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DOMINICAN REPUBLIC
INSTITUTO NACIONAL DE AGUAS POTABLES
Y ALCANTARILLADOS

THE STUDY ON GROUNDWATER DEVELOPMENT PROJECT IN THE WESTERN REGION DOMINICAN REPUBLIC

VOLUME III

SUPPORTING REPORT

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SUPPORTING REPORT A

GROUNDWATER DEVELOPMENT PLAN

SUPPORTING REPORT A

GROUNDWATER DEVELOPMENT PLAN

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CHAPTER I

INTRODUCTION

1.1 Objectives of the Study

The objectives of the Study are to evaluate the potentiality of groundwater resources and to prepare a water resources development plan in the four western provinces of Dominican Republic: Monte Cristi, Dajabon, Elias Piña and Independencia, on the basis of various hydrological and hydrogeological investigations.

1.2 General Conditions

1.2.1 Landforms and Geology

The Hispaniola is the second largest island of the Greater Antilles, after Cuba. The Dominican Republic occupies 74% of the eastern part of the Hispaniola, with a surface area of 48,442 km^2. It is bordered by the Atlantic Ocean to the north, the Caribbean Sea to the south, the Mona Passage to the east separating it from the neighboring island of Puerto Rico, and the Republic of Haiti to the west.

The country is traversed by four main mountain ranges. The first is the Cordillera Central which runs from Haiti and cuts through the central territory to reach south including the highest peak in the Antilles (Pico Duarte, 3,175m). The second is the Cordillera Septentrional which runs parallel to and north of the Cordillera Central separating Cibao Valley from the Atlantic Coast. The third is the Sierra de Neiba which runs parallel to the Cordillera Central forming the San Juan Valley, and the last is the Sierra de Baoruco in the southern part of the island. The Enriquillo Basin, of the salty Enriquillo Lake which is 40m below sea level, is located between Sierra de Neiba and Sierra de Baoruco.

Many rivers are distributed in the country dividing it into 14 major hydrological subdivisions. The Yaque del Norte and Yaque del Sur rivers form the main drainage systems of the country.

The geology of the country is mainly composed of basal metamorphic complex of unknown age in the western and central area, and of Mesozoic and Cenozoic formations which are widely distributed in the northern, the eastern, central and southern area. These rocks and formations are arranged and elongated in a direction parallel to that of the main mountain ranges.

1.2.2 Water Resources

The Dominican Republic has a topography rich in variation, which is reflected in its changeable climate ranging from humid regions with heavy rain to dry regions with little rain. The mean annual rainfall exceeds 1,400 mm, but actual rainfall ranges from 350 mm in Enriquillo Valley to 2,750 mm in Laguna de Limon, reflecting regional differences and variable seasonal distribution.

Generally, the driest month is March and the rainiest month is May. The period from December to March is ordinarily dry nationwide, with the exception of the northern (Septentrional) mountain range. The semi-arid zone, which widely covers the country, has a mean annual rainfall of less than 1,000 mm.

In 1983, the Dominican Government executed a nationwide evaluation of the potential of surface water and groundwater resources.

Groundwater is the safest available water resource used by rural residents as domestic water, however, its development and utilization have not been systematic. Furthermore, according to the above mentioned survey the development potential of groundwater is high and a detailed study is being proposed in order to proceed with its development and utilization.

In accordance with the above objectives, the Dominican Government formulated an integrated development plan for seven western provinces including the Study Area. This is the background of this study.

1.3 Scope of the Study

1.3.1 Study Area

The Study Area is located in the western region of the Dominican Republic and covers four provinces, namely Monte Cristi, Dajabon, Elias Piña and Independencia which are bordered by the Republic of Haiti on the west.

The Study Area is situated between 71°00 and 71°45 of west longitude and between 20°00 and 18°15 of north latitude. The area lies in a N-S direction with a length of 200 km, the widest at 77 km and narrowest at 20 km and an area of 6,527 km^2.

Annual rainfall in the Study Area averages 1,500~2,000 mm in the mountain area, and 700~1,000 mm in the plain.

Although the Study Area is blessed with abundant water resources, it is hindered by its geographical and topographical conditions. The development of water for domestic use, especially for the rural villages, and the improvement of social infrastructure are lagging behind.

Based on these circumstances and physical conditions, various hydrogeological investigations were carried out to clarify the existing groundwater conditions and to evaluate them for the development plan in this Area.

1.3.2 Study Components

The Study is comprised of the following:

1) Collection, review and analysis of all data and information relevant to the study.

2) Geological survey
   Geological field reconnaissance and interpretation of LANDSAT images and air-photographs together with existing information were used to produce geological and hydrogeological maps at a scale of 1 : 100,000.

3) Geophysical prospecting
   Detailed geophysical prospecting was conducted where test drilling had been planned, according to the results obtained from the geological survey.

4) Test drilling
   The location of test wells, were specified through discussions between the INAPA representatives and the JICA Study Team on the basis of survey results obtained during geophysical works.

5) Pumping test
   Pumping tests were implemented to determine the values of permeability coefficient, transmissibility coefficient and specific capacity in relation to water yield and drawdown.

6) Water quality analysis

Groundwater analysis were carried out after completion of the pumping tests in all test drilling wells.

CHAPTER II

REMOTE SENSING

2.1 Outline of the Remote Sensing Technique

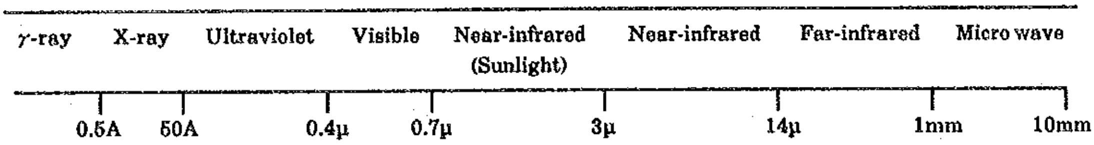
During the short-term field survey conducted in the wide Study Area, the geological and topographical investigations were carried out using the available remote sensing data, such as satellite images and aerial photographs.
Outline of the remote sensing technique is explained below.

Remote sensing refers to a technique which collects the reflecting or radiating electromagnetic waves from the surface, by using sensors mounted on a platform such as an aeroplane and a satellite, to provide information about the subjects and phenomena.
Remote sensing can provide data on information in a wide area within a short period.
These data are processed and analyzed for various types of investigations and are of immense help in understanding the geology, landforms, vegetation cover, and so on, of a whole area.
Platforms for data collection may be a satellite, an aeroplane, or a special ground vehicle.
Sensors used for remote sensing include camera, scanner and TV camera.
Remote sensing utilizes a wide range of waves from γ rays and millimeter waves to centimeter waves. The ranges most commonly used are the visible light range and the near-infrared and thermal infrared range.
Collected data are processed to analog data such as photographs and digital data for analysis by a computer. Analog data such as photographs provide easy understanding of the location and distribution of subjects. On the other hand, digital data which are subjected to image processing, such as automatic classification by a computer and image stressing, can be changed to different types of image, such as false color image, and can present the subject in different aspects.

2.2 Principle

All subjects (substances) carry inherent reflection characteristics of electromagnetic waves depending on their kind, and the intensity of the reflected electromagnetic wave is measured for every wave length from a satellite or an aeroplane to identify substances on the earth surface. This is the principle of remote sensing.

Electromagnetic waves are termed in accordance with wavelength bands. The wavelength region used in remote sensing covers the range from ultraviolet rays to microwaves as shown below.



2.3 Flow of Analysis

Remote sensing is subjected to analysis consisting of (1) data collection, (2) data processing/analysis, and (3) application to survey.

2.3.1 Data collection

1) Purchase from major agencies concerned
   1. LANDSAT Satellite data
   2. NOAA Satellite data
   3. SPOT satellite data

2) Data collection by photography/observation
   Data at the level of aeroplane

2.3.2 Data Processing/Analysis

1) Data processing techniques

   (1) Computer processing-based technique (Digital processing technique).

   (2) Photo processing technique (Analog processing technique)

2) Data analysis techniques

   (1) Analysis based on dialogue between an analyst and an image analysis system by computer

   (2) Visual interpretation by the analyst
   Visual interpretation using photos (for instance, extraction of geological structures)

2.3.3 Application to Survey

1) To be used as preliminary information for the survey

2) To be used when check-ups and corrections are to be made in the field survey

3) To be used for the preparation of necessary thematic maps

2.4 Remote Sensing Data

2.4.1 Types of Platforms

Currently used platforms are grouped into 1) satellite, 2) aeroplane, and 3) ground.

1) Satellite
Table 2.4.1 summarizes the details of major satellites used for earth observation.

2) Aeroplane

(1) Bimotored aeroplane – MSS for aeroplane mounting
(2) Single-engined aeroplane – Aerophotos
(3) Helicopter – Oblique photos

3) Ground Platform

(1) Crane vehicle — Observation of reflection-characteristics and radiation

(2) Cherry picker — Characteristics of substances

2.4.2 Types of Sensors

Figure 2.4.1 shows the relation between the ranges detected by currently used sensors and electromagnetic waves.

1) Camera

Aerial photographs are grouped as follows, according to combinations with films and filters to be used:
Panchromatic photo:
The visible ray range is recorded in a panchromatic film.

Color photo:

The visible ray range is recorded in a color film.

Infrared color photo:

Of the visible ray range, green and red lights and near-infrared rays are recorded in a color film.

2) MSS of LANDSAT Satellite

A MSS is a scanning type radiometer called Multispectral Scanner (MSS), which records visible rays (green and red rays) and near-infrared rays with 4 different wavelength bands. MSS is the sensor mounted on LANDSATs No. 1 to No. 5, and records 180km×180km as one scene, with the minimum resolution of approximately 80m×80m.

Band 4 = 0.5 - 0.6μm (Green light of visible rays)
Band 5 = 0.6 - 0.7μm (Red light of visible rays)
Band 6 = 0.7 - 0.8μm (Near-infrared rays)
Band 6 = 0.8 - 1.1μm (Near-infrared rays)

3) TM of LANDSAT Satellite

A Thematic Mapper (TM) is a scanning type radiometer similar to MSS, and records visible to far (thermal) infrared rays with 7 different wavelength bands. It has been mounted on satellites after No.4. TM records 180km×180km as one scene, with the minimum resolution of 30 m×30m.

Band 1 = 0.45 - 0.52μm (Blue light of visible rays)
Band 2 = 0.52 - 0.60μm (Green light of visible rays)
Band 3 = 0.63 - 0.69μm (Red light of visible rays)
Band 4 = 0.76 - 0.90μm (Near-infrared rays)
Band 5 = 1.55 - 1.75μm (Middle infrared rays)
Band 6 = 10.40 - 12.50μm (Far infrared rays)
Band 7 = 2.08 - 2.35μm (Middle infrared rays)

4) HVR of SPOT Satellite

This is a sensor mounted on SPOT Satellite launched by France. HVR is an abbreviation of High Visible Resolution imaging instrument. HVR produces two types of data.

Panchromatic mode:	Record 0.51 - 0.73μm with black-white single band
Multispectral mode:	Band 1 = 0.50 - 0.59μm
	Band 2 = 0.61 - 0.68
	Band 3 = 0.79 - 0.86

5) MSS for Aeroplane Mounting

This is a MSS of a similar type with MSS of LANDSAT mounted on an aeroplane. The MSS records visible rays to far (thermal) infrared rays from low altitude in higher precision than that of LANDSAT MSS.

This sensor is widely used including in areas of water temperature survey and geothermal survey.

2.5 Collected Data for the Study

The satellite images and airphoto-interpretations were introduced in this Study in order to prepare a geological map.

Landforms, land use and vegetation conditions were also studied.

Collection of all data relevant to the Study is described and listed below.

2.5.1 LANDSAT Images

The index map of the LANDSAT images is shown in Fig. 2.5.1. In this Study, the following LANDSAT TM-5 data (digital data) were employed:

Path 008; Row 046 to 047

Date; October, 06, 1987

2.5.2 Aerial Photographs

The index map at the employed panchromatic aerial photographs is shown in Fig. 2.5.2 and in Table 2.5.1.

2.5.3 Topographic Maps

The base maps on a scale of 1:100,000 used for the Study were maps compiled from the 31 sheets at a scale of 1:50,000 indicated in Fig. 2.5.3 and Table 2.5.2.

2.6 Analytical Method

2.6.1 Interpretation of Satellite Images and Aerial Photographs

Using the LANDSAT images, the drainage system, ridge system, photo-lineament and other elements were interpreted on an overlaid film.
The aerial photographs were interpreted, with attention to detail, under the stereoscope on the areas where a satellite image was not clear.
The accuracy of the photo interpretation was improved by the ground-truth along the main routes in the Study Area.
The elements listed below were interpreted mainly from the viewpoint of photo-geology.

Kind of Image	Method	Elements of Photo Interpretation
LANDSAT (False color)	Mono-scopic Observation	Major landforms, relief, structural landforms, ridge system, ridge forms, drainage pattern, drainage density, photographic texture, photographic color tone, photographic lineament.
Aerial Photographs	Stereo-scopic Observation	Micro relief, photographic texture, photographic tone, photographic lineament, drainage pattern, drainage density, cuesta, pediment, pediplain, karst landforms, fan, talus, terrace, coral reef, erosion surface, landslide, plain, basin, flood plain, marsh, lake. Fault, anti-and synclinal structure, scarp, vegetation cover (distribution and density) - forest, grass land, bare land, savannah, desert, plantation, cultivated land, main roads, built-up area.

2.6.2 Computer Image Analysis of LANDSAT-TM Data

The LANDSAT TM data are obtained in the form of CCT (computer compatible tape), which can be processed by the digital image analysis system to produce the desired images.
The flow chart of the analysis used in this Study is shown in Fig. 2.6.1.

