying the Kaibab is the Moenkopi Formation which underlies the roadway from the head of Black Rock Canyon to the Utah line. Within the area of the highway alignment the formation consists predominantly of thin-bedded siltstone and shale with occasional thin layers of silty limestone. A trace of gypsum is present throughout much of the shale. Both the shale and the limestone beds are weak, incompentent rocks, easily eroded, and unstable on steep slopes. In the vicinity of the Utah line, the beds have been subjected to considerable warping and folding. Across the flats at the head of Black Rock Canyon the formation is

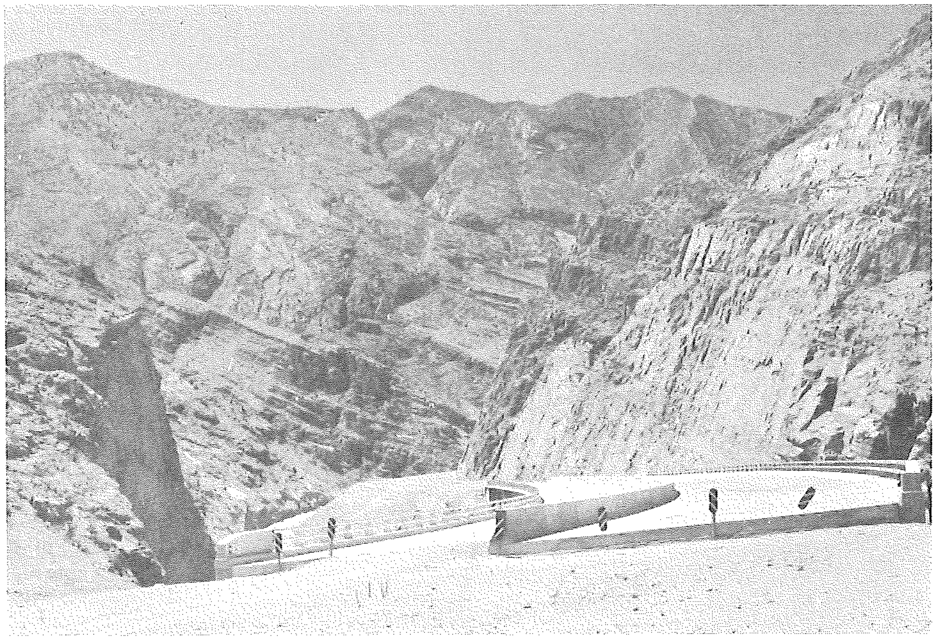

Photo courtesy Arizona Highway Department

Fig. 11. View southest from station 820 of east abutment of Bridge Three, channel relocation 5, and roadway constructed on fill placed in old channel. (Compare with Figure 1.)

covered to a variable depth by alluvium. Its attitude is similar to that of the underlying Kaibab Formation, that is, essentially flat with flexures in which dips of 3° to 7° in a northeasterly direction are developed locally.

ENGINEERING PLANNING AND CONSTRUCTION

Along segment 1, from the Nevada line east to the western flank of the Virgin Mountains, geologic conditions are simple and the engineering planning and construction of Interstate 15 along this segment was relatively straightforward. The only major earth moving project on this segment of the highway occurred approximately midway between Littlefield and the Nevada line where fills on the order of 160 feet in height were required in the crossing of Coon Creek and Big Bend Wash. Although the requirements for fill material exceeded that available from the cuts, suitable borrow was readily available in the immediate area.

Two structures were required on this segment—an interchange at Littlefield, and a bridge crossing the Virgin River approximately one-half mile north of Littlefield. As originally designed, the bridge crossing the Virgin River at Littlefield was to be supported on piers founded on spread footings. This design, however, was not predicated on actual field investigations of the foundation conditions and, when construction was started and excavation for the footing pads were made, it was found that quicksand conditions existed at about 30 feet below stream gradient and spread footings would not support the structure. To correct the situation, the excavations were backfilled with 6-7 feet of 1-2½ inch crushed rock and then with river run. Piling was then driven into the crushed rock zone and the piers were founded on the pilings.

