AN ABSTRACT OF THE THESIS OF

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ABSTRACT

The area discussed embraces about seven hundred square miles including Gatun Lake and environs. A coordinated field reconnaissance, map and aerial photograph study was made by the writer, as opportunity and time allowed, over a three-year period. The result is a general report of the Gatun Lake Area which gives the basic geological picture as evident from a strictly local study. All of the limited available previous work in the area was examined and utilized as background.

The Gatun Lake Area is a physiographic basin flanked by high hills on the east and west and by low ones on the south. The highest hill masses rising over large areas to more than 1000 feet A.T. are formed by pre-Tertiary Complex ("trap"). The main low part of the area is developed from Tertiary and Quaternary material and may be categorized in four classes:

a. Swamp and lowland areas up to 25 feet A.T.

b. Interlowland areas up to 300 feet A.T. (500 feet A.T. at extreme points)

c. Dissected highland up to 700 feet A.T.

d. Hills region up to 1100 feet A.T.

The oldest rocks of the area are the closely jointed, faulted, folded and partly metamorphosed pre-Tertiary Basement Complex. Over this old rock mass in the lower areas lies a variably discontinuous series of Tertiary sedimentary, igneous and pyroclastic rocks ranging from Eocene to late Upper Miocene. Quaternary deposits of unconsolidated sediments ranging from Pleistocene to Recent fill broad drowned areas and principal river valleys, locally to at least 300 feet depth below sea level. On a stratigraphic and partly on a lithologic basis, the following general correlation is made with other formations outside the Lake Area.

Gatun Lake Area	Pacific Cut Area
Gatun-Toro-Chagres Fms.	Missing
Upper Caimito Member	La Boca Fm. Cucaracha Fm.
Lower Caimito Member	Culebra Fm.
Basal Caimito Member	Las Cascadas Fm.
Bohio Fm.	Obispo Fm.
Pre-Tertiary Complex	Missing

All sedimentary formations are fossiliferous at least in part. The most detailed stratigraphic and lithologic examination possible was that of a 546-foot section of the Gatun formation. This examination shows a shallow-water marine series of marly, tuffaceous, highly fossiliferous sediments laid down under diastemic conditions. At least three cycles are represented at the site of this section.

Remote areas adjoining the Lake Area contain previously mapped little-known formations. Among these are:

a. The Eocene Gatuncillo formation, discovery of the extension of which into the Gatun Lake Area is the first record of Eocene sedimentary rock in the Canal Zone.

b. The Oligocene - Lower Miocene Quebrancha formation, considered by the writer to be stratigraphically equivalent to the Caimito formation.

c. Lower Miocene Alahuela member of the Caimito formation, which is the Gatun (?) formation of Ross and Reeves' Madden Dam Report.

d. Middle Miocene (?) Sabanitas formation, which is probably a continental and shallow-water facies of the lower Gatun formation.

The structure of this area is dominated by faulting. Four systems of faulting, representing as many stress conditions, are definitely recognizable in the area by study of maps and aerial photographs supported by field evidence. All the major faults indicate tearing as the principal strain component. The age and sequence of faulting are not yet deciphered, but movement as old as pre-Tertiary and as young as Quaternary is evident in parts of each system.

The history of the area is recorded in four sets of sediments separated by three major unconformities. The first set of sediments, those incorporated in the Basement Complex, is too crushed, cracked and folded to decipher. The second set, those of Upper Eocene through Lower Miocene time is moderately faulted and folded. They depict a history decipherable with difficulty. The third set of sediments is the Middle Miocene and Upper Miocene (?) coastal plain beds which reveal a simple history that could be easily worked out in greater detail. The youngest set is composed of the Pleistocene and Recent unconsolidated sediments which are so young their short history is that of slight uplift.

GEOLOGY OF GATUN LAKE
AND VICINITY

by

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INTRODUCTION

Area

The area discussed herein is part of the Isthmus of Panama, largely within the Canal Zone, and extends both north and west from Gamboa, C. Z., to the Caribbean Sea. It includes the towns of Cristobal, Margarita, Gatun, and Gamboa in the Canal Zone; and Colon, Lagarto, Pina, Escoval, Lagartarito, New Providence, and Nuevo Limon in the Republic of Panama.

The present report covers the portion of the Isthmus of Panama accessible by boat at the surface of Gatun Lake, and many inland areas reached by streams and trails. On the north is included the area between Gatun Lake and the Caribbean Sea. On the east the boundary lies northwest of the Trans-Isthmian (Boyd-Roosevelt) Highway. The western boundary is highly irregular and follows the lake shore closely. The southern border is arbitrarily placed at the Rios Chagres and Mandinga, and at the mouth of the Rio Pescado. The area is slightly trapezoidal in outline and includes about 700 square miles (see Plate 1, p. 2).

The Trans-Isthmian Highway and the Panama Railroad constitute the only modern land transportation through most of the region. The Panama Railroad on the east which parallels the Trans-Isthmian Highway at a distance up to 10 miles, is the best means of access to the various

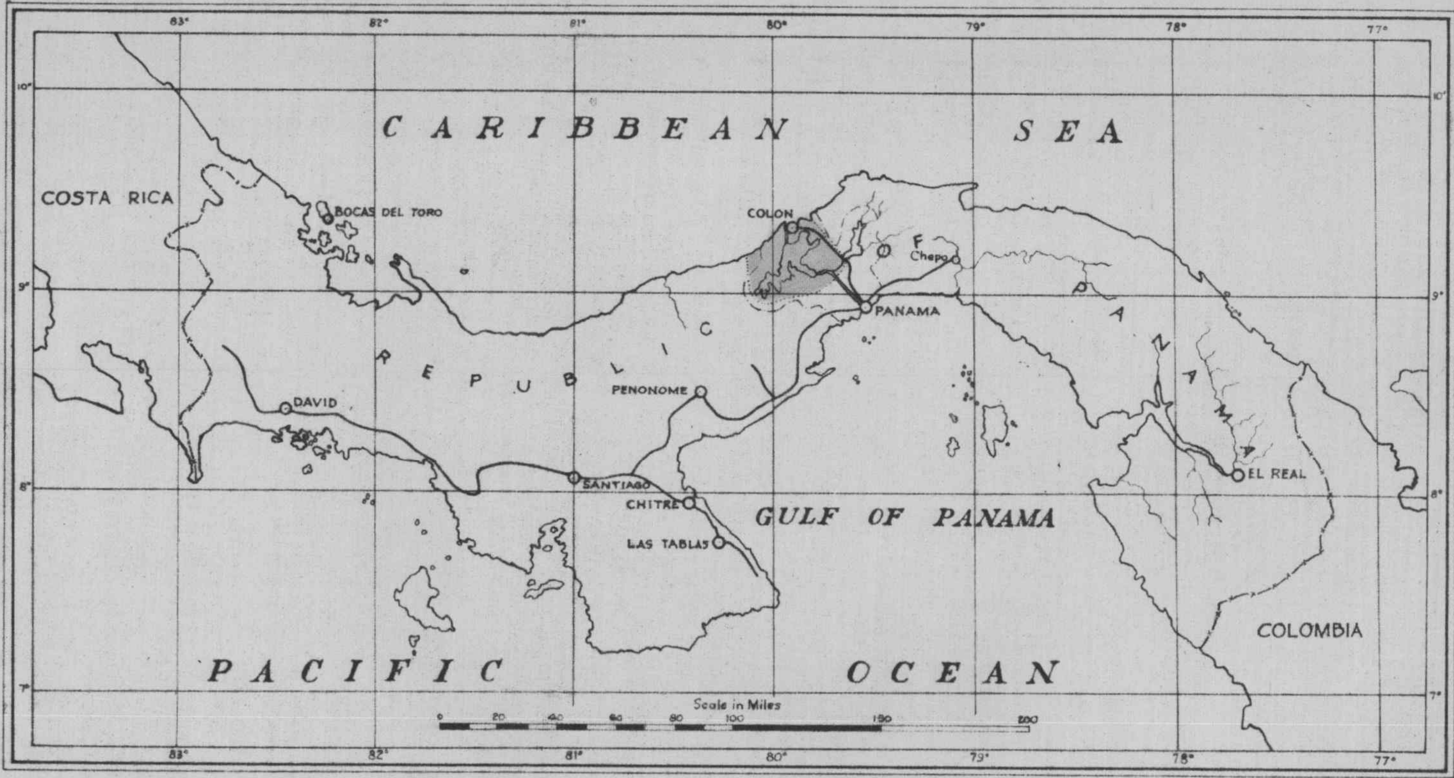

PLATE 1. - LOCATION MAP

eastern arms of the lake, from which the surrounding areas can be reached only by boat. The hill region between Gatun Lake and the Caribbean Sea is traversed sparsely by a road network which crosses few trails.

Trails are scarce within the limits of the Canal Zone, although abundant in the Republic of Panama, and afford few bedrock outcrops. The infrequent roads and the stream beds are the only traversable overland routes where exposures can be found regularly. Wherever stream gradients are steep, sound rock is abundant. Where the stream profiles are gentle bedrock projects through surficial deposits in only a few places and it is deeply weathered. It is very rarely possible to determine the character of the material underlying the extensive mantle by examination of the mantle alone. The dense jungle vegetation hides the topographic features and impedes the determination of one's position.

Purpose and Scope

The writer selected the Gatun Lake Area as the subject of a Master's thesis for two reasons: (1) to combine into a single entity his varied geologic studies of an area of international economic importance; (2) to present the results of his studies in a form useful to other geologists who will work in the area. The information included herein was obtained by the writer in part during official investigations*, and in part on field trips made on his own time.