The original LANDSAT data have various deformations. Geometric correction is made to the original data to convert the coordinates so that they may positionally coincide with topographic maps. To make the geometric correction to the LANDSAT data, it is necessary to determine the ground control points (GCP). Conspicuous points (like water fronts, rivers and roads) on both images and topographic maps are selected as ground control points. Coordinate conversion is made to the ground control points which were selected by measuring the coordinates on both images and topographic maps. Given the topographic coordinates (x, y)

and image coordinates (u, v), the conversion is made according to the following formula:

$$x = au_1 + bv_1 + c$$
$$y = au_2 + bv_2 + c$$

where a, b and c are unknown quantities to be estimated by the method of least squares from the coordinates of four (4) or more ground control points.

2.6.3 False Color Image

For this Study, land cover classification image and water content classification image are necessary in addition to the principal component image.

The geometric correction is then followed by the preparation of false color images, the color synthesis of three bands (Band 2, 3 and 4) out of seven bands of TM data.

The relation between the No. of Band and synthesized false color is shown below.

No. of Band	Wave Length Range		Synthesized false color
1	0.45~0.52	Blue light of visible rays	——
2	0.52~0.60	Green light of visible rays	Blue (B)
3	0.63~0.69	Red light of visible rays	Green (G)
4	0.76~0.90	Near-infrared rays	Red (R)

Characteristic of the false color image is to redden the appearance of near-infrared rays. Near-infared rays reflect high vegetation activity, but are absorbed in water.

A better interpretation can be, therefore, obtained from a false color image where distinction of water areas and degrees of vegetation activity are precisely visualized than from a real color image (synthesized from only visible rays of Band 1, 2 and 3).

Color tone and conditions of the earth surface required for a false color image are as follows:

Objective	Color Tone of Image
Water (normal)	Black~Dark blue
Water (contaminated)	Blue~Light blue
Marsh	Black~Dark blue~Dark brown
High activity Vegetation	Red~Crimson
Low activity Vegetation	Brown~Khaki
Burn-up Farmland	Black
Built-up Area	Blue gray
Sand	White~Yellow
Clay	Dark brown~Dark blue
Granitic Rock	Light color
Volcanic Rock	Dark color
Limestone	White~Very light color, sometimes dark
Sandstone and Mudstone	Sandstone is lighter than mudstone

Land cover classification image is prepared by classifying the false color image in accordance with the training fields (the areas where land cover is already known, and are called trainers).
On the other hand, water content classification image is prepared by level slicing for Band 6 which is near-infrared and absorbed in water.
The principal component image at a scale of 1:100,000 was prepared by edge emphasis technique to clarify the boundaries of land use, geology, topography, and others.
Example of the three (3) kinds of image mentioned above are shown in Figs. 2.6.2~2.6.4.

CHAPTER III

LANDFORMS

3.1 General Conditions

The western region of the Dominican Republic, which is the Study Area, is formed of mountain ranges extending from the northwest to southeast direction, and hills and plains alternating systematically from north to south. From the north, these mountains and plains can be classified into the following seven geomorphic provinces such as 1) Cordillera Septentrional, 2) Llano de Yaque del Norte, 3) Cordillera Central, 4) Valle de San Juan, 5) Sierra de Neiba, 6) Cuenca de Enriquillo, and 7) Sierra de Baoruco.

The distribution of ground elevation, the landform classification and land use in the Study Area are indicated in Fig. 3.1.1 to Fig. 3.1.3 respectively.

The Cordillera Septentrional faces the Atlantic Ocean forming long and narrow hilly-mountainous districts with 200~300m elevations above sea level. The study area has limited rainfall throughout the year and thinly wooded fields full of cactus which are mostly used for pasture. Some of these fields are partly used for tobacco production.

The Cordillera Central is the largest in the Republic, extending from the Republic of Haiti to the Santo Domingo area, the capital city of the Republic. There are 23 mountains in the Republic with an elevation of more than 2,000m. The Pico Duarte Mountain the highest in the Republic with an elevation of 3175 meters.

The Study Area is comparatively low near the drainage divide of Rio Dajabon flowing north and Rio Artibonito flowing south west, both rivers forming the boundary of the Republic of Haiti. A road is constructed across the lower area of the mountain ranges and small towns and villages are made along the road.

The Sierra de Neiba and Sierra de Baoruco are the southeast extensions of the Haiti Mountains. The ridges of these mountains are elevated up to more than 2,000m. The geology of both mountains are composed of limestones, while the tectonic valleys ascribed to the plate tectonic movement and the karst landforms are clearly observed.

The Llano de Yaque del Norte is located between Cordillera Septentrional and Cordillera Central. The Yaque del Norte river flows west and forms a wide plain of about 50m in elevation.

Rio Masacre and its tributaries Rio Dajabon and Rio Chaquey, and the main tributaries of Rio Yaque del Norte such as Rio Maguaca, Rio Guayubin, Rio Caña and Rio Gurabo are distributed at the north slope of the Cordillera Central. They provide the rainwaters of the Cordillera Central to Rio Yaque del Norte throughout the year. As a result, a large scale plantation is being managed in Llano de Yaque del Norte making the area the leading granary region of the Republic.

Valle de San Juan is located between the Cordillera Central and Sierra de Neiba. Rio Macasia is joined by the rivers of the southern and northern mountains and flows west to the central area. The basin of Rio Macasia and its tributaries are formed from wide plains and the hill-like landforms surrounding the plains. With an altitude of 200~300m, the plain is mainly used for cultivation and pasture. Furthermore, the hills of 300~400m in elevations are mainly used for pasture.

Between the Sierra de Neiba and Sierra de Baoruco is Lago Enriquillo, a lake with an elevation of –40m. This is a graben area formed from tectonic movement. The side of the mountains facing the graben forms a steep slope. Due to this arrangement, many rivers flowing down from both mountains form large alluvial fans at the exit of the graben.

3.2 Drainage System

Fig. 3.2.1 shows the drainage system around the Study Area.

In the Cordillera Septentrional, small-scale drainage systems are streaming down south ward in a parallel pattern. However, they become intermittent streams in the dry season owing to their very small accumulation (catchment) area and low rain volume (600-700 mm/year).

The Rio Yaque del Norte is a major river with a total catchment area of 7,000 km^2. Its upper stream, which covers two-thirds of the total area, extends over the Study Area.

The catchment area excluded from the Study Area includes the catchment area of large tributaries such as Rio Bao, Rio Amina, Rio Mao, and the upper streams of Rio Gurabo, Rio Caña and Rio Guayubin mentioned before.

The existing dams for agricultural use, water intakes and irrigation canals were implemented for the whole catchment area, making the evaluation of discharge and water balance in the Study Area very difficult.

Rio Artibonito and its tributaries contain relatively high discharge originating from the abundant rainfall (2,000 to 2,200 mm/year) in the Cordillera Central, and form a deeply transversed valley.

Half of the Rio Macasia catchment area also extends over the Study Area. No large rivers are distributed to the south of Sierra de Neiba. To the north and south of Lago Enriquillo, groundwaters passing through the karst mountain, fans, and old coral reef spring out in many places.

3.3 Landform Classification

3.3.1 Outline

The landform classification in the Study Area was carried out based on interpretation of false color images and aerial photographs, topographic maps and field observations (see Fig. 2.6.2 and 2.6.3).

As shown in Fig. 3.1.1, mountains (dense contour line, dark color) alternate with hills and plains (less dense to rough and white) in a NWW-SEE direction.

Each mountain, hill, and plain zone is clearly distinguished even on a false color image, as shown in Fig. 2.6.2. The Central part of the mountains shows a dark red color, while high activity forests appear to be widely distributed. Portions slightly pale on the fringe seem to indicate less vegetation.

The ridge and drainage pattern in the mountain can be clearly interpreted, and form eroded landforms.

Hills and plains are displayed in blue to dark blue owing to the high water contents of the soil. Different false color tones range in accordance with the degree of cultivation, vegetation cover and water contents.

Based on the ground elevation, topographic features, additional land cover conditions and geological conditions, it may be reasonable to classify the landforms of the Study Area into seven morphologic provinces, as described in 3.1 (General Conditions).

3.3.2 Characteristics of each Morphologic Provinces

1) Cordillera Septentrional

The eastern mountainous region is characterized by high relief, more or less steep mountains with an altitude of less than 700m above sea level, which progressively turn into low dissected hills in the west with an altitude of 40m above sea level.

Planation of flat and low relief range from the Central part to the west, where cultivated areas and residential areas have been developed. The main villages can be found in this Area. The slopes facing the Atlantic Ocean are comparatively steep, and a marsh of mangroves are distributed along the sea coast. Dissected hills and a very gently sloped plain are extended on the south of the planation and are almost covered by poor vegetation of savannah type.

2) Llano de Yaque del Norte

In the south side area of Rio Yaque del Norte, a triangle-shaped plain is distributed with an altitude of 0~50m above sea level, extending to about 20 km in the N-S direction and more than 30 km E-W.. This is the alluvial flood plain of Rio Yaque del Norte.

Rio Yaque del Norte has a violently meandering main channel and many small buried channels. Along these channels, many traces of flood are observable by airphoto-interpretation.

This wide and flat plain has been developed into rice fields, cotton farms, vegetable farms, large-scale banana plantations and urban areas. Many irrigation canals are widely distributed in the area, too.

Near the sea coastal zone, a marsh and a desert-savannah area are distributed and also used for large-scale salt field.

Sea coast forms barrier beach, and offshore coral reefs are distributed along the coast line.

In the southern sector of this flat land, the hills and intra-hill low lands, elevated to less than 100m above sea level, are widely distributed with very gently undulating slopes and low relief. This area is composed mainly of Tertiary system.

A dissected hilly and mountainous zone with an altitude of 100~200 m above sea level and a relative height of 100 m inclining diagonally to Rio Chaquey, Rio Maquaca, and Rio Guayubin at approximately 15 km from SE Dajabon, with a width of 2-5 km and a length of 20 km, can also be found in this area. This zone shows somewhat contrastic dissected relief surrounded by flat and low relief of Tertiary area.

This zone is composed of rocks older than the Tertiary system and is assumed to be a part of the marginal pediment zone of Cordillera Central.

3) Cordillera Central

The Cordillera Central is a mountain range extended southwards from the city of Dajabon to Banica at approximately 50 km. This region consists mainly of upper Mesozoic to lower Tertiary rocks. The highest elevation in the Study Area is 1,990m above sea level, and the maximum relative relief is 1,500m. Cordillera Central is divided from north to south into 4 morphologic unit zones.

- Hill~mountain subzone mainly composed of platonic rocks
- Mountain zone presenting a complex of contaminated rocks and sedimentary rocks.
- Mountain zone consisting of sedimentary metamorphic rocks.
- Mountain zone made of limestone.

(1) The plutonic rock mass extends in the south of the national road which passes by the cities of Dajabon, Santiago de la Cruz and Santiago Rodriguez, and around Loma de Cabrera. It is distributed at an elevation of less than 500m, and lies at the upstream basins of Rio Masacre, Rio Chaquey, Rio Maguaca and Rio Guayubin.

The ground surface is severely subject to deep weathering and laterization, and weathered zones of several meters to more than 10m thick are observed. Surface erosion rapidly progresses forming hilly undulating landforms of flat relief where dendritic drainage pattern predominates.

Some small scaled but deeply U-shaped valleys can be observed too. Vegetation is comparatively poor.

(2) These mountains with an altitude ranging from 500 to 1,000m are distributed south of the above mentioned rock mass, and characterized by many steep ridges, a predominating dense dendritic drainage system and a pattern of fine wrinkles. The morphological features clearly differ from the flat, smooth landforms pattern of the (1) zone, and several big scaled lineaments such as tectonic lines, faults, and topographic

boundaries are distributed in this zone. A large scale tectonic line borders this sector and the south of the (3) zone.

(3) Distributed 15 km in width from the south of Restauracion to the north of Pedro Santana, this mountain zone is located in the south of the (2) zone, and consists of Mesozoic formations of shale, slate, phyllite, and others.
The northern sector is made of high-relief mountains, and slightly round ridges or mountainsides. The upstream tributaries of the Rio Artibonito draw incised meanderings in deep valleys.
A great part of the forests that formerly covered this area was destroyed by felling and burn-away cultivation practices, leading to the widespread of grassland and sparse forests.
The southern sector chiefly consists of phyllite and forms the landforms of low relief hills and plateaus. A very dense dendritic drainage pattern is observed in this area.

(4) These limestone mountains form a distinct morphologic boundary with the south side of the above zone, and show more or less dissected landforms in the Study Area. However, the eastern mountain ranges, elevated from 1,000 up to 1,500m and more, are high relief, rounded mountains.
From the above descriptions it can be concluded that the litho-facies of rocks, which composing the mountain ranges of Cordillera Central are well-reflected in the landforms, geological structures, and degree of weathering.

4) Valle de San Juan

This area is located between the Cordillera Central and Sierra de Neiba, forming dissected hills and plain of 15 to 20 km wide and 300 to 500m in elevation, and occupies the west end of the Valle de San Juan.
Hills consist of the alternating beds of sandstone, shale and conglomerate of Tertiary period and form the catchment area of Rio Masacre.
The western part is predominated by the conglomerate of the upper horizon, and indicates morphologic features such as low relief, smooth ridges, a small-scale dendritic drainage pattern, and dissected ring ridges. In the eastern area, east-westward Cuesta caused by

alternating beds are particularly observable.
Flood belts about 100m up to 300m are observed along the channels of Rio Macasia and a river terrace is partly formed in this area. The surface pattern appears very smooth.
Gently undulated to flat plains, with a width of 3 to 5 km and a length of 25 km, are distributed from Elias Piña in a NW-SE direction and are dissected by rough dendritic drainage systems or used for cultivation.
The overall observation of the west of Valle de San Juan showed a distribution of hills encircling the plain of Elias Piña on the north, west, and south edges with the north-west being relatively elevated. The south-east is dissected and shows a formation of cuesta. Geologically, the upper part of the pitching anticline gently pitches north-westwards and appears to be an eroded area.

