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The validity of geologic projection; a successful example: The Straight Creek Tunnel pilot bore, Colorado

by

Charles S. Robinson and Fitzhugh T. Lee

U. S. Geological Survey

Denver, Colorado

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5. The validity of geologic projection; a successful example: The Straight Creek Tunnel pilot bore, Colorado, with an appendix of examples of types of data and methods of analysis used, by C. S. Robinson and F. T. Lee. 65 p., plus 19 p. of appendix (tables and illustrations).

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The validity of geologic projection; a successful example: The Straight Creek Tunnel pilot bore, Colorado[1]

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Abstract

Projection of details of surface geology to depth prior to construction has met with only limited success in many tunneling operations. In the Straight Creek Tunnel pilot bore good results were obtained by making predictions of the extent and kinds but not the exact locations of conditions that could be expected at tunnel level based on a statistical study of surface features.

Successful predictions were made regarding percentages of rock types, linear feet of faulted and sheared rocks, and attitudes of foliation and fractures, including faults and joints. Predicted rock loads and final swell pressures in gouge and altered rocks agreed well with actual measurements. Ground-water flows were encountered in expected amounts, but criteria for estimations proved to be unsound.

Estimates were made of the amount of temporary support, footage of exploratory feeler holes, and amounts of grouting and provided a sound basis for estimating total tunneling costs.

Introduction

The projection of geology to depth based on surface observations has long been the responsibility of geologists and geophysicists. Their success is attested to by many of the mines and petroleum fields of the world. The geologic geometry of ore deposits and areas of accumulation of petroleum has been the subject of intense study for many years. The present problem in mineral exploration is primarily the identification of this geometry at depth.

The case is somewhat different in dealing with the geology of tunnels. The location of a tunnel is defined within relatively narrow limits by the purpose of the tunnel and the location of appurtenant structures. Rather than looking for a set of geologic conditions, it is the responsibility of the geologist to define the geologic conditions--in terms usable by an engineer--within the area that will satisfy the engineering requirements for construction of the tunnel.

Tunnels have been built in many varied geologic environments throughout the world, and in most cases with the assistance and advice of geologists. In too few cases, however, has an attempt been made to compare the geology as determined prior to the construction of the tunnel with the geology as determined at the time of construction. A notable exception to this is a recent paper by Ernest E. Wahlstrom, "The validity of geologic projection: A case history," (1964, p. 465-474). In this paper Wahlstrom compared the surface geology of the Harold D. Roberts tunnel in Colorado with the geology found at the level of the tunnel. Many significant points were made as to the type of geology and the relative accuracy with which the different types could be projected to tunnel level. The borrowing, in part, of the title of Dr. Wahlstrom's article for this paper is intentional in order to emphasize that the geologic investigations for the Straight Creek tunnel were the direct outcome of the work of Dr. Wahlstrom and his associate Dr. L. A. Warner (Wahlstrom and Hornback, 1962; Warner and Robinson, in preparation). The purpose of this paper is to illustrate a new approach to surface geologic investigations and to the definition of the geology at depth for tunnel construction, and to show the value of this approach by comparing the predictions with the findings. This paper is organized in the order that the work was done: collection of data prior to construction, calculations and predictions, collection of data during construction, and comparison of predictions and findings.

Acknowledgments

The authors would like to acknowledge the participation of Dr. E. E. Wahlstrom, who encouraged the authors in their work through many stimulating discussions, and who reviewed the present paper. They would also like to acknowledge the full cooperation afforded them in their investigations of the Straight Creek tunnel pilot bore by the Colorado Department of Highways. In particular Charles E. Shumate, Chief Engineer, George N. Miles, District Engineer, and Fred A. Mattei, Project Engineer, are extended special thanks. Terrametrics, a Division of Patrick Harrison, Inc., was retained by the Colorado Highway Department to instrument the tunnel. All their pertinent records were made available, and the authors wish to acknowledge their full cooperation; particularly that of V. E. Hartmann, E. A. Wieselman, and J. F. Abel, Jr. The contractor, Mid-Valley, Inc. also cooperated fully with this project; in particular thanks are due, Ted Adams, General Superintendent, and Frank Merrick, Project Superintendent.

The authors were assisted at times by J. E. Sharp and M. J. Cunningham. Many other members of the Geological Survey assisted in geophysical and laboratory work, and are acknowledged under the appropriate sections.

History and location of the tunnel site

An all weather transmountain highway route has long been the desire of the people of Colorado. At present, highway travel between the eastern and western slopes of the mountains of Colorado may be interrupted for short periods at any time during about 7 months of the year, and for about 3 months travel may be difficult. A pioneer bore under the present Loveland Pass on U. S. Highway 6 (fig. 1)

Figure 1.--NEAR HERE.

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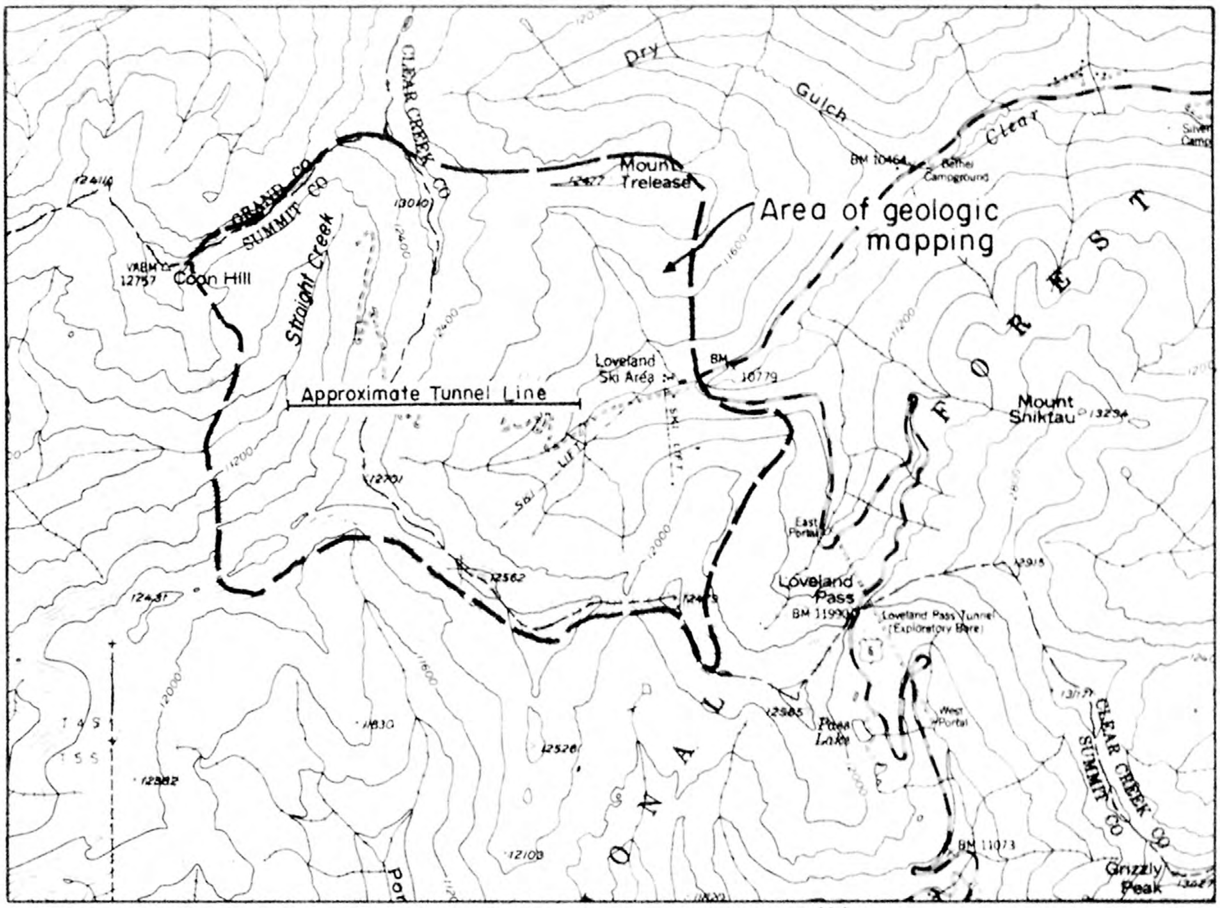
was completed in 1943, but geologic conditions as exposed in this bore precluded the construction of a highway tunnel. After many years of study of many sites, the present Straight Creek tunnel site was selected. A pilot bore about 13 feet in diameter and 8,300 feet long was started in November 1963 and completed in December 1964.

The U. S. Geological Survey requested the permission and cooperation of the Colorado Highway Department to conduct a research project on the Straight Creek tunnel site; the geological investigations were started in 1962 and have continued to the present. This paper describes the geologic research conducted in conjunction with the construction of the pilot bore.

The Straight Creek tunnel site, shown on figure 1, is about 55 miles west of Denver, Colo. The final tunnel will consist of twin bores, each about 8,300 feet long and 32 feet in diameter. The purpose will be to carry Interstate Highway 70 through the Continental Divide and so eliminate the use of Loveland Pass on the present U. S. Highway 6.

