Grenada

DATA COLLECTION SURVEY
FOR
GEOTHERMAL DEVELOPMENT
IN
GRENADA

FINAL REPORT

AUGUST 2016

JAPAN INTERNATIONAL COOPERATION AGENCY
(JICA)

NIPPON KOEI CO., LTD.
JMC GEOTHERMAL ENGINEERING CO., LTD.
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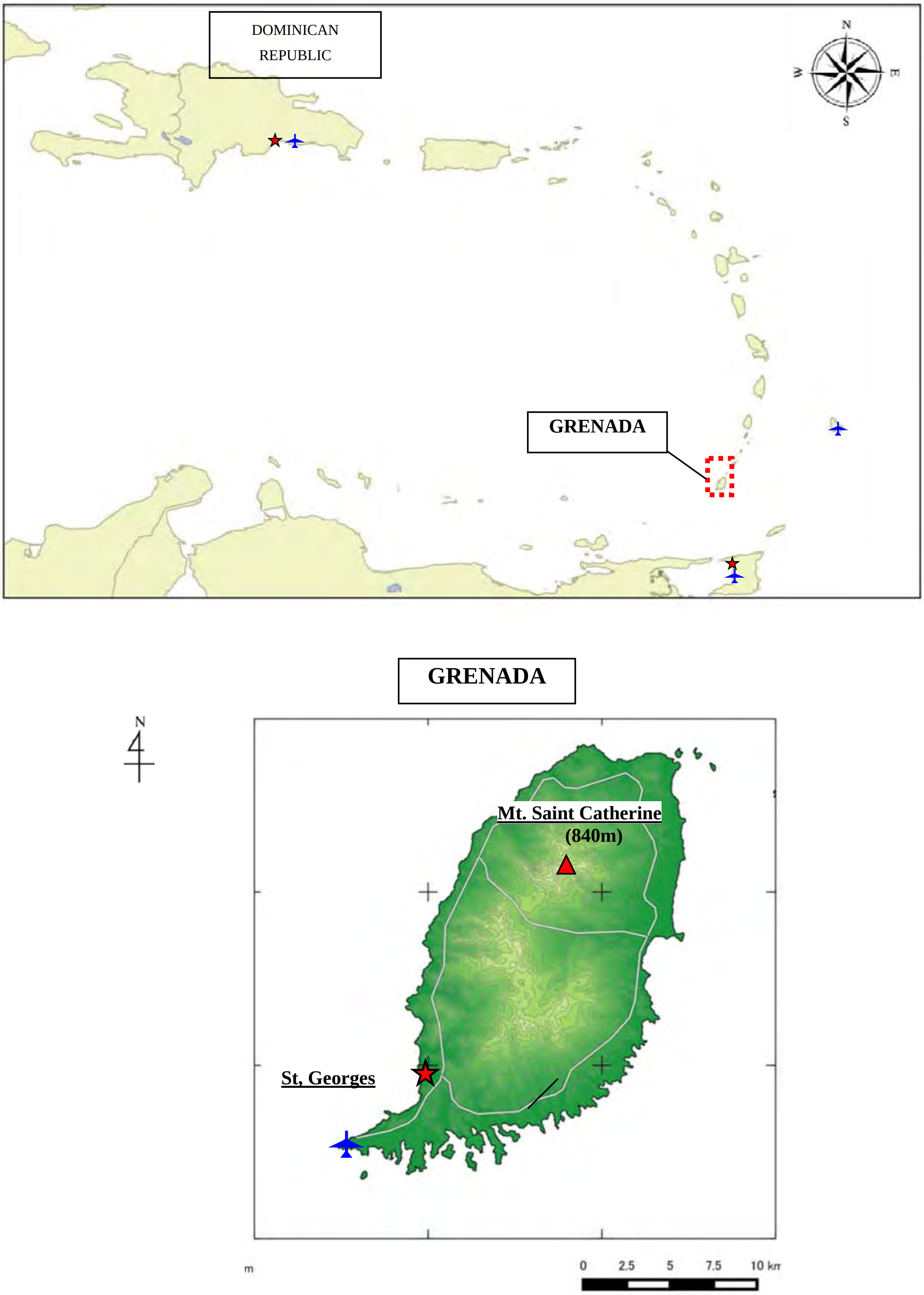


Location Map

(Source: JICA Survey Team, using SRTM-DEM)

Abbreviation

API	American Petroleum Institute
BOT	Build Operate Transfer
CARICOM	Caribbean Community
CDB	Caribbean Development Bank
CDC	Commonwealth Development Corporation
CFCs	Chlorofluorocarbon
CIF	Caribbean Investment Facility
CSAMT	Controlled Source Audio-frequency Magneto Telluric Method
DEM	Digital Elevation Model
DFID	Department of International Development
ECERA	Eastern Caribbean Energy Regulation Authority
EPC	Engineering, Procurement and Construction
ESCO	Energy Service Company/
ESIA	Environmental and Social Impact Assessment
EU	European Union
F/S, FS	Feasibility Study
GEF	Global Environmental Facility
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GPS	Global Positioning System
GRENLEC	Grenada Electricity Services Ltd.
HOT	Head of Terms
IDB	Intern-American Development Bank
IFC	International Financial Corporation
IPP	Independent Power Producer
IRR	Internal Rate of Return
IWRM	Integrated Water Resource management
JICA	Japan International Cooperation Agency
MT	Magnetotelluric Method/MT
NAWASA	National Water and Sewage Authority
NZ	New Zealand
OAS	Organization of American States
OECS	Organization of Eastern Caribbean States
O&M	Operation and Maintenance
PPA	Power Purchase Agreement
PPDA	Physical Planning and Development Control Authority/
PPP	Public Private Partnership
PPU	Physical Planning Unit
RESPV	Renewable Energy Special Purpose Vehicle
SEEC	Sustainable Energy for Eastern Caribbean
SEF	Sustainable Energy Facility
SEP	Stakeholder Engagement Plan
SGAS	Steamfield Above Ground System
SVG	Saint Vincent and the Grenadines
TEM	Transient Electro Magnetic Method
UNIDO	United Nations Industrial Development Organization
UTM	Universal Transverse Mercator
SRTM	Shuttle Radar Topography Mission
XRD	X-ray Diffraction

DATA COLLECTION SURVEY FOR GEOTHERMAL DEVELOPMENT IN GRENADA

FINAL REPORT

Executive Summary

Chapter 1 Introduction

1-1 Objectives

- To collect and review data and information to formulate the JICA preparation survey on the development of geothermal energy for technical and/or financial support; the data and information will include national policies, relevant laws, regulations, guidelines, and others that may deal with the participation of foreign entities.
- To conduct surveys such as field surface geological/geochemical survey, preliminary environmental survey, organizational/institutional survey and/or others; if and when deems to be necessary.

1-2 Target Site

The target site is the Grenada Island.

1-3 Relevant Organizations to the Survey

Relevant organizations are as shown in Table 1-1.

Table 1-1 Relevant Organizations

Name	Mandate
Division of Energy and Sustainable Development in the Ministry of Finance, Economic Development, Energy, and Foreign Trade	Policy making, its implementation and monitoring.
Grenada Electricity Services Limited **(GRENLEC)**	- The only electric service company that deals with power generation, transmission, and distribution. - Stockholders: WRB- enterprise, 50%; Government of Grenada and the National Insurance Scheme, 21%; employees, 4.5%; others, 24.5%;

Source: JICA Survey Team

Chapter 2 Present Conditions and Issues of the Energy Sector

2-1 National Energy Policy of Grenada

The Government of Grenada formulated the National Energy Policy of Grenada – A Low Carbon Development Strategy for Grenada, Carriacou and Petite Martinique, November 2011. The policy is based on the following eight guiding principles shown in Table 2-1.

Table 2-1 Eight Guiding Principles for the National Policy

• Energy Security • Energy Independence • Energy Efficiency • Energy Conservation	• Environmental Sustainability • Resource Exploitation • Energy Prices • Energy Equity and Solidarity

Source : The National Energy Policy of Grenada, November 2011

The national policy has set up the 11 goals, among those the goals relevant to geothermal development are as follows.

Amongst the above eleven goals, the goals closely related to geothermal development are picked up below.

- Establish an appropriate and enabling legal architecture
- Twenty percent of all domestic energy usage will originate from renewable energy sources by 2020

The strategy aimed at the commissioning of the first geothermal power station of 20 MW capacity in 2013 and a second with 20 MW capacity in 2016. However, none of these has been materialized.

The National Energy Policy of Grenada has also proposed a geothermal commercial arrangement. A key point of this proposal is that the so called “Grenada Geo Inc.” consisting of GRENLEC and its partner should undertake the geothermal energy development and power plant construction and operation, while GRENLEC should purchase the electricity from “Grenada Geo Inc.”.

2-2 Present Conditions of the Energy Sector

2-2-1 Institutional

All businesses of electricity supply such as power generation, transmission, distribution, and licensing are presently operated solely by the private company GRENLEC. GRENLEC originated from a company established by the Commonwealth Development Company (CDC) and the then- Government of Grenada on 27 September 1960. The new Electric Supply Act of 1994 reaffirmed the exclusive right to GRENLEC in electricity market and granted it a monopoly until 31 December 2073.

The Government of Grenada intends to submit the new Electricity Service Act (2015). The aims of these bills are to facilitate the permit and licensing for the geothermal resources in the country, and to encourage the private investors to explore the possibility to participate in the development. The government also plans to establish a public-private-partnership (PPP) bill to establish the legal basis for the private investment.

2-2-2 Organizational Framework

(1) Policy Planning Agency

The Energy Division in the Ministry of Finance, Planning, Economy, Energy, and Cooperatives (Ministry of Finance) was established in 1982. The Energy Division’s main function was to advise on key energy policy issues. Another important function of this division is collaborating with sub-regional, regional, and international organizations/ agencies on energy projects.

(2) Service Provider

GRENLE is the sole provider of electricity in Grenada, Carriacou and Petit Martinique, that provides integrated services of generation, transmission, and distribution of electricity.

(3) Current State, Issue, and Countermeasures

GRENLEC has essentially operated in a self-regulating manner. The criticisms received by the electricity sector (and GRENLEC) are the high electricity price levels and the lack of diversification of generation resources.

The government intends to transfer of certain electric regulatory functions to the anticipated Eastern Caribbean Energy Regulatory Authority (ECERA). The government aims to create a regulatory framework and give necessary incentives that will improve high efficiency of electricity generation, transmission, and distribution. The government also looks at the regulatory framework that promotes fair, efficient, and economically viable involvement of private investment in the power sector. The government has set a target for renewable energy to supply all Grenada’s electricity by 2030; and envisages the following initiatives to prepare for these objectives:

2-2-3 Existing Facilities for Power Generation and Transmission

All Grenada’s electricity is generated with diesel power plants. GRENLEC operates diesel power plants at Queens Park on the main island of Grenada with an installed capacity of 45.9 MW. In addition, it has a capacity of 3.2 MW in Carriacou, 0.5 MW in Petit Martinique, and 2.8 MW of backup capacity on the campus of St. George’s University.

The generated power is distributed through the seven transmission feeders (33 kV) to all areas around the island.

2-2-4 Demand and Supply – Present and Forecast

(1) Supply

GRENLEC has a total installed capacity of around 52.4 MW of diesel generation capacity.

GRENLEC's new Renewable Energy Strategic Plan and the Government's National Energy Policy of Grenada are strongly aligned to achieve mutual clean energy goals for the nation. The objectives are to stabilize and eventually lower energy costs, reduce dependence on imported fuel, support economic growth, and protect the environment by increasing the use of renewable energy.

(2) Demand

The peak demand for electricity on GRENLEC's system in 2010 was 30.8 MW. Electricity sales in 2010 totaled 185.79 GWh to 41,222 customers; and demand is expected to increase at 4% per annum.

(3) Electricity Prices

In 2008, the price of electricity increased to over ECD 0.81 (USD 0.30/kWh) when the fuel price was at the highest. This tariff was among the highest in the world due to the high price of imported fuel.

Chapter 3 Assessment of Natural Conditions

3-1 Objectives

The geological, geochemical, and geophysical survey, including review of existing information, were conducted to assess the geothermal energy potential for development. In addition, a reconnaissance type of field survey was conducted to assess the natural conditions in relation to civil works to be associated with drilling planning.

3-2 Review of Geological and Geographical Survey

3-2-1 Tectonic

The Grenada is located in the southern part of the Lesser Antilles, which is the eastern part of Antilles (the major part of the Western Indian Islands). The Lesser Antilles borders the Caribbean Sea in the west and the Atlantic Ocean in the east. The Lesser Antilles is located at the eastern border of the Caribbean Plate, while the eastern border where the North American Plate is subducted under the Caribbean Plate from the eastern or northeastern side.

3-2-2 Geology

Major geological layers are Tufton Hall Layer (Late Eocene ~ Early Oligocene), volcanic (Miocene ~ Pleistocene) and volcanic products (Pleistocene ~ Holocene). Volcanic products of Grenada have effused mainly at the five sites between early Miocene (21 Ma) and Holocene (0.9 Ma). The youngest volcano is the Mt. Saint Catherine located in the northern part of Grenada Island. It was reported that the village, which is assumed to have been formed within 1,000 years, had been covered by volcanic products (Global Volcanic Program, 2015).

3-2-3 Fractures

Both of the mapped lineaments and the measured data indicate a clear northeast-southwest direction.

3-2-4 Geothermal Manifestations

Geothermal manifestations of Grenada are identified in many places within the vicinity of Mt. Saint Catherine (Hapsack and Clabony) and in the northern part of the mountains (Castele Hill and Peggy’s Whim).

3-3 Field Survey and Analysis Conducted

3-3-1 Geological Survey

(1) Methodology

The survey carried out in the geothermal manifestation areas included the field observations of rock outcrop, spring/hot spring/ fumaroles, hydrothermal alterations, fractures, and other geological and geochemical related features. When deemed necessary, rock samples were collected for x-ray diffraction analysis and microscopic observation of thin section at home.

(2) Results

The JICA Survey Team visited five sites for the survey, which are the following: (i) Chambord, (ii) CastleHill, (iii) Hapsack, (iv) Peggy’s Whim, and (v) Clabony. The Adelphi-Saint Cyr was not visited because high temperature geothermal manifestation was not observed there. The survey results are as follows:

- Geological setting of the survey area is composed of Tufton Hall Layer formed in late Eocene ~ early Oligocene, volcanic ejecta formed in Miocene ~ Pleistocene, and volcanic ejecta formed in Pleistocene ~ Holocene. Volcano Saint Catherine is located in the center of the survey area. In northwestern piedmont of Volcano Saint Catherine, volcanic ejecta and Tufton Hall layer are covered by some lava domes.
- Volcanic activity might have occurred in Volcano Saint Catherine about 1000 years ago. Because geothermal manifestation zones concentrate around the volcano mountain, magma chamber of Volcano Saint Catherine is perhaps the heat source.
- Rocks are undergoing alteration in several geothermal manifestation zones around Volcano Saint Catherine. Among them, sulfur is depositing in Hapsack where silicification alteration occurred. In Peggy’s Whim, Castle hill and Clabony, smectite and mixed layer clay mineral are turned into rocks due to alteration process.
- Lineament extracted based on terrain analysis, and geothermal manifestation zones, fold axis, strike of the stratum confirmed by geological reconnaissance concentrate in NE-SW direction. Besides it, lineament is also found in NW-SE, NNW-SSE direction (Jacobs, 2015).

3-3-2 Geochemical Survey

The JICA Study Team conducted a geochemical reconnaissance involving sampling and field measurement. The summaries of the survey are as follows.

- Sampling activity and site measurement were conducted in Hapsack, Peggy’s Whim, Castle hill, Clabony and Chambord around Volcano Saint Catherine. The results showed almost the same analyzed value with the survey conducted by Jacobs (2015). In Hapsack, hot spring with the highest temperature of 61.4 °C was found.
- Hot spring water in Grenada can be divided into 3 types according to pH and cation composition, which are sulfuric acid type hot spring in Hapsack and Plaisance-Red

River, neutrality ~ alkalescency Na-Cl type hot spring in Peggy's Whim, Castle hill and Chambord, and bicarbonate type hot spring in Clabony. The gush of all these 3 types hot spring has been confirmed in andesite volcanic regions geothermal system with high temperature.

- Sulfuric acid type hot spring in Hapsack and Plaisance-Red River accompanies with bubbling of H_2S gas. Comparing with other types, this type of hot spring is usually located where is closed to the Volcano Saint Catherine with high elevation.
- Water-rock reaction in the hot spring of Grenada is still in immature stage. However, according to plotted diagram of Na-K-Mg components, the hot spring of Grenada possibly contains some hot water with 220 °C which gushes from geothermal reservoir and has reached equilibrium (immature) stage.
- Among the hot spring of Grenada, some bubble containing spring produce the gas which is confirmed to be contributing to the magma gas. The temperature was estimated to be about 290 °C based on gas thermometer.

3-3-3 Gravity Survey

(1) Objectives

To apply the gravity survey as reconnaissance in order to grasp the regional volcanic structure geologically and extract such fault systems as fracture zone which form the geothermal reservoir.

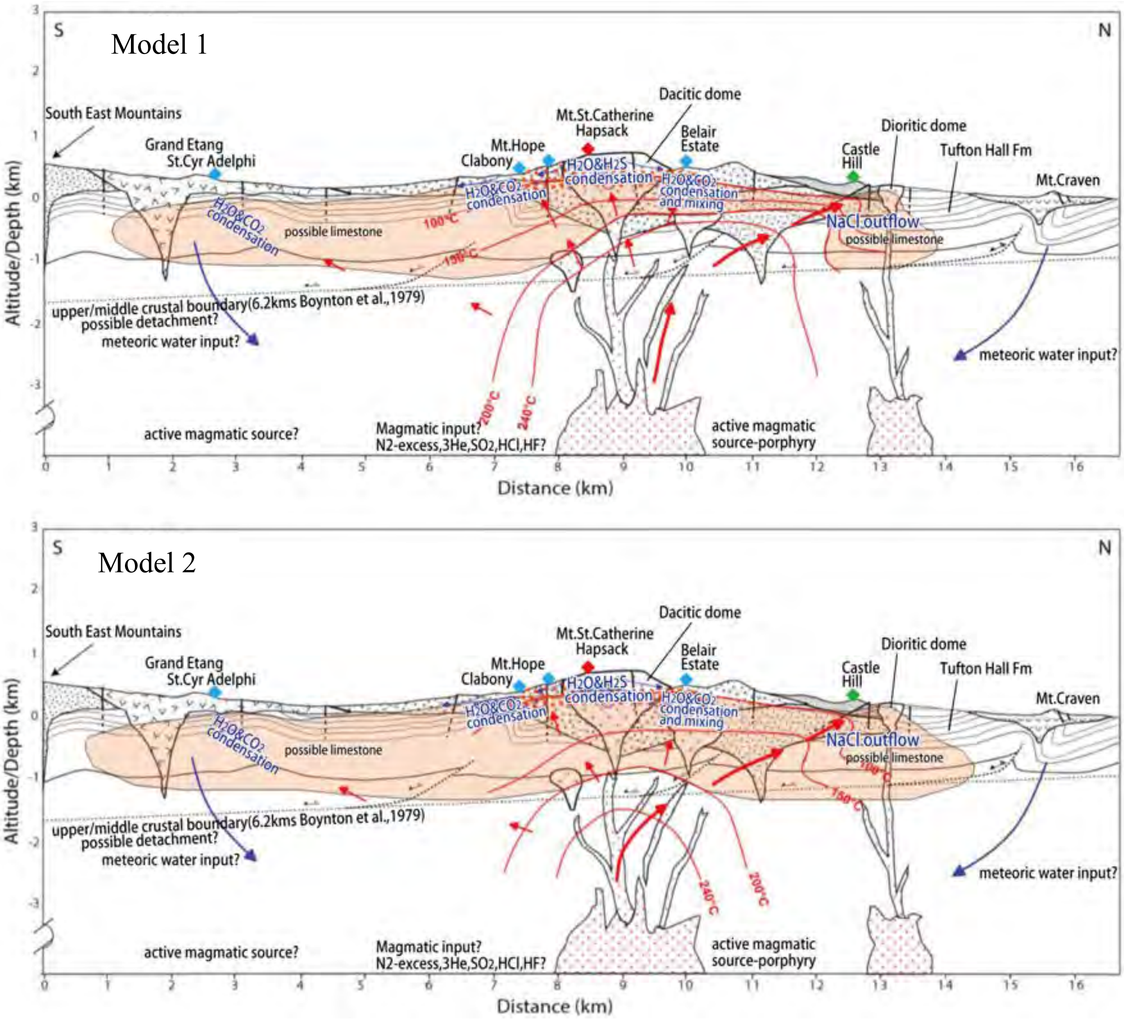
(2) Results

- As to the spatial distribution of resistivity in survey area, the layer with resistivity under 10 Ω·m is thin for those located in high elevation. The layer becomes thick from thin part towards periphery, and the bottom side of it shows a dome-shaped structure. The surficial geothermal manifestation zones are located in or around the area where low resistivity layer becomes thin. Because smectite and mixed layer clay mineral, which will lower the resistivity, distribute in these geothermal manifestation zones, it is possible that the layer with low resistivity is the rock cap of the geothermal reservoir.
- According to the gravity anomaly distribution of survey area, high gravity anomaly zones above -150 mgal can be found in north part of survey area including Hapsack and Pegg's Whim. Especially, the highest gravity anomaly value (above -136 mgal) was found located between Hapsack and Victoria. Around these zones, a steep gravity slope with sudden changes of Bouguer anomaly value exists, and this slope extends linearly along NE-SW direction in the vicinity of Hapsack and Pegg's Whim.
- From Hapsack to northeastern Pegg's Whim and Chambord along NE-SW direction, some places where 0 contour of First Vertical Derivative overlapped the high First Horizontal Derivative area dotted here. Because lineaments on the ground surface were also found in the same area along NE-SW direction, it can be concluded that faults exist along NE-SW direction with steep slope. Furthermore, due to the

existence of geothermal manifestation area in the vicinity of the faults, geothermal fluid flowing may be limited in this area.

3-4 Conceptual model of geothermal system and geothermal reservoir

Conceptual models of geothermal system are shown below.



Source: Jacobs (2016), revised by JICA Survey Team, 2016

Figure 3-1 Profile of estimated geothermal reservoirs

*Model 1 is built on the assumption that, according to the geochemical compositions of surface hot spring and distribution of specific resistivity, the geothermal reservoirs with temperature of 200~290°C wildly spread from deep to shallow depth, and the geothermal fluid flows in lateral direction in northern part of the survey area.

*Model 2 is built on the assumption that, due to the absence of the fumarolic area with boring spring, the temperature of geothermal reservoirs is perhaps lower than 200°C.

Based on the information obtained from these 3 structural boring wells, it is possible to make clear the temperature distribution under the ground and refine the geothermal model.

3-5 Geothermal reservoir assessment

Huttrer and Michels (1993) assessed the geothermal reservoir (about 200°C) around Volcano Saint Catherine at 30~50MW.

The JICA Team conducted the resource assessment with the volumetric method, resulting in the assessment shown in the table below. We used the improved calculation method that can use with specific temperature combination of separator and condenser.

Table 3-1 Eight Guiding Principles for the National Policy

Occurrence probability	80%	Mode	20%
Model-1	30 MW	53 MW	121 MW
Model-2	21 MW	39 MW	87 MW

Source: JICA Survey Team

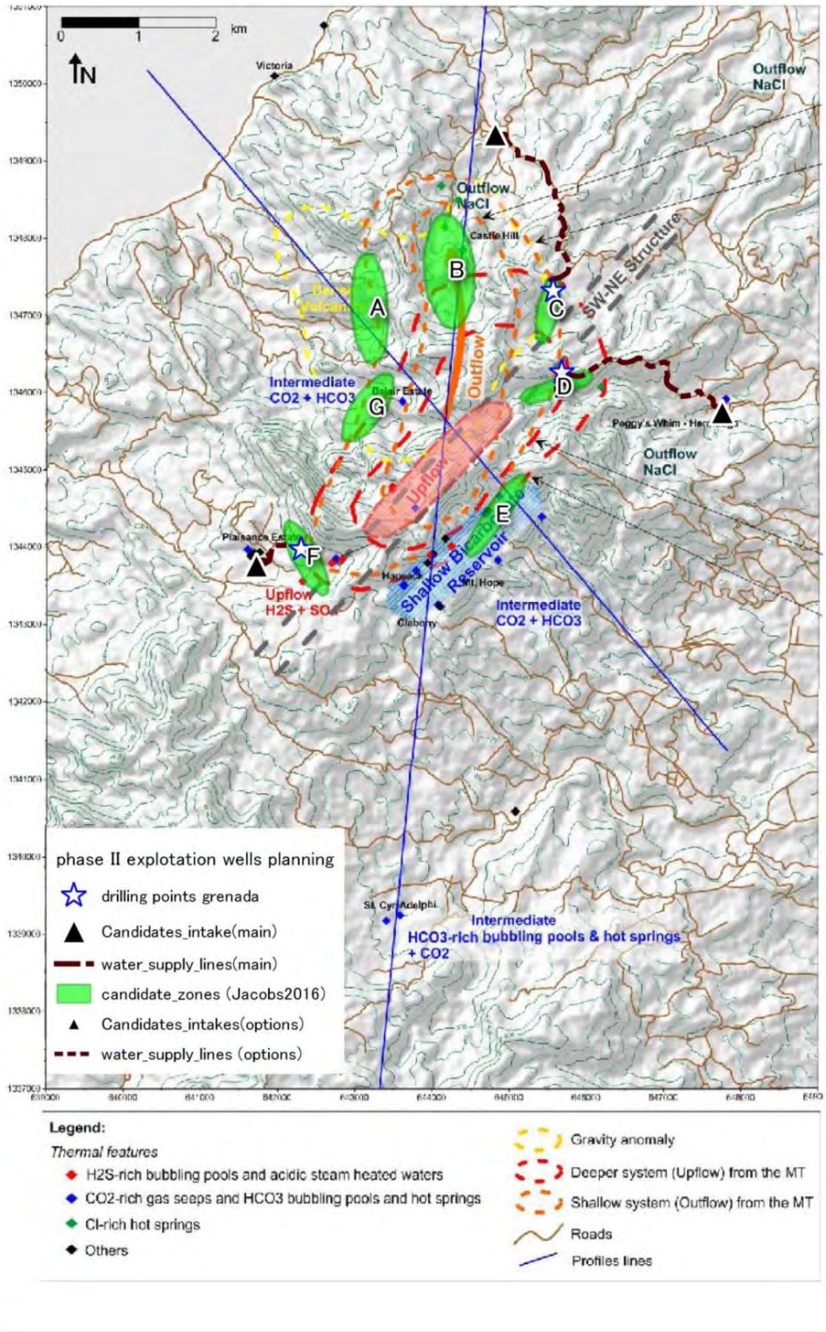
3-6 Exploratory drilling plan

3-6-1 Proposal for drilling slim-holes

The results of previous researches and the JICA survey suggest that geothermal reservoir may exist in North Grenada and piedmont regions of Mount St. Catherine. However, there are uncertainties to be clarified. We would thus recommend to provide slim-hole structural boring wells with smaller diameter but sufficiently larger for temperature/pressure well logging, before providing production wells with full specifications. This is to be provided to confirm the availability of the geothermal reservoir at a lower cost before investing relatively larger cost for production wells.

3-6-2 Selection of drilling sites

There are seven sites (A – G sites) identified where drilling work space may be made available from topographical point of view. Among those, three sites (C, D and F) have been selected since large scale civil works may not be necessary for bringing a drilling rig to the three sites (refer to the section 3-3-6).



Source : JICA Survey Team on Jacobs(2016) base figure

Figure 3-2 Drilling Plan-2：Vertical drilling from the sites C、D、F

C:Plaisance、D:Barique、F:Florida

3-6-3 Drilling Plan

(1) Casing Program for the slim holes

The requirment of the casing shall be as follows:

a) The diameter shall be large enough but minimum for the temperature – pressure well logging to be conducted,

b) The holes shall be vertical,

c) The materials of casing and well head assembly shall be durable against geothermal fluid with high presseure, high temperature and highly corrosive characteristics.

There are two types of drilling rigs available for slim hole drilling: one is the rotary type drilling rig and the other is spindle type drilling rig. The casing programs consist of conductor pipe, surface casing, production casiong and slotted liner. Depths of each casing varys depening on the rig types and the geological conditions infered from te available infromation. Propsed casing programs are summirized in the table below.

Table 3-2 Summary of Proposed Casing Program

Casing Programm									
Rotary type (6-1/2 tricon-bit to the bottom)					Spindle type (wire-line cored, HQ-diamond bid to the bottom)				
name	Dia (nominal)	Depth (m)			name	Dia (nominal)	Depth (m)		
		Florida	Barique	Plaisance			Florida	Barique	Plaisance
C/P	13-3/8”	50	50	50	C/P	350A	30	30	30
S/C	9-5/8”	600	600	600	S/C	9-5/8”	300	300	300
					I/C	7.0”	900	800	700
P/C	N-80	1400	1200	1100	P/C	4-1/2”	1400	1200	1100
S/L	4-1/2”	1990	1990	1990	S/L	80A	2000	2000	2000
C/P: Conductor pipe, S/C: Surface casing, I/C: Intermidiate casing, P/C: production casing, S/L: Slotted liner Casing shall be of API standard.									

Source: JICA Survey Team

Both types of drilling rig are applicable for the slim hole drilling proposed. The key points of selection of the rig type may be the availability of the rig in neighbouring counries and the transpotability and/or workability of the rig in sites to be selected.

(2) Drilling site of the structural boring wells

The construction of structural boring wells drilling with slim-hole needs, if thinking about the work efficiency, at least 2,000m^3 (about 40×50m) for depositing drilling equipment. In case of using rotary table type rig, it needs more space for setting water supply pit (about 12m×12m×1m ≈ 150m^3 is needed, equivalent 5 times volume of the biggest well). Moreover, it will be more efficient if a space for construction material temporary placing can be considered.

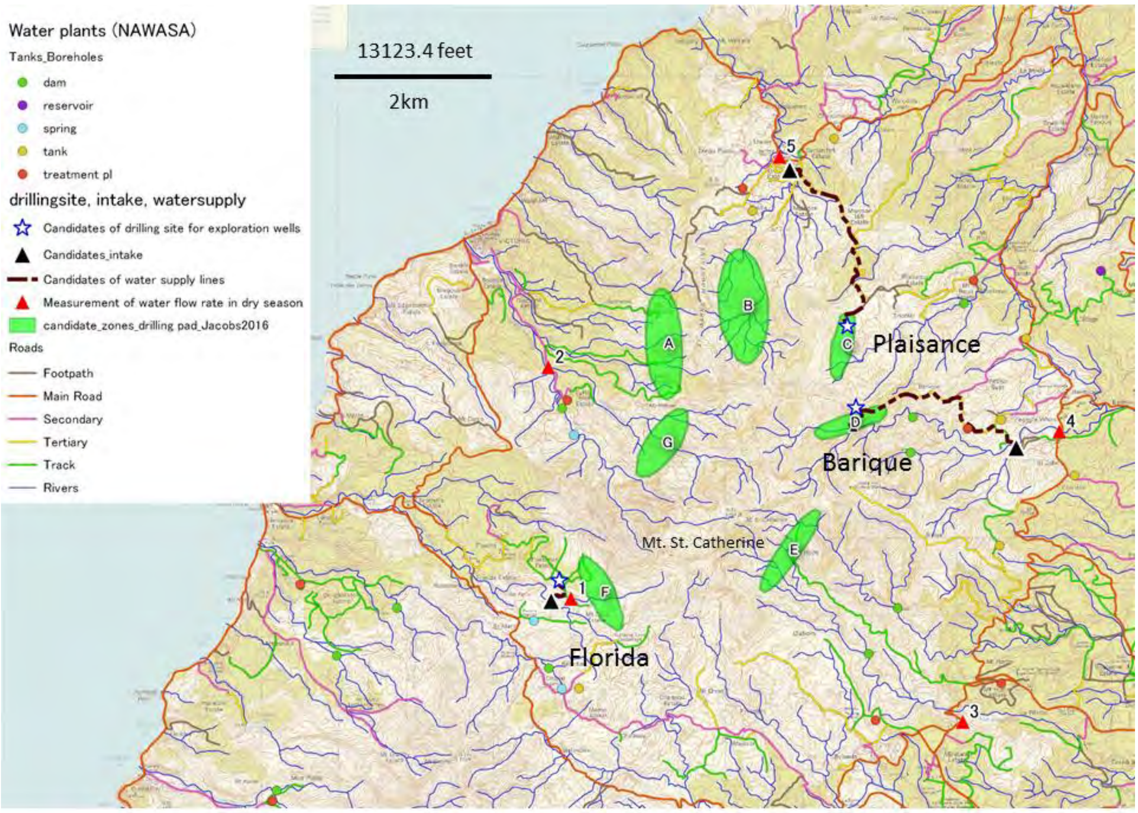
3-7 Civil Engineering Survey

Three candidate zones for drilling of structural boring wells are proposed as below:

Plaisance (Area C)
Barique (Area D)
Florida (Area F)

The location of selected zones is shown below.

For selecting candidate drilling zones from these areas, items below have been considered: a) base of drilling site; b) ability of water supply during drilling; c) location relationship with protected areas; 4) accessibility.



Source: JICA Survey Team

Figure 3-3 Location of candidate drilling zones, river flow measurement and NAWASA water plants

3-7-1 Construction of the base land for drilling sites

Based on the cost of roads preparation and the accessibility, three sites were selected. For the base land and water storage tank, a flat ground with at least 2,000 m^3 is needed.

3-7-2 Water supply for drilling

The water demand should be guaranteed for ground drilling (including total lost circulation of mud water drilling), pit suppression, pit cooling and cementing. In this survey, because river water is to be the water resources for drilling, some possible locations were selected based on the results of river flow survey in dry season. No water extraction from domestic water supply plants in rivers shall be made during drilling operation work. Although all planned water intakes are located in the rivers where there is no NAWASA plants, or in the downstream of the rivers where NAWASA plants, it is still necessary to negotiate appropriately with NAWASA and local land holders.

(1) Protected area

In Grenada, the center part of Mount St. Catherine and parts of coast area are designated as protected areas. All the drilling candidate zones is outside these protected zones. However, Zone Barique is near to one protected area.

(2) Accessibility

All drilling equipment are transported to drilling site from abroad through seaway. The port where large ships can enter is in St. George's only. For the transportation on land, trailer at 20 t level (length 15m × width 2.4 m × height 1.1m) is to be used. The paved roads are available to 500 m away from each drilling candidate zones, and the narrowest part of the road is about 3.5 m. Therefore, there is no need to build new roads for accessing.

Chapter 4 Environmental and Social Consideration

4-1 Environmental Legislation

4-1-1 Legislative Framework

Two legislations (the Waste Management Act No. 16 of 2001 and the Physical Planning and Development Control Act No. 25 of 2002) include provisions for environmental impact assessment (EIA) in Grenada.

Table 4-1 EIA Legislations

No.	Legislation	Description
1	Physical Planning and Development Control Act No. 25 of 2002	To make provision for the control of physical development, require the preparation of physical plans for Grenada, protect the natural and cultural heritage, and for related matters.
2	Waste Management Act No. 16 of 2001	To provide for the management of waste in conformity with best environmental practices and related matters

Source: Legislations in Grenada

The following development activities are subject to EIA under the Physical Planning and Development Control Act. Geothermal development activity should be classified under No. 10 (hydroelectric projects and power plants) and No. 15 (any development generating or potentially generating emissions, aqueous effluent, solid waste, noise, vibration or radioactive discharges), and will thus require the preparation of an environmental impact assessment report.

4-1-2 Terms of Reference of EIA

The EIA for the project should provide the information in Table 4.3.

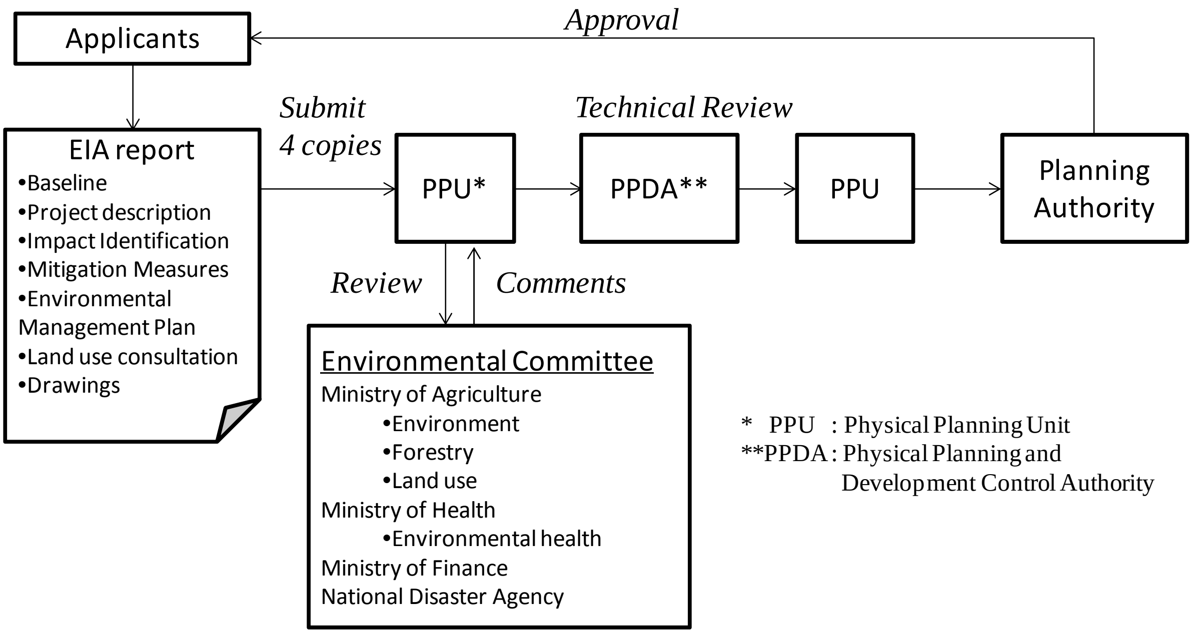
Table 4-2 TOR of EIA

No.	Terms of Reference
1	The background and objectives of the project
2	Specification of the binaries of the EIA study area
3	A description of the project from inception to operational phases
4	A description of the physical, chemical, biological, socioeconomic, and cultural characteristics of the existing environment of the study area
5	Legislative and regulatory requirements
6	Description and quantification of potential environmental effects of the project
7	Assessment of alternatives
8	Mitigation plan
9	Management and monitoring plan
10	A list of references, data sources, etc.

Source: Physical Planning Unit

4-1-3 EIA Process

The process of preparation and audit of EIA in Grenada is shown in the following Figure 4-1. After submission of the EIA report to the Physical Planning Unit, it normally takes about six weeks for the report to be approved.



Source: JICA Survey Team

Figure 4-1 EIA Process in Grenada

4-1-4 Relevant Environmental Legislation and Regulation

Since the 1940s, several pieces of legislation and regulation, including the Public Health Ordinance, have been enacted and amended with the view of providing the necessary legislative framework for the many different agencies dealing with environmental management matters.

Table 4-3 Relevant Environmental Legislations and Regulations

No.	Legislation	Description
1	The Beach Protection Amendment Act of 2009	To prohibit sand mining in Grenada.
2	Litter Abatement Act of 1973	It has been supplemented by the passage of the Waste Management Act of 2001 addressing pollution control and abatement of litter.
3	Solid Waste Management Act No. 11 of 1995	It has established the Solid Waste Management Authority charged with the duty of developing solid waste management facilities and improving the coverage and effectiveness of solid waste storage, collection, and disposal facilities of Grenada.
4	National Parks and Protected Areas Act of 1991	To designate and maintain national parks and protected areas.

No.	Legislation	Description
5	Environmental Levy Act No. 5 of 1997	To impose and collect environmental levy on certain goods and services.
6	Fisheries Act of 1986	To provide for the protection of the marine resources in Grenada; amended in 1999.
7	Forest, Soil, and Water Conservation Act, 1949	To make provision for the conservation of the forest, soil, water, and other natural resources of Grenada; amended in 1984.

Source: Legislations in Grenada

4-2 Institutional Framework of Environmental Management

4-2-1 Environmental Institutions

There are several different agencies involved in activities that impact on the environment; however, eight institutions, i.e, five government departments and three statutory bodies, are directly involved in environmental management activities.

Table 4-4 Environmental Institutions in Grenada

No.	Institutions
1	Physical Planning Unit, Ministry of Communication, Works and Physical Planning
2	The Ministry of Communication, Works and Physical Planning
3	Forestry Department, Ministry of Agriculture Forestry and Fisheries, Public Utilities, Marketing Board and Energy
4	Land Use Department, Ministry of Agriculture, Forestry, Fisheries, and Marketing Board
5	Environmental Health Department, Ministry of Health and the Environment
6	Physical Planning and Development Control Authority
7	Solid Waste Management Authority
8	National Water and Sewage Authority (NAWASA)

Source: Government of Grenada, 2010

4-2-2 Physical Planning Unit

The Physical Planning Unit (PPU) has the legal responsibility to deal with EIA in Grenada. PPU is under the Ministry of Communication, Works, Physical Development, Public Utilities, Information and Communications Technology (ICT) and Community Development. NAWASA, which deals with water resource management, is also in this chart.