5) Sierra de Neiba

The Sierra de Neiba is mainly composed of limestone, and is distributed in a NWN-SES direction, extending 30 km from Elias Piña to the north coast of Lago Enriquillo.
This is a large relief mountain range with a relative height ranging between 1,700 and 2,200m. The highest elevation above sea level in the Study Area is 2,200m.
Sierra de Neiba is divided into four parallel sub zones according to the disparity of topographic features.

(1) The south of Elias Piña where the elevation ranges from 800~1,200m is distributed with 4~5 km in width.

(2) These flat-topped dome-like mountains are located in the south of the above sub-zone (1) with a 10 km width and is indistinctive fault contact with sub-zone (1). The highest altitude is 1,700m above sea level, and the relative height is 500~900m. The summit is covered with relatively rich vegetation. The south edge is a steep slope forming the upstream Valley of Rio Caña that runs by El Cercado and Hondo Valle. Its width is 2 km (west) to 6 km (east), and its length exceeds 25 km.
Mountains of the eastern half are elevated to less than 1,000m and topographically characterized by a cuesta with a relative height of 200m. The western half shows intramountain lowlands sandwiched in between limestone mountains.

(3) This is the main zone of Sierra de Neiba. The northern edge consists of round mountain ridges, slightly dissected, extending to 2~3 km wide with an altitude of less than 1,500m, and followed by a Cuesta. The vegetation cover is poor.

Then a southern flat-topped zone succeeds to the steep slopes of the mountains.

These 3~4 km wide plateaus are distributed in an E-W direction. Elevation ranges from 1,500~2,000m. Located on the west side, Loma La Tasajera del Chivito is a gently undulated plateau endowed with an abundant vegetation cover, and very smooth surface. The plateau surface narrows on the east. Round mountain ridges and parallel valleys with eroded steep slopes predominate the area.

To the south of this zone are dissected steep slopes with a 300m relative height, followed by a karst plateau that extends up to 400m. Vegetation is poor, and many dolines are observed in the airphoto interpretation. The southern margin of the plateaus is characterized by continuous steep slopes with a relative height of 500~600m, and is connected with the southern sub-zone (4)

As mentioned above, the sub-zone (3) is, macroscopically a plateau extending in an E-W direction, and characterized by the presence of karst on the plateau surface.

(4) Located at the south of sub-zone (3), this sub-zone extends in an E-W direction, with a 5 to 10 km wide, until the Lago Enriquillo. Connected with sub-zone (3) by the steep slopes of 500 to 600 m in relative heights, this sub-zone has morphologically remarkable step.

Along the steep slopes the intermountain basins of Guayabal and Los Pinos can be found.

Large-scale fans are formed at the skirt of the slopes facing Lago Enriquillo.

Coral reef and organic sediments of more or less 10m thick are distributed parallel to the lake shore at about 1 km wide.

The water passes through the fans and coral reefs flows out to the lake shore. The good quality of the spring water makes it drinkable. The fans and coral reefs are covered with savannah.

6) Cuenca de Enriquillo

Cuenca de Enriquillo extends from the Haiti boundary, at the extreme west of the Study Area, to the east of BAHIA de NEIBA, and is 10 to 25 km wide and 100 km long. Cuenca de Enriquillo is a lowland zone, with an altitude ranging between −40m and 60m, extending in the East-West direction. Lago Enquirillo is a salt lake located in the middle west of this area (Length : a little less than 30 km, Width : a little over 10 km, Surface elevation : −40m).

The north coast line is a little rugged, but the south coast line is relatively straight. Emergent coral reefs and organic sediments are observed in the west of the Lake shore and in the lake bottom. At the eastern area, vegetation is poor, presenting a swamp, sandy marsh and/or savannah features.

The area is barren due to the large amount of salt within the soil. However, a sugarcane plantation is being managed at the eastern area of the lake through the use of large irrigation facilities.

7) Sierra de Baoruco

The Sierra de Baoruco is a large mountain range located in the southern side of Lago Enquirillo, and is mainly composed of limestone. The highest elevation in the Study Area reaches more than 2,200m along the southern marginal ridge.

Its maximum relative height is about 2,200m, and the maximum width is 20 km.

The Sierra de Baoruco was divided into 3 parallel subzones, according to their topographic features.

(1) This area consists of hilly lands distributed along the south coast line of Lago Enquirillo. It extends from Jimani in the west end of the study Area, lies parallel to the south bank of the lake and passes Duwerge towards the east of La Salina. It is 1 to 7 km wide and 70 km long. These spindle shaped, dissected hilly mountains have a relative height of 250~300m and are distributed along the northern piedmont of limestone mountains.

The zone is assumed to be originally made of marine deposits of the Cuenca de Enriquillo and to belong morphologic province 6). Flat-topped, small relief hills, originally formed from Tertiary deposits are presumed to have existed. However, half of them have been severely eroded off and many traces of failures, connecting each other, form steep slopes. The ground extends until the lake becomes flat forming a barren plain covered with savannah.

(2) This zone is chiefly composed of limestone and covers an area 3 to 8 km wide, and a length exceeding 60 km extending from the Haitian boundary at the westend of the Study Area in a NWW-SEE trend. Gentle dome-like mountains extend on a NWW-SEE oriented axis. Elevation is less than 1,000m, and relative height is 900 to 1,000m.
Relief is high and shows landforms such as bilge-shaped, dome and flat topped plateaus. The vegetation cover is good. Large scaled drainage is not distributed, but deep valleys are observed in the eastern flat surfaces.
Distribution of intermountain and buried basins are located along the general trend of mountains. The lowland which is situated westward in the vicinity of El Limon, and is 3 km wide and 15 km long, is assumed to be partially a salt lake, and to have dried up because of upheavals.

(3) Zone (3) is in contacts with the SW side of Zone (2), and is the main part of the Sierra de Baoruco, with an elevation of less than 2,000m, and a relative height ranging between 1,000 and 2,000m.
These dome mountains with a gentle anticlinal structure are mainly composed of limestone.
Even though the summit of the mountain ridges and the mountain slopes presents low relief and smooth plateaus, steep slopes and deep valleys dominate at the western and eastern extremities.
In the southern marginal zone of the Study Area, doline-like enclosed depressions are well-developed, where small-scale drainage systems are sometimes senm to converge to them.

3.4 Land Cover Classification

3.4.1 Preparation of Land Cover Classification Image

In order to clarify the land cover and vegetation cover conditions as well as land use conditions, the land cover classification image in the Study Area was prepared by color synthesis of six bands (except Band 6 of far infra red wave length) of LANDSAT TM data.

Classified items, false color tones and their characteristics on the false color image are as follows.

Classified item	Color tone of image	Characteristics
Forest (dense)	Dark green	Distributed in mountains, in deep and bright red in color
Forest (sparse)	Light green	Distributed in mountains pale and dim red in color
Rice field	Blue	Distributed along the rivers in plains and light and bright red in color
Cultivated field	Orange	Distributed in plains, red to orange in color and less brighter than a ricefield
Grassland I	Yellow	Distributed in hilly lands, brown to yellow in color and less bright
Grassland II	Dark yellow	Less lighter than (I)
Bare land	White	Light white in color
Marsh	Light blue	Distributed along coastal zone of sea and lakes
Water area	Blue	Dark blue to blue in color and clearly distinguished from land
Cloud	Gray~white	

Fig. 2.6.2 shows the false color image, and Fig. 2.6.3 shows the land cover and land use conditions.

3.4.2 Characteristics of Each Morphologic Provinces

1) Cordillera Septentrional

Sparsely distributed forests occupy the greater part of this area. Flat or low relief planation surfaces along the ridges are developed in order to produce tobacco and residential areas.
Dissected hills, with very gentle slopes, and plains are almost covered with savannah.

2) Llano de Yaque del Norte

This wide and flat plain has been utilized for the cultivation of paddy fields, cotton, vegetables, banana plantations and urban area are developed too. The sea coast area shows a wide desert to savanna area, and large-scale salt fields have been developed. Mangrove marshes are distributed along the coast.

3) Cordillera Central

The mountain ranges of high elevation are covered by dense and sparse forests, and/or by grasslands distributed around the forest area. The poor vegetation area seems to have been widened by forest felling and shifting cultivation.
The access road is distributed poorly due to the steep mountains and deep valleys

4) Valle de San Juan

This area consists of hilly lands and central flat plains.
Except for very few forest zones, sparse forests to grasslands and farm lands prevail in almost the whole area.

5) Sierra de Neiba

The northern area is covered mainly with sparse forests and grasslands. The southern area is covered by a relatively dense forest.
Distribution of access road is poor, especially in the North-south direction.
Driving through the Sierra De Neiba is impossible in the present road conditions.

6) Cuenca de Enriquillo

This area is a very flat lowland and is assumed to have been covered by coral reefs. At present, owing to the salty Lago Enriquillo and to the high salinity content of water, vegetation cover is poor in this area.
Savanna and barren grasslands are distributed along the marginal zone of Lago Enriquillo. Barren sandy lowlands are widely distributed at the east of the lake and some sugar cane plantations are being managed through large irrigation systems.

7) Sierra de Baoruco

A relatively dense forest zone covers almost the whole area.

CHAPTER IV

GEOLOGY

4.1 Outline

According to the plate tectonic theory, the Hispaniola Island which includes the Study Area, is located at the northern margin of the Caribbean Sea Plate and its north and east seafloors are in contact with the North American Plate by a boundary line linking the Cayman Trough-Puerto Rico Trench-Lesser Antilles. This boundary line passes by the south of the Cuba Island, the north of the Hispaniola Island and the east of the Lesser Antilles.

The neo-tectonic history is summarized as follows (See Fig. 4.1.1):

1) During the middle Tertiary period, the Caribbean Sea Plate which advanced eastward collided with the Bahama-Barracuda aseismic oceanic ridge.

2) A part of the Caribbean Sea Plate thrusts over the aseismic oceanic ridge.

3) Along the northern edge of the Plate, subduction almost came to a stop to be obstructive for that part of the Plate to advance eastward.

4) Then a fracture zone occurred in the main body of the Caribbean Sea Plate which was still advancing eastward. The stopped part, and the northern parts of the Plate (the north region of Hispaniola Island and the Puerto Rico Island) separated into another small plate.
   The southern margin of the fracture zone corresponds to the lowland zone of Cuenca De Enriquillo.

   Beneath the Caribbean Seafloor, the Western Pacific (North American) Plate crept into the earth of the eastside of Lesser Antilles, while the Pacific Plate crept into the earth beneath the Central American Trench, west of Central America. These plates lift up not only the Caribbean Islands but also the Caribbean Sea itself. The Caribbean Sea is assumed to be formed by uplifting. The present uplifting speed in the Jamaican Island is estimated to be 0.3 mm/year. The uplifted height is estimated to be 3,000 m for the last 10,000,000 years.

   Limestones of Sierra de Neiba and Sierra de Baoruco are primarily composed of submarine sedimentary coral remains. The basal sea bottom was assumed to be of submarine volcanic deposits metamorphosed into rocks and/or granitic rocks associated with the plate tectonic movements.

Such submarine-formed fracture zone is assumed to be lifted up to a narrow and long strait and to the lake.

As mentioned above, the Study Area is considered to have been situated in a field of violent tectonic movements since the middle Tertiary period. This tectonic movements may be reflected in the geostructural trends of oriented NWN to SES direction and in the morphological arrangements which are predominant in the Study Area.

4.2 General Geology

The geology of the Study Area is composed of various metamorphic rocks, intrusive rocks, volcanic rocks and sedimentary rocks formed from the Cretaceous period of the Mesozoic Era to the Quaternary period of the Cenozoic Era.

4.2.1 Geological Elements

1) Metamorphic Rocks

The metamorphic rock group forms the basement of the Study Area. Intrusive rocks of magmatic origin and sediments of submarine volcanic origin are supposed to be kinematically metamorphosed by the tectonic movement during the period ranging from later Mesozoic to early Cenozoic period. They are widely distributed in the Cordillera Central.

2) Intrusive Rocks

The intrusive rocks, such as granite, tonalite, norite, rhyodacite and rhyolite, intrude into the metamorphic rocks mainly in Cordillera Central. Intrusion is supposed to have occurred during the later Mesozoic and early Cenozoic. On the other hand, an ophiolitic rock group of unknown age, that is pyroxenite and gabbro, are observable too, and affects the regional metamorphism of the old rock body in the surroundings.

3) Volcanic Rocks

These rocks chiefly consist of basalt, andesite and tuff, and are locally distributed, forming small-scale rock bodies in Cordillera Septentrional, Cordillera Central, Sierra de Neiba and Sierra de Baoruco. They are supposed to be effused during the period from later Cenozoic to Quaternary.

4) Sedimentary Rocks

The sedimentary rock distribution extended on a long geologic range from later Mesozoic to Quaternary age.
A relatively older group, mainly composed of Flysh sediments such as sandstone, marl, mudstone, and conglomerate, is distributed in the northern Cordillera Central. However, these rocks are only observed locally in the Study Area. Limestone is the main formation observed in the south, and is distributed in the Cordillera Central, Sierra de Neiba and Sierra de Baoruco Mountains.

A relatively younger group consists of conglomerate, sandstone, mudstone, limestone, and are mostly distributed in hills and lowlands, of Cordillera Septentrional, in the hills and plains surrounding Rio Yaque del Norte, Valle de San Juan and coastal zone of Lago Enriquillo.

4.2.2 Geological Structure

As already stated in chapter 3-Landfrom, the Study Area consists of mountain ranges alternating with hills-plains, and extending from a northwest to a southeast direction. The geological elements above mentioned are also arranged in zones concordant with that direction. The characteristics of the landforms of the Study Area are reflected in the distribution, lithofacies and geological structure.

