A GEOLOGIC STUDY OF THE MADDEN DAM PROJECT, ALHAJUELA, CANAL ZONE

By Frank Reeves and Clyde P. Ross

ABSTRACT

This paper is based on a geologic study of the conditions that would affect the proposed Madden Reservoir, on the upper Rio Chagres, near Alhajuela, Canal Zone. The reservoir is intended for the storage of flood water for use, mainly in the dry season, for lockages in the Panama Canal, for the possible development of hydroelectric power, and to aid in avoiding disturbing currents in the canal.

The rocks are calcareous and tuffaceous sedimentary beds of Tertiary age, bent into a structural basin and resting on a volcanic complex of probable Eocene age. The structural basin corresponds approximately to the topographic depression in which the reservoir is to be formed. Some of the rocks are permeable to water and others are mechanically weak, but, in spite of such disadvantages, it is believed that, with proper precautions in constructing dams, the project is feasible, although it is recommended that the maximum water level be made 20 feet lower than originally contemplated. The geologic structure is such as to assure that any leakage will find its way into Gatun Lake, where it is desired.

INTRODUCTION

PURPOSE AND SCOPE OF THE REPORT

The necessity of a large and increasing supply of water for lockages in the Panama Canal has engaged the attention of the engineers in charge ever since the canal was planned. In recent years it has become increasingly evident that, if the canal is to meet the probable future demands on it, more water than is now available in Gatun Lake during the dry season must be provided. Consequently studies have been made of the feasibility of a storage reservoir on the upper Rio Chagres, the only conveniently located stream of adequate size. (See pl. 4.) Such a reservoir would conserve the flood waters for use in the dry season, which extends from January through April, and would also allow the development of additional hydroelectric power and aid in the prevention of dangerous currents in the canal near Gamboa during floods.

The present report is the result of a geologic investigation at and near the site of the proposed dam, known as the Madden Dam, carried on from January 16 to March 16, 1929, by Frank Reeves and Clyde P. Ross, of the United States Geological Survey, at the request of Governor Burgess, of the Panama Canal. It comprises a brief presentation of the available geologic data, interpretation of these data in their relation to the Madden project, discussion of the geologic aspects of the problems involved, and recommendations regarding these problems.

The investigation has included geologic study and mapping in and near the reservoir area, the work at a distance from the dam site being of a reconnaissance nature. A study was made of the cores from diamond-drill holes drilled in the vicinity of the dam site and of the water level in these holes. Pressure tests on some of the holes and experiments on the solubility and permeability of the reservoir rocks were also made. The ridge between the Azote Caballo and Chilibrillo Rivers and that between the Rio Chagres and Quebrada Madronal were studied in detail, inasmuch as they include the critical areas with respect to safety of the dam and watertightness of the reservoir.

PREVIOUS WORK

A great deal of hydrographic, topographic, and other work in relation to the Madden Dam project has been done by members of the section of surveys, Panama Canal. The engineering phases of the project have been considered by a committee composed of officers of the Panama Canal organization—R. Z. Kirkpatrick, chairman; George W. Green, A. C. Gerlington, and E. S. Randolph—in a report dated January 4, 1928. The data compiled in these studies have proved of great assistance in the geologic investigations, and acknowledgment is made of the generous manner in which they have been made available to the writers. Preliminary geologic studies have been made by Charles Terzaghi, of the Massachusetts Institute of Technology, in the summer of 1922, and by James Gilluly, of the United States Geological Survey, in September, 1928. The following publications have been of much value in furnishing a setting for the data obtained in the present investigation:

Hill, R. T., The geological history of the Isthmus of Panama and portions of Costa Rica: Harvard Coll. Mus. Comp. Zoology Bull., vol. 28, pp. 151–283, 1898.

Howe, Ernest, The geology of the Isthmus of Panama: Am. Jour. Sci., 4th ser., vol. 26, pp. 212–237, 1908.

MacDonald, D. F., Some engineering problems of the Panama Canal in their relation to geology and topography: U. S. Bur. Mines Bull. 86, 1915.

Vaughan, T. W., and others, Contributions to the geology and paleontology of the Canal Zone, Panama, and geologically related areas in Central America and the West Indies: U. S. Nat. Mus. Bull. 103, 1919.

GENERAL GEOLOGY

ROCKS

GENERAL SUCCESSION

The data on the rocks in and immediately adjacent to the proposed reservoir are presented below in tabular form, followed by brief descriptions of each with special reference to their engineering features. The different formations mapped have been tentatively correlated with those described by MacDonald[1] in the vicinity of the canal. As the purpose of the work did not require it and because of the impracticability of tracing beds for long distances through the jungle, paleontologic studies were not made, and field correlation between the formations in the reservoir site and those along the canal was not attempted. The descriptions of MacDonald and of Howe, in the publications above cited, indicate, with little likelihood of error, that the lowest sedimentary formation in the reservoir site corresponds to the Bohio conglomerate or formation and that the limestone near the middle of the section in the reservoir site corresponds to the Emperador limestone. The beds between these two in the reservoir site evidently correspond to the Cucuracha and Culebra formations of MacDonald, originally described together as the Culebra beds by Hill[2] and Howe.[3] As they were mapped as a unit in the work on the reservoir the older usage will be adopted in the present report. Lack of lithologic resemblance between the two formations above the Emperador limestone on the upper Rio Chagres and the Caimito and Gatun formations, which occupy similar stratigraphic positions near the canal, makes correlation doubtful, but for present purposes these two names will be used, with queries to indicate the uncertainty.

The formations are described in descending order—the order in which the engineers in charge are accustomed to think of the formations and which is followed in the preliminary reports by Terzaghi and Gilluly and in the present writers' report to the governor of the canal.

The distribution of the several formations is shown on the general geologic map (pl. 5) and in more detail near the dam sites on Plate 6. The structure is such that in a broad way the youngest formation, the Gatun (?), occupies an area in the vicinity of the dam site and is encircled by bands of successively older formations. This regular arrangement is interrupted in the vicinity of Quebrada

[1] MacDonald, D. F., The sedimentary formations of the Panama Canal Zone, with special reference to the stratigraphic relations of the fossiliferous beds: U. S. Nat. Mus. Bull. 103, pp. 525–545, 1919.

[2] Hill, R. T., op. cit., pp. 192–196.

[3] Howe, Ernest, op. cit., pp. 222–224.

Las Conchas, east of the dam site, by the absence of the Caimito (?) formation and Emperador limestone. This absence, however, results from irregularity in original deposition, possibly aided by erosion subsequent to the deposition of the Culebra formation. It is not due to faulting or other structural disturbance.

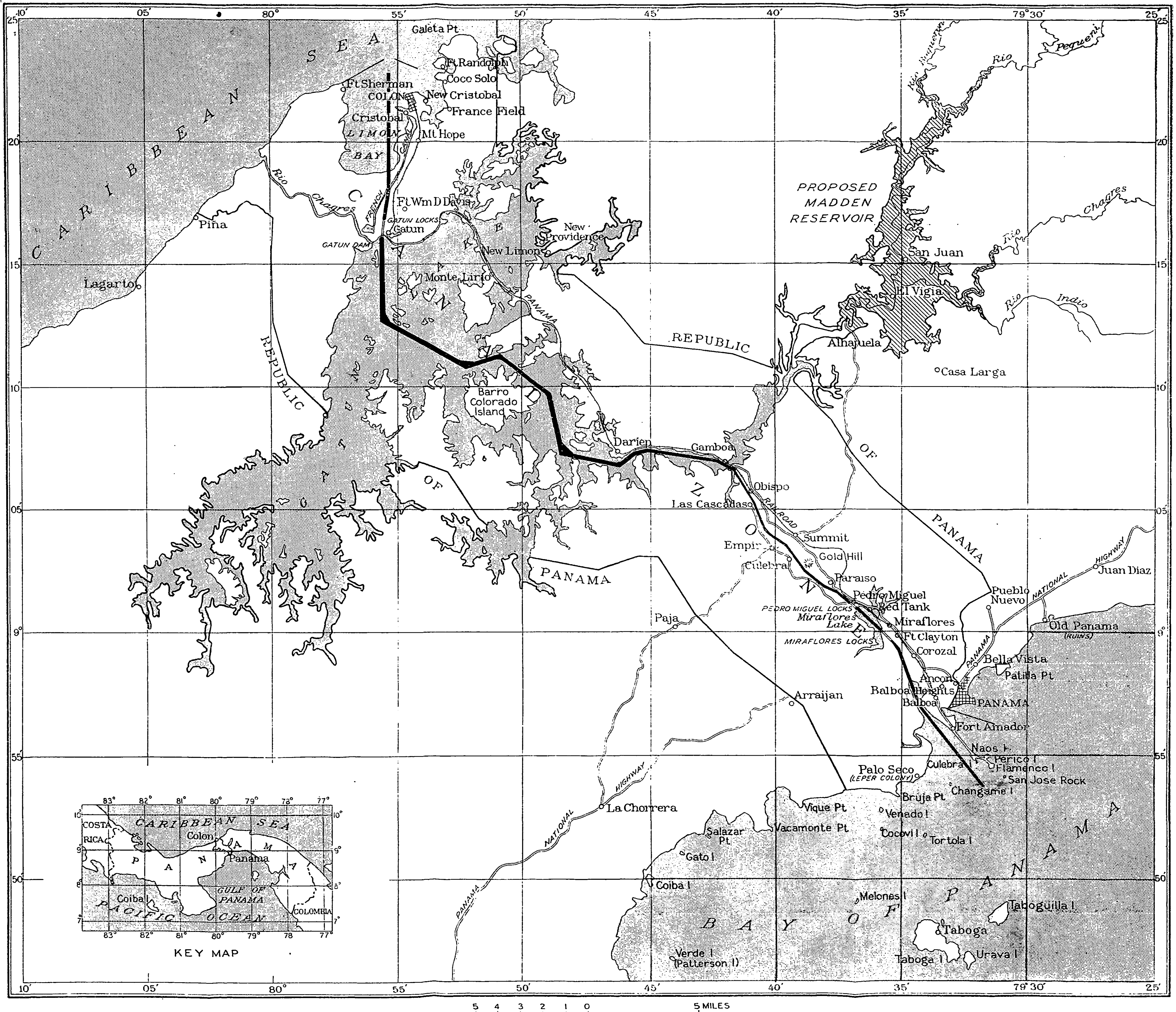
Rock formations in vicinity of Madden Dam project, Canal Zone

Name	Character	Thickness (feet)	Engineering features	Age [a]
Gatun (?) formation.	Bluish-gray fine-grained calcareous and tuffaceous sandstone with glauconite and fragments of igneous material.	250	Mechanically and chemically fairly strong and water-tight.	Miocene.
Caimito (?) formation.	Light-gray medium-grained, highly calcareous and tuffaceous sandstone with glauconite and fragments of igneous material.	65–70 at dam site; thins out eastward.	Nearly as strong mechanically but more permeable and soluble than the Gatun (?).	Do.
Emperador limestone.	Grayish-white and greenish-gray soluble limestone and marl and gray fossiliferous sandy limestone, with minor amounts of fragments of igneous material throughout.	100–107 at dam site; thins out eastward.	Mechanically weak and decidedly soluble.	Do.
Culebra formation.	Sandstone, grit, shale, and conglomerate. The conglomerate is in part calcareous, and all is tuffaceous. The shaly members contain much clay. The upper part of the formation is dominantly fine-grained dark sandstone and shale. The lower part is massive and coarse with numerous pebbles and boulders of volcanic rock.	350 (?) at dam site; may be thicker in places.	Upper part mechanically weak. Entire formation essentially water-tight.	Upper part Miocene(?); lower part Oligocene.
Bohio formation	Thick series of hard thin-bedded grayish-white fossiliferous soluble limestone, with some shale at top; clay shale, shaly sandstone, and thin limestone in lower part; and conglomerate of volcanic rocks at base. The shale is in part tuffaceous.	300–500	Limestone weak and highly soluble. Shale and sandstone mechanically weak but essentially water-tight.	Oligocene (?) and upper Eocene.
Volcanic complex.	Lava flows and volcanic breccias, cut by small intrusions of granitic, dioritic, and other rocks.	Several hundred.	Generally strong and water-tight, but some beds would be weak after exposure to air and water.	Eocene.

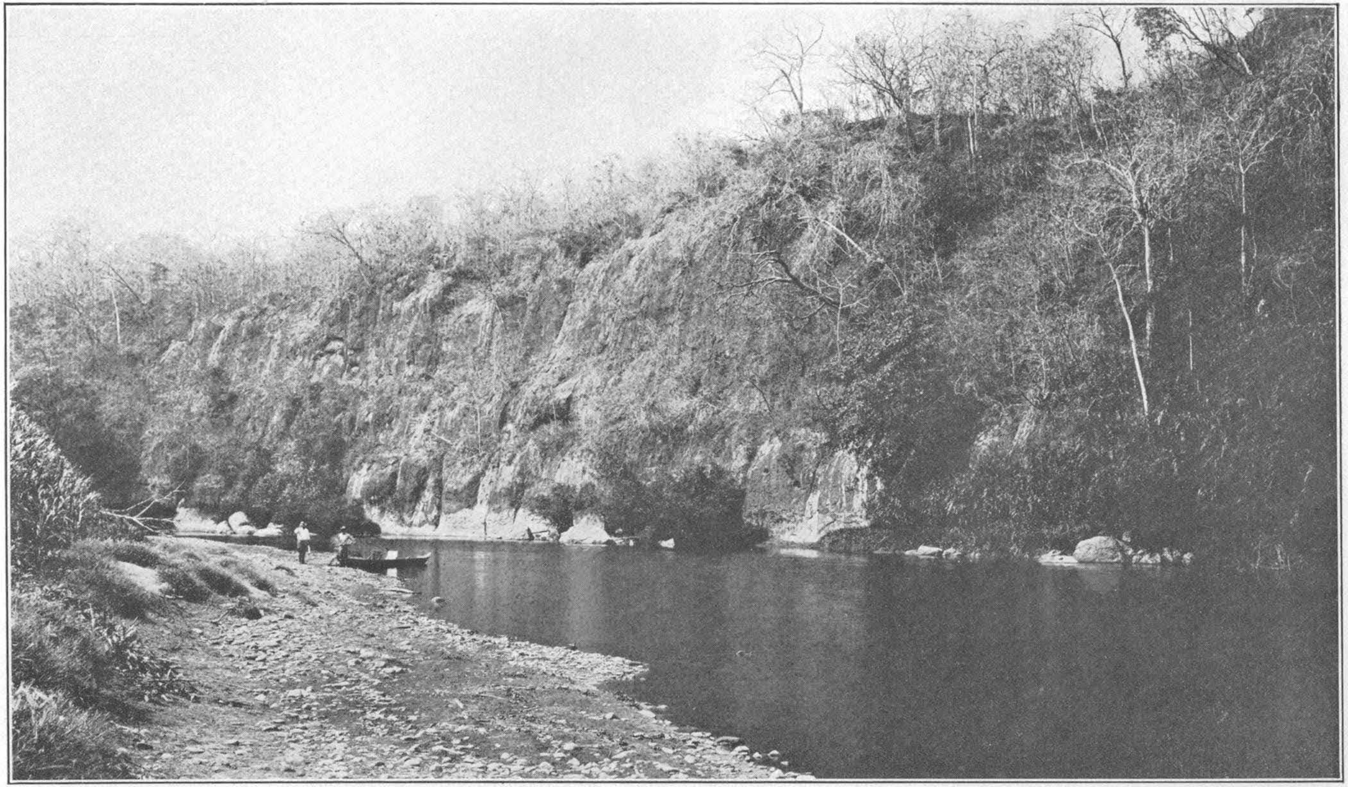
[a] Age modified in accordance with determinations by W. P. Woodring (Miocene mollusks from Bowden, Jamaica, pt. 2: Carnegie Inst. Washington Pub. 385, pp. 73–78, 1928) and T. W. Vaughan (The stratigraphic horizon of the beds containing *Lepidocyclina chaperi* in Haut Chagres, Panama: Nat. Acad. Sci. Proc., vol. 12, No. 8, pp. 519–522, 1926).

