# GEOLOGY OF SANTA CECILIA TUNNEL

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## INTRODUCTION

This tunnel was constructed by Morrison-Knudsen for the Brazilian Traction, Light & Power Co. Ltd. during 1946-1951. It was started in 1946 but construction was interrupted in late 1947 at station 0 + 725 for lack of funds to carry on the work. Work was resumed in 1949 and completed in 1951.

The first tunnel alignment was rather arbitrarily selected without adequate geologic investigations and explorations. During 1948 new geologic studies and explorations were made which indicated that the alignment of the tunnel could be changed slightly to encounter better rock conditions and that it could be shortened by substituting a canal for the last two kilometers of its extent. Decomposed rock existed along the original alignment in the valley near station 2 + 400, and the portion for which a canal was substituted also contained a high porcentage of decomposed rock that would have required heavy, closely spaced supports.

This tunnel will ultimately divert 160 cubic meters of water per second from the Paraiba River to the Santana Reservoir on the Pirai River and, eventually, to the Forçacava powerhouse. It has a length of 3,305 meters. The horseshoe section in the first 700 meters of its extent is 8.10 meters high and 5.84 meters wide while the remainder has a height of 6.90 meters and a width of 6.30 meters. The tunnel alignment is northwest-southeast, or essentially normal to the strike of the gneiss and schist in this region.

## LOCATION

Santa Cecilia Dam and the intake portal of this tunnel are located 2 Kms. upstream from the city of Barra do Pirai which is in turn situated 75 Kms. airline distance northwest of Rio de Janeiro.

## GEOMORPHOLOGY

The Paraiba River begins on a high plateau near the Serra do Mar, approximately midway between Rio de Janeiro and São Paulo. It runs southwest for 160 kilometers to Guararema, a small town only 60 Kms. from São Paulo, where it makes a 180 degree turn and flows between the Serras do Mar and Mantiqueira to enter the South Atlantic at Campos, 550 Kms. to the northeast. Throughout most of its extent it is parallel to the coast line and seldom more than 100 Kms. inland. The drainage pattern is generally dendritic, but it has been greatly influenced by the geologic structures.

The greater part of the valley is underlain by complex structures of crystalline metamorphic rocks and by large stocks of granites, nepheline syenites and lesser amounts of foyaite and diabase as dikes.

Since the area lies within the tropics, it has a warm, moist climate and heavy rainfall from November to April. A thick cover of residual soils and decomposed rocú, in places extending to a depth of over 50 meter's in common to areas underlain by gneiss and schist, but outcrops of granite and syenite are more common since they are less deeply weathered.

The river has, carved a narrow "U" shaped valley since the late Tertiary with a slope of about 1 meter per kilometer in the region of Barra do Pirai. The topography is hilly and undergoing rapid erosion. Landslides are common on the steeper slopes during the rainy season. Neither the streams nor the topography have become adjusted to the last uplift that occurred in late Tertiary. The elevation of the area varies from 350 m at the river to over 500 on the nearby hills.

## REGIONAL GEOLOGY

The structural valley of the Paraiba is best represented a considerable distance upstream between Cruzeiro and Jacareí, where it is partially filled with unconsolidated late Tertiary sediments. The graben in that area has an average width of 20 Kms, but it is less well defined near Barra do Pirai. A pre-cambrian horst of gneiss and schist having a width of 50-60 Kms. lies southeast of the graben between the river and the coast. It is a part of this horst through which the Santa Cecilia tunnel passes. This large block of gneiss and schist was last strongly compressed in the Caledonian orogeny. The graben was probably formed during the Mesozoic era and rejuvenated in late Tertiary. The latest movement were confined to adjustments along old faults.

The structure of the horst between the graben and the coast is rather simple for metamorphic rocks of this age. The foliations and schistosity are uniformly oriented N 50 to 60º E, or parallel to the coast line and the Paraiba valley. Steep dips of the foliations to the northwest or southeast are everywhere the rule except for small local areas near the crest of folds. Constant steep, dips for 2 Kms. or more are not uncommon. A "stratigraphic" thickness of 2 Kms. of biotite gneiss with some biotite or sericite schist is commom on the flanks of the large folds. Because of the deep decay of the rocks, unweathered exposures are not very common except along the stream banks but the structure of the rocks is well preserved in the saprolites.