The characteristics of the geological structure observable in LANDSAT images are as follows.

1) Groups of clear lineament are noticable in the areas where both Palaeogene and Neogene systems are distributed.
The dominant direction of these lineaments is N70° to 80°W, and almost runs parallel to the boundary between the Caribbean Sea Plate and the North American Plate, as well as the boundary between the main Caribbean Sea Plate and the separated small Plate.

2) In the distribution area of Palaeogene formation and some parts of Neogene formations, remarkably folded patterns are observable. Distribution of Neogene formations suggest a gently folded structure. These folding structures suggest the existence of active tectonic movements since the Tertiary period.

3) Lineation pattern are assumed to be subjected to stresses resulting from orogenies in the inland area.

4.2.3 Stratigraphy

Opinions are diverse concerning the stratigraphic position and the geologic age of rocks and formations mentioned before in some bibliographies. Further detailed paleontological zoning and/or radiocarbon dating will be necessary for the academic research, but for groundwater investigation, lithofacies and potential of rocks for aquifer are more important than stratigraphic position or geologic age.

In this Study, stratigraphy of the Area is established by consulting the Atlas Geologico Y Mineralogico De La Republica Dominicana 1969, 1 : 250,000 scale.

Standard stratigraphic order and symbol are shown in Fig. 4.2.1 after the Atlas above mentioned.

1) Metamorphic Rocks

According to the reference map, metamorphic rocks equivalent to the Ksv and Ksvts are widely distributed in the Cordillera Central. The geology of the area is assumed to be from the late Mesozoic (upper Jurasic) to the early Cenozoic (Oligocene) period. The distribution of the metamorphic rocks is largely divided into 3 zones.

Type Locality:
Group 1, which is to the east of Dajabon, is made up of dissected hilly mountains at the upstreams of Rio Chaquey and Rio Maguaca.

Group 2 and 3 are mountainous areas along the international road from the south of Dajabon to Elias Pina.

The geologic age of group 1 is unknown, however, it is assumed to be of the Cretaceous in age. The metamorphic rocks in this group are identified as dark green shales, phyllitic shales and phyllite, and

1 cm thick bedding planes are found to predominate. Numerous quarts veinlets are also found to penetrate the area, thus affecting chloritization and sericitization. The strike and dip in this area show N15° - 20° E, about 50° W and N15° - 30° W, 50° - 70° W, respectively, comparatively indicating a NS strike tendency and a W dip tendency.

The members of group 1 are in fault contact with granitic tonalite at the quarry 7 km SE of Dajabon.

Small scale intrusive rock bodies are observed to exist in each group. Although the areas are characterized with gentle relief, dendritic deep stream and fine branches, accompanied by several meters thick weathered zone, predominate.

Large intrusive rock bodies, mainly tonalite, are distributed between 1 and 2.

Group 2 consists of a kind of metamorphic or contaminated rock group formed as a result of the intrusive rock activity (tonalite, etc.), and is widely distributed in the Cordillera Central.

Group 2 metamorphic rocks are dark grey in color, compact, fine grained hard rocks where joint bedding, sheared cracks predominate. The nature of this group also indicates lithofacies of slate, shale and phyllitic mudstone which incurred kinematic metamorphism of submarine volcanic tuff origin. Although the nature of this group is similar to 1, lithofacies of igneous rocks were also observed.

This rock group is usually transformed into friable cube like structures, and their color changes into brown due to weathering. Generally, however, it is mostly crimson in color due to the remarkable effect of laterization, and difficult to distinguish from weathered tonalites.

Irregularly shaped rock bodies of serpentinite, andesitic to dacitic tuff breccia (2-5 km in diameter) intrude the metamorphic rocks in the Restauracion area.

According to the microscopic observation of the hornfels-like crushed rocks at the La Vigia quarry, 3km north of Dajabon, quartz, plagioclase, hornblende and opaque grains gather at random indicating sandstone-like textures. Grain-sized quartz measure 50 - 600 µmm, while the others measure 40 - 250 µm.

The expected presence of biot ite and recrystallized calcite due to the sandstone origin of the hornfels was not, however, confirmed in the samples. On the contrary it is thought to be a part of fine grained tonalites based on the zonal structure of the plagioclase and the color of the hornblende. It is assumed that sedimentary rocks of an older age were metamorphosed into complex rock bodies consisting every kind of lithofacies, due to the intrusion of igneous rocks.

Conclusively, the rock mass of group 2 is considered to indicate a very complicated change in the facies as a result of the effect of intrusive rocks.

Group 3 is distributed 10km south of Restauracion at the southern side of group 3's metamorphic complex up to Pedro Santana at a width of approximately 15km. The geology of this group is asspmed to originate from the upper Cretaceous to the lower Tertiary period. The rock group consists of greywacke, slate, phyllite, etc., and the strike is thought to be regular as it tends N30° - 60° W and about 70° E or W, dipping steeply to the east or west. The formation of a small repetetive folding structure is also asspmed in this area.

About. 10km to the north, the rocks are characterized as grey to greenish grey in color and mainly consist of hard sandstone to shale with blackslates. The thickness of the unit bed ranges from 1 or 2 cm to several 10 cm. Npmerous calcite and quartz veinlets are found to penetrate the area in an interlaced manner. On the other hand, calcareous to argillaceous phyllites are observed to dominate the area about 5km to the south.

The microscopic characteristic of the representative rock sample in the northern side is as follows:

Main component minerals are quartz, plagioclase and carbonate minerals and well sorted sub-angular to sub-rounded grains about 30 - 250 µm in diameter. The groundmass is argillaceous and this rock sample is determined as greywacke.

2) Intrusive Rocks

Intrusive rocks are situated between metamorphic rocks 1 and 2, and are widely distributed east-southeast of Cordillera Central. According to the reference map, these intrusive rocks are equivalent to the toh, dv, db rock bodies.

The type localities of these rocks are the southern area of the national road passing by Dajabon-Santiago de la Cruz-Santiago Rodriguez, the mountainous area around Loma de Cabrera, and the northwest of Limpio.

Although the rock facies vary depending on the localities, they are mainly melanocratic, medipm grained and holocrystalline biotie-hornblende quartz-diorite (tonalite). They range from melanocratic quartz diorite to leucocratic granite and the grain size is from porphylitic containing quartz of over 5mm in diameter and hornblende crystals of over 1 cmm in length to fine granules. Sometimes the texture is gneissose to schistose.

The rocks are penetrated by small aplitic and felsitic dykes at many places.

The color of the rocks often times vary from light brown to yellow coarse sands near the surface of the earth due to deep weathering. The color also changes to red or crimson due to laterization. The weathering zone sometimes becomes more than 10m thick and it forms hilly landforms with gentle relief and a dendritic drainage pattern.

The miscroscopic observation revealed the following on standard rock facies:

The principal minerals are hornblende > plagioclase > quartz, while the accessory minerals are apatite, biotite and opaque minerals. Epidote, chlorite, muscovite and limonite are categorized as secondary minerals. The phenocryst in hormblende is 600 - 3,000 μm, 600 - 1,800 μm in plagioclase and 200 - 1,500 μm in quartz.

Another intrusive rock body is situated at the southeast part of Santiago de la Cruz on a scale of 15km long and 4km wide.

This rock body shows discordant intrusive relation with the surrounding quartz-diorite (tonalite) and forms relatively steep mountains with an elevation of 800m above sea level. It also shows a relative relief of 400m from the surrounding gently sloping hills of weathered tonalite.

This rock body is composed of basic to ultra-basic rocks such as peridotite, serpentinite and gabbro, and is penetrated by many quartz veinlets. Its surface is altered and weathered violently.

Its piedmont is covered by thick brecciated talus deposits and the fissure system of the NE-SW direction is predominant.

The microscopic observation of the rock sample obtained from Cerro Chaquey revealed the following:

The rock sample is serpentinite with a layered structure derived from peridotite. The melanocratic layers are composed of chromite and serpentine and the non-opaque layers are mainly of serpentine > olivine and amphibole. The principal minerals are serpentine (assemblage of fibrous crystals), exchanged olivine by serpentine, hornblende and talc. The diameter of the crystals or the pseudomorph ranges from 600 to 800 μm.

3) Volcanic Rocks

All volcanic rock bodies distributed in the Study Area are small in scale and their details are unknown.

4) Geological Relationship between Metamorphic and Intrusive Rocks

The detailed geological condition of the Cordillera Central such as the distribution of each different rocks, their lithological variation, mutual relation, geologic age, geologic structure, etc., remains unknown mainly due to steep mountains, poor access and violent weathering.

The relationship between the metamorphic rock 1 and the intrusive rock in the northern zone is inferred to be faulty and intrusive.

The intrusive rock and metamorphic rock 2 is assµmed to be mainly in intrusion along the north margin. Metamorphic rock 2 itself is geologically complex having a faulty or intrusive relation with other different intrusive rock bodies.

The metamorphic rock 2 is in falut or thrust contact with 3 on large scale.

The bending boundary zone which is accompanied with complicated fracture pattern is traceable by air photo interpretation. This may verify the traced plate tectonic movement.

Metamorphic rock 3 is also inferred to be bounded by a large fault or thrust zone to the south.

5) Sedimentary Rocks

The sedimentary rocks distributed in the Study Area are mainly composed of the Tertiary and the Quarternary system. Within the Tertiary system, limestone can be mainly found in the Palaeogene system and is distributed in the south end of the Cordillera Central and the main areas of Sierra de Neiba and Sierra de Baoruco. Conglomerate, sandstone, mudstone and limestone form the Neogene system and they are distributed in the main areas of Cordillera Septentrional, at the plains and hills on both banks of the Rio Yaque del Norte, and the hilly areas of Valle de San Juan and Lago Enriquillo area. (Some formations span the time from Palaeogene to Neogene Period).

On the other hand, the Quarternary system is mainly distributed at the Rio Yaque del Norte plain and Lago Enriquillo lowland.

The rock bodies will be described in detail according to unit area.

(1) Cordillera Septentrional

a) Formation Emcg, Ec

This is the most inferior formation of the Tertiary system distributed in the Cordillera Septentrional as the distribution is restricted. This formation can be found in the eastern marginal piedmont of the Study Area near La Caya-Pozo Prieto-Arroyo Cana, and in the hilly part near Loma Isabel Torres, the western region of the Study Area.

Conglomerate or calcareous sandstones and shales can be found in the east, while the west is mainly composed of shales.

This formation is an unbedded mass and is dark brown or dark chocolate in color. It is associated with a network of calcite veinlets, is brittle to cubic in shape.

The pebbles are composed of fossil rich limestone, hornfels and cherty rocks with a diameter ranging from 3 to 30 cm. The strike and dip are irregular at N30° E20° to 35° E or N50° -80° W 50° to 85° SW, but are generally controlled by fissures of E-W direction and trend W-NW, similar to that of the Cordillera Septentrional.

Air photo lineaments are remarkable along the boundary zone of the adjoining formation. This formation forms a relatively distinct and continuous fault landform in the utmost east area.

Under the microscope, the matrix of the conglomerate is calcareous mudstone. The pebbles consist of limestone and bio-remains. The constituent of sand-sized grains are bio-remains, quartz, plagioclase, chlorite rock, limestone and volcanic rocks. The bio-remains, moss-animalcule, calcareous algae, coral, bivalves, crinoids, and foraminifers are observable as they range from 100 - 1,400μm in length. Clastic grains are subangular to subrounded and 70 to 1,000 μm in diameter.

This formation is inferred to be a flysh deposit from the Eocene to middle Oligocene Age.

b) Formation O'Mce

This formation is distributed in the northern half zone of the Cordillera Septentrional inclining toward a NWW-SEE(N70°W) direction. It is 4 - 6km in width, more than 60km in length and is observable along the cross roads in the N-S direction.

This formation is a series of alternating beds of calcareous sandstones (biomicritic limestone to biosparite) and calcareous siltstones - shales, and is accompanied by coral reef limestone at the uppermost horizon. It is 300 - 600m thick.

In the eastern part, it is in fault contact with the fossil bearing dark brown and hard calcareous sandstone or mudstone (members of Emcg). The contact zone is fractured and brittle.

The overlying formation forms a series of alternating beds of yellow brown or khaki colored, compact, hard and platy calcareous sandstones and the white or white-yellow and somewhat brittle calcareous siltstones or shales. The thickness of the unit bed ranges from 3 to 10 cm.

Siltstone or shale are sometimes weathered into white colored, fragile powder-like rockfacies.

In some places, the foraminifer bearing, compact, hard and massive limestone overlies the above mentioned alternating beds. These alternating beds strike N70°W - EW - N70°E, in concordance with the extending direction of the Cordillera Septentrional, and mostly dips 20° - 50° N. Sometimes they dip south and are disturbed and undulated along the boundary zone of the southern formation.

Many continuous fault-like and topographic airphoto lineaments of N-W to N70°W directions are remarkably interpreted. Also, many diagonal lineaments are observable. The boundary zone of the southern formation (Mice) is clearly traceable and is assumed to be a fault zone.

The blocked, divided and dissected hills controlled by lineaments (faults) are arranged along the northern coastal zone. Interhill parts are buried by thick talus deposits. In this zone, the sawteeth-like questa landforms are arranged at the areas that alternate well.

The microscopic observation of calcareous sandstone is as follows:

It is found to be a biomicrite composed of matrix of fine carbonate minerals, well sorted clastic grains and bioremains.

The clastic grains are composed of quartz, chalcedony, plagioclase, chromespinel, polycrystalline quartz, and microfragments of chert and volcanic rocks. These rocks are sub-angular or sub-rounded in shape and are 40 - 600 µm in diameter.

The bioremains are composed of crinoid, foraminifer, moss-animalcule and bivalves, and are 65 - 700 µm in length.