GATUN (?) FORMATION

The Gatun (?) formation is one of the best rocks, both mechanically and chemically, in the area. It will form the abutments of the proposed dam. The rock is light bluish gray at the surface but, like most of the other rocks in the sedimentary series, is darker at depth, mainly because of the presence of small amounts of organic matter. The rock is throughout a fine-grained calcareous and tuffaceous sandstone, of unusually uniform texture. Bedding

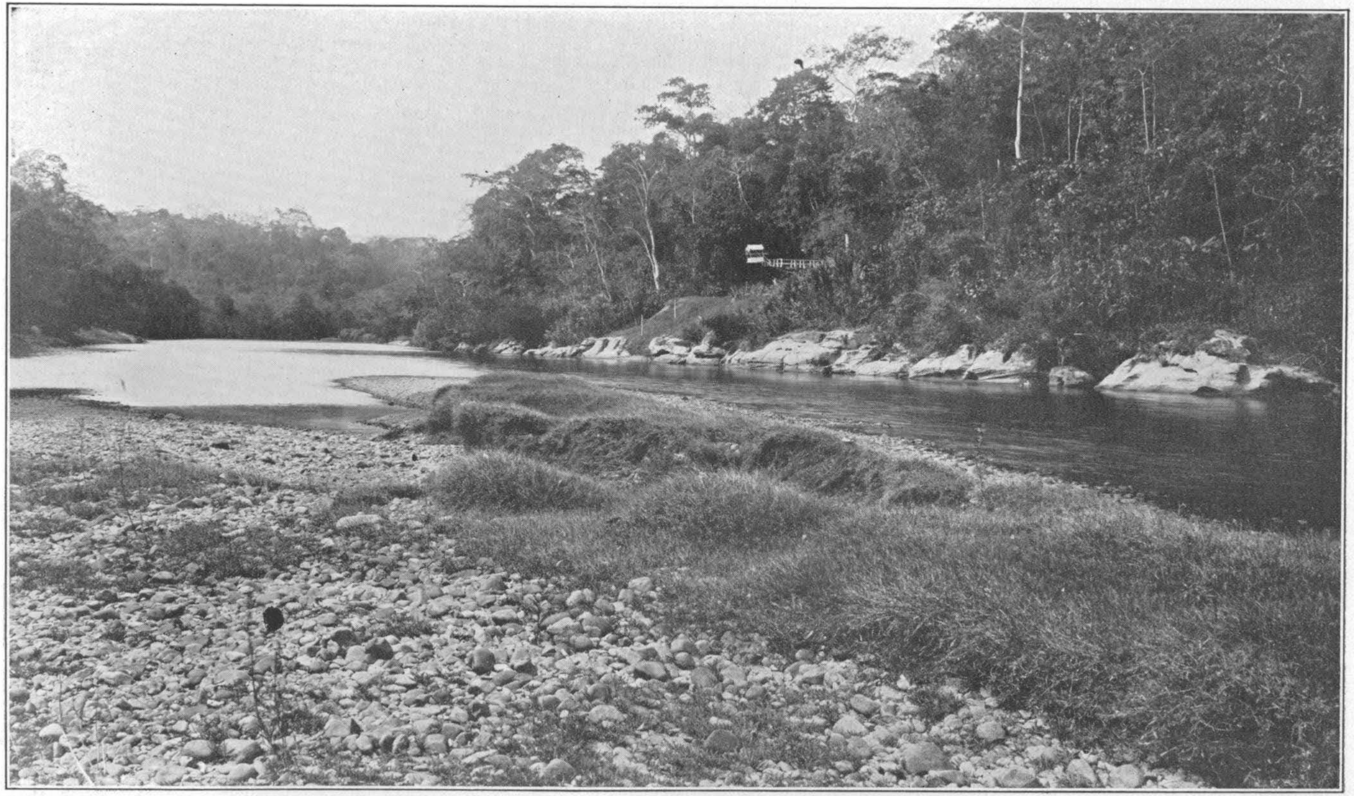


MAP OF THE CANAL ZONE, SHOWING POSITION OF THE PROPOSED MADDEN RESERVOIR



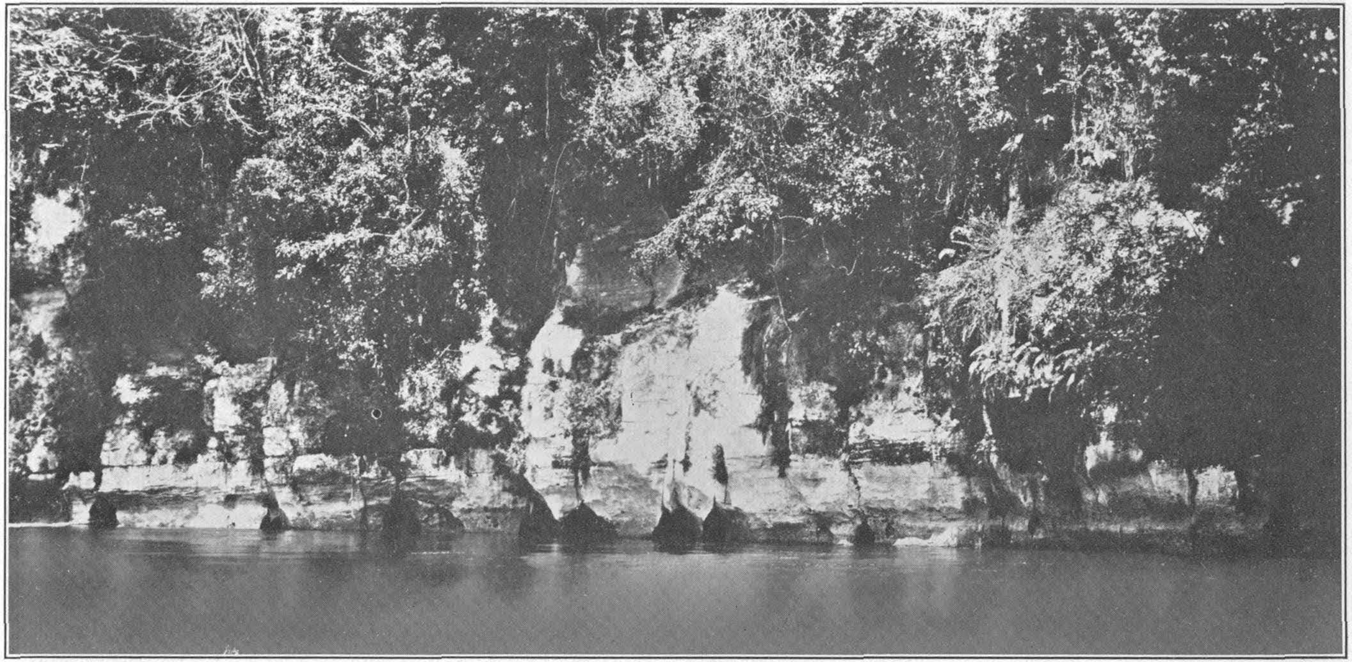
CLIFF ON THE NORTH SIDE OF THE DIKE RIDGE ABOVE DAM SITE 1

Shows massive Gatun (?) formation, with slight solution on joints.

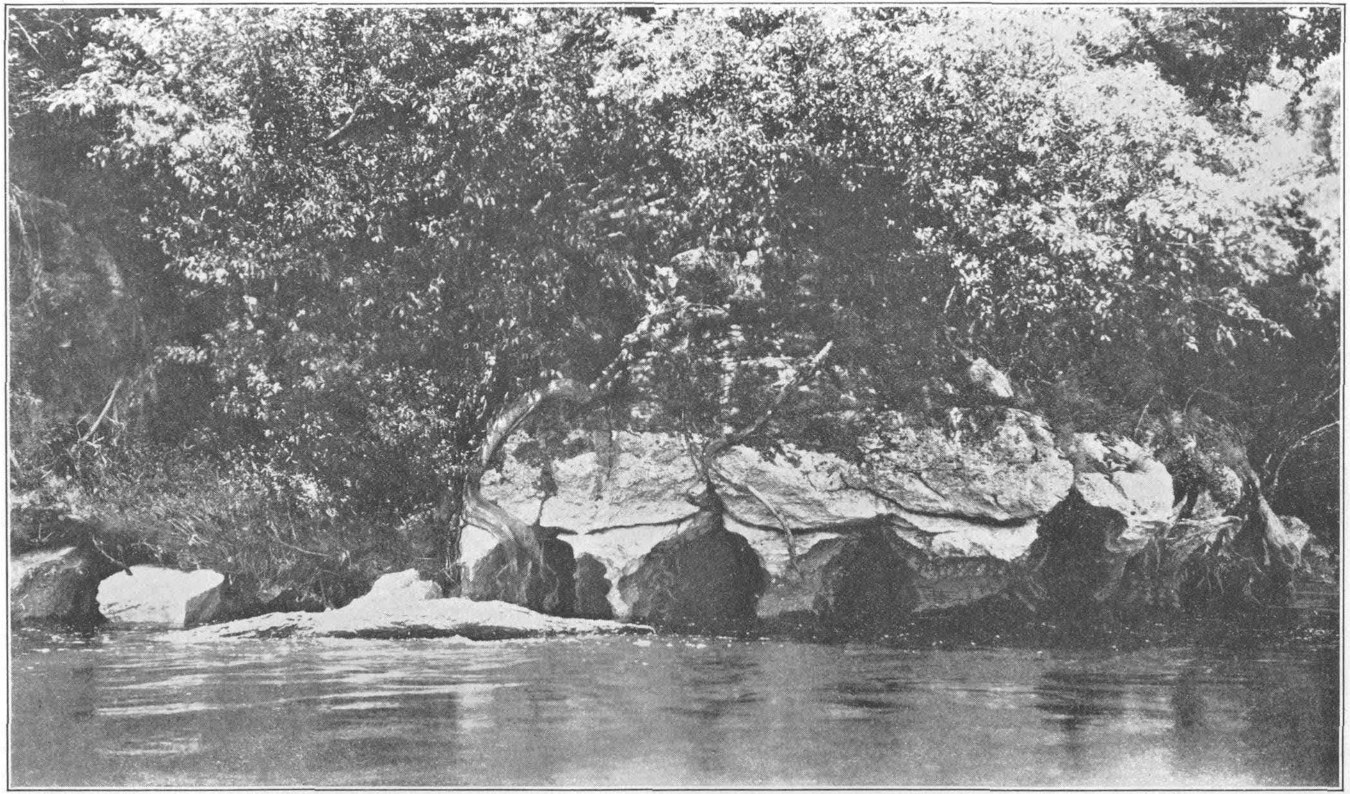


THE RIGHT BANK OF THE RIO CHAGRES, LOOKING DOWN THE CALLE LARGA STRETCH

Shows characteristics of the Caimito (?) formation—fairly distinct bedding and solution along joints.



CHARACTERISTIC EXPOSURE OF THE EMPERADOR LIMESTONE ON THE RIO CHAGRES NEAR THE THIRD TURN ABOVE THE UPPER END OF CALLE LARGA



CLOSER VIEW ON THE RIO CHAGRES AT THE SAME LOCALITY AS PLATE 8

Shows undercutting and solution on joints.

everywhere is only faintly marked or invisible, and nowhere are there notable partings along it. (See pl. 7.) The rock is jointed along lines approximating N. 5° E., N. 50° E., and N. 75° E.; the joint planes are nearly vertical. The N. 75° E. set is by far the most pronounced and persistent. The joints of this set are spaced from 1 foot to several feet apart and wherever exposed, on old weathered surfaces, are followed by indentations of the surface from a few inches to (rarely) a few feet deep, produced primarily by solution. Below these indentations the joints are essentially as water-tight as the rest of the rock, though constituting lines of potential weakness.

The test trenches at dam sites Nos. 1 and 5 indicate that weathering rarely extends to a depth of more than 5 feet. In a few places it penetrates several feet farther along slightly shaly beds. Weathering has also penetrated to depths of 10 feet or more along joints in favorable locations on the ridge tops, resulting in the loosening of boulder-like blocks, some of which are of considerable size. This accounts for the rounded forms visible in the trenches and in natural exposures, especially high on the right bank at dam site No. 5. Except that it may be necessary to remove or strengthen blocks thus loosened which happen to be in critical locations, this feature will not prove of much engineering importance.

CAIMITO (?) FORMATION

The Caimito (?) formation is coarser grained and more calcareous than the Gatun (?) formation but otherwise similar. Tests so far available indicate that mechanically the two are of roughly equal strength, but the Caimito (?) is distinctly more permeable and soluble than the Gatun (?), and as exposed on the ridge above the Quebrada Madronal it weathers more deeply. The bedding is more conspicuous than in the Gatun (?). There is also considerable cross-bedding, which will tend to hinder direct passage of water along the beds. Joints similar to those in the Gatun (?) formation exist, and those trending approximately N. 75° E. show distinctly greater solution. (See pls. 8, 10.)