One further interesting aspect of the Littlefield bridge centers on the occurrence of numerous springs in the vicinity of the eastern approach. These have been responsible for extensive deposits of travertine, and it was necessary to excavate to the base of the spring aquifiers and backfill, placing French drains for a distance of 700-800 feet east of the abutment, in order that the bridge approach and roadway in that area could be founded on firm material. Geological examination of this area, however, had predicted the necessity for this and appropriate measures were taken during the engineering planning phase to accommodate the condition.

Once the decision to follow the Virgin River Gorge with Interstate 15 had been made, the detailed topographic features of the area became the primary factors controlling the precise location of the alignment. These dictated following very closely the Virgin River channel within the lower gorge and, at the eastern end of the alignment, the bed of Black Rock Canyon; it is within these areas that the geologic conditions had the most important bearing on design and the future performance of the route.

The Virgin River, in cutting its way through the main mass of the Virgin Mountains, drops from an elevation of 2,195 feet above sea level at the mouth of Sullivan's Canyon (figure 2C) to an elevation of 1,890 feet at the west end of the Lower Gorge—a descent of only 305

Photo courtesy Arizona Highway Department

Fig. 12. View looking west at side-hill cut near station 845. Although the rock is moderately fractured, presplit blasting produce a smooth and even face.

Photo courtesy Arizona Highway Department

Fig. 13. View west toward Cedar Pocket — Grand Wash fault segment of I-15.

feet in a channel distance of about 4.81 miles. The channel thus offers a highly desirable alternative to the Shivwitz Summit Route, which crests at an elevation of nearly 5,000 feet. However, among the interstate specifications that must be met, the more important minimums are: design speed, 60 miles per hour; maximum horizontal curve, 6 degrees; maximum grade, 4.1 percent; maximum length of crest or sag of vertical curves, 400 feet; and a minimum width (four lanes, median, and shoulders) of 80 feet.

In general, the Inner Gorge section presents no problems as far as maintaining required grade and vertical curve specifications. The river, however, was not constrained by interstate specifications concerning maximum horizontal curves, and it becomes readily apparent that in order to construct a highway to these specifications a number of modifications would be required in the gorge in order to straighten it out. This is perhaps best illustrated by the fact that the final alignment in this segment is approximately 17 percent shorter than the original channel length (4.81 miles of channel vs. 3.99 miles of alignment).

Several combinations of channel relocations, tunnels, and bridges were considered. In the final analysis, all tunnels were eliminated because faulting and attendant fracturing proved to be severe at each provisional tunnel site, thus indicating the necessity for excessive support. In essence, then, it became necessary to "daylight" these tunnels, and very deep side hill cuts resulted. In designing the cut slopes, a fine balance had to be struck between the maximum steepness that could be maintained in order to produce the least rock breakage, and thus the greatest economy, vs. the susceptibility of the several rock units to raveling and caving on overly steep slopes, in part as the result of the fractured nature of the rock. In practice, it was possible to maintain relatively steep slopes through the use of presplit blasting (figures 3, 4, 7, 8, and 9). Notwithstanding this technique, however, considerable benching, and in places, flattening of slope was required; and, as between Stations 675 and 695, a distance of 2,000 feet, about 300,000 cubic yards of overbreak occurred. Side hill cuts on the order of 300 feet in height are not uncommon in the Lower Gorge, and some of these required as many as 5 benches, each approximately 50 feet high, as catchments for falling rock.

The extensive amount of channel relocation, approximately 2.5 miles in a road distance of not quite 4 miles, required a fairly detailed hydrologic study be made of the present and potential gorge section. The U.S. Geological Survey has maintained gaging stations on the Virgin River since 1929, including a station at Littlefield where the maximum flood of record, occurring in March 1938, is 22,000 cubic feet per second. The peak flows at Littlefield were taken as representative of the flow in the River throughout the length of the project. It further was deemed necessary, however, to determine the peak river flow on the basis of a 50 year recurrence interval as a safe criterion for the design of the channel relocations and the several bridges to be located within the gorge.