Previous Work in the Area

Extensive surface and subsurface exploration and study have been completed within the area under discussion, and the results** thereof have been utilized as valuable sources of information and background. The previous works which have contributed information on the Gatun Lake Area are summarized as follows:

(a) Studies made for the French companies;

(b) Studies made for the Isthmian Canal Commission;

(c) Studies made for the Third Locks Project.

The best general bibliography of the geology of the Isthmus of Panama is that included in a report by the Chief, Geology Section, Special Engineering Division, The Panama Canal (11). This report should be read by everyone contemplating geologic work in any part of the Canal Zone. It summarizes the valid published material and the knowledge of Canal Zone geology acquired to the date of its publication.

Field Methods

The field work began on January 9, 1942, and was carried on intermittently until May 16, 1947. Field equipment consisted of the following: Brunton compass, geologic hammer, hand lens 14x, jacknife,

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* Third Locks Project and I. C. S. - 1947.
** Bibliography herewith.

hand level, protractor, tape measure, machete and barometer altimeter. The maps used were waterproof acetate overlays of Panama Survey Army Topographic Sheets, 1:20,000 scale. Notes were penciled on the overlays in the field and later transferred to permanent records in the office. The field work was carried out on foot along shorelines, stream beds, trails, roads, and railroads, and in excavations such as quarries and the Gatun Third Locks Cut.

Reliability of Areal Geologic Map (Plate 4)

Rather definite variations in reliability of various parts of Plate 4 are acknowledged by the writer. These variations are attributable to several factors:

(a) Extreme variation in accessibility of different parts of the area depicted;

(b) The concentration of the writer's efforts during the official part of the field work on several very narrow belts across the area;

(c) Differing accuracy among available maps;

(d) Variable quality of aerial photograph coverage;

(e) Water and mantle distribution;

(f) Changing complexity of geologic structure.

The writer therefore qualifies Plate 4 as follows:

(1) The portions of Boyd-Roosevelt Highway and the Panama Railroad transecting the area, and every army road terminating in a pier at Gatun Lake's edge have been covered on foot.

(2) The entire Lake shoreline within Quadrangles* 17, 18, 21, 22, 23, 24, 25, and 46, has been covered in detail by rowboat.

(3) The Lake shoreline within Quadrangles 19, 26, 28, and 29, has been spot-checked by boat.

(4) The Caribbean coast and shores of Limon Bay have been studied in detail, in part by auto, in part on foot, from Salud to Coco Solo.

(5) All other roads in the area have been traversed by automobile, and every known outcrop of bedrock examined.

(6) Nearly every stream and trail on Barro Colorado Island has been traversed.

(7) All the principal trails and streams ending at the Lake's edge between the Boyd-Roosevelt Highway and a line connecting Escoval to the mouth of the Rio Pescado have been traversed.

(8) All roads northwest of Boyd-Roosevelt Highway have been traversed on foot.

(9) The shoreline from Escoval to the Rio Ciri Grande has been scanned at close-range from a launch, and the trails in the vicinity from the Ciri Grande to the Ciricito Rivers traversed on foot.

(10) All intervening areas have been filled in by careful map and aerial photograph study coordinated with careful consideration of topography and geology worked out in the field.

(11) In general, reliability decreases west of 80° 00' W, south

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* Refers to 05' quadrangles assigned numbers for Panama Survey by U. S. Army as indicated on Plate 4

of 9° 05' N, east of 79° 40' W, north of Boyd-Roosevelt Highway, and toward an E-W centerline through Quadrangles 41 and 42.

Rock Terminology

Sedimentary rock.

No generally accepted system of rock nomenclature could be found to distinguish the sedimentary rocks of this area unequivocally and simply. A megascopically applicable system of nomenclature suitable to this region was developed as a modified composite of several pre-existing systems and is presented herewith and in Table 1, p. 9. The combined forms of the rock names in Table 1 are made by hyphenation between two or three of them, proportions of which in the rock lie between 25 and 75 per cent. Under this taxonomy combined forms are mandatory where applicable, except where an inclusive term is present in the table when the inclusive term must be used instead of the combined form. Use of the adjectival forms of the rock names is optional but restricted to constituents composing up to 25 per cent of the rock.

Among the fine grained sediments, claystone, siltstone, and mudstone are thickly to massively bedded; shales are fissile to thinly bedded; tuff claystone and tuff siltstone are thinly to massively bedded. The waxy luster of claystone distinguishes it from siltstone. The latter has a gritty dull luster when cut with a knife.

In the sand-size range, fine grains are not readily visible to the naked eye but are easily seen with the aid of a 14x hand lens. Medium grains are readily visible to the naked eye but are not much over a half a mm. in diameter. Coarse grains are up to 2.5 mm. in diameter. Granules are not distinguished from pebbles.

Among the coarse sediments, "breccia" refers to fragments owing their angularity or subangularity to their most recent transportation or to intra-formational activity; "agglomerate" refers to fragments initially of pyroclastic origin which still retain enough of their primary shape that their pyroclastic origin is apparent. Only some agglomerates are volcanic breccias. Volcanic breccias are but a small proportion of the coarse clastics.

Practical examples:

(1) sedimentary rock containing:
10% particles less than .05 mm.
30% particles less than 2.5 mm. and more than .05 mm.
60% particles more than 2.5 mm.
Name: sandstone-conglomerate; optional adjective: shaley

(2) massive sedimentary rock containing:
40% clay-size particles
40% silt-size particles
20% sand-size particles
Name: mudstone; optional adjective: sandy

(3) sedimentary rock containing:
30% agglomerate
30% conglomerate
30% quartz sandstone
10% tuff
Name: sandstone-conglomerate-agglomerate;
optional adjective: tuffaceous

(4) sedimentary rock containing:
10% clay-size tuff(?) bentonite
10% tuff siltstone
20% tuff sandstone
40% agglomerate
10% conglomerate
10% limestone
Name: tuff-agglomerate;
optional adjectives: conglomeratic, limy, bentonitic

Table 1 Sedimentary Rock Classification

Grain Size mm.	Predominantly Inorganic						Predominantly Organic (CaCO3 more than half)	
	Less than half volcanic constituents				More than half volcanic constituents			
.000--	Claystone	Mudstone	Clay shale	Shale	Tuff claystone	Tuff	Limestone	
.0005--	- - - - -		- - - - - -		- - - - - - - -			
	Siltstone		Silt shale		Tuff siltstone			
0.05--	fine grained	Sandstone			Tuff sandstone			
00.2--	- - - - - -			--	-			
	medium grained							
00.6--	- - - - - - -			--	-			
	coarse grained							
02.5--	pebble	Conglomerate	Breccia		Agglomerate		(Shell) breccia	Coquina
25.0--	- - -							
	cobble							
305.--	- - -							
	boulder							
3000--								

Igneous rocks.

Igneous rocks in the area all fitted megascopically into the categories of Table 2 where they will remain until additional divisions are necessary. The terms used here are in general accord with Johannsen's definitions expanded to include the few specimens that should be classified more exactly in intermediate categories not given in this table.

Table 2 Igneous Rock Classification

	acidic		basic
fine grained	rhyolite	dacite	basalt
			basalt-agglomerate
medium grained & porphyritic	rhyolite porphyry	dacite porphyry	dolerite
coarse grained	granite	quartz diorite	

Metamorphic rocks.

The only metamorphic rocks found in the area are metabasalts, metatuffs and hornfels of the Basement Complex. These names require no explanation.

PHYSIOGRAPHY

General Character

The Gatun Lake Area, topographically compared to the rest of the Isthmus of Panama (see Plate 2, p. 14), is a lowland basin covered with Tertiary and Quaternary sediments. It opens northwestward into the Caribbean Sea and is flanked by high hills of the pre-Tertiary Basement complex on the northeast, by the upfaulted Tertiary rocks of the Continental Divide on the southeast, and by the very high El Valle crater and associated late Tertiary and Quaternary rocks of volcanic origin on the southwest.

The physiography of the Gatun Lake Area is the expression of the humid cycle of stream erosion developed to varying degrees on a semi-drowned peneplane which has been rejuvenated locally to variable degrees by uplift. The area can be divided into two major topographic types: mountain and intermontane areas.

Mountain Areas

The mountain areas are of generally late youthful topography dissected in old hard rocks of the pre-Tertiary Basement Complex. This topography may have been developing much longer than the intermontane topography but remains in an early erosional stage because of the greater resistance of the underlying hard rock to weathering and erosion.

Intermontane Areas

The intermontane areas are of early youthful to extreme old age topography variably developed on young soft Tertiary rocks and Quaternary sediments. This topography can be subdivided into four physiographic subtypes summarized as follows:

(a) Swamp and lowland areas of the Chagres, Trinidad, Gatun and other Pliocene(?) river valleys with associated inland and coastal swamp areas. These are virtually flat areas of aggradation on former land surfaces still below sea level. They are all less than 25 feet above sea level and most are underlain by Quaternary muck and alluvium.

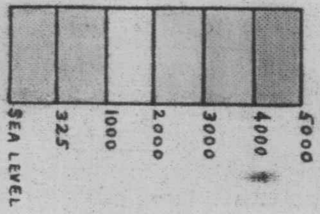
(b) Interlowland areas represented by the Gigante-Agua Clara Peninsula. These areas are the unrejuvenated portions of an old peneplane standing generally between 100 and 200 feet A.T.(above sea level), with a few monadnocks of harder rock, such as Cerro Gigante (520 feet A.T.), and some outliers of basalt locally rising above 300 feet A.T.