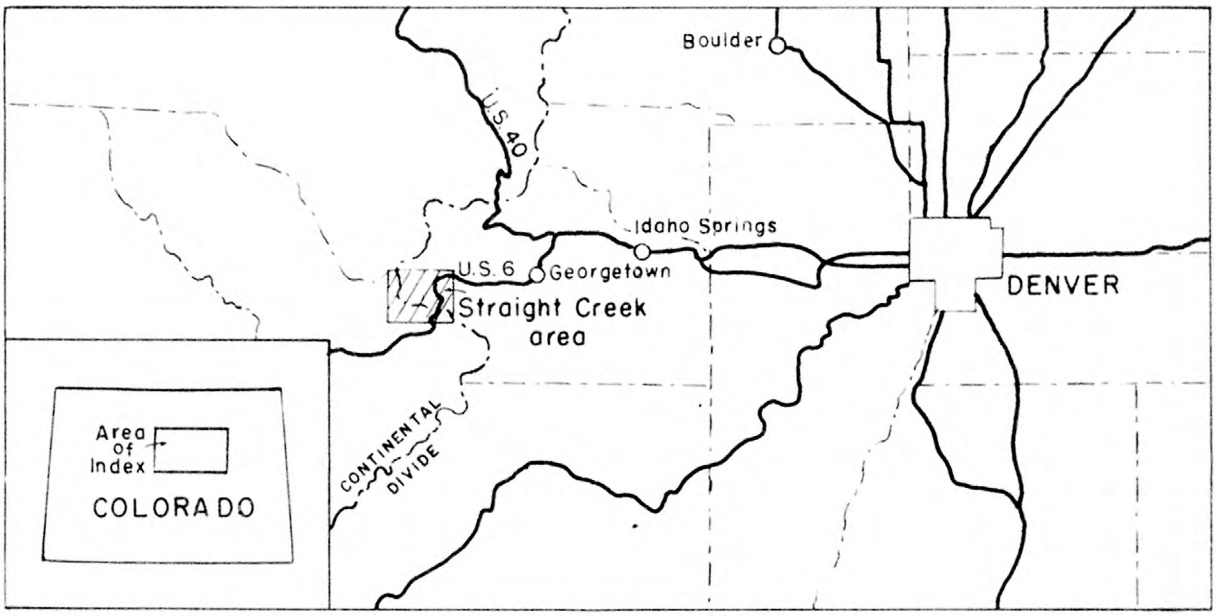


Base map from Loveland Pass quadrangle, 1958

0 1 2 Miles

Datum is mean sea level
Contour interval 40 feet

Map of Straight Creek area



0 5 10 25 Miles

Location of Straight Creek area

Figure 1.--Index map of Straight Creek area, Colorado

General geology

The bedrock of the Straight Creek tunnel site consists of Precambrian igneous and metasedimentary rocks with a few Tertiary dikes. The bedrock has been highly faulted and sheared and locally altered. Overlying the bedrock are a variety of surficial deposits including colluvial, glacial moraine, talus, alluvial, and locally swamp deposits. The area is within the Front Range Mineral Belt as defined by Lovering and Goddard (1950), who have described the regional geology.

Geologic formations

The area consists predominantly of granite, equivalent to the Silver Plume Granite, and metasedimentary rocks, equivalent to the Idaho Springs Formation, both of Precambrian age, as defined by Lovering and Goddard (1950). Figure 2 is a generalized geologic and

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Figure 2.--NEAR HERE.

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outcrop map of the Straight Creek area showing the distribution of the rock types and foliation.

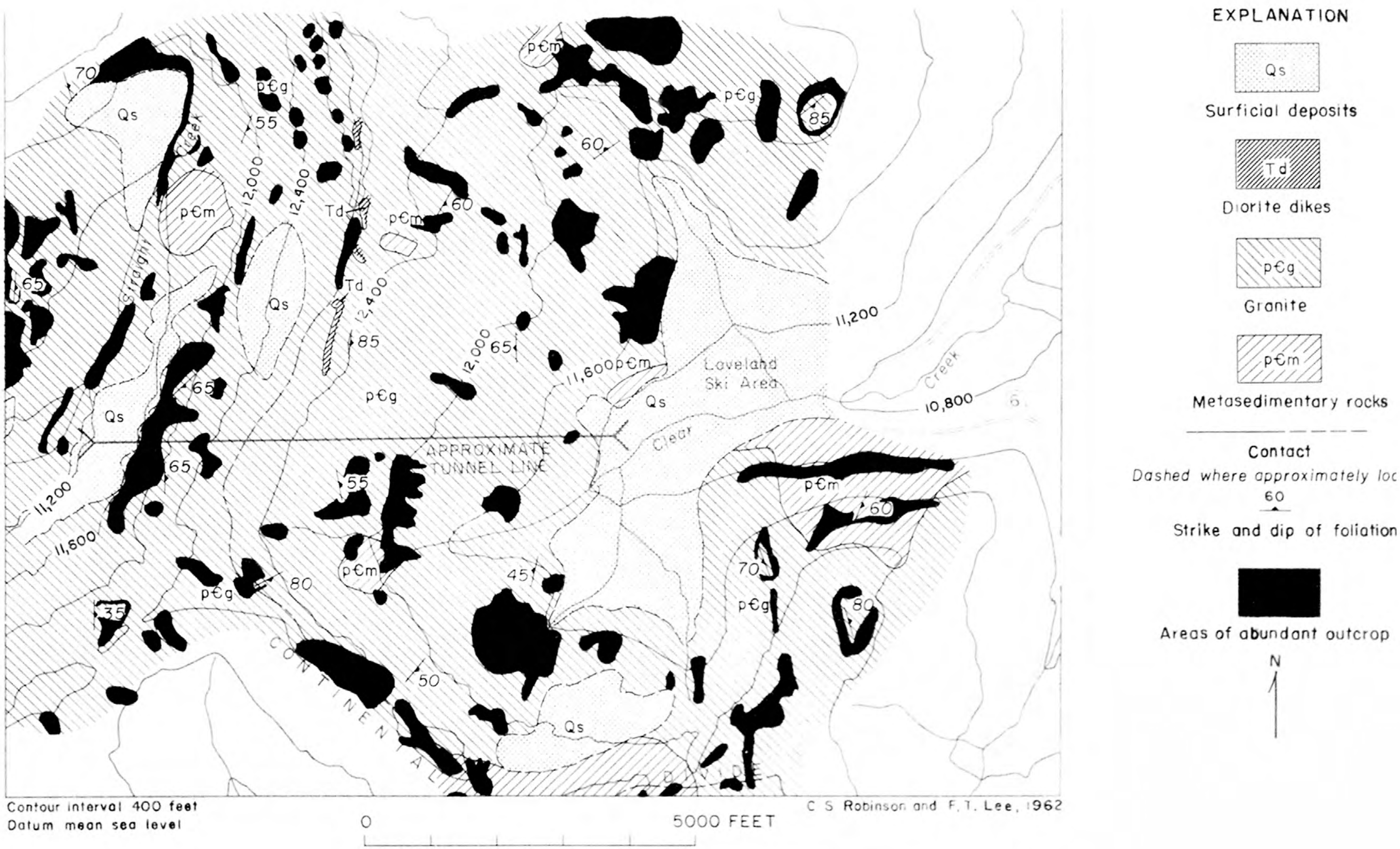

Figure 2.--Generalized geologic and outcrop map of the Straight Creek area showing the distribution of rock types and foliation

Metasedimentary rocks.--The metasedimentary rocks consist of a variety of biotite-rich gneisses. Common types are biotite-quartz-microcline gneiss, biotite-quartz-plagioclase gneiss, hornblende-biotite-plagioclase gneiss, and sillimanitic biotite-quartz-plagioclase gneiss. The metasedimentary rocks are generally fine grained. Granitic material commonly occurs along the layering of the metasedimentary rocks near their contacts with the granite. In nearly all outcrops the biotite, and where present, commonly the hornblende, is partially altered to chlorite. In and adjacent to the faults and shear zones, the metasedimentary rocks are commonly altered to a green plastic clay, in which the foliation, although considerably contorted, is still recognizable.

Granite.--The granite is medium to fine grained and consists of approximately equal amounts of quartz, potash feldspar (microcline), and plagioclase feldspar (oligoclase), and generally from 5 to 15 percent biotite. The average composition approximates a quartz monzonite. The amount of biotite locally ranges between wide limits depending upon the amount of partially assimilated metasedimentary rock. The outcrops of granite appear fresh, but petrographic examination shows that some of the biotite has been altered to chlorite and that the plagioclase feldspar has been slightly altered to sericite. The granite is extensively altered along some joints, along faults, and within shear zones. Associated with the granite are small dikes of pegmatite consisting predominantly of quartz and potash feldspar or coarse-grained quartz.

Diorite dikes.--Augite diorite dikes, probably of Tertiary age (Lovering, 1935, p. 30-31), crop out north of the tunnel line (fig. 2) and were intersected in the tunnel. The dikes range from a few feet to more than 1,000 feet in maximum dimension. They consist of fine-grained to aphanitic augite and plagioclase (andesine) with variable and smaller amounts of biotite and hornblende. These dikes rarely show any alteration.

Surficial deposits.--The bedrock throughout much of the area is mantled by Quaternary surficial deposits (fig. 2). These include swamp, morainal, and alluvial deposits at lower elevations in the valleys, and colluvial deposits of soil, talus, and landslides on the upper slopes.

Structure

Planar structure include the foliation of the bedrock and the joints, faults, and shear zones. The attitudes of the foliation are shown on figure 2. Figure 3 is a generalized map showing the faults

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Figure 3.--NEAR HERE?

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and shear zones that are greater than 5 feet in width.

Foliation.--A distinct foliation is recognizable in most of the outcrops. The foliation in the granite is the result of a subparallel orientation of the potash feldspar grains. In the typical granite, the biotite has a random orientation, but in biotiterich outcrops, the biotite is oriented parallel to the potash feldspar grains. The foliation in the metasedimentary rocks is the result of the concentration and orientation of the constituent minerals into bands that range from less than 1 to 10 mm in width.

Faults and shear zones.--The area lies within a zone of faulting and shearing about 2 miles or more wide that is probably related to the Loveland Pass fault (Lovering and Goddard, 1950, pl. 2). The distinction made between faults and shear zones was only one of magnitude; faults are elongate zones of crushed rock from 5 to 50 feet wide and shear zones are zones more than 50 feet wide.

