SPC Recovery Support for Tropical Cyclone Pam

Groundwater Investigation
North Tanna and Middle Bush, Vanuatu

Andreas Antoniou, Aminisitai Loco, Anesh Kumar and Peter Sinclair

Geoscience, Energy and Maritime Division of the Pacific Community

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- United Nations Children's Fund
- World Health Organization
- The Australian Department of Foreign Affairs and Trade
- The New Zealand Ministry of Foreign Affairs and Trade

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1. Introduction

1.1 Project background

In March 2015, one of the Southern Hemisphere's most intense tropical cyclones ever recorded caused widespread damage and loss of life across four countries: Kiribati, Solomon Islands, Tuvalu and Vanuatu. Some of the greatest impacts were felt in Vanuatu, which suffered a direct hit from the category 5 cyclone. Significant damage to a range of services occurred in Vanuatu's eastern islands and provinces. Following on from the immediate humanitarian disaster response needs of the countries, which were supported by a range of regional and international organisations and governments, ongoing recovery efforts to the many services that were impacted was required. In February 2016, the Pacific Community, in collaboration with the German banking group KfW, developed a suite of multisectoral activities under the 'SPC Recovery Support for Tropical Cyclone Pam' to support the recovery needs of Kiribati, Solomon Islands, Tuvalu and Vanuatu, which were the Pacific Island countries most impacted by Tropical Cyclone Pam.

1.2 Project phases

This report summarises the findings from the second of two groundwater assessment missions under the agreed activities. The groundwater assessments formed the first phase of the 'Support for domestic water supply rehabilitation' project component for Vanuatu. The purpose of this phase was to conduct geophysical surveys in selected locations in order to identify fresh groundwater potential and locate drilling targets for the development of community water supply boreholes. The first mission was conducted in West Ambae in March 2017 and the findings are summarised in a separate report (Loco et al. 2017).

The second phase involves investigating and developing the groundwater potential by drilling in locations indicated by geophysical surveys. The installation of PVC pipes, borehole development and pumping tests are part of the second phase of the project's component. KfW's contribution to the second phase through the 'Recovery Support for Tropical Cyclone Pam' project, in collaboration with the European Union-funded 'EDF10 Building Safety and Resilience in the Pacific' project, has enabled the purchase of a suitable drilling rig capable of drilling and constructing water supply wells to required depths in the expected geology. In addition, KfW's Recovery Support for Tropical Cyclone Pam project will assist with the cost associated with mobilising the drill rig to the outer islands, for four villages on two islands. The costs for the drilling will be borne by the Government of Vanuatu, and includes fuel, drilling fluids and casing, drilling consumables for construction, and staff salaries. Advice on borehole completion, pumping tests and options for groundwater development will be supported by SPC (through the KfW's Recovery Support for Tropical Cyclone Pam project) for the selected sites.

Finally, the third phase consists of equipping the boreholes with submersible solar pumps, connecting them with existing water tanks, installing additional storage tanks and installing reticulation systems. This phase is currently outside the project's scope and funding, but a number of actors (United Nations Children's Fund, Australian Department of Foreign Affairs and Trade, New Zealand Ministry of Foreign Affairs and Trade, and nongovernmental organisations) have already indicated their interest to support the project.

This report synthesises the results of the groundwater assessments performed in North Tanna and Middle Bush area councils for the purposes of: 1) improving the understanding of the geology and hydrogeology of the selected sites, 2) assessing the fresh groundwater potential of the selected sites for domestic water supply purposes, and 3) guiding the drillers of the Department of Water Resources of Vanuatu during the drilling of the identified targets.

2. Background

2.1 Geographical location and land use

The Republic of Vanuatu is an island nation in the South Pacific Ocean, northeast of New Caledonia, east of Australia and west of Fiji. The archipelago has a population of 272,459 (Vanuatu National Statistics Office 2017) and is divided into six provinces. Tanna is located in Tafea Province and has a total area of 550 square kilometres. It is the most populous island in the Province, with a population of about 32,400 based on the 2016 national census (Vanuatu National Statistics Office 2017) and one of the most populous islands in the country.