4-2-3 Physical Planning and Development Control Authority (PPDA)

PPDA is the authority which deals with the identification, protection, conservation, and rehabilitation of the natural and cultural heritage in Grenada. The authority consists of the following members based on the *Physical Planning and Development Control Act No. 25*:

(a) A chairperson (who may be a public officer) appointed by the minister;
(b) An executive secretary (who may be a public officer) appointed by the minister;

(c) Three other members appointed by the minister from the private sector;
(d) The following public officers as ex officio members:
  (i) The head of the Physical Planning Unit;
  (ii) Environmental Protection Officer;
  (iii) Director of Housing;
(e) Two senior public officers dealing with the following matters and nominated by the respective ministers:
  (i) Agriculture
  (ii) Public works

as ex officio members; and

(f) The manager of NAWASA as an ex officio member.

4-3 Environmental and Social Conditions

In this section, the current environmental and social conditions of Grenada, especially around Mt. St. Catherine, are analyzed using existing information in order to identify the items to be considered at the geothermal drilling stage.

4-3-1 Natural Environment

(1) Meteoric and Hydrological Environment

Grenada lies in the humid tropical zone within the Atlantic northeast trade wind belt and the seasonal shift in these winds give rise to the wet season (June to December) and dry season (January to May). The average annual rainfall for mainland Grenada is about 2,000 mm and it ranges from between 1,000 mm and 1,500 mm along the coastal zone to approximately 4,000 mm in the interior.

(2) Natural and Cultural Heritage[1]

Grenada currently has seven protected areas designated by legislation, as follows:

1) Grand Etang Forest Reserve
2) Annandale Forest Reserve
3) High North Forest Reserve
4) Perseverance Protected Area
5) Woburn/Clarks Court Bay Marine Protected Area
6) Moliniere/Beausejour Marine Protected Area
7) Unspecified crown lands at Pearls are designated as a protected area

The Organization of Eastern Caribbean States (OECS) has prepared the “Systems Plans for the Protected Areas in the OECS” in 2009 in Grenada. The Figure below shows the zones of designated protected area and proposed area in the system plans. Protected areas are categorized into four groups as follows. The areas around Mt. St. Catherine are proposed for

[1]OECS Protected Areas and Associated Livelihoods (OPAAL), Grenada Protected Area System Plan, 2009 (Funded by the Global Environmental Facility (GEF) through the World Bank, and the Fonds Français pour l’Environnement Mondial (FFEM))

immediate designation and forest reserve and local area planning and prepared to be designated by the Government of Grenada.

Table 4-5 Types of Protected Area

Category	Feature	Area (Selected)	Designation
Designated Protected Area	Already designated by the government (7 areas)	Grand Etang	Forest Reserve
Local Area Planning	Areas that should be reviewed in the context of best land use and the local area planning process. (14 areas)	Mt. St. Catherine Addition	Mt. St. Catherine Forest Reserve Addition
Priority Area of Interest	Existing land use pressures from residential, tourism, and industrial development have the potential to threaten future protected area. (8 areas)	South Carriacou Islands	Marine Protected Area
Immediate Designation	Areas which should be designated immediately due to the importance to Grenada's endangered species and habitats. (16 areas)	Mount Hartman	National Park
		Mt. St. Catherine	Forest Reserve

Source: OPAAL. 2009

(3) Flora[2]

There is little formal documentation available on the composition and status of Grenada's forests. Although some research has been conducted on a few species of trees, very little attention has been given to herbaceous and nonvascular plants. There is no information available on threatened or endangered plant species.

(4) Fauna

There is little hard data about faunal species numbers, distribution, and their current status. Grenada's terrestrial wildlife is thought to consist of four amphibian species, eight species of lizards, five species of snakes, and 150 species of birds (Groome, 1970), of which, 18 species are thought to be threatened or endangered, i.e., four native species of terrestrial mammals and 11 native species of bats (Groome, 1970). One of the most important fauna is the Grenada Dove and its habitat. It is the national bird of Grenada and considered to be an endangered species located at Mt. Hartman, in the southern part of the island.

[2] The Convention on Biological Diversity in Grenada, Biodiversity Strategy and Action Plan, 2011

4-3-2 Social Environment

(1) Land Use

Most of the island is used for “Agriculture”, “Abandoned Cultivation”, and “Forest”. “Buildup area” is distributed mainly in the southwest region and some town areas around the island. Main crops are nutmeg, cocoa, banana, sugar cane, and variety of fruits. The frank area of Mt. St. Catherine, where potential area for geothermal development can be found, is widely used for agriculture, while some areas are privately owned.

(2) Residents

The population of Grenada is 105,000 (2013, World Bank) and most of the people are living in the southwest of St. George’s (5,000-25,000/km^2) and along the main roads (500-5,000/km^2). Some resettlement should be implemented for geothermal development project around Mt. St. Catherine.

4-3-3 Preliminary Scoping for Environmental and Social Items

In order to identify the environmental and social consideration items for the project, preliminary scoping was conducted. The items analyzed in the preliminary scoping were selected based on the check items listed in the JICA Guidelines for Environmental and Social Considerations (April 2010). The degree of impacts were assessed for the preparation stage (test drilling, land acquisition), construction stage (construction of facilities), and operation stage (operation of facilities) assuming that the case cannot be avoided and mitigation measures are taken. As a result of preliminary scoping, environmental impacts are to be expected on air quality, water quality, waste, noise, protected area, ecosystem/flora and fauna, hydrology, topography, geology, landscape, and climate change.

Chapter 5 Pre-Feasibility Study

5-1 Project Goal and Objective

5-1-1 Goal

The National Energy Policy of Grenada – A Low Carbon Development Strategy for Grenada, Carriacou and Petite Martinique, November 2011 set up the 11 goals to be achieved. The JICA Survey Team has selected the following two goals as goals of the geothermal energy development in Grenada.

Renewable Energy Goal: Twenty percent of all domestic energy usage (electricity and transport) will originate from renewable energy sources by 2020.

Power Sector Goal: Transition to an efficient, low-carbon, national electricity generation and interconnection network that ensures safe, efficient, affordable and environmentally friendly energy services.

5-1-2 Project Objective

The immediate and direct objective of the project is to construct a geothermal power station together with related auxiliary facilities.

5-2 Outline of the Project

5-2-1 Geothermal Power Plant

(1) Types of Geothermal Power Plant

The JICA Survey Team recommends a single flash condensing type of power plant because of its structural simplicity and expected range of geothermal enthalpy of the reservoir.

(2) Installed Capacity

The JICA Survey Team proposes that the installed capacity of the geothermal power station shall be 15 MW.

(3) Turbine and Generator

Three sets of 5 MW turbine generator units are recommended. The turbine shall be of the single flash condensing type, the generator will be of totally enclosed water- to air-cooled type with major specifications of 11 kV voltage, three phases, 50 Hz frequency, and 3, 000 rpm rotating speed.

5-2-2 Fluid Collection and Reinjection System（FCRS）

(1) Production Well and Re-injection Well

The JICA Survey Team assumes that three wells are to be converted into production wells and one into the re-injection well. The wells are of 8-1/2’ inch drilling diameter at the bottom, 2,000 m length and directional.

(2) Fluid Transportation Pipeline

As the topography is intensely undulating in the target area, the lengths of the fluid transportation line may vary according to the pipeline route to be decided. Here, the JICA Survey Team assumed an average length of 3 km between the production base and the power plant, totaling to 9 km. The diameter should be 500 mm.

5-2-3 Electricity Transmission Facility

The total length of the transmission line will be not more than 40 km. As the total installed capacity is 15 MW, the 33 kV capacity of the transmission facility will be suitable. The transmission facility shall be installed along the existing road; shall have two new transmission lines, each with 100% capacity to provide full redundancy.

5-3 Project Cost Estimation

The costs of the surface surveys are not included in the cost estimates because they have been completed by the JICA Survey Team and New Zealand Team (2016). The JICA Survey Team made the preliminary estimation of the costs of the activities to be conducted after the completion of the surface survey. The activities include: i) slim hole drilling, ii) appraisal well drilling, iii) production well drilling, iv) transmission facility construction, and v) power plant construction including steam field development.

The estimated cost totaled to USD 123 million.

Table 5-1 Summary of Cost Estimation

Cost Items	Cost (US$)
Civil Works & Preparation	17,700,000
Slimhole Drilling (3 Wells)	7,500,000
Appraisal Drilling (4 Wells)	20,800,000
Production Drilling (2 Wells, Production Test)	12,400,000
Field Development	6,000,000
Construction of Power Plant	35,200,000
Transmission Line (2 lines)	18,000,000
Consultancy Services (DD, SV)	5,800,000
Total	123,400,000

Source: JICA Survey Team

5-4 Project Implementation Models

The JICA Survey Team assumed four models for the financial analysis based on variations of the cost bearing (investing) entities, i.e., Grenada government or private entity/ies, as shown in Table 5-2. For all the models, the JICA Survey Team assumed that the government will invite private entity/ies for power plant construction (including steam field development - FCRS), transmission line construction, and operation and maintenance. Also, the JICA Survey Team assumes that slim hole drilling will be conducted through grant finance to be made available to the government.

Table 5-2 Implementation Models for Financial Analysis

Model	Entity	Work Allocation
Model-1	Government:	Slim holes, appraisal well, production wells, and tendering for procurement of one year
	Private:	FCRS and power plant
Model-2	Government:	Slim holes, appraisal well, and tendering for procurement of one year
	Private:	Production wells, FCRS and power plant
Model-3	Government:	Slim holes and tendering for procurement of two years (A period of two years for tendering is assumed to allocate a longer period for tender preparations because appraisal wells are not completed at this stage)
	Private:	Appraisal wells, production wells, FCRS and power plant (A period of two years for tendering is assumed to allocate a longer period for tender preparations because appraisal wells are not completed at this stage)
Model-4	Government:	Tendering for procurement of two years (A period of two years for tendering are assumed to allocate a longer period for tender preparations)
	Private:	Appraisal wells, production wells, FCRS and power plant (A private entity is assumed to participate in the project only when he/she should be confident that geothermal energy would be available without providing slim holes or additional appraisal wells.)

Source: JICA Survey Team

5-5 Financial Analysis

5-5-1 Financial Analysis for Geothermal Development in Grenada

The government looks for public-private-partnership (PPP) for the investment to the geothermal resources development. The financial analysis aims to examine the financial viability of the project and to compare the investment options for the government.

5-5-2 Project Scheme

The financial analysis examines the following three options for the project schemes. Models-1 to -3 are PPP options where the government and private company will demarcate the activities of the project implementation. The development of the slim hole drilling would be covered by a grant fund. Even in the case where the grant finance would not be realized, the private sector could participate in the development without slim hole drilling. There would also be an option (Model-4) for the traditional build-operate-transfer (BOT) scheme, which is practically similar to Model-3 if the private sector does not choose to invest in the slim hole drilling. Therefore, the financial analysis for BOT (Model-4) is studied in Model-3.

Table 5-3 Project Scheme

<table>
<tr><th colspan="3" rowspan="2">Particular</th><th>Model 1</th><th>Model 2</th><th>Model 3</th></tr>
<tr><th>(PPP Model No.1)</th><th>(PPP Model No.2)</th><th>(PPP Model No.3)</th></tr>
<tr><td rowspan="5">Development Activity & Entity</td><td>1</td><td>Exploration Slim Hole Drilling</td><td>Government (Grant Fund)</td><td>Government (Grant Fund)</td><td>Government (Grant Fund)</td></tr>
<tr><td>2</td><td>Appraisal Drilling</td><td>Government</td><td>Government</td><td>Private</td></tr>
<tr><td>3</td><td>Production Drilling</td><td>Government</td><td>Private</td><td>Private</td></tr>
<tr><td>4</td><td>Field Development and Construction of Power Plant</td><td>Private</td><td>Private</td><td>Private</td></tr>
<tr><td>5</td><td>Operation</td><td>Private</td><td>Private</td><td>Private</td></tr>
<tr><td colspan="2" rowspan="2">Debt Financing</td><td>Government</td><td>Concessional Loan</td><td>Concessional Loan</td><td>Concessional Loan</td></tr>
<tr><td>Private</td><td>Commercial Loan</td><td>Commercial Loan</td><td>Commercial Loan</td></tr>
<tr><td colspan="3">Remarks</td><td>Sales agreement of steam or sales of production wells to power producer</td><td>Transfer cost of appraisal drilling to power producer</td><td>No costs will be transferred to the private entity.</td></tr>
</table>

Source: JICA Survey Team

It is assumed that the costs of the development by the government would be recovered by the revenue of the charges from the private company. The charge will be included in the operating expenses of the private company. It is also assumed that the private company obtains the revenue from the power sales to GRENLEC; the government and GRENLEC could also be a shareholder of the generation company; the equity return would be an ordinary return for similar projects, which would be approximately 20%. However, the financial analysis does not specify the composition of the shareholders.

5-5-3 Assumptions for the Financial Analysis

The conditions for debt financing have been estimated based on recent trend and examples of similar projects with concessional loans of the cooperating partners and commercial loans of commercial banks. The equity return for the private company was assumed to be 20%. The depreciation of the plant is the same period as the lifetime of the power plant.

5-5-4 Results of the Financial Analysis

(1) Analysis-1: Comparison of Project IRRs and WACCs with fixed power sales price to GRENLEC US¢ 0.15/kW

It is assumed that the private company can sell the generated electricity at a sale price (US¢0.15/kW) acceptable to GRENLEC.

In all the models, the government shall recover the investment costs from the private company during the operation phase. The charges by the government to the private company however should be kept at a minimum in order to encourage investment from the private sector.

A project will be judged financially viable when the project IRR should not smaller than WACC. The results of the financial analysis are as shown below.

Table 5-4 Results of the Financial Analysis

(When selling price to GRENLEC is fixed at US¢0.15/kW)

Entity	Item	Model 1	Model 2	Model 3
Public (Government)	Debt	USD 41.5 mil.	USD 27.1 mil.	USD 0.6 mil.
	Equity	USD 20.6 mil.	USD 13.8 mil.	USD 0.3 mil.
	WACC[3]	2.6%	2.6%	2.6%
	Project IRR	3.5%	3.7%	4.3%
	Equity IRR	- 1.1%	- 0.9%	1.7%
Private	Debt	USD 50.3 mil.	USD 66.3 mil.	USD 92.6 mil.
	Equity	USD 12.6 mil.	USD 19.1 mil.	USD 23.1 mil.
	WACC	8.4%	8.7%	8.4%
	Project IRR	13.9%	11.0%	8.5%
	Equity IRR	34.9%	31.8%	22.2%
Public-Private Consolidated	Project IRR	8.2%	8.4%	8.4%

Source: JICA Survey Team

The project IRRs in all cases exceed the WACC for both parties of the Public and the Private, thus the project should be judged financially variable.

(2) Analysis-2: Variation of power sales prices with fixed IRR 20 %

The results of the financial analysis with fixed IRR at 20% is shown below.

Table 5-5 Analysis of Power Sales Prices

Assumption	Indicator		Model-1	Model-2	Model-3
Equity IRR (20%)	Power Sales Tariff	USc/kW	12.1	12.9	14.3

Source: JICA Survey Team

Since the power sales prices will be lower than the prices US 15 cents/kWh that GRENLEC may accept, the geothermal development project would contribute a lower power price.

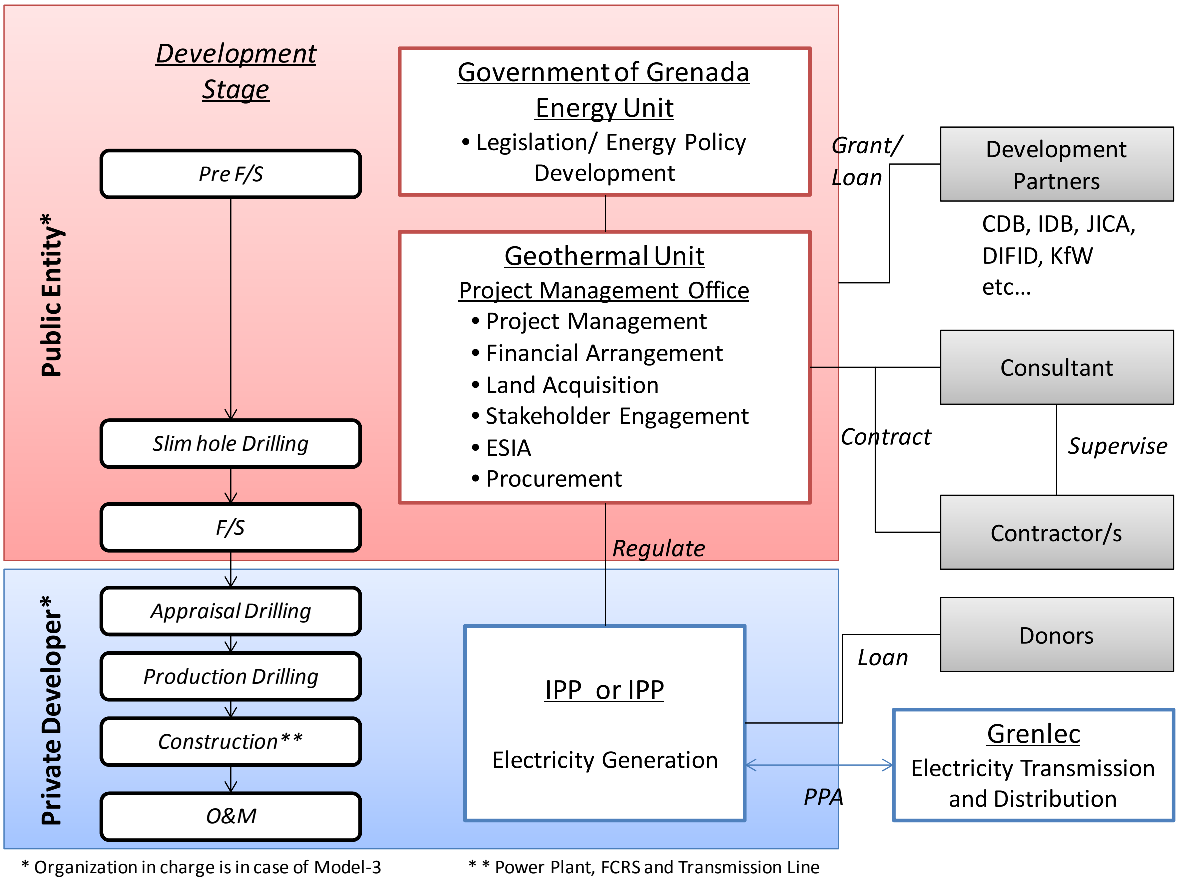
[3] WACC: Weighted Average Cost of Capital, FIRR: Financial Internal Rate of Return

5-6 Project Implementation Structure

The proposed project structure for the geothermal development in Grenada is shown in the following figure. Here model case 3 is taken as a typical project scheme.

During the F/S stage, the government of Grenada is required to establish a legislation and regulation in order to promote geothermal project. Regarding a project management, formulation of a special Geothermal Unit under the Energy Unit is recommended. The Geothermal Unit will conduct a project management, financial arrangement for test wells, land acquisition and ESIA for test drilling as well as tender process and contract matters.

For technical management such as drilling supervise and ESIA study, consultants shall be employed by the government or other development partners.



Source: JICA Survey Team

Figure 5-1 Project Structure

5-7 Project Evaluation

The project is evaluated from the following DAC evaluation 5 points of view.

- Relevance
- Effectiveness
- Efficiency

- Impact
- Sustainability

  As the result, the project is judged viable on condition that the following external conditions should be satisfied.

5-8 External Conditions

Envisaged external conditions identified at this stage are as follows:

- Relevant laws and/or regulations are to be implemented.
- Grant funds, soft loans, and/or local finance for implementing the project are to be made available on time.
- Technical assistance to identify the resources and to construct the geothermal power plant is to be provided.
- Geothermal resources are to be identified and developed in economical ways.
- IPP or PPP is to be formulated through participation of private firm/s.
- Requirements relating to ESIA are to be satisfied.

Potential funds for the geothermal development projects are listed below.

Table 5-6 Potential Funds for the Project

Scheme	Fund	Activity
Grant	CDB, IDB, Bilateral donors (e.g. UK)	- Test well drilling
Loan	CDB, IDB (e.g. Clean Technology Fund), Bilateral donors (e.g. JICA), IRENA	- Appraisal well drilling - Production well drilling - Plant construction - Transmission line construction - Consultancy service
Technical Assistance	Bilateral donors (e.g.NZ, JICA), Other organizations (e.g. UN organizations), Sustainable Energy Facility (SEF)	- Project progress and capacity management - ESIA - Assistance for Construction works including drilling work (Specification, Tender, Supervision, Well test, etc.)

Source: JICA Survey Team

Chapter 6 Action plan and issues in project implementation

6-1 Action Plan of the Government of Grenada and Partners

Action plans for the government, donors and IPP/PPP are shown in Figure 6-1 in case of model-3. The geothermal project in Grenada is now at the end of exploration stage and preparation for test well drilling is needed in the next stage.

In order for inviting private developers for the project investment, the government of Grenada is recommended to conduct following actions.

6-2 Potential Supports from Japan

The JICA Team identified potential work items for further assistance from Japan subject to mutual discussions among relevant parties.

- Technical assistance regarding ESIA for test well drilling
  - ➢ Baseline survey, scoping survey
  - ➢ ESIA for test well drilling including stakeholder engagement
- Technical assistance for procurement with grant assistance
  - ➢ Preparation of tender documents and procurement of drilling contractor,
  - ➢ Drilling supervision
- Procurement or preparation of grant assistance for the test well drilling

6-3 Conclusions

(1) Necessity of Geothermal Power Plant in Grenada Island

- Almost all the electric power is being generated by diesel engine power generation plants, thus the electric prices are strongly affected by the oil price fluctuations.

- Under such circumstances, it is urgent requirement that the indigenous geothermal energy will have to be developed.

(2) Geothermal Energy Resources

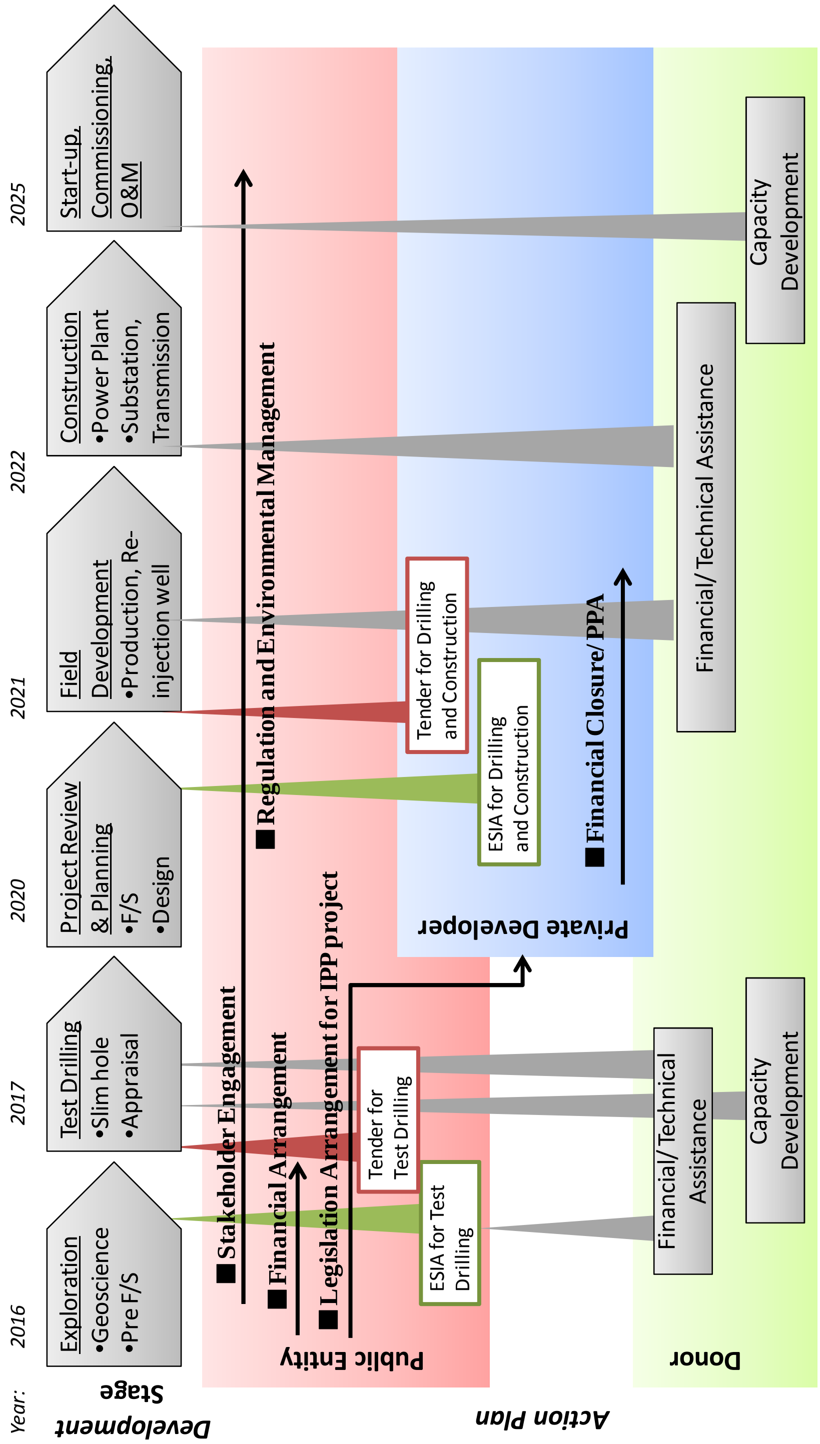
- The survey concluded that there should be 20 – 95 MW potential of geothermal energy in Grenada Island.

(3) Geothermal Energy Development Plan

- The project is judged financially feasible to construct a geothermal power station with 15 MW installed capacity utilizing the geothermal resources.
- The project is also judged feasible from the DAC 5 evaluation point of view, provided the external conditions should be satisfied including confirmation of the geothermal resources.

(4) Test well Drilling (slim hole drilling)

- Drilling of three slim holes is recommended to obtain geological information and to confirm the availability of the geothermal reservoir.



Source: JICA Survey Team

Figure 6-1 Action Plan for Geothermal Development Project in Grenada

6-4 Recommendations

The following actions are recommended for a smooth implementation of the project.

(a) Establishment of the Geothermal Unit and capacity building

(b) Preparation and enforcement of relevant lows and regulations
(c) Procurement of technical assistance and grant finance for the test well drilling
(d) Implementation of ESIA for the test well drilling, and test well drilling for the confirmation of the geothermal reservoir
(e) Information collection and sounding to potential financers for appraisal well drillings
(f) Information collection and sounding to potential developers of the geothermal power generation

DATA COLLECTION SURVEY FOR GEOTHERMAL DEVELOPMENT IN GRENADA

FINAL REPORT

Location Map
Abbreviation
Executive Summary

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Appendixes

Figures and Tables

Exchange Rate at July 2016

1.0 US$ = 2.689 XC$ (EC$) = 102.28 JPY

Chapter 1 Introduction

1-1 Background of the Survey

Development of renewable energy is one of the emerging issues to attain energy security and economic stability in Grenada, a member of the Caribbean Community (CARICOM), where other sufficient natural energy resources are not necessarily available. The Government of Grenada intends to promote the development of a geothermal power station since geothermal energy is conceived to be available in Grenada. However, the development has not proceeded well yet since the development of geothermal energy usually needs up-front large investment.

On the other hand, the Japan International Cooperation Agency (JICA) entered into an agreement with the Inter-American Development Bank (IDB) in 2013 regarding “Co-financing for Renewable Energy and Energy Efficiency (CORE Scheme)”; followed by a signing on the Memorandum of Cooperation with the Caribbean Development Bank (CDB) and IDB in Port of Spain, Trinidad and Tobago on 28 July 2014 with the aim of building a new partnership to promote renewable energy and energy efficiency in the Eastern Caribbean Region.

With such background, JICA was requested to conduct a data collection survey for geothermal development that could be promoted with co-financing from CDB, IDB, and JICA.

The JICA Survey Team consisting of three Japanese consultant firms was selected by JICA to conduct the requested survey.

1-2 Objectives

- To collect and review data and information in order to formulate the JICA preparation survey on the development of geothermal energy for technical and/or financial support; the data and information will include national policies, relevant laws, regulations, guidelines, and others that may deal with the participation of foreign entities.
- To conduct surveys such as field surface geological/geochemical survey, preliminary environmental survey, organizational/institutional survey and/or others; if and when deems to be necessary.

1-3 Target Site

The target site is the Grenada Island.

1-4 Relevant Organizations to the Survey

Relevant organizations are as shown in Table 1-1.

Table 1-1 Relevant Organizations

Name	Mandate
Division of Energy and Sustainable Development in the Ministry of Finance, Economic Development, Energy, and Foreign Trade	Policy making, its implementation and monitoring.
Grenada Electricity Services Limited **(GRENLEC)**	- The only electric service company that deals with power generation, transmission, and distribution. - Stockholders: WRB enterprise, 50%; Government of Grenada and the National Insurance Scheme, 21%; employees, 4.5%; others, 24.5%;

Source: JICA Survey Team

1-5 JICA Survey Team

The JICA Survey Team is composed of experts from different fields as shown in Table 1-2.

Table 1-2 JICA Survey Team Members

Name	Responsible for
TAKAHASHI Shinya	Team Leader/ Geothermal Energy Development/ Reservoir Assessment
AKATSUKA Takashi	Vice Team Leader/ Geology/ Drilling Planning
FUKUDA Daisuke	Geochemical
KAWASAKI Kiyoshi/ TAKEDA Masahiro	Geophysical Survey
TERAMOTO Masako	Environmental Social Consideration
KIKUKAWA Takeshi	Electricity Policy/ Investment Policy
MOMOSE Yasushi/ YOSHIDA Satoshi	Civil Engineering Planning

Source: JICA Survey Team

1-6 Overall Survey Schedule

The overall survey schedule of the JICA Survey Team is shown in Table 1-3. The schedule was subject to modification.

Table 1-3 Overall Survey Schedule

No.	Position	Name										2016							
			4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8
1	Team Leader/Geothermal Development Plan/Reservoir	TAKAHASHI		■		■	■	■									■		
2	Sub-Team Leader/ Geology/Drilling Engineer	AKATSUKA		■				■							■		■		
3	Geochemistry	FUKUDA		■															
4	Geophysics	KAWASAKI/ TAKEDA		■				■											
5	Environmental and Social Considerations Evaluation	TERAMOTO		■				■				■		■	■		■		
6	Energy Policy Analysis/Project Finance	KIKUKAWA		■		■	■					■		■	■		■		
7	Civil Engineering Planning	MOMOSE/ YOSHIDA		■				■							■				
Report			△ IC/R							△ PR							△ DF/R		△ F/R

*Intermittent
IC/R: Inception Report, P/R: Progress Report, DF/R: Draft Final Report, F/R: Final Report

Source: JICA Survey Team

Chapter 2 Present Conditions and Issues of the Energy Sector

2-1 Outline of Social Conditions of Grenada

General social conditions are summarized in Table 2-1.

Grenada is an Eastern Caribbean State consisting of small islands of a land area of 345 km^2 with a population of approximately 106,000, independent since 1974 from the United Kingdom. The official language is English.

Table 2-1 Social Conditions of Grenada

1	**General**			
a.	Area	345 km^2		
b.	Population	106,000		（WB, 2014）
c.	Capital	St. Georges		
d.	Language	English (Official）, Grenadian Creole French		
e.	Independence	1974, from GB		
2	**Politics**			
a.	Political System	Constitutional monarch		
b.	Head of State	Queen Elizabeth II		
c.	Assembly	Two-Chamber system（Upper/Lower 13/15 seats ）		
d.	Main party	New National Party, National Democratic Congress		
3	**Diplomacy**			
a.	Member of CARICOM			
b.	Member of OECS			
4	**Economy**			
a.	Major Industry	Agriculture, tourism		
b.	GNI	840 M USD		（WB, 2014）
c.	GNI per capita	7,910 USD		（WB, 2014）
d.	GDP growth rate			（WB）
	i)	2012	-1.20%	
	ii)	2013	2.40%	
	iii)	2014	5.70%	
e.	Infration Rate			(consumer price basis IMF）
	i)	2012	2.40%	
	ii)	2013	-0.04%	
	iii)	2014	-0.80%	
f.	Unemployment rate	N/A		
g.	Trade			（WB, 2014）
	i)	Export	37 MUSD	
	ii)	Import	340 M USD	（C.I.F)
h.	Major Trading Goods			
	i)	Export	Banana, Cocoa, Nutmeg, fruits, Vegetables, Clothes, Sea Food	
	ii)	Import	Food, Machinery/transportation equipment, industrial/chemical go	
i.	Major Trading Countries			（WB, 2014）
	i)	Export	Dominica, USA, EU, St. Lucia, Barbados	
	ii)	Import	USA, TT, EU, Venezuela, Japan	
j.	Currency	Eastern Caribbean Dollar (EC$)		
k.	Exchanging rate	1USD = 2.7 EC$ (Fixed)		
l.	Major Donors			(OECD/DAC. 2013)
	i)	(1) German,（2）Australia、(３)USA		
	ii)	(4) Cabada（5）Japan		

（Source：Web-site of Ministry of Foreign Affairs, updated on 15 June 2016）

Grenada is one of the Commonwealth of Nations having Queen Elizabeth II as the reigning constitutional monarch, adopting a two-chamber democratic political system. There are two major political parties, either of which has taken office through election. It is a member of the Caribbean Community and Common Market (CARICOM) and the Organization of Eastern Caribbean States (OECS), using the Eastern Caribbean dollar as the common currency in the eight eastern Caribbean countries.

Although agriculture and tourism have been the major industries, the service industry has become dominant as well as tourism after the devastating damages on the agricultural industry by Hurricane Ivan of 2004. Possibly due to this reason, the sum of import of goods in 2013 recorded about ten times as that of export. In addition, Grenada is the 2nd largest nutmeg producing country in the world next to Indonesia.

It should be noted that about 50% of fuel are consumed for the electric power production[1]. The fuel is one of the major goods that Grenada has to import.

[1] Source: Energy Policy and Sector Analysis in the Caribbean 2010-2011, NREL US

2-2 National Energy Policy of Grenada

The Government of Grenada formulated the National Energy Policy of Grenada – A Low Carbon Development Strategy for Grenada, Carriacou and Petite Martinique, November 2011. The policy is based on the following eight guiding principles shown in Table 2-2.

Table 2-2 Eight Guiding Principles for the National Policy

• Energy Security • Energy Independence • Energy Efficiency • Energy Conservation	• Environmental Sustainability • Resource Exploitation • Energy Prices • Energy Equity and Solidarity

Source : The National Energy Policy of Grenada, November 2011

The national policy has set up the eleven goals to be achieved as shown in Table 2-3.

Table 2-3 Eleven Goals of the National Policy

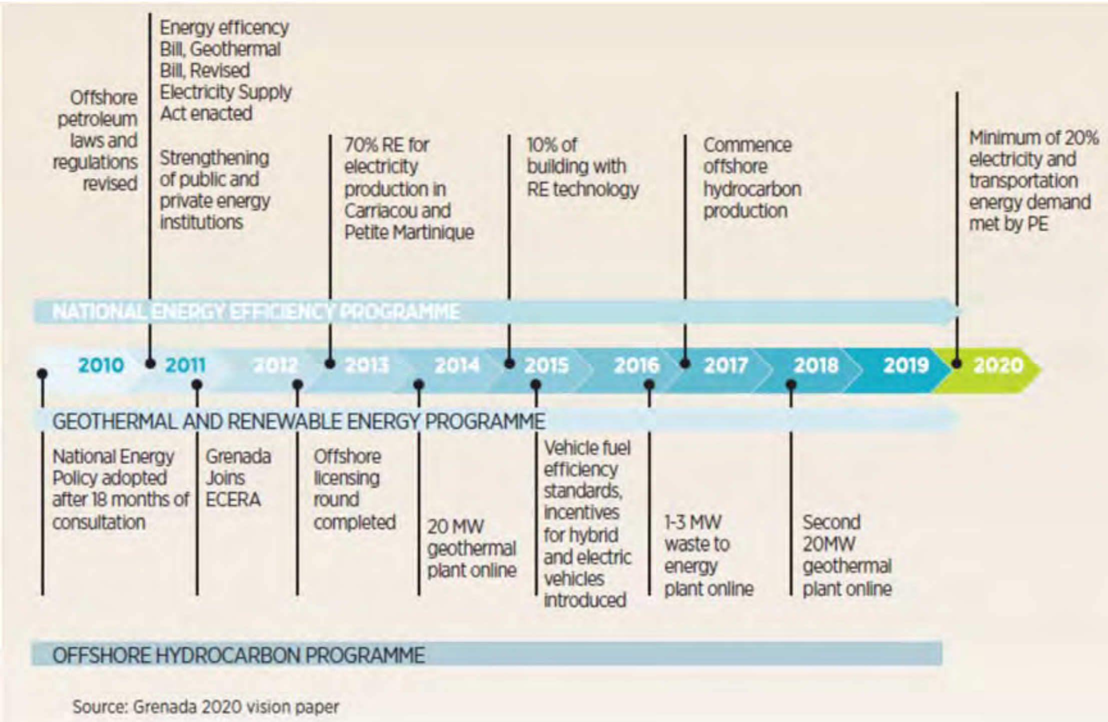
Subject	Goal
1. Institutional issues	Build and establish the adequate human capacity and institutional regime to guarantee appropriate allocation and management of resources to achieve the energy policy goals.
2. Legal and regulatory framework	Establish an appropriate and enabling legal architecture on which the policy can rest and be implemented to achieve the government's national development policy objectives and create a climate to materialize the long-term vision of achieving a sustainable energy development.
3. Hydrocarbons	Exploit indigenous hydrocarbon resources in the most efficient way as part of a long-term transition version using such resources as export commodities for revenue generation and allocate financial resources to achieve the National Energy Policy goals.
4. Renewable energy	About 20% of all domestic energy usage (electricity and transport) will originate from renewable energy sources by 2020.
5. Energy efficiency and conservation	Reduce the national rate of energy consumption while increasing the economic growth (decoupling) by adopting the best practices in energy efficiency and conservation.
6. Power sector	Transition to an efficient, low-carbon, national electricity generation, and interconnection network that ensures safe, efficient, affordable, and environmentally friendly energy services.
7. Transport sector	Establish an affordable and reliable public transport sector and increased use of more efficient public and private vehicles and transport alternatives to reduce energy consumption.
8. Agricultural sector	Facilitate the production and manufacturing of primary, value added agricultural and tertiary goods and products in the most efficient and sustainable manner deemed viable under Grenadian conditions.
9. Hotel and commercial sector	Ensure that the hotel and commercial sectors lead the national thrust for sustainable energy use, green procurement, and protection of natural resources from rapid consumption and depletion.
10. Manufacturing sector	Encourage the manufacturing sector to incorporate and use energy efficiency and sustainable production methods in their operations.
11. Household sector	Achieve a diversified supply of energy services with lower energy intensity and carbon emissions that will result in lower prices for household and domestic purposes.

Source : The National Energy Policy of Grenada November 2011

Amongst the above eleven, the goals closely related to geothermal development are picked up below, which correspond to the shaded parts in Table 2-3.

- Build and establish the adequate human capacity and institutional regime
  (1. Institutional issues).
- Establish an appropriate and enabling legal architecture
  (2. Legal and regulatory framework).
- Twenty percent of all domestic energy usage will originate from renewable energy sources by 2020.
  (4. Renewable energy).
- Reduce the energy consumption while increasing the economic growth by adopting the best practices in energy efficiency and conservation
  (5. Energy efficiency and conservation).
- Transition to an efficient, low-carbon, national electricity generation, and interconnection network
  (6. Power sector).

The national policy (2011) has set up a time for the framework as shown in Figure 2-1.

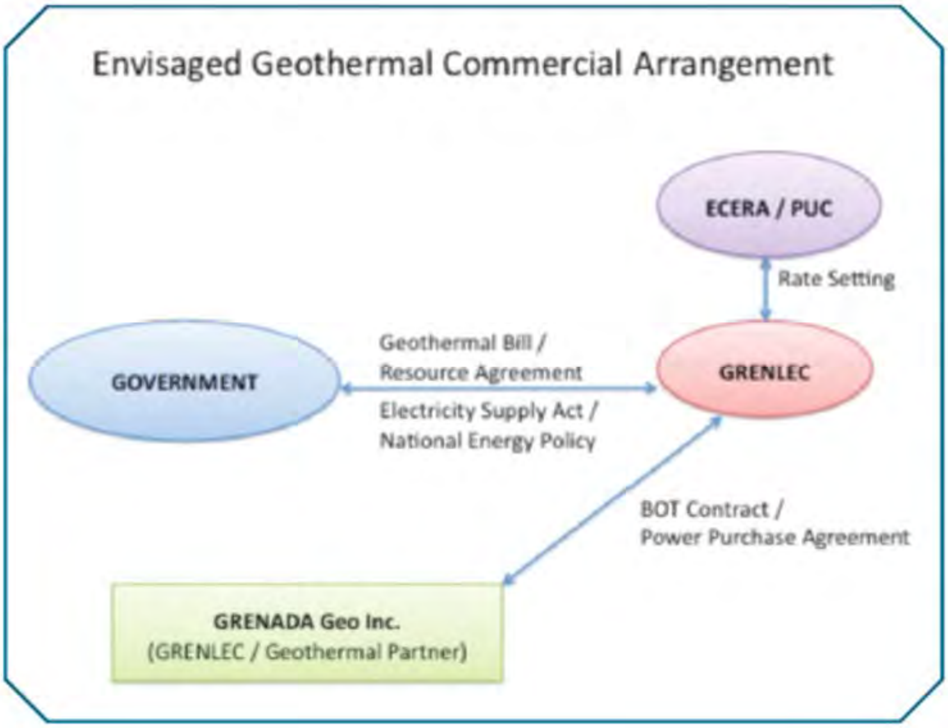


Source：GRENADA Renewables Readiness Assessment, 2012 IRENA

Figure 2-1 Grenadian Energy Development Strategy (2010 – 2020)

The strategy aimed at the commissioning of the first geothermal power station of 20 MW capacity in 2013 and a second with 20 MW capacity in 2016. However, none of these has been materialized.