The older gneiss and schists were invaded first by several stocks and dikes of Archean granites followed later by stocks and dikes of nepheline-sâenites in the Mesozoic and still later by dikes of diabase, also in the Mesozoic era. The largest of the nepheline-syenite intrusives is represented by Agulhas Negras, one of the higher mountains in Brazil, which is located just north of Rezende, a city nearly 60 Kms. upstream from Barra do Pirai. Dikes of foyaite are not uncommon. They are apparently the same age as the large stocks of nepheline-syenites.

A thick cover of residual clay prevents the accurate mapping of the faults that form the graben in the Barra do Pirai area, and the topography is not helpful. Because decomposition progresses at a faster rate than erosion, the residual soils completely hide the faults except in a few larger road cuts.

## SOILS AND DECOMPOSED ROCK COMPRISING THE OVERBURDEN

Unweathered gneiss and schist are seldom exposed in this area, except in or near the stream beds or in large excavations for railroads or highways. A top layer of 1 to 3 meters of tan, fine-grained, lateritic silty clay everywhere covers the surface except where broken by recent landslides and gully erosion. It is homogeneous in character and retains none of the original rock structures. Normally the contact with the underlying saprolite is sharp and sometimes marked by thin, disconnected, aligned, sub-angular fragments of vein quartz. The contact probably represents the lower limits of soil affected by creeping movements, effects of organisms, vegetation and many other chemical and physical changes that influence this outer layer of soil. All of the many agents acting on the "top layer" have acted to reduce the grain sizes without appreciable movement from its original position. Seldom does the percent of clay (smaller than 0.005 mm) exceed 30% and the percent of sand larger than one millimeter does not normally exceed 5%. The Atterberg liquid and plastic limits vary between 50-70% and 10-30% respectively.

Underlying the top layer is a zone of variable thickness of soft, decomposed gneiss in place, or saprolite. It resembles the saprolites on the piedmont of the southern states of the United States. It retains all of the delicate structures in the original rock, but it no longer has any properties which would classify it as a rock. It has decomposed in place to a silty, dense sandy clay. The feldspars and biotite have decomposed. This material usually has less than 10% (0.005 millimeter) clay and more than 10% of sand larger than one millimeter. Some small zones are non-plastic but usually the liquid and plastic limits vary between 25-50% and 1-20% respectively. The transition from this type of material to hard rock occurs abruptly. Hard, unweathered rock may have small open, oxidized seams which have developed along the joints and foliation for a few meters below the top and to a greater depth than shown on th geologic section in some cases, since the core drill holes are not close enough together to reveal such details.

## EXPLORATION

This tunnel was started in 1946, when 725 meters were excavated at the northwest or intake end without an adequate geologic survey and exploration. Tunneling operations were closed down in late 1946 and, before they were resumed in 1949, a geologic study of the area was made, including a geologic map and a geologic section based on 13 diamond core drill holes plus numerous wash borings.

Along the original route there was no sound rock at tunnel level in the valley between station 2 + 300 and 2 + 400 even though it was located a few hundred meters upstream of the route selected, where normally the rock should have been higher in elevation. A more serious defect found by exploration along the original alignment in 1948 was two large areas with no rock in the part later replaced by a canal. It was largely for this reason that the tunnel alignment was changed.

A rather accurate preliminary geologic section was prepared from the information obtained from the borings and surface indications. The attached geologic section, Figure A, contains more details than the original sections but it required little modification in the structure of the gneiss.

The gneiss was quite abrasive on the diamond core drill bits which cored less than 10 m apiece. Most of the holes were started with Nx-size bits to penetrate all of the zone of weathered rock before changing to Ax-size. No other bit sizes were available. Ex-size cores would have been satisfactory and cheaper but at that time all bits had to be imported, which required considerable time.