EMPERADOR LIMESTONE

The Emperador consists principally of limestone, which is highly soluble under favorable conditions, as indicated by the marked corrosion in most outcrops, the grooving along joints in stream beds to depths as great as 5 feet or more, tufa deposits in stream beds, and the presence of numerous sink holes and caves. Those sections of the banks of the Rio Chagres which are composed of this formation show marked undercutting and deep solution along joints, but the openings rarely extend more than 10 feet into the bank. (See pl. 9.) All the sink holes of any consequence in the two ridges flanking the dam site are either in this formation at the surface or in the Caimito (?) at points where it is underlain by the Emperador at slight depths. The sink holes of the latter class are due principally to solution in the Emperador, although the outcrop is in the Caimito (?). The well-known caves[4] on a tributary of the Chilibrillo River and south of that stream are probably in the Emperador. In February, 1929, when visited by C. P. Ross, the Chilibrillo River a short distance above the mouth of the Concha was flowing below the surface for several hundred feet. The material which conceals the stream consists mainly of detached blocks of the Emperador limestone, apparently resulting from the collapse of a natural tunnel or bridge. In the rainy season water evidently flows over these blocks. This locality is close to the place where the caves occur.

The bedding planes in the Emperador are somewhat more distinct than those in the overlying rocks, but in places there is considerable cross-bedding. Artesian water may find passage through narrow beds more porous than those which have been examined, but it is probable that any artesian flows through this formation find their way along partings, either on the bedding planes or on joints.

CULEBRA FORMATION

The Culebra formation consists of sandstone, shale, grit, and conglomerate, all more or less calcareous, and in places soft chalky limestone, in part shaly. In general the finer and more shaly beds predominate in the upper part and grit and conglomerate in the lower part, but there is considerable variation in different locations. Unfortunately, there is a considerable proportion of the shaly and chalky beds on the Azote Caballo-Chilibrillo ridge. As shown both by surface exposures and by the core of diamond-drill hole No. 5, the saddle containing this drill hole is in such rock. This saddle is the lowest one on the rim of the reservoir (altitude 219.77 feet) and is directly attributable to the lack of resistance to erosion of the underlying rocks.

The rocks composing the Culebra formation are, in general, relatively water-tight. The more calcareous members, such as the conglomerate in the Azote Caballo River near the point where the trail crosses it and the similar rock that floors much of the Chilibrillo River, are probably a little more soluble than the Caimito (?) but by no means so soluble as the Emperador. The conglomerate and grit beds possess fairly high resistance both to compressive stresses

[4] Rogers, M. T., letter to C. M. Saville, May 1, 1929.

and to erosion. Even the shale is sufficiently compact to be mechanically fairly strong at depth, though it would tend to flow under pressure. Its composition is such, however, that it slacks, swells, and softens when exposed to the atmosphere and in this condition is mechanically weak. Heavy structures placed on it would tend to cause rock flowage and sliding. Water flowing over it would cut rapidly. Saturation of the material with water would tend to produce landslides, especially where the topography is steep. It should be noted that the Culebra formation of this locality corresponds in stratigraphic position and to a large extent in character of rock to the Cucuracha and Culebra formations, which produced slides along the canal.

BOHIO FORMATION

The Bohio formation as here mapped includes the limestone with *Lepidocyclina chaperi*,[5] which is of upper Eocene age and has not previously been recognized as the equivalent of the Bohio conglomerate. The Bohio formation is composed of two very different kinds of rocks. In most localities there is a thick series of hard thin-bedded fossiliferous limestone at its top, the rest of the formation consisting largely of soft shale and clay interbedded with lenses of similar limestone. In addition there is at the base a conglomerate consisting largely of volcanic boulders. Conglomerate beds so greatly predominate in the vicinity of the canal that the formation was termed Bohio conglomerate by MacDonald, but here such rock is subordinate.

The limestone, being comparatively pure, is very soluble. It forms the natural bridge and tunnel on the Puente River and the caves and sink holes near this stream and has resulted in the underground flow along parts of the Marcelito and neighboring streams. It is harder than the Emperador limestone and somewhat less corroded and channeled in surface exposures, but it dissolves with sufficient readiness to produce large amounts of tufa in suitably situated stream beds.

The shale, on the other hand, is relatively impervious but offers little resistance to erosion. It probably suffers somewhat less from exposure to the atmosphere than the shale beds in the Culebra formation, but nevertheless it is somewhat weakened by such exposure. The topography of the southeastern part of the ridge between the Azote Caballo and Chilibrillo Rivers bears eloquent testimony to the feeble resistance offered by the shale under attack by stream erosion. The part of the Bohio exposed on this ridge contains more shale and

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[5] Vaughan, T. W., The stratigraphic horizon of the beds containing *Lepidocyclina chaperi* in Haut Chagres, Panama: Nat. Acad. Sci. Proc., vol. 12, No. 8, pp. 519–522, 1926.

shaly sandstone and proportionately less limestone than in the valley of the Puente River.

VOLCANIC COMPLEX

The series of rocks here called the volcanic complex differs fundamentally from all the others described. It is dominantly of volcanic origin, although cut in places by intrusive rocks, and is generally referred to by local engineers as trap. Most of it is strong, both mechanically and chemically. It will resist the passage of water except where fractured, and it is not appreciably soluble. Certain parts of it, especially those colored green, will slack and soften on exposure to the atmosphere.

The rock is generally nearly black on the surface of natural outcrops, although on fresh fractures or in stream beds it shows purple, red, green, and other colors. In most of it bedding is indistinct or absent, although it can be discerned in some of the breccias and flows. The granitic and dioritic rocks that cut this member are, of course, not bedded. They have been forced in a molten state into the volcanic strata subsequent to the cooling of those strata. Such rock was noted in place only along the Rio Chagres above the mouth of the Indio River and at the head of the Azote Caballo River. Individual masses, so far as observed, are small and were not mapped separately. The contact between the Bohio formation and the volcanic complex has been crossed in several places but has not been traced in any detail. The distribution of the complex sketched on the general geologic map is based in part on interpretation of the topographic base map.

STRUCTURE

The sedimentary rocks underlying the reservoir area have been folded by earth stresses into a synclinal basin. This basin is broad and has gentle, undulating slopes in the topographic depression near old San Juan, the area where the greatest volume of the reservoir will be, narrows southward, and is deepest in the vicinity of the dam site. (See cross section C–C′, pl. 6.) The sharp ridges that border the reservoir on every hand reflect the fact that the sides of the structural basin underlying the reservoir tilt up at angles so steep as to bring to the surface the resistant limestone and conglomerate of the Culebra and Bohio formations and the harder volcanic rocks underlying them.

The most pronounced belt of tilted rock lies on the west side of the basin, east of the Quebrada Madronal. The steeply dipping strata of this belt are well exposed on the right bank of the Rio Chagres, a quarter of a mile below Alhajuela Camp. This belt extends southward, but the outcrops of the rocks are concealed beneath a cover of old river gravel appearing again at the surface in the ridge south of the Moja Polla. At the south end of this ridge they bend sharply to the northeast, where the dip rarely exceeds 10°. In this part of the area the continuity of exposure of the formations is interrupted by the absence for some 7,000 feet of the Caimito (?) formation and Emperador limestone. East of this area the strata are in general even more gently inclined. Locally the dip is to the east, but the average dip is northwestward. The effect is to bring the beds here lower than at any other place in the rim of the structural basin along the borders of the proposed reservoir. In a sense, the rim of the basin is in the high ridges near the head of the Chilibrillo River 3 or 4 miles southeast of the reservoir border.

Farther east the rocks are again tilted more sharply, bringing the rim of the structural basin closer to the reservoir site. On the ridge west of the head of the Azote Caballo River dips as high as 50° W. exist, and in places the headwater branches of the river expose igneous rock. Toward the north, near the Puente River, the hills are again somewhat farther away from the edge of the proposed reservoir, but the dips in the Bohio formation are consistently 20°–25° NW., toward the reservoir.

The ridges that encircle the reservoir site at varying distances everywhere except where cut through by the Rio Chagres above Gamboa are probably composed in large part of the hard igneous rock of the volcanic complex, although the Bohio rises well up on their flanks and in some localities mantles the ridges almost completely. For example, the ridges between the Limon and Gatuncillo Rivers and between the Gatuncillo and the Agua Sucia, in the pass followed by the tentative location of the proposed transisthmian road, are composed at the surface almost exclusively of the Bohio, although here and there this has been cut through, exposing the lava below. The Bohio in these ridges is composed predominantly of resistant limestone.

It is evident from Plates 5 and 6 that the axis of the structural basin trends approximately north. Throughout the area the master jointing in the sedimentary rocks is approximately at right angles to this axis. The average trend of the joints is about N. 75° E., although variations as great as 15° from this occur in places. The subsidiary joint systems are less regular and far less pronounced than this master system. Except as they tend to control weathering in a minor way, as already noted, they are negligible as matters of engineering concern. The major joints produce the grooving which is so notable a characteristic of many of the stream beds, and to some extent control the courses of minor streams. These joints, however, have no displacement along them. No evidence of the existence of faults was obtained anywhere in the area examined.

WATER TABLE

In accordance with the suggestion of James Gilluly in his report to Major Wheeler, a series of small diamond-drill holes were bored on the ridges adjacent to dam site No. 1, to determine the depth to ground water. This information was desired chiefly for the light

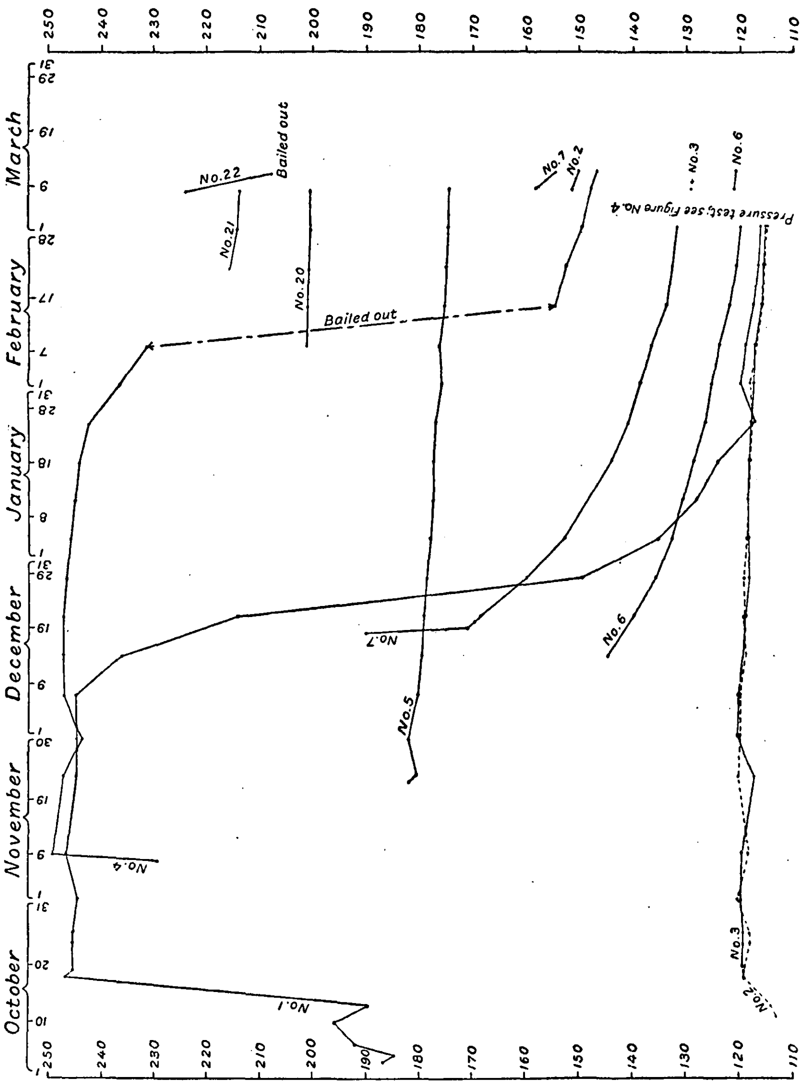


FIGURE 1.—Altitude of water table in drill holes on Madden Dam project, Canal Zone, from date of completion of holes to March 12, 1929

it would throw on the possibility of leakage through these ridges. Inasmuch as solution channels do not commonly form below ground-water level, a high-water table would be indicative of favorable conditions and a low-water table of unfavorable conditions. The results are given in graphic form in Figure 1. The data available, coupled with observations on springs, indicate that the dry-season water table on the Madronal ridge in holes 21 and 22 is above the 200-foot level, which in itself is indicative that sink holes and solution channels in this area do not extend to a very great depth.