The National Energy Policy of Grenada has also proposed a geothermal commercial arrangement as shown in Figure 2-2. A key point of this proposal is that the so called "Grenada Geo Inc." consisting of GRENLEC and its partner should undertake the geothermal energy development and power plant construction and operation, while GRENLEC should purchase the electricity from "Grenada Geo Inc.".



*Note: Eastern Caribbean Energy Regulatory Authority (ECERA)
Public Utility Commission (PUC)

Source : The National Energy Policy of Grenada, November 2011

Figure 2-2 Envisaged Geothermal Commercial Arrangement

In connection to the national policy, the Grenada Renewables Readiness Assessment (International Renewable Energy Agency: IRENA, 2012) states the following recommendations:

An exclusive license to explore geothermal resources and to produce electricity from a geothermal resource will be granted to the geothermal renewable energy special purpose vehicle (RESPV) and not directly to GRENLEC.
GRENLEC must purchase electricity from the RESPVs at a reasonable rate to be determined by the proposed independent regulatory authority, Eastern Caribbean Energy Regulatory Authority (ECERA).

Source : The National Energy Policy of Grenada November 2011.

2-3 Present Conditions of the Energy Sector

2-3-1 Institutional

All businesses of electricity supply such as power generation, transmission, distribution, and licensing are presently operated solely by the private company GRENLEC. GRENLEC originated from a company established by the Commonwealth Development Company (CDC) and the then- Government of Grenada on 27 September 1960. The company was licensed with power generation and transmission for 80 years by the Electric Supply Ordinance of 1961. In 1982, the independent Government of Grenada became the solo owner of GRENLEC by purchasing all stocks from CDC. In 1994, the government in turn sold all stocks with 10% stake to investors, 50% to a USA-based private company, and the rest (40%) to the employees and Caribbean investors. The new Electric Supply Act of the same year reaffirmed the exclusive right to GRENLEC in electricity market and granted it a monopoly until 31 December 2073.

The Government of Grenada intends to submit the new Electricity Service Act. The government also wishes to submit the new Geothermal Development Bill in 2015 in order to prepare for the geothermal development. The aims of these bills are to facilitate the permit and licensing for the geothermal resources in the country, and to encourage the private investors to explore the possibility to participate in the development. The government also plans to establish a public-private-partnership (PPP) bill to establish the legal basis for the private investment.

2-3-2 Public Utilities Regulatory Communication Bill 2015

In September 2015, the Government of Grenada published the draft for Public Utilities Regulatory Commission (PURC) Bill 2015. The bill will basically replace the Public Utilities Commission Act (PUCA) 1994, aiming to open the sector to investment particularly in renewable energy. The bill will accompany the Electricity Supply Bill 2015 to regulate the power sector.

The bill also intends to liberalize the power sector and stipulate the procedures for setting tariff. The licensing for private companies is dealt in the Electricity Supply Bill 2015. The members of the commission will be appointed by the governor-general, then acting on the advice of the cabinet. There will be a representative from the general public and consumer organizations.

In determining the power tariff, the commission shall ensure that the public utility receives a fair return and that the public utility rates are fair. Furthermore, the commission will be established as a tribunal and will have such power as vested in the courts. The commission is well designed to manage the tariff setting issues. However, it is still early to judge how the commission would function since in many countries similar commissions are not always politically independent.

2-3-3 Electricity Supply Bill 2015

The Government of Grenada also published the draft for Electricity Supply Bill 2015. The bill will replace the 1994 Electricity Supply Act, and will open the sector to domestic and international investment for new projects. The bill is expected to result in lower electricity prices.

The licensing matters are stipulated in the Electricity Supply Bill rather than the Public Utilities Regulatory Commission Bill. In addition, the roles of the minister in the licensing are larger than the case of the power tariff setting. The strategy for electricity sector development may be established in documents other than the bill, for instance based on the recommendations by the committee as a consultative body. With respect to the rates for the supply of electricity, there are clauses for the tariff setting in the “Public Utilities Regulatory Commission Bill, 2015”. Grid code would need to be accompanied with the licensing, particularly for private investment.

Based on the draft bill, GRENLEC would continue to hold the current license, which however, shall be subject to the Electricity Supply Bill in all aspects.

2-3-4 Organizational Framework

(1) Policy Planning Agency

The Energy Division in the Ministry of Finance, Planning, Economy, Energy, and Cooperatives (Ministry of Finance) was established in 1982. The Energy Division’s main function was to advise on key energy policy issues, as well as, to attend to electricity generation and distribution, petroleum product pricing, petroleum imports and consumption data, and to the collection and collation of energy related data. Another important function of this division is collaborating with sub-regional, regional, and international organizations/agencies on energy projects. The main objectives of the energy division are:

- Ensure adequate, reliable, and economical energy services to sustain economic development while satisfying the current and projected demands;
- Encourage and promote the use of renewable energy technologies and energy efficiency alternatives;
- Promote energy efficiency and energy conservation at all levels of the economy in order to achieve optimum economic use of renewable and non-renewable sources of energy;
- Encourage the establishment of energy service companies (ESCOs);
- Enhance the security of energy supply and services for all sectors of the economy; and
- Promote, encourage, and facilitate petroleum exploration and development in an environmentally friendly manner.

(2) Service Provider

GRENLEC, the sole provider of electricity in Grenada, Carriacou and Petit Martinique, is publicly traded on the Eastern Caribbean Securities Exchange (ECSE). Two hundred and thirty-five employees provide integrated services of generation, transmission, and distribution of electricity to more than 40,000 customers. WRB Enterprises of Tampa, Florida owns 50% of the issued ordinary share capital of the company. While the Government of Grenada and the National Insurance Scheme together own 21%, employees 4.5%, and the remaining 24.5% is owned by approximately 1,600 Grenadian and Caribbean investors.

(3) Current State, Issue, and Countermeasures

GRENLEC has essentially operated in a self-regulating manner. The criticisms received by the electricity sector (and GRENLEC) are the high electricity price levels and the lack of diversification of generation resources.

(i) Approach of the Government

The government intends to establish the Public Utility Regulatory Commission (PURC) to monitor and regulate the power sector. The Ministry of Finance and Energy will remain and assume the function of policy development and advisor to the Prime Minister.

The PURC contains provisions that contemplate transfer of certain electric regulatory functions to the anticipated Eastern Caribbean Energy Regulatory Authority (ECERA). The ECERA is a project of the Organization of Eastern Caribbean States (OECS) that seeks to address the electricity challenges common to its members. These issues are high electricity price levels and diversification of generation resources.

The government aims to create a regulatory framework and give necessary incentives that will improve high efficiency of electricity generation, transmission, and distribution. The government also looks at the regulatory framework that promotes fair, efficient, and economically viable involvement of private investment in the power sector.

The government has set a target for renewable energy to supply all Grenada’s electricity by 2030; and envisages the following initiatives to prepare for these objectives:

- A 100 renewable energy showcases study to be conducted by a consortium of firms and specialists, including GRENLEC;
- Renewables Readiness Assessment focused on policy, regulation, infrastructure, and finance to be conducted by the International Renewable Energy Agency; and
- Potential partnership for Island Economies through the Global Sustainable Energy Islands Initiative, ‘Vision 2030’.

(ii) Present Status of Geothermal Energy Development

In the past, the survey of geothermal energy was conducted by Arclus (1976), Geothermica Italiana (1981), and Huttre and Michels (1995).

Under the technical assistance of New Zealand in 2015, a comprehensive surface survey including geophysical magnetotelluric (MT) survey was conducted. The survey was supplemented by an additional MT survey in the latter part of 2015. It was expected that the survey would be completed by the end of March 2016, with presentation of the pre-feasibility output.

2-3-5 Existing Facilities for Power Generation and Transmission

(1) Current States

All Grenada's electricity is generated with diesel power plants. GRENLEC operates diesel power plants at Queens Park on the main island of Grenada with an installed capacity of 45.9 MW. In addition, it has a capacity of 3.2 MW in Carriacou, 0.5 MW in Petit Martinique, and 2.8 MW of backup capacity on the campus of St. George's University. The details of the generation plants are shown in Table 2-4.

Table 2-4 Generation Capacity in Grenada

Location	Capacity (kW)
Queens Park	45,890
St. George's University	2,800
Carriacou	3,200
Petit Martinique	480
Total	52,370

Source: GRENLEC

In addition to diesel power, an approximately 0.1 MW of photovoltaic generation capacity is installed island-wide (0.3% of peak demand). There is an established private sector energy service company (GRENSOL) specializing in grid-connected photovoltaic systems.

The generated power is distributed through the seven transmission feeders (33 kV) to all areas around the island. The voltage being distributed to the end consumers stepped down to 400 V for commercial applications and 230 V for domestic applications.

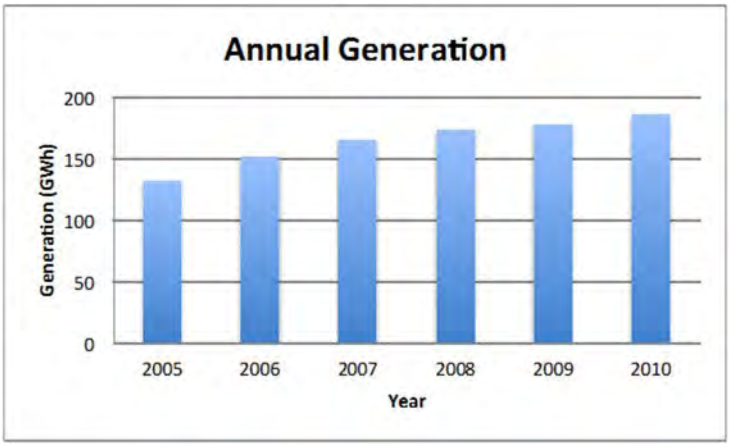
(2) Issues

The generation diversification and power distribution are the two primary issues for small island states. Dependence on imported fossil fuels has been the cause of the high electricity rates. The tropical storms have provided threats to the power distribution systems. Thus, the government aims to develop more renewable energy such as geothermal, solar, and wind through policy and regulatory changes for renewable energy.

2-3-6 Demand and Supply – Present and Forecast

(1) Supply

GRENLEC has a total installed capacity of around 52.4 MW of diesel generation capacity. There is also about 380 kW of small-scale, distributed generation operated by households, businesses, and hotels including around 300 kW of solar photovoltaic systems, and 80 kW of wind energy. Several households and businesses also own small diesel generator but only use this as a backup option in case of power cuts. Figure 2-3 shows the annual generation by year.



Source: GRENLEC (2011)

Figure 2-3 Annual Generation

GRENLEC also aims to increase the renewable energy to 20% of the total generation by 2020, aggressively pursuing additional renewable energy initiatives and clean energy technologies for electricity generation and use. GRENLEC's new Renewable Energy Strategic Plan and the Government's National Energy Policy of Grenada are strongly aligned to achieve mutual clean energy goals for the nation. The objectives are to stabilize and eventually lower energy costs, reduce dependence on imported fuel, support economic growth, and protect the environment by increasing the use of renewable energy.

(2) Demand

The peak demand for electricity on GRENLEC's system in 2010 was 30.8 MW. This system demand is met by the existing power generation facilities of GRENLEC. Electricity sales in 2010 totaled 185.79 GWh to 41,222 customers; and demand is expected to increase at 4% per annum in the business as usual (BAU) scenario.

Electricity consumption in Grenada is dominated by the commercial sector, which accounts for 57% of consumed electricity and followed by the residential sector at 38%. The industrial consumption accounts for 3% and street lighting at 2%.

(3) Electricity Prices

The electricity tariff in Grenada is summarized in Table 2-5.

Table 2-5 Electricity Tariff (2015, EC)

Charge	Domestic Customer	Commercial Customer	Industrial Customer	Street Lighting Customer
Applies to	Electricity supplied to a residential property for non-commercial activities	Electricity supplied for non-residential or business activities	Electricity supplied for industry or where electric motors have an aggregate maximum power output rating of 5 or more horse power and are not normally used between 6.00 p.m. and 10.00 p.m.	Electricity supplied to Government, local authorities for street lights. Private customers who apply for street lights
Government Charges (VAT)	15% of non-fuel charge after the first 99 units consumed.	15% of non-fuel charge	15% of non-fuel charge	15% of non-fuel charge
Environmental Levy	Less than 99 kW/h - $0, 99 – 149 kW/h - $5.00, 150 kW/h & above - $10.00	NA	NA	NA
Fuel Charge (effective 8th June 2015)	$0.3908 per kWh or unit (Calculated monthly)	$0.3908 per kWh or unit (Calculated monthly)	$0.3908 per kWh or unit (Calculated monthly)	$0.3908 per kWh or unit (Calculated monthly)
Non-fuel Charge	$0.4155 per kWh or unit Minimum - $4.00	$0.4480 per kWh or unit	$0.3284 per kWh or unit	$0.3931 per kWh or unit
Floor Area Charge (per 50 sq. feet of floor area)	NA	2 cents (per month)	NA	NA
Horsepower Charge	NA	NA	$2.00 (per horsepower) Minimum - $10.00	NA

Source: GRENLEC (2015)

In 2008, the price of electricity increased to over ECD 0.81 (USD 0.30/kWh) when the fuel price was at the highest. This tariff was among the highest in the world due to the high price of imported fuel. The high price of electricity gave the negative impact on commercial businesses and industry. Thus, it is critical to lower the electricity services to the consumers just to ensure rational and effective market conditions.

2-3-7 Activities of Other Donors, International Organizations, and/or Private Sector

(1) CDB/IDB

IDB and CDB agreed upon the Sustainable Energy Facility (SEF) in 2015 to facilitate geothermal energy and sustainable energy development in eastern Caribbean countries. The SEF will be a financial source for renewable energy development including geothermal power, energy efficiency, and institutional capacity projects in six Eastern Caribbean countries. It is a US$ 71.5 million loan and grant package. SEF is a financial source for CDB's GeoSmart Facility that facilitates financial assistance for various risks during geothermal development in the Caribbean countries.

Presently, CDB/IDB provide the government with relevant information and advice since the geothermal development project has not yet matured to a level to attract any specific financial assistance. At the donor forum held in June 2016, CDB introduced its facilities for financial assistance for geothermal development when the government requested for grant financial assistance for the proposed slim hole drilling.

(2) CDB/DFID, EU-CIF

DFID provided CDB with a financial input of GBP 2.5 million for Sustainable Energy for the Easter Caribbean SEEC) Programme. SEEC is a program to promote renewable energy and energy efficiency with grant finance from DFID and European Union-Caribbean

Investment Facility (EU-CIF) as well. DFID, who participated in the donor forum in June 2016 received information that the government of Grenada is in need of grant finance for slim hole drilling.

(3) New Zealand

The government of New Zealand has dispatched an expert (Jacobs - NZ) for geothermal development in the Caribbean countries, who now stations in Grenada. A NZ team conducted a comprehensive geothermal surface survey including geophysical MT survey and its 3D analysis.

(4) World Bank

WB financed for Regional Disaster Vulnerability Reduction Program (RDVRP). The Program aims at measurably reducing vulnerability to natural hazards and climate change impacts in the Eastern Caribbean Sub-region. The objective of the Project in Grenada is to measurably reduce vulnerability to natural hazards and climate change impacts in Grenada and in the Eastern Caribbean Sub-region.

(5) Organization of American States (OAS)

The Organization of American States (OAS) provides a technical assistance called the Caribbean Sustainable Energy Program (CSEP) to the regional members including Grenada. The project aims to accelerate the transition toward cleaner, more sustainable energy use in the seven countries of the Caribbean. The project addresses market conditions for the development and use of renewable energy and energy efficient systems by mitigating the barriers to their implementation and use. In particular, actions are focused on improving energy sector governance and management in the project countries. The main actions include (i) the establishment of national sustainable energy goals/targets through the adoption of sustainable energy plans (SEPs) and (ii) the targeted support for the implementation of activities that address specific challenges or barriers.

OAS also assisted the Government of Grenada in drafting and negotiating heads of terms (HOT) for the build-up of the legal framework for geothermal energy in Grenada. These include (i) identifying the key terms to be incorporated in the future Geothermal Resource Development Agreement through a pre-negotiation support to the government and GRENLEC; (ii) draft a HOT based on the results of the pre-negotiation consultations; (iii) discuss and finalize the HOT by first supporting the government to negotiate the HOT with GRENLEC, and then prepare the final HOT with the key commercial terms that the parties agreed to include; and (iv) provide follow-up support on an as-needed basis, such as proposing additional legal language for amending the draft Geothermal Bill and Environmental Regulations, and providing a roadmap with next steps toward concluding a Geothermal Resource Development Agreement.

(6) United Nations Industrial Development Organization (UNIDO)

The United Nations Industrial Development Organization (UNIDO), in partnership with OAS, provided a long-term loan of USD 65,000 to the Grenada Public Service Cooperative

Credit Union by providing loans for solar water heaters. The program included a public outreach component to inform consumers of the financing options available to them. Credit union employees were also trained in administering solar water heater loans. The program's goal was to serve as a catalyst for greater lending for solar water heaters by building public awareness and institutional capacity.

(7) Global Environmental Facility

The Global Environmental Facility (GEF) initiated the Energy for Sustainable Development in Caribbean Buildings with six other financiers. The program, a 48-month project beginning in November 2012, demonstrates technologies to achieve 20% reduction of GHG emissions and put in place policies or programs to roll out these technologies to the marketplace.

(8) China

The Government of China provided the assistance in energy efficiency through the China Climate Change Adaptation Pilot Program (CAAP). The technology transfer program between 2012 and 2017 will provide public sector agencies with financing for the acquisition of hardware, equipment, and training from China with repayment linked to the savings in fuel imports.

(9) Gesellschaft für Internationale Zusammenarbeit: GIZ

The German Agency for International Cooperation (*Gesellschaft für Internationale Zusammenarbeit*: GIZ) is currently conducting the technical assistance project entitled "Reform of the Electricity Sector to Support Climate Policy in Grenada (G-RESCP)". The project aims to achieve the government's climate policy goals (use of renewable energy and reduction of CO_2 emissions) via the opening of the energy sector to allow for more investments in renewable energy and energy efficiency.

The four key foci of the project include:

(i) Support to the Government of Grenada to implement amendments of the Electricity Supply Act (ESA) and of the Public Utilities Commission Act (PUCA) including the regulatory models for the operation of the sector, competition models, interconnection rules, procedures to promote renewable energies, and their technical link with the existing grid. The new legislation is being drafted by the consultants under the regional ECERA project funded by the World Bank; however G-RESCP will support swift technical and legal assessment and consultation of these drafts, by ensuring faster implementation and more robust framework.

(ii) The establishment of a structured dialogue between GRENLEC and the Government of Grenada to support cooperative development of the required amendments to the legal framework, identifying and using measures of mutual interest and benefit to support a smooth transition into a new regulatory and institutional structure.

(iii) The support for the development of a roadmap to identify the steps required for a roll-out of renewable energies and energy efficiency and the challenges with these steps, as well as the support required. This includes, if required, support for issues like grid stability questions, net metering/net billing regulations, and technical standards for renewable energy.

(iv) The establishment of a national platform on RE/EE to exchange information and knowledge as well as concepts and ideas, where GRENLEC, the government, private sector (households and businesses), and investors could participate. This also includes new financing models to attract impact capital and enhance cooperation with the CDB.

Chapter 3 Assessment of Natural Conditions

3-1 General

3-1-1 Objectives

The geological, geochemical, and geophysical survey, including review of existing information, were conducted to assess the geothermal energy potential for development.

Also, a reconnaissance type of field survey was conducted to assess the natural conditions in relation to civil works to be associated with drilling planning.

3-1-2 Survey Contents

The Japanese International Cooperation Agency (JICA) Survey Team conducted the following surveys:

- ✓ Review of the Existing Geothermal Resource Assessment
    - ➢ Topography, geology, fracture, and geothermal manifestation
    - ➢ Geochemistry
    - ➢ Geophysical survey (Magneto-telluric (MT) survey)
- ✓ Surface Survey
    - ➢ Geological survey（field survey, rock thin sample observation, and x-ray diffraction）
    - ➢ Geochemical survey (chemical analysis of hot spring)
    - ➢ Gravity survey

Site inspections for civil engineering for drilling planning were the following:

- ➢ Drilling site candidate
- ➢ Drilling base
- ➢ Drilling water
- ➢ Protected area
- ✓ Access road investigation

3-2 Review of the Existing Geothermal Resource Assessment

Existing geothermal survey reports for Grenada are listed in Table 3-1. In this section, the JICA Survey Team reviewed these reports from the viewpoints of geological/geographical survey, geochemical survey, and geophysical survey, for consideration of additional surveys as necessary.

Table 3-1 Existing Information

Information	Name
General	Geotermica Italiana S.r.l. (1981) Reconnaissance Study of the Geothermal Resources of the Republic of Grenada: Final Report to Latin American Energy Organization
	Jacobs (2015) Grenada Geothermal Surface Exploration, Integrated Report: Geology, Geochemistry, and Geophysics
Geology	Arculus (1976) Geology and Geochemistry of the Alkali Basalt – Andesite Association of Grenada, Lesser Antilles Island Arc. Geological Society of America Bulletin
	Huttrer and Michels (1995) Potential for Geothermal Development in Grenada, West Indies. Proceedings of the 1995 World Geothermal Congress, Florence, Italy
Geochemistry	Huttrer and Michels (1993) Final Report Regarding Prefeasibility Studies of the Potential for Geothermal Development in Grenada, W.I.: Prepared under Geothermal MgMt Co., Inc, Frisco, Colo., Submitted to the National Geothermal Association

Source: JICA Survey Team

3-2-1 Review of Geological and Geographical Survey

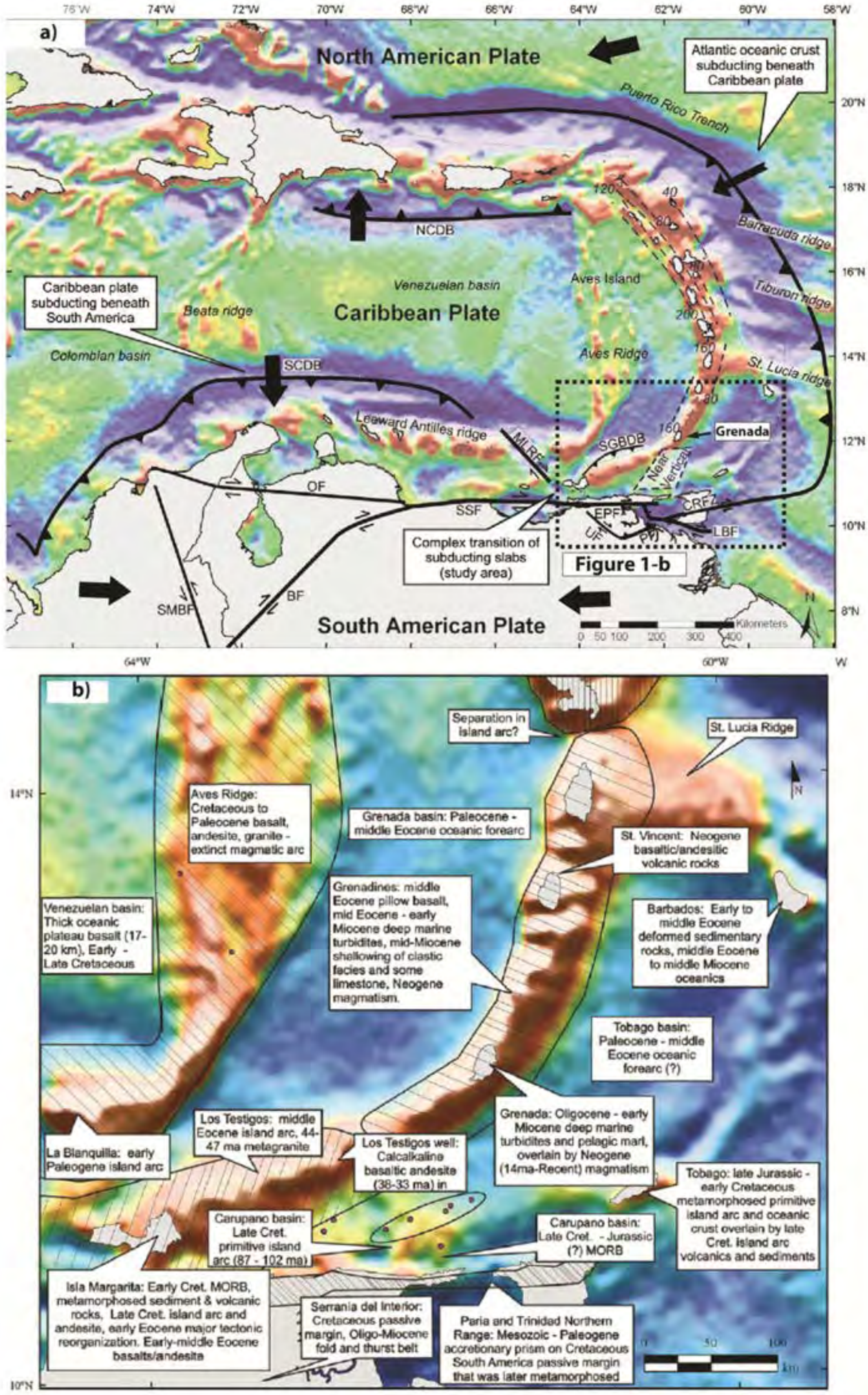
The geological reports of Grenada have been made by Arculus (1976), Geotermica Italiana (1981), Huttrer and Michels (1995). Jacobs (2015), in particular, has summarized the results of these surveys together with their comprehensive geological, geochemical, and geophysical survey.

(1) Tectonic

The Grenada is located in the southern part of the Lesser Antilles, which is the eastern part of Antilles (the major part of the Western Indian Islands). The Lesser Antilles borders the Caribbean Sea in the west and the Atlantic Ocean in the east. The Lesser Antilles is located at the eastern border of the Caribbean Plate, while the eastern border where the North American Plate is subducted under the Caribbean Plate from the eastern or northeastern side as shown in Figure 3-1. The Caribbean Plate is distorted and broken into micro-plates in the zone of Lesser Antilles as shown in Figure 3-1. A volcanic front was formed 5.6 million years ago in the Lesser Antilles, whereas a volcanic front was formed 10,000 years ago in the islands of Grenada, Saint Vincent, and Saint Lucia as shown in Figure 3-2.

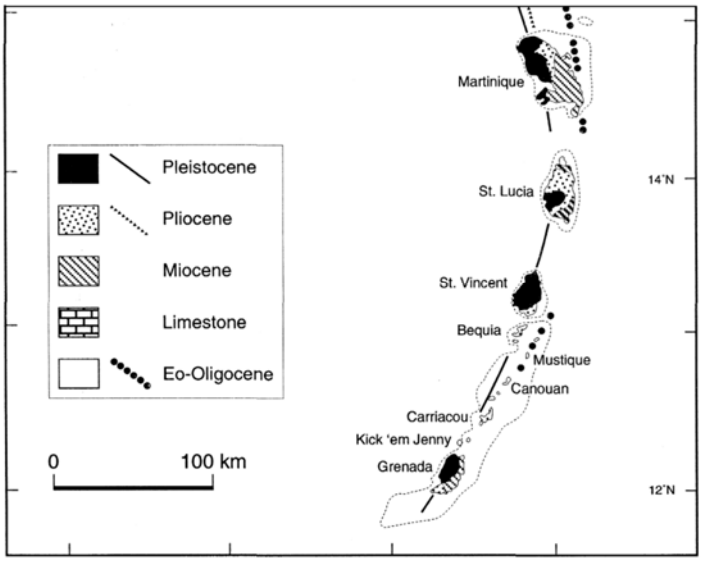
(2) Geology

Major geological layers are Tufton Hall Layer (Late Eocene ~ Early Oligocene), volcanic (Miocene ~ Pleistocene) and volcanic products (Pleistocene ~ Holocene) as shown in Figure 3-3. Volcanic products of Grenada have effused mainly at the five sites between early Miocene (21 Ma) and Holocene (0.9 Ma). The youngest volcano is the Mt. Saint Catherine located in the northern part of Grenada Island. It has no eruption records in historic times but was reported that the village, which is assumed to have been formed within 1,000 years, had been covered by volcanic products (Global Volcanic Program, 2015).



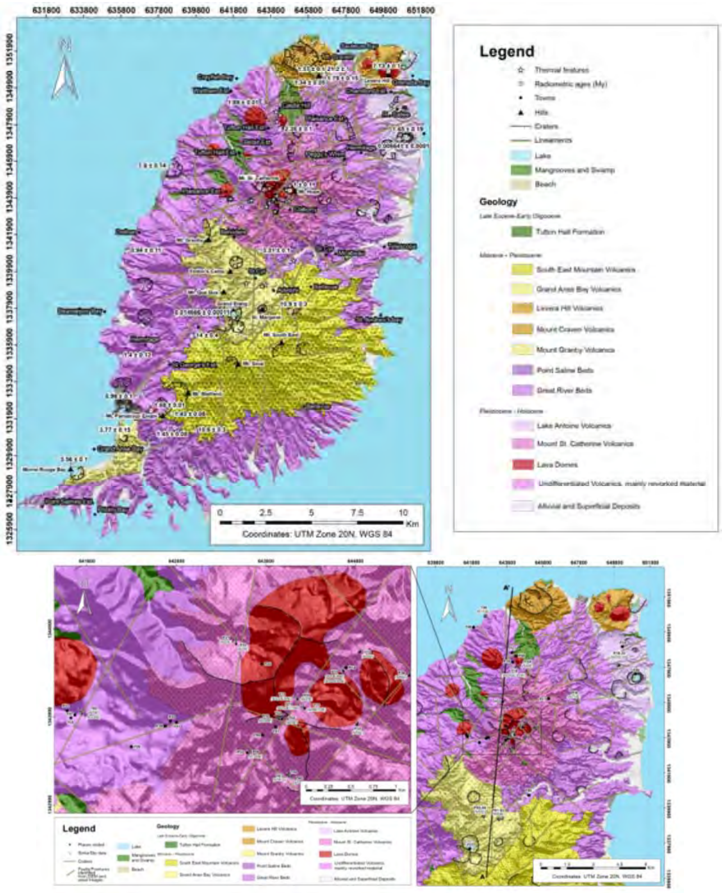
Source: Jacobs (2015)

Figure 3-1 Plate Distribution around the Lesser Antilles Arc



Source: Jacobs (2015)

Figure 3-2 Transition of the Volcanic Front of the Lesser Antilles Arc

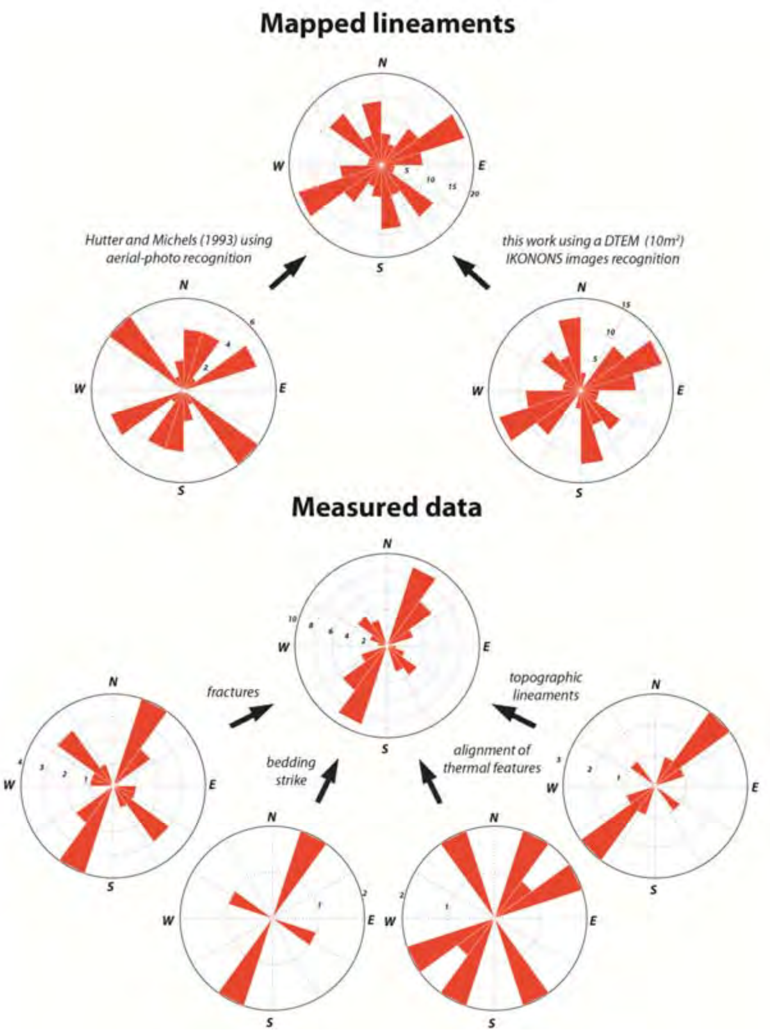


Source: Jacobs (2015)

Figure 3-3 Geological Map of Grenada

(3) Fractures

Lineament-related features were measured by Jacobs (2015) including mapped lineament, all measurements on site regarding fractures, bedding strikes, alignment of thermal features, and topographic lineaments. Both of the mapped lineaments and the measured data indicate a clear northeast-southwest direction as shown in Figure 3-4 below.

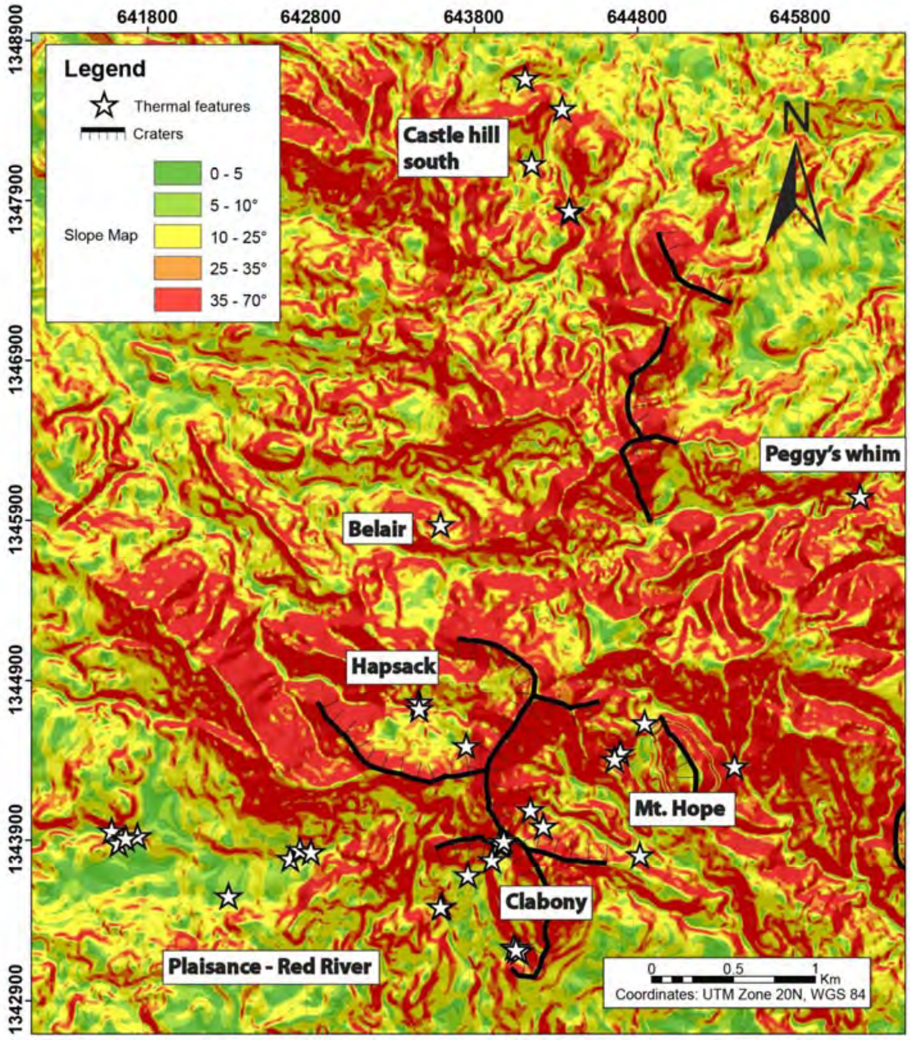


Source: Jacobs (2015)

Figure 3-4 Rose Diagrams of the Northern Island of Grenada (Top: Mapped Lineaments; Bottom: Measured Data)

(4) Geothermal Manifestation

Geothermal manifestations of Grenada are identified in many places within the vicinity of Mt. Saint Catherine (Hapsack and Clabony) and in the northern part of the mountains (Castele Hill and Peggy's Whim) as shown in Figure 3-5.



Source:
Inclination classification: Jacobs (2015)
Volcano location: Global volcanism program(2015) http://volcano.si.edu/volcano.cfm?vn=360170

Figure 3-5 Geothermal Features in Grenada

(5) Observations and Survey Approach

Jacobs (2015) carried out a detailed survey (such as geological structure, geographical analysis, and fracture system survey) in the northern part of Grenada and clarified the characteristics of geology and fracture systems. In addition, about the bedrock in the northern part, Jacobs (2015) clarified that smectite was included in the rock, which was sampled from the outcrop along the shore of the northern area. They pointed out that resistivity distribution with the geothermal reservoir may become indistinct because clay mineral formed by geothermal activity is mixed with clastic clay mineral of Tufton Hill rock (specifically, the possibility of excessive estimation of clay altered area caused by geothermal activity). The JICA Survey Team agreed to this opinion.

On the other hand, in Jacobs (2015), the distribution of altered rock and mineral is not investigated. It becomes clear with the resistivity distribution of Jacobs (2015) that there is a difference in resistivity between the area of Hapsack of St. Catherine and the area of Peggy's Whim, Castle Hill which is a different geothermal manifestation site from the one in Hapsack. In this survey, the JICA Survey Team will analyze the alteration rock of each geothermal manifestation site and identify the species of alteration minerals. This will be helpful in the analysis of interpretation of resistivity distribution.

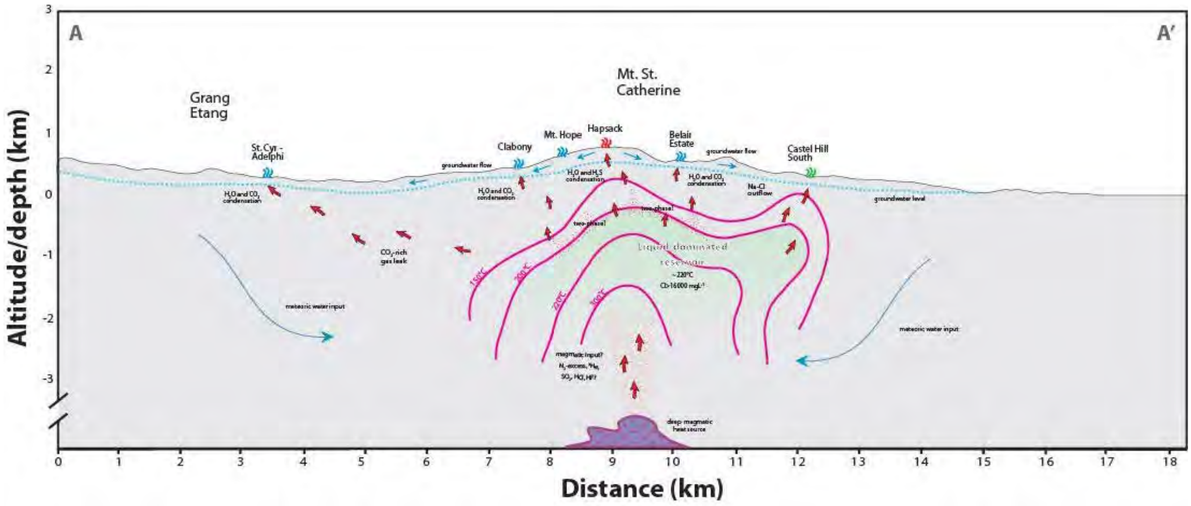
3-2-2 Review of Geochemical Survey

(1) Overview of the Existing Report

The latest technical report on the survey for characterizing a geothermal system in Grenada has been made by Jacobs, NZ (Jacobs, 2015). Jacobs (2015) conducted a field survey involving water/gas sampling, chemical analysis of the samples, and geochemical interpretation of the obtained data to evaluate the existence of a high-temperature geothermal system available for commercial power generation in Grenada. In the geochemical interpretation, Jacobs (2015) has carefully referred existing chemical data from previous technical reports such as Geotermica Italiana (1981) and Huttrer and Michels (1993). For this reason, it can be said that the chapter about geochemical study in Jacobs (2015) is a comprehensive research on the geothermal potential in Grenada on the basis of geochemistry.