Contrary to my expectations, wash borings gave a reasonably accurate profile of the top of hard rock as later checked by the diamond drill. This was possible since there is a rather sharp line separating the completely decomposed rock in place and the hard rock with open, oxidized joints. There were no boulders in the saprolite. The wash borings were made with unskilled labor more rapidly and much more economically per meter than the diamond core drill holes. It was found through practice, for such geologic conditions, that it is more economical to first explore the area with numerous wash borings to obtain a profile of the top of rock. By using the wash boring data and surface geologic information, a wiser and more economical use can be made of expensive diamond core drill holes. Diamond drilling in this country is more expensive than in many other countries because most of the equipment, bits and other parts, have to be imported.

Groundwater levels were determined in the core drill holes at the beginning of the day shift and for a few days after the holes were completed. The water table was frequently at the surface in the valleys, but normally slightly below the top of hard, weathered rock in the intervening hills. There are usually at the top of hard rock a few meters of the partially weathered rock which contains numerous open joints. Therefore, the water table seldom is lower than the top of sound, unweathered rock and frequently slightly above this level. A water table above tunnel level did not mean that excessive water would be encountered by the tunnel since there was not a large quantity of water present in the overburden and weathered rock. Seepage into the tunnel was common along joints nearly everywhere. An open fissure in the gneiss near station 1 + 800 gave a flow of 200 gallons per minute for a few days and later decreased to about half this amount. It is possible that this water was trapped in some way by the dikes of diabase on either side of this zone.

## TUNNEL GEOLOGY

This tunnel penetrates for more than 3 Kms. a part of the Brazilian Archean complex. For the most part the tunnel is in a hard, evenly-banded, biotite garnitiferous gneiss. Biotite mica is commonly heavily concentrated along the foliations, which caused the gneiss to cleave easily at the areas of low dip of the foliations, and was a hazard which frequently required supports. Therefore, not only the character of the gneiss but also the structure relationship to the tunnel influenced the tunneling conditions. Normally, less supports were required where the foliations of the gneiss had a steep dip.

Two dikes of altered, fine-grained, nepheline syenite were encountered at station 0 + 450 and 1 + 010. Hydrothermal alteration had changed these dikes to a blocky, seamy rock and clay along the contacts and the central portions were also partially decomposed. Slightly swelling ground was noticed after the supports were placed at 0 + 60. Before the concrete lining was placed, several steel sets were replaced in this area. The small syenite dike at station 1 + 010 was also altered, but the diabase dike was not and, consequently, must be later than the syenite. Similar relationships have been noted in the area.

Eight small dikes of diabase were encountered, two of which were less than one meter thick. The larger diabase dikes were sound and unaltered, but always closely jointed. Many of the joints were slickensided, and while the diabase was sound otherwise, the close jointing required supports to keep it from caving. The contacts of the diabase showed a fine-grained to dense texture for about one meter away from the gneiss. The contact with the gneiss was sharp and the gneiss showed alteration or brecciation. At other localities in Brazil the diabase dikes are believed to have entered along faults, or faulting has taken place during the intrusion, but such conditions are absent in this tunnel.

Close jointing, which produces what tunnel men know as blocky ground, was one of the principal causes for using supports. Why the joints were more closely spaced in one area than in another is not clear. Large dip joints, which paralleled the first 350 m of the tunnel at the intake portal, caused serious overbreakage and one serious accident.

A large fault zone at station 7 + 80 caused considerable delay and extra expense. By chance, core drill hole No. 2 penetrated this fault zone and its existence was known prior to encountering it. However, the hanging wall portion did not appear to offer any tuznneling hazards, but serious difficulty was met with when a meter of soft, clay-like gouge along the foot wall was penetrated. During a period when no one was working in the tunnel, the back of the tunnel caved in because of improper supports. A large hole was formed in the roof which required extensive supports and considerable delay. This zone was grouted after the lining was placed with a slurry of neat cement, to fill up the voids above the tunnel lining. A total of 65,409 bags of cement was used in grouting all of the tunnel.