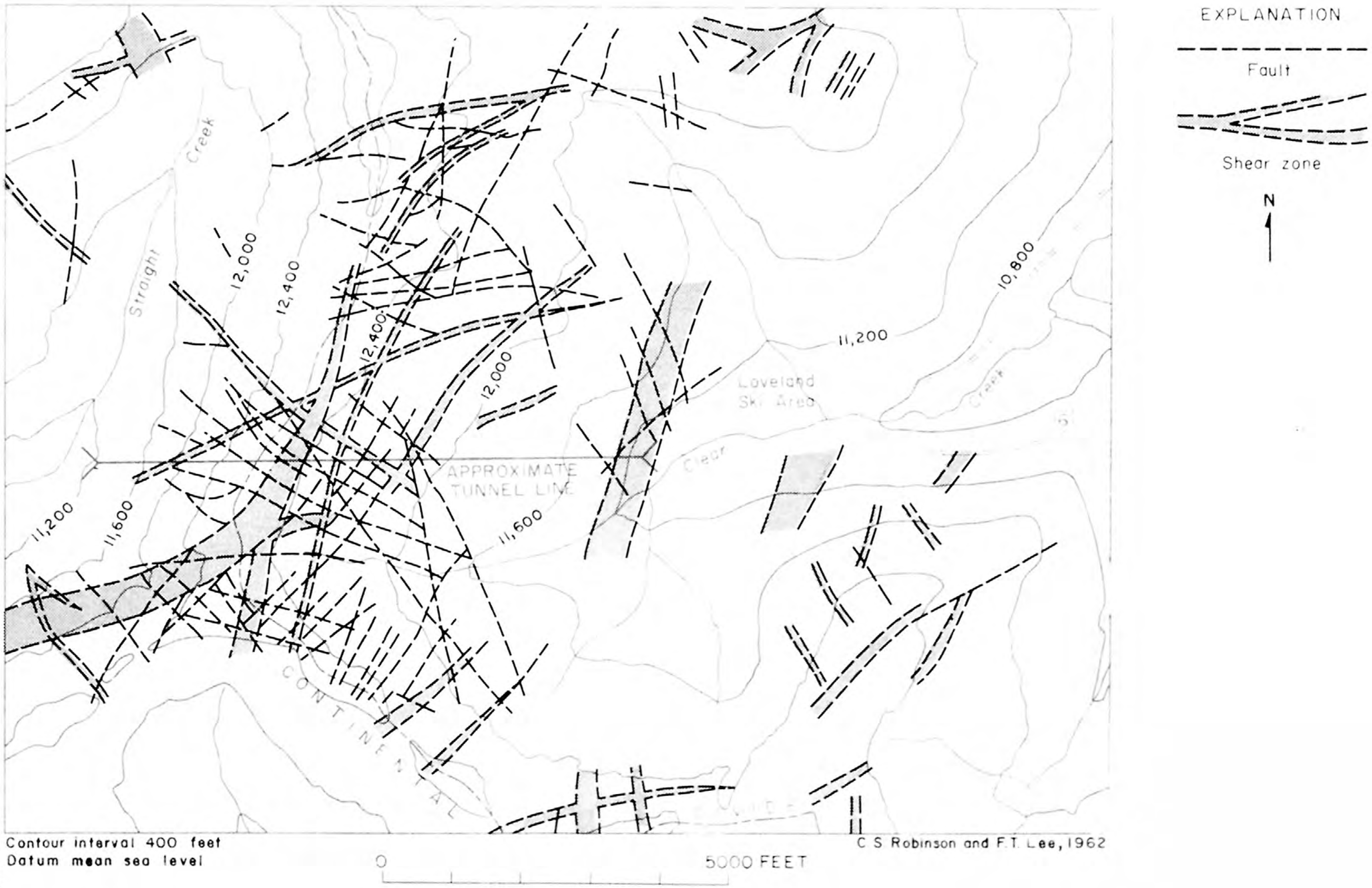

Figure 3.--Generalized map of the Straight Creek area showing faults and shear zones greater than 5 feet wide

The faults and shear zones consist of rock showing varying degrees of crushing or shearing. The borders of these zones are gradational--the intensity of shearing decreasing outward from the center of the zone. Near the margins, the rock consists of pieces from less than 0.1 foot to 0.5 foot in maximum dimensions bounded by generally subparallel slickensided shear planes. Where the shearing was more intense, the rock has been crushed to a coarse to fine sand and the shear planes are less than 0.1 foot apart and lie in all directions. Where the most intense shearing occurred--usually accompanied by some alteration--the material consists of clay (gouge) with variable amounts of quartz and feldspar grains. The gouge usually does not occur near the center of the sheared zone but near one margin or the other, and as disconnected streaks elongated parallel to the trend of the shear zone. The faults and shear zones vary in width within short distances. The individual faults or shear zones pinch and swell and may end abruptly against relatively unsheared rock. Some shear zones contain blocks of rock, up to 100 feet in maximum dimension, that are relatively unsheared although surrounded by intensely sheared rock.

Joints.--Most of the fractures recorded as joints are probably microfaults or shears. An effort was made initially to distinguish between tension and shear joints, but nearly all joints showed some evidence of shearing. Joint surfaces are commonly coated with chlorite, silica, calcite and dolomite, selenite, epidote, and clay minerals, and show slickensides. The rock beyond the joint surface coating commonly shows some alteration.

Structural history.--At least two major periods of tectonic activity are recognized in the Colorado mineral belt (Tweto and Sims, 1963); one during Precambrian time and the other principally in Tertiary time. Evidences of both periods of activity are recognized in the Straight Creek area. The Precambrian rocks are locally sheared and recrystallized in the Loveland Pass fault zone. Bands of mylonite, recrystallized breccia, and cataclastic gneiss are common; particularly along the Continental Divide. These bands commonly include coarse-grained dikes of quartz that trend parallel to the bands. Associated with these zones of Precambrian cataclasis are veins of fluorite and calcite or dolomite and silica. Locally, coarse-grained specular hematite occurs in the quartz veins or as a cement to the breccia. The zones of Precambrian shearing are parallel to and cut by faults and shear zones presumed to be related to the Laramide period of orogeny. The Laramide faults and shear zones were the main geologic features that influenced the construction of the pilot bore. There was more than one period of Laramide faulting as many of the shear zones and faults are cut and offset by other faults and shear zones.

Preconstruction investigations and compilation

Geologic mapping of about 6 square miles in the vicinity of the proposed tunnel was done in 1962. At the same time the Colorado Department of Highways constructed a drilling road between Loveland Basin and the head of Straight Creek, and contracted for the drilling of core holes, two of which were logged by the authors. The field work was supplemented by geophysical logging of the drill holes and by laboratory investigations.

Field mapping.--The field mapping was done with the aid of aerial photographs on a 1:12,000 scale topographic base prepared from the U.S. Geological Survey's 7½-minute Loveland Pass quadrangle. The Colorado Department of Highways surveyed and staked the proposed tunnel line and located the drill holes. They also made available a 1:1,200 scale topographic map and 1:6,000 aerial photographs prepared for them by Continental Engineers, Inc. of Denver, Colo.

The area mapped comprised about 6 square miles and was principally determined by the natural drainage divides north and south of the tunnel line (fig. 2). All outcrops within this area were examined and the rock type and structure recorded. It has been calculated, using the method described by Wahlstrom (1964, p. 468), that 4 percent of the area was bedrock. Particular attention was paid to the structure as it had been determined from the compilation of the data on the Roberts Tunnel that the structure, and the relation of the attitude of the structures to the trend of the tunnel, were probably the most significant geologic features in the construction of tunnels (Wahlstrom, 1964, p. 471).

Foliation, commonly a direction of weakness in rocks, is one of the important structural elements. The foliation of granite is probably the result of flow and is normally not a principal direction of weakness except where joints occur parallel to the foliation. The foliation of the metasedimentary rocks is a principal direction of weakness because of the concentrations of cleavable minerals along certain layers. The foliation direction normally is a joint direction, and where the metasediments occur in a shear zone, the foliation direction is usually a direction of shearing. The foliation of the granite and the foliation and mineral lineation of the metasediments were compiled separately for a 1-mile strip along the tunnel line. As the maxima for the foliation of the two rock types agreed, the diagrams were combined, and are shown on figure 4A.

Figure 4.--NEAR HERE.