Jacobs (2015) surveyed the following ten thermal areas in Grenada, which are the Castle Hill South, Chambord, Belair Estate, Peggy's Whim, Hermitage, Hapsack, Mount Hope, Clabony, Plaisance Estate, and Adelphi-Saint Cyr as in the case of the previous surveys. The most important conclusion of the geochemical study in Jacobs (2015) is that "the overall impression of the thermal activity in Grenada is of a mature magmatic-driven geothermal system centered in the area of Mt. Saint Catherine." In terms of reservoir temperature, the report estimated 200–220 °C at the shallow part and less than 290 °C at the deep part on the basis of geochemical thermometers. Furthermore, Jacobs (2015) estimates the resource area to be 8 km^2 based on the distribution of thermal bubbling pools. As shown in Figure 3-6, geochemical characteristics are reflected in a conceptual geothermal system model that is of a typical high-temperature geothermal system hosted in andesitic volcanic regions. The characteristics are summarized as follows:

- Zones of upflow and outflow of geothermal fluid inferred from chemical types and distribution of thermal waters,
- Magmatic gas contribution seen in the bubbles from the bubbling pools,
- Water–rock interaction at high temperature in the reservoir based on geochemical thermometers,
- Recharge of meteoric water into the reservoir inferred from isotopic compositions of oxygen and hydrogen in water,
- Redox conditions of bubbling gases equivalent to that of a hydrothermal system and not a volcanic system, and
- Possible scrubbing (neutralizing) process for magmatic acid gases (e.g., HCl and SO_2), if the gases intrude into the root of the reservoir.



Source: Jacobs (2015)

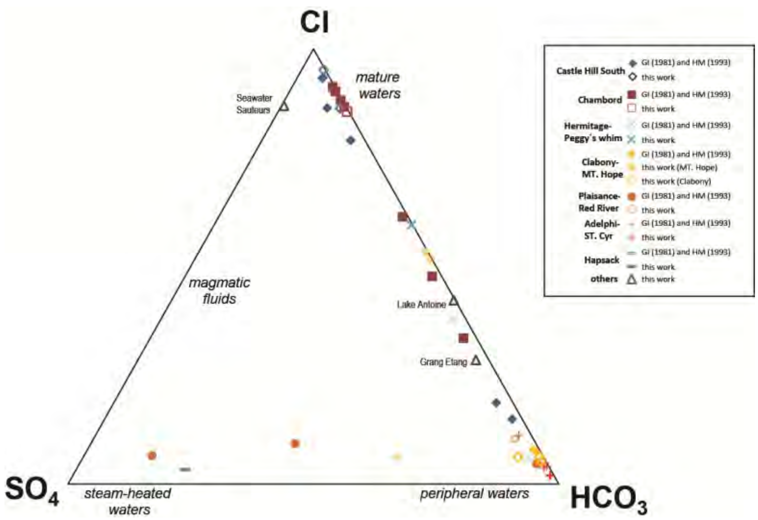
Figure 3-6 Conceptual Geothermal System Model Proposed by Jacobs (2015)

Several important points are intensively discussed below.

【Origin of Hot Springs】

The most basic method to interpret the origins of thermal water is classifying the water into several chemical types reflecting their origin. Figure 3-7 shows a result of the classification using relative contents of the major anions, Cl, SO_4, and HCO_3 from Jacobs (2015).

This diagram, along with pH and cations, demonstrates three types of thermal waters in Grenada such as acid-sulfate water, NaCl water with a near-neutral to slightly alkaline pH, and HCO_3-rich water. The occurrence of these three types of water is common in a high-temperature geothermal system hosted in andesitic volcanic regions. As mentioned in Jacobs (2015), acid-sulfate water indicates the hydrothermal conditions equivalent to an upflow zone of a geothermal system. This is because these water classifications can be produced by condensing the acid steam separated from high-temperature geothermal fluid. This type of water is found in Hapsack and the Plaisance-Red River areas as shown in Figure 3-7. Also, NaCl water can be considered as the best indicator of high-enthalpy and liquid-dominated geothermal systems because such water is commonly found at such systems worldwide. The Castle Hill South, Chambord, and Peggy's Whim areas produce NaCl water. Considering the distance of 3 km to 8 km from the center of Mt. Saint Catherine (an assumed center of upflow) and temperatures of silica and K-Mg geochemical thermometers that are lower than that of Na-K thermometers, these chloride water can be recognized as outflow of deep circulating geothermal fluid traveling a long distance from the center of the upflow zone. At lower elevations and the surroundings of the acid-sulfate springs, there are HCO_3-rich bubbling pools and springs. The high concentration of HCO_3 is typical to a peripheral area of a geothermal system due to absorption of CO_2-rich steam by cooler groundwater.

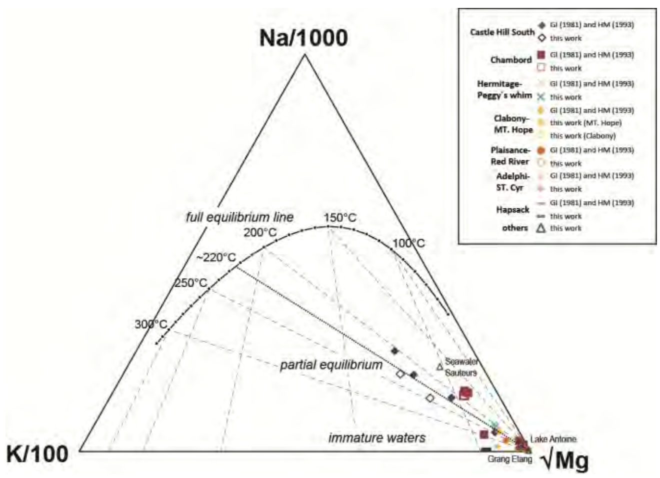


Source: Jacobs (2015)

Figure 3-7 Relative Contents of Cl, SO_4, and HCO3 from Jacobs (2015)

【Equilibrium State of Thermal Water】

In order to discuss the equilibrium state of thermal water, which is the maturity of water/rock interaction in a geothermal system, the relative contents of Na, K, and Mg are plotted in a trilinear diagram. As shown in Figure 3-8, there is no thermal water fully equilibrated with the reservoir rock in Grenada. NaCl water from Castle Hill South and Chambord is, however, partially equilibrated with the surrounding rock, and the chloride water creates a linear trend on the diagram. Jacobs (2015) interpreted that this trend suggests a transition from immature water, such as HCO_3-rich and acid waters, to a fully equilibrated fluid having a temperature of ~ 220 °C.

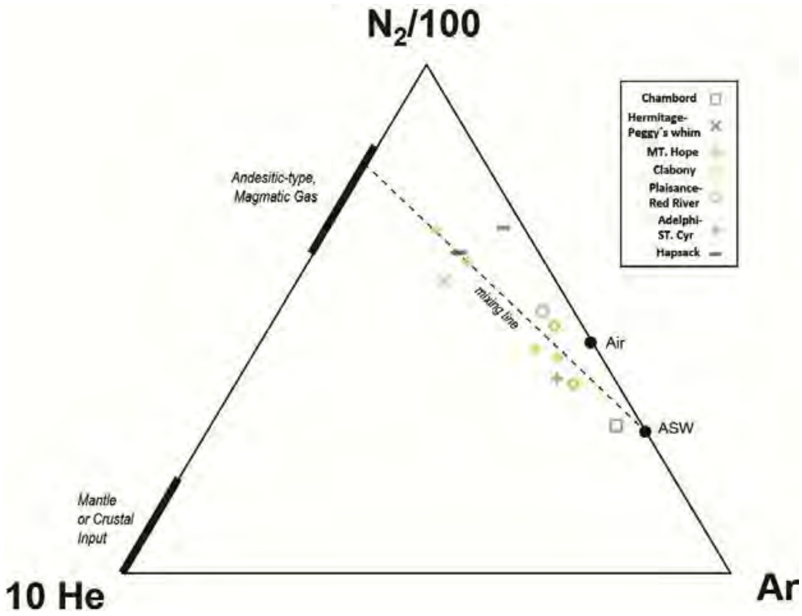


Source: Jacobs (2015)

Figure 3-8 Relative Contents of Na, K, and Mg from Jacobs (2015)

【Gas Chemistry】

Jacobs (2015) studied gas chemistry of bubble gas emerging from bubbling pools as well as water chemistry of thermal water. As seen in Figure 3-9, the relative contents of He, Ar, and N_2 clearly show the contribution of magmatic gas, inferring a condition of a high-temperature geothermal system as commonly found in andesitic volcanic regions.



Source: Jacobs (2015)

Figure 3-9 Relative Contents of He, Ar, and N2 from Jacobs (2015)

(2) Observations and Survey Approach

As mentioned so far, Jacobs (2015) reasonably and scientifically pointed out that the thermal features in Grenada can be considered those of a high-temperature, liquid-dominated geothermal system. Nevertheless, it is worth mentioning that some geochemical characteristics do not completely follow some features seen in typical high-temperature geothermal systems.

One of such features is that NaCl water in Grenada contained Mg in remarkably high concentrations, meanwhile typical high-temperature geothermal fluid is considerably depleted in Mg due to lower solubility of Mg bearing minerals (Mg-carbonate and silicate) at high temperatures. Jacobs (2015) suggests that this concentrated Mg is due to the transition in reaction of water with Mg-rich minerals in Tufton Hall rock basement that is a possible reservoir formation. This transition, however, seems to oppose a mechanism of water/rock interaction at high temperatures because as mentioned above, the solubility of Mg-minerals lowers with increasing temperature.

Another geochemical characteristic not following the typical conditions of high-temperature geothermal systems is the lack of fumaroles, steaming ground, and boiling springs on the surface. Those active and boiling manifestations are frequently seen in high-enthalpy geothermal systems. As a reason for the lack of manifestations, Jacobs (2015) assumes a well-capped system or high groundwater flow quenching upwelling geothermal fluids. In addition to the assumed condition, it can be also considered that having a low flux of the upwelling geothermal fluid beneath the upflow zone is possibly due to a small-sized heat source of the system. The upwelling geothermal fluid with low flux is readily cooled by a heat loss to the surrounding rock or by groundwater flow. In these conditions, the actively boiling manifestations are hardly created.

The characteristics such as high Mg concentration and the lack of fumaroles, steaming ground, and boiling springs, which are not of a typical high-temperature geothermal system, are crucial in constructing a conceptual model of the geothermal system. The geochemical data collected so far in the surface surveys hardly answer the question why the actively boiling manifestations are never seen in the geothermal radial drilling (GRD). Results can be given through test drilling involving logging and production test, which directory offers real physical and chemical conditions of the underground. For this reason, for the next step of the project, it is worth considering test drilling to verify and improve the current understanding about the conditions of geothermal system in Grenada.

3-2-3 Review of Geophysical Survey

(1) Overview of the Existing Report

The MT method of the electromagnetic survey was conducted in Grenada to clarify the subsurface resistivity structure. The contents of the survey is shown in Table 3-2 below.

Table 3-2 Overview of MT Survey Conducted by Jacobs (2015)

Purpose	To clarify subsurface resistivity structure for the estimation of geology and geological structure related to the geothermal reservoir.
Survey method	MT method with remote-reference processing
Survey site	In and around Mt. Saint Catherine
Survey period	From March to April 2015
Number of stations	59 stations; The remote station was installed about 5 km far southeast from the survey site (suburbs of Crochu)
Equipment	Metronix Geophysics ADU-07e System
Acquisition data	Time series data of the three orthogonal components of the magnetic field (Hx, Hy, and Hz), two horizontal components of the electric field (Ex and Ey); Range of measurement frequency: 10,000 Hz to 0.001 Hz and; Measuring time: 8～15 hours night each station, at most two days
Data processing and analysis	One-dimensional (1D) inversion modeling using the invariant resistivity curves and three-dimensional (3D) inversion modeling were conducted. 3D modeling on finely separated grids adequately deals with any static shift. The subsurface resistivity structure was obtained through the results of 1D and 3D inversion modeling; Geology and the geological structure which comprise the geothermal reservoir system were estimated.

Source: JICA Survey Team

(2) Summary of the Existing Report

To clarify the subsurface resistivity structure at the survey site for geothermal development, the MT method was conducted and results were given in Figure 3-10 as location map of MT station. Figure 3-11 shows the elevation map of the base of the cap rock conductor layer, while Figure 3-12 gives the resistivity cross section (SN and WE).

【Obtained Data】

There was a good quality of data acquired for the majority of stations over the frequency range (10,000 to 0.01 Hz).

【Analysis Method】

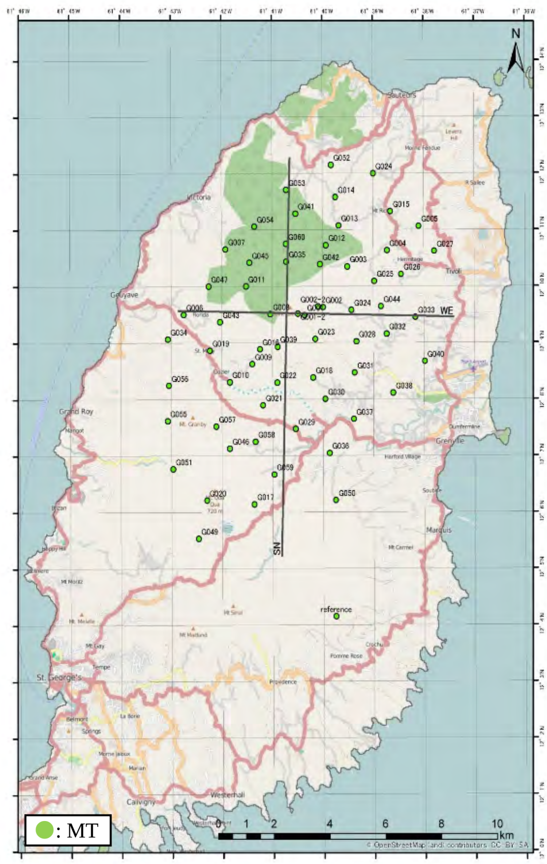
Dimensionality parameters show 1D structure at high frequencies (10,000 to 0.1 Hz) and 2D or 3D at lower frequencies (<0.1 Hz). The 1D inversion modeling using invariant resistivity curve and 3D inversion modeling on finely separated grids to solve static shift effects were executed adequately. SRTM DEM Data of 20 m contour interval were used as the topographic data. Each method of modeling has certain advantages and limitations and so the models differ in detail. But, there is a characteristic pattern of a conductive layer and the conductor of less than 10 ohm-m is thin at highest elevation and thick on the sides while the base of the conductor has the domed structure.

【Distribution of Low Resistivity Zone and Interpretation】

The conductive layer is interpreted as a clay cap and the base of the conductive layer rises to the north of Mt. Saint Catherine under Belair and Hapsack. This highest elevation of the base of the conductor is around the north to northwest of Mt. Saint Catherine and shows the doming of the base of the conductor which indicates that there is a possibility for an upflow to be found beneath the flank of Mt. Saint Catherine. The doming structure seems to have a direct correlation with the surface thermal features. The high temperature geothermal reservoir at the site, which is composed of the clay cap of less than 10 ohm-m, the doming of the base of the conductor, and the deep resistive zone under the clay cap was proposed.

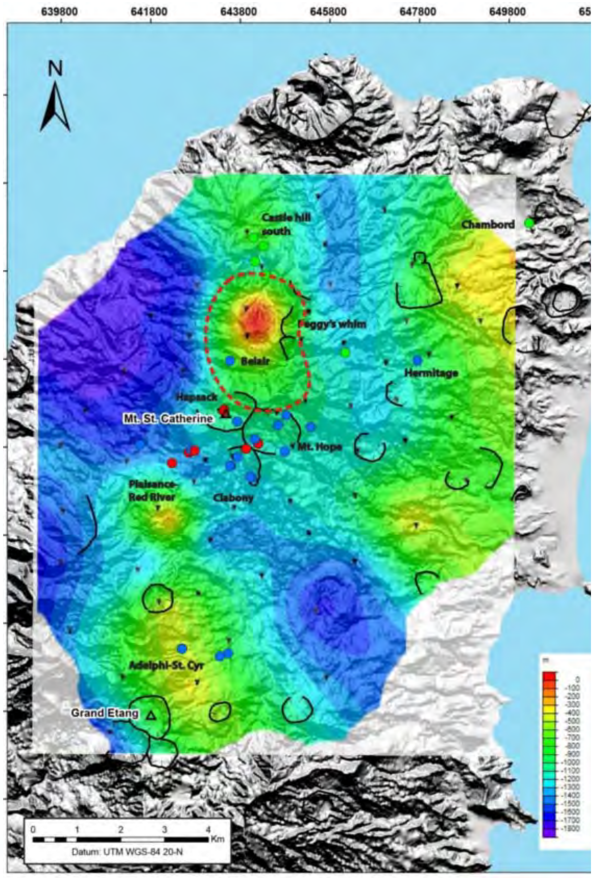
(3) Observations and Survey Approach

Good quality data were collected mostly throughout the survey. Using the acquired data, 1D and 3D inversion modeling analysis were conducted and the conductive layer distributed widely in the survey site. The deep resistive zone and the doming of the base of the conductor were identified. The resistivity structure was inferred as the typical high temperature geothermal reservoir with a clay cap. As data quality is good and 3D inversion modeling was executed, the results would be reliable. The geothermal reservoir system of the site was proposed after considering the information of the geology and geological structure through the results of geochemical investigations.After adequate understanding of the geology and geological structure of the survey site, the minute verification to the geothermal reservoir system is needed. The additional investigations of MT method or the gravity survey which gets different physical value from the resistivity of MT method is recommended to enhance the quality of analysis. It is desirable to comprehensively estimate the geothermal reservoir system by adding the results of the gravity survey conducted to reflect its results to the planning of exploration drilling and reduce possible risk in exploration drilling.



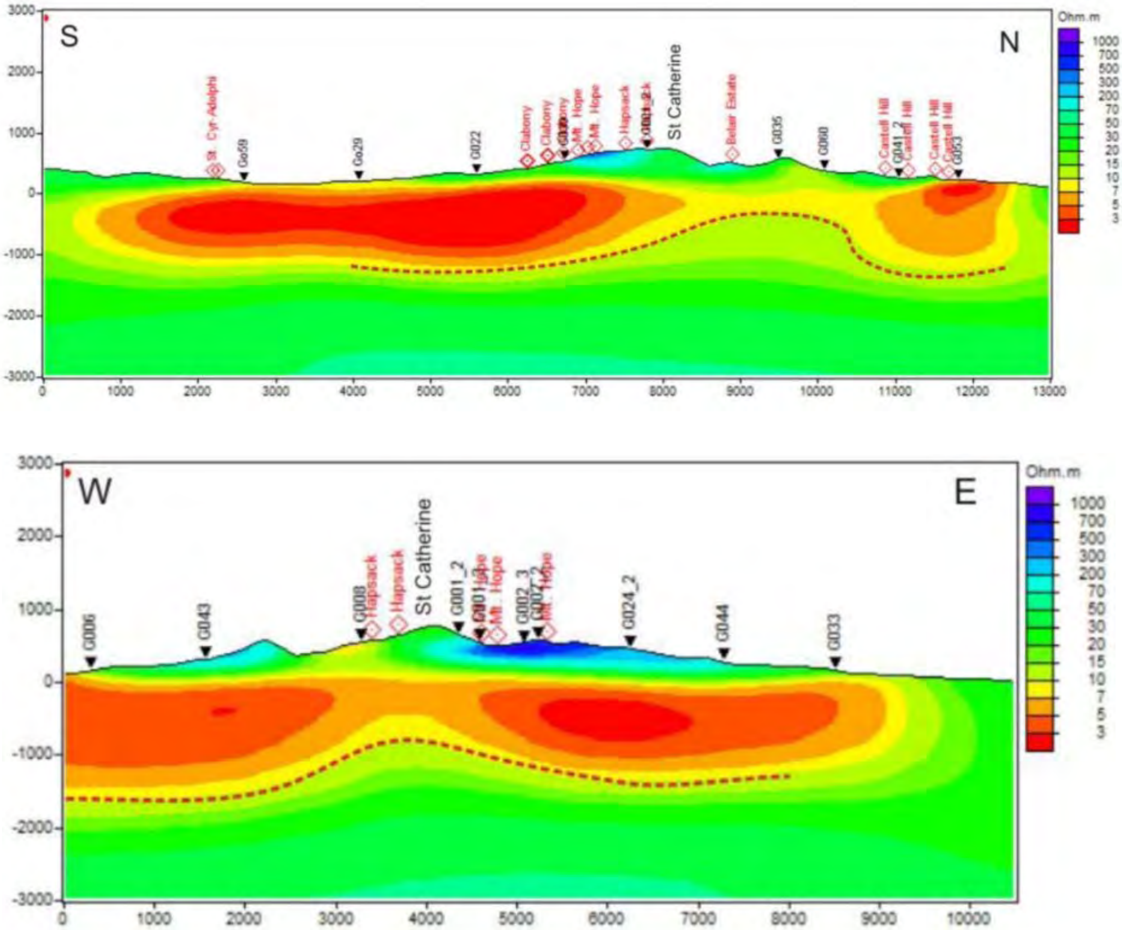
Source: Jacobs (2015)

Figure 3-10 Location Map of MT Stations



Source: Jacobs (2015)

Figure 3-11 Elevation Map of the Base of the Cap Rock Conductor Layer



Source: Jacobs (2015)

Figure 3-12 Resistivity Cross Section (SN and WE)
(3D inversion analysis)

3-3 Field Survey and Analysis Conducted

3-3-1 Geological Survey

(1) Objectives

In order to obtain the data for consideration of geothermal model, the JICA Survey Team conducted the geological survey to verify the geology, alteration, and fracture systems in the northern part of the Grenada Island.

(2) Methodology

The field survey was carried out in the geothermal manifestation areas located in the northern part of the Grenada Island. The survey included the field observations of rock outcrop, spring/hot spring/ fumaroles, hydrothermal alterations, fractures, and other geological and geochemical related features. When deemed necessary, rock samples were collected for x-ray diffraction analysis and microscopic observation of thin section at home.

【Microscope Observations of Rock Sample Thin Sections】

The rock sample specimens sampled were cut into approximately 35 x 25 x 5 mm small blocks, pasted each piece on microscope's slide and thinned to a thickness so that it can be observed under open nicol and crossed nicols. Names of rock forming minerals and textures were observed. In particular, alteration minerals and mineral veins were important to interpret the history of geothermal system forming process.

【X-Ray Diffraction (XRD) Analysis】

To carry out the XRD analysis, oriented sample and non-oriented sample were created. Oriented sample is created by hydraulic elutriation method.

Oriented specimens and/or non-oriented specimens were prepared for the XRD analysis. Oriented specimens were prepared through hydraulic elutriation method.

For specimens, from which refraction of 14–15 was recognized, oriented specimens were prepared through hydraulic elutriation method and were treated by ethylene glycol (hereinafter under referred to as EG). For specimens, from which refraction of seven was recognized and confirmation of Kaolinite was required, HCl treatment was conducted. Measurement conditions are as follows:

・X-ray : CuKα1
・Tube voltage : 40 kV
・Tube current : 20 mA
・Scan speed
  Non-oriented sample : 2°/min
  Oriented sample (Untreated, EG processing, HCl processing) : 1 °/min
・Scan range
  Non-oriented sample : $2\theta = 2\sim62°$
  Oriented sample (Untreated, EG processing, HCl processing) : $2\theta = 2\sim32°$

(3) Results

Huttrer and Michels (1995) reported the six geothermal sites as shown in Figure 3-13. Among those, the JICA Survey Team visited five sites for the survey, which are the following: (i) Chambord, (ii) CastleHill, (iii) Hapsack, (iv) Peggy's Whim, and (v) Clabony. The Adelphi-Saint Cyr as shown in No. 6 of Figure 3-13 was not visited because high temperature geothermal manifestation was not observed there. The survey results are as follows:

【Chambord】

- Chambord is located in the northeastern part of the Grenada Island.
- Travertine consisting of calcite was confirmed. Lake Antonie volcanics (tuff - sandstone) overlaid by travertine.
- Alteration and mineral veins were not confirmed.

【Castle Hill】

- Castle Hill is located in the northern part of the Grenada Island.
- Hot springs, located along the river, were welling from undifferentiated volcanics (35.9 ~ 46 ºC).
- Lava domes were seen in the vicinity.
- Travertine consisting of carbonate mineral calcite covers the volcanic ejecta as shown in Figure 3-15.
- Volcanics is tuff breccia and contains a lot of altered clay rock pieces.
- By XRD analysis, smectite was identified from the tuff breccias.
- Fault and mineral veins were not confirmed.

【Hapsack】

- Hapsack is located on the west side of Mt. Saint Catherine.
- Hot springs located along river were welling from volcanics (47.7 ~ 61.4 ºC).
- Sulfur was precipitated in the altered rocks with gas as shown in Figure 3-16 and Figure 3-17).
- The hot springs of Hapsack indicate the highest temperature in Grenada.
- Mt. Saint Catherine volcanics (pyroclastic rock) has been altered to be silicified with cristobalite and adularia as shown in Figure 3-16 and Figure 3-17).
- Fault and mineral veins are not confirmed.

【Peggy's Whim】

- Peggy's Whim is located on the northeastern side of Mt. Saint Catherine.
- Hot springs located along the river are welling from Mt. Saint Catherine volcanics (38.7 ºC).
- Week alteration was remarked (smectite and halloysite are identified by XRD) (Figure 3-18 and Figure 3-19).
- Fault and mineral veins are not confirmed.

【Clabony】

- Clabony is located on the southeastern side of Mt. Saint Catherine.
- Hot water discharges from debris formation with bubbling (33.6~34.9 ºC) as shown in Figure 3-20.
- Most of the plagioclase and mafic mineral are fresh. But some alteration are remarked such as halloysite, kaorinite, fine quarts, and sericite-smectite mixed-layered clay mineral were identified by XRD as shown in Figure 3-21 and Table 3-4).
- Fault and mineral veins are not confirmed.

Lava domes, which penetrate the undifferentiated volcanics which are the tufton hill layer and Mt. Saint Catherine volcanics have formed around Mt. Saint Catherine and the northwestern side as shown in Figure 3-22. Three manifestation sites seem to be located in the vicinity of the lava dome (suggesting a possible relationship between the geological structure of the lava dome and hot springs).

Comparing the resistivity distribution of the shallow part (-250 masl) and geological/alteration distribution, the geothermal manifestation sites where identified with smectite or mixed layer clay mineral showing lower resistivity than Hapsack as shown in Figure 3-23. In general, it is known that smectite and mixed layer clay minerals reduce the resistivity of rocks. It is considered that resistivity structure in the shallow part of Mt. Saint Catherine is regulated through the distribution of smectite and mixed layer clay minerals.

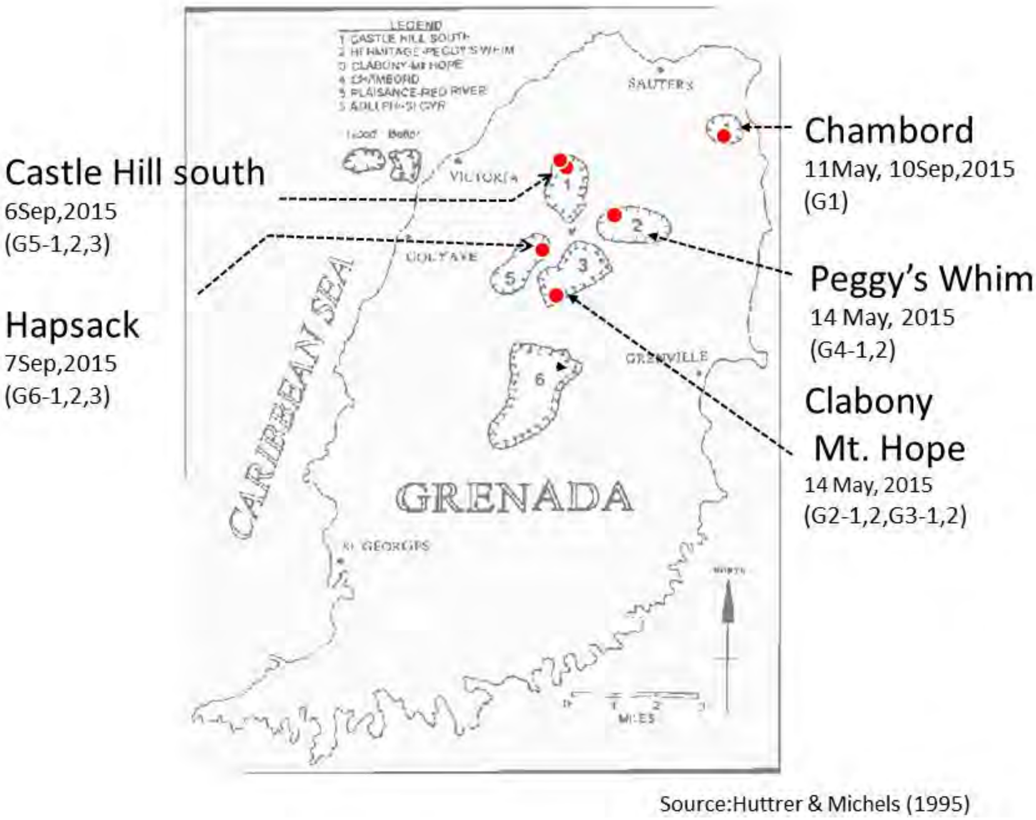


Figure 3-13 Location Map of Geological Survey

Table 3-3 Summary of Geological Survey Results

sample no.	location(UTM Zone 20N)			field name	geology	memo				labo	
loc	X	Y	elev.		formation	mechanical name	descriptive name	alteration	Manifestation	XRD	TS
G1	650269	1349059	40	Chambord	lake Antonie Volcanics	debris flow	wacke	none	Hot spring	Yes	
G2-1	644090	1343227	426	Clabony	Mt. Catherine volcanics	debris flow	Gravel with clay	none	Hot spring		
G2-2	644062	1343251	430	Clabony	Mt. Catherine volcanics	debris flow	Gravel with clay	none	Hot spring	Yes	
G3-1	644071	1343244	432	Clabony	Mt. Catherine volcanics	debris flow	Conglomerete	none	Hot spring	Yes	Yes
G3-2	643996	1343049	426	Clabony	Mt. Catherine volcanics	Tuff	Tuff	none	none		
G4-1	646174	1346072	298	Pegg's Whim	Mt. Catherine volcanics	debris flow	tuff breccia	green	Hot spring	Yes	Yes
G4-2	646174	1346072	298	Pegg's Whim	Mt. Catherine volcanics	debris flow	tuff breccia	none	Hot spring	Yes	
G5-1	644140	1348137	215	Castle Hill south	Undifferentiated volcanics	rework	tuff breccia	none	Hot spring	Yes	
G5-2	644384	1347861	264	Castle Hill south	Undifferentiated volcanics	travertine	none	none	Hot spring	Yes	
G5-3	644123	1348692	209	Castle Hill south	Undifferentiated volcanics	rework	tuff breccia	none	Hot spring	Yes	
G6-1	643475	1344773	580	Hapsack	Mt. Catherine volcanics	rework(breccia)	pyroclastic rock	Silicification	Hot spring	Yes	
G6-2	643475	1344773	580	Hapsack	Mt. Catherine volcanics	rework(matrix)	pyroclastic rock	Silicification	Hot spring	Yes	Yes
G6-3	643480	1344757	568	Hapsack	Mt. Catherine volcanics	rework(matrix)	pyroclastic rock	Silicification	Hot spring	Yes	

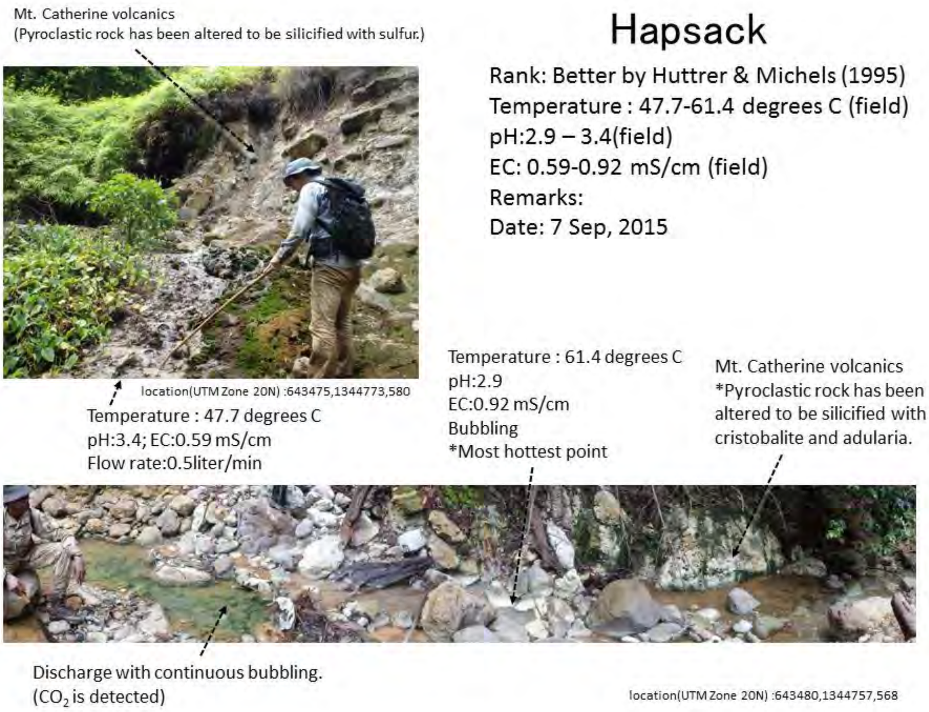
Source: The JICA Survey Team

Source: JICA Survey Team

Figure 3-14 Travertine Observed in Chambord

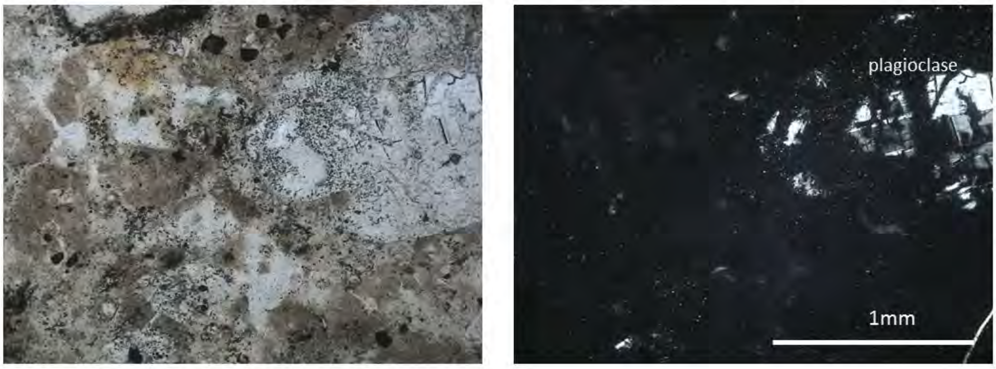
Source: JICA Survey Team

Figure 3-15 Travertine Observed in Castle Hill South



Source: JICA Survey Team

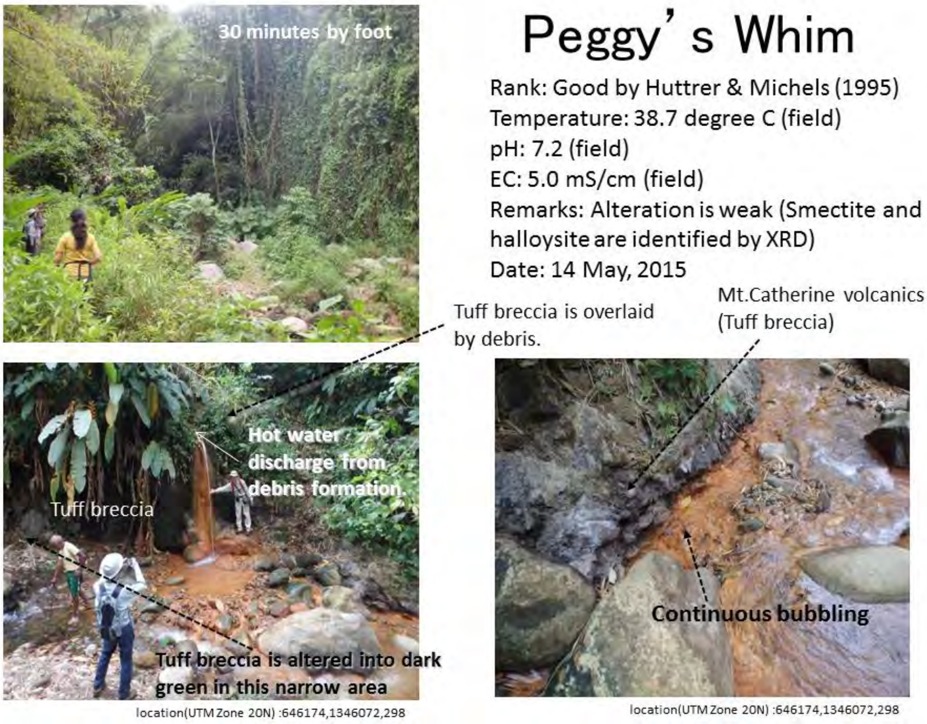
Figure 3-16 Alteration Zone Observed in Hapsack



Locarity: Hapsack
Rock name:Tuff breccia
Remarks
Small amount of Plagioclase(primary mineral), pseudomorphes of mineral crystal and brown-colored lithic fragments are contained. Matrix of tuff breccia and lithic fragments are altered to be amorphous material, fine quartz and opaque mineral(pyrite). Several plagioclase altered to feldspar(adularia).
Note: A large amount of fine abrasive compounds (high refractive) are contaminated.

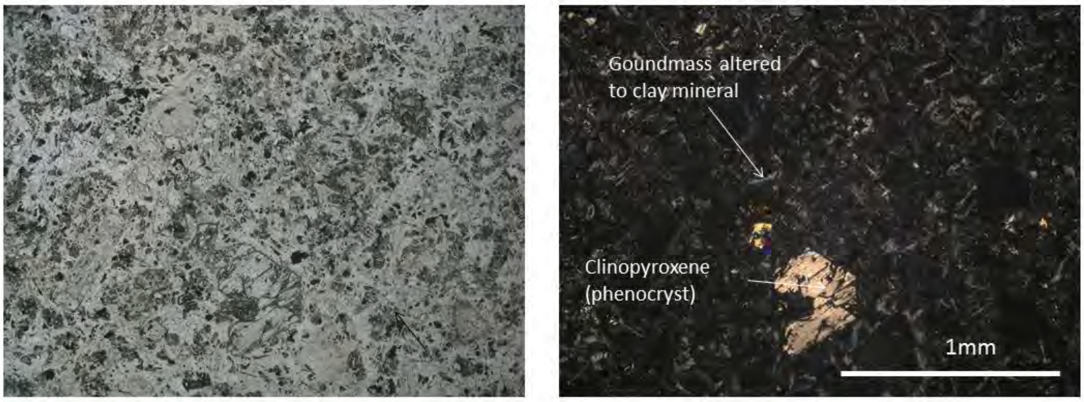
Source: JICA Survey Team

Figure 3-17 Micro-photographs of Tuff Breccia Distributed in Hapsack



Source: JICA Survey Team

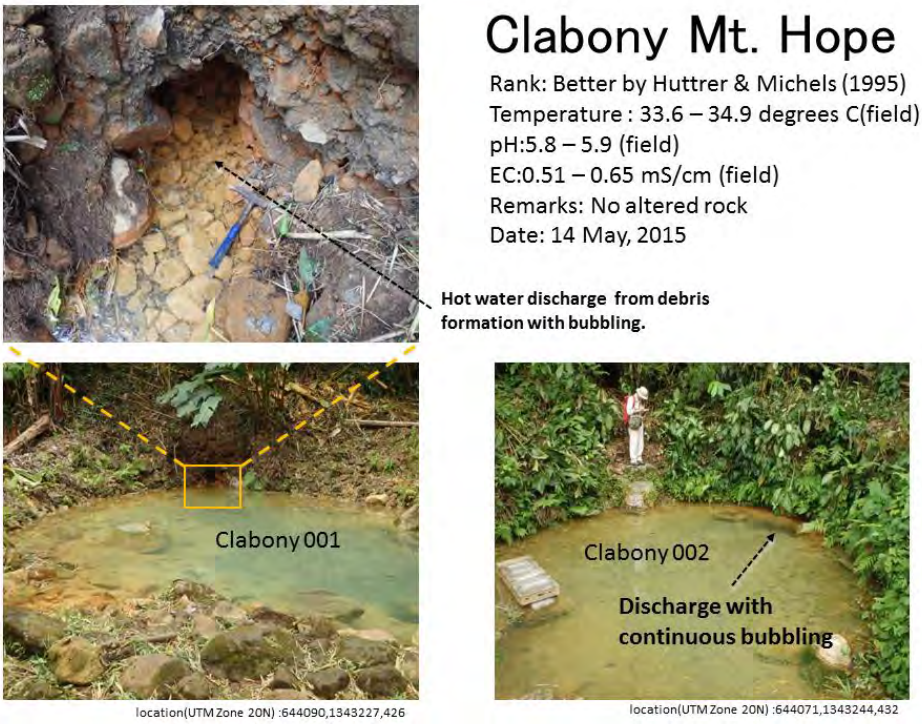
Figure 3-18 Tuff Breccia Distributed in Peggy's Whim



Locarity: Pegg's Whim (G4-1)
Rock name: pyroxene andesite (fragment of tuff breccia)
Remarks
Many pseudomorph crystals and small amount of plagioclase and pyroxene are contained as phenocryst in andesite. Some parts of groundmass and phenocrysts are altered to fine quartz and fine brown-colored clay mineral (smectite is detected by X-ray diffractometer) .