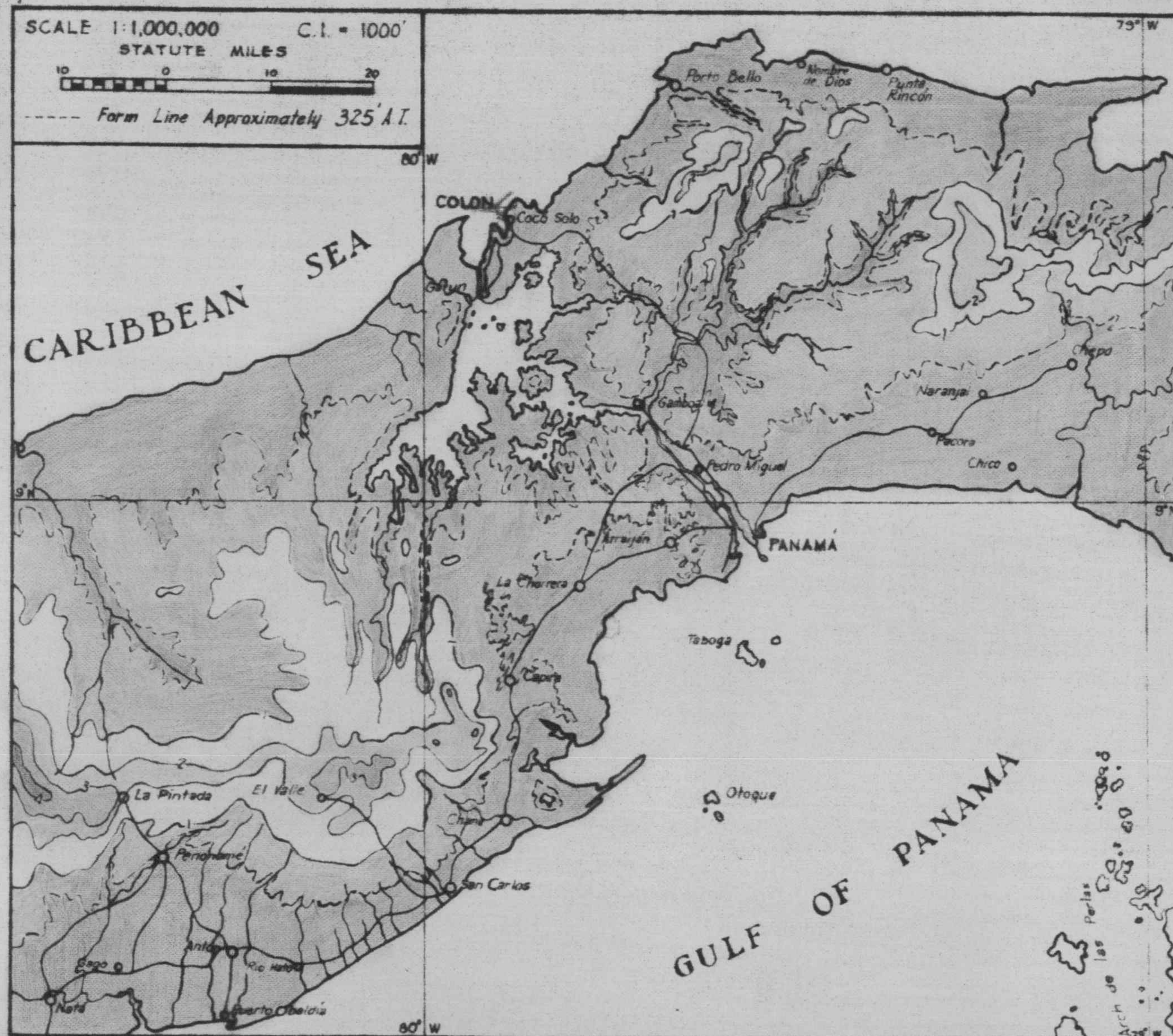
(c) Dissected highland areas represented by the land between Gatun Lake and the Caribbean Sea, the Bohio Peninsula, Barro Colorado, and Juan Gallegos Island. In part these are areas of the former peneplane which have been rejuvenated by upward faulting and tilting. The resulting landforms where soft rocks are present are narrow valleys, steep hillsides and rounded hilltops; where hard rocks are present, they form hogbacks and dome-shaped hills with small, steep-profiled streams. Relief ranges from 5 to 10 feet per mile at the Caribbean shore up to nearly 700 feet per mile near Gatun Lake and on Barro

Colorado.

(d) Hills region with relief up to 1100 feet per mile in the southeastern border of the area is an extension of a province of fault blocks bounded by closely spaced major shear faults with many sympathetic cross-faults and much tilting and displacement of the fault blocks. Many basic dikes and flows in the area transect softer Caimito and Las Cascadas rocks, and the present relief is attributed to the resulting differential sculpturing after disruption of the initial structure by complicated faulting. Balboa High southwest of Gamboa is a typical peak in this area.

PLATE 2. - REGIONAL MAP





DETAIL STRATIGRAPHY

Summary

The rocks encountered in the Gatun Lake Area include marine and fluviatile sediments and igneous flows and intrusives, ranging in age from Upper Eocene to Recent* and overlying a probably pre-Tertiary Basement Complex (see Table 3, p. 18). All but the first of the below named formations are described in the existing literature on Canal Zone geology. T. F. Thompson's report (11) contains a digest of the knowledge, including a review of the literature on each formation and a bibliography. This report served as the starting point for much of my current work in the Gatun Lake Area. Changes in concept of the Gatun Lake Area stratigraphy included herein are the result of the observation of many more outcrops and of several discussions and field trips with Dr. W. P. Woodring of the U. S. Geological Survey. Dr. Woodring determined the ages of the fossiliferous formations among those listed below and in Table 1. Although his fossil and age identifications were the result of field examinations only, they fitted the correlations previously made on a stratigraphic basis by the author and T. G. Moran, the Pacific Cut Area Geologist. This correlation is shown in Table 1.

In the detailed description of each formation lithologic and structural features are emphasized because they have been the most

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* Ages of fossiliferous formations after field identifications by W. P. Woodring.

useful, reliable, and in most exposures the sole criteria for distinguishing formations. Furthermore, in this area these are the features of greatest interest. However, wherever fossils or other criteria were available they were studied in an attempt to find additional bases for distinguishing formations. The differences between my usage of each formational name and its previous usage, and the reasons therefor, are explained in the detailed descriptions. In order from oldest to youngest the formations present are:

(a) Basement Complex -- Metabasalts, metatuffs, basalts, hornfels, and other rocks, closely jointed and faulted. Thought to be pre-Tertiary.

(b) Bohio formation -- Massive basaltic sandstones and sandstone-conglomerates. Oligocene.

(c) Las Cascadas formation -- Massive to thin-bedded acidic and basaltic tuffs, tuff-conglomerates, and tuff-agglomerates. Unfossiliferous except for locally abundant petrified wood. Upper Oligocene (?)

(d) Caimito formation -- Thinly and thickly bedded tuffs, tuffaceous sandstones, tuffaceous sandstone-conglomerates and limestones. Very sparsely fossiliferous. Upper Oligocene and Lower Miocene.

(e) Bruja Island Dolerite, Cerro Gigante Basalt, and related basic igneous rocks -- Hard, generally moderately jointed, black flows, plugs, and dikes. Lower Miocene.

(f) Gatum formation -- Thickly and massively bedded, variably marly and tuffaceous siltstones and sandstones. Very fossiliferous at intervals. Middle Miocene.

(g) Toro Limestone -- A well-cemented, massive, shell and coral fragment limy sandstone-coquina. Upper Miocene (?).

(h) Chagres formation -- Massive, fine-grained, silty, gray sandstone. Fossiliferous. Upper Miocene (?).

(i) Atlantic muck -- Clays, silts, and fine to medium-grained sands containing much carbonaceous leaf and wood material and the shells of marine and brackish water animals. Pleistocene to Recent.

(j) Chagres gravel and Chagres alluvium -- Clay, silt, sand, and gravel. Stream bottom deposits. Pleistocene to Recent.

TABLE 3 TENTATIVE CORRELATION OF STRATIGRAPHIC COLUMNS, CANAL ZONE*

AGE	Gatun Lake Area FORMATION	Thickness (in feet)	Pacific Area FORMATION
Recent / Pleistocene	Chagres Alluvium & Chagres Gravel and Atlantic Muck	300 +	Chagres Alluvium & Chagres Gravel and Pacific Muck
	-0-0-0-0-0-0-0-0-0-0-0-		-0-0-0-0-0-0-0-0-0-0-0-0-
Pliocene	Missing (?)		Missing
	-0-0-0-0-0-0-0-0-0-0-0-		----
U.Miocene(?)	Chagres Fm.	1500-	Missing
	Toro Ls. (intergrading facies)	500±	Missing
M.Miocene	Gatun Fm.	3000±	Missing
	-0-0-0-0-0-0-0-0-0-0-0-		-0-0-0-0-0-0-0-0-0-0-0-0-
L.Miocene	Chorrera Basalt, Cerro Gigante Basalt, Bruja Dolerite, etc.	1000±	Sosa Hill Basalt
	-0-0-0-0-0-0-0-0-0-0-0-		-0-0-0-0-0-0-0-0-0-0-0-0-
			La Boca Fm.
	Upper Caimito Fm.	1750±	Pedro Miguel Agglomerate -o-o
			Cucaracha Fm.
	-o-o-o-o-o-o-o-o-o-o-o-		-0-0-0-0-0-0-0-0-0-0-0-0-
U.Oligocene	Lower Caimito Fm.	450±	Culebra Fm.
	-o-o-o-o-o-o-o-o-o-o-o-		-o-o-o-o-o-o-o-o-o-o-o-o-
	Basal Caimito / Las Cascadas	300±	Las Cascadas Fm.
	-o-o-o-o-o-o-o-o-o-o-o-		-0-0-0-0-0-0-0-0-0-0-0-0-
L.Oligocene	Bohio Fm. Obispo Fm.	2500±	Obispo Fm.
	? ?base not exposed ?	? ? ?	? base not exposed ? ?
U.Eocene	Gatuncillo Fm. west of Madden Basin only		
	-0-0-0-0-0-0-0-0-0-0-0-		-0-0-0-0-0-0-0-0-0-0-0-0-
Pre-Tertiary	Basement Complex		not exposed

Legend:
- -0-0 Unconformity
- -o-o Local unconformity
- ---- Conformity or disconformity
- _-‾ Intergrading facies
- ? ? Contact not known

* Modified slightly from Jones & Bartholomew, (3) Appendix A.