The results of the measurements of the holes east of the dam site along the ridge herein called the dike ridge (see pl. 6) are somewhat variable. Holes 2, 3, 5, and 6 show a gradual and not very large drop in altitude of the water level from the time they were drilled, during the wet season, up to March 16, 1929. Although there was a slight continued fall in some of the holes throughout the period of dry weather, the water table on this date stood at essentially the ground-water level of the dry season. It appears that the water level in Nos. 1 and 7 when first measured was abnormally high, but it later became adjusted, and on March 16 the level was essentially that of the dry-season water table. Hole 4, for a considerable period, showed a disproportionately high water level as compared with neighboring holes. On February 14, 1929, it was bailed out to an altitude of 154.1 feet, 77 feet below its previous level. The next day it had recovered only 0.6 foot, and thereafter the level of the water fell regularly until the observation on February 23. The water in holes on the ridge east of the Quebrada Madronal when similarly bailed out came back promptly to approximately the former level. Apparently the former high water level in hole 4 was due to some abnormal condition—possibly, at least in part, to puddling

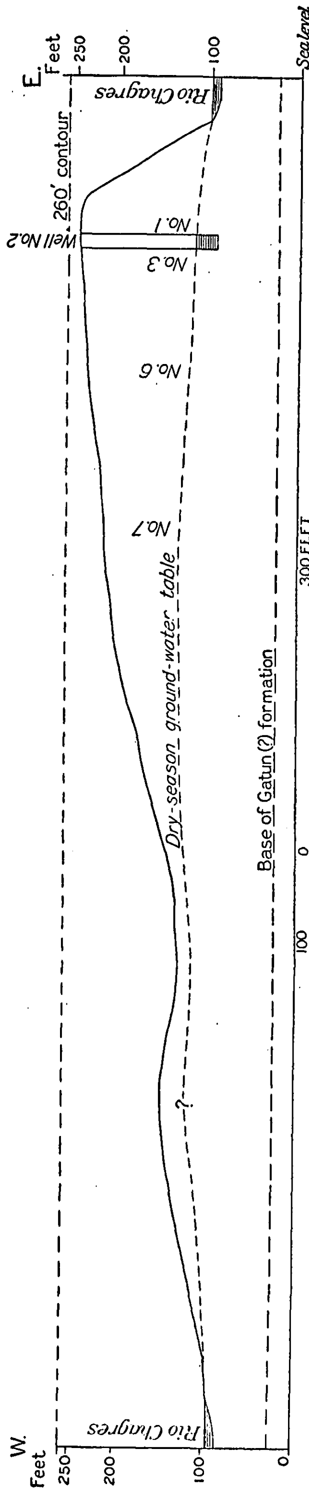
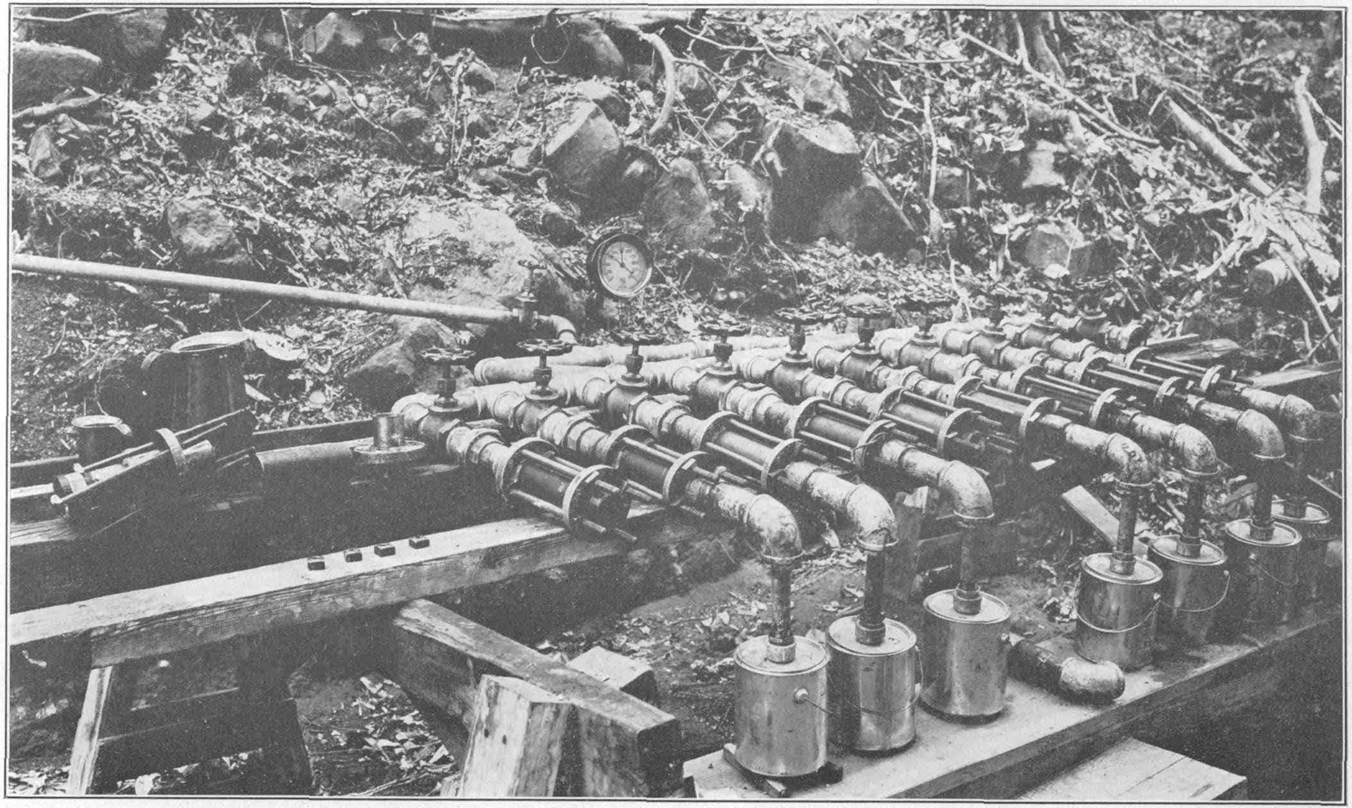


FIGURE 2.—Profile across dike ridge on Madden Dam project. Hole 2 is on the profile; other numbers show relative position of holes not on profile

when the hole was being drilled. Measurement of the water level in the holes on the dike ridge has been continued, and data on the results up to September 13, 1929, are now available. The behavior of the holes during the wet season of 1929 corresponds approximately to that in 1928 except that in the relatively long record of 1929 there are fluctuations not recorded in the season of 1928.

The low altitude of the dry-season water table in the holes along the dike ridge results from the proximity of the holes to the river bluff, which here has a sheer drop of 140 to 150 feet, and from the narrowness of the ridge. (See fig. 2.) An examination of the positions of these holes as shown in Plate 6 and in section in Figure 2 and of the water-table data in Figure 1 indicates that the height of the water table above the Rio Chagres in the holes is approximately proportional to their distance from the stream. This fact is brought out also in the subjoined table. The water table in holes 6 and 7 is relatively lower than in the others, presumably because the river surrounds these holes on three sides. The form of the water table in this ridge indicates that the rock below the dry-season water table is uniform in texture and that drainage into the river takes place slowly through the pores of the rocks rather than along joints or solution channels. However, the sharp departure in the wet season from dry-season conditions and the erratic behavior in detail in many of the holes, as illustrated by Figure 1 and by the subsequent data, indicate that the observations in many of the holes do not record the position of a water table, in the ordinary sense, but merely that of relatively small bodies of water lying well above the true water table. These holes were originally located largely for the purpose of testing the water-tightness of the numerous vertical joints that cut the rock of the dike ridge, and consequently they are on or close to such points. It appears that the water present in the holes is in large part water which has penetrated the ridge through the joints and perhaps in part directly through the holes, rather than by permeating the whole mass of the rock. On this conception, at times when high-water levels are observed in particular holes, unfractured ground at comparable altitudes may be essentially dry a short distance away from such holes on the joints which feed them. The rapid fluctuations recorded during the rainy season of 1929 indicate that relatively free passage of water takes place locally in the ridge, and this can be attributed only to the existence of openings along joints above the dry-season water table. The erratic behavior of some holes may result from variation in the ease with which water can find its way into passages along individual joints at different times. The pressure tests proved that a small amount of mud in the water introduced into the holes had a large influence on the rapidity with which the holes would take water. It may well be that variations



OUTFIT USED IN TESTS OF THE SOLUBILITY OF PIECES OF CORE FROM THE 2-INCH DIAMOND-DRILL HOLES NEAR DIAMOND-DRILL HOLE L-1

DIAMOND DRILL SINKING HOLE L-1 ON WEST SIDE OF DAM SITE 1

Pipe leads from tank above to solution-testing outfit hidden by bushes at right side of view. Pressure-testing outfit on hole L-2 in foreground.

in the distribution of soil and débris on the surface of the ground or of loose material in the joints would account for the erratic behavior noted.

The above discussion indicates that in places in the dike ridge above altitudes of 120 to 130 feet above sea level there are openings large enough to permit the passage of water, although the quantities involved under present conditions may be small. The principal danger suggested by such a condition is that some of the openings may be or become large enough to permit water to pass through them with sufficient velocity to erode and dissolve the rock and eventually to enlarge the opening greatly. If a dry specimen of the rock of the Gatun (?) formation is plunged into water a small amount of material immediately spalls off of it, illustrating its weakness under conditions of alternate wetting and drying such as would exist in the upper part of the ridge as a result of fluctuations in the level of the reservoir. It is believed that serious consideration should be given to the possibility of grouting the dike ridge to guard against the danger suggested.

Relation of height of water table in holes on the dike ridge to distance from Rio Chagres

Hole	Altitude of water table Feb. 23, 1929 (feet)	Altitude of Rio Chagres (feet)	Height of water table above Rio Chagres (feet)	Distance of hole from river (feet)	Ratio of height of water table to distance from river
1	116.8	96	20.8	154	0.135
2	115.8	96	19.8	125	.158
3	115.8	96	19.8	130	.152
4	152.9	96	56.9	485	.117
6	120.8	95	25.8	260	.099
7	132.9	95	37.9	425	.089

The water level in hole 5, situated in the lowest saddle along the ridge above the Azote Caballo at an altitude of 219.3 feet, is decidedly low. Measurements during March and April, 1929, show that it stands at 175 feet above sea level in the dry season and rises only a little above this in the wet season. It is clear, however, that this low water table is not representative of conditions along the ridge in general, for the altitude at which water stands at the surface in stream beds indicates that the average altitude of the water table along the axis of the ridge between the Azote Caballo and Chilibrillo Rivers is over 200 feet. In the part of the ridge between the Azote Caballo and the Calle Larga stretch of the Rio Chagres the water table is specially high. There is flowing water in small streams close to the Azote Caballo in this area at about 260 feet above sea level.

The opinion here expressed has been confirmed by the results of drilling six additional holes close to hole 5. One of these, located like hole 5 on the axis of the saddle, has a correspondingly low water level, but the water in the others, on the flanks of the saddle, stands at altitudes between 210 and 220 feet above sea level.

SOLUTION TESTS

In an attempt to get some quantitative idea as to the permeability and solubility of the rocks of the reservoir area, pieces of core 5 inches long from the 2-inch diamond-drill hole L-2 were tamped into pieces of pipe with lead wool and steam packing and subjected at one end to the pressure of water led in a pipe down a cliff from a tank at such a height as to give a hydrostatic head of 184 feet, or a pressure of 80 pounds to the square inch. An idea of the layout for this test may be obtained from Plate 11.

The first five cores tested were placed in the pipes unbroken. They comprised one specimen each of the Gatun (?), Caimito (?), and Culebra formations and two of the Emperador limestone. The specimen of the Culebra was the rather fine calcareous sandstone encountered near the top of the formation. Both this and the specimen of the Gatun (?) proved almost impervious, no water appearing through the cores during the 16 days for which the tests were continued. The specimens of Emperador limestone, cores 3 and 4, were only slightly permeable, yielding daily but 5 to 10 milliliters of water each. The specimen of the Caimito (?), core 2, was the most permeable, yielding from 45 to 125 milliliters of water daily. Additional tests were made with specimens of the Gatun (?) and Emperador, cores 6 and 8, which were split longitudinally, and of cores of the Caimito (?) and Emperador, cores 7 and 9, which after being split had a groove cut with a hacksaw in the fractured surfaces. (See fig. 3.) Another test was made with a core of the Emperador, core 10, that had a much larger groove cut through its center. Water passed through the prepared cores rather freely, especially through No. 10. The flow from cores 2, 3, 4, 6, 7, 8, and 9 was caught in gallon vessels with closed tops, and the total flow was measured about once a day. The flow from No. 10, being large, was gaged with a stop watch once daily. Because of its large volume of flow, water was turned on this core only during periods when an observer was available to make certain that the small tank feeding the water to the cores was not emptied. During these periods it showed a uniform flow of approximately 4 gallons a minute. The data obtained from the other tests of cores 2, 3, 4, 6, 7, 8, and 9 are presented graphically in Figure 3. This graph shows (1) that the rate of flow was rather uniform through cores 2, 3, and 4, in which the flow was through the pores of the rocks; (2) that there was a slight decrease through core 6; and (3) that through cores 7, 8, and 9 the rate of flow decreased rapidly during the first four days of the test, increased for a few days, and decreased uniformly during the remainder of the test.

The cause of the fluctuation in flow through cores 7, 8, and 9 is not known, nor can any definite explanation be given for the de-

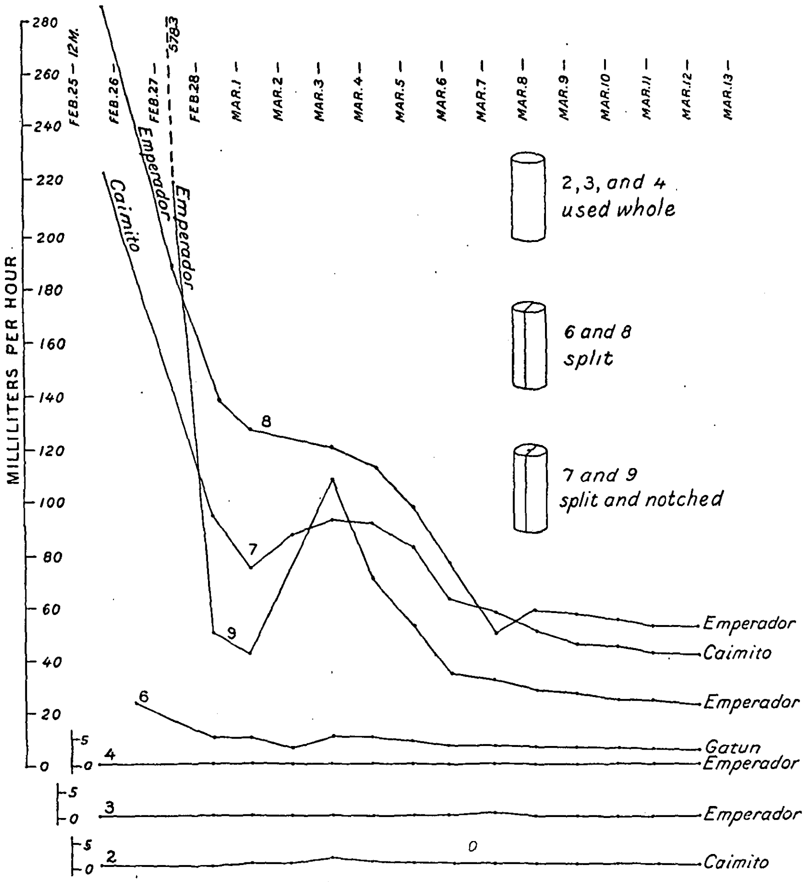


FIGURE 3.—Results of solution tests on cores of rocks of Madden Dam project

crease in flow through cores 6, 7, 8, and 9 throughout the period of the test. Polished sections of the cores showed evidence of solution that was decreasingly active through the cores from the intake end. It is possible that this decrease was due in part to chemical precipitation of calcite dissolved out of the cores at the end of high pressure and deposited toward the end of low pressure.