This O'Mce formation was estimated to have been formed from the lower Oligocene to the upper Miocene or Pliocene age.

c) Formation Mice, Mmca, Mscm

This formation is distributed widely in the southern half-hilly mountainous zone of the Cordillera Septentrional and in the low relief hills and plain of north Rio Yaque del Norte. In the reference map it is classified into 3 strata correlating from lower to upper Miocene. In another map, it is summarized and rejuvenated as ranging from upper Miocene to Pliocene.

The components of this formation resemble each other and are varied in their lithology and lithofacies, making them very difficult to distinguish during field observations.

In contrast to their resemblance, they show somewhat remarkable differences in their topographic and air-photo patterns.

In south Rio Yaque del Norte, the formation, which is correlative with the aforementioned formation, is distributed widely in the plains and hills. In this report, three formations were classified for the convenience of description.

(a) Formation Mice (lower horizon)
This formation is distributed along the south of the aforementioned formation (O'Mce). It is also in fault contact with the latter. It forms dissected hilly mountains and hills of gentle relief with an elevation of less than 400m above sea level.

The type localities are as follows:

1. Road cut in the town of Monte Cristi
2. Many road cuts along the national road from Monte Cristi to Villa Elisa
3. Agua de la Palma, 8km north of Villa Elisa
4. Sabana Cruz Surrounding Area
5. El Manantial and its neighborhood, 20km east of Monte Cristi

This formation is generally composed of alternating beds of fine to coarse grained calcareous sandstone and fine to medium grained sandy shale.

In the upper horizon, it sometimes contains interbedded conglomerate beds (at the eastern hills of Villa Vasque) and sometimes underlies gravel beds (at the surrounding plain of Hatillo Palma, Arroyo Cana to Agua Luis). The lower horizon is well observed along the national road that passes through the plain, and the upper horizon is relatively situated at the hilly area.

The fresh calcareous sandstone beds are compact and hard and dark green to grey in color. The unit bed is 0.5 to 2 meters thick. The color, however, varies from greenish brown to light khaki at the weathered parts, and the texture is brittle. The weathered shale beds are friable into small cubes.

Along the national road, the local anomalous sedimentary structure, such as repetetive lenticular expansion and pinching of sandstone beds, formation of pot holes and ranging of nodules or blocks of the original fresh rock, can be observed. An alternation of more than 10 times is observable along the national road. At the hilly area, the rhythmically repeated alternation of sandstone and shale beds are observable in many places.

The lower part of the beds often strike N70° - 80° W and dips 15 degrees to 30 degrees south or north. This tendency is in concordance with the Cordillera Septentrional trend, although a north-south strike is sometimes evident. A long wavelength undulation extending NWW-SEE in direction and an assμmed anticlinal structure with the axis in the same direction can be observed too.

Although the strike and dip of the upper part (hilly area) varies, macroscopically, it is in concordance with the general trend as it tends toward N70° W-EW-N60° and dips 15 to 30 degrees to the south or north. Further, repeated anticlinal and synclinal structure on a small scale are assμmed, too.

The microscopic observation of the calcareous sandstone showed the following results:

It is composed of grains of quartz, plagioclase, hornblende, epidote, chlorite, muscovite, biotite, non-opaque minerals, polycrystalline quartz, and microfragments of Tonalite and volcanic origin. These sandstones are well sorted and sub-angular or sub-rounded grains of 50 - 1,200 μm in diameter.

Groundmass is composed mainly of carbonate minerals and partly of patchlike or amoeba like argillaceous matters.

They contain a small quantity of bioremains such as foraminifer and moss.

Shaley sample is also essentially the same as the calcareous sandstone, except for the finer grain size.

The difference in the quantity of clastic grains and bioremains indicate the following lithological differences between O'Mce and Mice.

	O'Mce	Mice
grain	none or less	much
bioremains	much	none or less
characteristic	chromespinel	microfragment
kind of grain	chalcedony	of tonalite origin

(b) Formation Mmca (middle horizon)
This formation is distributed along the southern area of the planation surfaces extending 4 km wide and 20km long at central Cordillera Septentrional.

The type localities are as follows:
1) The hill, 6km east-southeast of El Cayal
2) A road cut, south of Agua del Palma
3) Southern hills of Agua de Luis

This formation is composed of alternating beds of light-brown to orange colored coarse and slightly porous calcareous and pebbly sandstones and greenish grey calcareous shale or siltstone. It also contains interbedded conglomerate beds. Gravels are rounded or sub-rounded and compact limestones range from 3 to 20 cm in diameter.

The fossiliferous limestone bed sits on the uppermost horizon of the alternating beds. These alternating beds strike in the west-northwest direction and dip to about 15 degrees north in the northern side. In the southern side it strikes in the east-northeast and dip to 15-30 degrees south, indicating the possibility of an anticlinal structure.

Calcareous sandstones or shales are identified as biomicrites in the microscopic observation. They are found to consist of a groundmass of fine carbonate minerals, many bioremains and small amount of detrital grains. The bioremains contain echinoids, foraminifer, bivalve and moss, and range from 80 to 1,800 μm in length. Detrital grains contain sub-angular or sub-rounded plagioclase, quartz and polycrystalline quartz and range from 40 to 280 μm in diameter.

(c) Formation Mscm (upper horizon)
The consolidated and unconsolidated conglomerate or gravel beds are distributed in the eastern plain of the Study Area (east of Villa Elisa and north of Rio Yaque del Norte) and in the central hilly area (Villa Vasque and Guayubin vicinity).

These beds were classified in the reference map as belonging to the upper Miocene (Mscm), and they are widely distributed in both sides of the Rio Yaque del Norte bank.

Another map identified the eastern area as fluviatile deposits of the Quarternary age, and the central area as continental mollasse deposits of the Pleistocene age.

In the eastern piedmont area of the Cordillera Septentrional, this formation consists of alternating beds of white yellow, massive calcareous sandstones or pebbly sandstones, khaki colored massive and friable shales or siltstones and half consolidated pebble or gravel bed.

The quantity of gravel increases in ascending order and thinly covers the earth surface. Gravels consist of black shale, compact limestone, schist and volcanic rocks of 3cm - 30 cm in diameter.

The upper gravel bed is about 3m thick and the lower alternating bed is more than 10m.

The rockfacies of the sandstones distributed in the plain or gently sloping hills considerably resemble (Mice) beds observable along the national road. Gravel beds cover and intercalate the upper horizon of sandstone beds. Many gravels are distributed in the piedmont and dissected hilly area. Sometimes they are scarcely distributed in the plains.

From the east of Villa Vasque to the east-south of Villa Sinda, the hills of less than 100m in elevation are aligned and trend west-eastwest in concordance with the general trend of the Study Area. Gravel or conglomerate beds cover the top of the hills.

The type locality is the hill located southwest of Villa Sinda where the antenna of CODETEL is located.

The alternating beds of the yellow to khaki massive coarse sandstone and the bluegrey siltstone contain somewhat consolidated interbedded, lenticular and overlain conglomerate beds. The interbedded parts dip 20 - 30 degrees and the overlain parts are almost horizontal.

Gravels consist of lots of limestone, black shale, volcanic rocks and granitic rocks, and are sub-angular to flat in shape at less than 5 - 20 cm in diameter.

The distribution pattern shows that the upper horizon of the correlatives of (Mice) is interbedded and overlain by gravel or conglomerate beds. These gravel beds at the eastern and central parts contain the same constituents based on the kind of gravel. On the other hand, gravel distribution is scarcely observed in the northern plain area of the national road and the western area from Villa Vasque.

There are many problems concerning these gravels that need to be solved such as their sedimentary environment, whereabout of washed away gravels and little residues at the plains.

Although gravel beds of the same quality are thinly distributed at the western area of the confluence of Rio Guayubin and Rio Yaque del Norte, and at the southern side of the latter, they become looser and thinner at the utmost western margin.

(2) Llano Rio Yaque del Norte

The Neogene formation of the southern side of Rio Yaque del Norte is vastly distributed along the river with an elevation ranging from 0 - 50m above sea level and at the hilly northern piedmont of gentle and low relief of the Cordillera Central with an elevation of less than 100m.

The southern formation of Rio Yaque del Norte is correlated with that of the Cordillera Septentrional in the reference map, and a gentle and broad synclinal structure, which tends west-northwest, overlain by thick alluvial deposits is also assumed.

Although another reference map does not especially correlate, they are all included together within the lower Miocene to Pleistocene age.

This report classifies the formation as possible as it could, although outcrops, fewer compared to the Cordillera Septentrional area, are observed due to strong weathering and cultivation activities.

(a) Formation Mice

This formation underlies the lowest horizon of the Neogene formation of this area and is distributed at the dissected hills of low relief or the intramountainous hill area of the southmost zone .

This formation consists of alternating beds of light yellow or khaki colored pebbly or coarse sandstone and siltstone, and is accompanied by a thick basal conglomerate bed.

The type localities of the basal conglomerate are the national road cuts between Santiago de la Cruz (south of Dajabon) and Partido, and the riverbank of Rio Guayubin, 8 km west of Santiago Rodriguez.

Sub-rounded gravels of 5 - 30cm in diameter of black slate, tonalite, diorite and claystone, and lenticular beds of 1m thick coarse sandstone are almost horizontally accumulated in the considerably consolidated matrix of pebbly and coarse sands. Their thickness ranges from 0 to more than 20 meters.

At the riverbank of Rio Guayubin, the conglomerate beds cover the black or brown shale and phyllite beds regarded as Mesozoic in origin, and forms the basement of the Neogene formation.

The type localities of the alternating beds of sandstone and siltstone is the riverbank of Rio Chaquey located 18km due east of Dajabon. The basal conglomerate bed in this locality is lacked. The alternating beds of light yellow coarse and massive sandstones and siltstones contain lenses of pebble and greenish grey fresh and hard sandstone regarded as the original rock of the sandstone bed. It also covers the assembled dark green breccia bed and hard bed of more than 7m thick. The total thickness of the alternating beds at this place exceeds 20 meters.

This formation is strongly weathered in all area to the khaki to brown colored, brittle and massive sandstone and argillaceous loose bed. The weathered zone range from 5 to 10 m in thickness.

Although outcrops scarcely have clear strikes and dips, this formation generally strikes west-northwest and dips about 10 degrees to the north.

(b) Formation Mmca

This formation is basically correlative with Mmca in Cordillera Septentrional and conformably or slightly unconformably overlies the above mentioned khaki colored massive sandstones. Type localities are the road cuts between Copey (north of Dajabon), the quarry located 2km east-southeast of Santa Maria and the surrounding area of INDRHI dam, southwest of Las Matas de Santa Cruz. The estimated thickness is more than 100 meters. This formation is estimated to grow thinner westward and thicker eastward.

The lower parts are the alternating beds of white yellow, massive, compact pebbly or fine calcareous sandstones and siltstones. They contain many fossils of gastropods, bivalves and corals and coral fragments. Weathering converts these beds into white, powdery fragile rocks.

The upper parts consist of porous fossiliferous limestone and partly contain intercalated conglomerate beds of 5 - 6 meters thick. The gravels consist of rounded or sub-rounded fossil bearing compact limestone or calcareous sandstone less than 20 cm in diameter.

According to the microscopic observation of the sample obtained from the quarry in Santa Maria, the rock is identified as biomicritic limestone composed of bioremains and groundmass of carbonate minerals. The observation also indicated a lack in detrital grains.

Bioremains consist of foraminifer, gastropods, crinoids, and mostly of moss. The length of the moss generally ranges from 200 to 1,800 μm, although some are 7,000 μm long. The bioremains were found to have a relatively clear texture.

Sierra Zamba forms the boundary of the Monte Cristi and Santiago Rodriguez provinces. It is 5km wide and more than 20km long as it extends southeast from the confluence of Rio Guayubin and Rio Yaque del Norte. This area consists of limestone.

The limestone in Sierra Zamba is very hard, compact and fossiliferous, and is broken into boulders or blocks. Lithologically, it considerably differs from the ordinary rock facies of the aforementioned limestone and might have possibly originated from an older limestone.

c) Formation Mscm

The gravel bed is distributed at the western area of the confluence of Rio Guayubin and Rio Yaque del Norte. The gravels are rounded or sub-angular and are less than 5 cm in diameter. The gravel composition includes chert, hard sandstone, black shale, schist and tonalite. The matrix is composed of pebbles or coral fragments bearing limonitized and lateritized coarse sandstone and siltstone. Less than 5m thick assembled or swarmed and loose gravels were observed to cover the Mmca formation.

This bed is considered to be correlative with the conglomerate and the gravel beds on north Rio Yaque del Norte. Their distribution, however, was observed to be restricted. Further, gravels are hardly observed in the western plain area due to cultivation. At any rate, this gravel bed is not so thick to be classified as an independent formation.

(d) Alluvial Deposits

The low and flat area of the lower part of Rio Yaque del Norte appears to be a delta area, but the distribution of the alluvial deposits seems to be unexpectedly thin.

It is largely possible that the Tertiary formation and its weathered zone on both sides of the national road from Monte Cristi to Copey and southwest of Rio Yaque del Norte, is exposed without overlying alluvial deposits. This is attributable to the fact that the few gravel distributed, which is regarded as alluvial deposits, can be observed along Rio Yaque del Norte, even along the profile of the irrigation channels. The residual weathered sands from the Tertiary formation are undistinguishable from alluvial sands, and some weathered zone and coral beds still Tertiary in texture are observable in the savannah and undeveloped areas.

(3) Valle de San Juan

The formations correlated with the Eocene to the Plio-Pleistocene age are vastly distributed in Valle de San Juan Occidental. Problems concerning detailed lithostratigraphy, geologic age and the mutual relationship of each bed, however, are still unsettled.

(a) Formation Ee, Es and Ec

This formation is composed of limestone and is distributed eastward from Pedro Santana forming a narrow mountain ridge that is 1 km wide, 10km long, with an elevation ranging from 1,000 to 1,500m.