Source: JICA Survey Team

Figure 3-19 Microphotograph of Pyroxene Andesite (Peggy's Whim)



Source: JICA Survey Team

Figure 3-20 Debris Distributed in Clabony

Locarity: Clabony (G3-1)
Rock name:Tuff breccia (Congromerate)
Remarks
Small amount of quartz, plagioclase, hornblende, biotite, clinopyroxene and lithic fragments are contained. Most of plagioclase and mafic mineral are fresh. Some parts of matrix are altered to fine quartz and fine clay mineral (halloysite and sericite-smectite mixed-layered clay mineral are detected by X-ray diffractometer) . Small veins of clay mineral and calcedony are distributed in the matrix and fragments.

Source: JICA Survey Team

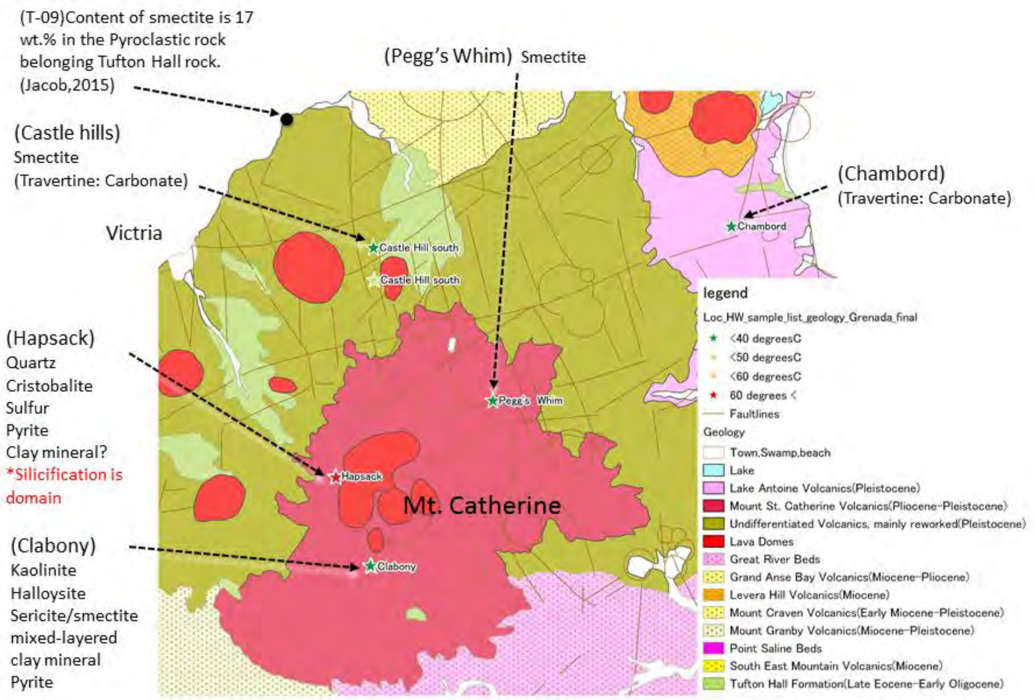
Figure 3-21 Microphotograph of Tuff Breccia Distributed in Clabony

Table 3-4 Summary of XRD Analysis (Quartz Index)

Mineral (2 theta to intensity)				Clay mineral					Silica mineral			Silicate mineral				Carbonate			element mineral		Sulfide mineral		oxide mineral		unidentified diffraction line (2 Theta)
				Smectite	S/S	clay mineral	Kaolinite	Halloysite	Quartz	Cristobalite	Tridymite	Plagioclase	Alkali Feldspar	Hornblende	Clinopyroxene	Calcite	Aragonite	Vaterite	Sulfur		Pyrite		Magnetite	Goethite	
No.	Locarity	Rock	state	5.2～6.2°	7.0～8.8°	6.2～7.0°	12.4°	12.4°	26.6°	22.0°	22.0°	27.8～28.0°	27.4～27.5°		30.0°	29.4°	°	°	°		33.1°		35.1°		
1	G1 Travertine	Chambord	Bulk													34.7									
			UT																						
			EG																						
			HCl																						
2	G2-2	Clabony	Bulk				0.1		0.8			2.4		0.2										0.1	
			UT				Yes																		
			EG				Yes																		
			HCl																						
3	G3-2	Clabony	Bulk		0.7			0.6	7.5	10.0		0.8	1.2	1.3							1.1		0.5		
			UT		Yes			Yes																	
			EG		Yes			Yes																	
			HCl																						
4	G4-1	Pegg's Whim	Bulk	0.5								9.5			0.7						0.4		2.1		
			UT	Yes																					
			EG	Yes																					
			HCl																						
5	G4-2	Pegg's Whim	Bulk	0.4						7.8		5.9	0.9		1.3										
			UT	Yes																					
			EG	Yes																					
			HCl																						
6	G5-1	Castle Hill south	Bulk	0.7					2.9			16.8		0.7											
			UT	Yes																					
			EG	Yes																					
			HCl																						
7	G5-2 Travertine	Castle Hill south	Bulk									2.6				2.3	3.2	0.5							15.1
			UT																						
			EG																						
			HCl																						
8	G5-3	Castle Hill south	Bulk	0.6						9.7	5.2	14.0		1.4											
			UT	Yes																					
			EG	Yes																					
			HCl																						
9	G6-1	Hapsack	Bulk						19.5				1.1								8.3				
			UT																						
			EG																						
			HCl																						
10	G6-2	Hapsack	Bulk			0.2?			20.7				1.4						1.7						
			UT																						
			EG																						
			HCl																						
11	G6-3	Hapsack	Bulk							32.0		1.9	0.6												
			UT																						
			EG																						
			HCl																						

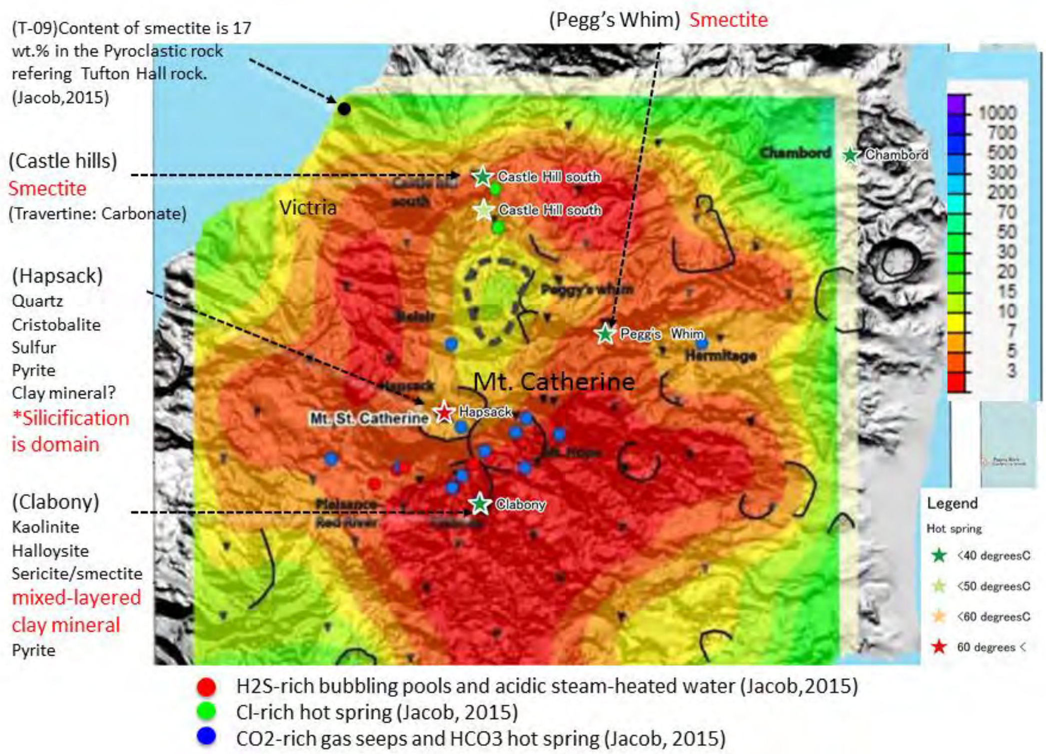
UT :Air dried sample by preferred orientation method
EG :Ethylene glycol solvated
HCl :acidum hydrochoricum solvated

Source: JICA Survey Team



Source: JICA Survey Team

Figure 3-22 Distribution of Altered Mineral on the Geothermal Manifestations



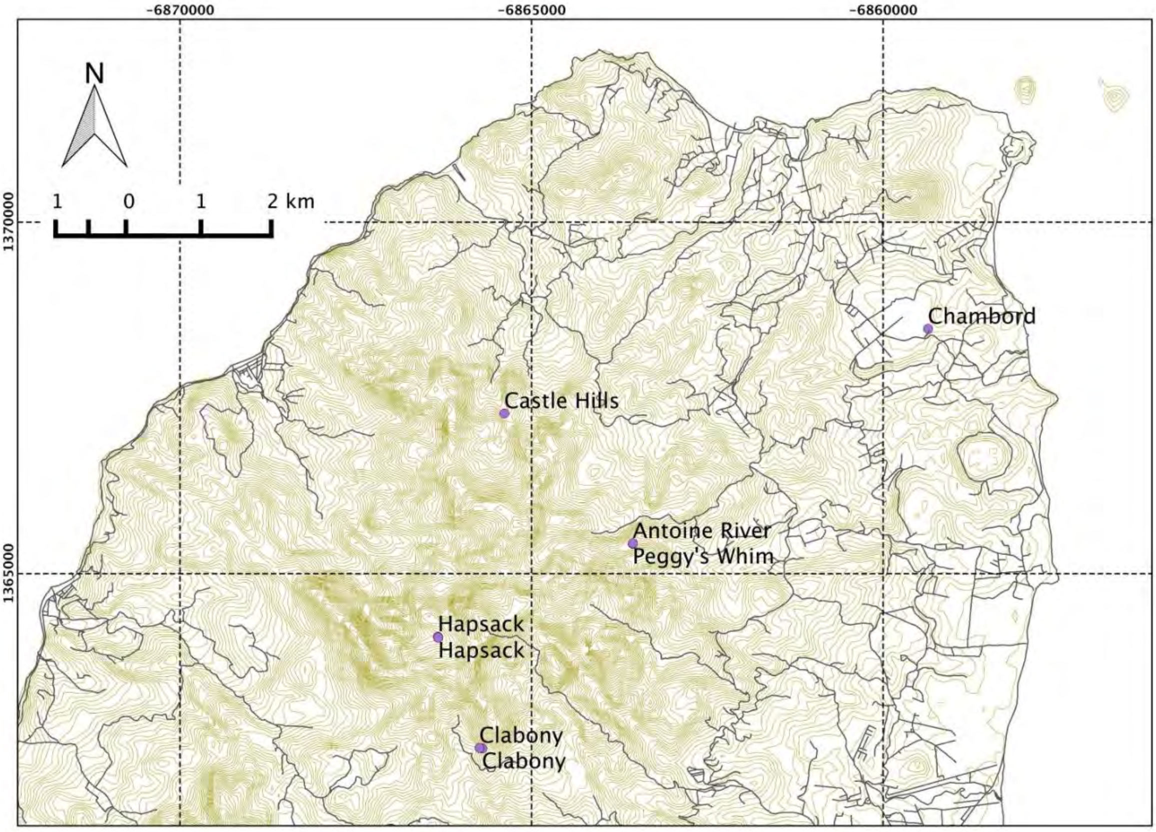
Source: JICA Survey Team

Figure 3-23 Distribution of Altered Minerals with Resistivity Map (-250 masl)

3-3-2 Geochemical Survey

In order to inspect thermal features in Grenada and compare the results with those in the previous surveys, the JICA Study Team conducted a geochemical reconnaissance involving sampling and field measurement (e.g., temperature, pH, and conductivity). The locations, which are coordinated through a portable global positioning system (GPS) and the results of the field measurement for the visited thermal features are listed in Table 3-5. The locations are also shown on the map in Figure 3-24. The field temperatures are similar to those of the reference data as summarized in Jacobs (2015).

The thermal water samples and river water sample from the Antoine River have been analyzed at the laboratory of JMC Geothermal Engineering Co., Ltd. The chemical species and the methods for the chemical analysis are shown in Table 3-6 and the results are shown in Table 3-7.



Source: JICA Survey Team

Figure 3-24 Location of the Thermal Features

Table 3-5 Location and Results of the Field Measurement in Geochemical Reconnaissance

Location	Sample name	Type of manifestation	Sample	Date	Longitude (N)	Latitude (W)	Elevation (masl)	T atm (°C)	P atm (hPa)	T water (°C)	pH	EC (mS/cm)	Note
Clabony	CBN 001	Thermal water	Yes	2015/05/14	12.147650	61.675667	400	26.0	971	34.9	5.9	0.51	–
Clabony	CBN 002	Thermal water	Yes	2015/05/14	12.147708	61.676018	466	26.0	971	33.6	5.8	0.65	–
Peggy's Whim	Chacha	Thermal water	Yes	2015/05/14	12.173224	61.656430	287	23.8	983	38.7	7.2	5.0	A hot spring flows out from a hole in debris covering andesite lava.
Peggy's Whim	Antoine river	River water	Yes	2015/05/14	12.173269	61.656415	297	23.8	983	24.4	6.8	0.69	Taken from the rever bank close to the Chacha thermal fearure
Castle Hills	AG001-2	Thermal water	Yes	2015/09/06	12.189496	61.672834	264	25.7	–	46.0	5.67	> 4.0	Hot water flows out from the debris overliying undifferentiated volcanics.
Hapsack	AG016-1	Thermal water	Yes	2015/09/07	12.161614	61.681328	580	24.4	–	47.7	3.35	0.593	Hot water flows out form altered pyroclastic rock (Mt. Catherine volcanics).
Hapsack	AG016-3	Thermal water	Yes	2015/09/07	12.161476	61.681283	568	24.4	–	61.4	2.86	0.923	bubbling pool
Chambord	Chambord	Thermal water	Yes	2015/09/10	12.200061	61.618701	40	20.5	–	32.7	6.02	> 4.0	Calcite deposits to form Travertine.

Source: JICA Survey Team

Table 3-6 Chemical Species and Method for Chemical Analysis

Aqueous species	Analytical method
pH	pH meter
EC	Conductivity meter
Cl, SO_4	Ion chromatography
HCO_3	Infrared spectroscopy
Na, K	Flame emission spectroscopy
SiO_2, Ca, Mg, Fe, Al, B	ICP/AES

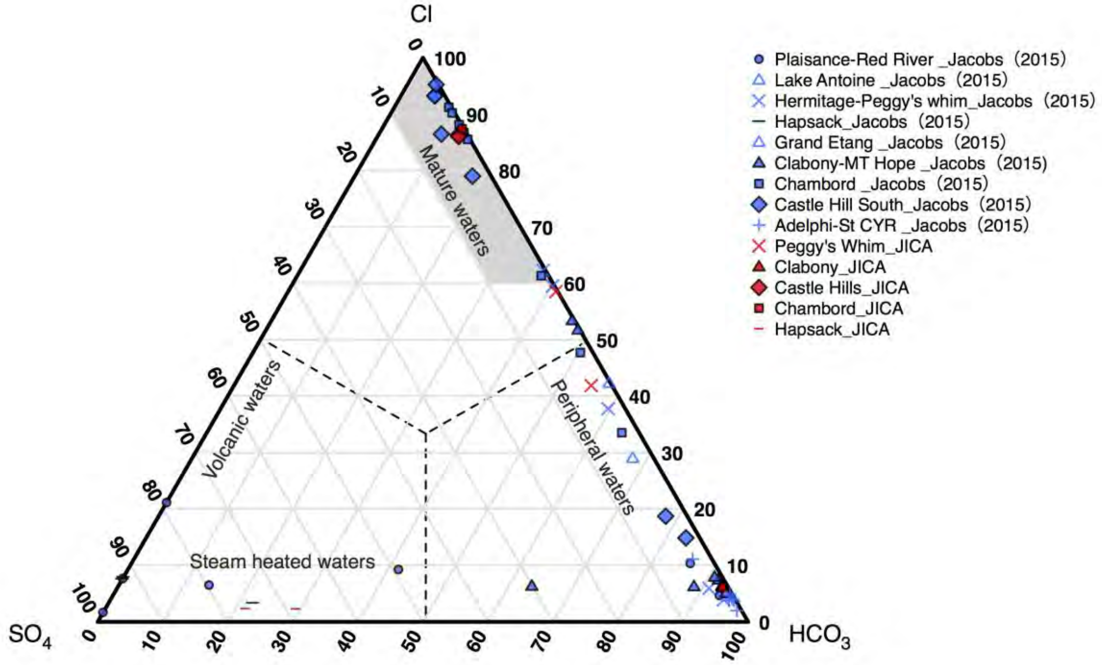
Source: JICA Survey Team

Table 3-7 Results of Chemical Analysis of the Water Samples

Sample	Location	Type	Date	pH	EC	SiO_2	Cl	SO_4	t-HCO_3	Na	K	Ca	Mg	Al	Fe	B
					µS/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
CBN 001	Clabony	Thermal water	2015/5/14	6.3	694	152	31	4.6	456	53	6.0	56	25	<0.01	<0.01	1.1
CBN 002	Clabony	Thermal water	2015/5/14	6.1	648	147	31	4.2	466	50	5.7	52	22	<0.01	<0.01	0.96
Chacha	Peggy's Whim	Thermal water	2015/5/14	6.8	5180	167	1320	6.9	928	668	44	126	86	<0.01	<0.01	17
Antoine river	Peggy's Whim	Thermal water	2015/5/14	7.0	693	43	132	9.9	173	71	5.2	37	14	<0.01	<0.01	2.0
AG001-2	Castle Hills	Thermal water	2015/9/6	6.0	9880	136	3190	55	463	1470	153	470	59	<0.01	<0.01	39
AG016-1	Hapsack	Thermal water	2015/9/7	3.1	755	117	8.5	259	111	11	20	5.2	3.6	15	5.4	0.02
AG016-3	Hapsack	Thermal water	2015/9/7	3.2	823	117	9.8	329	93	23	5.3	31	8.3	17	2.4	0.0
Chambord	Chambord	Thermal water	2015/9/10	6.2	21800	114	7820	28	1101	3610	166	798	333	<0.01	<0.01	54

Source: JICA Survey Team

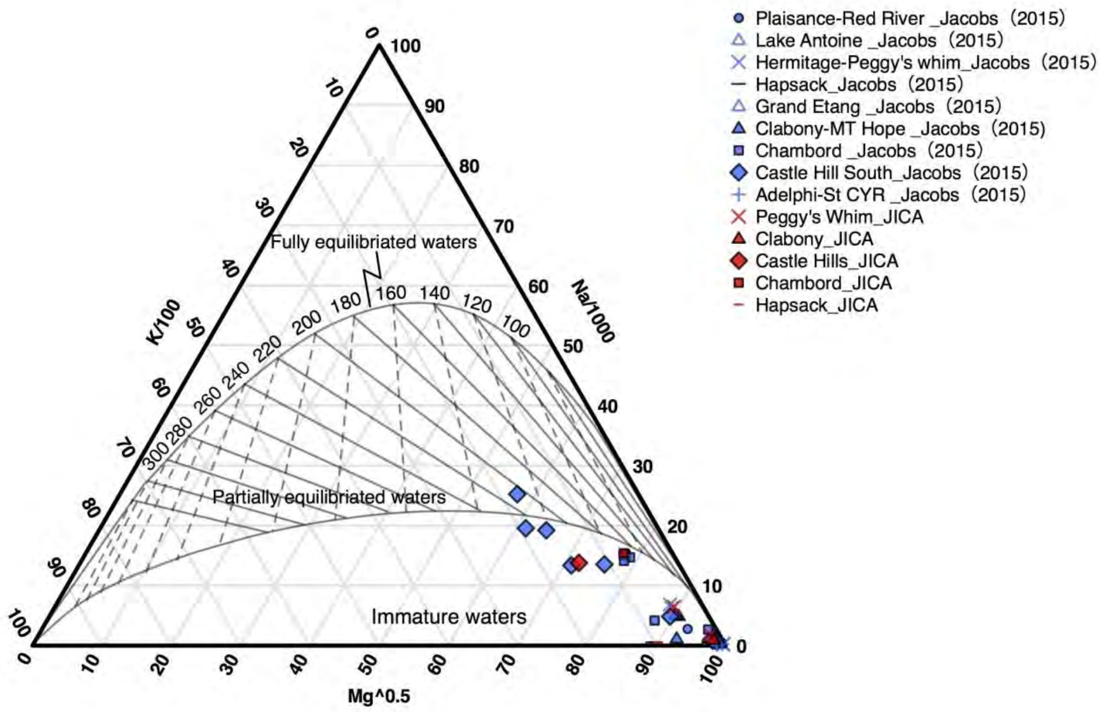
In order for the JICA Survey Team to compare the chemical composition of thermal waters (hereinafter referred to as the JICA data) with those of reference data summarized in Jacobs (2015), both of the chemical compositions are plotted together on the diagrams of the relative contents of Cl, SO_4, and HCO_3 and of relative contents of Na, K, and Mg as shown in Figure 3-25 and Figure 3-26, respectively.



Source: JICA Survey Team

Figure 3-25 Relative Contents of Cl, SO_4, and HCO_3 for Thermal Waters

In Figure 3-25, the JICA data are plotted close to the reference data, indicating that both data are consistent with each other and reflect the origin of the thermal water. Also, as shown in Figure 3-26 is a diagram to assess equilibrium conditions of water-rock interaction (maturity of the reaction) proposed by Giggenbach (1988) and accepted by professionals. Acceding to the Figure 3-26, the JICA data and the reference data are mostly plotted together around the Mg corner, which means that both data show an immature state of the thermal water in water/rock interaction.



Source: JICA Survey Team

Figure 3-26 Relative Contents of Na, K, and Mg for Thermal Water

Geochemical thermometers were calculated for the JICA data as shown in Table 3.8. Comparing the calculated results of the quartz thermometer (Founier and Potter, 1982), Na-K thermometer (Giggenbach, 1988), Na-K-Ca thermometer (Founier and Truesdell, 1973), and K-Mg thermometer (Giggenbach, 1988) between the JICA data and the reference data (Jacobs, 2015), the calculated temperatures are virtually consistent with each other for each thermometer.

As a result of the discussion above, the JICA data confirm the validity of existing chemical data and geochemical interpretation by Jacobs (2015) for the thermal features in Grenada.

Table 3-8 Geochemical Thermometry Temperatures

Sample	Location	Water Type	Date	Quartz	Quartz	Chalcedony	Chalcedony	Cristobalite	Na-K	Na-K	Na-K	Na-K	Na-K-Ca	K-Mg
				Founier and Potter (1982)	Arnórsson et al. (2000)	Founier (1977)	Arnórsson et al. (1983)	Founier (1977)	Truesdell (1976)	Founier (1979)	Giggenbach (1988)	Arnórsson (2000)	Founier and Truesdell (1973)	Giggenbach (1988)
				℃	℃	℃	℃	℃	℃	℃	℃	℃	℃	℃
CBN 001	Clabony	Thermal water	2015/5/14	162	152	138	134	112	201	228	242	212	54	46
CBN 002	Clabony	Thermal water	2015/5/14	160	150	136	132	110	202	229	243	214	54	46
Chacha	Peggy's Whim	Thermal water	2015/5/14	168	159	145	141	118	147	184	201	168	166	76
AG001-2	Castle Hills	Thermal water	2015/9/6	155	145	131	127	105	192	220	236	205	193	114
AG016-1	Hapsack	Thermal water	2015/9/7	(146)	(135)	(120)	(118)	(96)	(1135)	(713)	(653)	(748)	(342)	(95)
AG016-3	Hapsack	Thermal water	2015/9/7	(146)	(135)	(120)	(118)	(96)	(304)	(304)	(312)	(296)	(54)	(54)
Chambord	Chambord	Thermal water	2015/9/10	145	133	119	117	94	117	158	177	144	161	92

Because pH of Hapsack (AGO16-1, 16-3) is as low as about 3 which is not considered applicable to geochemical thermometry, the temperatures are listed for reference in parentheses.

Source: JICA Survey Team

3-3-3 Gravity Survey

(1) Objectives

To apply the gravity survey as reconnaissance in order to grasp the regional volcanic structure geologically and extract such fault systems as fracture zone which form the geothermal reservoir.

(2) Methodology

[Measuring equipment]

Relative gravimeter (Syntrex Ltd., U.S.) was used for gravity measurement in the field survey. Position information was obtained by using D-GPS.

[Field survey]

Gravity survey was conducted in northern Mount St. Catherine and half of north island including the areas where geothermal manifestation was confirmed. Measurement interval was 500 m~1 km in horizontal distance. Measurement error of the altitude is about ±5 cm.

It is often the case that there is no way to access measurement station, or the station is covered by lush vegetation and with steep terrain. In the case that it is impossible to access planned gravity stations, or the GPS measurement are not possible due to the influences of vegetation covering, the gravimetric measurement will be conducted in a new gravity station near to the old planned one. The field survey was conducted from August 25 to September 13, 2015. Initially, there were 105 planned gravity stations, but in 116 stations the measurement has been conducted finally.

The locations of the gravity stations are shown in Figure 3-28, and Table 3-9 shows an example of the measurement results. The list of the measurement results is attached at the end of this report.

[Datum point and standard gravity value, measuring station and relative gravity value]

Gravimetric measuring value usually changes without fixed value because it is always influenced by various factors. For this reason, during gravity measuring on field survey, a fixed standard point will be set for measuring standard gravity value, and the value measured on other stations will be corrected based on this standard value. This is a method of calculating relative gravity value by fixing a value of a datum point station as standard value.

In this field survey, as the standard point for calculating relative gravity of the other stations, the datum point station is set in Laurant Point (See No. 1412 and No.1111 in Figure 3-28) in a hotel in the northernmost area. Measurement in standard point station will be conducted very morning before the survey and very evening after the survey. The difference between this two measurements (drift value) will be estimated whether exceeding the permissible value. Because in Grenada there is no standard point representing absolute gravity value with world standard, this report will use *standard gravity value* of the datum point station and corresponding *relative gravity value* instead of *absolute gravity value*.

The gravimetric value measured in each stations will be corrected by measurement time, height of gravimeter above ground, longitude and latitude of measuring station, and terrain conditions. After this, the measuring value will be corrected into *relative gravity value* by comparing with *standard gravity value*. The relative gravity value can be changed into tentative absolute gravity value of each stations if it is suitable for this field survey. In order to correct it into absolute gravity value, it is necessary to make clear the relationship with the absolute gravity station set in Barbados the neighboring country.

[Bouguer correction]

Relative gravity value of each stations obtained in above way still includes the influence of topographic reliefs which can induce the change of gravity acceleration. Therefore, this value cannot reflect the gravity changes induced by underground gravimetric structure properly. For removing this influence, a correction needs to be conducted. Such kind of correction is called Bouguer correction.

During Bouguer correction processes, a G-H correlation figure was drawn based on the rock types of survey area and the assumed rock density, and then the suitable corrected density was discussed by comparing Bouguer anomaly map with terrain. In the survey area, the most suitable rock density for correction is estimated to 2.2 g/cm^3 (Figure 3-29). Bouguer anomaly map based on this density value is shown in Figure 3-30, and this map will be the base for further drawing other analysis diagrams of gravimetric survey.

[Analysis diagram of gravimetric survey]

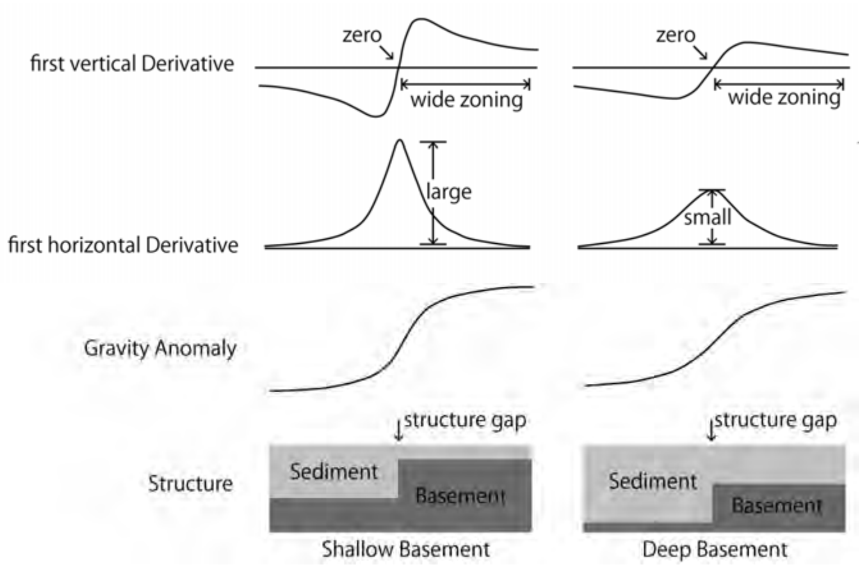
By using the data of Bouguer anomaly map, following analysis diagrams have been drawn considering the objective of this field survey.

Table 3-9 List of Gravimetric Survey Analysis Diagrams

Name	Analyzing method	Represented information	Application
Trend surface residual gravity map	Remove the influences of gravimetric density of deep underground	Gravimetric (density) information in relatively shallow underground	Make clear the situation of 3D gravity anomaly. Estimate the depth of bed rock.
First Horizontal Derivative map	Calculate the first derivative of gravity value of Bouguer anomaly in horizontal direction	Absolute slope of gravity value change in horizontal direction	The bigger the value is the bigger the density change is underground. Indicate the rock boundary of fault and so on.
First Vertical Derivative map	Calculate the derivative of gravity value change rate	Location with 0 derivative value represent the peak of gravity value	0 value locations coincide with the locations where the biggest density change are. Indicate the center position of the rock boundary of fault and so on.

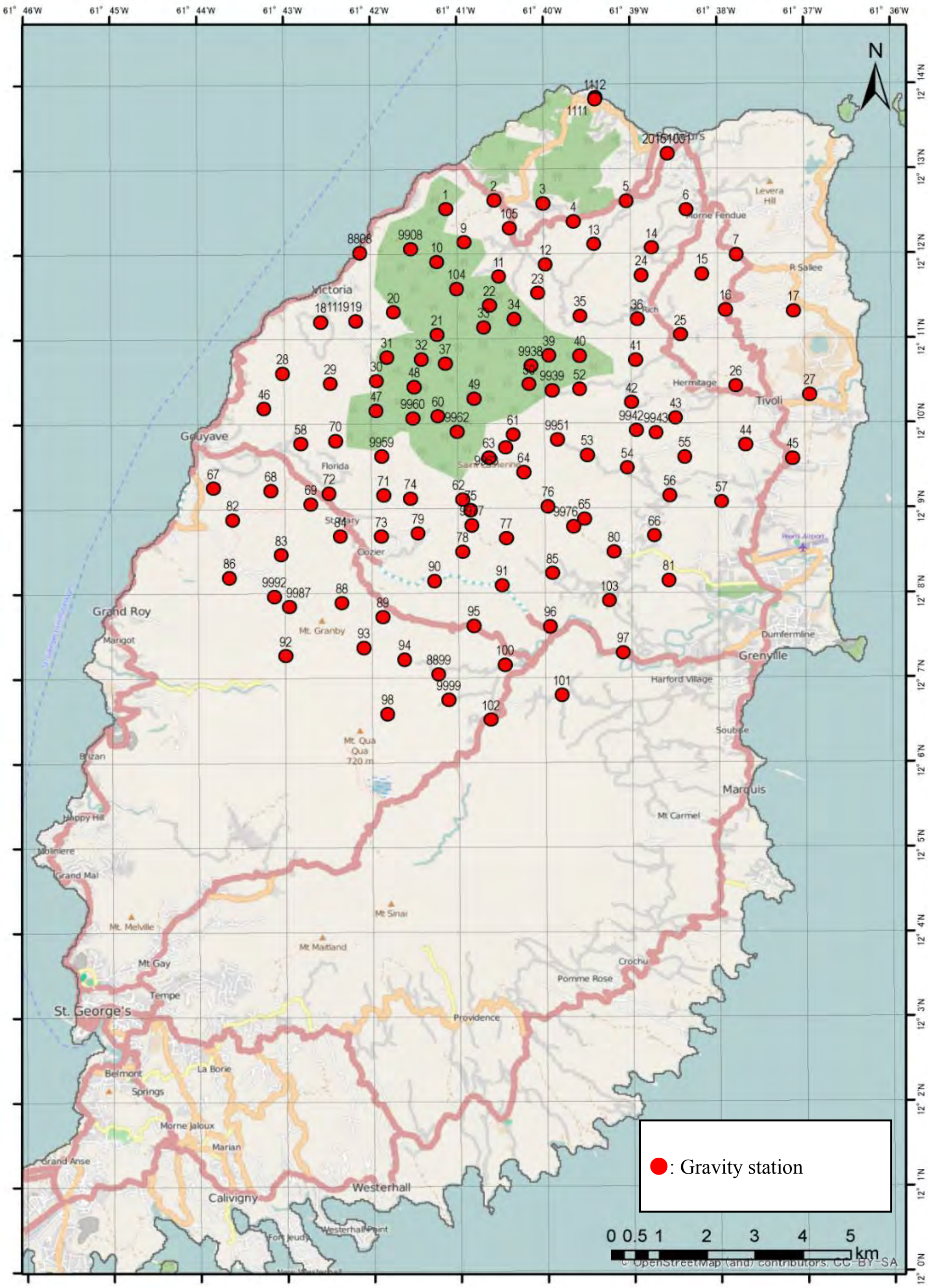
Source: JICA Survey Team

The relationship between contour and underground density structure represented by using First Horizontal Derivative and First Vertical Derivative is shown in Figure 3-27.



Source: JICA Survey Team

Figure 3-27 Comparison between the First Vertical Derivative and the First Horizontal Derivative in Fault Structure Presenting



Source: JICA Survey Team

Figure 3-28 Location of the Gravity Stations

Table 3-10 Example of the Measurement Results

GRAVITY LOOP PROCESSING REPORT

Project:	GrenadaGravity 2015	Loop:	62 Aug29.TXT	Processing status:	Solved (s.d. = 0.000 mGal)
Date:	2015/08/29	Instrument type:	Scintrex CG-5	Serial No.	41062
No. of stations:	6	No. of readings:	7	Reduct. density:	2.67g/cm3
Gravity formula:	IGS 1980	Coordinate system:	WGS 84 / UTM zone 20N	Elevation datum:	Ellipsoidal

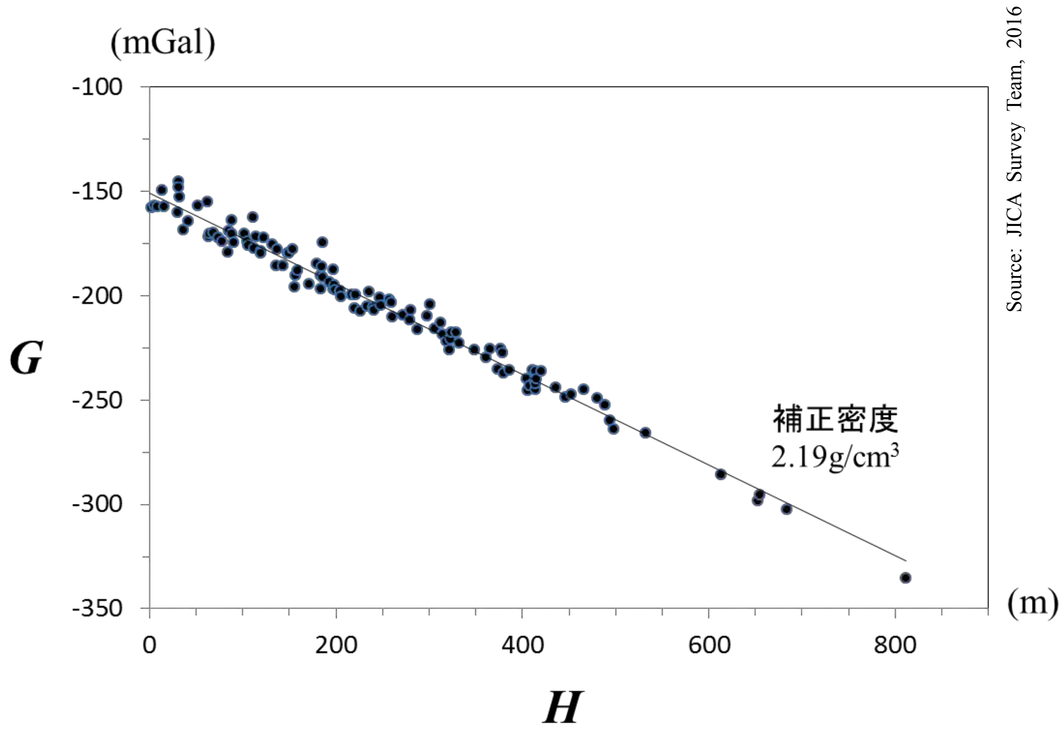
Loop closure processing:

Line No.	Station No.	Local time	Instr. reading	Instr. height [m]	Tidal corr. [mGal]	Drift corr. [mGal]	Abs. gravity [mGal]	Resid. [mGal]	Remarks
0	1111	16:50:48	3316.861	0.160	0.192	0.000	979000.000	0.000	BASE
0	6	17:44:12	3306.604	0.170	0.151	0.010	978989.695	0.000	
0	14	18:33:25	3288.674	0.110	0.096	0.019	978971.701	0.000	
0	35	19:46:47	3261.551	0.160	0.002	0.033	978944.513	0.000	
0	36	20:40:48	3287.785	0.180	-0.057	0.043	978970.704	0.000	
0	24	21:37:49	3285.455	0.170	-0.097	0.054	978968.342	0.000	
0	1111	22:28:20	3317.115	0.160	-0.105	0.063	979000.000	0.000	BASE

Legend: BASE = gravity base, REP = in-loop repetition

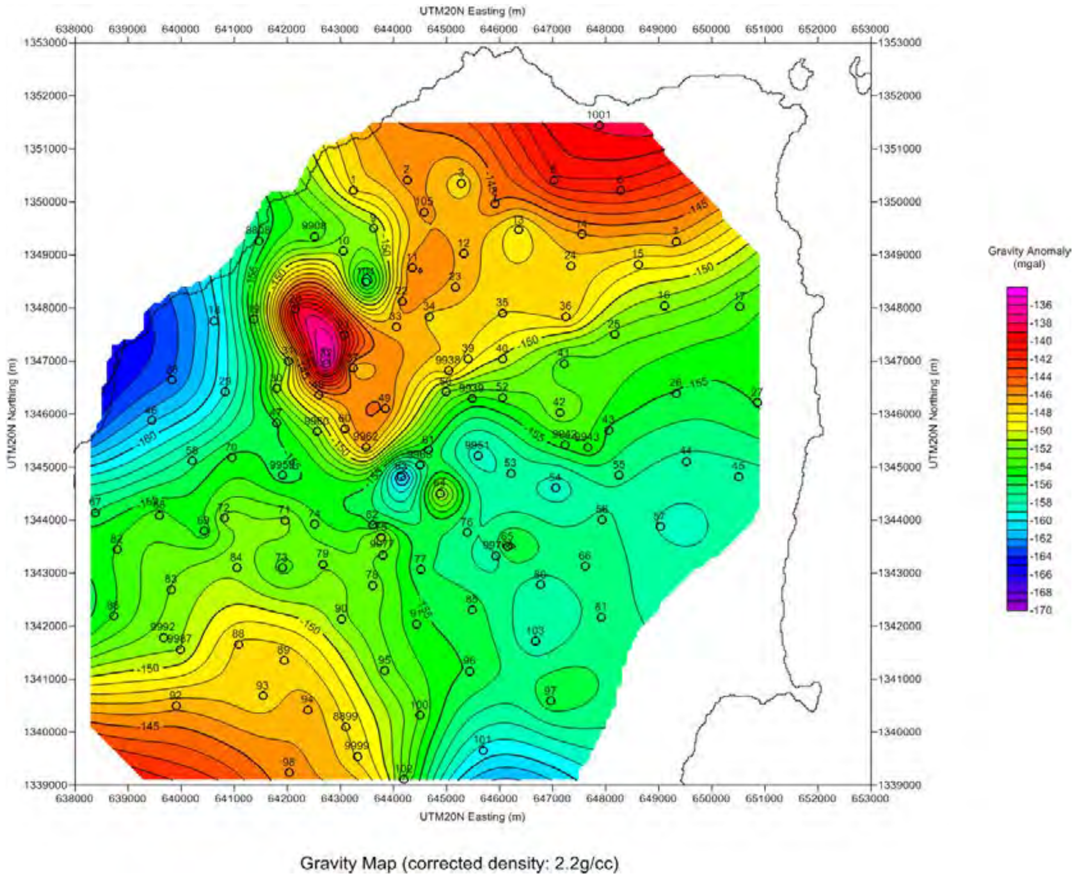
Stations results summary:

Line No.	Station No.	Geodetic latitude [−]	Geodetic longitude [−]	Altitude [m]	Number of obs.	Abs. gravity [mGal]	RMS [mGal]	Max. error [mGal]	Theor. gravity [mGal]	Free air anom. [mGal]	Bouguer anom. [mGal]	Local [mGal]	Regional [mGal]	Total corr. [mGal]	Complete Bouguer [mGal]	Remarks
0	1111	12.23277749	61.65429942	-5.621	6	979000.000	0.000	0.000	978264.518	733.747	734.376	N/A	N/A	N/A	N/A	BASE
0	14	12.20316952	61.64366593	122.706	1	978971.701			978263.414	746.154	732.423	N/A	N/A	N/A	N/A	
0	24	12.19779141	61.64559346	131.665	1	978968.342			978263.214	745.760	731.027	N/A	N/A	N/A	N/A	
0	35	12.18980949	61.65742295	235.214	1	978944.513			978262.917	754.183	727.863	N/A	N/A	N/A	N/A	
0	36	12.18918468	61.64645173	114.002	1	978970.704			978262.893	742.992	730.235	N/A	N/A	N/A	N/A	
0	6	12.21066138	61.63689578	62.702	1	978989.695			978263.693	745.352	738.335	N/A	N/A	N/A	N/A	



Source: JICA Survey Team

Figure 3-29 G-H correlation



Source: JICA Survey Team

Figure 3-30 Bouguer Anomaly Map (Corrected Density: 2.2 g/cm³)

(3) Results

Figure 3-30 shows the Bouguer anomaly map created with the corrected rock density of 2.2 g/cm[3] (see terrain conditions in Figure 3-31). The northern part of the survey area including Hapsack and Pegg's Whim represents relatively high gravity anomaly with the value higher than -150 mgal. Especially, the highest gravity anomaly within the survey area is found in the area between Hapsack and Victoria with the value of -136 mgal. The high gravity anomaly area is surrounded by densely spaced contours, which indicates steep changes in gravity (see dense part of contours in Figure 3-30). The steep changes in gravity extends in the direction of NE-SW between Hapsack and Pegg's Whim, and extends in the direction of NW-NNW from the vicinity of Hapsack. Unlike this, a wide area around Pearls in the eastern part of the survey area, the Bouguer anomaly shows minor changes.