Basement Complex

The Basement Complex is a pre-Tertiary(?) mass of basalts, metabasalts, tuffs, hornfels, and possibly other rock types. This mass of rock is closely jointed, abundantly sheared, and complexly faulted. Close folding and steep tilting of the sediments appear to have been extensive prior to their secondary induration. All fresh bedrock exposures exhibit chloritization, silicification, kaolinization, and/or other alteration. Joints in the basalt and metabasalt are typically spaced so closely that few sound rock parallelepipeds over two inches on an edge and not containing manganese oxide-stained joints have been discovered. The metasediments are even more closely jointed by platy bedding joints. The rocks are so altered that field differentiation between the igneous and sedimentary rocks in some places is impossible. Exposures of fresh rock are rare because the mantle of weathered material averages 50 feet thick. This mantle is generally undisturbed by creep and most cuts in it exhibit the initial rock structure and texture even though weathered to sandy clay. The Basement Complex is probably part of the Isthmian pre-Tertiary core which has long been below sea level in much of the Gatun Lake Area.

Bohio Formation

The Bohio formation is an early Upper or late Lower Oligocene series of siltstones, sandstones, and sandstone-conglomerates, very hard and massively bedded and jointed. It contains angular to rounded pebbles, cobbles, and boulders locally up to as much as six feet in diameter in a dark gray, generally coarse-grained, angular-grained sandstone matrix. Both the sandstone matrix and conglomeratic fragments are notably basaltic. Some tuff-siltstone interbeds as much as 90 feet thick are present. Exposures of this formation show dips of 15° to 20°. The formation is characteristically transected by basaltic intrusions ranging in width from a few inches to an observed maximum of 200 feet. These intrusions are more or less localized, being very numerous in the vicinities of Gamboa and Darien. They are so numerous and discontinuous, in fact, that only the large ones are mappable units. The Bohio formation in localities containing numerous faults and basaltic dikes has been highly indurated over broad areas by fusion, probably hydro-thermal, and by other intrusive effects. From Darien to Gamboa the overall outcrop picture is one of uneven increase in both coarseness of matrix and angularity of fragments of all sizes. At Darien some welded sandstone-agglomerate is present; at the Obispo High locality some hard, friable sandstone-conglomerate is exposed. But eastward from Gamboa, angularity of fragments and induration of the Bohio formation by basaltic intrusives are progressively greater to the extent that at Obispo Pt. across the Chagres River Bridge from Gamboa and at Bas Obispo and eastward therefrom the rock is considered to be the Bas Obispo (agglomerate) formation. That the Bas Obispo and Bohio formations are stratigraphically equivalent is now apparent through field mapping along the west bank of the present canal in the vicinity across from the town of Gamboa. Here numerous rock exposures have demonstrated a gradual change in character from that of the typical Obispo agglomerate to that of the Bohio sandstone-conglomerate.

The Bohio formation as originally proposed by R. T. Hill (1) was essentially as exposed in quarries at the former town of Bohio Soldado and in French excavations between Orchid and DeLesseps Islands north of Barro Colorado Island and in other exposures now submerged in Gatun Lake. The rocks at the type localities not now submerged are essentially basaltic sandstones and sandstone-conglomerates of the series which are mapped herein as the Bohio formation.

Subsequent to Hill's work, MacDonald described beds containing Oligocene foramenifera and plants which he considered to be part of Hill's Bohio formation. This "thin bed or series of lenses of marly limestone containing Lepidocyclina cannellei Lemoine and Douvile" overlying the Bohio conglomerate beds at "several places in the vicinity of Bohio Ridge" and "known from several other stations in the region of the Canal" (6), are included in the Caimito formation because the evidence now at hand indicates a major unconformity at the top of the Bohio formation of Hill; that is, between the fossiliferous zone described and included in the Bohio formation by MacDonald and the Bohio formation as originally described by Hill.

The unconformity at the top of the Bohio formation is irregular and represents a period of erosion during which the Obispo-Bohio formation land surface was dissected to maturity with a relief of an undetermined number of scores or possibly hundreds of feet.

Olsson considered it "probable that the zone of Lepidocyclina *cannellei* marks a fairly constant horizon lying conformably on the Bohio conglomerate" (6). The writer agrees with him in the stratigraphic position of this zone but substitutes "Bohio formation" for "Bohio conglomerate" and concludes that the zone now appears to be separated from the Bohio formation by a strong unconformity and perhaps locally by a considerable thickness of sediments.

Foramenifera collected by the writer from gritty basaltic sandstone interbeds of the Bohio sandstone-conglomerate were identified (10) as *Lepidocyclina cannellei* Lemoine and Douvile. This fact places the age of this part of theBohio conglomerate as "late lower or early middle Oligocene." (10)

Las Cascadas Formation

The Las Cascadas formation is an Upper Oligocene (?) series of massive to thin-bedded tuffs, tuff-conglomerates and tuff-agglomerates of terrestrial origin. Matrix material ranges from tuff-claystone to coarse, finely agglomeratic tuff. Conglomerate fragments are pebbles, cobbles, and boulders of basalt and pebbles (rarely cobbles) of tuff. Basalt fragments are reworked from the underlying formations. They are generally rounded where they overlie the Bohio formation and sub-angular over the Obispo formation. All surface exposures are deeply and highly weathered. Only the centers of some of the larger cobbles and boulders show sound black basalt in outcrop. Fifty feet of weathered rock overburden is common over this formation. The Las Cascadas formation is a mass of reworked basic material from the underlying Bohio-Obispo formations mixed with proportions ranging from 0% to 100% of the later acidic tuffs and agglomerates. Therefore some outcrops are impossible to distinguish from the supra- and subjacent formations except after consideration of outcrops over a broad area.

Mapping of the Las Cascadas formation is made difficult by its variability and localization. Its distribution and variability are attributed to its origin as a formation of reworked material (in the Gatun Lake Area) and to subsequent erosion, weathering, faulting and intrusion by igneous bodies.

The upper contact is not exposed but is believed to be an unconformity in the vicinity of Gamboa and Darien where overlain by limestone but a conformity in the vicinity of Barro Colorado where it seems to grade up from a tuff-conglomerate into limy tuff siltstone. Where it is conformable under the Caimito formation (apparently north and west of Darien) it has the lithologic characteristics of conglomeratic Caimito tuffs and is mapped with the Caimito formation. Perhaps more detailed study in the future will enable this unit to be separated from the Caimito formation in the northwest Lake Area. On the other hand, the basal Caimito in this area may prove to be a marine equivalent of the continental Las Cascadas formation and be rightfully included in the Caimito formation. At present its age is inferred in accordance with its stratigraphic position with respect to over- and underlying fossiliferous beds.

Caimito Formation

General Character

The Caimito formation is an Upper Oligocene and Lower Miocene series of tuffs, tuff-agglomerates, tuff-conglomerates, and limestones, all medium hard, thinly and thickly bedded and closely to moderately jointed. All are probably marine. Acidic tuff is the predominant constituent of this formation and in discussing it the term "tuff" refers to "acidic tuff". Some beds contain sparse, poorly preserved, marine megascopic and microscopic fossils. The attitude of the beds is highly variable due to faulting and folding. Dips range from 5° to over 40°. The formation is divisible on the basis of lithology into three phases: "basal", lower, and upper.

"Basal" phase

The "basal" phase is a tuffaceous sandstone-conglomerate of local extent containing pebbles, cobbles and boulders of basalt and pebbles of tuff. The basalt fragments are reworked from the underlying Bohio formation. All exposures are highly weathered indicating that this phase of the Caimito formation either weathers very deeply upon exposure or was completely weathered during its deposition. It is present only along thebottoms and side slopes of the Bohio surface where the pebbles, cobbles, boulders, and some of the sand weathered out of the Bohio formation, were reworked and deposited with the first of the tuff which marked the new era of deposition. It is probably a facies of the Las Cascadas formation and should be separated from the Caimito formation when sufficient evidence is available to warrant it.

Lower phase

The lower phase, so-called because the status of the "basal" phase is still uncertain, is a series of slightly fossiliferous tuff-aceous sandstones and limestones. This phase may be local in extent and may intergrade in part with the "basal" phase, although it is more widespread. But whether or not it was originally deposited throughout the Gatun Lake Area has not been determined. The limestone beds within it are, however, discontinuous. The zones of <u>Lepidocyclina cannellei pancanalis</u> and <u>vaughani</u> appear in this phase and are found on the peninsula jutting into Zetek Bay, Barro Colorado Island, in the Panama Railroad cut at the east side of Bohio Peninsula, and at other points indicated on the Map of Fossil Localities, Plate 3.

Upper phase

The upper phase is a widely distributed series of tuffs and tuff-agglomerates, with sandy limestone beds interspersed throughout at irregular intervals. It is the thickest, most widely distributed part of the formation. When sufficiently detailed field mapping, laboratory study, or core drilling, can be undertaken, it may be mappable as another or as more than one other formation. At the present time the entire formation appears to be increasingly uniform and fine-grained toward the west, away from Barro Colorado and Bohio Peninsula, so that in these areas of distribution it is essentially a tuff-siltstone series.