This formation is believed to have formed the southern marginal zone of the Cordillera Central and is observed to be in big fault contact with the metamorphic formation of the Mesozoic Era.

This is composed of milky white to pale yellow white, compact and hard limestone and partly indicates a sawteeth-like weathered landform. The southern side of the limestone mountain ridge is the dissected low mountains and hill area of 300 - 500m in elevation.

The alternating beds of shale, sandstone and conglomerate cover the hilly area. They generally strike in the eastwest direction and dip more or less 50 degrees to the south. The formation is generally composed of alternating beds of light brown calcareous coarse sandstone, greenish, massive siltstone and conglomerate which is 3 - 5m thick. These constituents are arranged in an ascending order and is sometimes accompanied with an intercalated pink colored limestone bed. It becomes coarser and grain-like in size as it moves upward from the lower horizon, and tends to be overlain by the assembled or swarmed conglomerate beds at the uppermost horizon.

The gravels consist of rounded or sub-rounded to flat black shale, greywacke, hard, compact limestone, and volcanic rocks of 5 to 20cm in diameter.

The matrix is composed of consolidated calcareous sand, silt and coral fragments. At the western side, the conglomerate is distributed at the upper area of the hills and shows a small dendritic drainage pattern, and a smooth and ring-like ridge pattern. At the eastern side, however, they are sometimes scattered. The continuous questa landforms by the underlying alternating beds extend in the east-west direction and are well observed.

b) Formation Pcmg

This formation is distributed in the surrounding area of Elias Piña in the northeast to the east-west direction at about 3 to 5 km wide and more than 25km long.

This area forms the gently undulated to flat, well cultivated plains. Outcrops in the area are scarcely observed.

This formation is composed of alternating beds of massive siltstone, massive sandstone, coarse pebbly sandstone, coral limestone and gravel. The distribution area of this formation converges and pinches out in the northwest direction at about

10km of Elias Piña under the conglomerate beds correlative with Formation Mg.

The outside marginal zone of the area is surrounded by the zonal hills of 10 - 40 m in relative height. The width of the hill zone on the northern side of Elias Pina is narrow at less than 100 - 200 meters, but extends eastward to 200 - 400 meters near the area between San Rafael del Yano and Las Matas del Farfan. Remarkable questa landform is indicated.

The formation at the northwest side of Elias Pina is composed of alternating beds of compact, massive and hard siltstone and shale and contains intercalated gravel bed. It is also overlain by gravel beds at the upper horizon. This formation strikes north-east-north and dips more or less 20 degrees to the west and is more than 40m thick.

The formation at the northern side is composed of alternating beds of massive siltstone, medium to coarse sandstone and pebble to gravel beds. It strikes north-east-north and dips 30 to 40 degrees northeast. At the eastern area, the alternating beds are arranged in questa landforms dipping north. Gravels are scarcely distributed.

From a structural point of view, an anticline which gently pitches northwest around the plain of Elias Pina is assumed. The summit of the anticline was eroded out to an enclosed depression.

c) Formation Mg

This formation is vastly distributed at the north and south hilly areas of Rio Macasia. This area consists of hills of less than 500m in elevation and a relative height of about 200m. There is a dissected small dendritic drainage that shows a fine wrinkled pattern. A series of peaks and ridges are mostly of the same height and are more dissected in the eastern part and extends to the rounded and smooth surface.

This formation is composed of alternating beds of conglomerate, sandstone and siltstone. Conglomerates are most predominant and consist of swarmed gravels of hard grey sandstone, limestone, phyllite, black shale, and decayed volcanic rocks. They are also rounded, sub-rounded to flat in shape and are 10 to 20 cm in diameter. The matrix is composed of unconsolidated to semiconsolidated coarse to pebbly sand. In lower horizons, the conglomerates contain alternating beds of sandstone and siltstone and interbedded lenticular sand, silt and pebble. As it ascends upward, the gravel composition predominates occupying the summit part of the hills in an almost horizontal condition. The estimated thickness is more than 40 meters.

d) Alluvial Deposits

Alluvial deposits are distributed in the flooded zone 100 to 300m wide and in small terraces along the channels of Rio Macasia and its main tributaries. These deposits contain loose gravel and sand and form very smooth surface patterns as they are flushed with water. They are sometimes graded into hills.

In this area, problems on the exact relationship of each alternating beds of formations (a),(b), and (c), and the stratigraphic correlation and the geologic age of each conglomerate still remain unsolved.

(4) Sierra de Neiba

Sierra de Neiba is mainly composed of Palaeogene limestones and some Neogene formation.

a) Formation Oce

A Tertiary formation 2 to 6 km wide and more than 25 km long is distributed west-eastward along Rio Cana from Hondo Valle, near the border of Haiti to El Cercado along the central zone of Sierra de Neiba.

The western part is an intermountainous narrow lowland zone between the limestone mountain range. The eastern part consists of mountainous zones of less than 1,000m in elevation and 200m in relative height, which form remarkable questa landforms.

The formation is made of alternating beds of greenish grey siltstone, light brown sandstone and of interbedded limestone beds. The siltstones dominate this formation and the unit bed is 2 to 10 cm thick.

This formation strikes N70° to 80° W and dips 50° to 60° N or S, showing repeated small foldings or anticlines and synclines. Based on the lithofacies and the questa landform, this formation is possibly correlative with formation Pcmg in Valle de San Juan.

b) Formation Mc
This formation is distributed in the northern coastal zone of Lago Enriquillo along the southern marginal piedmont zone from Postre Rio to Neiba, and is in fault contact with the limestone of Sierra de Neiba.

This formation is composed of alternating beds of conglomerate and reddish brown coarse sandstone to silty sandstone.

It is composed of conglomerates of white limestone, calcareous sandstone and brecciated rocks 3 to 20cm in diameter. They are rounded in shape and are consolidated by cementation of calcareous matter.

The strike and dip are difficult to measure and are, therefore, assµmed to be disturbed near the fault.

c) Formation Ec and Oc
Limestones of Sierra de Neiba show violent change and the lithofacies show similar appearances. In addition, poor access led to a difficult stratigraphical classification. They were accurately divided into the four zones below, which was also described in 3.3.2-5, only by landform characteristics and aerophotographic patterns.

Zone 1: This zone is composed of alternating beds of clearly stratified, milky white to white yellow colored limestones to fine calcareous sandstones. The unit bed is 30 to 50cm thick and strikes N50° to 80° W and dips about 20° north. Calcareous sandstones are sometimes altered into white powdery sands by weathering.

The type locality is road cuts along the road from Elias Pina to Hondo Valle.

Under microscopic observation, this formation is composed of limestone (biomicrite) and is composed of bioremains and groundmass of carbonate minerals. Detrital grains are not observed in this formation.

The bioremains consist of foraminifer, moss, bivalve and echinoids. They range from 100 to 700μm in length, ordinarily from 200 to 400μm, and are generally fine in size.

The groundmass consists of slightly coarse, non-opaque carbonate minerals mosaic in texture. The non-weathered part is recrystallized to some extent, and the slightly weathered part is very porous.

It is assμmed that the low-recrystallized groundmass is weak against weathering, as it is transformed into porous sand to powder.

Zone 2: This zone is also made up of alternating beds of limestone and calcareous sandstone of various lithofacies.

The type locality is the big quarry located 1km north of Hondo Valle.

Many facies, such as those listed below, are observable at the quarry.

- Milky white colored and very compact hard facies, and its altered facies,
- Coarse calcareous sandy facies,
- Brecciated facies,
- Facies with surface covered by film of solved $Ca\ CO_3$

This zone forms a dome-like landform which is 10km wide and is in fault contact with zone 1. Although the presence of gentle anticlinal structure is assμmed, it has not been ascertained. The surface is mostly lateritized to crimson.

Under microscopic observation, the constituent materials are almost the same as in zone 1.

Zone 3: This zone forms the main area of Sierra de Neiba and is mostly composed of limestone.

The type locality is the road cuts along the road from La Descubierta, west of Lago Enriquillo, to Hondo Valle.

This zone is generally composed of milky white limestones, but is complex as it contains a wide variety of lithofacies such as a well stratified part, well jointed and cracked breccia-like part, massive part, and weathered, friable white sand to powdery parts.

The beds generally strike N60° W and dip 20° to 50° south.

Under microscopic observation, the limestone in this zone is made up of bioremains and groundmass of fine carbonate minerals, and is classified as biomicrite. Some of the groundmass are recrystallized to form mozaic aggregates of carbonate minerals. Detrital grains are not observable. The bioremains consist of moss, crinoids, foraminifer, bivalve and echinoids. Further, the bioremains show a relatively complete shape and a length ranging from 200 to 2,200 μm.

Zone 4: This zone is mainly composed of limestone and some younger geological formation.

The type localities are the road cuts along the road from Descubierta to Hondo Valle via Los Pinos, and the road cuts along the north coast of Lago Enriquillo. Limestone is mainly composed of milky white hard limestone with varied lithofacies such as stratified, brecciated, massive and weathered white powdery facies. Caves are sometimes observable in the area.

Under microscopic observation, limestone in this zone is composed of biomicrites and groundmass of slightly recrystallized fine carbonate minerals. It is classified as biomicrites.

The bioremains consist of foraminifer, crinoids, moss and braciopods. The length ranges from 100 to 300μm and the size is relatively fine.

As mentioned above, the limestones in zone 1 to 4 have almost the same lithofacies and are, therefore, hard to classify. These limestone formations are assumed to range in age from Eocene to Oligocene, and possibly even to Upper Miocene.

(5) Cuenca de Enriquillo

This area forms a low-flat zone about 10 to 25km wide and more than 100km long. It extends in an east-northeasterly direction from the border of Haiti to Bahia de Neiba, which is located in between Sierra de Neiba and Sierra de Baoruco. Lago Enriquillo, a saline lake about 10km wide, 30km long, and −40m above sea level, is located at the western central part of this area.

This area is assumed to have been formed as a result of an intense plate tectonic movement which was accompanied by the formation of fracture zones or grabens, transgression and uplifting during the period ranging from upper Cretaceous to middle Miocene.

This area is underlain by coral reefs in the western terrain and widely distributed Quarternary lacustrine sediments in the eastern area. Swamps, sandy marshes and savannah are formed in the eastern part of this area.

a) Coral Reef

The emergent reef is distributed along the coast of Lago and forms a terrace and flat hills of low relief. Good springs can be found in some parts of this area.

b) Quarternary Sediment

This is composed of alternating beds of unconsolidated sand and silt, and is sometimes covered by educed white salt.

(6) Sierra de Baoruco

Sierra de Baoruco is composed of Palaeogene limestones and some Neogene formations, and can be divided into three parallel zonal unit blocks as mentioned in (3.3.2 - 7). Neogene formations are distributed in zone 1, and limestones in zone 2 to 3.

a) Formation Mpg and Mpc

This formation forms a semi-spindle shaped zone with a width ranging from 1 to a maximμm of 7km and a length of 40km. This zone extends in an east-westerly direction along the south coast of Lago Enriquillo, from Jimani, which is located westmost of the Study Area, to Duverge.

In general, this formation is composed of alternating beds of semi-consolidated conglomerates and calcareous fine sandstone to limestone.

The type localities are the road cuts along the road from Jimani to Duverge. At the western part of the formation are alternating beds and conglomerates from the lower horizon moving upwards. At the eastern part, calcareous fine sandstone containing many coral fossils and alternating beds of silt and shale predominate.

Conglomerates in this zone consist mainly of milky white hard and rounded limestone gravels less than 20 cm in diameter. These gravels are consolidated to some extent.

The sandstones are white, fine, calcareous sandstone to micritic limestone, and are friable into fine sand and powder, sometimes containing many bivalves and coral fossils.

Under microscopic observation, these limestones were found to consist of well sorted detrital grains, bioremains and groundmass of fine carbonate minerals. They are classified as micrite.

Detrital grains consist of transparent carbonate minerals, quartz, epidote, opaque minerals, and fragments of chert and chloritized rocks. these grains range from 8 to 200 μm in diameter and are sub-angular or sub-rounded in shape.

The bioremains in this zone are not abundant. Those observed were fine grains with a diameter ranging from 8 to 25m. Foraminifer are observed in this zone, too.

The detrital grains represents the lithological difference between the above mentioned limestone and those forming the mountains of north and south Lago Enriquillo.

This formation strikes NW-NWW-EW and dips 20° to 70° north and south. Repeated anticline and syncline with axis in concordance with the elongating direction of the formation is also assumed.

b) Formation Mscy

This formation is shaped like a spindle and is 6 km wide and 30 km long. It starts near Duverge, southeast corner of Lago, southeastward of La Salina up to Laguna del Rincon.

This formation is composed of alternating beds of siltstone, sandstone and gravel and is characterized by thick intercalated gypsum and rock salt beds.

The type locality is the old rocksalt mine near La Salina.

At the ridge area of this mine, the lower horizon consists largely of light brown silstones and medium to coarse grained sandstones accompanied by intercalated beds of pale brown and hard calcareous shale and calcareous hard sandstone. The upper horizon consists of intercalated beds of gypsum and rock salt. There are 50 to 60 unit beds and they are 0.5m thick.

This formation strike NW to EW and dips 45° to 75° north and south, indicating an anticlinal structure.

The cuesta landform based on the alternating beds are predominant in this area. At the dissected lowland area, alternating beds of gravel, medium to coarse calcareous sandstone and porous silty sandstone containing fossils of coral, bivalve, and gastropoda are distributed.

Some gravel beds remain isolated and form low mounds or a small ridge and range intermittently in a parallel northwest direction showing apparent air photographic lineation pattern.

The formations of Mpg, Mpc and Mscy are assumed to possibly range in age from Miocene to Pliocene.

c) Formation Oc

This formation is composed mainly of limestone and is distributed in zone 2. The type locality is the road cuts along the recently constructed road from Duverge to Puerto Discondido.