Although it is not possible in such a test to duplicate all the conditions that exist in nature, the tests indicate definitely that all the rocks where unbroken by joints or other fissures are reasonably impervious to water. This is especially true for the Gatun (?) formation, in which the dam will be built. The tests on specimens with artificially created openings also seem encouraging, for they at least suggest that small openings in the reservoir rock will not be widened by solution. Larger openings, however, will undoubtedly be widened both by corrasion and by chemical solution.

PRESSURE TESTS

Five wells were tested by pumping water into them under pressure. These are, in the order in which the tests were made, large drill hole L-2 and small drill holes 7, 2, 1, and 3. The pressure test on hole L-2 was undertaken to determine whether the slight artesian flow of 1.2 gallons a minute of water that was encountered in the top of the Emperador limestone in this well had an outlet where the Emperador comes to the surface along the Rio Chagres near the mouth of the Quebrada Madronal. Several gallons of water colored with fluorescein dye was poured into the hole, after which a volume of 664 cubic feet of water was forced into the hole under a pressure varying from 42 to 105 pounds to the square inch. No evidence of the dye appeared at the outcrop of the Emperador limestone, either along the Chagres or in the Madronal bluffs. Furthermore, the high pressures on the hole did not affect the pressure gage on hole L-3, 800 feet down the river, which encountered a flow of water at about the same depth as hole L-2. After the pressure test was discontinued in hole L-2, it immediately resumed both its normal flow of 1.2 gallons a minute and its closed pressure of 13 pounds to the square inch. The conclusion reached as a result of the test was that the flow encountered in hole L-2 is due to slight seepages into the well from the Emperador limestone and possibly the Caimito (?) formation, rather than to a flow from one restricted permeable bed. Whether this conclusion is valid or not, it is evident that the rocks furnishing the flow are too tight to transmit pressures more than a few hundred feet. This makes the possibility of artesian leakage from the reservoir through the Caimito (?) and Emperador formations appear unimportant.

The pressure tests on drill holes 7, 2, 1, and 3 were initiated to determine to what extent, if any, water will leak through the dike ridge along joints and solution channels. (See fig. 4.) The amount of water forced into these holes was as follows: No. 7, 1,413 cubic feet; No. 2, 3,702 cubic feet; No. 1, 3,362 cubic feet; No. 3, 1,221 cubic feet. The pressure gage while the water was forced into the holes read from 0 to 50 pounds to the square inch; the rate of intake ranged from 1 to 4 cubic feet a minute. Although the amount of water that could be forced into the wells with the apparatus available was probably insufficient to form a basis for definite conclusions, it appears improbable that the ridge will leak water to any great extent, for only three slight seepages, aggregating about 2 gallons

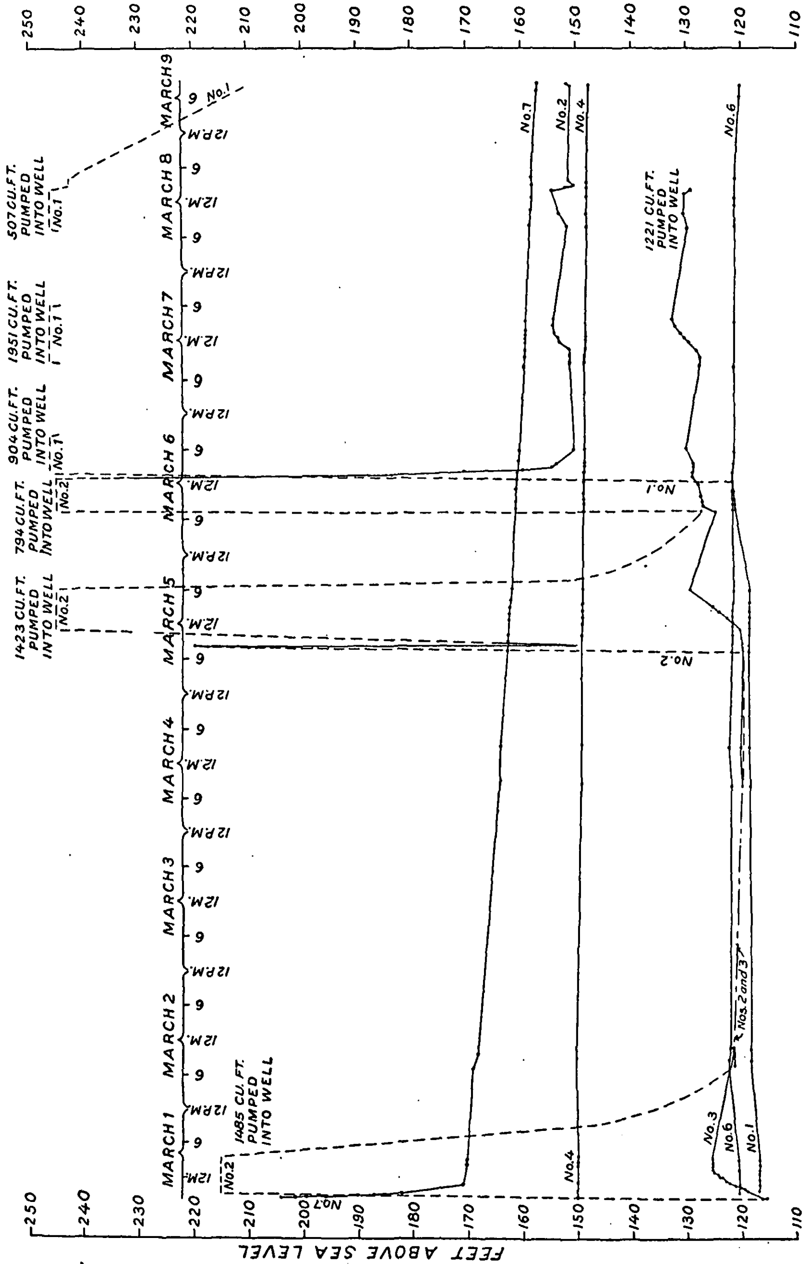


FIGURE 4.—Water table in wells on dike ridge during period of pressure tests on wells 1, 2, 3, and 7, Madden Dam project

a minute, occurred in the river bluff during the pressure tests, and these appeared only in joints that showed visible signs of being widened by former seepages. Along most of the joints, which had all the appearances of being water-tight, no seepage occurred, and there is little reason to expect that they will furnish channels for the escape of water from the reservoir. The channels already opened undoubtedly lie above the dry-season ground-water table and probably extend upward to the top of the ridge rather than across it. These conclusions are based on the fact that the height of the water table in the different holes is proportional to their distance from the river. (See p. 22.) If free movement of water took place along joints there would be no such relation. In any event, slight seepages of water through the ridge after the reservoir is filled will probably be stopped by the silt carried with the water. Some information on this possibility was obtained in the pressure tests by the introduction of muddy water in holes 1, 2, and 3. In hole 1, 15 gallons of muddy water stopped the flow of water entirely, although a pressure of 50 pounds to the square inch was kept on the hole for five hours after the muddy water was put in it. About 120 gallons of muddy water was forced into each of holes 2 and 3, with the result that the rate at which the holes took water was decreased 30 and 60 per cent, respectively.

PROBLEMS

The problems arising in the geologic study of the Madden project are considered below in the approximate order of their importance.

LOCATION OF THE DAM

At the time Mr. Gilluly made his examination four possible dam sites were under consideration, all along the Rio Chagres within a relatively short distance of one another. Mr. Gilluly concluded that of these four, site 1 was decidedly the best with reference to geologic conditions. The results of the present investigation are entirely in accord with this conclusion. In the course of the study these four and other sites were given consideration, but it is clear that a location at or close to site 1 is the best for a reservoir in the position contemplated, mainly because dams built anywhere in the gorge above site 1 must rest largely on the relatively soluble Caimito(?) or Emperador formations. The disadvantages of all other possible locations outweigh their advantages.

After Mr. Gilluly's visit a modification of the position of the dam at site 1 was proposed by Mr. W. W. Schlecht, a construction engineer. This consists in swinging the center line of the dam downstream so that it forms an angle of 66° with the center line at site 1, the end of the line on the left side of the Chagres remaining as before. This modification is known as site 5. The relative advantages of sites 1 and 5 are discussed below.

In accordance with the classification of the cores here adopted, hole L–3 of dam site 5 enters the Caimito (?) formation at a depth of 17.4 feet below that at which this rock is entered in holes L–1 and L–2 of dam site 1, as is shown in Figure 5. In other words, the Gatun (?) formation extends 17.4 feet deeper at site 5. As the Gatun (?) is a better rock for dam foundations than the Caimito (?), this difference would be in favor of site 5 except for the fact that bedrock in the Gatun (?) at site 1 lies shallower than at site 5.

At the northwest side of dam site 5 weathering along joints has produced rounded forms and in places has gone far enough to form detached, boulder-like masses. Similar weathering has occurred in other places, but it is more pronounced here than elsewhere in the two dam sites. These masses are not transported stream boulders, and the effect of the weathering that caused them would in most places be imperceptible at a depth of 10 feet. This feature does not constitute a disadvantage of any consequence.

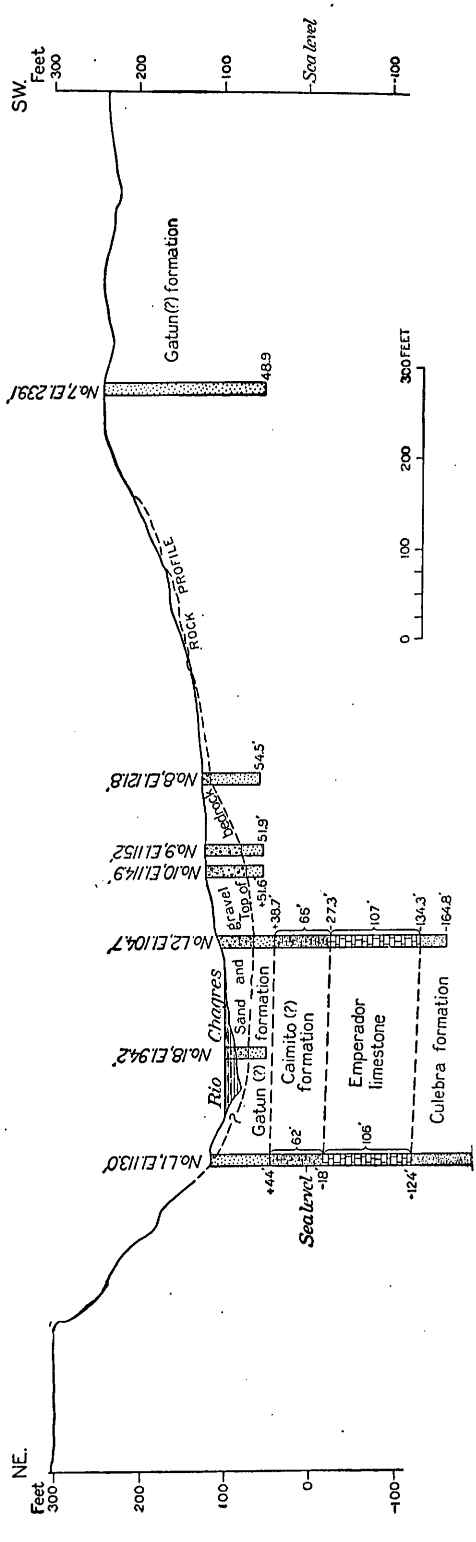


FIGURE 5.—Profile of dam site 1, Madden Dam project, showing bedrock profile and diamond-drill holes

3074°—31——3

Construction of the dam on site 1 would necessitate building a saddle dam to close the gap between the hill on which its north end would rest and the main ridge. This saddle dam would be necessary if the dam were constructed on site 5. Unless it should be desired to utilize the saddle for a spillway, this constitutes a distinct advantage in favor of site 5.

The set of major joints that cut the rocks with an average trend of N. 75° E. constitute possible channels for solution and possible sources of mechanical weakness. Both tests and inspection indicate that these joints are not sufficiently open to give ready passage to water, although some increase in seepage through them might take place under sufficient hydrostatic pressure. In so far as the solution tests (see pp. 24–26) are comparable to natural conditions they indicate that such leakage will be stopped by chemical precipitation or by silting. No evidence of mechanical weakness along the joints has been observed. It would be of advantage, both for mechanical strength and to impede possible leakage, to put the dam in such a position that it would be as nearly as possible parallel to the average trend of the joints. Site 1 forms an angle of 48° with this trend, and site 5 an angle of 66°. The difference is not sufficient to constitute an argument in favor of either location.

The above discussion shows that so far as geologic conditions are concerned, there is little to choose between the two sites. The final decision depends mainly on cost and convenience of construction. From geologic considerations it would be best to eliminate all possible saddles, thus favoring site 5, but engineering considerations may outweigh this advantage.

RESERVOIR LEAKAGE

The possibility of leakage from the reservoir presents difficult and vital problems with respect to the ultimate success of the project. It is almost a foregone conclusion that rocks of the general type which exist in the area—that is, young sedimentary strata, largely calcareous—will be subject to leakage. It is necessary to determine as closely as possible the extent and effect of the leakage.

The geologic and topographic situation of the reservoir site—a structural and topographic basin, rimmed on all sides by high ridges of resistant and relatively impermeable rock and breached only by the Rio Chagres above Gamboa—makes it possible to predict with confidence that whatever water leaks out will eventually find its way into Gatun Lake, where it is desired. To this extent the disadvantage of leakage is minimized. One possibly serious disadvantage remains—namely, that leakage may increase in time to such an extent that it will produce a breach either in the dam foundation or in some part of the ridges close to the dam, with consequent catastrophic results. The possibility of such a breach is the only thing that would seem sufficiently serious to warrant condemnation of the project, for in view of the need for the reservoir and the lack of other suitable locations, even considerable uncontrolled leakage into Gatun Lake would be preferable to no reservoir.

It is believed that with proper precautions in construction a dam which will be safe from danger of breach can be built at either site 1 or site 5. These precautions are set forth on pages 40–42.

Leakage through the boundary ridges, apart from actual rupture, can take place in three ways—(1) by seepage through pores of rocks that lie above the dry-season ground-water table; (2) by leakage along relatively large openings, such as joint planes or other partings enlarged and extended by solution; (3) by artesian circulation.

LEAKAGE THROUGH PORES

The character of the rocks and the results of the tests on permeability indicate that passage of water through the pores will everywhere be slow. In the shaly beds it will be negligible, and in unweathered portions of the Gatun (?) formation and the upper half of the Culebra formation it will be essentially negligible. Such leakage as does take place in this manner will be decreased through partial sealing of the pores by the silt that will settle out of the water impounded in the reservoir and possibly by chemical precipitation. In spite of this, some leakage through pores may persist, but it is not likely to be sufficient to be of any serious consequence.