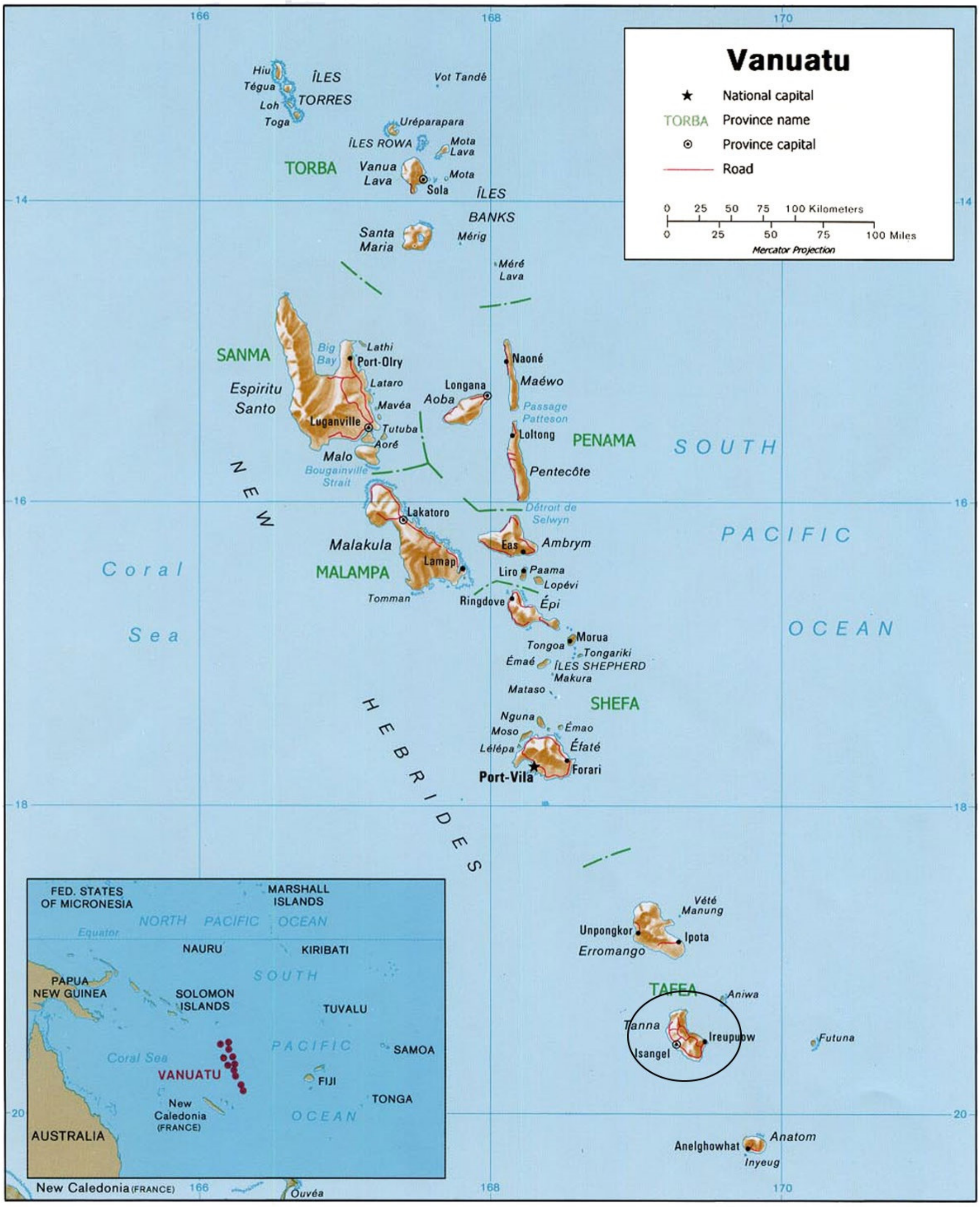

Figure 1. Administrative map of the Republic of Vanuatu. Source: www.nationsonline.org

Tanna is divided into six area councils. The two area councils of North Tanna (population of 4,165) and Middle Bush (population of 5,994) were indicated by the Government of Vanuatu as areas that were highly affected by Tropical Cyclone Pam in March of 2015 (Vanuatu National Statistics Office 2017). Recovery and development of a resilient domestic water supply was indicated by the Department of Water Resources as a priority.