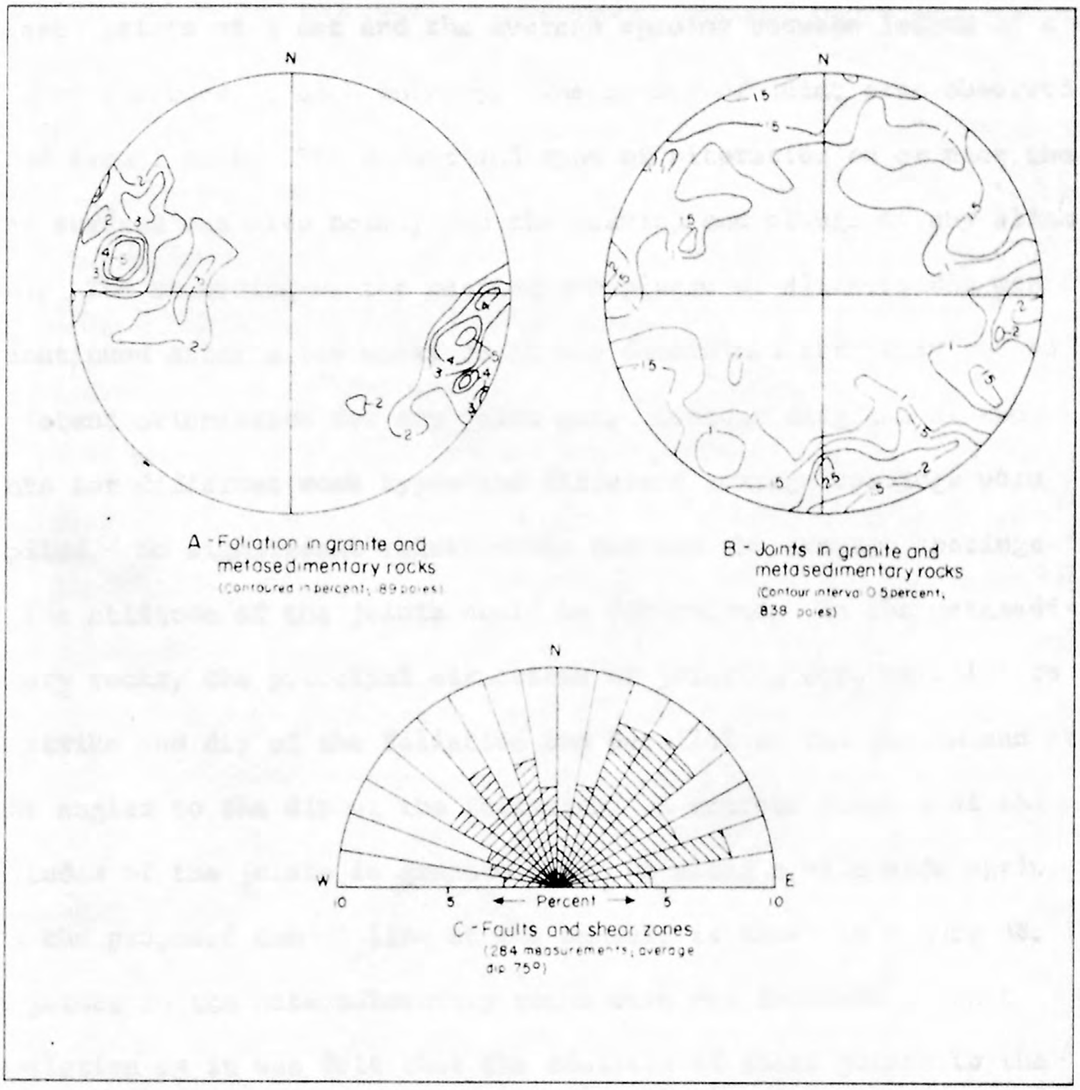

Figure 4.--Contour diagrams of the poles of the foliation and joints, and a strike-frequency diagram of faults and shear zones compiled from surface mapping

The attitudes of conspicuous joint sets and the range of spacing between joints of a set and the average spacing between joints of a set were recorded at each outcrop. The number of joint sets observed ranged from 1 to 6. The amount and type of alteration on or near the joint surface was also noted, and the bearing and plunge of any slickensides. The recording of the bearing and plunge of slickensides was discontinued after a few weeks as it was determined that they had no consistent orientation for any joint set. Contour diagrams of the joints for different rock types and different average spacings were compiled. No significant relationship between the average spacings and the attitude of the joints could be determined. In the metasedimentary rocks, the principal directions of jointing were parallel to the strike and dip of the foliation and parallel to the strike and at right angles to the dip of the foliation. A contour diagram of the attitudes of the joints in granite outcrops along a mile-wide strip, with the proposed tunnel line at the center, is shown in figure 4B. The joints in the metasedimentary rocks were not included in this compilation as it was felt that the addition of these joints to the diagram might mask a strong joint trend that might be related to the tectonic evolution of the area.

The strike or trend of 284 faults or shear zones greater than 5 feet wide were recorded during the areal mapping. It was difficult to determine the attitude of a fault or shear zone even if exposed because of the diverse directions of shearing within a zone. It was therefore necessary to measure the average trend as determined principally by the topographic expression. The attitude of 74 of the 284 faults and shear zone could be measured. Commonly it was the attitude of a gouge seam within a fault or shear zone. The dip of these ranged from 35°-90°, and averaged 75°. Figure 4C is a strike-frequency diagram compiled from the strikes and trends of the faults and shear zones.

Core logging.--Four holes were drilled about along the proposed tunnel line. Two of these were shallow holes, 75 to 100 feet deep, near each portal that were drilled principally as shot holes for geophysical work (fig. 6). Generalized logs of the cuttings or core from these holes were made. Two holes spaced about an equal distance from each portal were drilled for geologic information. Additional holes had been proposed at the start of the project but it was felt, based on the surface mapping, that in this type of geologic environment additional holes would contribute very little additional information relative to their cost. Also, logs of four holes drilled during preliminary investigations in 1955 were made available by the Colorado Department of Highways.

A special effort was made to obtain a maximum amount of engineering geologic data from the drill holes. Figure 5 is an

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Figure 5.--NEAR HERE.

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example of a portion of one of the logs from one of the drill holes. The first column, starting at the left, shows the range in length (shaded portion) and the average length of the pieces of core (numbers in shaded portion) as they were recovered from the core barrel for each run. These figures are indicative of the relative competency of the rock--other things being equal--and how the rock will behave on mining. The second column shows the percent core recovery per run and the cumulative percent core recovery to the end of that run. The third column shows the size bit and the type of core barrel used. Both these factors influence the size of the pieces of core recovered. The fourth column shows the intervals cased or cemented and the date the casing was installed. This information was necessary for the interpretation of the geophysical logging. The fifth column shows the rock type and the dip of the foliation. The foliation was assumed to strike north and dip east. The sixth column shows the attitude of the joints measured in reference to the foliation. For example, a joint that had a strike of 45° to the left of the foliation is plotted as striking N. 45° W. and with a dip measured from the vertical axis of the core. The seventh column is a summary description of the core.

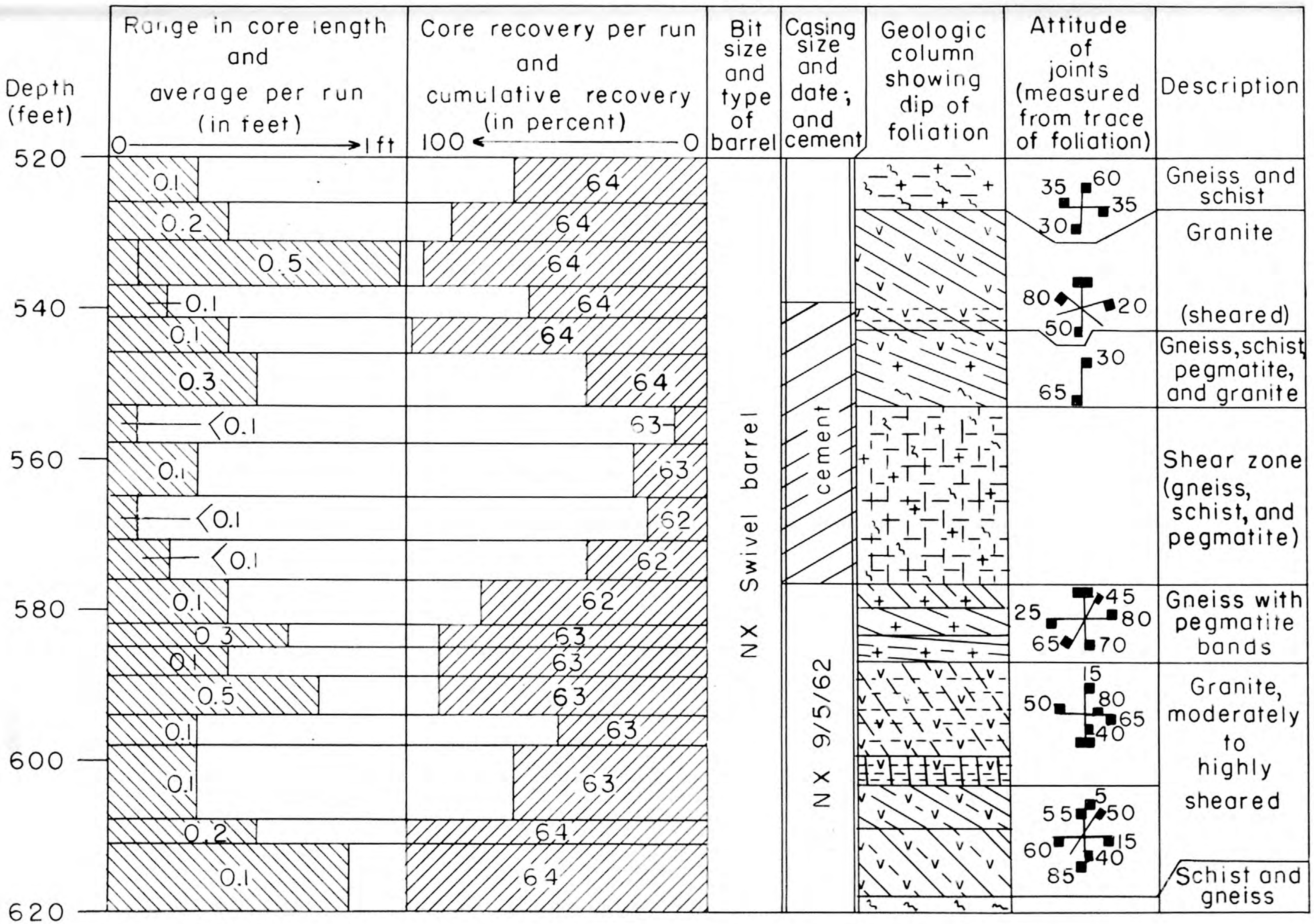

Figure 5-- Example of drill hole log, Straight Creek project

The recording of the joints in the core in reference to the foliation made it possible to plot the joints on an equal-area net, and then to rotate the net so that the assumed north strike of the foliation agreed with the foliation maxima determined from the surface mapping, and so orient the joint plots. The joint plots, when the probable errors in measurements were considered, were isotropic. The only significant information obtained was that the average dip of the joints in the core was 50° as compared to an average dip of 70° from the compilation of the surface joints.

Geophysical Investigations.--Geophysical investigations consisted of resistivity, radioactivity, and gamma-ray density logging of the drill holes, and seismic profiles along and at right angles to the proposed tunnel line. The purpose of the geophysical logging of the drill holes was to supplement the geologic data obtained from the geologic logging of the holes. The resistivity measurements were made by C. J. Zablocki, and the radioactivity and gamma-ray density logs by W. A. Bradley, both of the U.S. Gological Survey.