LEAKAGE ALONG OPENINGS

Passage of water through open channels along joints or other crevices will obviously be far more rapid than that through pores. It will not be so readily checked by natural processes, and if allowed to persist it will tend constantly to increase as a result of additional solution.

Joints cut all the rocks, but in the Gatun (?) and Caimito (?) formations, especially the Gatun (?), openings along them are small or absent above the present dry-season water table, and probably nonexistent below that level. Both the Emperador limestone and the limestone of the Bohio formation contain openings of considerable size in some places. It is not known whether any such openings persist below the present dry-season water table, but they probably do not. Most of the Culebra, all of the volcanic complex, and the shaly and sandy parts of the Bohio contain no subsurface openings of consequence. Therefore, leakage of this type need be guarded against only where the Caimito(?) and Emperador and the calcareous parts of the Bohio form the retaining walls of the reservoir between the flow line and the dry-season water table.

Fortunately the greater part of the Bohio formation can be eliminated from consideration in the present connection, because the beds dip toward the reservoir and are underlain by the impermeable volcanic rocks. The channels, caves, and other openings known to exist in the valley of the Puente River and similar openings elsewhere will undoubtedly become filled with water, but the principal effect of this will be to increase somewhat the effective storage capacity of the reservoir. Incidentally the artificial raising of the water table may increase the fertility of the sabanas at and near Casa Larga.

The only place where the Bohio formation could cause direct leakage or possible breach of the reservoir is where it forms part of the ridge south of the Azote Caballo River near the head of the river. As Plate 4 shows, the Bohio crosses this ridge in a band over 6,000 feet wide. Limestone crops out here, but it appears that shale and shaly sandstone make up a large part of the Bohio on this ridge. If the limestone is lenticular it would not furnish a continuous passageway for escaping water. This point could be positively determined only by a very extensive campaign of drilling. However, it is certain that shaly beds are abundant and will restrict the leakage and that the prevailing westward dip would tend to carry the water downward and in the general direction of the dam, rather than across the ridge. Under these circumstances it is to be expected that some water will escape into the Chilibrillo River across the part of the ridge composed of the Bohio formation, but it is improbable that leakage will be sufficiently rapid and vigorous to cause collapse and breach of the ridge by the water of the reservoir.

The Emperador limestone crosses the boundary ridges on both sides of the proposed dam, and the Culebra (?) also crosses the Madronal Ridge. In the ridge east of the Madronal the rocks are tilted up sharply, so that they dip toward the reservoir. The sink holes in this area permit water to drain down the dip of the rocks—that is, toward the southeast—but there is no outlet through the ridge to its Madronal side. The structural conditions across the ridge are shown in sections A–A′ and B–B′ of Plate 6. For most of the extent of the ridge there is no opportunity for leakage across it, because the base of the Emperador limestone at the outcrop in the Madronal bluff lies above the 260-foot contour, the flow line of the proposed reservoir, and the fine-grained impermeable sandstone of the Culebra beneath the Emperador will not permit leakage. (See section A–A′, pl. 6.) These conditions hold for the ridge from its northeast end, east of the head of the Quebrada Madronal, to a point about 100 feet south of drill hole 21. Thence southward to and beyond the Chagres the base of the Emperador limestone at its outcrop lies below the 260-foot contour. The structure in this part of the ridge is shown in section B–B′ of Plate 6. In this area, therefore, there is possibility of leakage out of the top of the reservoir if the flow line stands at the 260-foot level. If the dam is so built that the water does not rise above the 240-foot contour the retaining rock will have a thin blanket of the impermeable Gatun (?) formation, and there will probably be no leakage. If water should seep through at this level it probably could be stopped by puddling or grouting. If leakage can not be stopped by such methods and becomes serious, an earthen dike could be thrown across the gap between the two hills at the position marked X–X′ on Plate 6.

On the ridge east of the proposed dam the Emperador limestone is more gently inclined and close to the reservoir dips downstream. Sink holes are smaller and less numerous, mainly because of the less rugged topography, but it is clear that openings of appreciable size exist in the limestone. However, the outcrop of the formation on the reservoir side is everywhere above the 260-foot contour except in the immediate vicinity of the Rio Chagres. Water will enter the limestone at that place and will percolate into it elsewhere through the underlying beds. Both these things will contribute to loss by leakage, but neither is likely to produce such rapid flow as to endanger the permanence of the ridge. The breadth of the ridge where crossed by the soluble limestone is so great as to make breach highly improbable.

LEAKAGE BY ARTESIAN CIRCULATION

Artesian flows were encountered in diamond-drill holes L–2 and L–3 at depths of 156 and 185 feet respectively. The rate of flow, however, which was only about 1 gallon a minute from each hole, was so small as to be negligible with reference to reservoir leakage. If there is any artesian flow in hole L–1, which was still being drilled when this investigation terminated, it escapes into the walls and does not reach the collar of the hole, even though the drill penetrated considerably below the horizon at which the flow in holes L–2 and L–3 was encountered. If artesian circulation exists in appreciable amounts in any of the sedimentary formations at greater depth or in other locations than those tested by these drill holes, the geologic structure would cause it to appear in springs where the formation comes to the surface along the Chagres River a quarter of a mile below Alhajuela. Yet with the exception of slight seepages that issue from the Caimito (?) formation and are undoubtedly not of artesian origin, no springs occur in this locality.

The data above presented show that although artesian circulation must be included in possible sources of leakage from the reservoir, the amount of such leakage is not likely to be large. Like the leakage from all other causes, any leakage which does take place will not be able to escape from the drainage basin of the Rio Chagres anywhere except into Gatun Lake. There is no probability of artesian flow resulting in dangerous weakening of the foundations of the dam or any part of the ridges on either side.

DAM FOUNDATIONS

At either site 1 or site 5 the abutments of the dam will rest on the Gatun (?) formation and the base will, if carried much below the bedrock surface, rest on the Caimito (?) formation. Both are firm, fairly massive rocks, of nearly equal mechanical strength, but in all respects the Gatun (?) is somewhat superior to the Caimito (?). The rock exposures at site 1 are shown in Figure 5.

A sample from the Gatun (?) formation tested by the United States Bureau of Standards was found to have a compressive strength of 3,500 pounds to the square inch when dry and 850 pounds to the square inch when wet, and a similarly tested sample of the Caimito (?) formation showed a compressive strength of 2,300 pounds to the square inch when dry and of 550 pounds to the square inch when wet. The marked decrease in the strength of the rocks when wet led to further petrographic examination by C. S. Ross and C. P. Ross in order to determine as far as possible the reason for the weakness. The principal new fact brought out by this examination is the presence of a clay mineral, which occurs mainly as films coating many of the feldspar and other grains. The films are so thin as to have escaped detection in the various previous examinations, but they are so situated as to greatly weaken the bond between the grains. Undoubtedly the presence of clay in such positions is one of the principal reasons for the weakness of the rock when wet. The abundant glauconite, which resembles clay in some of its properties, also contributes to the weakness.

As the rock forming the abutments of the dam will be saturated with water when the reservoir is full it is the strength when wet rather than dry which must be considered in the design of the dam. There is no reason to anticipate any material inequality in the behavior under load anywhere along the line at either site. It is believed that the difficulty introduced by the comparative weakness of the foundation rocks when wet can be met by suitable design.

The Caimito (?) formation is far more permeable and soluble than the Gatun (?), and this must be taken into account in the design of the dam. If solution channels should form in the Caimito (?) under the base of the dam, they might so weaken the formation as to imperil the whole structure in the course of time. But in view of the fact that the Caimito (?) in the bed of the river at the dam site and for half a mile up the river is blanketed with several feet of the relatively impermeable Gatun (?) formation, no serious leakage under the dam foundation through the Caimito (?) formation is anticipated. Such leakage as may tend to occur will probably be stopped naturally by silting and chemical precipitation.

SADDLES

According to the original survey, there would be six saddles, if dam site 5 is chosen, or seven, if site 1 is chosen, that would be below an altitude of 260 feet above sea level, the proposed height of the dam. In addition, at either site there is the dike ridge, which for a distance of 3,000 feet is mainly below this altitude. A traverse of the crest of the ridge between the Azote Caballo and Chilibrillo Rivers made in connection with the geologic study here described indicates the existence of four additional saddles which are close to or below the 260-foot contour. One of these low places is over 400 feet long, measured on the line of traverse. Later, more complete topographic surveys prove the existence of a total of 16 saddles. These surveys were made too late for the results to be incorporated in the maps accompanying the present paper.

The approximate situation is shown in Plate 13, which is a profile drawn along the crest of the ridge above the Quebrada Madronal, across the Rio Chagres at dam site 5, along the dike ridge, and thence along the crest of the ridge above the Azote Caballo River. (See line A–B, pl. 5.) A stretch of some 1,600 feet on this profile is left blank for lack of accurate data, but the ground in this stretch is all above the proposed height of the dam. The ground along the entire periphery of the proposed reservoir not included in this profile, with the possible exception of a few hundred feet southeast of monument 19, at its east end, is so far above an altitude of 260 feet as to be eliminated from consideration in the present connection.

All the low places shown on the profile are sources of potential danger, and each must be given careful individual attention. The low ground close to the Rio Chagres records erosion by that powerful stream in an early stage of its history and does not necessarily indicate weakness in the underlying rocks. The other low places, however, result from sapping by minor streams, whose courses are, in large part, controlled by the structure and relative resistance to erosion of the underlying rocks. Hence each saddle records weakness in the rocks in and near it.

The low places on the ridge above the Quebrada Madronal are in the comparatively resistant rocks of the Gatun (?) or Caimito (?) formation at the surface, which should make it possible to anchor saddle dams effectively in the gaps without special difficulty. None of these rocks, however, are highly indurated, and all are calcareous. If it should be planned to spill water through any of the saddles on this side of the dam these facts must be borne in mind and adequate measures taken to prevent or retard erosion.

The rock of the dike ridge is the Gatun (?) formation. Except that it is cut by numerous joints nearly at right angles to the ridge this rock is firm and resistant and in all tests made on it has proved comparatively impermeable. It may be necessary to excavate 10 feet or somewhat more in places to get below gaping joints and weathered rocks, but the construction of a dike here should offer no special difficulties.

On the ridge above the Azote Caballo River, southeast of the broad spur followed by the telephone line, the situation is more serious. This ridge is composed of the Emperador limestone, which is soluble and already much channeled; the Culebra formation, with its weak shale beds; and the Bohio formation, which contains both shale and soluble limestone. Some parts of the ridge near its crest are extremely narrow. The tendency for the rocks to weaken when exposed to air and water must be remembered. Little confidence should be placed in the resistance to pressure of narrow parts of the ridge crest, and care should be taken that provision is made for abundant height of either a natural or an artificial wall above the maximum possible level of water in the reservoir. Slumping and erosion in the shale and solution in the limestone exposed to the action of the reservoir water are to be expected. If at any point the shaly part of the ridge should be overtopped by water and flow started, downcutting would be extremely rapid.

During a second visit to the Canal Zone made by C. P. Ross in March, 1930, a trip was made to Gatun Lake to observe reported results of wave erosion there. Wave-cut terraces some 25 to 30 feet wide cut in the solid rock of the Bohio conglomerate, as mapped by MacDonald,[6] were seen, and even greater erosion is reported farther north. The lake was first filled to an altitude of about 85 feet at the end of 1913, so that erosion has proceeded at the rate of nearly 2 feet annually. This rapid rate of cutting appears to result largely from the presence of considerable bentonitic clay in the

[6] MacDonald, D. F., Some engineering problems of the Panama Canal in their relation to geology and topography: U. S. Bur. Mines Bull. 86, pl. 1, 1915.

matrix of the conglomerate. Much of the rock on the Azote Caballo ridge contains similar clay and is similarly vulnerable to wave action. Most of the wave erosion in Gatun Lake is on the northward-facing shores, because the prevailing wind is from the north during a large part of the year. The proposed reservoir will be on the north side of the Azote Caballo ridge.

HEIGHT OF DAM

The problem of the height to which it is wise to carry the dam is directly connected with the saddles discussed above. It would be entirely practicable to carry the dam to the proposed altitude of 260 feet above sea level or even a little more at either site 1 or site 5. Such a height, however, would involve the construction of long dikes and increase to this extent the danger of possible failure should any unforeseen weakness develop either in the rocks of the ridge or in the construction. The rocks are not sufficiently resistant to be trusted without reinforcement at any point where the maximum possible level of the reservoir is near the top of the ridge.

The weakness of the rocks along the ridge above the Azote Caballo River and the numerous saddles there make the question of the maximum height of water a serious one. It is probably unsafe to assume that an unprotected natural ridge of such rocks extending 25 feet above high-water line would be proof against breach by the water of the reservoir. In places where the slope on the reservoir side is steep and there is possibility of undercutting with consequent slumping an even greater height would be unsafe, if left unprotected.

The top of the dam has been tentatively fixed at 260 feet above sea level for the purpose of allowing all possible storage capacity in the proposed reservoir. The committee that studied the project recommended that 240 feet should be adopted as the normal operating level of the reservoir, with high flood-water level between 255 and 260 feet, the exact level and the height of the parapet wall being left for later determination. It proposed to provide space for "retention volume" in the reservoir above 240 feet to help take care of the floods that normally come late in the wet season, when the reservoir would be essentially full up to operating level. The data presented by the committee constitute strong, valid arguments for providing retention volume rather than attempting to take care of the late floods through spillways alone. At the same time, these data emphasize the danger of carrying the maximum flood level of the reservoir too close to the limit of safety. If a large flood occurred when the reservoir was already full to flood level, the results might easily prove disastrous, unless the sides of the reservoir at all points were amply strong.

It is clear that whatever the height of dam finally decided on the reservoir will at times be filled to its maximum capacity—that is, to the top of the dam—even though the operating level is supposed to be 20 feet lower. Occasional large floods, occurring when the reservoir is already nearly full, would bring this about. Furthermore, as the committee has pointed out, it is probable that at some future time the canal officials will risk raising the operating level somewhat above that originally figured, increasing the danger of filling the reservoir to overflowing in sudden floods. In view of the danger of breach at any of the saddles or along low places in the ridge above the Azote Caballo River it is not safe to build the dam as high as 260 feet.