The majority of households on Tanna are dependent on subsistence agriculture, which involves the production of root crops, other vegetables and fruits (Nixon et al. 2012). The cooler climate and fertile soil of Tanna contribute to good growing conditions for cash crops. Temperate vegetables produce good yields and contribute to household incomes through sales at the Lenakel (the largest town on Tanna) and Port Vila markets. Other crops contributing to rural household income include kava, coconut, cocoa, taro and peanuts. Since the early 1980s, coffee has been cultivated in North Tanna and Middle Bush. According to the 2007 agricultural census, 97% of households practice shifting cultivation to sustain household consumption and provide cash through sales of surplus crops (Vanuatu National Statistics Office 2007).

2.2 Climate and rainfall analysis

In Vanuatu there are currently 47 operational meteorological stations (BoM and CSIRO 2011) although only 8 have a long-term database available for analysis (Table 1). Also, the elevation of these long-term stations is close to sea level so major orographic effects are absent.

Rainfall in Vanuatu is seasonal, with a wetter period from about November to April and a drier period from about May to October. The relative intensity of seasonality increases with increasing southerly latitudes. The northern-most stations in Vanua Lava (Banks Islands) have the largest mean annual rainfall and lowest variability, while Whitegrass on Tanna has the lowest annual rainfall and the highest variability (Table 1). It is noted that Whitegrass is on the leeward side of Tanna. Whitegrass also has the lowest recorded minimum annual rainfall, followed by Pekoa Airport on Santo. Also, the minimum recorded rainfalls in Whitegrass (not shown in Table) indicate that significant water shortages can occur in both wet and dry seasons.

Based on a recent 'hot spot' analysis for Vanuatu (White 2016), Whitegrass on Tanna has a high probability of annual water shortages of over 40%, or a frequency of about 5 years in every 12. For the same station, dry season water shortages can be expected, with a higher frequency, 10 years in every 12. This indicates that locations around Whitegrass can expect frequent water shortages, especially during the dry season. Rainwater deficits at an annual time scale may also have implications on groundwater resources.

In total, there are six rainfall stations on Tanna (Table 2, Figure 3). Besides Whitegrass, the other five stations show frequent gaps in their records, with four of them only recording daily rainfall during the last ten years.

It becomes clear that the western part of the island (stations Burtonfield, Whitegrass and Lenafa) experiences leeward conditions with less rainfall throughout the year compared with the other stations. Also apparent is the orographic effect for the higher-elevation stations of Green Hill and Iewell, which receive higher amounts of rainfall. The lower coefficients of variation in Green Hill and Iewell stations, which are respectively located in the two study areas, indicate lower rainfall fluctuation throughout the year and suggest a higher resilience against droughts as compared with the coastal areas, which show a very high variation, especially during the dry season.

Table 1. National-level rainfall summary from the eight, long-term rainfall stations in Vanuatu

Station name	Island	Elevation (m)	Years	Mean rainfall (mm)			Standard deviation			Coefficient of variation		
				Annual	May-Oct	Nov-Apr	Annual	May-Oct	Nov-Apr	Annual	May-Oct	Nov-Apr
Port Patterson	Vanua Lava	42	1954–1972	4067	1839	2310	762	529	393	0.187	0.287	0.17
Sola	Vanua Lava	18	1971–2016	4080	1766	2249	915	612	580	0.224	0.347	0.258
Pekoa Airport	Santo	45	1971–2016	2423	873	1547	694	387	415	0.287	0.443	0.268
Lamap	Malekula	24	1961–2016	2018	735	1268	534	290	349	0.265	0.395	0.275
Bauerfield	Efate	21	1972–2016	2259	733	1490	550	308	394	0.244	0.421	0.264
Port Vila	Efate	20	1953–2016	2165	717	1444	542	291	376	0.25	0.405	0.26
Whitegrass	Tanna	8	1972–2016	1255	411	830	362	198	282	0.289	0.482	0.34
Aneityum	Aneityum	7	1952–2016	2314	811	1501	515	257	472	0.222	0.316	0.314