Seismic surveys were conducted along the tunnel line under the direction of R. A. Black and B. L. Tibbetts of the U. S. Geological Survey. The purpose was to determine the seismic velocities, and changes therein, across the surface and with depth; it was hoped that these velocities could be correlated with the geologic mapping and its resulting definition of rock conditions. Geophones were set along and at right angles to the proposed tunnel line at the surface, and seismometers (specifically designed for the purpose) were placed in the two core holes. Records were obtained from charges detonated in the drill holes near the portals and from airblasts above ground. The results have not been as satisfactory as hoped for, although the analyses are as yet completed. The investigation was hampered by a lack of precedent on which to design the equipment and the test procedures.

Another seismic survey was made by R. M. Hazelwood and C. H. Miller, of the U. S. Geological Survey, in the vicinity of the east portal to determine the thickness of the surficial material that had to be excavated at east portal. This survey showed that the surficial material ranged from less than 1 foot to 50 feet in thickness.

Laboratory investigations.--A continuing program of laboratory investigations is being conducted in coordination with the geological and geophysical field investigations. The purpose is not only to furnish the data that was necessary for the interpretation of the field geologic and geophysical data for engineering purposes, but also to attempt to correlate physical and engineering properties as determined in the laboratory with those determined in situ, and to conduct research on new techniques and instruments for determining physical and engineering properties in the laboratory and in the field. The laboratory investigations were under the general supervision of T. C. Nichols of the U. S. Geological Survey. Many of these laboratory investigations do not have a direct quantitative bearing on the construction of the final Straight Creek tunnel because the samples were in general the most homogeneous geologically.

For purposes of interpretation of the field data, and the predictions of conditions at the depth of the pilot bore, the mineralogy, porosity, grain density, dry bulk density, saturated bulk density, and the powder grain density were determined for samples from the surface and from the drill holes. The swelling properties and mineralogy of samples of fault gouge were also determined. Static and dynamic elastic moduli were also determined on samples from the surface and the core holes, but were of only limited value as they could not be considered as representative of the rock in situ.

Calculations and predictions

At the Straight Creek site, the projection of surface geologic features to tunnel level was considered, based on Wahlstrom's (1964, p. 474) conclusions, to be impractical. Rather, following the suggestion of Wahlstrom (1964, p. 474) the geologic data was was compiled statistically and presented in terms that could be used by the engineers in calculating design requirements and cost. One of the principal purposes of the Straight Creek tunnel project was to attempt to do this, and then to evaluate the results after completion of the pilot bore. The predictions have previously been made available to the Colorado Highway Department (Robinson and Lee, 1962) and summaries published (Robinson and Lee, 1963, 1964).

Geologic calculations and predictions

Rock type.--The relative percentages of the granite and metasedimentary rocks were determined for each of the two core holes drilled in 1962, and from the logs of the four holes drilled in 1955 and logged by R. H. Carpenter, and these figures combined. The total of these calculations showed that about 75 percent of the rock is granite, and related pegmatite and aplite, and 25 percent metasedimentary rock. It was assumed that these would be the same relations at the depth of the tunnel.

The maximum dimensions of the inclusions of the metasedimentary rocks were compiled from the surface mapping and the logs of drill holes. The sizes ranged from less than 0.1 foot to about 2,000 feet; the average maximum dimension was 20 feet.

Augite diorite dikes crop out north of the tunnel line, but it was considered possible that similar dikes might be encountered in the construction of the pilot bore.

The swelling pressure of the altered rock and fault gouge of samples from the surface and the drill holes were determined by the method described by Wahlstrom, Robinson, and Nichols (in press), and ranged from 1,400 to 2,900 psf with an average of about 2,235 psf. It was assumed that the fault gouge encountered in tunnel would have about the same swelling pressures.

Foliation.--The foliation of the granite and the metasedimentary rocks at the surface strikes in general from N. to N. 30° E. and dips 60°-90° NW. or SE. (fig. 4A). The average dip at the surface is about 70°. In the drill holes, the average dip was determined as about 50°. It was predicted that the strike of the foliation at tunnel level would be the same as calculated at the surface and that the average dip would be between the average dip of 70° determined at the surface and the average dip of 50° calculated from the drill holes, or about 60°.

Joints.--The joints at the surface and in the drill holes strike in all directions. Joints measured at the surface ranged in dip from about 45°-90° with an average dip of about 70° (fig. 4B). In the drill holes, the joints had an average dip of about 50°. It was predicted that the joints at tunnel level would strike in all directions and that the average dip would be about 60°.

Faults and shear zones.--The faults and shear zones trend in all directions; most of them, however, strike between N. 20°-50° E. The dips range from 35°-90° with an average dip of 75° either east or west. It was predicted that the faults and shear zones at tunnel level would have the same average trends and dips. It was stated that no fault greater than 5 feet wide would be expected to follow the proposed tunnel line at the depth of the tunnel.

The geologic data was summarized and presented at a scale of 1:1,200 on a geologic section along the proposed pilot bore. A smaller scale generalized version of that section is shown on figure 6.

Figure 6.--NEAR HERE.

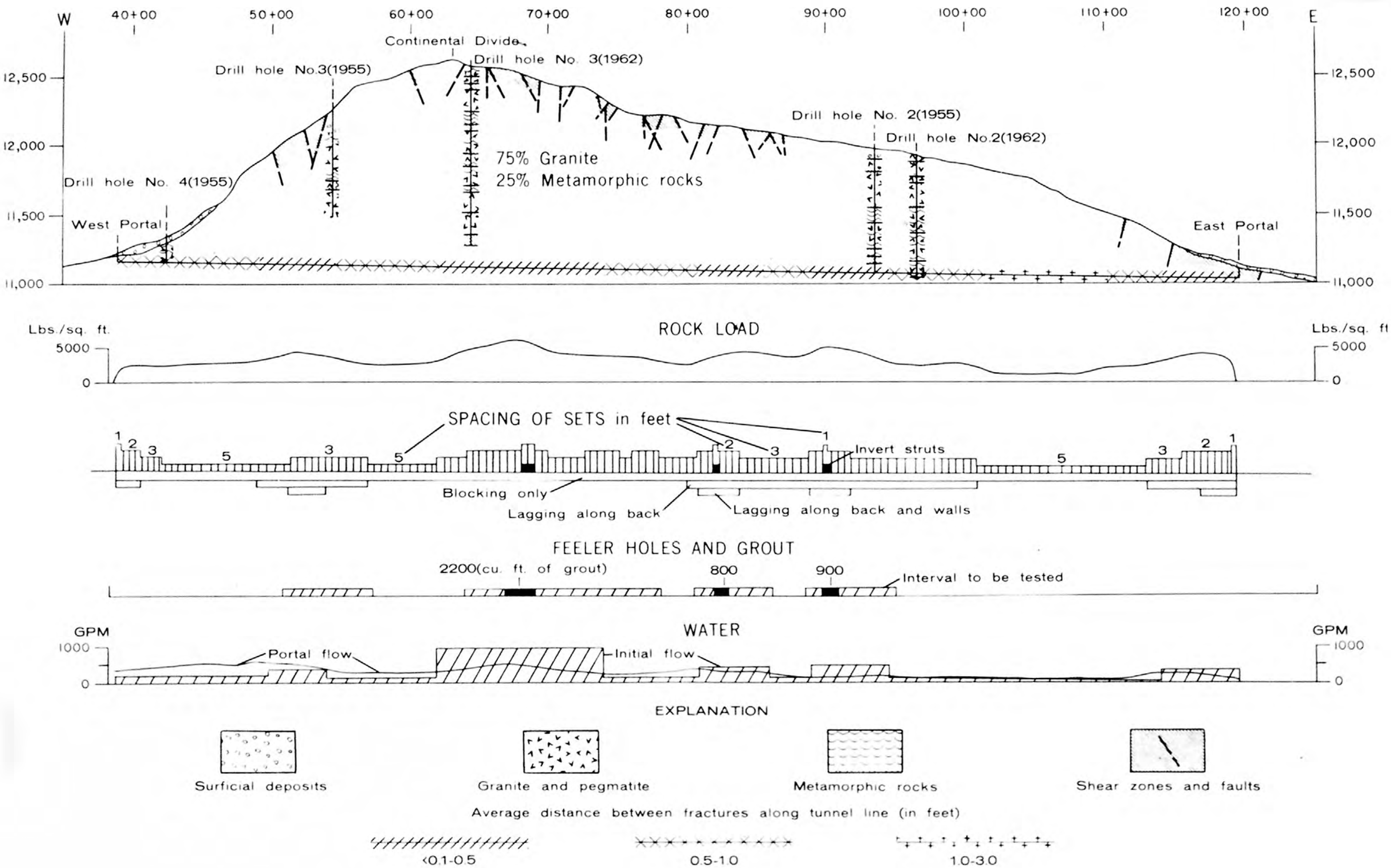

Figure 6.--Predicted geologic section and engineering data along proposed Straight Creek tunnel pilot bore.

In constructing the geologic section, no effort was made to project individual rock units, faults or shear zones to tunnel level. The rock at the pilot bore level was assumed to be 75 percent granite and 25 percent metamorphic rock. The minimum, maximum, and average distance between fractures (including joints, faults, and shear zones) for each set of fractures as measured in the field were plotted on the geologic and topographic map of the area. The average distances between fractures of different sets under different geologic conditions as determined from the mapping and the logging of the drill core were used for the covered areas. The average distances between fractures used in the covered areas depended upon the interpretation of the geologic conditions within a covered area. The average spacing between fractures, or the average size of the piece of unfractured rock, which were defined as the "fracture density," was then contoured. It was then possible to divide the map into a series of zones with a range in average fracture density and a percentage volume of faults. The zones so defined were: a) zones of greatest fracturing where the average distance between fractures was less than 0.1 foot to 0.5 foot (these were essentially the major shear zones); b) zones of intermediate fracturing where the average distance between fractures was 0.5 foot to 1 foot with about 20 percent of this zone represented by faults and shear zones; and c) the zones of least fracturing where the average distance between fractures was 1 to 3 feet with about 10 percent of this zone represented by faults and shear zones. These zones were projected to tunnel level based on the distribution of the range in dips as determined from the statistal plots of the joints and faults and shear zones. The three categories of fracture density are shown by different patterns along the proposed tunnel line. On this basis it was calculated that 40.1 percent of the tunnel length would be in the fracture density category of less than 0.1 foot to 0.5 foot, 49.3 percent in the category of 0.5 foot to 1 foot, and 10.6 percent in the category of 1 to 3 feet. The total number of feet of faults or shear zones to be intersected by the tunnel was calculated from these figures, and was 51 percent of total length of the tunnel.