The formation is composed of milky white limestones with a wide variety of lithofacies such as stratified, massive, brecciated, powdery and intercalated conglomeratic facies.

Under microscopic observation, limestone was found to be composed of fine carbonate minerals, 8 to 16μm in diameter and is accompanied by some bioremains (100 to 200μm long) consisting of moss, crinoids, and echinoids. Detrital grains were not observed in this limestone. The limestone in this formation is classified as micrite.

Aerophotographic lineaments in the NW to SE direction are observed to predominate.

A somewhat large tectonic fault line is assμmed to form the boundary between this formation and Mscy.

On the whole, the formation forms a dome-like anticlinal structure which is ascribed to the small repeated anticlines and synclines. A somewhat apparent morphological gap is observable along the boundary of this formation and Ec distributed in the south.

d) Formation Ec

This formation is composed mainly of limestone and is distributed in zone 3, which is divided into 2 sub-zones based on a topographic difference regardless of the similarities in the lithofacies.

Subzone 1 is 6 to 13km wide and is assμmed to be in fault contact with Formation Oc, based on the many lineaments distributed along the boundary zone. The type locality is the road along the border of Haiti.

This formation is composed of white to milky white compact and hard limestone with varied lithofacies which are stratified, brecciated, and massive. Powdery facies are very scarce in this zone. This formation strikes N30° or 70° W and dips 60° northeast.

An anticlinal dome-like structure that extends northwest is generally assumed.

Subzone 3 - 2 forms mountains at the southwestern side of subzone 3-1. It is composed of limestones with lithofacies similar to that in subzone 3-1. This zone is a flat-topped dome like plateau with doline-like largely enclosed depressions in some places.

Under the miscroscope, limestone was found to consist bioremains and groundmass of coarse, recrystallized, and mozaic textured and transparent carbonate minerals. Detrital grains were not observed. The bioremains in the limestones were 100 to 1,600μm in diameter and consist of foraminifer, bivalve, crinoids, echinoids and moss.

(7) Lithofacies of Limestone

Limestone beds are widely distributed in Sierra de Neiba, Cuenca de Enriquillo, and Sierra de Baoruco. These limestones are considered to come from the Palaeogene (Eocene to Oligocene) period. During the field investigation, it was difficult to classify and arrange these rock units in a stratigraphic sequence because of their similar appearances and the violent change in the facies. They were, however, approximately divided into large zonal units, based on their different landform characteristics and aerophotographic patterns, as described in (3.3.2-5 and 6).

The microscopic observation of the typical limestone samples of each zone are summarized as follows:

Sierra De Neiba		refer to 3.3.2	Lithofacies	Fossils of Bioremains							Size μm	Recrystallization
				f	m	c	e	b	br	g		
Zone	1	5) - (1)	biomicrite	○	○		○	○		○	100~600	weak
	2	5) - (2)	biosparite (?)	○	○	○	○	○			100~700	moderately
			biomicrite	○	○	○	○				100~1,000	strong
	3	5) - (3)	biomicrite	○	○	○	○	○			200~2,2000	very strong
	4	5) - (4)	biomicrite	○	○	○			○		100~1,600	very strong
Sierra De Baoruco												
	5	7) - (2)	micrite		○	○	○				200~1,000	weak
	6	7) - (3)	biosparite	○	○	○	○	○			300~600	strong

f : foraminifer
m : moss
c : clinoids
e : echinoids
b : bivalves
br : brachiopods
g : gastropoda

Each limestone is composed of bioremains and groundmass of carbonate minerals. Detrital grains such as quartz or plagioclase are not included. Bioremains are almost mainly of the same composition. The degree of recrystallization was found to be somewhat varied but difficult to classify.

The grain size of the bioremains of formation Ec is coarser than that of Oc. As shown above, the limestones distributed in the southern mountain area are difficult to classify. Their geological age is also difficult to determine.

The classification and geological dating of limestones are not necessarily very important in this hydrogeological study. In academic research, however, the distinct identification of numerous fossils is required.

CHAPTER V

HYDROGEOLOGY

5.1 Geophysical Prospecting

Two types of geophysical prospecting, such as vertical electrical sounding of electrical resistivity and electromagnetic sounding, have been implemented by the current works.

Vertical electrical sounding was carried out to cover a most part of the project area, while, electromagnetic sounding was to cover the area thin-overlain by superficial sediments.

The tools used by the current work are listed below:

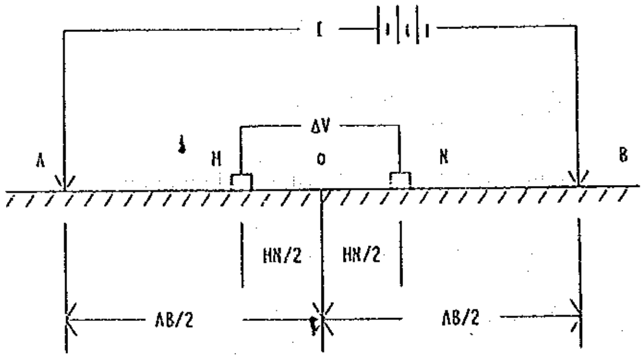
Method	Tools	Form	
Vertical electrical sounding	McOhm 2115 Transmitter	OYO Corp.	
		Output voltage	400V, P-P
		Range of current	1, 2, 5, 10, 20, 50, 100, 200 mA
	Receiver	Input impedance	1M.
		Range of	0.0 mV - 0.6 V
		Measurement	0.001
	Resolution		0.001
	Power	Intrnal battery or External battery of 12V	
	Power booster	350 mA + 200 V 500 mA + 200 V 650 mA + 200 V 800 mA + 200 V	
Electro-magnetic sounding	EM-34-3DL	GEONIX Ltd.,	
		Canada	0-3, 10, 30, 100, 300
		Range of conductivity	mS/m
		Measurement	+5% at 20 mS/m
		Accuracy	Less than 0.2 mS/m
		Noise level	6.4 KHz (10m)
		Operating frequency	1.6 KHz (20m)
			0.4 KHz (40m)

5.1.1 Principle and Method of Geophysical Prospecting

1) Principle

(1) Vertical electrical sounding

Vertical electrical sounding by the current work was implemented by electrodes allocation of the Schlumberger type as shown in following Figure. Electrical current I was run into the earth through a couple of the current electrodes A and B to measure the potential difference, generated between the two potential electrodes M and N by the current I. Two potential electrodes were symmetrically allocated on a traverse line as to substantially uphold such a relationship between the spacings of AB and MN as to being that AB/2 > 3 x MN/2, while, station O is on the center of the traverse line to being that OA = OB = AB/2 and OM = ON = MN/2.



The apparent resistivity value in the occasion of the above is shown below:

$$Pa = K\ V/I$$

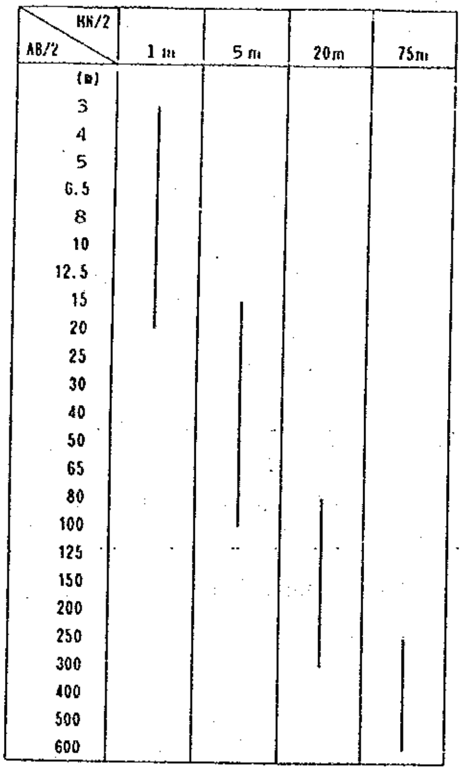
where,

- Pa : Apparent resistivity
- V : Potential difference between the electrodes, M and N
- I : Intensity of current
- K : Electrode configuration coefficient, $[(AB/2)^2 - (MN/2)^2] / MN$

The smaller spacing value of MN of two potential electrodes, as small as possible, against the spacing value of AB of two current electrodes, should provide more effective geophysical achievements, since smaller V value is prone to be hardly measured if AB value get larger, as shown in the following equation:

$$V = Pa\,I\ \frac{MN}{(AB/2)^2 - (MN/s)^2}$$

Based on the above relationship, the current vertical electrical sounding has been substantially operated under a conditional combination of AB/2 and MN/2 as shown in the following Table. Current electrodes spacing, AB/2, was substantially upheld to be of 250 m by the current work in general with such exceptions as to be of 50 to 150 m in southern Dajabon, where basement rocks are exposed on ground surface and of 300 to 600 m in northern mountainous regions in Monte Cristi, Dajabon and Elias Pina.

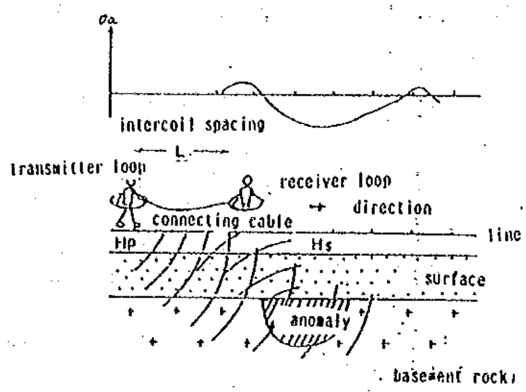


(2) Electromagnetic sounding

Electromagnetic sounding by the current work was implemented by the loop-loop method as shown in the following Figure.

The loop-loop is equipped with a couple of loop coils of transmission and receiving.

Ground conductivity value, a, which responds to a ground resistivity, is determined by establishing a ratio of the primary magnetic field, Hp, output by transmitter coil and the secondary magnetic field, Hs, measured by receiver coil. Variations of a values would help to delineate occurrences of such anomalous objectives underground as faults, ore mineral bodies, hydrothermally altered walls, aquifers and etc.



Conductivity value, a, is shown in the following equation:

$$\sigma_a = \frac{4Hs}{w\,\phi\,L^2\,Hp} \qquad \text{unit : s/m}$$

where,

Hp : Primary magnetic field at the receiver coil
Hs : Secondary magnetic field at the receiver coil
Φ : permeability of free space
w : $2\pi f$, f = frequency, π = circular constant
L : intercoil spacing in meter

The model of EM 34-3DL, capable of direct reading of conductivity values, made by Geonics Limited, Canada was utilized by the current work.

5.1.2 Interpretations

1) Vertical Electrical Sounding

Vertical Electrical Sounding (hereinafter referred as "VES") curves, obtained by the field work, are generally provided for a perused collation with the VES master curves, previously formulated. Master curves for 2-layer- and 3-layer-structure, and auxiliary curves have been applied by the current work. Six types of master curves as follows, based on the varied combinations of specific resistivity values, i.e., P1-P2 in 2-layer-structure and P1-P2-P3 in 3-layer-structure, are normally provided for applications. Formulation of master curves of multi-layer structure in varied combinations of number of structure layer and specific resistivity values are also theoretically possible.

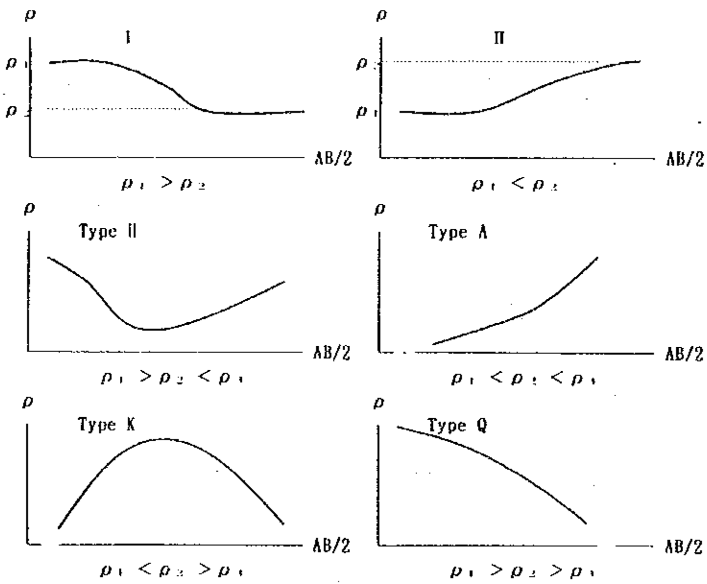
2-layer-structure

I P1 > P2	Overlain by higher-specific-resistive layer
II P1 < P2	Overlain by lower-specific-resistive layer

3-layer-structure

Type-H P1 > P2 < P3	Inserted by lower-specific-resistive layer
Type-A P1 < P2 < P3	Specific resistivity values turn to be higher underneath
Type-K P1 < P2 > P3	Inserted by higher-specific-resistive layer
Type-Q P1 > P2 > P3	Specific resistivity values turn to be lower underneath

Those types are illustrately shown below:



Multi-layered structure, composed of more than 4 layers, could be interpreted by an application of those VES master curves, the above.

For instance, a VES curve, composed of 5 layers, specific resistivity values of which should be P1 > P2 < P3 < P4 > P5, could be interpreted that the former 3 layers would be represented to be of Type H, while the middle 3 layers would be of Type A, and the latter 3 layers would be of Type K. As shown the above, a given multi-layered structure could be interpreted by a turnedly successive application of the master curves of 3-layer-structure.

The master curves are generally formulated on the basis of a horizontal model structure on an assumption that P1 is equal to 1, whereby, the ratio of P2/P1 in case of 2-layer-structure and that of P2/P1 and P3/P1 in case of 3-layer-structure are to be diversely variegated. The master curves of 24 cases of 2-layer-structure model, 334 cases of 3-layer-structure model of type-H, 158 cases of that of type-A, 331 cases of that of type-Q and 163 cases of that of type-Q, which totally make up 1010 cases of model structure, have been formulated to establish perused collations with the VES curves of the current work studies.