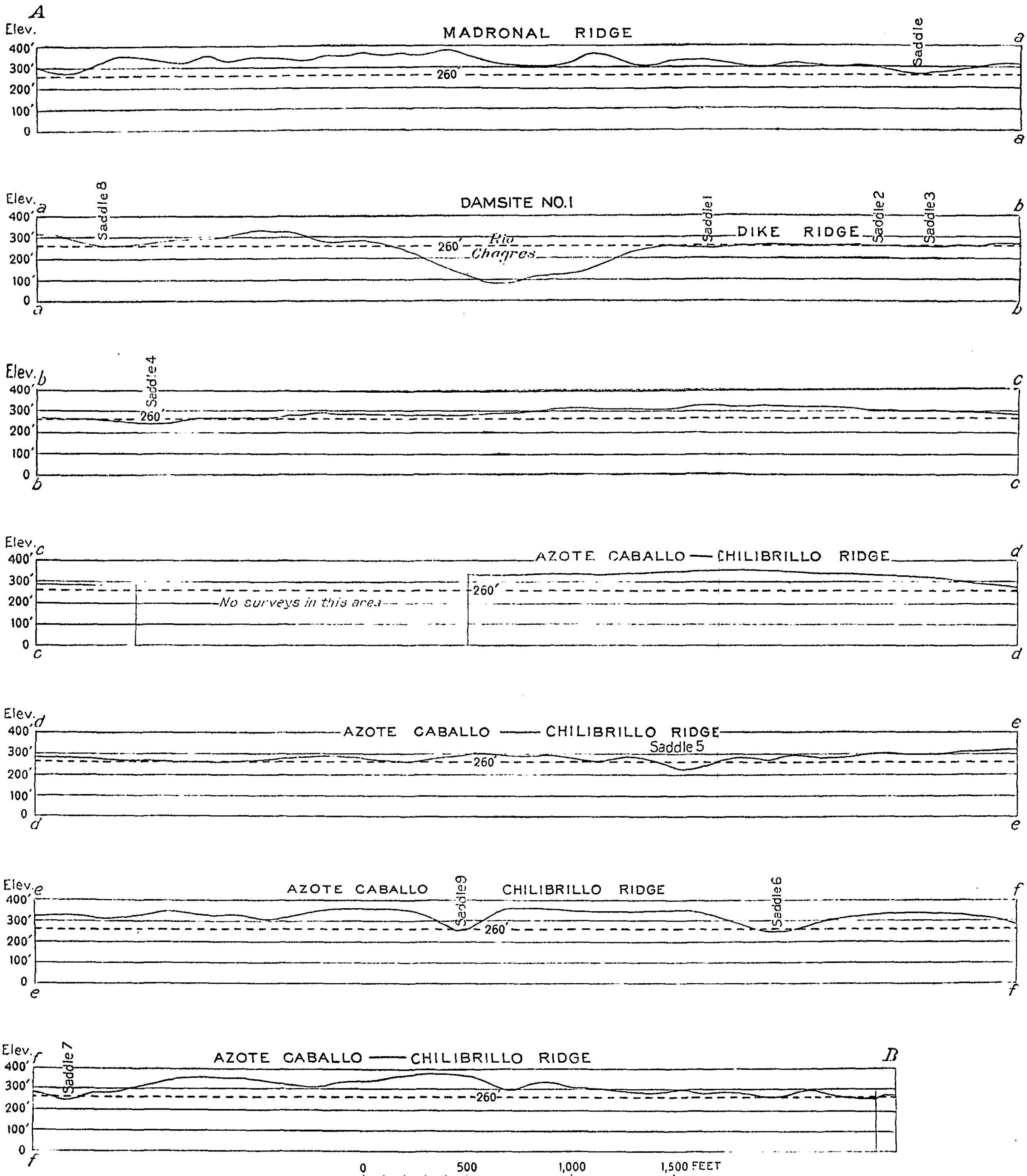
Whatever the height of dam finally adopted, provisions for retention volume should be made. Hence the operating level should be kept fully 20 feet below the top of the dam. If it should be determined to lower the top of the dam to such an extent as to decrease the volume available in the upper 20 feet of the reservoir much below the 10.62 billion cubic feet figured as desirable retention volume by Kirkpatrick in the report of the committee, the difference between normal operating level and the top of the dam should be correspondingly increased. Kirkpatrick qualifies even this figure by the statement that if there is any likelihood that the operating level may be in the future temporarily increased it may be necessary to provide spillways over the low saddles. In view of the weakness of some of these saddles any spillways over them, even for temporary emergency use, would have to be constructed with great care and amply protected. It may be noted that, although a reduction of 20 feet in the height of the proposed reservoir would not eliminate the need of protection along the dike ridge it would materially reduce the amount and cost of construction there.

CONSTRUCTION MATERIALS

It is assumed that the dam, dike, some or all of the saddle dams, and buildings in connection with the project will be constructed of concrete. In addition the road to and beyond the dam will be of concrete construction. A very large amount of sand and of crushed rock or gravel will be needed for use in the concrete, and it may be pertinent to present such data on suitable material as were obtained incidentally to the geologic examination of the reservoir project.

CRUSHED STONE

Of the several kinds of rock in place near the dam site, the Gatun (?) and Caimito (?) formations and the shaly parts of the Culebra and Bohio formations are unsuitable for crushed stone. No



PROFILE ALONG CRESTS EXTENDING SOUTH AND EAST ALONG THE RIDGE ABOVE THE QUEBRADA MADRONAL TO AND ACROSS DAM SITE 1, THENCE ALONG THE DIKE RIDGE AND THE RIDGE ABOVE THE RIO AZOTE CABALLO adequately large exposures of the Emperador or Culebra formations exist in favorable situations for quarrying, even if any parts of these formations should, on test, prove good enough to use.

There are considerable quantities of the limestone of the Bohio in the valleys of the Gatuncillo and Limon Rivers, on the ridge between the Gatuncillo and Agua Sucia in the vicinity of the present tentative location of the road to Porto Bello, and on the Madronal ridge near the mouth of the Quebrada Madronal. This rock is fairly hard and dense and breaks with sharp edges. It is not hard enough for high-grade concrete but might, when tested, prove sufficiently resistant for use in concrete for many purposes, including roads not subjected to extremely heavy wear. On roads it would be found sufficiently soluble to be self-binding to a moderate extent. Bold bluffs adapted to easy quarrying were not noted in the reconnaissance of this area, but it is believed that search among the steep ridges would result in the discovery of sufficiently favorable quarry sites.

The only other suitable bedrock material is that of the volcanic complex, although the conglomerates of the Culebra and Bohio formations, composed largely of material from the complex, might be crushed, washed, and used, if found in favorable situations. Some of the granitic and dioritic rocks present in places in the complex would be excellent, but none of these are known in suitable locations. The volcanic rock crops out on both sides of the Gatuncillo River near its mouth, and suitable quarry sites could probably be found near by. It is also exposed in places high on the ridges but not, so far as known, close to the road in locations suitable for quarrying. The rock is exposed in stream beds high on the Gatuncillo slope near the pass followed by the road location, and it is possible that search in this vicinity would reveal suitable quarry sites. Much of this rock would make good crushed stone for concrete of any type and would also be suitable for rough masonry (not dimension stone), but some of it has been so altered that it softens markedly when exposed to air and water. The altered rock is obviously unsuitable, and its use should be carefully guarded against.

GRAVEL

The gravel in the channel of the Rio Chagres and in near-by bars is on the whole of good quality for use in concrete. It will probably be found to be of somewhat better quality than that at the gravel plant at Gamboa, because it contains a smaller proportion of pebbles derived from the Gatun (?), Caimito (?), and other relatively soft rocks. A large proportion of the gravel along the

Chagres above the dam site is derived from the harder parts of the volcanic complex, including granitic and dioritic rocks. It contains also some limestone derived from the Bohio and Emperador and a small proportion of softer rocks. A large part of the gravel is over 2 inches and some of it over a foot in maximum diameter, so that it will require crushing for use in concrete for most purposes. Advantage could be taken of this fact to eliminate part of the soft material by crushing in such a manner as to make the maximum amount of fines. The fines removed by screening would contain a high proportion of the soft rocks in the original gravel mixture.

SAND

A considerable quantity of sand can be obtained by screening the gravel before crushing and also from sand bars free from gravel. However, in much of this, especially that from the sand bars, there will be so much silt and organic matter as to be detrimental. Hence the sand will require careful washing before use.

CONCLUSIONS AND RECOMMENDATIONS

The geologic examination shows that the reservoir site has disadvantages that must be carefully considered, but none of these are believed to be sufficiently serious to vitiate the project. It is clear that leakage from the reservoir will take place. The amount of leakage can not be stated, but as all the water, except such as is lost through evaporation or retained in the rock pores, will eventually find its way into Gatun Lake, it is believed that this leakage will not seriously interfere with the success of the project. With the modifications and precautions summarized below, there should be no danger of failure of either the dam or the walls of the reservoir. Consequently, as here modified, the project is recommended.

The principal recommended modification is in the height of the proposed dam. It is believed that a dam as high as 260 feet above sea level would imperil the safety of some of the saddles and low ridges. Recommendation is made that the maximum flood-water level be reduced from 260 to 240 feet, the operating level to be at least 20 feet below the flood level, to provide retention volume.[7]

Dam sites No. 1 and No. 5 are both approved, subject to the choice of the designing engineer. None of the other possible sites possess advantages commensurate with their disadvantages.

[7] Since the original report to the governor of the canal was written a board of review of the United States Geological Survey, while concurring in the findings here set forth, has decided to withdraw the specific recommendation as to the height of the dam, on the ground that it is the province of the engineer rather than the geologist to make decisions of this nature.

All spillways, wherever located, should be provided with ample aprons, and every precaution should be taken against the start of downcutting by the water passed through them in time of flood.

It is recommended that no water be permitted to spill through the low saddle where small diamond-drill hole 5 is situated, this being the weakest of all the saddles. Nor is it advisable to spill water through the saddles on the Madronal Ridge unless aprons are constructed to carry the water down to the Quebrada Madronal. It is also inadvisable to permit spillage through any of the saddles along the ridge above the Azote Caballo River except in rare emergencies or after taking great precautions against cutting. The saddle dams should be built somewhat higher than the main dam, and most of them should be so built that weirs or other openings through them would be operative only in exceptional floods. If any of the saddles are used for spillage other than during such floods, the saddles situated in the Gatun (?) formation should be selected for this purpose.

The saddles and the narrower and lower ridges, especially those underlain by the Culebra and Bohio formations, should be protected in every possible way from wave cutting and other erosion and from slumping and landslides. Earth blankets or equally effective means should be used in places like the saddle containing hole 5 and wherever the ridge is narrow and is steep on the reservoir side. In order that such precautions can be adequately planned a detailed topographic survey should be made of the entire ridge from the Rio Chagres to the extreme head of the Azote Caballo River. In the dense vegetation and irregular topography existing on this ridge the most careful inspection without the aid of instrumental surveys is inadequate to give a clear conception of conditions. The designing engineer will probably find it advisable to have additional diamond drilling done in all the saddles on this ridge in order to plan in detail the proper protection for each.

The reservoir should be so filled as to take all possible advantage of the protection against leakage to be obtained from the silt carried by the river water—that is, in such a way that silt will not settle out in the upper part of the reservoir. A proper control of discharge from the reservoir while it is being filled will result in silt being carried to the lower end of the reservoir, where leakage is to be guarded against. Advantage should be taken also of the fact that the Rio Pequeni in flood carries more silt than the Chagres. Once a silt blanket has been formed care should be taken not to erode it away through the action of swift currents.

In so far as it is practicable, vegetation in the basin should be destroyed prior to the filling of the reservoir, and drifting organic matter should be removed as thoroughly as possible both during and subsequent to the filling of the reservoir. The presence of decomposing vegetable and other organic matter in the water of the reservoir would produce organic acids, which would tend to promote somewhat more rapid solution of the limestone than would take place with water free from such acids. Also such organic material mixed with the silt as it settles out would interfere with the hardening of the silt deposits and hence would tend to interfere with their effectiveness in retarding leakage. Moreover, large accumulations of such material would so contaminate the water as to increase materially the difficulty of purifying it for human consumption.

It is inevitable that some leakage will take place. Precautions should be taken to guard against rapid leakage through possible open channels in the soluble limestones, especially those of the Emperador and Bohio formations. Such leakage might result in too rapid depletion of the stored water and possibly might produce cavities large enough to cause danger of failure of the reservoir walls. It would be impracticable to attempt to seal all possible openings in advance of the filling of the reservoir, but during the course of this filling and after its completion leaks should be systematically sought. Any found should be plugged as far as possible by earth blankets, grouting, or other means.

The search for possible leaks should be carried out both by systematic inspection by competent men and by thorough stream gaging. Measurement of the flow of the larger streams is not sufficient. It would be well to measure the flow of all streams, no matter how small, on the Madronal and Chilibrillo sides of the confining ridges. This gaging should be initiated during the dry seasons before the reservoir is filled. It will be unwise to allow the reservoir to fill to its top for the first time before the beginning of the dry season, because it will be difficult to detect leaks during the rainy season. Inasmuch as solution is a slow process, it will be necessary to continue the stream gaging long after the reservoir is filled, the amount done depending on the results of experience.