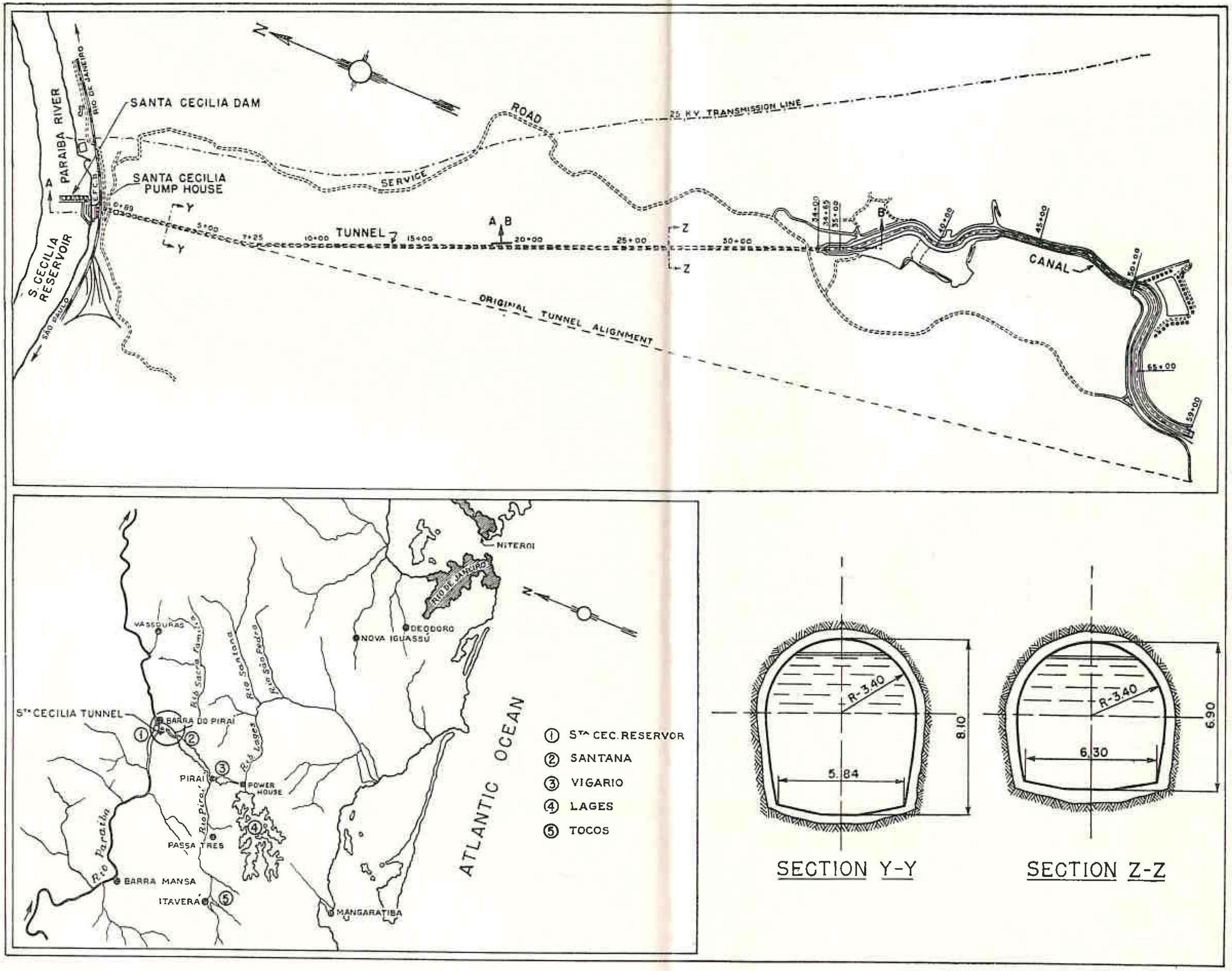
## SUPPORTED TUNNEL

A total of 1575 meters, or 48% of the overall tunnel length of 3,305 meters, was supported by steel. Several other sections of the tunnel were protected with gunite and a few timber sets were also used.