On the basis of the hydrologic study, it was recommended that a design flow of 46,900 cubic feet per second in the Virgin River be used. On this basis, a channel width of 50 feet was assumed and using the design discharge of 46,900 cubic feet per second, the channel section would flow a maximum depth of about 26.5 feet and have a maximum velocity of 24 feet per second. In general, topographic considerations already

Photo courtesy Arizona Highway Department

Fig. 14. Aerial view of Bridge Five across Virgin River. The original proposal called for an arch structure but foundation conditions were later found to be unsuitable and a three-span pier-supported structure was built.

dictated that the proposed highway grades were to be carried between 50 and 60 feet above this channel bottom, thus indicating that the channel section proposed would be satisfactory. In fact, at a depth of flow of 40 feet, the channel would have a capacity of about 91,000 cubic feet per second which is in excess of the projected 500 year frequency flood, as determined in the hydrologic studies.

A second phase of the hydrologic study involved the type and extent of embankment protection required. All the embankment in the gorge was constructed of randomly placed material from the rock cuts, but, because of the volume and velocity of the water expected to be carried in the channels, it was recommended that the slopes of all roadway embankments which form a side of the river channel be protected with individually placed, that is derrick placed, stone or riprap having an equivalent diameter of 4.5 feet or an equivalent cube of about 3.7 feet, using smaller stones as necessary to fill the voids. Rock of that size was readily available from the blasting operation required to excavate the roadway and channel cuts. It was also recommended that the selective placement of rock be to a thickness of at least 10 feet.

Four bridges were required in the Lower Gorge section of the alignment (figure 2B) and on two of these geologic conditions dictated special procedures be adopted for the stabilization of the abutments and piers.

On bridge 1 (figures 2B and 6), the central pier is founded on the lower member of the Redwall Limestone which in this area (figure 2C) dips downstream (westerly) at about 35° and is moderately fractured due to the proximity of the major fault. The fracturing, coupled with the slabby nature of the lower Redwall, created a very unstable foundation condition upon which to support the bridge pier. In order to stabilize the rock, a 2.5 foot cap of concrete was poured on the area of the footing. A total of 40 holes, each 40 feet deep, were drilled into the concrete and rock and then rock bolts were set in tension in these holes. The whole unit was then pressure grouted to form a massive footing for the pier.

On bridge 4 (figure 2B), cavernous conditions were found in the area of the east abutment which were too great in volume to permit economic filling by grouting. An alternate solution was therefore developed whereby the cavern was alternately filled with readily available broken rock and then blasted to compact the fill material. After the caves had been essentially elmininated in this way, a pad was prepared for the poured abutment by alternately placing broken rock and mortar over the filled area until the required thickness of pad was attained.

In segment 3, the roadway is founded almost entirely on beds of the Supai Formation and no major planning or construction problems were encountered. Although somewhat more rugged than segment 1, rock volumes in cuts and fills were fairly well balanced and there was little excess rock breakage required. The fractured nature of the Supai in the vicinity of the Grand Wash fault, and to a lesser degree at the western end of the segment, required that slopes be cut back somewhat flatter than might have been desired from an economic point of view. This did not, however, pose a serious construction problem.

At the eastern end of this segment, the alignment crosses the Virgin River before entering into Black Rock Canyon. As originally recommended, the structure proposed for this location was an arch bridge, presumably with the skewbacks founded on firm Supai Sandstone in either embankment. Site examination prior to final design, however, indicated that bedrock at the eastern abutment was more than 50 feet beneath sand fill as the result of an old scour hole cut by the Virgin River. This necessitated that the design be changed and that a pier-supported bridge be substituted for the arch structure.

It seems desirable at this point to stress the importance of making preliminary site examinations and subsurface studies of foundation conditions before any final design criterion are established for such structures as bridges and overpasses. The money saved by eliminating unnecessary design and redesign is frequently greater than that which would be spent on the actual site examination. Unfortunately, such site examination and exploratory work frequently only shows up as important in retrospect, and the "buyer" of the structure usually finds it hard to see beforehand that such expenditures can contribute greatly to both the success and economy of the project.

The principal factor that dictated locating the alignment along the south side of the drainage in Black Rock Canyon was the relative susceptability of the slopes to rockfalls and landslides. On-site examination indicated that these hazards were greatest on the north slopes where, because of the attitude of the formations and the steepness of slope, several slides and rockfalls had occurred in past time. These were in all cases initated near the contact of the Supai-Kaibab formations, where the softer Supai rocks, eroding more rapidly, were removed from beneath the Kaibab, leaving it unsupported and suceptable to caving.

FIELD NOTES
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