Possible equivalents

The author believes the Pena Blanca Marls and Vamos-a-Vamos beds of earlier writers represent some of the finer grained facies of the Caimito formation in the northwest Lake Area. Conversely, the Caimito formation grades progressively coarser toward the southeast, presumably toward the higher summits of the Continental Divide. Thus the "basal" phase is distinguishable as the Las Cascadas (tuff-agglomerate) formation south of Gamboa. Likewise north of Gamboa the Quebrancha formation (See p. 41) and the "Alahuela formation"(See p. 42) appear equivalent to all or parts of the Caimito formation.

"Caraba member"

A heretofore unrecognized facies presumably of parts of the lower and upper phases of the Caimito formation appears typically exposed along the Rio Caraba southwest of Gamboa and in gullies along the south bank of Chagres Crossing Reach due south of Beacons 29 and 30. The Rio Caraba exposure is good and reveals a thick, massive, very sparsely jointed sandstone-conglomerate-breccia, overlain by a thick section of thin-bedded limestone and limy fine-grained sandstone. The sandstone-conglomerate of the "Caraba member" is composed of angular to sub-angular grains, whose angularity decreases slightly in the larger fragments. Composition is distinctive with a marked preponderance of quartz, hornblende, biotite, and pumice composing the matrix; while the psephytic components are essentially porphyritic and coarse-grained acidic igneous rocks of variable texture and composition but containing much quartz, hornblende, biotite and albite. Rhyolite porphyry, dacite porphyry, and granite are plentiful. Both the coarse constituents and the matrix apparently are derived from a common source. Rhyolite dikes transect the "member" locally. The limestone of the "Caraba member" has the abundant fossils characteristic of the Caimito formation: Lepidocyclina cf. canalis, cf. pancanalis, and cf. vaughani. This sandstone-conglomerate and limestone may later be referred to as the "Caraba formation" or the "Caraba facies of the Caimito formation", whichever is more convenient for local engineering purposes.

Bruja Island Dolerite, Cerro Gigante Basalt, and related basic igneous rocks

Under this heading are included Lower Miocene flows, plugs, and dikes of basic rock, hard and generally moderately jointed. Columnar jointing is pronounced at some localities, such as on the south side of Barro Colorado where columns as much as six feet in diameter have been observed. The most characteristic type of exposure is dark red-brown sandy and silty clay containing spheroidally weathered boulders as large as six feet in diameter with cores of hard, black basalt. The originally basaltic texture is observable in much of the undisturbed clay. The intrusives of this group of rocks are found transecting every formation below the top of the Caimito formation, but the flows are found only on the unconformity over the Caimito formation.

The best hard-rock quarry sites in the Gatun Lake Area are in rocks of this classification. Cerro Gigante and Barro Colorado are believed to be two of the best prospective sites, while Bruja Island and the island northwest of Mesa Verde Island have already been developed. The latter two sites are dikes. Cerro Gigante is a basalt plug similar to Sosa Hill. Barro Colorado is capped by a basalt flow with many associated feeder dikes.

The most promising site for water power development in the entire area appears to be near the mouth of the Rio Ciri Grande. Here the river has cut a deep canyon through a high ridge of basalt just downstream from a sizeable basin probably easily adaptable as a reservoir. The available head of water would be about 300 feet.

Gatun Formation

The Gatun formation is a Middle Miocene series of sandstones, siltstones, conglomerates, and tuffs, all thickly and massively bedded. The siltstones, sandstones, and conglomerates are variably marly and tuffaceous, highly fossiliferous, and massively jointed, with nearly vertical joints spaced at intervals greater than 20 feet. The tuffs are uniformly fine-grained siltstones and claystones, except for local streaks sparsely scattered with pumice, pebbles, and cobbles. Jointing in the tuffs is well developed at moderate intervals. The formation has a known thickness exceeding 1400 feet*, and probably much more. The beds in this area dip in a northwesterly to northerly direction at angles ranging from 2° near the shore of Limon Bay to as much as 20° in a few places near its southeastern border. The depth of overburden and weathered rock averages about 30 feet on this formation. The weathered rock is soft and grades imperceptibly into red clay soil.

The Gatun Third Locks Excavation afforded an unusual opportunity to study a 546-foot section of the Gatun formation. Observations of the sound rock section in this cut are summarized on the following page (Table 4) with bed thicknesses and types of contact indicated. Detailed description of each bed follows the table. The details here recorded are significant in revealing some of the conditions extant in the Isthmian region during Gatun time.

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* (11) p. 20, para. 3-59 "Based on the results of a water well drilled in the Mt. Hope area)".

Table 4 Inter-relationship of Beds exposed in Gatun Third Locks Cut

Bed No.	Bed Letter		Thickness (Variable)	Contacts and other features
12	A	A4	26.2'	Maximum thickness exposed. Top removed by erosion.
				Facies boundary.
		A3	11'	
				Sharp textural contact.
		A2	28'	
				Sharp textural contact.
		A1	5'-0'	
				Sharp contact associated with .2' to .6' fractured zone. Key.
11		B	25'-30'	
				Very gradational.
10		Bco	10'	"Upper Conglomerate."
				Angular unconformity and compositional sharp change. Key.
		Cco	2'	"Upper Conglomerate"
				Very gradational.
9		C	48'-60'	"Blue-grey Sandstone".
				No boundary. Completely gradational.
8		Cg-Du		
				Gradational.
7		Db	20'-12'	"Ash No. 1"
				.5' white tuffbed. Sharp contact below it. Key.
6		Eu	4'	Conglomerate.
				Slightly gradational. Changes in less than 1.0'
5		Eb	38'	
				Sharp contact.
4		Fu		
				Very gradational change.
		Fm	110'	
				Very gradational change.
		Fb		Ash-Ss. interbedded. "Ash No. 2".
				Ripple-marked disconformity, containing .1' to .2' Ss. Key.
3		G	70'	Echinoids, shark teeth, wood, nuts, etc.
				Very gradational. Pumice boulders in gradation
2		H	6'	"Ash No. 3".
				Ripple-marked disconformity containing .1' to .2' Ss. Key.
1		I	102.2'	
				Sharp contact containing 1' Ss-clastic, cr.gr.
		J	27'	
				Sharp contact.
		K	5'	
Total			546'	

Bed A4 Silty Sandstone: Hard; well-indurated; massively jointed; massively bedded; grains uniformly sorted from 1 mm. in diameter to dust size, angular; some euhedral feldspar laths present; local .1-foot thick conglomeratic lenses contain .05 to .1-foot diameter round pebbles of finely vesicular lava and of other materials of basic igneous origin; some fossil molds are present; non-calcareous; some excellent carbonaceous leaf impressions (elm) were found in this bed and are in the Geology Section collection; dull lavender when fresh; weathers to light buff, locally iron-stained yellow and brown; spheroidal weathering is characteristic. This sandstone is different lithologically from all the underlying beds, but it grades laterally into beds A3 and A2. The line of facies change has an apparent dip northward considerably less than the true bedding. Bed A4 thins northward.

Bed A3 Siltstone: Medium hard; jointed slightly more massively than underlying A2, which it closely resembles in most characteristics. Differs from A2 in the following ways; it is coarser-grained; slightly marly; contains more abundant calcareous fossils; contains moderate abundance of carbonized leaves, wood, nuts, etc.; grades into A4 several stations farther north; is less competent. Bed A3 is composed predominantly of clay particles with fragments of rock material similar to tha grains in A4 (but no feldspar grains) and with numerous grains of chalcedonic quartz. Predominantly fine-grained. Beds 1 foot thick grade into each other; most are distinguishable only by color shading from a distance. The texture and weathered appearance of this subdivision is midway between that of A2 and B.

Bed A2 Argillaceous siltstone: Medium hard; fairly well-indurated; blockily jointed with high angle joints in random orientation, averaging 4 feet apart. Joints are tight and impermeable until brought into the influence of weathering. The rock is dark grey when fresh but upon exposure to air it dries to a light grey and checks closely into conchoidally broken pieces of .025-foot diameter (like fissile shale). This siltstone is much more heterogeneous than Bed B, as it is distinctly bedded and some beds of it lense out laterally. Although many of the beds have distinct contacts above and below, bedding and lamination within the individual beds are very poor. Bedding parting is uncommon, and best indication of bedding is the banding of light and dark grey colors of various beds as seen from a distance. The material ranges from medium fine-grained at the top to very fine-grained at the base. Coarse-grained well-indurated sandstone lenses up to .2-foot thick are present locally. This bed grades southward into A4. The waxy lustre of a scratched surface of A2 is characteristic. Non-calcareous; few fossils well-preserved, and plant remains. Probably contains fine-grained ash. Chalcedony is rarer and in smaller grains than in A3.

Bed A1 Sandstone: Lens of sandstone having identical outward appearance of Bed B with the fossils missing. Appears to owe its origin to submarine erosion of the southern upthrown block of a pre-A2 fault now obscured by compaction. The southern edge of the lens strikes N 66° E and crosses the excavation at about its midpoint.

Bed B Calcareous Argillaceous Sandstone: Medium soft; incom-

incompetent; very few widely spaced vertical joints; joints mostly closed. Few bedding plane joints well-developed; these zones are permeable and locally carry water. Massively bedded; matrix homogeneous, medium fine-grained, marly, slightly quartzose, very argillaceous; abundant .05-mm. angular rock grains. The calcareous shells, foramenifera, and carbonized wood fragments are abundant, especially the calcareous shells in zones usually concordant with the bedding, but not demarked by it. Irregular pockets of masses of shells, whole and broken are also common. Lack of orientation of fossil fragments with respect to bedding, even where layers rich in these fragments are obviously parallel to the bedding, suggests disturbed conditions of sedimentation. The basal 10 to 12 feet of this bed are increasingly conglomeratic and fossiliferous downward; the base contains .2-foot subrounded basaltic pebbles, and thick-shelled fossils characteristic of near-shore faunas.