More than half of the supported tunnel section required light supports spaced at intervals of 2 to 3 meters because the rock was either slightly blocky, or because of large joints in the rock. If the tunnel had been half the diameter, supports would not have been required in such zones. A large portion of the light supports was used between stations 1 + 400 and 2 + 070 where the gneiss and schist had a low dip on the flanks of the anticline. Because of the concentrations of biotite along the foliations in this area, and jointing at right angles to the foliation, this rock would not stand safely without supports. Also a single small, nearly vertical seam of clay of only 1 to 2 cm in thickness which paralleled the tunnel between 1 + 158 and 1 + 280 dictated the use of supports in this area. A small amount of movement along a former, large dipjoint had produced this soft rock flour or fault gouge which, unfortunately, paralleled the tunnel for many meters.

Closely spaced, steel supports were required only at relatively few zones such as the fault zone at 0+ 780 and the altered zones of rock at 1 +020 and 0 + 450.

São Paulo, December 10, 1952



PARAIBA RIVER
SANTA CECILIA DAM
SANTA CECILIA PUMP HOUSE
S. CECILIA RESERVOIR
RIO DE JANEIRO
SÃO PAULO
ROAD
SERVICE
25 K.V. TRANSMISSION LINE
TUNNEL
ORIGINAL TUNNEL ALIGNMENT
CANAL
N
A
B
Y
Z
0+89
5+00
7+25
10+00
15+00
20+00
25+00
30+00
34+00
34+65
35+00
40+00
45+00
50+00
55+00
59+00
VASSOURAS
NITEROI
RIO DE JANEIRO
DEODORO
NOVA IGUASSÚ
Sta CECILIA TUNNEL
BARRA DO PIRAI
PIRAI
POWER HOUSE
PASSA TRES
BARRA MANSA
ITAVERA
MANGARATIBA
Rio Paraíba
Rio Piraí
Rio Sacra Família
Rio Santana
Rio São Pedro
Rio Lages
ATLANTIC OCEAN
① Sta CEC. RESERVOR
② SANTANA
③ VIGARIO
④ LAGES
⑤ TOCOS
R-3.40
5.84
8.10
6.30
6.90
SECTION Y-Y
SECTION Z-Z