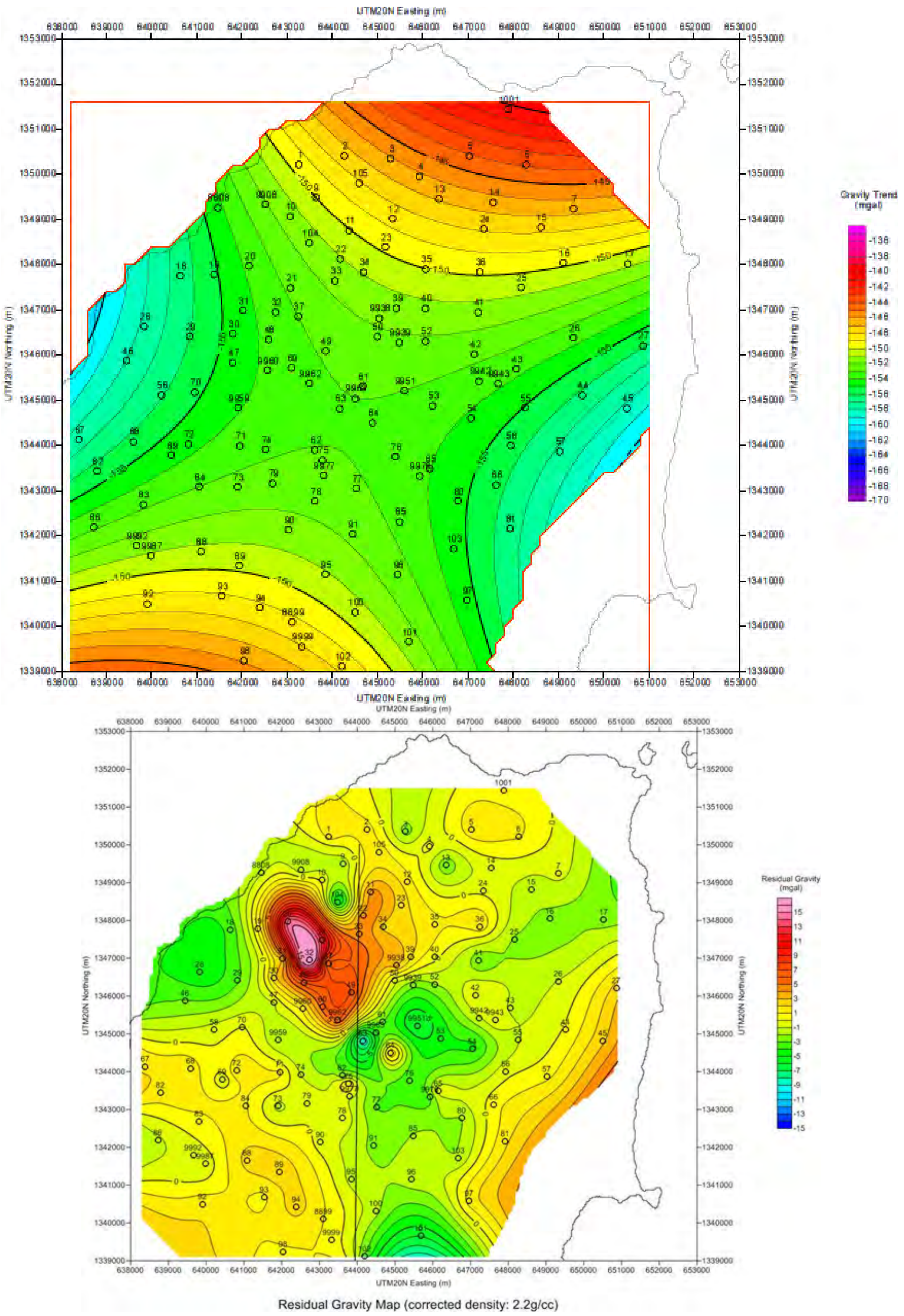
Various analyzing maps were created based on the Bouguer anomaly map.

Source: JICA Survey Team

Figure 3-31 Map of North Grenada

Removing the influences of the lower crust and mantle density from the Bouguer anomaly map, "trend-surface map and its residual map" was created as shown in Figure 3-32. The corrected density of 2.2 g/cm[3] was used (Figure 3-29). On the trend surface residual map, density distribution of shallow crust can clearly be observed. The map reveals that a high gravity anomaly over about 1 mgal exists in the northern part of the survey area including Hapsack and Pegg's Whim. Especially, an area with the high gravity anomaly over 5 mgal found between Hapsack and Victoria. Around the gravity anomaly area, a sudden change in

Bouguer anomaly exists (see dense part of contours in Figure 3-32). In the vicinity of Hapsack and Pegg's Whim, the steep gravity change is roughly along the direction stated above and NE-SW direction.



Source: JICA Survey Team

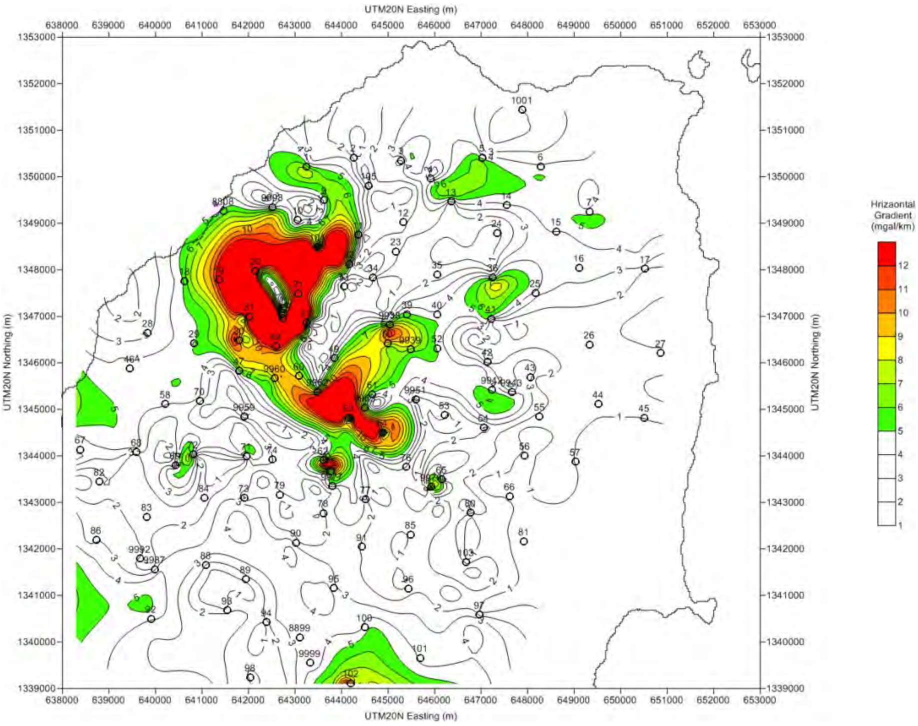
Figure 3-32 Trend-Surface Map (upper) and Trend-Surface Residual Map (under)

The first horizontal derivative map with corrected density of 2.2 g/cm^3 is shown in Figure 3-33. The map presents the horizontal change of the derivative gravity value. The larger the values are, the larger density differences exist under the ground. A high first horizontal derivative zone is found in the vicinity of Hapsack, which extends in 2 directions. One is NE-SW direction towards Pegg's Whim, the other is NW-SE direction towards Victoria. One more location showing a high first horizontal derivative value is found in the areas between Waltham and Victoria in Northwest Grenada.

The first vertical derivative map with corrected density of 2.2 g/cm^3 is shown in Figure 3-34. The map presents the change rate of the derivative gravity value. The zero-contour represents zones of the largest density differences under the ground (see Figure 3-27). The zero-contour distributes from Hapsack to Pegg's Whim and Cambord in NE-SE direction, and from Hapsack to Victoria in northwestern direction, and from Gouyave in the north of Hapsack pass through Clabony in NW-SE direction. In the vicinity of Castlehill the zero contour also stands out in NW-SE and NE-SW direction.

Interpreted density distribution inferred from the trend-surface residual map is shown in Figure 3-35. Such density distribution is a kind of 3D version of the density distribution under the ground (a density distribution with 2D structure represents density distribution of the bed rock layer). Between Hapsack and Victoria where the remarkable high gravity anomaly distributes, a lot of spots with high densities can be found in shallow depths (zero msl). With depths increasing, these spots will merge each other into a high density zone in NW-SE direction. Several spots coincide with the locations where the intrusive rock exists on ground, which indicates that the intrusive rock masses may concentrate between Hapsack and Victoria.

On the other hand, the interpreted density in Mt. St. Catherine and its surroundings is relatively smaller than those out of this zone (See Figure 3-35 lower). This zone corresponds to the low gravity anomaly (Figure 3-32 Lower) and to the distribution areas of unconsolidated volcano clastics and undifferencital volcanis (Figure 2-3). This coincidence suggests that there may be a caldera structure under the area of Mt. St. Catherine.



Source: JICA Survey Team

Figure 3-33 The First Horizontal Derivative map

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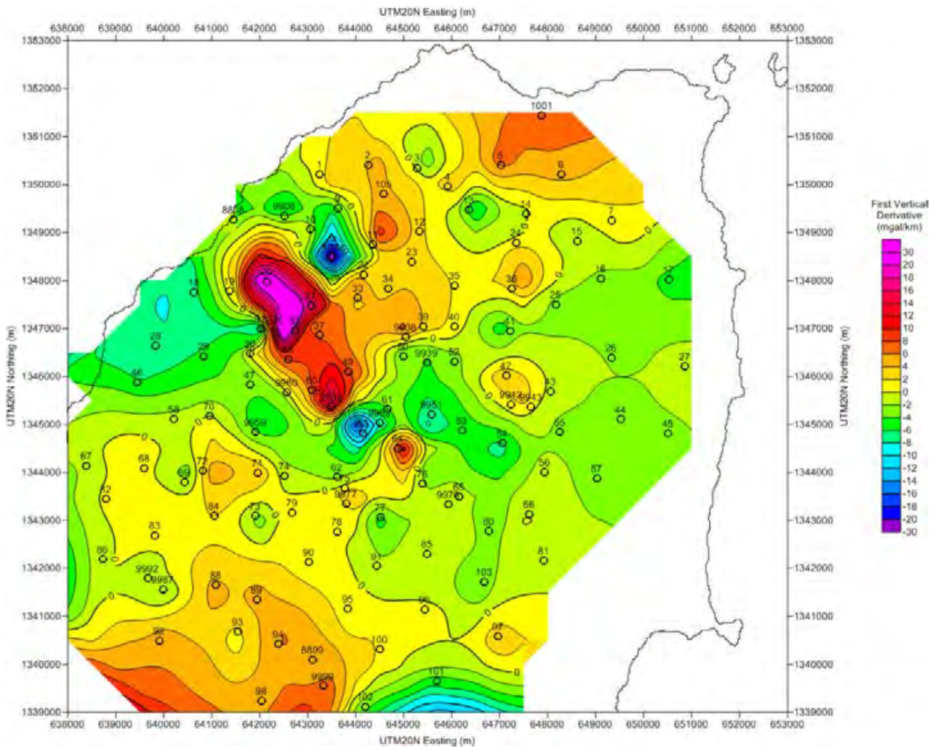
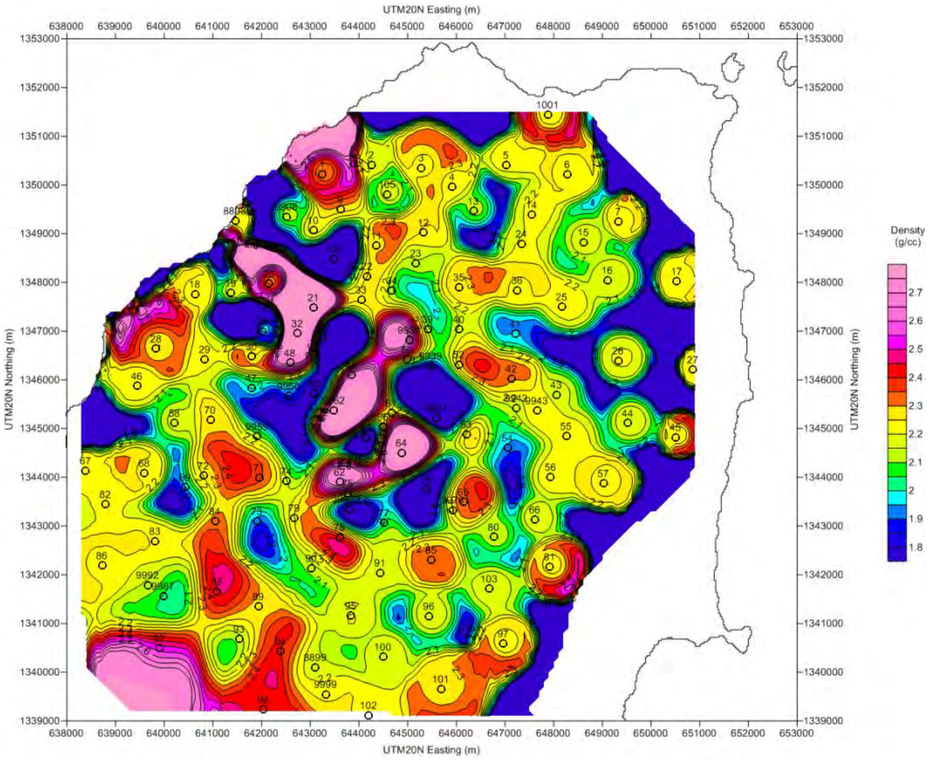
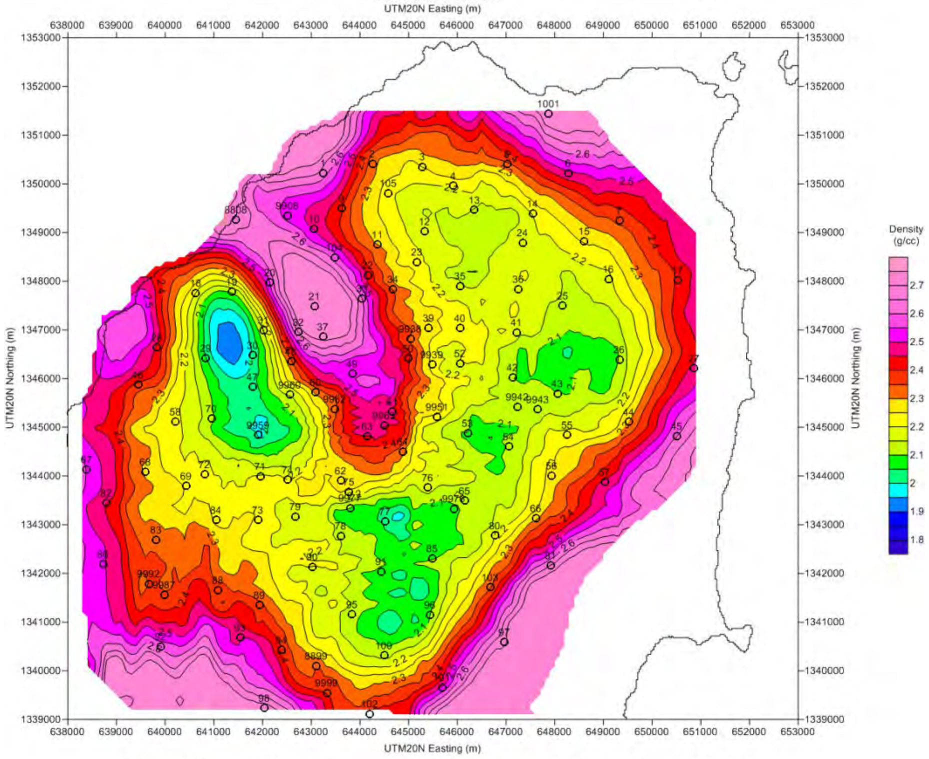


Source: JICA Survey Team

Figure 3-34 The First Vertical Derivative Map



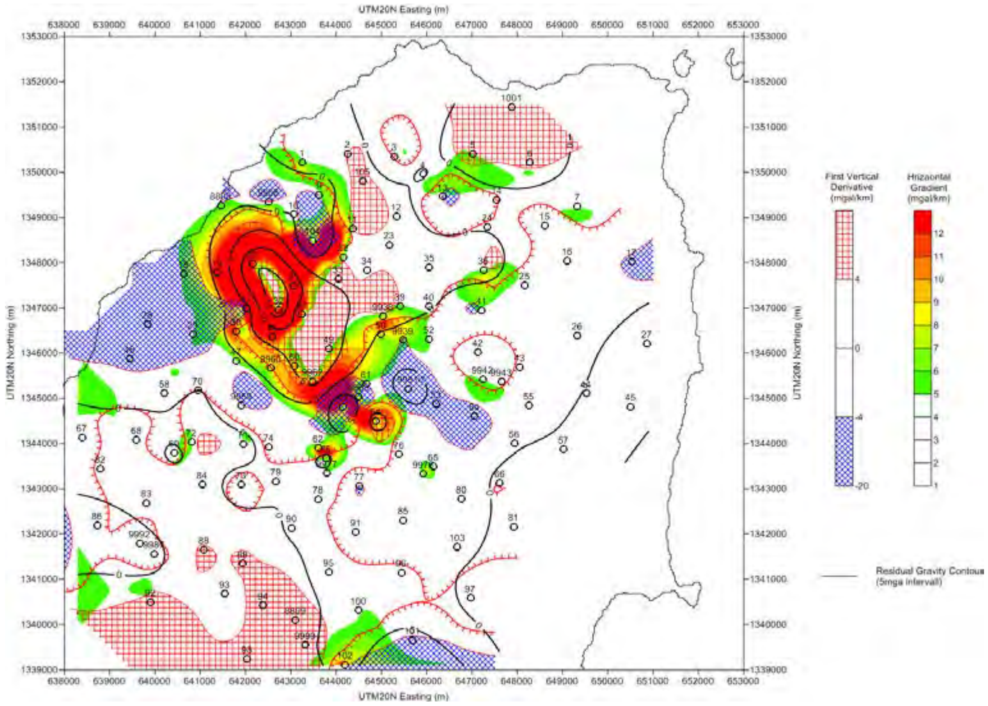
Density Map made from 3D inversion of Residual Gravity (corrected density: 2.2g/cc)
Elevation: 0m SL



Density Map made from 3D inversion of Residual Gravity (corrected density: 2.2g/cc)
Elevation: -2000m SL

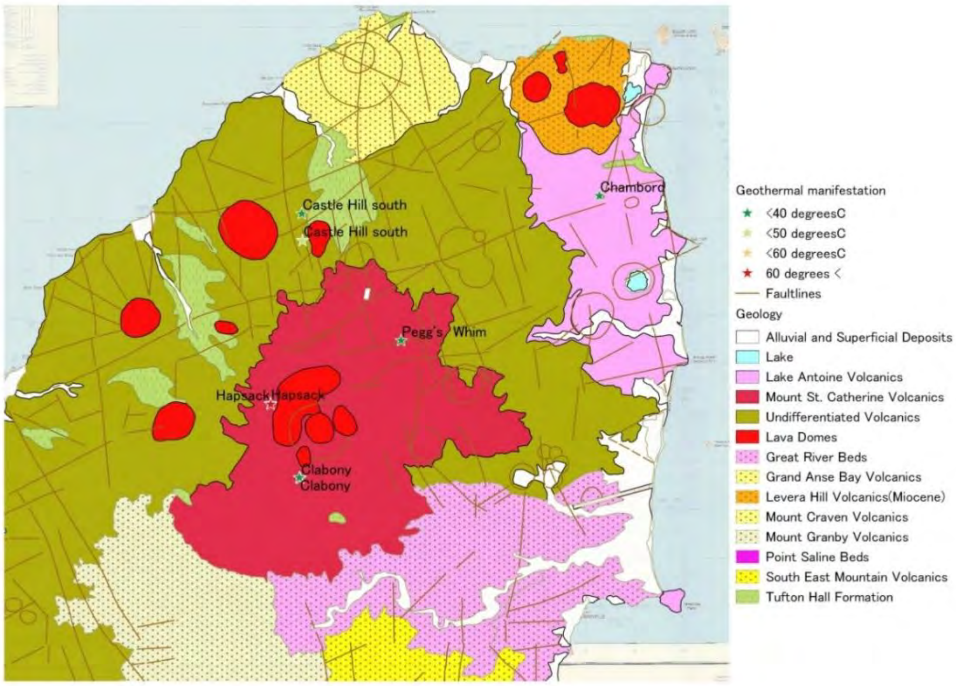
Source: JICA Survey Team

Figure 3-35 Interpreted Density Distribution Underground



Source: JICA Survey Team

Figure 3-36 Overlay of First Horizontal Derivative Map and First Vertical Derivative Map



Source: JICA Survey Team

Figure 3-37 Geological Setting of North Grenada

An overlay map of the first horizontal derivative and first vertical derivative results is shown in Figure 3-36. A geological setting map is shown in Figure 3-37 for comparison. From Hapsack to northeastern Pegg's Whim and Chambord along NE-SW direction, some places where zero contour of the first vertical derivative overlapped the high first horizontal derivative area dotted here. Because lineaments on the ground surface were also found in the same area in NE-SW direction, it can be concluded that faults exist in NE-SW direction. Furthermore, due to the existence of the geothermal manifestation area in the vicinity of the faults, geothermal fluid flowing may be limited in this area.

In addition, the zero contour of first vertical derivative also overlapped the high first horizontal derivative area along St. Marks River between Hapsack and Victoria. Therefore, faults may also exist along St. Marks River. However, because lots of lava domes concentrate between Hapsack and Victoria, it is also possible that it just reflects the density boundary of the intrusive rocks, which may underlie or fills up the volcanic vent underneath lava dome, and the host rock under the ground.

3-3-4 NZ support – Summary of Ground Survey Results

(1) Summary of Survey Content

Results of the ground survey are summarized as below:

1) Geological survey results

- Geological setting of the survey area is composed of, from bottom to top, Tufton Hall Layer formed in late Eocene ~ early Oligocene, volcanic ejecta formed in Miocene ~ Pleistocene, and volcanic ejecta formed in Pleistocene ~ Holocene (Figure 3-3). Volcano Saint Catherine is located in the center of the survey area, and lava domes is formed on the top of this volcano mountain. In northwestern piedmont of Volcano Saint Catherine, volcanic ejecta and Tufton Hall layer are covered by some lava domes.
- It is reported that volcanic activity might have occurred in Volcano Saint Catherine about 1000 years ago (Global volcanic program, 2015). Because geothermal manifestation zones concentrate around the volcano mountain, magma chamber of Volcano Saint Catherine is perhaps the heat source.
- Rocks are undergoing alteration in several geothermal manifestation zones around Volcano Saint Catherine. Among them, sulfur is depositing in Hapsack where silicification alteration occurred. In Peggy's Whim, Castle hill and Clabony, smectite and mixed layer clay mineral are turned into rocks due to alteration process.
- Lineament extracted based on terrain analysis, and geothermal manifestation zones, fold axis, strike of the stratum confirmed by geological reconnaissance concentrate in NE-SW direction. Besides it, lineament is also found in NW-SE, NNW-SSE direction (Jacobs, 2015).

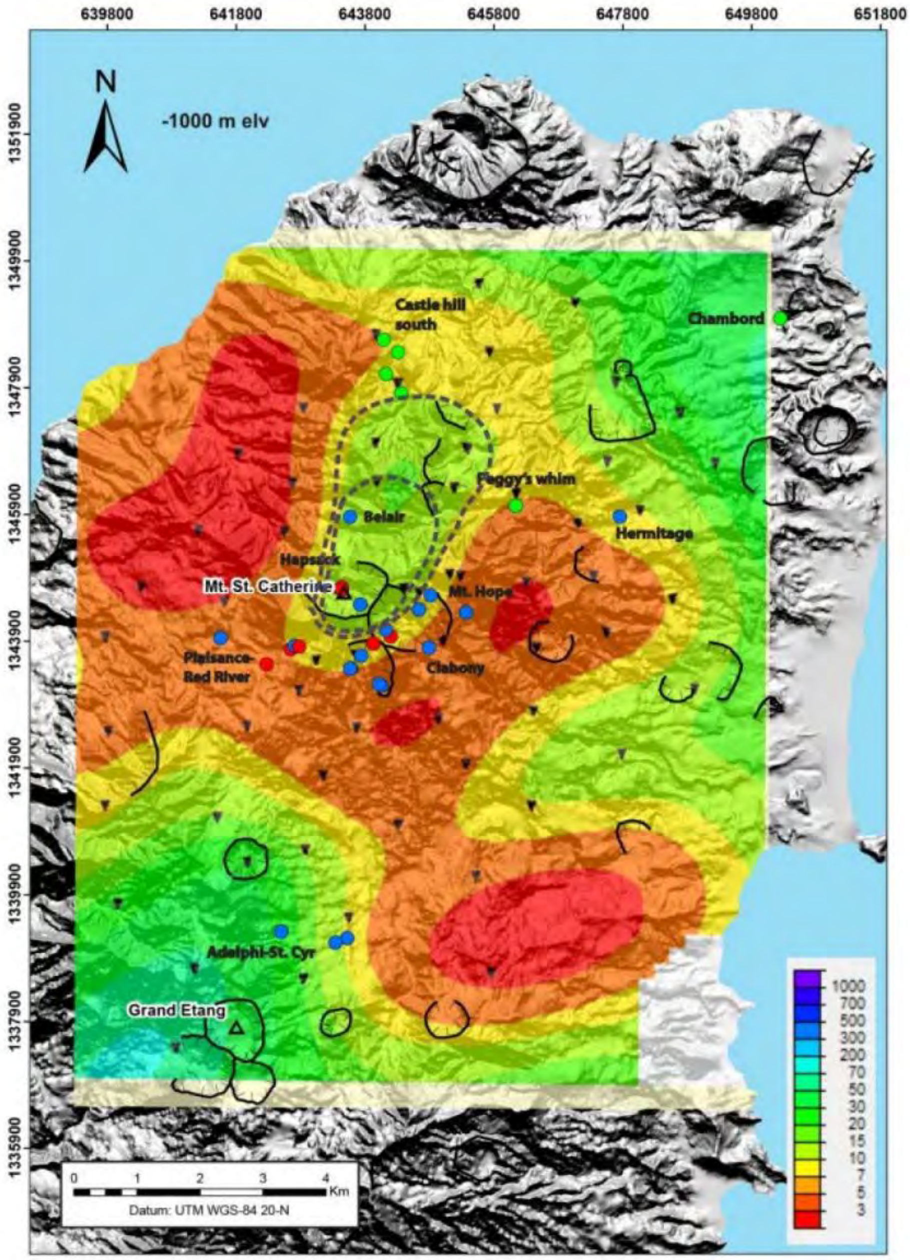
2) Geochemical survey results

- Sampling activity and site measurement (temperature, pH, electric conductivity) has been conducted in Hapsack, Peggy's Whim, Castle hill, Clabony and Chambord around Volcano Saint Catherine. The results showed almost the same analyzed value with the survey conducted by Jacobs (2015). In Hapsack, hot spring with the highest temperature of 61.4 °C was found.
- Hot spring water in Grenada can be divided into 3 types according to pH and cation composition, which are sulfuric acid type hot spring in Hapsack and Plaisance-Red River, neutrality ~ alkalescency Na-Cl type hot spring in Peggy's Whim, Castle hill and Chambord, and bicarbonate type hot spring in Clabony. The gush of all these 3 types hot spring has been confirmed in andesite volcanic regions geothermal system with high temperature.
- Sulfuric acid type hot spring in Hapsack and Plaisance-Red River accompanies with bubbling of H_2S gas. Comparing with other types, this type of hot spring is usually located where is closed to the Volcano Saint Catherine with high elevation.
- Water-rock reaction in the hot spring of Grenada is still in immature stage (Figure 3-25). However, according to plotted diagram of Na-K-Mg components Figure 3-8), the hot spring of Grenada possibly contains some hot water with 220 °C which gushes from geothermal reservoir and has reached equilibrium (immature) stage.
- Among the hot spring of Grenada, some bubble containing spring produce the gas which is confirmed to be contributing to the magma gas (Figure 3-9). The temperature was estimated to be about 290 °C based on gas thermometer (Jacobs, 2015).

3) Geophysical survey results

- As to the spatial distribution of resistivity in survey area, the layer with resistivity under 10 Ω·m is thin for those located in high elevation. The layer becomes thick from thin part towards periphery, and the bottom side of it shows a dome-shaped structure. The surficial geothermal manifestation zones are located in or around the area where low resistivity layer becomes thin. Because smectite and mixed layer clay mineral, which will lower the resistivity, distribute in these geothermal manifestation zones, it is possible that the layer with low resistivity is the rock cap of the geothermal reservoir.
- According to the gravity anomaly distribution of survey area, high gravity anomaly zones above -150 mgal can be found in north part of survey area including Hapsack and Pegg's Whim. Especially, the highest gravity anomaly value (above -136 mgal) was found located between Hapsack and Victoria. Around these zones, a steep gravity slope with sudden changes of Bouguer anomaly value exists (see dense contour part in Figure 3-30), and this slope extends linearly along NE-SW direction in the vicinity of Hapsack and Pegg's Whim.
- From Hapsack to northeastern Pegg's Whim and Chambord along NE-SW direction, some places where 0 contour of First Vertical Derivative overlapped the high First Horizontal Derivative area dotted here. Because lineaments on the ground surface were also found in the same area along NE-SW direction, it can be concluded that faults exist along NE-SW direction with steep slope. Furthermore, due to the

existence of geothermal manifestation area in the vicinity of the faults, geothermal fluid flowing may be limited in this area.

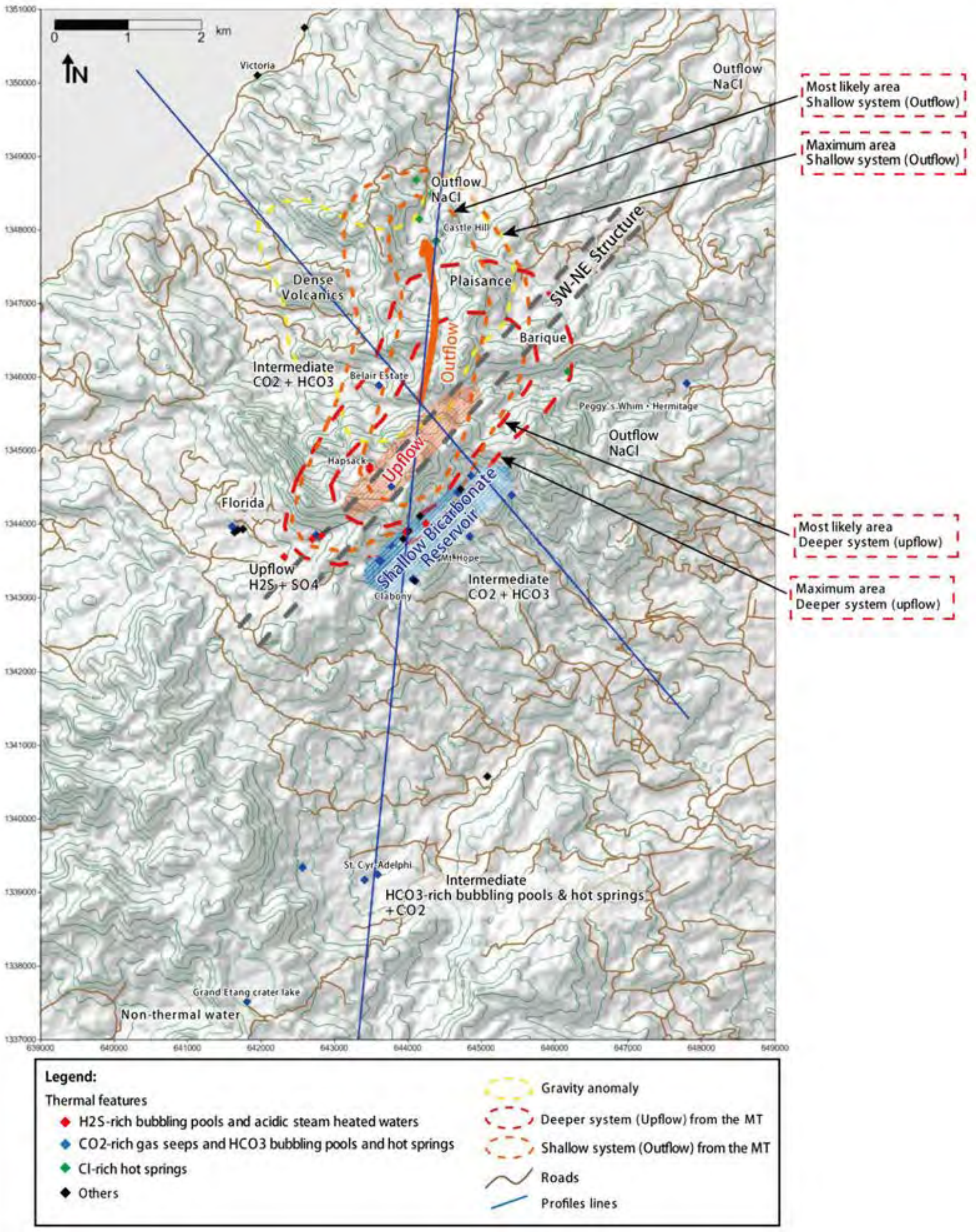


Source: Urzua *et al*., 2015

Figure 3-38 Spatial Distribution of Resistivity based on 3D Analysis (-1000 msl)

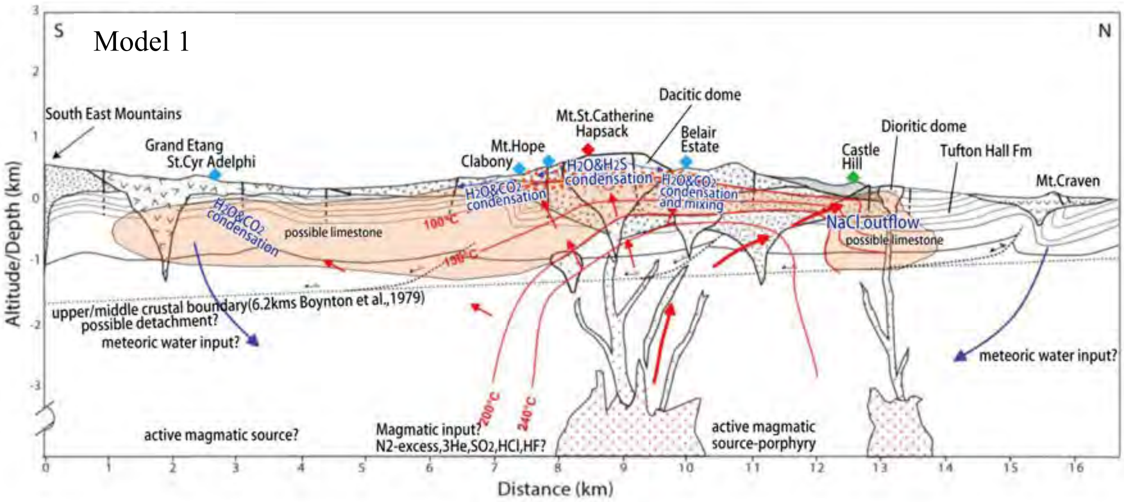
(2) Conceptual Model of Geothermal System and Geothermal Reservoir

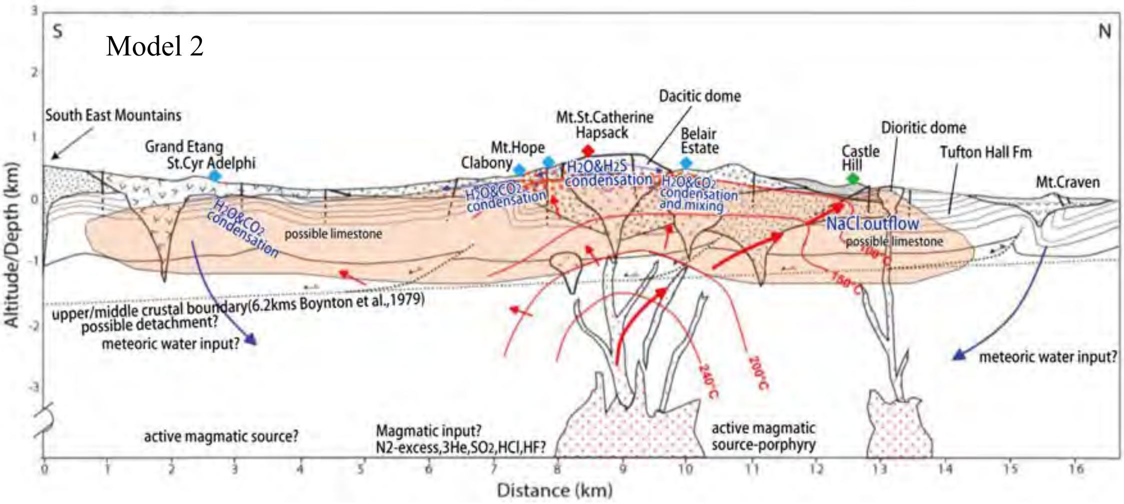
A conceptual model of geothermal system is shown in Figure 3-39 and Figure 3-40.



Source: Jacobs (2016), revised by JICA Survey Team, 2016

Figure 3-39 Estimated area of Geothermal Reservoir





Source: Jacobs (2016), revised by JICA Survey Team, 2016

Figure 3-40 Profile of Estimated Geothermal Reservoirs

*Model 1 is built on the assumption that, according to the geochemical compositions of surface hot spring and distribution of specific resistivity, the geothermal reservoirs with temperature of 200~290°C wildly spread from deep to shallow depth, and the geothermal fluid flows in lateral direction in northern part of the survey area. *Model 2 is built on the assumption that, due to the absence of the fumarolic area with boring spring, the temperature of geothermal reservoirs is perhaps lower than 200°C.

Based on the survey results of Jacobs (2016) together with the supplemental survey by JICA Team, we have proposed the following two models shown in Figure 39 and Figure 40. The reservoir type may be classified to a model of Cl-rich fluid dominant geothermal reservoir, characterized by faults structures, without manifestation of natural fumaroles and boiling hot springs. There may be two different interpretations that have led to the proposed two geothermal reservoir models.

1) Geothermal reservoir Model -1

<Fracture Structures>

- There is a set of major fracture structures extending NE – SW directions near Mt. St. Catherine (Figure 3-39). These fractures may be zones of upflow of the inferred geothermal reservoir.
- There is a set of minor fracture structures extending NW – SE directions in the northern side of Mt. St. Catherine

<Geothermal Fluid>

- Acid-sulfuric hot springs locate in the area near the summit of Mt. St. Catherine (Hapsack, Plaisance-Red River), whereas neutral chloride rich hot springs locate in the northern flank of the Mt. St. Catherine (Castle Hill South、Chambord and Peggy's Whim).
- The acid-sulfuric hot springs are produced from groundwater that are heated and/or reacted by steam and gases (CO_2 and/or H_2S) that are separated from the geothermal fluid and coming up to the area near the summit of the Mt. St. Catherine (up flow zone). However, owing to a plenty amount of groundwater supplemented by rainfall, the steam and gas may have condensed before manifesting as boiling hot water with fumaroles on the ground.
- On the other hand, the neutral chloride rich hot springs observed in the northern flank of the Mt. St. Catherine may be the results of deep side flow of the geothermal fluid being diluted by groundwater. Chloride rich hot springs are a good indication of a geothermal fluid dominant reservoir with high enthalpy.
- Surrounding areas of Mt. St. Catherine may be recharging areas of groundwater by meteoric water through faults and fractures.