Bed C Tuff-sandstone: Soft, friable, not jointed; even-grained, coarse-grained, angular-grained, cross-bedded. Blue-grey to lavender when unweathered. Commonly weathered to yellow-green or buff. Constitution is chiefly of reworked basic volcanic rock grains, angular quartz, pyraboles, pumice, and other tuffaceous material. Fossils sparsely present only as empty molds. Top 1 to 2 feet is conglomeratic, (C_{co}), decreasingly so downward. Local thin conglomeratic lenses of a few feet lateral extent occur throughout the bed. All conglomeratic pebbles in Bed C are identical to those in the base of Bed B, although the matrices of the pebbles in these two divisions are separated by a sharp contact which is an angular unconformity. This continuity of pebbles through the unconformity suggests the possibility that the basal conglomerate of Bed B is reworked from the top of Bed C. The fine volcanic material eroded from C would have been carried seaward, distributed over a broad area, and hence not be evident in the base of B.

Bed Cg-Du Tuff-sandstone and tuff-siltstone: Medium-soft at top, medium-hard below. Forms gradation without break between sandstone above and tuff below. Grades to fine-grained downward with increase in quantity of .025-foot pumice inclusions, and disappearance of lavender rock grains. The composition change results in color change to light buff. Joints appear at top and become more prominent and plentiful downward. Non-calcareous. Fossil molds sparse.

Bed D_b Tuff-siltstone: Hard, competent, much jointed with vertical joints; impermeable; fine-grained, angular-grained, and even-grained (with exception of .025-foot abundant pumice fragments). Composed chiefly of volcanic glass shards with a few angular quartz grains, clay grains, and indeterminable opaque grains. Few scattered lumps of pumice up to .2-foot in diameter are present. Dark grey-brown speckled with white when fresh; dries and turns white upon exposure, hence all natural outcrops are white.

Beds E_u and E_b Sandstone: Massively bedded, dark grey. Conglomeratic top portion, Bed E_u, about 4 feet thick, grades sharply into lower portion, Bed E_b. Bed E_u about 4 feet thick, grades sharply into lower portion, Bed E_b. Bed E_u is medium-soft, little-jointed, coarse

coarse-grained, even-grained; grains are sub-rounded, opaque, few of quartz. Slightly marly, very friable and loosely cemented. Grains average .5-mm. in diameter. Abundant calcareous fossils in poor state of preservation because of rock permeability. This 4-foot permeable layer permits continuous water seepage which keeps the wall of the cut damp below the D - E contact. Black when fresh, dark blue-grey when dried out upon exposure. Bed E_b - medium-hard; few vertical joints, but .1 to .2-foot permeable bedding joint zones common about 3 to 6 feet apart. Poorly sorted in grain size, ranging from silt size to .5-mm. in diameter. Predominantly medium-fine grained. A few scattered rounded basalt pebbles present throughout. Ashy and slightly marly. Lignitized wood chips, fossil molds and calcareous, poorly preserved fossils all common. Dark grey.

Bed F Tuff-sandstone and Tuff-siltstone: This sequence of reworked volcanic material is coarse at the top (Fu), and grows finer-grained downward, with minor fluctuations from coarse to fine and back to coarse-grained throughout. The prominence of pumice is notable. It is identical in physical properties and composition (as determinable in the field) to the sequence C_{co} to D_b described in the preceding pages. In the sequence C_{co} to D_b, F_u corresponds to C_{co} and C; Fm corresponds to Cg-Du; F_b corresponds to D_b. F_b is the Ash #2 of the old longitudinal profile. F_b differs from D_b in that D_b consists of a single massive bed, whereas F_b consists of alternating beds .5-foot to 3 feet thick, of fine-grained tuff with included pumice pebbles and cobbles and coarse-grained pumice rock with tuffaceous matrix. The fine-grained beds become more prominent downward.

Bed G Sandstone: medium-soft to medium-hard; little-jointed with joints nearly vertical. Bedding very massive. Uneven-grained, very fine to medium-grained. Lignitized wood and calcified vegetable fibers are common. Calcareous shell fragments common, but abundant echinoids are the distinguishing fossil. Perfectly preserved shark teeth are frequently found. Quartz and calcite grains, opaque rock grains, altered ferro-magnesian minerals and glass are all sparingly present. The bed is slightly marly and ashy and of uniform texture to within about 10 feet of the base where the marl gradually disappears, ash increases in quantity, and the grains approach the clay size of Bed H below, into which Bed G grades. This gradation zone between G and H is distinguished by its content of scattered pumice cobbles averaging .4-foot in diameter. Bed G is grey.

Bed H Tuff-claystone: Hard; well-jointed with vertical joints; bedding massive. Extremely fine-grained. Upon exposure to air it dries and develops shrinkage cracks (which may appear after only 15 minutes' exposure). Under continued exposure the cracks form a network of progressively finer texture until the rock disintegrates into many small fragments. No organic remains are present. A scratched surface gives a very waxy lustre. Grain size is so fine (about clay size) that constitution is not determinable megascopically. Bed H is Ash #3 on old longitudinal profile. Dark slate-grey. Contact below is abrupt.

Bed I Sandstone: Medium-soft to medium-hard; joints are few and mostly at a high angle; bedding is massive. Medium fine-grained; silty and marly. Calcareous shell fragments are abundant but in a chalky poorly preserved condition. Orientation of fossils is lacking. Shark teeth occasionally are found perfectly preserved. In general, the texture of this bed is uniform but irregular lenses (seen in cores but not exposed by excavation) of fine-grained ashy character and of hard $CaCO_3$ - cemented quality occur. The bed is dark greenish grey. The underlying contact is sharp and marked by about a 1-foot thick layer of coarse-grained clastic sandstone.

Bed J Sandstone: soft; friable; few joints; bedding massive; tuffaceous; limy with calcareous fossils abundant. Medium fine-grained. Blue-grey. (Seen in cores but not exposed by excavation).

Toro Limestone

The Toro limestone is an Upper Miocene (?) limy sandstone-coquina series, typically exposed at Toro Pt. across Limon Bay from Colon. The entire formation is massively jointed and thickly to massively bedded without bedding parting. It is hard and well cemented with lime except where weathered to a poorly cemented, friable condition.

The matrix of the coquina is coarse-grained sandstone of rounded quartz sand and sand-size shell fragments. The coquina is of angular mollusc and coral fragments, all up to .03- to .04-foot in diameter but averaging .01- to .02-foot in diameter. Both matrix and psephitic fragments range in proportion from 0% to 100% in the various beds. Some of the beds are made up of topset lenses overlying foreset lenses (dipping 30° to 40°), in turn overlying bottomset lenses. The beds themselves have an average dip of 3 $1/2^{\circ}$ to 4° N 45° to 55° W at Toro Pt., the type locality. This formation represents a beach sand deposit presumably laid down by progressive overlaps and offlaps during a period of extensive emergence and submergence between deposition of the Gatun and Chagres formations. The Toro limestone grades upward into the Chagres sandstone.

Chagres Sandstone

Chagres sandstone is an Upper Miocene (?)* sandstone and siltstone deposit, extremely massively bedded, medium soft, and fine-grained. A few calcareous stringers all less than 1 foot thick are present. Practically no open joints exist in this formation. It contains a few fossils, principally pelecypods (Pectens) and gastropods. All fossils are excellently preserved, a few specimens even exhibiting some of the original shell pigmentation. The highly massive nature of the formation makes bedding difficult to determine. One core-drill hole extended for a depth of more than 300 feet into this formation with nearly 100% core recovery without revealing any indication of bedding other than a few thin limestone stringers.

The contact between the Toro limestone and the Chagres formation is gradational where observed in detail in the hills on the southwest

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* Some authors in the past have called the Chagres formation Pliocene (?); but Dall and Woodring now consider optional the choice between Upper Miocene (?) and Pliocene (?) for the age of this formation.

side of the lower Chagres River. Because of this gradational contact the above age was assigned the Chagres formation and for the same reason its dip is thought to be in general gently northward toward the Caribbean Sea at a low angle. No indication of bedding sufficiently well-defined to determine dip and strike in this formation has ever been seen by the writer.

The formation resembles the Gatun formation but is much more massive, does not contain the tuff or conglomeratic beds of the Gatun, and is less fossiliferous. The weathered rock and overburden over the Chagres sandstone average less than 10 feet thick. The overburden is red sandy clay.

Atlantic Muck

The Atlantic Muck is a Pleistocene and Recent formation consisting of swamp deposits, both alluvial and marine, largely composed of clays, silts, and fine sands irregularly intermixed, uniformly soft and weak, and having a very high moisture content.

> As described by T. F. Thompson with reference to its occurrence in the north approach to the new Gatun lock, the muck is divided into four phases. The lower phase, adjacent to its contact with older formations, consists of grey to blue-grey silty clay. The phase deposited in brackish marine waters contains abundant mollusc shells in an organic, black-silt matrix. The littoral swamp deposit is composed of semi-decayed wood and other organic vegetable matter, intermixed with silt, and has a characteristic dark brown to black color. A soft, light grey, weak, plastic clay overlies the organic phase. The four phases intergrade, with sand lenses locally present. The muck was deposited upon a stream-eroded topography of considerable relief. Old core borings reveal depths of over 200 feet for this deposit. Hills of the Gatun formation protrude thru the black muck and in the

area south of Gatun these hills form islands that are completely surrounded by the swamp muck deposits.*

Later observation of drill cores throughout the Gatun Lake Area indicates that the four phases of the Muck as described by Mr. Thompson are present in all thick muck deposits. In addition, the top and bottom phases appear to be thinnest and most widespread; the two middle phases are much the thickest, form the bulk of the formation, and interfinger so extensively that individual drill holes may show interbedding of these two phases. The brackish marine phase is to the north, or downstream from the littoral swamp phase, and interfingers seaward with extensive beds of unconsolidated finger and brain coral fragments north of Gatun.