It should be emphasized that the boundaries between the different fracture density categories are gradational and indefinite--this was an interpretation--and that the location of each zone was based on the projection of statistical values. The length and position of these zones was considered to be in error by as much as 50 percent, but the percentage of the tunnel in the different fracture density categories in relation to the total length of the tunnel was considered to be correct within less than 25 percent error.

Engineering data calculations and predictions

The definition of geologic conditions is of little value unless these definitions can be interpreted in terms that can be used by engineers to design and estimate the cost of construction. For this purpose, estimates were made of the probable rock loads, spacing of the support and the amount of lagging, the need for feeler holes and grouting, and the amount of ground water. These estimates were based on information used in compiling the geologic section, laboratory data, and experience in other tunnels. A generalized summary is shown by the graphs below figure 6.

Rock loads.--The calculations for rock load were based on the assumptions that the pilot bore, outside the timbers, would be about 10.5 feet wide and 11.5 feet high; and that the rates of driving the pilot bore and of installing supports--both factors effect the rock load--would be as efficient as possible. The rock load, then, would primarily be the result of geologic conditions.

The calculations were made using the following formula, which is modified from Terzaghi (1946, p. 61):

$$P = C (b + h) \cdot W$$

in which

P = rock loads in psf,

C = a constant depending on rock conditions,

b = width of tunnel,

h = height of tunnel, and

W = weight per cubic foot of rock.

The value for W was determined to be 166.88 pounds based on the weighted average of the measurements of the saturated bulk density of samples. The values of C ranged from 0.35 to 1.60 depending on the interpretation of the rock conditions expected and the possible presence of fault gouge. A maximum rock load of about 5,900 psf was calculated.

Spacing of sets and lagging.--Rock loads, fracture density, and the amount of fault gouge or clay alteration products vary from place to place, although they are interrelated to a considerable degree. The total effect of these geologic factors on tunnel construction can be expressed, more or less quantitatively, by the amount of support that may be required.

For the purposes of calculation, it was assumed that the sets would be so designed as to support a load of 10,000 psf and that the tunnel would be driven on a 3-shift-a-day basis. Wahlstrom (1962, p. 8-9) pointed out the relation of the rate of driving to support requirements. The principal factor then that will influence the amount of support will be the fracture density. Note on figure 6 that invert struts are indicated for some sections. These are sections where wide zones of squeezing fault gouge might be encountered.

The prediction of the spacing of sets and amount of lagging is empirical. It was recognized that the actual spacing of the sets and the amount lagging that would be required could only be determined at the time of construction. The purpose of these calculations was only to estimate the probable total amount of support that would be required and the approximate location of where this support would have to be installed.

Feeler holes and grout.--It was recognized that it would probably be advisable to test the ground in advance of the face if there was any possibility of encountering badly broken and crushed rock saturated with water, and to consolidate and seal that ground by grouting before it was penetrated by the tunnel. Those intervals to be tested, based on the fracture density calculations, are shown on figure 6. This totaled about 2,900 feet of feeler holes. It was also calculated that to seal these zones would require about 4,000 cubic feet of grout. This figure was based on the grout used in the Roberts Tunnel, which averaged about 10 cubic feet per foot of grouted section.

It should be emphasized that the sections indicated to be tested by feeler holes and the sections to be grouted were predictions only. It was recognized that in practice the face would have to be carefully and continually observed, and that feeler holes should be drilled if there were any indication of a water-bearing section ahead of the face. The purpose of the predictions was again only to determine a probable number of feeler holes and total length of drilling, and the probable amount of grout that would be required in order to arrive at a more accurate cost estimate.

Ground water.--The amount of ground water that would be encountered in driving the tunnel was considered to be dependent upon the porosity and permeability of the rock and the height of the water table above the tunnel level. The porosity of the rock was considered to be dependent primarily on the fracture density and the number of faults and shear zones for the different intervals of the tunnel. The permeability of the rock was considered to be primarily dependent upon the size and interconnection of the fractures. The height of the water table was taken as the level of the water as measured in the drill holes. The porosity and permeability were calculated from records of pumping tests on wells in the crystalline rocks of the Front Range, from records of water flows obtained in the Roberts Tunnel, and from the reports of water flows from the old Loveland Pass pioneer bore. In making these calculations, the authors were assisted by G. H. Chase of the U. S. Geological Survey.

The average amount of water that was predicted to flow from the pilot bore portal is shown by a graph on figure 6. This flow was calculated on the basis of an average advance from the east portal of the heading at 1,000 feet per month, and a drawdown rate of one-half of the initial flow from any zone in 5 days and one-tenth of the initial flow in 10 days. With these assumptions, an increase in the rate of advance would increase the flow, and conversely, a slower rate of advance would decrease the flow. It was calculated that the maximum flow from the portal would probably be about 500 gpm and that the rate of flow 2 weeks after completion of the pilot bore would be about 300 gpm and after 1 year about 100 gpm.

A possible maximum initial flow that might occur from any zone of fractured rock within the pilot bore was also calculated based on the maximum values of porosity, permeability, and head. These are shown by histograms on figure 6. The maximum initial flow for any zone of the tunnel was predicted to be 1,000 gpm.

Investigations and results during construction

A contract of $1,300,000 for construction of a pilot bore was awarded to Mid-Valley, Inc. in October 1964 and construction began in November 1964. During the construction of the pilot bore, geological, geophysical, laboratory, and engineering research was conducted, and to a limited extent, is continuing now that the pilot bore has been completed. All the results of this work are not yet available, but enough of the work has been compiled to evaluate the validity of the geologic projections and the predictions made prior to the start of construction.

Geologic investigations

As the tunnel progressed, the geology was mapped by the authors at a scale of 1:600. In addition to recording rock type, the attitude of foliation, joints, and faults and shear zones, the fracture density and an estimate of the percentage of the minerals in the wall rock that were altered was recorded. As a result of the records from the instrumentation, the categories of fracture density as defined on the surface--that is, less than 0.1 foot to 0.5 foot, 0.5 foot to 1 foot, and 1 to 3 feet--were changed in the underground mapping to less than 0.1 foot, 0.1 foot to 0.5 foot, 0.5 foot to 1 foot, and greater than 1 foot. It was also the records from the instrumentation that showed the necessity for recording the percentage of the minerals of the rock that were altered. The geology of one wall for 50 feet to either side of each instrument station was mapped at a scale of 1:60. The face of the tunnel at various points was mapped geologically by the Engineers of the Colorado Department of Highways and by the authors at a scale of 1:24. About 800 face sections were made. The wooden blocking placed between the instrumented set and the rock was mapped at 1:24. Contour diagrams of the attitudes of the foliation, joints, and faults and shear zones compiled from wall and face mapping are shown on figure 7.

Figure 7.--NEAR HERE.

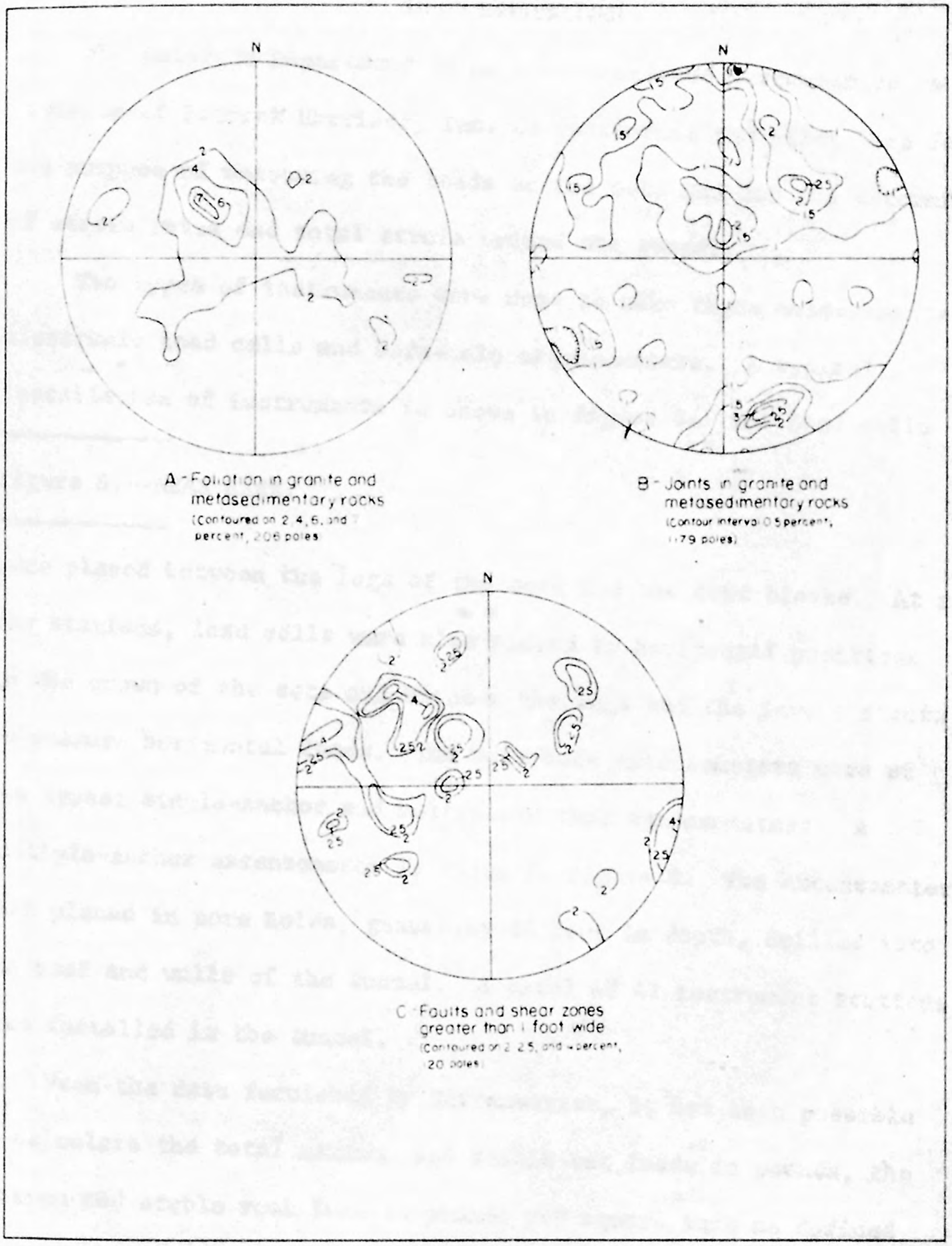

Figure 7.--Contour diagrams of poles of the foliation, joints and faults and shear zones compiled from pilot bore mapping

Instrumentation

The Colorado Department of Highways retained Terrametrics, a division of Patrick Harrison, Inc. to instrument the pilot bore for the purpose of measuring the loads on the sets and for the determination of strain rates and total strain around the tunnel.