<Temperature>

- The temperature at the bottom of iso-resistivity line of 10 Ωm may correspond to 200ºC or more based on the geo-thermometer, the resistivity contour map and the clay alteration analysis,
- The reservoir temperature may range from 200 ºC to 290 ºC based on geothermal manifestations, geo-thermometers of hot springs and fumaroles collected.

<Geothermal Reservoir>

- The locations and elevations of the acid-sulfuric hot springs and neutral chloride hot springs suggest that the side flow of the neutral chloride may take place at shallower zones; thus the geothermal reservoir may be not deeper than about 1,000 m below the sea level, based on field experiences in NZ.
- Approximate areal size of the geothermal reservoir may range from 4 to 8 km^2 based on the distribution of the geothermal manifestation and resistivity.

2) Geothermal reservoir Model -2

<Fracture Structures>

- Same as the ones of Model-1

<Geothermal Fluid>

- Same as the case of the Model-1, the area of the acid-sulfuric hot springs may be the upflow zone, and the neutral chloride rich hot springs may be resulted from the side flow of the geothermal fluid up flowing in the area near the summit of Mt. St, Catherine.
- Contrary to the Model-1, however, the reason why the geothermal manifestations are not observed may attribute to the deeper geothermal reservoir due to possible thicker cap rock than the case of Model-1. Steam and/or gas may condense while traveling through the thick cap rock.
- Similar to the explanation right above, the geothermal side flow may have cooled down while traveling through the thick cap rock and manifesting in the flanks of the Mr. St. Catherine.
- Same as the case of the Model-1, surrounding areas of Mt. St. Catherine will be recharging areas of groundwater by precipitations through faults and fractures.

<Temperature>

- Similar to the Model-1, the reservoir temperature may range from 200 ºC to 290 ºC based on geothermal manifestations, geo-thermometers of hot springs and fumaroles collected.
- However, the geothermal reservoir may be located deeper ground than the case of Model-1 because no fumaroles with boiling water are observed that are usually associated with high enthalpy geothermal prospects.

< Geothermal Reservoir>

- Based on the experiences in NZ, the geothermal reservoir may exist below 1,500 deep or more for geothermal prospects where no manifestations are observed on the ground.

(3) Geothermal Reservoir Assessment

Huttrer and Michels (1993) assessed the geothermal reservoir (about 200 °C) around Volcano Saint Catherine at 30~50MW.

Based on the results of the present geothermal surface survey, the geothermal reservoir may have a development potential ranging from 20 to 95 MW.

【Assessment by Volumetric Method (improved calculation method)】

The JICA Team conducted a geothermal reservoir assessment by the volumetric method. The calculation method used was improved to include the following specific plant conditions in order to exclude ambiguities included in the existing calculations methods. The explanation of the methodology is given in the article included in the attachments.

- Plant type: Flush- condensing type
- Separator temperature: 151.8 °C
- Condenser temperature: 40 °C
- Exergy efficiency: 0.77 ±0.05 （for the above two temperature condition）

The calculation results are shown in the Table 3-10, the parameters used in the calculation are given in the Table 3-11. Table 3-10 shows that the calculated resource of Model-2 is in a similar range to the ones (20 – 95 MW) estimated by Jacobs above, whereas the calculated resource of Model-1 is larger than the estimation of Jacobs (2015, 2016).

Table 3-11 Resource Assessment by Volumetric Method (Improved Calculation Method)

Occurrence probability	80%	Mode	20%
Model-1	30 MW	53 MW	121 MW
Model-2	21 MW	39 MW	87 MW

Source: JICA Survey Team

Table 3-12 Parameters Used for Volumetric Resource Assessment

Parameters			Unit	Min	Mode	Max	Distribution	Note
Size of Area		A	km^2	4	6	8	triangle	
Thickness	Model-1	d	m	-	1500	-	fixed	Depth: 1000-2500 m
	Model-2	d	m	-	1000	-		Depth: 1500 -2500 m
Reservoir temperature		t_r	℃	200	245	290	triangle	
Rock density		ρ_r	kg/m^3	-	2600	-	fixed	
Rock volumetric specific heat		C_r	kJ/kg	-	1	-	fixed	
Fluid volumetric density		ρ_f	kg/m^3	-	950	-	fixed	
Fluid specific heat		C_f	kJ/kg	-	5	-	fixed	
Porosity		φ	%	5	-	10	uniform	
Recovery factor		R_g	%	3		17	uniform	
Separator temperature		t_{sp}	ºC	-	151.8	-	fixed	
Condenser temperature		t_{cd}	ºC	-	40	-	fixed	
Exergy efficiency		η_{ex}	%	72	77	82	triangle	t_{sp}=151.8 ºC, t_{cd}40ºC
Plant factor		F	%	-	96	-	fixed	
Plant life		L	year	-	25	-	fixed	

Source: JICA Survey Team

This assessment was made based on the information of surface survey only, thus and as a matter of course, this assessment has to be re-assessed when direct information should be made available from test well drilling.

References

Huttrer, G., W. and Michels, D., E. (1993) Final report regarding prefeasibility studies of the potential for development in Grenada. W., I.: Prepared under geothermal mgmt. Co. Inc., Frisco Colo., submitted to national geothermal association, march, 73pp.

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3-3-5 Exploratory Drilling Plan

(1) Proposal for Drilling Slim-Holes

The results of previous researches and the JICA survey suggest that geothermal reservoir may exist in North Grenada and piedmont regions of Mount St. Catherine. However, there are three uncertainties to be clarified as mentioned below (Urzua *et al.*, 2015):

- Geothermal reservoir temperature: Temperature of the reservoir was estimated to be approximately 200~290°C according to the geochemical composition of surface hot spring and the specific resistivity distribution. Absence of the boiling spring, however, implies that the reservoirs temperature may be lower (under 200°C) than estimation.

- Permeability: a geothermal reservoir in volcanic zone usually exists inside volcanic rocks and/or volcano-clastic rocks, which usually have high permeability. In the case of Grenada, however, the geothermal reservoir of Grenada may exist in Tufton Hall formation that consist of such sedimentary rocks such shale, silt rock and maar, and perhaps limestone underlain. Since those sedimentary layers may have lower permeability, it is still uncertain that good geothermal reservoir that produce sufficient geothermal fluid should be available in Tufton Hall formation.

- Reservoir sized: Reservoir size has been roughly estimated based on the distribution geothermal manifestation and the zones with low resistivity, especially these with resistivity under 10 Ω·m, because low resistivity is usually induced by the existence of clay minerals (the cap rock) created by geothermal hot water alteration. However, since Tufton Hall formation contains native clay minerals (such as smectite), the estimated reservoir size (Model-1) may be larger than actual size.

Under such situations above, we would recommend to provide slim-hole structural boring wells with smaller diameter but sufficiently larger for temperature/pressure well logging, before providing production wells with full specifications. This is to be provided to confirm the availability of the geothermal reservoir at a lower cost before investing relatively larger cost for production wells.

(2) Selection of Drilling Sites

There are seven sites (A – G sites in Figure 3-41) identified where drilling work space may be made available from topographical point of view. Among those, three sites (C, D and F) have been selected since large scale civil works may not be necessary for bringing a drilling rig to the three sites (refer to the section 3-3-6). While the drilling plans are proposed for the three sites, a location on the geothermal upflow zone was selected for an alternative consideration since the three sites are located on the marginal area of the geothermal upflow zone (Figure 3-41). The following sections describe the examination results about the drilling location from the following three points of view.

① Drilling plan-1: Vertical drilling from an area of the upflow zone, ② Drilling plan-2: Vertical drilling from C, D and F sites

③ Drilling plan-3: Directional drilling from C, D and F sites

As the results of the examination, we recommend the drilling plan-2 for the proposed slim-hole drilling.

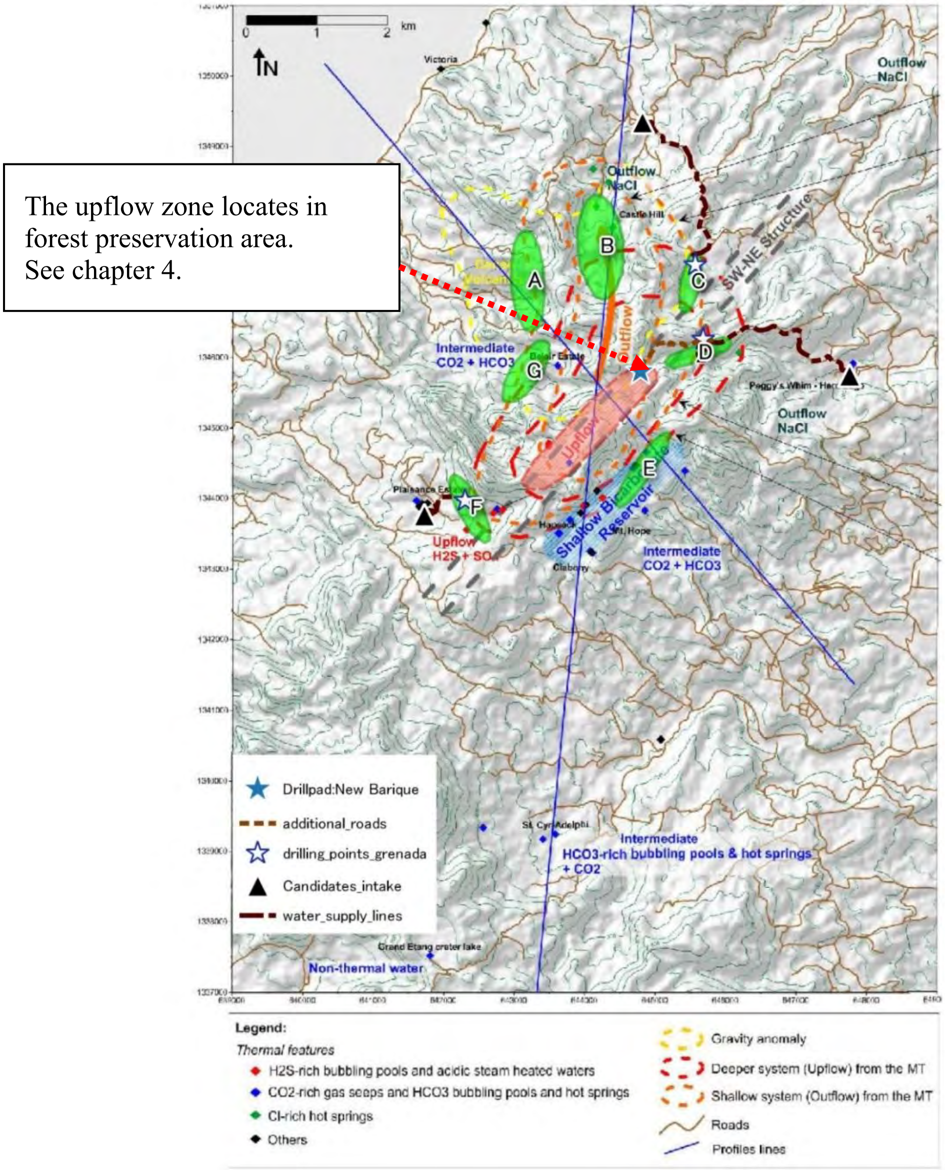
< Drilling plan -1 : Vertical drilling from an area of the upflow zone>

A location was select in the area of the upflow zone for this alternative from the accessibility point of view. The site is located about 1.5 km southwest from the D site (Bariquez). However, this site may not be recommended from the following reasons.

- The upflow zone is located in the forest protected zone designated (Figure 3-60).
- There is only a tracking access road to the site from Bariquez, and therefore a large scale civil works may be required to bring a drilling rig.
- As experienced, Grenadian are keen to protect natural environment.
- It will not be easy to obtain the consensus from Grenadian for such drilling works together with a large scale civil works.
- Thus, this site may not be suitable for a slim hole drilling.

<Drilling Plan-2: Vertical Drilling from the Sites C, D and F>

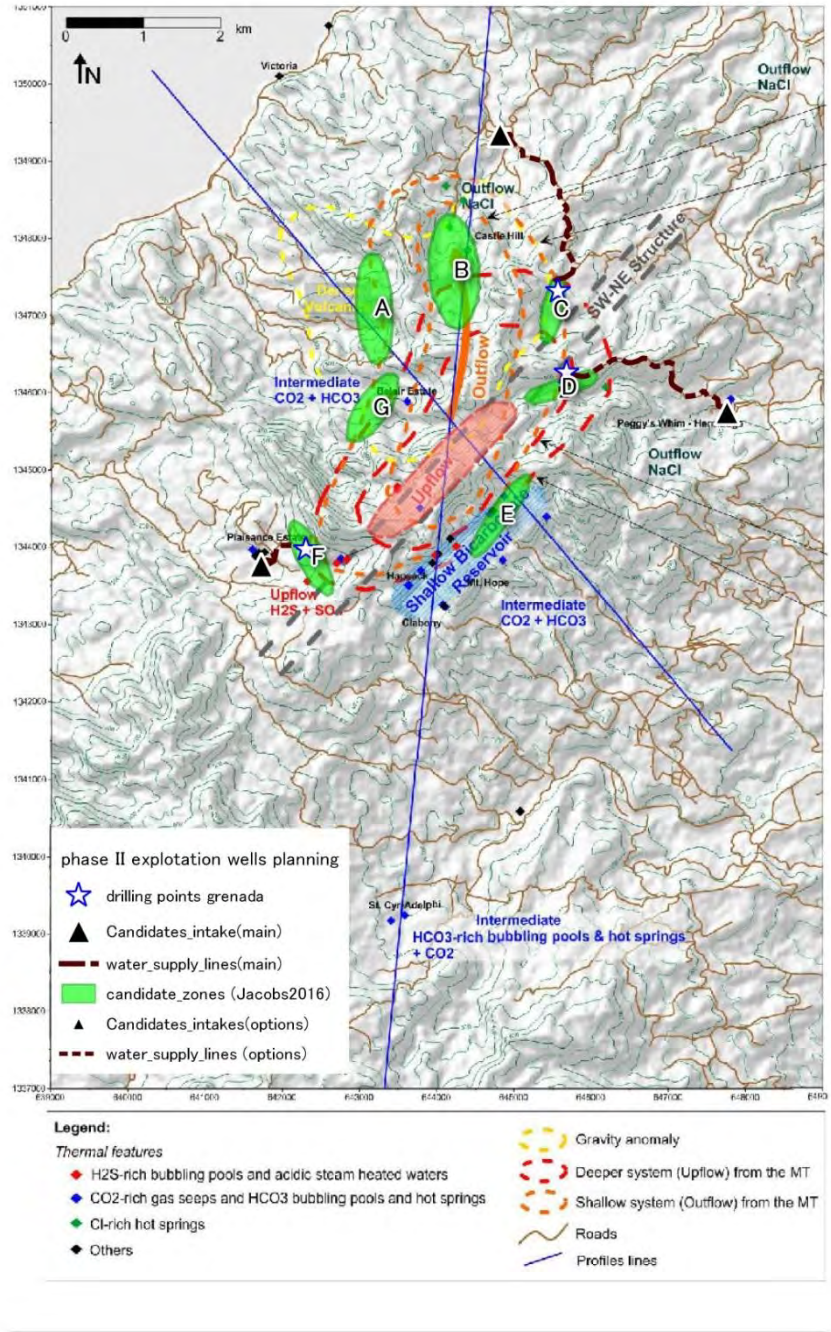
The sites C, D and F are relatively suitable for the rig transportation and drilling works compared to the other sites (refer to the section 3-3-6). The drilling sites are shown in Figure 3-42, and the drilling targets in the geothermal models 1 and 2 are shown in the Figure 3-43. A 2,000 m depth is assumed to reach the geothermal reservoir even in the Model-2 thereby information of geology, fracture, temperature and pressure distribution, and so on will be made available. A track mounted, relatively small size of drilling rig can attain the vertical 2,000 m drilling. Table 3-10 shows the targets to be drilled by the slim holes from the sites C, D and F.



Source: JICA Survey Team on Jacobs(2016) base figure

Figure 3-41 Drilling plan -1 : Vertical Drilling from Area of Upflow Zone

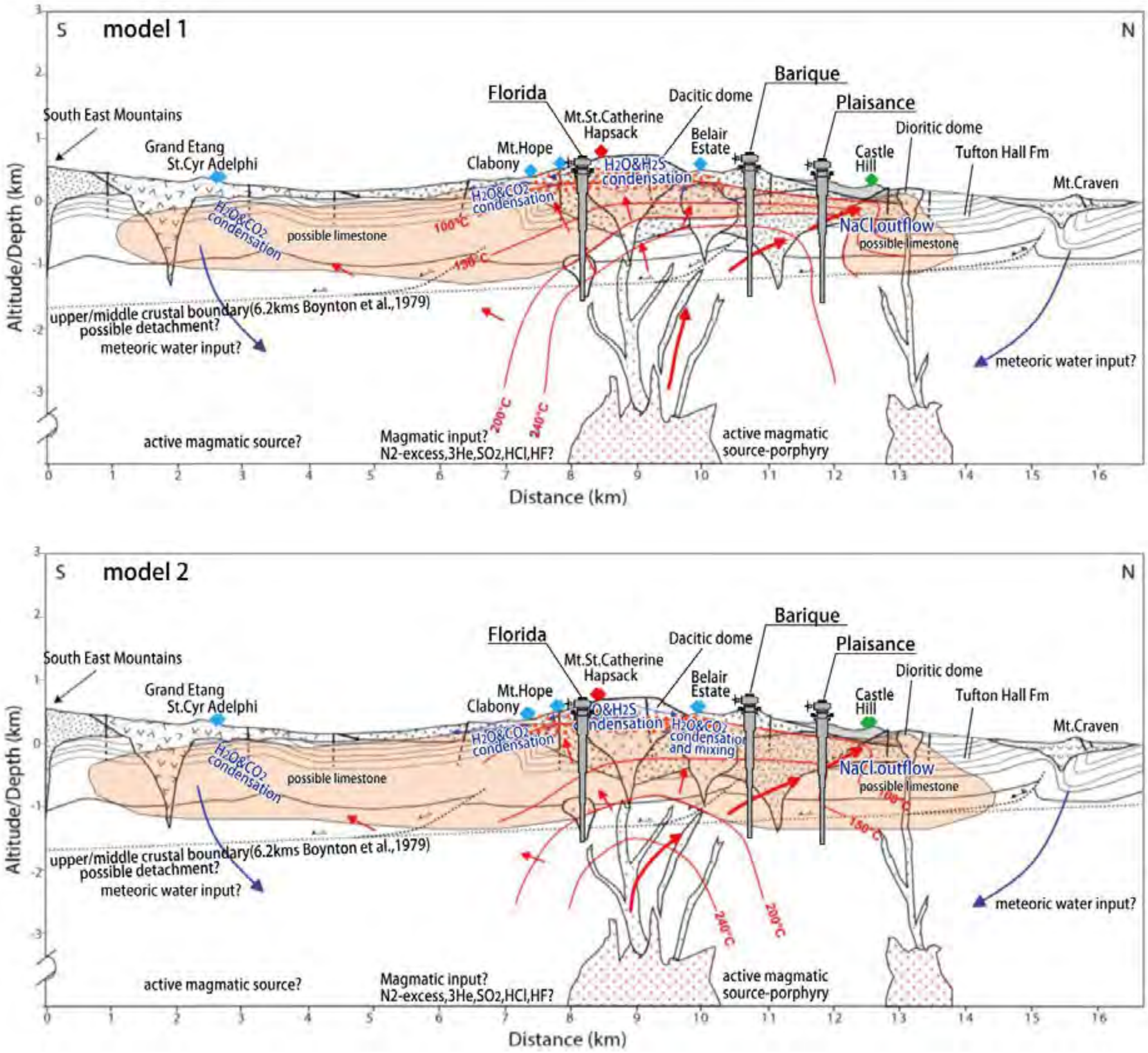
The site is in the forest protection zone. The hurdle to obtain a consensus is high.



Source: JICA Survey Team on Jacobs(2016) base figure

Figure 3-42 Drilling Plan-2：Vertical Drilling from Sites C、D、F

C:Plaisance、D:Barique、F:Florida



Source: JICA Survey Team on Jacobs(2016) base figure

Figure 3-43 Drilling Plan-2 Drilling Targets

＊C:Plaisance、D:Barique、F:Florida

A drilling depth of 2000 m is proposed on the assumption that the cap rock would be thick as considered in the Model-2.

Table 3-13 Targets for Slim Holes Proposed

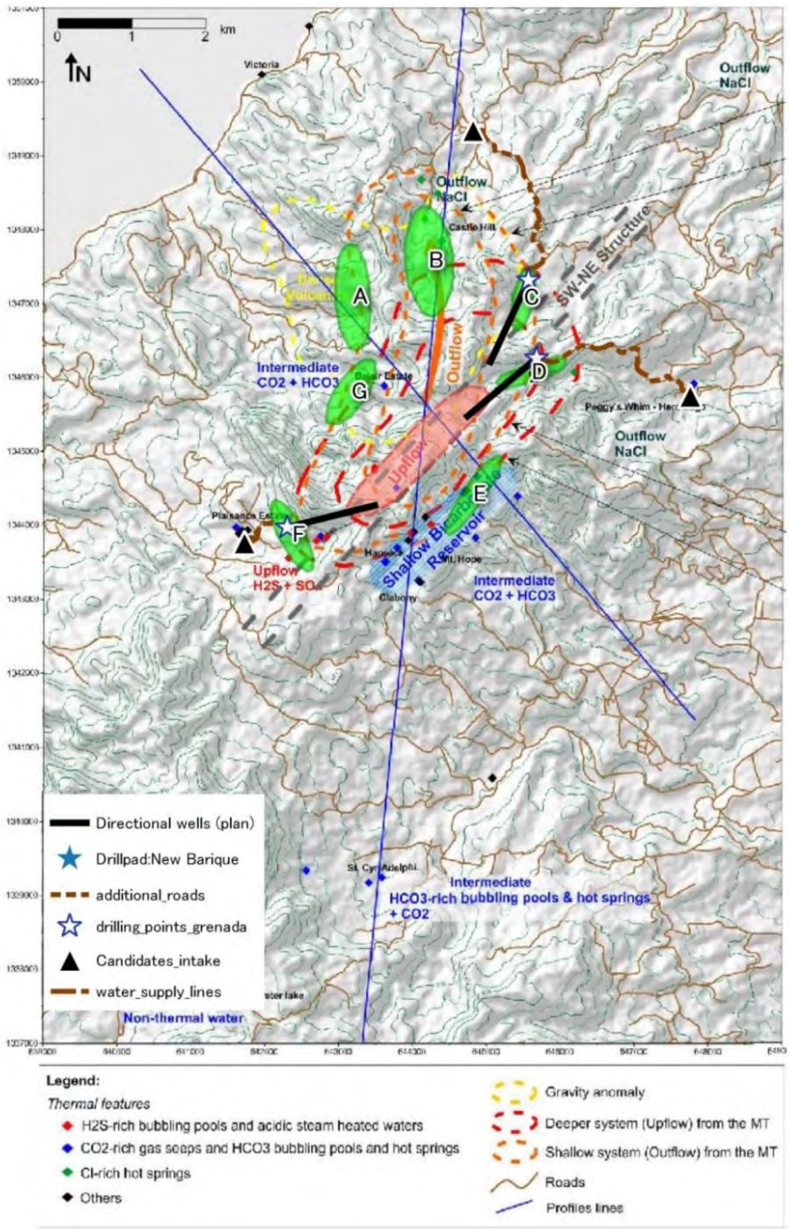
		Plaisance	Barique	Florida
Well location	x	645567	645677	642305
	y	1347313	1346258	1343971
Wellhead Elevation(above sea level)	meter (feet)	366 (1200)	469 (1540)	408 (1340)
Drilling Depth	meter (feet)	2,000 (6561)	2,000 (6561)	2,000 (6561)
Inclination		vertical	vertical	vertical
Target Depth	meter (feet)	1,900 (4634)	1,900 (4634)	1,900 (4634)
Purpose		1) Data collection: Temperature, Geology, Fracture distribution (evaluation of SW-NE structure) 2) Improvement of geothermal model 3) Drilling plan of appraisal wells	1) Data collection: Temperature ,Geology, Fracture distribution (evaluation of SW-NE structure) 2) Improvement of geothermal model 3) Drilling plan of appraisal wells	1) Data collection: Temperature ,Geology, Fracture distribution (evaluation of SW-NE structure) 2) Improvement of geothermal model 3) 3)Drilling plan of appraisal wells

Source: JICA Survey Team

<Drilling Plan-3: Directional hole from the sites C, D and F>

Possibilities of the directional wells from the sites C,D and F are examine. The wells are designed to reach the upflow zone (Figure 3-44, 3-45).

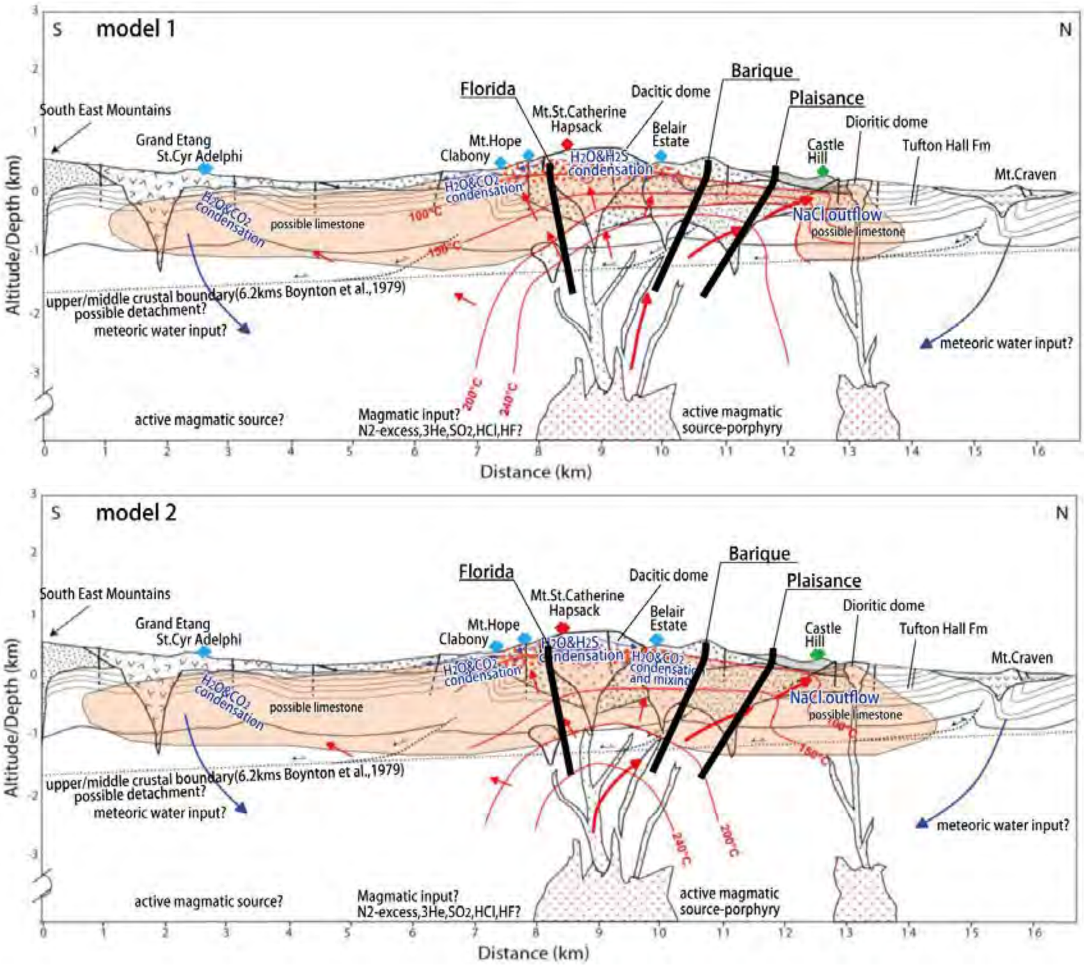
Deviation to the target will be 1.0 km from Barque and Florida site. The drilling depth will be 2,200 m – 2,300 m when directionally drilled with the allowable largest drilling angle of 40 degrees. The total drilling length will be much larger when drilled from Plaisance located about 1.7 km from the targets. To drill this length of directional holes, a more capable rig that could drill 3000 m – 4000 m vertical holes rather than a track mounted small drilling rig. To use such a more capable (powerful) drilling rig will cost much and will be beyond the basic consideration to provide the slim holes.



Source: JICA Survey Team on Jacobs(2016) base figure

Figure 3-44 Drilling Plan: Directional Wells from Sites C, D and F to Upflow Zone

C:Plaisance, D:Barique, F:Florida



Source: JICA Survey Team on Jacobs(2016) base figure

＊C:Plaisance, D:Barique, F:Florida

> The proposed directional holes need about 2,200 – 2,300 m length from Barique and Florida. The total length from Plaosance will be much longer than those. A powerful rig rather than a small track mounted rig will be necessary for this scale of drilling, which may be beyond the scope of the slim holes proposed.

Figure 3-45 Drilling Plan-3: Directional Wells from Sites C, D and F to Upflow Zone

(3) Drilling Plan

1) Casing Program for the slim holes

The requirment of the casing shall be as follows:

a) The diameter shall be large enough but minimum for the temperature – pressure well logging to be conducted,

b) The holes shall be vertical,

c) The materials of casing and well head assembly shall be durable against geothermal fluid with high presseure, high temperature and highly corrosive characteristics.

There are two types of drilling rigs available for slim hole drilling: one is the rotary type drilling rig and the other is spindle type drilling rig. The casing programs consist of conductor pipe, surface casing, production casiong and slotted liner. Depths of each casing varys depening on the rig types and the geological conditions infered from te available infromation. Propsed casing programs are summirized in Table 3.14 and shown in Figure 3-46 and Figure 3-47.

Table 3-14 Summary of Proposed Casing Program

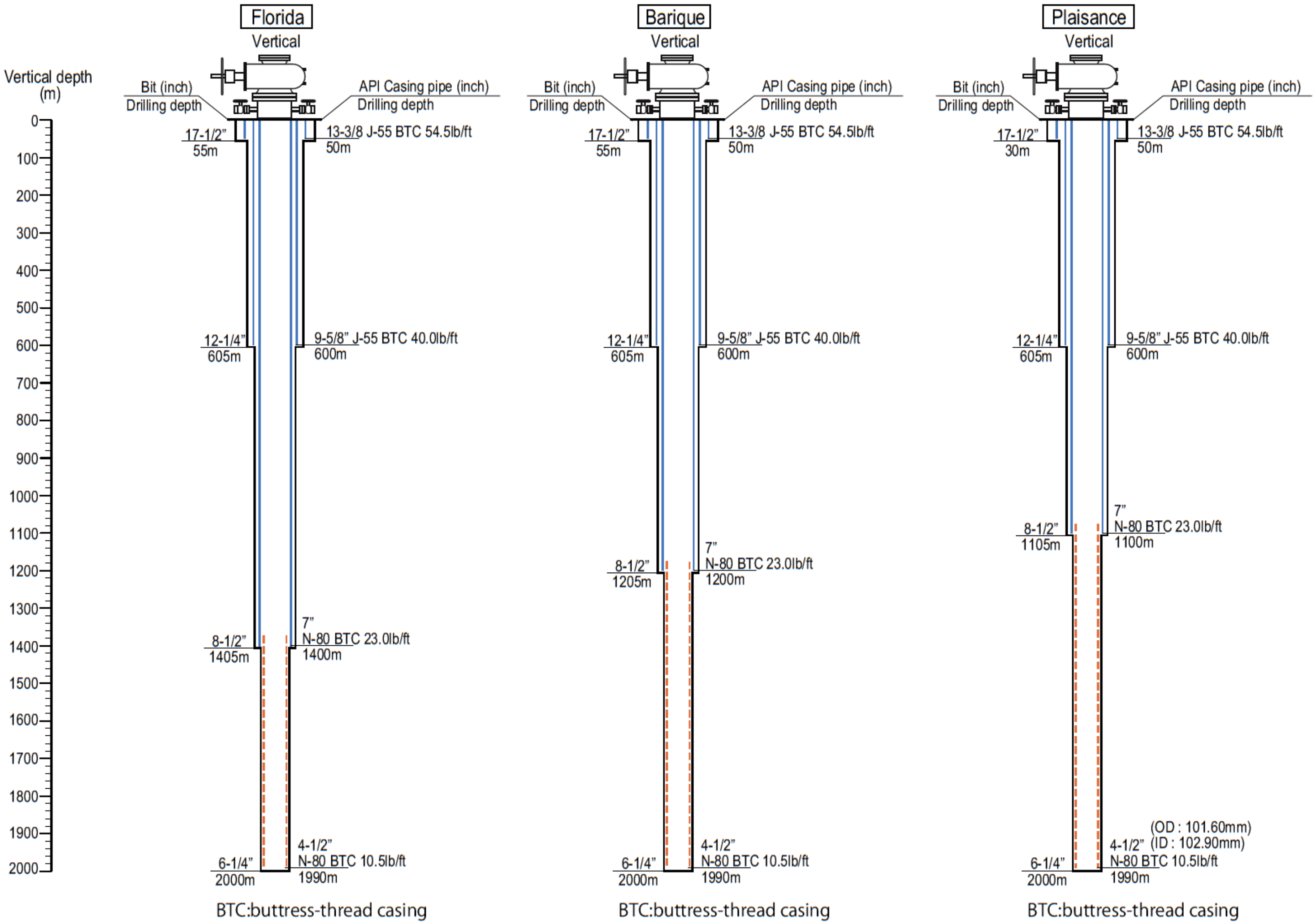
<table>
<tr><th colspan="12">Casing Programm</th></tr>
<tr><th colspan="6">Rotary type
(6-1/2 tricon-bit to the bottom)</th><th colspan="6">Spindle type
(wire-line cored, HQ-diamond bid to the bottom)</th></tr>
<tr><th rowspan="2">name</th><th rowspan="2">Dia
(nominal)</th><th colspan="3">Depth (m)</th><th rowspan="2">name</th><th rowspan="2">Dia
(nominal)</th><th colspan="3">Depth (m)</th></tr>
<tr><th>Florida</th><th>Barique</th><th>Plaisance</th><th>Florida</th><th>Barique</th><th>Plaisance</th></tr>
<tr><td>C/P</td><td>13-3/8”</td><td>50</td><td>50</td><td>50</td><td>C/P</td><td>350A</td><td>30</td><td>30</td><td>30</td></tr>
<tr><td rowspan="2">S/C</td><td rowspan="2">9-5/8”</td><td rowspan="2">600</td><td rowspan="2">600</td><td rowspan="2">600</td><td>S/C</td><td>9-5/8”</td><td>300</td><td>300</td><td>300</td></tr>
<tr><td>I/C</td><td>7.0”</td><td>900</td><td>800</td><td>700</td></tr>
<tr><td>P/C</td><td>N-80</td><td>1400</td><td>1200</td><td>1100</td><td>P/C</td><td>4-1/2”</td><td>1400</td><td>1200</td><td>1100</td></tr>
<tr><td>S/L</td><td>4-1/2”</td><td>1990</td><td>1990</td><td>1990</td><td>S/L</td><td>80A</td><td>2000</td><td>2000</td><td>2000</td></tr>
<tr><td colspan="10">C/P: Conductor pipe, S/C: Surface casing, I/C: Intermidiate casing, P/C: production casing, S/L: Slotted liner
Casing shall be of API standard.</td></tr>
</table>

Source: JICA Survey Team

Basic principles of the proposed casing progrma are as follows:

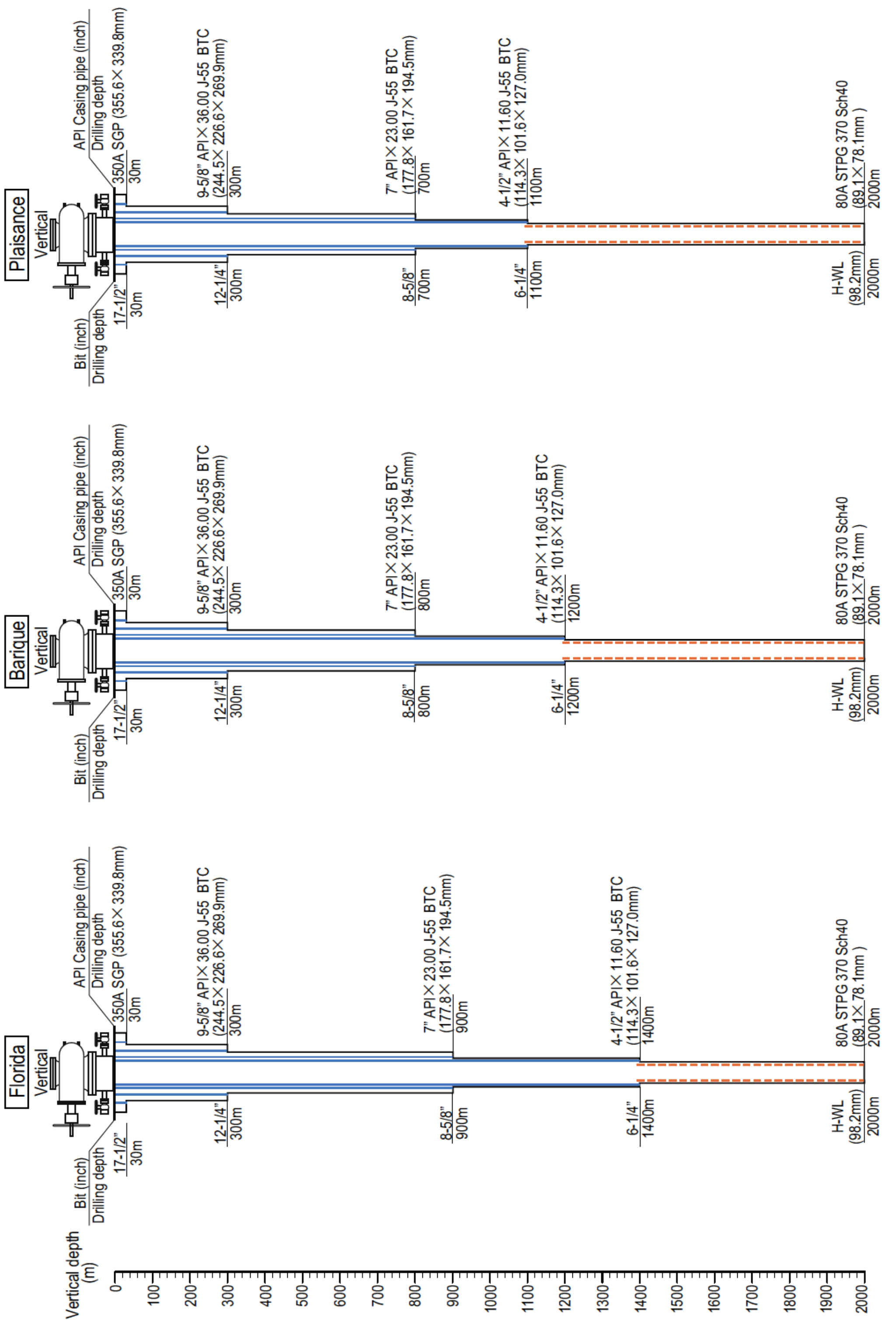
- Production casing is to be installled to the bottom of the cap rock, thereafter slotted line to be installed,
- For the rotaly type drilling rig,
  - Conductor pipe is to be installed to 50 m deep and Surface casing to 600 m deep,
- For spindle tyoe drilling rig,
  - Conductor pipe is to be installed to 30 m deep, Surface casing to 300 m deep, and Intermediate casing to a depth inbetween surface casing and intermidiate casing.

Both types of drilling rig are applicable for the slim hole drilling proposed. The key points of selection of the rig type may be the availability of the rig in neighbouring counries and the transpotability and/or workability of the rig in sites to be selected.