Chagres Gravel and Chagres Alluvium

These are Recent and Pleistocene alluvial deposits of interbedded clays, silts, sands, and gravels, variably loose to well-compacted. The cobbles and pebbles composing the gravel are very hard and range in composition from basalt to granite. This deposit is found along the old Chagres River valley and its principal tributaries, the Rio Gatun and Rio Trinidad, and along other principal valleys. It intergrades locally with the Atlantic Muck and is included with the Atlantic Muck on Plate 4, p. 58. The boundary of these surficial deposits and the underlying bedrock is generalized from old French maps showing the margins of the pre-Gatun Lake lowland.

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* Condensed by writer from description of Atlantic Muck by Thompson, (11) p. 23.

RECONNAISSANCE STRATIGRAPHY

General Statement

Little known or only locally investigated formations previously mapped in remote areas adjacent to and extending into the Gatun Lake Area deserve some mention and are discussed below:

Gatuncillo Formation

The Gatuncillo formation includes Upper Eocene shales, fine-grained limestones and limy sandstones. It has been described and mapped by Mr. T. F. Thompson for a distance of many miles up and down the Gatuncillo River Valley. Its extent was generalized by the author on Plate 4, p. 58, from a field traverse and from topographic map and aerial photograph studies. Recent identification by R. H. Stewart (9) of Upper Eocene fossils (fossil locality #23, Plate 3, p. 49, from limestone samples taken at the head of Quebrado Chinilla in the Canal Zone prove this area also to be underlain by the Gatuncillo formation. This is the first rock found in the Canal Zone of age established paleontologically as Eocene.

Quebrancha Formation

This formation of Oligocene and Lower Miocene age has been described and mapped in detail by Mr. T. F. Thompson for distances of several miles around the Cemento Panama Plant in the Republic of Panama. Its extent was generalized on Plate 4 by the same method as was the Gatuncillo formation.

"Alahuela Formation"

The "Alahuela formation" is Lower Miocene in age. The author considered this to be the "Alahuela Member of the Caimito formation" in accordance with the statement (to the author on February 4, 1947) by Dr. W. P. Woodring that "the series should be considered the upper member of the Caimito formation of Olssen", inasmuch as "Olssen suggests Alahuela Member as a name for this series" (6). The author has generalized the boundary of this series on Plate 4 from the areal geologic map by Ross and Reeves (7), Plate 6, to show how it fits into the overall picture.

Sabanitas Formation

This is tentatively considered a Middle Miocene (?) continental facies of the basal part of the Gatun formation. It is typically a tuff-conglomerate unconformably overlying the pre-Tertiary Basement Complex. Over wide areas it is deeply weathered to an altered ash and gravel. It is unsorted and massive in type exposures along the Boyd-Roosevelt Highway northeast of Sabanitas. The best exposure yet found of the Sabanitas formation, showing its relation to the Basement Complex, is at Station 324 on the Boyd-Roosevelt Highway. Here the matrix of the tuff-conglomerate is generally white siltstone or silt; the psephitic fragments range in size up to large pebbles and may be classified in three categories: (a) angular chert (resistant vein remnants from Basement Complex), (b) subangular weathered basalt, and (c) subrounded, soft, weathered tuff-siltstone. Elsewhere, as along Puerto Pilon Road and to the end of the Army Road north of Puerto Pilon, it is interbedded with and gradational into the fossiliferous Gatun formation thick-bedded marly tuffs and clastic sandstones. The eastern edge of the Sabanitas formation, where it is bedded, is a shallow water deposit. Dips exposed along Trans-Isthmian Highway - Puerto Pilon Road rather uniformly conform with those of the Gatun formation in the area -- about 10-12° N 30-45° W. The shallow water facies forming the western border ranges from tuff-siltstones (locally shaley with carbonaceous partings) to coarse quartzose sandstones. The latter are conglomeratic with granules which are replicas in miniature of the gravels at the type locality northeast of Sabanitas.

STRUCTURE

The structure of the Gatun Lake Area is dominated by several systems of faults and associated structures, ranging in age from pre-Tertiary to Quaternary. The complete determination of the various fault patterns of the area appears from the writer's present study to be a problem that would require co-ordinated field, map, and aerial photograph study of several years' duration, covering a much larger region than this relatively small area. On Plate 3, p. 49, are indicated the faults which became apparent through the writer's present field, map and aerial photograph study. Discussions with Mr. L. H. Henderson, of the Geology Section, concerning the preliminary phase of his current stereoscopic study of aerial photographs of the Isthmus of Panama, covering the entire Canal Zone and vicinity, indicate that physiographic expressions of some of the major faults transecting the Isthmus become less conspicuous where they cross the Lake Area, and in some instances give the false impression of being features of minor faults in this area. Likewise many of the major faults are far less apparent in this local area than are some of the minor sympathetic ones. Each fault shown on Plate 3 is either indicated by some field evidence, and extended by map and photograph study, or is determined by map and photograph study to be part of a system including faults identified in the field.

The criteria on which field identification of faults was based are: observable bedding offset, slip-plane structures, anomalous dips and rock distribution, and physiographic features peculiar to this area.

Because of the low elevation and extensive surficial deposits of the central part of the area, fewer faults are detectable there than in the higher marginal land.

Based on the evidence of the few exposures visible in bedrock, the faults all are high-angle (hade less than 30°), and most of them show normal but some a reverse component of displacement. More or less of the horizontal component of motion generally is indicated by slickensiding, inasfar as it is observable. The general lack of key horizons, the great abundance of faults, and the paucity of bedrock exposures make field determination of vertical displacement impossible without detailed study. The large displacement of vertical or steeply dipping dikes, such as that of the Juan Grande Peninsula, and the undetectable displacement of flat structures, such as the Toro-Gatun contact along faults, indicate that most are tear faults. The general fault pattern shown on Plate 3 can be resolved into four systems, the inter-relationship of which is not yet completely determined.

All the major faults along which the displacement is apparent show that the northeast, east, or southeast side has moved respectively northwest, north, or northeast, and usually downward with respect to the opposite side.

The general arrangement and curvature of the major northeast-striking fault system make up a pattern which depicts the rotational strain resulting from a stress directed in a west-southwest direction from the northeast around a stable mass to the south-southeast.

The major northwest-striking faults, most of which are concentrated in a belt passing between Pina and Lagarto, are the result of a northwesterly thrust exerted on the northeast relative to a southeasterly thrust exerted on the southwest.

Another major system is apparent in the numerous shorter northerly striking faults, many of which are arranged <u>en echelon</u> in a pattern which reveals a rotational strain caused by a stress from the north exerted in a south-southeasterly direction against a relative counterthrust from the south.

The one long fault striking north 3° - 5° east and extending from the south edge of the area into Limon Bay appears to be unrelated to the other faults shown. It seems to be the result of a northerly thrust from the south with possibly some underthrusting between Escoval and Limon Bay, judging by the scarp topography of the lake shore and the long backslope (dissected to late youth) sloping northwest therefrom.

As yet insufficient study of these fault systems has been possible to enable one to determine their sequence. However, the present topography appears to be at least locally the direct result of Quaternary movement along parts of all systems. Such topographic evidence is the drowning and silting of the major drainage south and east of Lagarto and Pina and of the Trinidad, Chagres, and Gatun valleys; the youthful dome of Barro Colorado Island; and the numerous fault scarps such as those east-northeast from Nuevo Limon, eastward from Gatun, along the south edges of Tigres and Lion Hill islands, and northward from Escoval.

Moreover, the progressively more disturbed condition of the older formations throughout the area, suggests that diastrophism has been practically continuous during all of Cenozoic time.

Table 5 Index to Fossil Localities on Plate 3*

Loc. No.	Formation or Age	Loc. No.	Formation or Age
1	Chagres Fm.	13	Caimito Fm.
2	Toro Ls.	14	" "
3	" "	15	" "
4	Gatun Fm.	16	" "
			Topotype locality for Lepid. vaughani
5	" "		
6	" "	17	Caimito Fm.
7	" "	18	" "
8	" "	19	" "
9	Caimito Fm.	20	" "
10	" "	21	" "
11	" "	22	" "
12	" "	23	Gatuncillo Fm.
	Topotype locality for Lepid. pancanalis	24	" "

* Some identifications by W. P. Woodring (2)