Two types of instruments were used to make these measurements; electronic load cells and bore-hole extensometers. A typical installation of instruments is shown in figure 8. The load cells

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Figure 8.--NEAR HERE.

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were placed between the legs of the sets and the foot blocks. At a few stations, load cells were also placed in horizontal positions in the crown of the sets and between the legs and the invert struts to measure horizontal loads. The bore-hole extensometers were of two types; single-anchor and multiple-anchor extensometers. A multiple-anchor extensometer is shown in figure 8. The extensometers were placed in bore holes, generally 25 feet in depth, drilled into the roof and walls of the tunnel. A total of 41 instrument stations were installed in the tunnel.

From the data furnished by Terrametrics, it has been possible to calculate the total maximum and stable set loads in pounds, the maximum and stable rock load in pounds per square inch as defined by Terzaghi (1946), the wall and arch deflections in inches, and the height of the ground arch (Terzaghi, 1946, p. 60) in feet, and to relate these to the geologic conditions and the engineering practices in the pilot bore (Robinson and Lee, 1965).

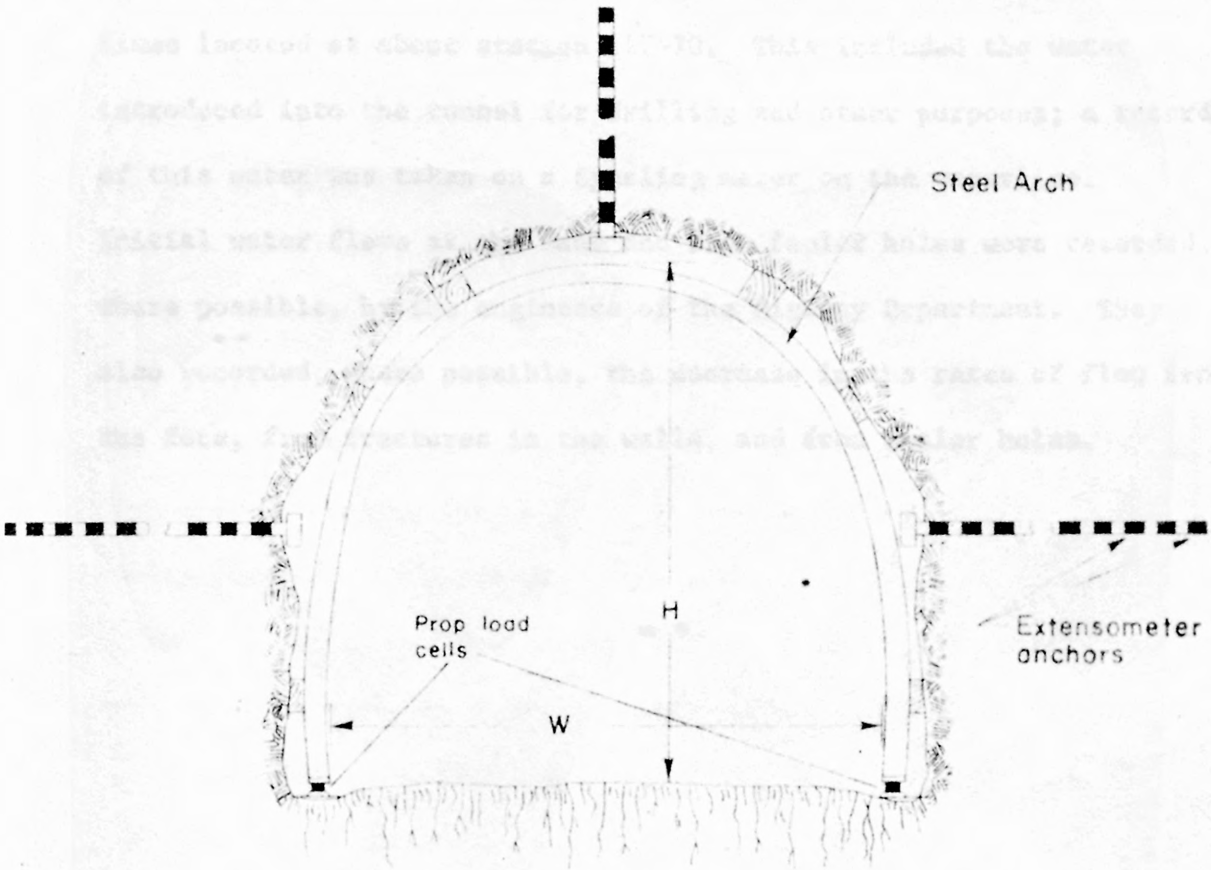

Figure 8.—Typical Terrametrics' instrument installation, Straight Creek tunnel pilot bore

Ground water

The total water flow from the tunnel was recorded at a Parshall flume located at about station 117+70. This included the water introduced into the tunnel for drilling and other purposes; a record of this water was taken on a Sparling meter on the waterline. Initial water flows at the face and from feeler holes were recorded, where possible, by the engineers of the Highway Department. They also recorded, where possible, the decrease in the rates of flow from the face, from fractures in the walls, and from feeler holes.

Comparison of predictions and findings

One of the main purposes of the Straight Creek project, as previously stated, was to evaluate a statistical method of compiling geology and predicting geologic conditions at tunnel depth. The predictions were published prior to the construction of the pilot bore by the authors (Robinson and Lee, 1962, 1963, and 1964). Table 1 is a compilation of the predictions and the findings of this project. It is to be noted that there is, in general, a relatively close agreement between most of the predictions and the findings--indicating the validity of the method or luck, or both. As important as the cases where the figures agree are the cases where they don't, and the reasons for the lack of agreement. The table too, does not tell all the story where the figures are in close agreement, and is in need of explanation.

The predictions were based on a tunnel of 8,050 feet in length and 10.5 feet wide and 11.5 feet high to be supported by square set timbers. As a result of a landslide at the east portal (Robinson, Carroll, and Lee, 1963), the east portal was moved about 150 feet south and the portal grade lowered about 16 feet. This lengthened the tunnel to about 8,300 feet. Also, during construction, steel, rather than timber sets were used for the most part and the diameter of the tunnel outside the steel averaged about 13 feet. Two types of steel sets were used: 4-inch "I" beam weighting 7.7 pounds per foot and 6-inch "H" beam weighing 25 pounds per foot.

Geologic measurements

The geologic features predicted were the percentage of rock types, the percentage of the pilot bore that would be within the different categories of fracture density, the percentage of the length of the pilot bore that would be in faults or shear zones, and the attitudes of the foliation, joints, and faults and shear zones.

Rock types.--The percentage found in the pilot bore of 75.4 percent granite, 23.8 percent metasedimentary rocks, 0.8 percent diorite dikes compare well with the predictions of 75 percent granite and 25 percent metasedimentary rock predicted. The figures show that the sample used--the number of feet of drill holes logged--was adequate to define the rock types.

Fracture density.--The fracture density categories as defined on the surface were modified in the underground mapping. The fracture density categories shown on Table 1 are a combination of the two systems used in order to make the predictions and finding comparable.

A preliminary analysis of the results of the instrumentation and the geology of the pilot bore indicates that these categories are probably not the significant ones from an engineering standpoint (Robinson and Lee, 1965). Apparently, when the average size block of rock or the average distance between fractures exceeds 0.5 foot, the loads that develop are more dependent upon the nature of the surface of the fracture than the size of blocks or the spacing of fractures. Also, the loads increase greatly with an increase in rock alteration. The largest loads developed in the shear zones where the rock had been ground to fine sand or smaller size, where most of the minerals altered to clay minerals, and where the zone was damp. A better definition of fracture density, taking into account the amount of alteration, is needed.

Faults and shear zones.--Underground, only faults or shear zones greater than 1 foot wide were used to calculate the sum of the widths of the faults and shear zones. The prediction of 51 percent of the total length of the tunnel in faults and shear zones is considered within the limits of mapping accuracy for the measured 49 percent.

Attitudes of faults and shear zones.--At the surface, the strike or trend of 284 faults greater than 5 feet wide in the 6 square mile area were measured, but the dip could be measured on only 74. Of these, 24.7 percent had a strike or trend between N. 20° E. and N. 50° E. and 44.8 percent between N. 20° E. and N. 80° E. The average dip of 74 of the faults was 75° either east or west. Underground the attitude of 120 faults and shear zones greater than 1 foot wide were measured. Two maxima are defined; one representing faults that strike about N. 45° E. and dip 40°-60° SE. and one representing faults that strike about N. 20° E. and dip about 75° SE.