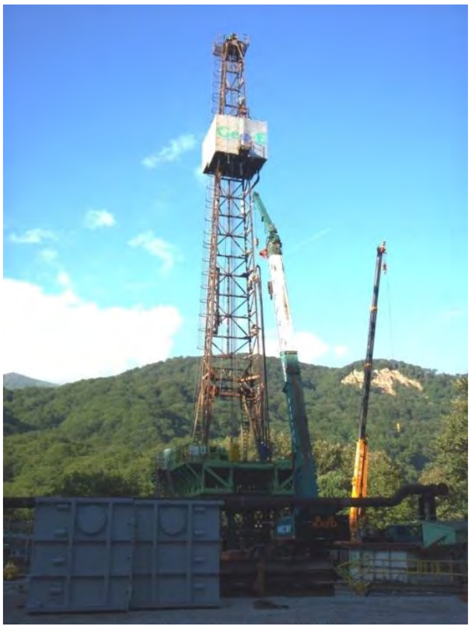
Source: JICA Survey Team

Figure 3-46 Proposed Casing Program for Rotary Table Type Drilling Rig



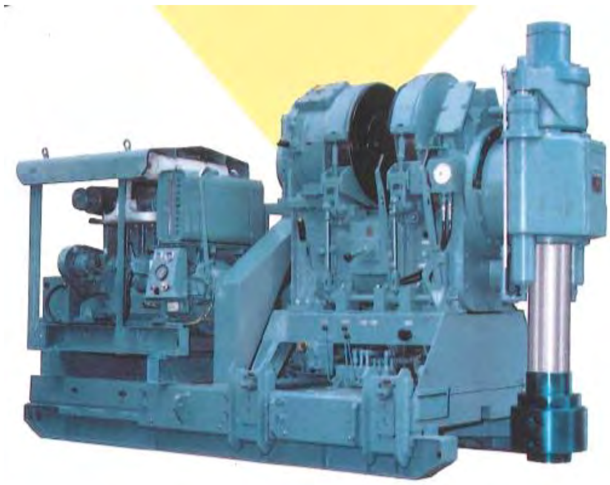
Source: JICA Survey Team

Figure 3-47 Proposed Casing Program for Spindle Type drilling rig



Source: JICA Survey Team

Figure 3-48 Rotary Table Type Drilling Rig



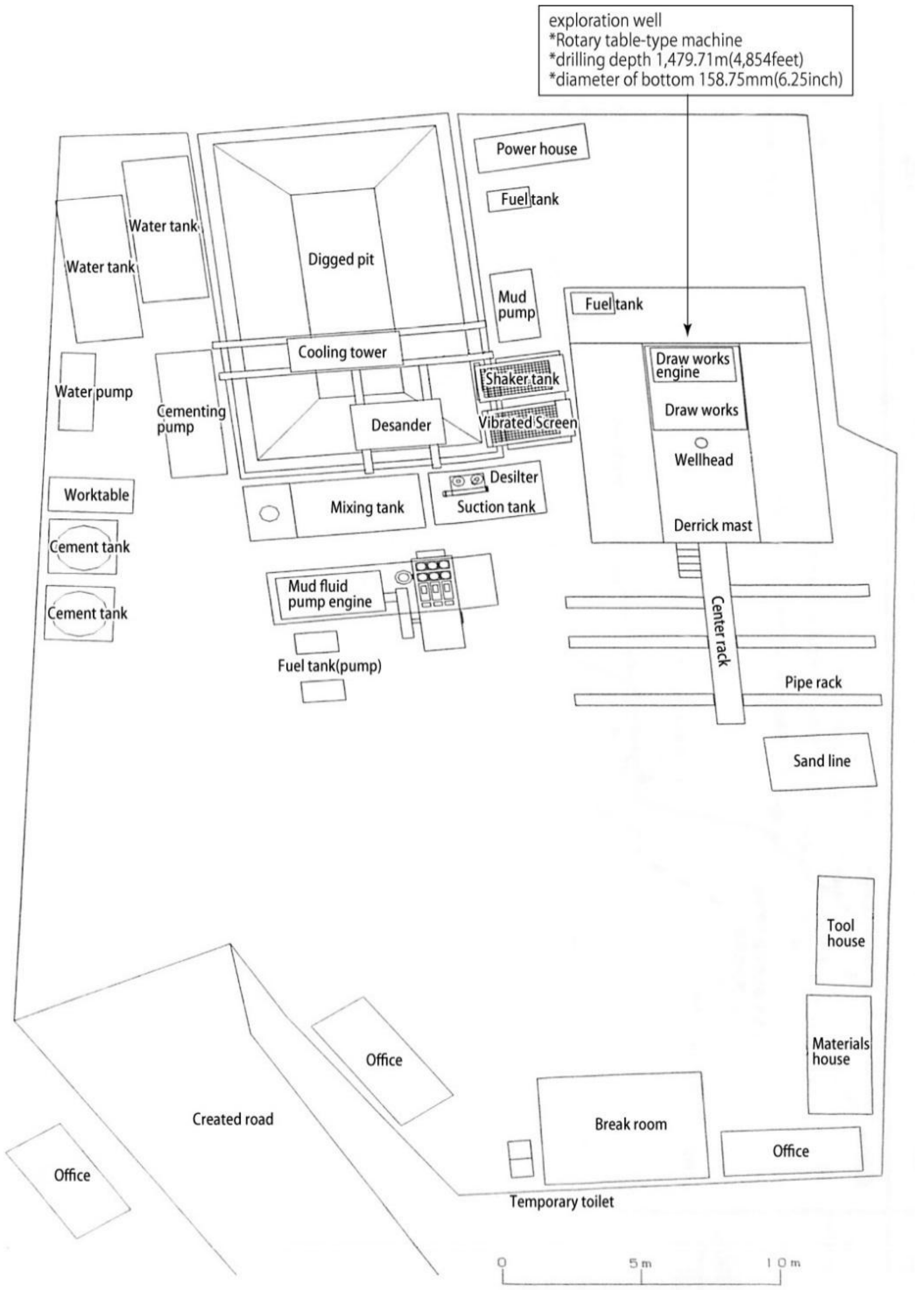
Source: JICA Survey Team

Figure 3-49 Spindle Type Drilling Rig

2) Drilling site of the structural boring wells

The construction of structural boring wells drilling with slim-hole needs, if thinking about the work efficiency, at least 2,000m^3 (about 40×50m) for depositing drilling equipment. In case of using rotary table type rig, it needs more space for setting water supply pit (about 12m×12m×1m ≈ 150m^3 is needed, equivalent 5 times volume of the biggest well). Moreover, it will be more efficient if a space for construction material temporary placing can be considered.

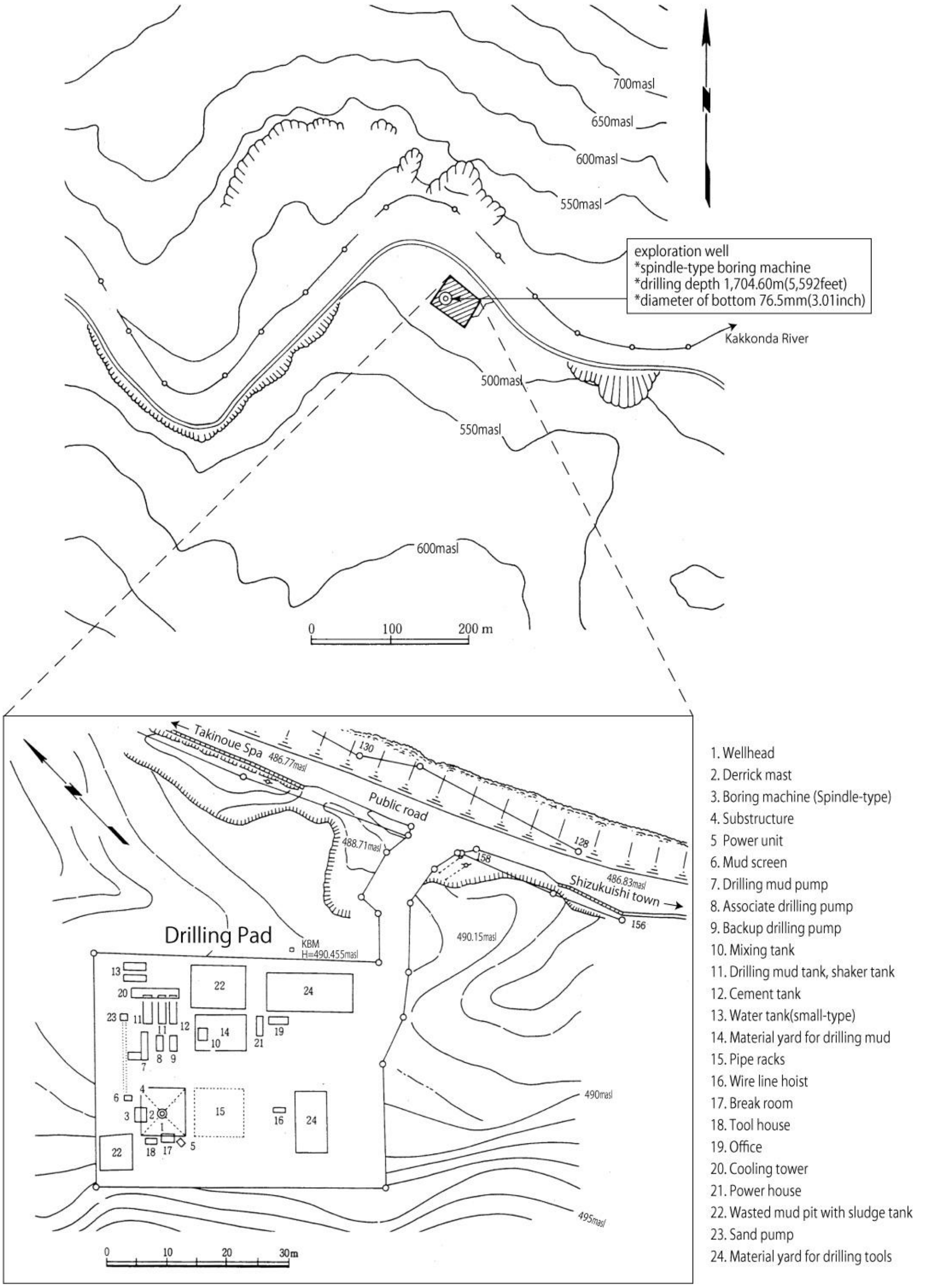
Besides, during construction, it is important to ensure the site space if considering the drilling equipment holding by contractor and land use situation. Figure 3-50 and Figure 3-51 below shows an example of drilling site layout in case of drilling structural boring well with slim hole.



Source: JICA Survey Team

Figure 3-50 Drilling Site Layout Example in case of Drilling with Rotary Table Type Rig

* Dig pit is set nearby rig for temporary storage of drilling waste



Source: JICA Survey Team

Figure 3-51 Drilling Site Layout Example in Case of Drilling with Spindle-Type Rig

* Since a river flowing nearby the drilling site can supply the water, the site here is a little bit small.

3-3-6 Civil Engineering Survey

Based on the evaluation results by Jacobs (2016) about the geothermal reservoirs, and results of local investigation in this research, and furthermore considering the domestic infrastructure situation, 3 candidate zones for drilling of structural boring wells are proposed as below:

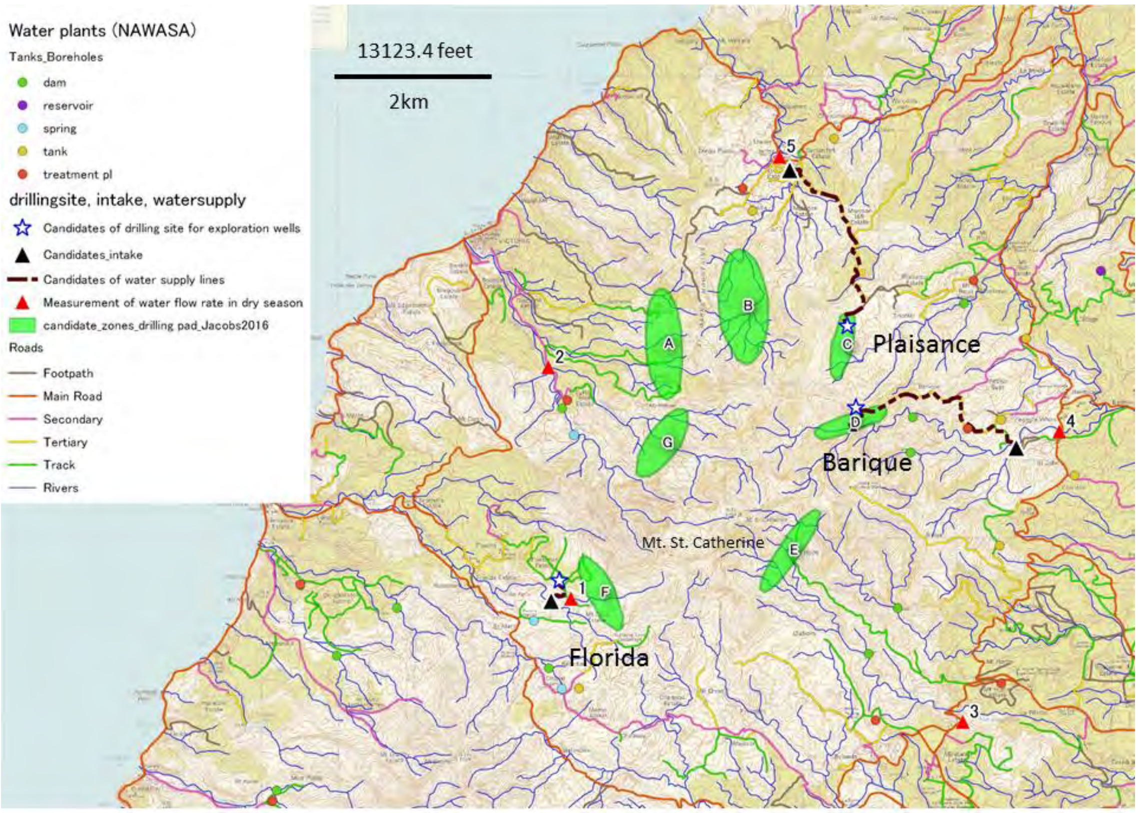
Plaisance (Area C)

Barique (Area D)

Florida (Area F)

The location of selected zones above is shown in Figure 3-55 and Figure 3-61.

Jacobs (2016) assessed the areas where geothermal reservoir possibly exists based on surface survey, and then determined the areas where exploratory well can be drilled by topographic analysis (see zones A~G in yellow green in Figure 3-61). For selecting candidate drilling zones from these areas, items below have been considered: a) base of drilling site; b) ability of water supply during drilling; c) location relationship with protected areas; 4) situation of accessibility. The assessment results of these items are shown in Table 3-3 and Table 3-4. Additionally, river flow (see measurement location in Figure 3-61 in red triangle) in dry season is shown in Table 3-4.



Source: JICA Survey Team

Figure 3-52 Location of Candidate Drilling Zones, River Flow Measurement and NAWASA Water Plants

Table 3-15 Assessment Items for Drilling Zones Selection

Candidate zone	Name	Drilling base land	Water supply for drilling	Protected area	Resettlement ＊	Accessibility	Remark
A	Mt.Stanhope	×	△	○	○	×	×
B	Castle hills	×	○	△	○	×	×
C	Plaisance	○	△	○	○	△	○
D	Barique	○	△	○	○	△	○
E	Mt.Hope	?	△	×	○	×	×
F	Florida	○	△	△	○	○	○
G	Belair	△	△	◦	○	×	×

○ Good condition △Available if being improved ×Bad condition ? Unclear

＊No resettlement is expected for test drilling, however there may be some land acquisition needed.

Source: JICA Survey Team

Table 3-16 Location Information of Candidate Zones

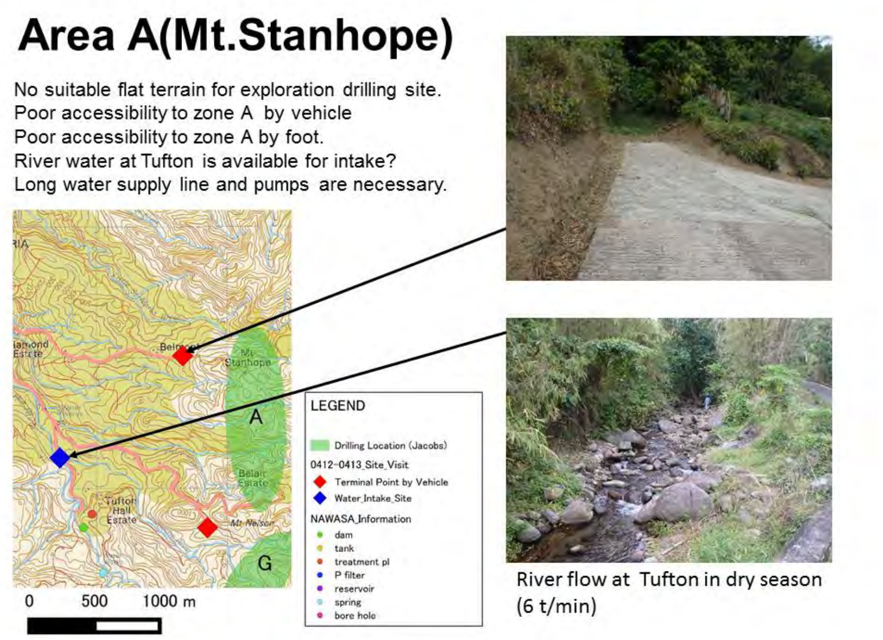
Candidate zone	Name	Coordinate (WGS 84)		Coordinate (WGS84 UTM 20N)		Elevation	
		Longitude	Latitude	x	y	(meter)	(feet)
A	Mt.Stanhope	-61.68895	12.18689	642632.27239	1347563.68493	216	709
B	Castle hills	-61.67472	12.19260	644177.11680	1348202.87879	232	761
C	Plaisance	-61.66236	12.18448	645526.63128	1347311.24066	362	1188
D	Barique	-61.65986	12.17486	645804.45375	1346249.09689	459	1506
E	Mt.Hope	-61.66834	12.15569	644892.08482	1344124.22713	409	1342
F	Florida	-61.69672	12.15578	641803.54203	1344119.33544	346	1135
G	Belair	-61.68726	12.17500	642822.08164	1346250.01831	256	840

Source: JICA Survey Team

Table 3-17 Results of River Flow Measurement in Candidate Zones in Dry Season

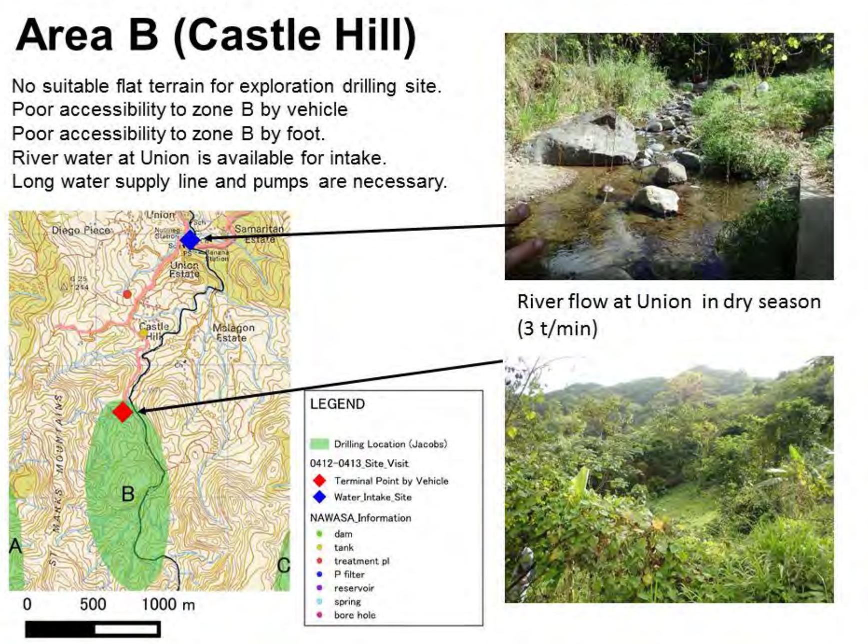
No.	Name	Coordinate (WGS 84)		Coordinate (WGS84UTM 20N)		Elev. (m)	Water flow	
		Longitud e	Latitud e	x	y	Elev.(feet)	ton/min	method
1	Florida	-61.69507	12.15278	641983.92965	1343788.04394	326 1070	1	floating
2	Tufton	-61.69764	12.17987	641690.55011	1346783.12274	88 289	6	floating
3	Grand Bras	-61.64848	12.13814	647061.97909	1342193.60908	180 591	3	visual judgment
4	Peggy's Whim	-61.63682	12.17204	648312.70767	1345949.87691	127 417	4	floating
5	Union	-61.66996	12.20437	644688.65174	1349508.14247	86 282	3	Floating

Source: JICA Survey Team



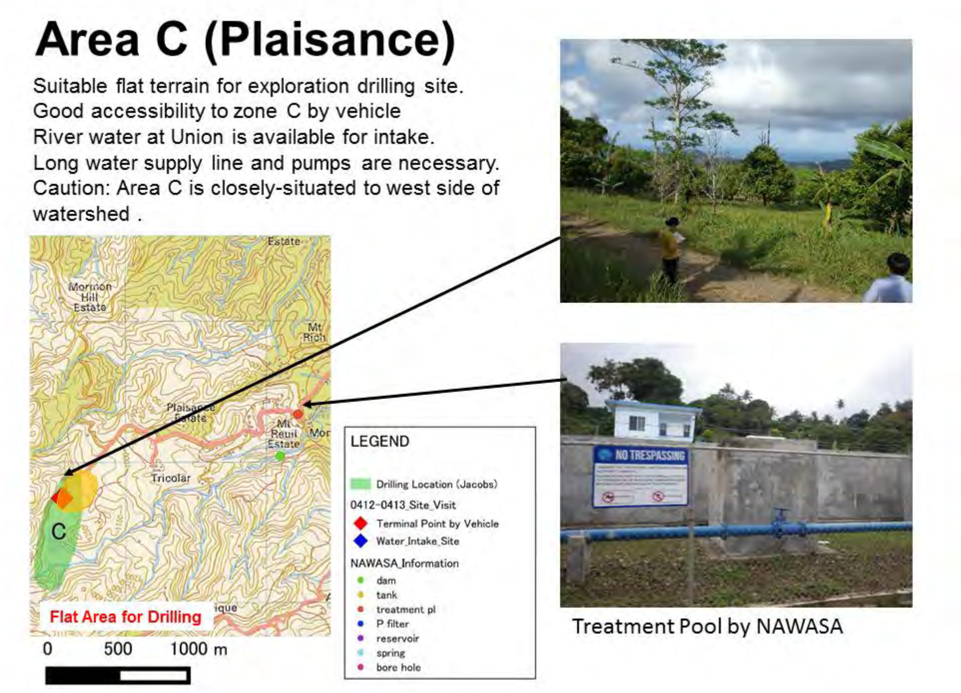
Source: JICA Survey Team

Figure 3-53 Drilling Site and River Flow Survey in Vicinity of Zone A



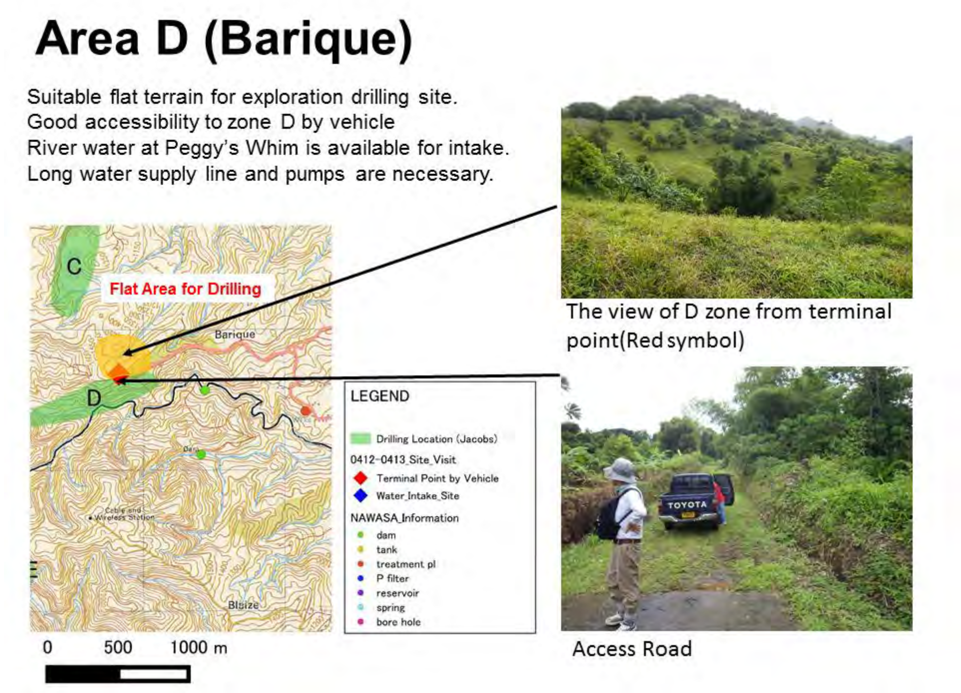
Source: JICA Survey Team

Figure 3-54 Drilling Site and River Flow Survey in Vicinity of Zone B



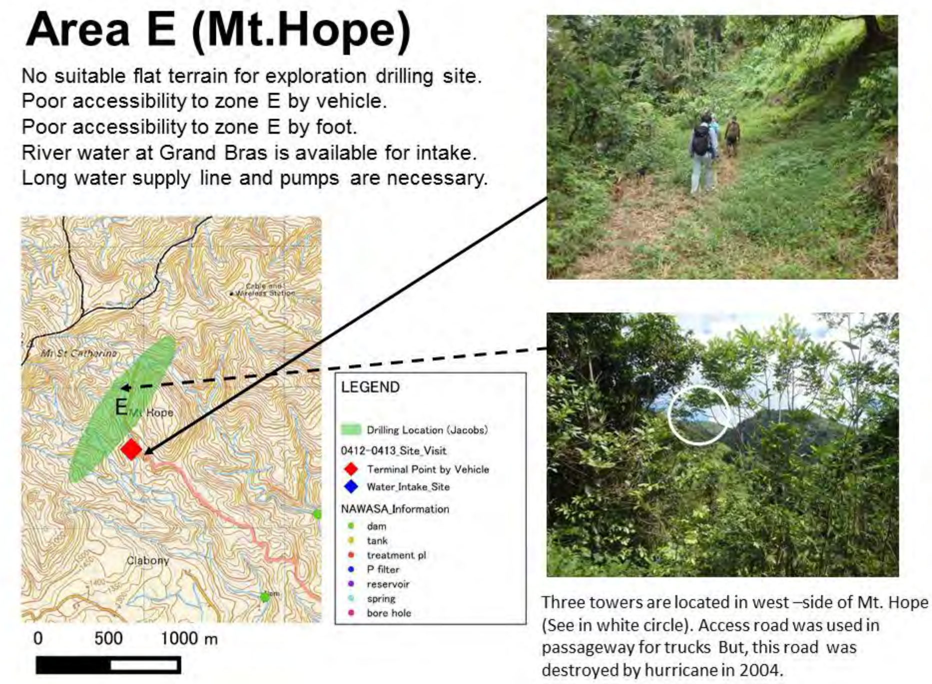
Source: JICA Survey Team

Figure 3-55 Drilling Site and River Flow Survey in Vicinity of Zone C



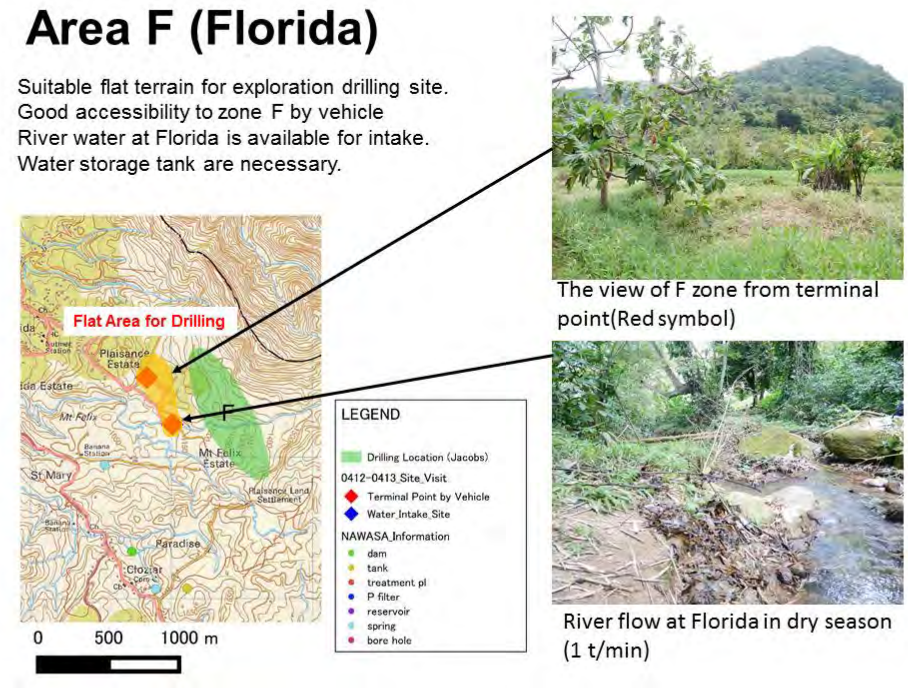
Source: JICA Survey Team

Figure 3-56 Drilling Site and River Flow Survey in Vicinity of Zone D



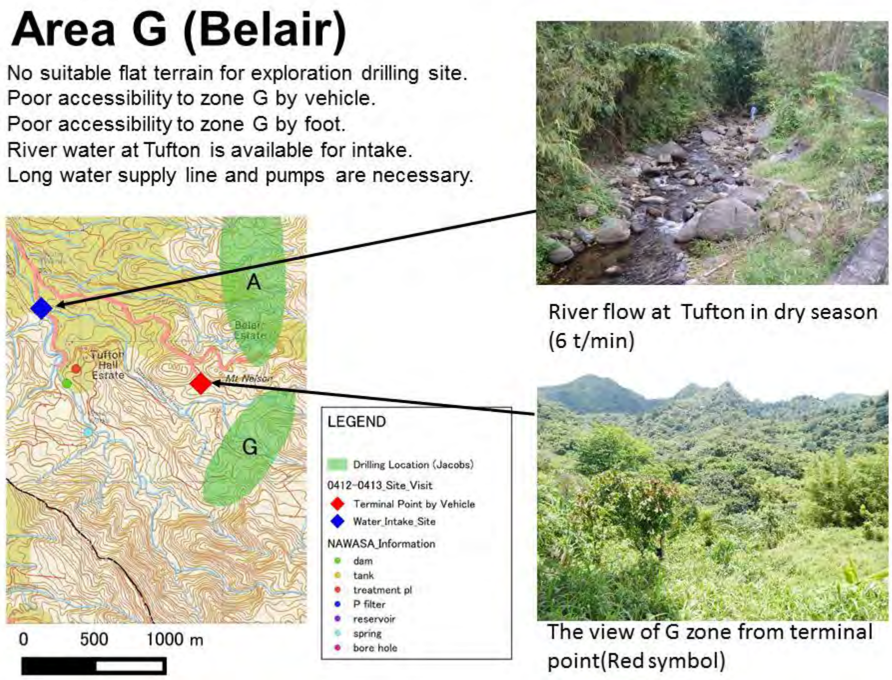
Source: JICA Survey Team

Figure 3-57 Drilling Site and River Flow Survey in Vicinity of Zone E



Source: JICA Survey Team

Figure 3-58 Drilling Site and River Flow Survey in Vicinity of Zone F



Source: JICA Survey Team

Figure 3-59 Drilling Site and River Flow Survey in Vicinity of Zone G

Below the assessment items for drilling zone selection will be discussed in detail.

(1) Construction of Base Land for Drilling Sites

In order to build the base land and water storage tank, a flat ground with at least 2,000 m^3 is needed. The general information of each candidate zones is shown in Figure 3-61 ~ 3-63. Considering the cost of roads repair and enlargement, and the roads accessibility for vehicles, 3 sites for drilling are selected:

- Zone C (Plaisance): A flat farmland with more than 80m×100m area was confirmed. However, due to the existence of wetland in the east of this zone, it might be an obstacle for the base land construction. So when setting up the rig, it is necessary to ensure the ground strength by some means. Besides, the east side of this zone is the upstream of the dam belonged to NAWASA.
- Zone D (Barique): A farmland (for grazing) of about 200m×200m area with slight undulation was confirmed.
- Zone F (Florida): A flat farmland with more than 200m×200m area was confirmed.

As to the other candidate zones, due to steep topography, it is difficult to construct the base land for drilling in Zone A and Zone B. In Zone E, the road condition was too bad to confirm the flat land which is suitable for drilling. In Zone G, although a flat farmland with about 80m×100m area was confirmed, comparing wit Zones C, D and F, Zone G is a little bit far away from the areas where geothermal reservoir might exist. Besides, the means of transportation in Zone G is by walking only. For these reasons, the importance of this zone is low as the zones for drilling.

(2) Water Supply for Drilling

Water demand is different in different processes during drilling operation. The water demand should be guaranteed for ground drilling (including total lost circulation of mud water drilling), pit suppression, pit cooling and cementing.

- Ground drilling (without mud water, long time): little (several L/min ~ several hundred L/min)
- Ground drilling (with mud water, short ~ long time): much (several tons/min)
- Pit cooling, pit suppression and cementing (short time): much (several tons/min)

In case of structural drilling well construction proposed in this survey, it is necessary to set up a water storage pit for water supply in emergency if considering the water supply capability is 1~1.5 ton/min.

In this survey, because river water has been considered as the water supply resources, some possible locations (see black triangle mark in Figure 3-61) has been selected based on the results of river flow survey in dry season (see survey locations with red triangle in Figure 3-61, and Table 3-4). However, because river water supply more than half of the domestic water use in Grenada, it is important to make sure there is no influence of water extraction from river on domestic water supply plants during drilling operation work.

Considering the viewpoints talking about above, the suitable river water-intake locations for each candidate zones are discussed based on the water flow survey in April dry season as below.

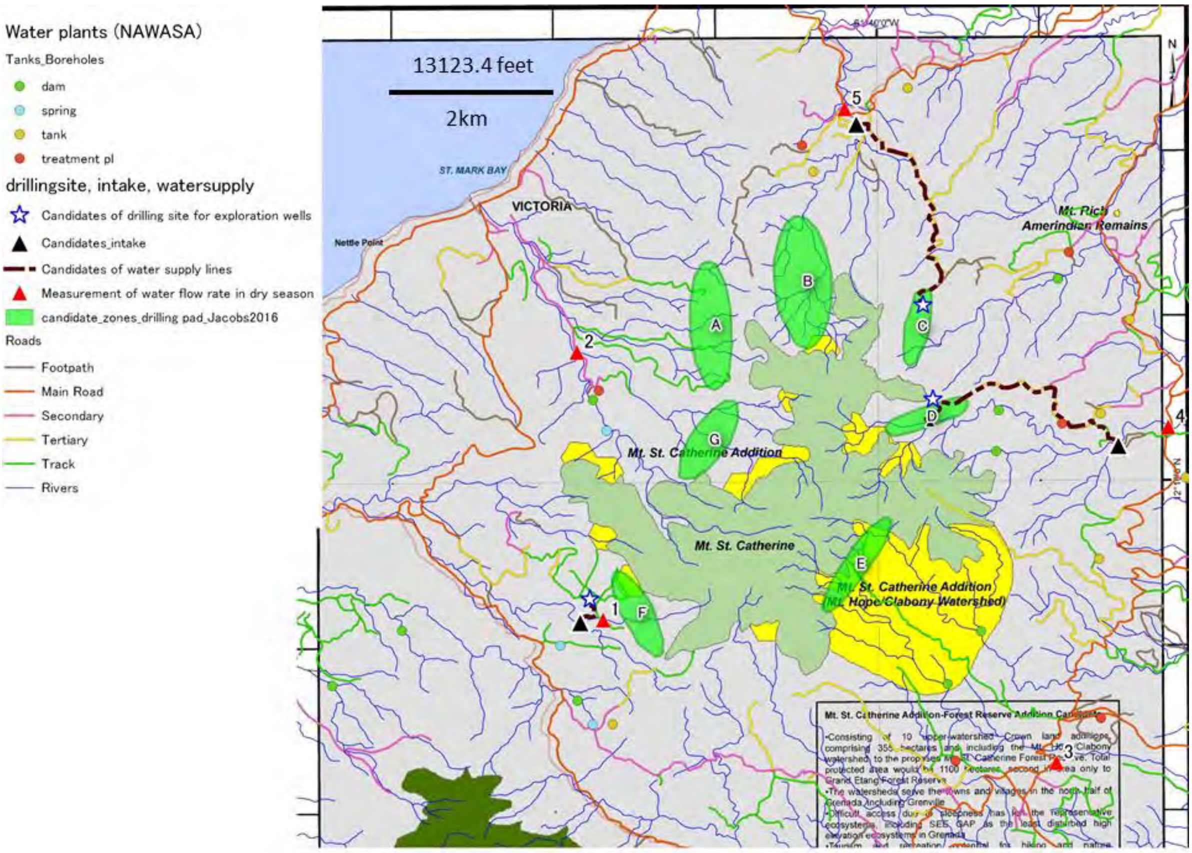
- Zone C (Plaisance): Because there is no suitable river for water intake around this zone, water will be taken from Union (near to No.5 in Figure 3-56) 3 km away from this zone in North. Due to low elevation (above 100m) of the water intake location, many relaying water tanks from intake to drilling site are also necessary. Besides, although river flow is sufficient enough, water storage pit is also needed to set up in drilling sites.
- Zone D (Barique): Water intake is located in downstream part, east 3 km away from the site. Due to low elevation (above 100m) of the water intake location, many relaying water tanks from intake to drilling site are also necessary. Besides, although river flow is sufficient enough, water storage pit is also needed to set up in drilling sites.
- Zone F (Florida): Because the flow of the river at the side of the area is not sufficient, water storage pit is necessary.

One more thing is that, although all planned water intakes are located in the rivers where there is no NAWASA plants, or in the downstream of the rivers where NAWASA plants, it is still necessary to negotiate appropriately with NAWASA and local land holders.

(3) Protected Area

In Grenada, the center part of Mount St. Catherine and parts of coast area are designated as protected areas. The location of protected areas and candidate zones is shown in Figure 3-60

Figure 3-64. All the drilling candidate zones is outside these protected zones. However, Zone Barique is near to one protected area.



Source: JICA Survey Team

Figure 3-60 Relationship between Protected Areas and Candidate Zones

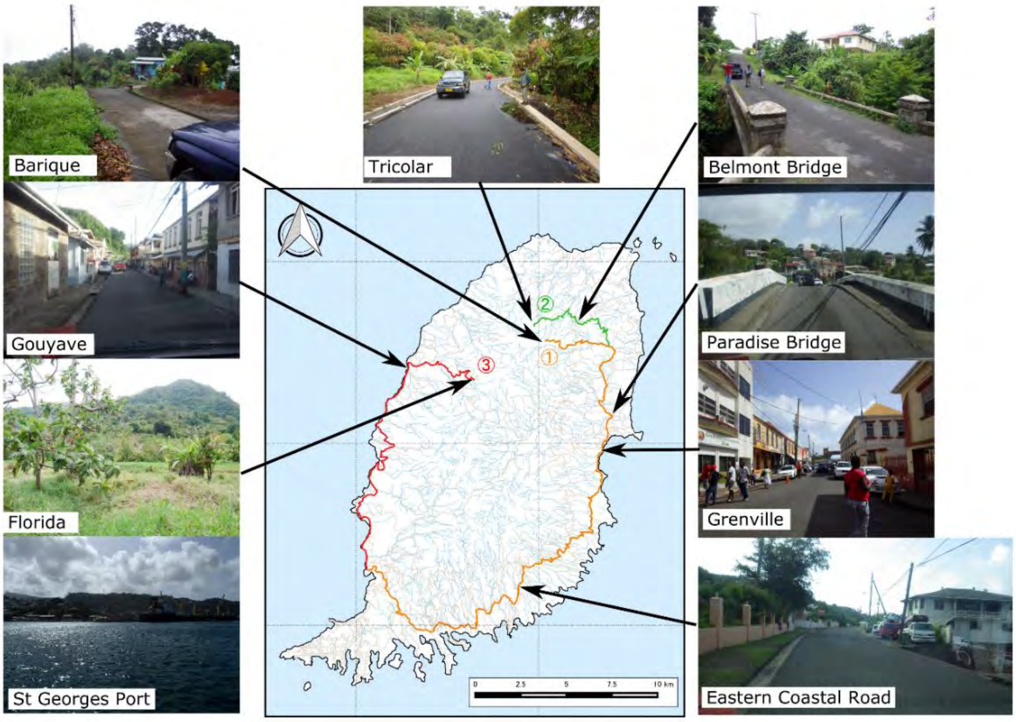
(4) Accessibility

During drilling operation work in Grenada, all drilling equipment are transported to drilling site from abroad through seaway. The port where large ships can enter is in St. George's only. Therefore, the accessibility from this port to drilling site has been discussed. Besides, for the transportation on land, trailer at 20 t level (length 15m × width 2.4 m × height 1.1m) is considered to be used. The important points of the accessibility of each routes to drilling sites are as below. Figure 3-61 shows the possible routes which are being considered.

- Barique: Road is relatively wide, and the Eastern Costal Road is considered to be used. However, due to narrow streets in Grenville City, the trailer transportation may bring some obstructions to the city traffic. Also, it should be careful enough when trailer pass through the Paradise Bridge which is with only 4 m width.
- Plaisance: Road is relatively wide, and the Eastern Costal Road is considered to be used. However, due to narrow streets in Grenville City, the trailer transportation may bring some obstructions to the city traffic. Also, it should be careful enough when trailer pass through the Paradise Bridge which is with only 4 m width.

- Florida: The Western Coast Road is considered to be used. Comparing with the eastern road, road curve and abrupt slope in western side become a little more. Besides, due to narrow streets in Gouyave the half-way city, the trailer transportation may bring some obstructions to the city traffic.

The paved roads are available to 500 m away from each drilling candidate zones, and the narrowest part of the road is about 3.5 m. Therefore, there is no need to build new roads for accessing.



Source: JICA survey Team

Figure 3-61 Routes to Drilling Sites