An example of the interpretation procedure is shown in Figure 5.1.1. In this occasion, the given curve should be firstly apprehended to be of type-K with high specific-resistivity-valued layer in the middle. Then, the most-resembled master curve of type-K to the given curve, Master curve K-14 in this occasion, has been selected for a collation. The given curve was drawn of a diaphanous logarithmic graph paper to superpose it on the Master Curve K-14, as reasonably as possible while the vertical axes of both curves has been sustained to be properly parallel and be matched with. Thence, the both of curves have been rightly collated, an interpolation on an approximate master curve is allowable if required, then the origin of coordinates of the master curve, P1 = 1 and AB/2 = 1 in this occasion, could designate that the specific resistivity value of the first layer should be of P1 = 85 m, while, the layer thickness value should be of E1 = 2.3 m, respectively, in this occasion. The specific resistivity value of the second layer could be calculably obtained by multiplying the specific resistivity value of the first layer by the numbered index mark of the master curve, 10 in this occasion, which fits to the given curve, P2 = 85 x 10 = 850 m.

After the above procedure, the single curve, which corresponds to the numbered index mark, the above, 10 in this occasion, of the auxiliary curve of type-K has been drawn on the given VES curve, then the master curve of 2-layer-structure, which had a reasonable resemblance to the right-hand-sided portion of the given curve, has been superposed on it. On the procedure, it has been to be remarked that the position of the second origin of the master curve, 21 m and 42

42 m in this occasion, should be sustained on the auxiliary curve and the axes have ever been sustained parallel.

The layer thickness ratio, E2/E1, designated on the auxiliary curve by the origin point, has been determined to be of 3, then, the layer thick value of the second layer has been calculated to being as E2 = 2.3 x 3 = 6.9 m, in this occasion. The specific resistivity values of the third layer, P3, has been calculatedly obtained in accordance with the numbered index mark, 0.02 in this occasion, of the master curve of the 2-layer-structure to being as P3 = 420 x 0.02 = 8.4 m in this occasion.

2) Electromagnetic sounding
Electromagnetic sounding, implemented by the current work, is a type of direct reading of measured values to be plotted on sheets during the course of field work. The profiles have been qualitatively interpreted.

Basement rocks and overlying weathered zones are shown with a remarkable contrast of conductivity values in Dajabon. A horizontal demarcation, envisaged to be of a fault occurrence, is sharply specified in some place.

5.1.3 Quantity of Work

1) The quantity of geophysical prospecting works, implemented on the Phase I and Phase II levels of the current program are shown below in the following Table, Figures 5.1.2 (1)-(10) and Tables 5.1.1 (1)-(8).

	Phase I	Phase II	Total
Vertical electrical sounding	212 stations in 62 districts	275 stations in 69 districts	487 stations
Electro-magnetic sounding	436 stations in 8 districts	560 stations in 11 districts	996 stations

5.1.4 Results of Geophysical Prospecting Works

1) The later Figures 5.1.5 (1) through 5.1.5 (24) show the complied results on profiles by vertical electrical sounding and drill research on 24 traverse lines, where drill operations were carried out.

Figures 5.1.3 (1) and 5.1.3 (2) show the allocations of traverse lines by the current works, while, Figures 5.1.4 (1) to (4) provides geological structural interpretations along traverse lines.

Approximate ranges of apparent specific resistivity values, in accordance with the rock faces shown by drill log sheets, are listed in Table 5.1.2.

Apparent specific resistivity values of Tertiary beds are estimated to be generally low, while, extremely low such as 3 to 7 Ω·m in occasions of mudstone bed. Apparent low resistivity values of Tertiary beds are inferredly estimated to be caused by occurrences of ground water with some variable salinity.

2) Rio Yaque del Norte

Based on the results of the stations, T-1 to K-3 (Figure 5.1.4 - (1)), traversedly lined on the low land, about 15 m high above sea level, flat low land of Rio Yaque del Norte generally show a relatively constant distribution of specific resistivity values as stated below:

(1) In general, the low land shows a 2-layer-structure with continuity, i.e., overlying high specific resistivity layer of 9 to 23 Ω·m and underlying low specific resistivity layer of 2-8 Ω·m.

(2) Overlying high specific resistivity layer is locally intercalated by low specific resistivity layer of lenticular form.

(3) Overlying high specific resistivity layer is estimated to be thick, reaching to about 80 m, in the low land and further south. However, the overlying layer is considered to be turned to be thin nearby southern bank of Rio Yaque del Norte, nearby central part of the low land, while, surface of underlying layer is estimated to be remarkably elevated up.

Those geophysical estimations have been interpreted by two drill holes operations in central part of the flat land and associated geophysical hole logging works to show an occurrence of overlying high specific resistivity layer and underlying low specific resistivity layer. General thickness of the former are shown to be remarkably variable, i.e., about 80 m thick in Hole 3 and about 27 m thick in Hole 4. Ground water is yielded in both of Holes 3 and 4. Those are considered to provide for an estimation that the overlying high specific resistivity layer might geologically accord with an occurrence of the Quaternary sediments bed dissectedly formed by Rio Yaque del Norte.

3) Stations on K-1 to W-3 (Figure 5.1.4 - (2)), extended southerly from the above traverse lines in b), the above, resultantly show the geophysical characters as follows:

(1) 2- or 3-layer-structure, with an intricate distribution of specific resistivity values, is shown in the project district.

(2) Distributions of identical specific resistivity value are discontinuously shown.

(3) Remarkable rises of high specific resistivity values, with close to "unlimitedly high" values in maximum, up to nearby ground surface, are shown in two locations.

The project district is widely covered by Tertiary beds with rock exposures on ground surface. The relation between specific resistivity values and hydrogeology is shown in Table 5.1.3. Sandstone or calcareous sandstone beds are estimated to represent specific resistivity values of 10 to 50 Ω·m. Based on the results by drill holes operation, Holes 5 and 9, sandstone beds nearby stations E and G (Palo Blanco) and calcareous sandstone beds deep underground of stations F and K are elucidated to carry aquifers. Ground water level is situated at shallow depth nearby Palo Blanco. Deep-seated sandstone beds are inferred to provide a high possibility of occurrence of excellent aquifers.

Discontinuity of the representations of specific resistivity values in the project district are likely shown in accordance with the configuration of NW-SE-directional depressed land lay or step-wise variations of land lay to lead to an implication of an occurrence of fault of significance. Very high specific resistivity values, close to "unlimitedly high" values, are estimated to be in accordance with occurrences of limestone beds nearby station A, while, of volcanic rocks of Cretaceous age nearby station W. The latter is remarked to be located at the northern-most end of the Cretaceous System, which forms the Cordillera Central.

4) Stations Ep-4 to Ep-9 (Figure 5.1.4 - (3)) are traversingly allocated in northern half of San Juan Basin. Measurement results show the following geophysical characters.

(1) A 6-layer-structure, with intricate distributions of specific resistivity values, is shown.

(2) General continuity of respective specific resistivity values are considered to be disrupted in connection with the elevation variations of land lay.

(3) Extremely high apparent specific resistivity values are not observed in the project district.
Discontinuities of the respectively identical specific resistivity values on profiles are considered to be shown in connection with the elevation variations of land lay of river terraces, developed on both banks of Rio Macasia basin. Discontinuities of the values are observed at the topographical turning of high-elevated, middle-elevated and low-elevated river terraces, while, a relatively constant-valued layer with relatively in variable thickness is observed in connection with the occurrence of any-elevated river terrace, the above, respectively.
River terraces on both banks of Rio Macasia show similar values of specific resistivity at every elevated portions, while high-elevated river terraces on both banks commonly show 5- to 6-layer-structure with remarkable variable distributions of specific resistivity values. Those may pose a consideration of geological possibility that the project district had been repeatedly subjected the erosions and sedimentations more than two times, while, the erosion surfaces might provide discontinuous causes of specific resistivity values distributions.
Apparent high specific resistivity values are in the range of 13 to 36 m, which accord with the occurrence of sand-gravel beds with abundant quantity of pebbles. The sand-gravel beds are thick-bedded in Rio Macasia basin and further north. The beds are about 100 m thick nearby the station Ep-5 (Las Rosas) to provide an occurrence of aquifer.
Apparent low specific resistivity values are chiefly represented in accordance with an occurrence of mudstone beds.

5) Stations Ep-3 through Ep-11 (Figure 5.1.4 - (4)) have been allocated in southern half of San Juan Basin in the west to show the geophysical characters as stated below:

(1) Low specific resistivity values distributions are extremely-thickly and widely observed generally.

(2) High specific resistivity values distributions are thin observed close to the ground surface.(3) Apparent specific resistivity values in the project district are rather shown in a relatively low range.

Mudstone beds exposures are widely observed in the project district to provide a geological accordance with the results by current vertical electrical sounding.

Occurrences of ground water deep underground in the project district are estimated to be unlikely possible on the bases of geology and geophysics of the current work, meanwhile, drill operation results in the district by the current work show to be of dry holes. High specific resistivity vales distributions nearby the ground surface are thin observed and the above values are evaluated to be in the range of relatively low apparent specific resistivity in a possible occasion of an occurrence of conglomerate bed, possibly cemented by fine-grained clay and silt.

6) Electromagnetic sounding operation have been implemented in the area, covered by basement rocks. Electrical conductivity values toward depths are to be determined in connection with the variations of intercoil spacing as being that about 15 m deep in the occasion of 10 m-spacing, while, about 30 m deep in that of 20 m-spacing.

Faults and fracture zones are estimated to be shown as a representation high conductivity zones with low specific resistive features, particularly in areas of granitoids and Cretaceous volcanic rocks, which carry a remarkable difference of weathered and unweathered parts. Obscure results of electromagnetic sounding operations have been shown in the area of mudstone beds or alternations of mudstone-sandstone beds.

Figures 5.1.5 - (1) and 5.1.5 - (2) show the operation results in El Cajuil and Piedra Blanca. Remarkable variations of conductivity values along the possible locations of deep-seated weathered parts along faults or joints in tonalite body. An abrupt variation of conductivity values in the district of volcanic rocks of Cretaceous age, nearby the station 1300 in Piedra Blanca, may pose a geological possible occurrence of faults. Ground water of good quality are current yielded by hand pumping operation in the district.

Electromagnetic sounding operations are estimated to be effective to specify the occurrences of deep-seated weathered parts in basement rocks area.

5.2 Test Drilling

The test drilling consists of the drilling work and pumping test work.

5.2.1 Drilling

1) Drilling sites

The 27 sites were selected for drilling positions, the 24 sites based on the result of the geophysical prospecting and the 3 sites needful for the groundwater survey and the water supply. Among those, the 14 sites were drilled by the machine donated from JICA and INAPA (hereafter written as JICA machine) and the 13 sites were done by the machine of the drilling company of the Republic of Dominica (hereinafter written as the Dominica machine). Those sites are shown on the Figure 5.2.1 and listed on the Table 5.2.1.

The JICA machine has the functions of rotary and down the hole percussion methods. As compared with that, the Dominica machine has only the function of cable percussion method.

2) Drilling Method

For the JICA machine, they were prepared wing bits, tricon bits and down the hole percussion bits. That is to say, it was performed to insert casing pipes with 14" in diameter at the most superficial part and to set ones with 10" in diameter at the tender part only during the drilling work term. But if the hole wall was good condition, it was carried out a orthodox method at the lower part of the casing pipe with 14" in diameter to use no casing pipe of 10" in diameter.

The Dominica machine team used the orthodox percussion bits with about 10" in diameter.

3) Process

(1) Drilling Work

The drilling work terms are shown in the Fig. 5.2.2, and the processes are also shown in the Figure 5.2.3 about the each JICA machine work. The geologies in the holes are described in the item 5.3.1.

(2) Logging and Completion of Well

It is performed to operate a electrical logging after the termination of drilling work for determination of the screen position, to insert the screens and to fill gravels between the screens and the hole wall. The Wells have the screens and the well casing pipes with 150 mm in diameter.

5.2.2 Pumping Test

The pumping test consists of the field work and calculation of transmissivity.

1) Field Work

The field work of the pumping test consists of the hole cleaning, step drawdown method, constant method and recovery method.

(1) Developing

It was performed by the air lift method to clean up the well hole. The work has the objects of not only hole cleaning but also developing of the permeability by elimination of the materials of mud solution. This works were continued for 24 hours in principle for each hole.

(2) Step drawdown method

The step drawdown method is carried out to check the safe yield and to determine the discharge quantity for operating the undermentioned constant method. It was performed the 5 steps on yield in principle from small to large quantities, and each step was continued for 3 hours.

(3) Constant Method

This method is important for estimation of ability of aquifer and/or a well. In this study, the constant method was operated for 24 hours under the discharge quantity decided by the above mentioned step drawdown method.

The data of this method are used for the calculation of transmissivity that suggests the ability of aquifer and/or a well.

(4) Recovery Method

The dynamic water level is recovered by the recovering groundwater after stopping the discharge. It is suspected that the recovering groundwater quantity would be similar to the discharge volume, and the transmissivity is calculated by using the residual drawdown that is difference between the static water level and recovering water level.

2) Calculation of Transmissivity

Three kind of transmissivities of all the drilled holes (wells) were calculated from the data of the above-mentioned pumping tests. Those are ones based on the Theis's and Jacob's nonequilibrium formulas and on the formula for recovery method, and those are listed on the Table 5.2.2.

The specific capacity is calculated by using the discharge quantity and the maximum drawdown during the constant method test (Q/s), and this value is used for determing the reasonable discharge quantity of the future project within the about 15 to 20 m on the drawdown. And the later-mentioned Hydrogeologic provinces are divided based on this reasonable discharge quantity, the depth and the lithofacies of the aquifer.