These figures would appear to compare favorably with the predictions when it is considered that there is only 4.0 percent outcrop at the surface in a 6 square mile area, and that the pilot bore is essentially a linear feature across the area, but with 100 percent exposure. The prediction that no fault or shear zone greater than 5 feet in width would be expected to follow the tunnel for any distance was upheld--probably by luck as the tunnel line was moved 150 feet south.

The preliminary analysis of the geology and the results of the instrumentation in the pilot bore (Robinson and Lee, 1965) indicates that in part the loads are probably related to the apparent angle of dip of the faults and shear zones in relation to the trend of the pilot bore. The maximum loads developed where the apparent dip of faults and shear zones was about 45°. The loads were less where the dips were greater or less than 45°. It was also indicated that the width of a fault or shear zone in a tunnel must be about one-half the diameter of the tunnel before its effect on the loads can be noticed. Better methods--possible geophysical methods--for defining the magnitudes and attitudes of faults and shear zones at the surface are needed.

The prediction that the joints in the pilot bore would strike in any direction was upheld by mapping in the pilot bore. The average dip of 60° determined at the surface was high when compared to the average dip of 45° determined in the pilot bore.

Joints mapped on the walls and on the heading faces were compiled separately and yielded considerably different plots. On the walls, relatively fewer joints were recorded with a N. 45° E. strike and northwest dip whereas on the faces fewer joints striking N. 20° E.-N. 20° W. and dipping northwest or southwest were recorded. This comparison indicates that what is considered a significant joint, and so recorded, depends upon the trend of the surface in the tunnel being mapped in relation to the attitude of the joint and the direction of driving the tunnel. Figure 5B was compiled from all the joints recorded on the wall and from about an equal number randomly selected from the face mapping. About 4 times as many joints were measured on the faces as on the walls because of the scale of mapping and the number of faces mapped--about 800 maps at 1:24.

Attitudes of foliation.--The strike of the foliation at the surface and in the pilot bore is close, but the dip is considerably lower in the pilot bore. A possible explanation of the difference in the dip may lie in the relative number of measurements made in the granite and in the metasedimentary rocks; the foliation as measured in the two rock types have been combined on the same diagrams. At the surface, figure 4A represents 161 measurements in granite and 28 in the metasediments; in the pilot bore, 93 measurements were in the granite and 113 in the metasediments. Also, probably the relation of the surface of measurement in the pilot bore to the attitude of the foliation (as with the joints) influences the number of observations made.

Engineering measurements

The items considered under the engineering measurements are geologic rock load, final swell pressure of fault gouge, and ground-water flows.

Maximum geologic load.--The maximum rock load of 5,900 psf was calculated based upon the theories of Terzaghi (1946), as previously discussed. This figure was based on the preliminary design of a 10.5- x 11.5-foot tunnel. The pilot bore averaged about 13 feet in diameter. Using the same formula, the predicted maximum rock load for this size tunnel would be 6,970 psf.

As the result of the instrumentation, the theories as to the stress around a tunnel as discussed by Terzaghi (1946) have been changed. It is known that as the face advances away from a point, a maximum load develops at that point, which after a period of time drops off to a stable load. The time for, and the magnitude of the development of the maximum load, and the time required for the load to stabilize and the magnitude of the stable load, are dependent upon the geologic conditions, the engineering practices, and the dimensions of the tunnel. It is possible within certain limits to determine the part of the load that is the result of the engineering practices and the part that is the result of geologic conditions (Robinson and Lee, 1965).

The predicted rock load and the measured geologic load cannot be compared because we now know that the existing theories for predicting loads are not adequate. Probably, the calculated geometric midpoint for the worst geologic conditions most closely fits the theory as developed by Terzaghi (1946).

Fault gouge final swell pressure.--It was assumed that weathering and ground water would not appreciably change the clay mineralogy of fault gouge and altered rock at the surface, and that the final swell pressures of this material in the pilot bore would be about the same. The average final swell pressures of 29 samples collected from the pilot bore was 1,727 psf which compares favorably with an average final swell pressure of 2,233 psf based on six samples from the surface. The assumption that the final swell pressures of samples from the surface would be about the same as for samples from the tunnel would appear to be valid.

Ground-water flows.--The figures for the prediction of the average flow from the portal and the flow actually measured have little significance. The authors failed in their original calculations and predictions to consider the time of year and the influence of the spring runoff. The normal ground-water flow from the portal was increased by a factor of 7.5 times as a result of the spring runoff.

The predicted flow from the portal 2 weeks after completion of the tunnel was based on a constant rate of advance of the tunnel of 1,000 feet per month. The average rate for the tunnel was about 610 feet per month. At this rate of advance, the estimated flow would have been about 183 gpm. These figures, although comparable, are meaningless because the influence of the spring runoff was not considered, and if the tunnel had been completed in the spring, the measured flow would have been greater than the predicted flow.

All the water calculations were based on an interpretation of the porosity and permeability of the faults and shear zones. In the pilot bore, however, the faults and shear zones were essentially dry until they had been opened up. The principal water flows came from relatively competent rock with open joints that normally were beyond the limits of the faults and shear zones. The approximate agreement of the ground-water flows, then, can be considered due more to luck than skill.

Engineering practices

The predictions of the spacing of sets, lagging and blocking, feeler holes, and amount of grout were, of course, empirical because actual requirements can be determined only at the time of construction. It was felt that such predictions would be of value in estimating the cost of construction. Geologic conditions alone do not determine requirements. Other factors, some of which have been discussed in relation to the geologic load, also exert an influence.

Set spacing.--In the pilot bore, the sets were not uniformly spaced, particularly where jump sets were added. For the purpose of comparison with the prediction, spacing of 0.5 foot to 1.5 feet are combined and compared with 1 foot, 1.5 to 2.5 with 2 feet, 2.5 to 4.5 with 4 feet, and 4.5 and greater with 5 feet.

These figures are considered to agree very well when all the factors that influence support are considered; also the length of the tunnel was increased by approximately 300 feet. The total number of sets predicted was 2,691. The actual number used was 2,059, although the calculated number of sets based on our adjustment of actual set spacings is 2,274.

For invert struts, it was predicted that 1.4 percent of the tunnel length would require struts on 1-foot centers, or 113 struts. The contractor used struts for 8.0 percent of the tunnel length, but these were on 1- to 3-foot centers. The total number used was 210.

Lagging and blocking.--The predictions for lagging and blocking specified sections of the tunnel that would require blocking only, blocking and lagging along the back, and blocking and lagging along the arch and walls. In practice, it was more convenient to record the percentage of blocking and lagging around the walls and arch. The predicted figures have been converted to percentages for comparative purposes and are shown on Table 1.

Feeler holes.--The drilling of feeler holes was recommended in the preconstruction report (Robinson and Lee, 1962), and the approximate areas in which they might be advisable was indicated. In practice, the Colorado Department of Highways and the contractor considered it advisable to keep at least one feeler hole about 40 feet in advance of the face for most of the length of the tunnel, a decision in which the authors concurred. For that reason, there is a considerable difference--by a factor of almost 4 times--between the predicted number of linear feet of feeler holes and the footage actually drilled. With hindsight, it is obvious that the large percentage of the holes did not intersect broken, water-saturated ground, which was their purpose. From an economic and safety point of view, however, they were advisable in that they gave the contractor a better idea of the ground in advance of the face and allowed him to more economically plan such things as lengths of round and supplies--sets, timber, etc.--needed in the tunnel.

Grout.--It was predicted that it would be economically advantageous to grout certain types of ground as determined by feeler holes in advance of the face. The purpose of the grout is to consolidate the ground and seal off water and so reduce the amount of support required and the difficulty of driving through that section. The alternative is closely spaced steel supports and essentially hand mining. This decision is the prerogative of the contractor and his employer, and in the pilot bore the decision was that grout was not needed.

Cost.--The pilot bore was holed through during the first week of December 1964 and cleanup work completed in January 1965. The cost of the contract plus force account work was approximately $1,400,000.

Conclusions

The validity of a geologic projection depends upon the geometry of the geology, the amount of time available for surface examination, the amount of time and money available for drill-hole investigation, and the application of geophysical techniques--and the knowledge and experience of the geologist in charge. The Straight Creek Tunnel, Colorado project has established that geology can be treated statistically to predict the kinds and percentages of different geologic conditions at depth, and that engineering requirements can be equated with predicted geologic conditions to permit reasonable estimates of construction costs. The failures of some of the predictions have revealed those fields in which there is not adequate geologic and engineering knowledge. Stress history around openings in nonisotropic and nonhomogeneous rocks, and the factors that affect the flow of ground water in crystalline rocks need more study. Continued research in the field of predicting geologic and engineering conditions at the depth of a tunnel will allow more accurate predictions to be made, and so reduce the cost of construction by the amount that is required for unforeseen contingencies.

The Straight Creek Tunnel project was analyzed with a limited number of geologic variables, which probably in part accounts for its success. It is believed, however, that a similar approach--with similar success--can be applied to the projection of geology to depth in any geologic environment if the geometry of the geology is understood and carefully analyzed.

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Appendix

Examples of types of data and methods of analysis mentioned in report.

Geologic map of a portion of the tunnel at 1 inch=50 feet. The entire tunnel has been geologically mapped at this scale, and the maps used to compile a map at 1 inch=100 feet.

Geologic plan of south wall of the tunnel at 1 inch=5 feet at instrumentation station SIS 2 and PLC 4. Such maps were made for each instrument station, and from them an analysis made of the principal structural elements.

Analysis of principal structural elements for station SIS 2.

Example of geologic section at 1 inch=2 feet of the tunnel face. These were made at least once a shift.

Example of blocking (1 inch=2 feet) for each of the instrumented sets in the pilot bore. These examples are for instrumented sets at PLC 4.

Results of mineral analyses of two samples taken from the walls of the tunnel at SIS 2.

Size analyses of two samples taken from walls of tunnel at SIS 2.

Table of swell capacity and PVC swell index of samples taken from faults near SIS 2.

Electrical resistivity measurements at instrumentation station SIS 2.