DRILL-HOLE RECORDS

The following are the logs of the diamond-drill holes drilled in the area:

Records of drill holes on Madden Dam project

2-inch diamond-drill hole L–1

[Still being drilled. (See pl. 12.) Total depth, 397 feet. Collar 113 feet above sea level; bottom 284 feet below sea level. Summary: 0–24, sand; 24–69, Gatun (?) formation; 69–131, Caimito (?) formation; 131–237, Emperador limestone; 237–277, Culebra formation; 277–397, Bohio formation]

	Feet
No core; sand and weathered rock	0–24
Light-gray fine-grained calcareous sandstone	24–69
Light-gray medium-grained calcareous sandstone	69–79
Chips of light-gray medium-grained calcareous rock	79–79.5
Dark-gray medium-grained calcareous rock	79.5–111
Dark-gray medium-grained fossiliferous calcareous sandstone	111–124
Dark-gray medium-grained calcareous sandstone	124–131
Light-gray sandy limestone	131–192
Light-gray fossiliferous limestone	192–207
Greenish-gray rotten marly limestone	207–227
Light-gray fossiliferous and sandy limestone	227–237
Light-gray fine-grained sandstone	237–250.6
Dark fine-grained sandstone	250.6–251.6
Nearly black sandstone; flow of water at 261 feet	251.6–274
Sandstone, more calcareous; many fossils	274–277
Coarse calcareous grit with pebbles	277–295
Fine calcareous grit	295–298
Coarse sandy limestone with few pebbles	298–302.4
Gritty limestone; scattered pebbles	302.4–330
Fine calcareous grit	330–335
Gritty limestone	335–340
Darker and finer limestone	340–346
Gritty limestone	346–351
Calcareous grit	351–360.6
Limestone conglomerate	360.6–370.6
Dark fine grit	370.6–382.6
Dark fine grit with large shells	382.6–390.6
Grit with irregular green shale masses	390.6–393
Coarse black grit with pebbles	393–397
Sandstone	397–427
Shale	427–441
Sandstone with pebbles	441–464
Sandstone	464–472
Conglomerate	472–476
Shale	476–484
Conglomerate	484–494
Sandstone with pebbles	494–503
Sandstone and shale	503–514
Conglomerate	514–525
Soft sandstone	525–535

	Feet
Sandstone	535–541
Sandstone and shale	541–545
Soft sandstone	545–570

2-inch diamond-drill hole L–2

[Drilled January 28, 1929. Total depth, 269.5 feet. Collar, 104.7 feet above sea level; bottom 164.8 feet below sea level. Summary: 0–42.9, sand and gravel; 42.9–66, Gatun (?) formation; 66–132, Caimito (?) formation; 132–239, Emperador limestone; 239–269.5, Culebra formation]

	Feet
No core; sand and gravel	0–42. 9
Chips of calcareous sandstone	42. 9–52. 9
Bluish-gray fine-grained sandstone	52. 9–66
Coarser and more calcareous than above	66–76
Dark-gray medium-grained calcareous sandstone	76–105
Coarser and more calcareous than above	105–132
Light-gray limestone	132–175
Gray to white soluble limestone	175–185
Light-gray sandy limestone	185–200
Grayish-white soluble limestone	200–210
Gray and greenish-gray soft rotten marl	210–227
Gray sandy limestone	227–239
Gray fine-grained sandstone	239–269. 5

2-inch diamond-drill hole L–3

[Drilled February 18, 1929. Total depth, 314.7 feet. Collar 115.3 feet above sea level; bottom 199.4 feet below sea level. Summary: 0–12, sand and gravel; 12–84, Gatun (?) formation; 94–164, Caimito (?) formation; 164–268, Emperador limestone; 268–314.7, Culebra formation]

	Feet
Sand and gravel	0–12
Bluish-gray fine-grained calcareous sandstone	12–35
Soft clay	35–35. 1
Gray fine-grained calcareous sandstone	35. 1–80
Darker and coarser grained than above	80–94
Gray calcareous sandstone, slightly coarser and more calcareous than above	94–104
Light-gray medium-grained calcareous sandstone	104–164
Light-gray limestone	164–209
Grayish-white soluble limestone	209–218
Gray sandy limestone	218–232
Grayish-white soluble limestone	232–242
Gray and greenish-gray rotten marl	242–260
Gray sandy limestone	260–268
Dark-gray fine-grained sandstone	268–314. 7

1-inch diamond-drill hole 1

[Drilled October 3, 1928. Total depth, 152.3 feet. Collar 241.7 feet above sea level; bottom 94.4 feet above sea level. Summary: 0–6, earth; 6–152.3, Gatun (?) formation]

	Feet
Earth; no core	0–6
Fine-grained gray calcareous sandstone	6–30
1-inch core; fine-grained gray calcareous sandstone	30–40

	Feet
Fine-grained gray calcareous sandstone	40–120
Fine-grained gray calcareous and fossiliferous sandstone	120–152. 3

1-inch diamond-drill hole 2

[Drilled October 11, 1928. Total depth, 152.3 feet. Collar 245.2 feet above sea level; bottom 92.9 feet above sea level. Summary: 0–5.6, soil; 5.6–152.3, Gatun (?) formation]

	Feet
Earth; no core	0–5. 6
Soft yellowish weathered sandstone	5. 6–5. 8
Fine-grained light-gray calcareous sandstone	5. 8–110
Fine-grained dark-gray calcareous sandstone	110–121
Fine-grained light-gray calcareous sandstone, with slightly weathered rock at 125 and 126 feet	121–152. 3

1-inch diamond-drill hole 3

[Drilled October 19, 1928. Total depth, 151.6 feet. Collar 245.8 feet above sea level; bottom 94.2 feet above sea level. Summary: 0–1, soil; 1–151.6, Gatun (?) formation]

	Feet
Earth; no core	0–1
Light-gray fine-grained calcareous sandstone	1–125
Light-gray fine-grained calcareous and fossiliferous sandstone	125–141
9 feet of core; light-gray fine-grained calcareous sandstone	141–151. 6

1-inch diamond-drill hole 4

[Drilled November 8, 1928. Total depth, 149.2 feet. Collar 249.2 feet above sea level; bottom 100 feet above sea level. Summary: 0–7, soil; 7–149.2, Gatun (?) formation]

	Feet
Earth; no core	0–7
Light-gray fine-grained calcareous sandstone	7–125
Dark-gray fine-grained calcareous sandstone	125–145
2-foot core; chips of sandstone	145–149. 2

1-inch diamond-drill. hole 5

[Drilled November 22, 1928. Total depth, 101.5 feet. Collar 220 feet above sea level; bottom 118.5 feet above sea level. Summary: 0–23, earth; 23–71, Culebra formation; 71–106.5, Bohio formation]

	Feet
No core	0–23
2-foot broken core; weathered greenish-yellow fine-grained calcareous sandstone	23–30
Bluish-gray fine-grained sandy limestone	30–40. 5
Limy shale	40. 5–40. 9
Dark bluish-gray medium-grained sandy fossiliferous limestone	40. 9–51
3 feet of core; upper part coarse-grained grit, rest more calcareous, with some conglomerate of coarse light-gray sandy limestone	51–61

	Feet
6 feet of core; coarse light-gray sandy limestone	61–71
4 feet of core; grayish-white coarse-grained sandy limestone	71–81
2 feet of core; light-gray limestone with yellowish tinge	81–91
1½ feet of core; medium-grained sandy limestone with black pebbles	91–101.5

1-inch diamond-drill hole 6

[Drilled December 7, 1928. Total depth 150.4 feet. Collar 247.9 feet above sea level; bottom 97.5 feet above sea level. Summary: 0–1, soil; 1–150.4, Gatun (?) formation]

	Feet
Earth; no core	0–1
Soft yellowish-gray calcareous sandstone	1–2
Light-gray fine-grained calcareous sandstone	2–31
4 feet of core; chips of sandstone	31–32
Light-gray fine-grained calcareous sandstone	32–53
1 foot of core; fine-grained calcareous sandstone	53–55
Light-gray, fine-grained calcareous sandstone	55–124
Light-gray fine-grained calcareous and fossiliferous sandstone	124–144
Light-gray fine-grained calcareous sandstone	144–150.9

1-inch diamond-drill hole 7

[Drilled December 18, 1928. Total depth, 190.2 feet. Collar 239.1 feet above sea level; bottom 48.9 feet above sea level. Summary: 0–2, soil; 2–190.2, Gatun (?) formation]

	Feet
Fine-grained calcareous weathered sandstone	0–2
Bluish-gray fine-grained calcareous sandstone	2–121
Light-gray fine-grained sandstone, more calcareous and coarser grained than rock above	121–135
Dark-gray fine-grained calcareous sandstone	135–190.2

1-inch diamond-drill hole 8

[Drilled December 20, 1928. Total depth, 25.7 feet. Collar 121.8 feet above sea level; bottom 96.1 feet above sea level. Summary: 0–7, soil; 7–25.7, Gatun (?) formation]

	Feet
No core; soil, sand, and gravel	0–7
Light-gray sandstone	7–8.5
Gray calcareous sandstone with sandy streaks	8.5–10.5
Bluish-gray calcareous sandstone	10.5–25.7

1-inch diamond-drill hole 9

[Drilled January 2, 1929. Total depth, 63.3 feet. Collar 115.2 feet above sea level; bottom 51.9 feet above sea level. Summary: 0–40, gravel; 40–63.3, Gatun (?) formation]

	Feet
Gravel	0–40
Gray calcareous sandstone	40–42.5
Fine-grained calcareous sandstone	42.5–61
No core	61–63.3

1-inch diamond-drill hole 10

[Drilled January 9, 1929. Total depth, 63.3 feet. Collar 114.9 feet above sea level; bottom 51.6 feet above sea level. Summary: 0–38, boulders; 38–63.3, Gatun (?) formation]

	Feet
Boulders	0–38
No core	38–45
Calcareous sandstone	45–63.3

1-inch diamond-drill hole 11

[Drilled January 17, 1929. Total depth, 51.4 feet. Collar 92 feet above sea level; bottom 45.6 feet above sea level Summary: 0–18, gravel; 18–51.4, Gatun (?) formation]

	Feet
No core	0–18
Boulders; 6-foot core of calcareous sandstone	18–38
Fine-grained calcareous sandstone	38–51.4

1-inch diamond-drill hole 12

[Drilled January 22, 1929. Total depth, 52.9 feet. Collar 120 feet above sea level; bottom 67.1 feet above sea level. Summary: 0–42, gravel; 42–52.9, Gatun (?) formation]

	Feet
Sand and gravel	0–42
Bedrock, gray sandstone	42–52.9

1-inch diamond-drill hole 13

[Drilled January 25, 1929. Total depth, 50.2 feet. Collar 102 feet above sea level; bottom 51.8 feet above sea level. Summary: 0–36, gravel; 36–50.2, Gatun (?) formation]

	Feet
Sand and gravel	0–36
Bedrock, gray sandstone	36–50.2

Wash-drill hole 14

[Drilled January 17, 1929; redrilled April 30, 1929. Total depth, 75 feet. Collar 121.5 feet above sea level; bottom 46.5 feet above sea level]

	Feet
Sand, gravel, and boulders	0–55.0
Bedrock	55.0–75.0

Wash-drill hole 15

[Drilled January 25, 1929; redrilled April 26, 1929. Total depth, 74 feet. Collar 103.9 feet above sea level; bottom 29.9 feet above sea level]

	Feet
Sand, gravel, and boulders	0–54
Bedrock	54–74

Wash-drill hole 16

[Drilled January 25, 1929; redrilled May 7, 1929. Total depth, 94 feet. Collar 113.9 feet above sea level; bottom 19.4 feet above sea level]

	Feet
Sand, clay, and gravel	0–74
Bedrock	74–94

Wash-drill hole 17

[Drilled January 25, 1929; redrilled May 24, 1929. Total depth, 150 feet. Collar 100.4 feet above sea level; bottom 50.4 feet above sea level]

	Feet
Sand and gravel	0–25
Sand, gravel, and boulders	25–53
Bedrock	53–150

1-inch diamond-drill hole 18

[Drilled March 15, 1929. Total depth, 42 feet. Collar 86.2 feet above sea level; bottom 44.2 feet above sea level]

	Feet
Water	0–0.5
Gravel	0.5–18.7
Sandstone	18.7–42

1-inch diamond-drill hole 20

[Drilled February 4, 1929. Total depth, 140.7 feet. Collar 227.8 feet above sea level; bottom 87.1 feet above sea level. Summary: 0–5, soil; 5–140.7, Gatun (?) formation]

	Feet
Soil	0–5
2 feet of core; chips of brownish-gray calcareous sandstone	5–10.5
10 feet of core; light-gray fine-grained calcareous sandstone with 1 to 2 inches of brownish-gray sandy limestone every 2 to 3 inches, in which minerals are decayed	10.5–26
Light-gray fine-grained calcareous sandstone	26–39
Chips of calcareous sandstone showing solution	39–40
Light-gray calcareous sandstone	40–90
6 inches of core; soluble gray calcareous sandstone	90–100
Dark-gray soluble calcareous sandstone	100–120
Fine-grained gray calcareous sandstone	120–140.7

1-inch diamond-drill hole 21

[Drilled February 21, 1929. Total depth, 157.2 feet. Collar 277.6 feet above sea level; bottom 120.4 feet above sea level. Summary: 0–3, soil; 3–15, Caimito (?) formation; 15–85, Emperador limestone; 85–157.2, Culebra formation]

	Feet
Soil	0–3
1½ feet of core; brownish-gray medium-grained calcareous sandstone	3–10
1.2 feet of core; more calcareous than above rock	10–15
1.2 feet of core; grayish-white sandstone	15–20
0.3 foot of core; soluble grayish-white sandstone	20–25
2 feet of core; soluble grayish-white sandstone	25–30
No core; sand and gravel filling sink hole	30–40
2 inches of core; sand and igneous pebble	40–42
4 inches soluble white limestone	42–55
3 feet of core; dark fossiliferous limestone	55–60
2 feet of core; soluble white limestone	60–75
1 foot of core; dark-gray, fossiliferous limestone	75–80
4 inches of dark-gray fossiliferous limestone with igneous pebbles	80–85

	Feet
3 feet of core; fine-grained calcareous sandstone	85–90
4 feet of core; dark fine-grained sandstone, sandy gray limestone, and greenish fine-grained sandstone	90–100
6 inches of core; greenish medium-grained calcareous sandstone	100–120
1 inch of core; dark-gray medium-grained sandstone, lower 8 inches saturated with oil	120–131
Lignitic coarse sandstone, sandy clay	131–142
Soft sandy dark-gray clay	142–145
Dark clay	145–146
Green clayey soft limestone	146–152
Green sandy clay	152–156
Dark sandy clay	156–157.2

1-inch diamond-drill hole 22

[Drilled March 8, 1929. Total depth, 140 feet. Collar 303 feet above sea level; bottom 163 feet above sea level. Summary: 0–5, soil; 5–24, Caimito (?) formation; 24–120, Emperador limestone; 120–140, Culebra formation]

	Feet
Soil	0–5
5 feet of core; grayish-white calcareous medium-grained sandstone	5–24
4 feet of core; white limestone and greenish-white sandy limestone	24–40
2 inches of core; chips of white limestone, one chip of calcite half an inch in diameter	40–60
No core	60–80
2 inches of core; fossiliferous grayish-white limestone	80–90
3 inches of core; fossiliferous grayish-white limestone with black pebbles	90–100
4 inches of core, chips of brownish-gray porous conglomerate and fossiliferous limestone	100–110
3 inches of core; chip of dark-gray fossiliferous and conglomeratic porous limestone	110–120
Fine-grained sandstone and sandy clay	120–135
Greenish clay	135–140

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