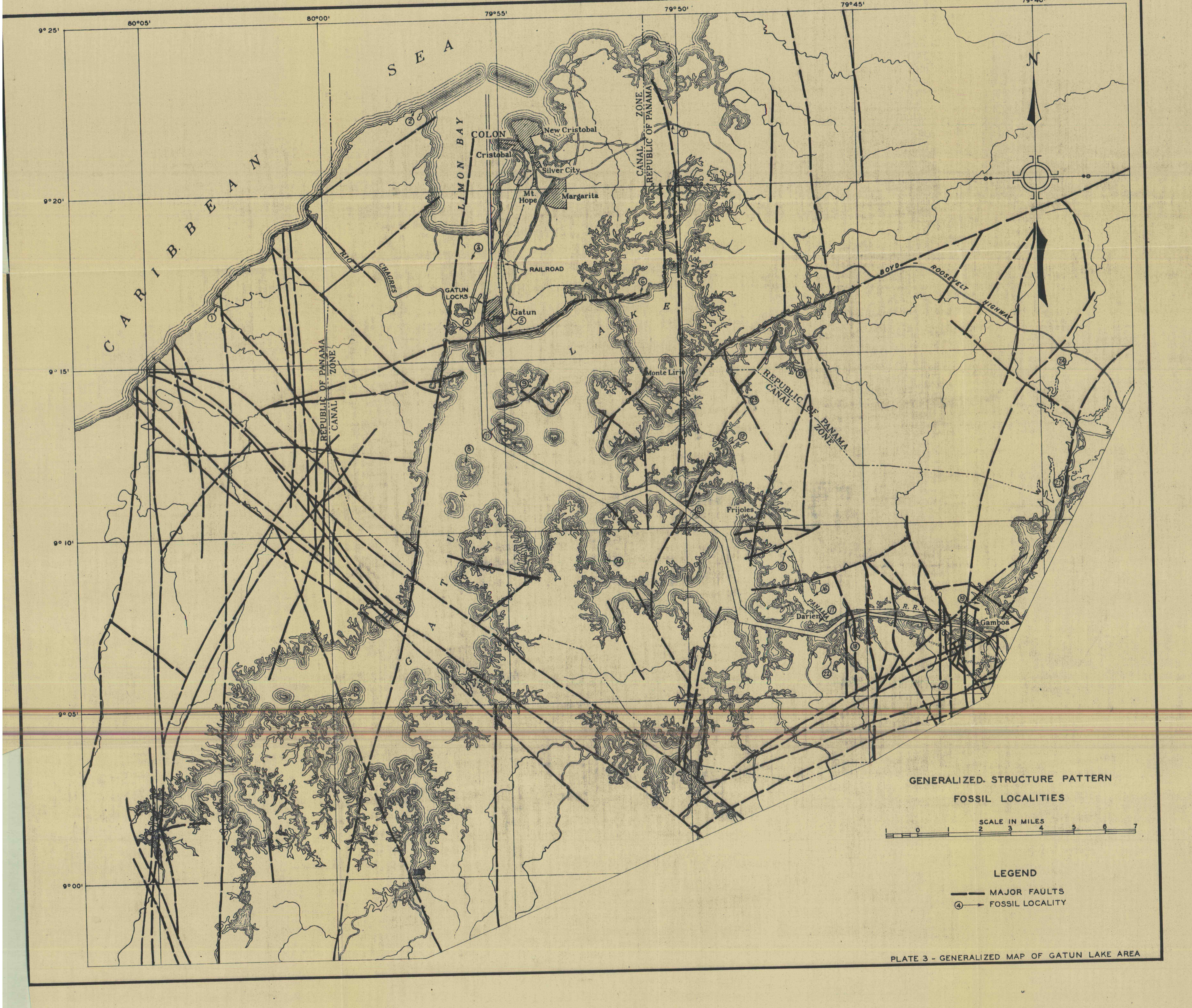

PLATE 3 - GENERALIZED MAP OF GATUN LAKE AREA

GEOLOGIC HISTORY

The oldest rocks in the Gatun Lake Area, the Basement Complex, form a structurally and stratigraphically heterogeneous mass. The common features which unite them under the heading "pre-Tertiary" are:

(a) a major unconformity between their collective upper surface and all younger rock systems;

(b) a major diastrophic hiatus between them and all other rock systems, a hiatus of such magnitude that the structure within the Basement Complex is utterly chaotic whereas the oldest known overlying system, Upper Eocene, is believed structurally decipherable in as much detail as may be desired.

The known history of the Gatun Lake Area therefore opens with the existence of a land mass of unknown shape, formed at an unknown date during one or more of the first four eras of geologic time. This land mass had been subjected variably to much diastrophism, plutonism, and sedimentation prior to Upper Eocene time. During Paleocene or Lower Eocene time it was eroded to a relief of several hundreds or thousands of feet. In Upper Eocene time the area was submerged in part or in whole. Some of the low areas resulting from Paleocene or Lower Eocene erosion are the sites of the sediments now comprising the Upper Eocene Gatuncillo formation, some of which were deposited at ocean depths of more than a thousand feet.

How much more extensive the Upper Eocene inundation was than its deposits now remaining is not known; but the sedimentaries of the Upper Eocene, just as those of the rest of the Cenozoic Era, have not yet been found outside the intermontane areas.

Between the topmost known Upper Eocene (Gatuncillo formation) beds and the lowermost observed Oligocene (Bohio formation) beds is an unobserved section which leaves a gap in the early Tertiary record.

The history is resumed in beds of the Bohio formation which indicate by their character that in at least part of Lower and probably in part of Upper Oligocene time considerable sections of the Gatun Lake Area were submerged and were receiving great quantities of basic clastic sands and gravels from a nearby terrestrial source of high relief. Great regional relief was produced near the end of Upper Eocene time probably by an uplift. Large areas of Upper Eocene deposition may then have been stripped by erosion. During this time slow submergence would have favored formation of a marine deposit like the Bohio formation of very coarse terrestrial sediments like those usually found on the flanks of mountains.

Early in Upper Oligocene time (end of Bohio-Obispo time) much block- and tear-faulting occurred and some basaltic dikes and sills were intruded. The activity was greatest in the southeast, apparently increasing in intensity toward the axis of the Continental Divide. The result within the Gatun Lake Area was partial emergence of a variably block-faulted land surface. During the emergence the land portions were maturely dissected to considerable relief. Then the area slowly sank again. During sinking the violent explosive vulcanism began, inception of which marked the beginning of "Basal" Caimito - Las Cascadas time. This vulcanism centered a short distance southeast of the Gatun Lake Area, was most violent during its earliest (Las Cascadas) phase, and continued intermittently through early Quaternary time. This is as evidenced by rock texture and distribution within the Gatun Lake - El Valle areas. Las Cascadas time ends with the cessation of violent vulcanism, and continuation of faulting, of igneous intrusion and of erosion of emergent areas.

After the violent outbursts of Las Cascadas time the entire area subsided approximately to sea level and comparative quiet ensued during those parts of the Upper Oligocene and Lower Miocene ages represented by Lower and Upper Caimito time. Different parts of the area were slightly above and below sea level during different intervals of these two ages, but the break between Lower Caimito and Upper Caimito time is represented by a geographically more extensive local unconformity than any other break within these two periods. Upper Caimito sedimentation was more extensive and uniform than that of Lower Caimito, probably because of a continuing slight subsidence and of the progress of erosion in lowering relief. Upper Caimito sedimentation was ended during Lower Miocene time by uplift accompanying much additional block- and tear-faulting, emplacement of many basaltic dikes, plugs, and flows, and by much erosion both before and after the igneous activity. Southeast of the southern margin of the Gatun formation no further rock record in the Lake Area exists; and here the second greatest unconformity of the Gatun Lake Area, that between the Gatun formation and the Caimito formation forms the present erosion surface. Continuing southeastward this great unconformity splits into the Caimito formation-

Chorrera Basalt unconformity and the present erosion surface over the Chorrera basalts.

During Middle Miocene time the northwest margin of the area was part of a continental submarine shelf receiving sediments eroded from the Caimito - Chorrera land surface and from contemporaneous intermittent vulcanism in the distant southeast. The numerous local unconformities and variations in texture indicate considerable unimportant diastrophism through Gatun time. Toward the close of Gatun time the ocean receded permanently from much of the land now underlain by the Gatun formation, but fluctuated back and forth over the extreme northwest margin (site of Toro limestone) during Toro time, working over and depositing a thick beach sand. Later in Chagres sandstone time the land subsided very gradually and smoothly.

Following Chagres time the entire Isthmus was elevated during Pliocene (?) time to more than 300 feet above its present level with respect to the ocean. During this time the major drainage lines of today were established. Such rivers as the Chagres, Gatun, Trinidad, Cano Quebrado and Lagarto carved in some places very wide valleys, all to depths below sea level at their mouths and to very low gradients. Because of block-type fault components, uplift was uneven and some of the valleys cut during these Pliocene (?) times were very narrow and deep instead of broad.

During Pleistocene and early Recent time the Isthmus subsided gradually and uniformly to about 25 or 30 feet below its present level with respect to the ocean, and the major Pliocene (?) valleys were drowned and gradually filled with sediments. The drowning and alluviation was accentuated locally by Quaternary faulting, such as that which locally blocks the valley of the Cano Quebrado southeast of Lagarto.

In late Recent time and continuing to the present the area has emerged to the total extent of about 25 feet with respect to sea level. This emergence has been scarcely enough to do more to the topography than convert large areas of marine, brackish and fluvial lagoons to mangrove swamps.

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APPENDIX 1 PALEONTOLOGICAL AIDS TO FIELD MAPPING

1. Lepidocyclina chaperi & gigas are common in Eocene sediments such as the Gatuncillo formation. The former is saddle-shaped, about .075- to .1-foot in diameter. The latter is discoid and generally somewhat larger. Discocyclina sp. are also abundant.

2. Lepidocyclina cannellei, (no pustules), Lepidocyclina pancanalis, (fine pustules), and Lepidocyclina vaughani, (coarse pustules), all are common in limestones, limy siltstones, and limy fine-grained sandstones of the Lower Caimito formation. The specimens are about dime-size with central portion about lentil-size.

3. Siphogenerina transversa is sparsely present in the Lower and Upper Caimito formation.

4. Excellently preserved fossilized wood (chert) is common as float (lag gravel) over some areas of Las Cascadas and Caimito formations. However, since similar silicified chert logs have been seen in bed-rock of the Bohio formation, such float is not an infallible criterion for use in mapping.

5. The Gatun formation is the most fossiliferous in the Canal Zone. Familiarity with the faunal assemblages visible in fossil localities of the Gatun formation, indicated on Plate 3, makes this formation easily recognizable in any fossiliferous area.

6. The Toro and Chagres formations are characterized by a predominance of Pectens, some as much as .4-foot in diameter.

PLATE 4 - AREAL GEOLOGY MAP - GATUN LAKE AREA AND VICINITY, CANAL ZONE - APRIL, 1947