Fig. 1

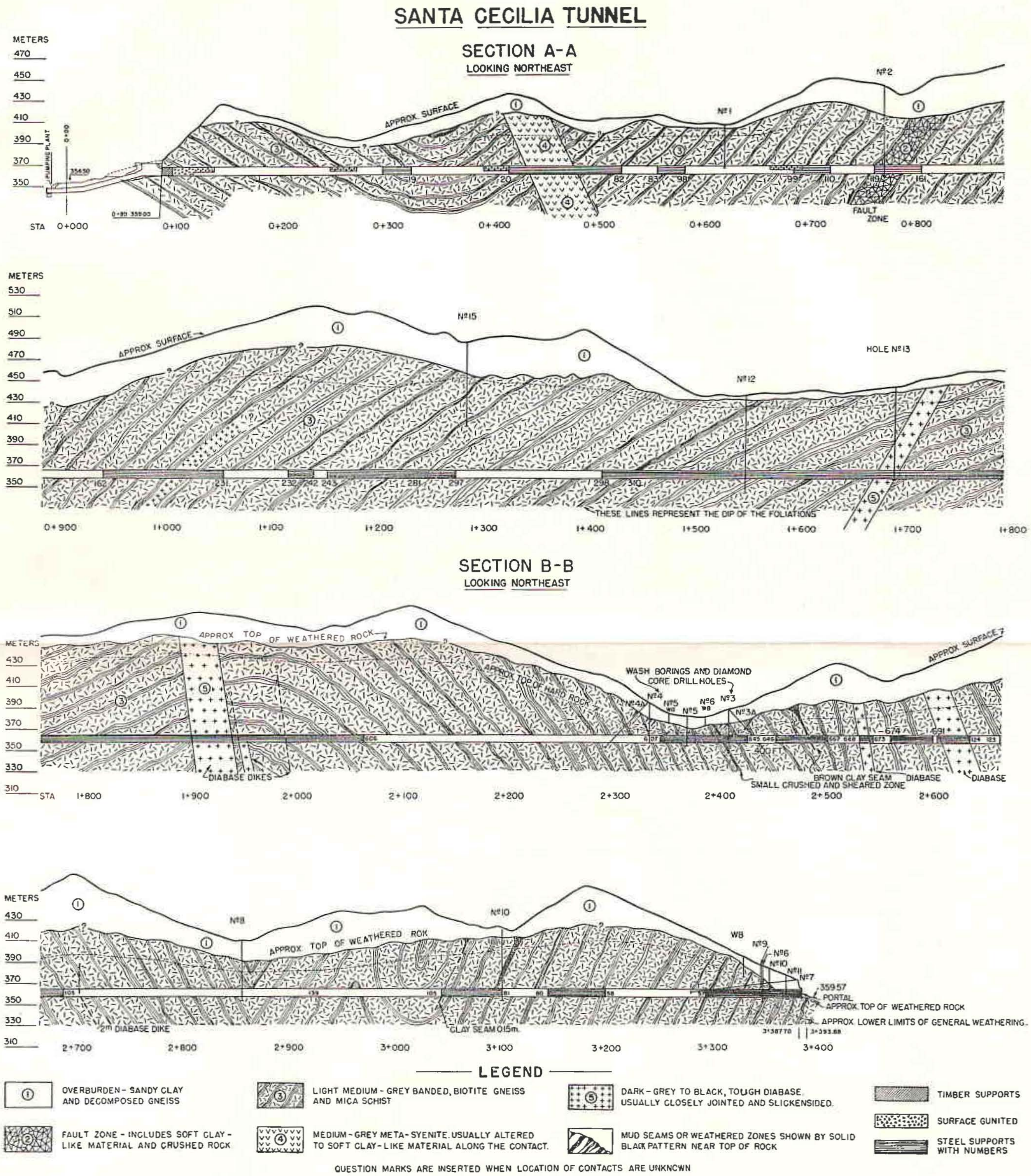

SANTA CECILIA TUNNEL
SECTION A-A
LOOKING NORTHEAST
METERS
APPROX. SURFACE
PUMPING PLANT
FAULT ZONE
STA 0+000
0+100
0+200
0+300
0+400
0+500
0+600
0+700
0+800
APPROX SURFACE
HOLE Nº13
THESE LINES REPRESENT THE DIP OF THE FOLIATIONS
0+900
1+000
1+100
1+200
1+300
1+400
1+500
1+600
1+700
1+800
SECTION B-B
LOOKING NORTHEAST
APPROX TOP OF WEATHERED ROCK
APPROX TOP OF HARD ROCK
APPROX SURFACE
WASH BORINGS AND DIAMOND CORE DRILL HOLES
DIABASE DIKES
BROWN CLAY SEAM
DIABASE
SMALL CRUSHED AND SHEARED ZONE
STA 1+800
1+900
2+000
2+100
2+200
2+300
2+400
2+500
2+600
APPROX TOP OF WEATHERED ROK
2m DIABASE DIKE
CLAY SEAM 0.15m.
PORTAL
APPROX. TOP OF WEATHERED ROCK
APPROX. LOWER LIMITS OF GENERAL WEATHERING.
2+700
2+800
2+900
3+000
3+100
3+200
3+300
3+400
LEGEND
OVERBURDEN - SANDY CLAY AND DECOMPOSED GNEISS
LIGHT MEDIUM - GREY BANDED, BIOTITE GNEISS AND MICA SCHIST
DARK - GREY TO BLACK, TOUGH DIABASE. USUALLY CLOSELY JOINTED AND SLICKENSIDED.
TIMBER SUPPORTS
SURFACE GUNITED
FAULT ZONE - INCLUDES SOFT CLAY-LIKE MATERIAL AND CRUSHED ROCK
MEDIUM - GREY META-SYENITE. USUALLY ALTERED TO SOFT CLAY-LIKE MATERIAL ALONG THE CONTACT.
MUD SEAMS OR WEATHERED ZONES SHOWN BY SOLID BLACK PATTERN NEAR TOP OF ROCK
STEEL SUPPORTS WITH NUMBERS
QUESTION MARKS ARE INSERTED WHEN LOCATION OF CONTACTS ARE UNKNOWN

Fig. 2