Table 2. Island-level rainfall summary from the six short-term stations on Tanna

Station name	Elevation (m)	Years	Mean rainfall (mm)			Standard deviation			Coefficient of variation		
			Annual	May-Oct	Nov-Apr	Annual	May-Oct	Nov-Apr	Annual	May-Oct	Nov-Apr
Burtonfield	74	1981-2016	1186	359	827	359	153	280	0.30	0.43	0.34
Green Hill	289	2008-2017	2141	905	1236	526	230	418	0.25	0.25	0.34
Iewell	357	2009-2016	1853	743	1111	444	187	318	0.24	0.25	0.29
Lenafa	17	2008-2017	1503	559	943	326	236	216	0.22	0.42	0.23
Whitegrass	8	1972-2016	1255	411	830	362	198	282	0.289	0.482	0.34
Yanimakel	74	2008-2017	1673	640	1033	619	302	365	0.37	0.47	0.35

2.3 Current water supply situation

The two area councils of North Tanna and Middle Bush were indicated by Vanuatu's Department of Water Resources as priority areas. Within the two areas, communities with the greatest water shortages were indicated by the area administrators, the chairmen of the area councils, and the provincial water officer.

North Tanna generally relies on rainwater harvesting for potable water needs, while during prolonged dry periods, communities resort to streams for all their water needs. Rainwater catchment systems are often inadequate and tanks are frequently uncovered and vulnerable to contamination. Fluoride contamination of rainwater tanks, associated with the continuous volcanic activity at Yasur volcano, was assessed by Cronin and Sharp (2002). Reported fluoride levels were, however, below the World Health Organization drinking water guidelines, and only posed concerns in areas adjacent to the active volcanic cone. A number of boreholes exist along the western coast but these are too far for the highland communities to access them.

In 2015, the United Nations Children's Fund installed 31 ram pumps[1] in the Middle Bush area to support access to water by the communities there (Water for Life project). The water is pumped from streams and springs and pushed uphill towards a number of villages at a rate of approximately 1.7 litres per minute (L/min). In addition, in 2014 the Adventist Development and Relief Agency installed (New Zealand WASH Bilateral project) four 22,500-L water tanks and a 24-km pipeline network to connect the tanks with a number of communities, as depicted in Figure 2. The four water tanks, located at high-elevation areas, are filled using ram pumps, which push stream and/or spring water uphill. Water volumes and pump capacities, however, are small and the tanks cannot provide enough water to feed the entire pipeline network. During the time this mission was undertaken, water was pumped into one tank at a time with a rate of ~0.5 litres per second (L/sec), thus producing a total of 43,200 L/day. According to personal communications with local communities, the water currently provided is sufficient only to serve the first downstream villages. Assuming 50 L/day is the minimum water quantity needed per capita during emergencies for domestic use (WHO/SEARO 2005), the population of Middle Bush would require 300,000 L to cover its daily needs. Additional water supplies, such as groundwater could, therefore, feed into the existing high-capacity reticulation system and benefit all communities connected to this network.

[1] A hydraulic ram pump is a water pump powered by water with a height difference. In areas where natural flows exist with a height difference of the water over a small distance, hydraulic ram pumps can be used to transport water to higher grounds without using electricity or fuel. The hydraulic ram uses the water hammer effect to develop pressure that allows a portion of the input water that powers the pump to be lifted to a point higher than where the water originally started. Apart from the kinetic energy of the water, no other source of power is needed (from http://akvopedia.org)

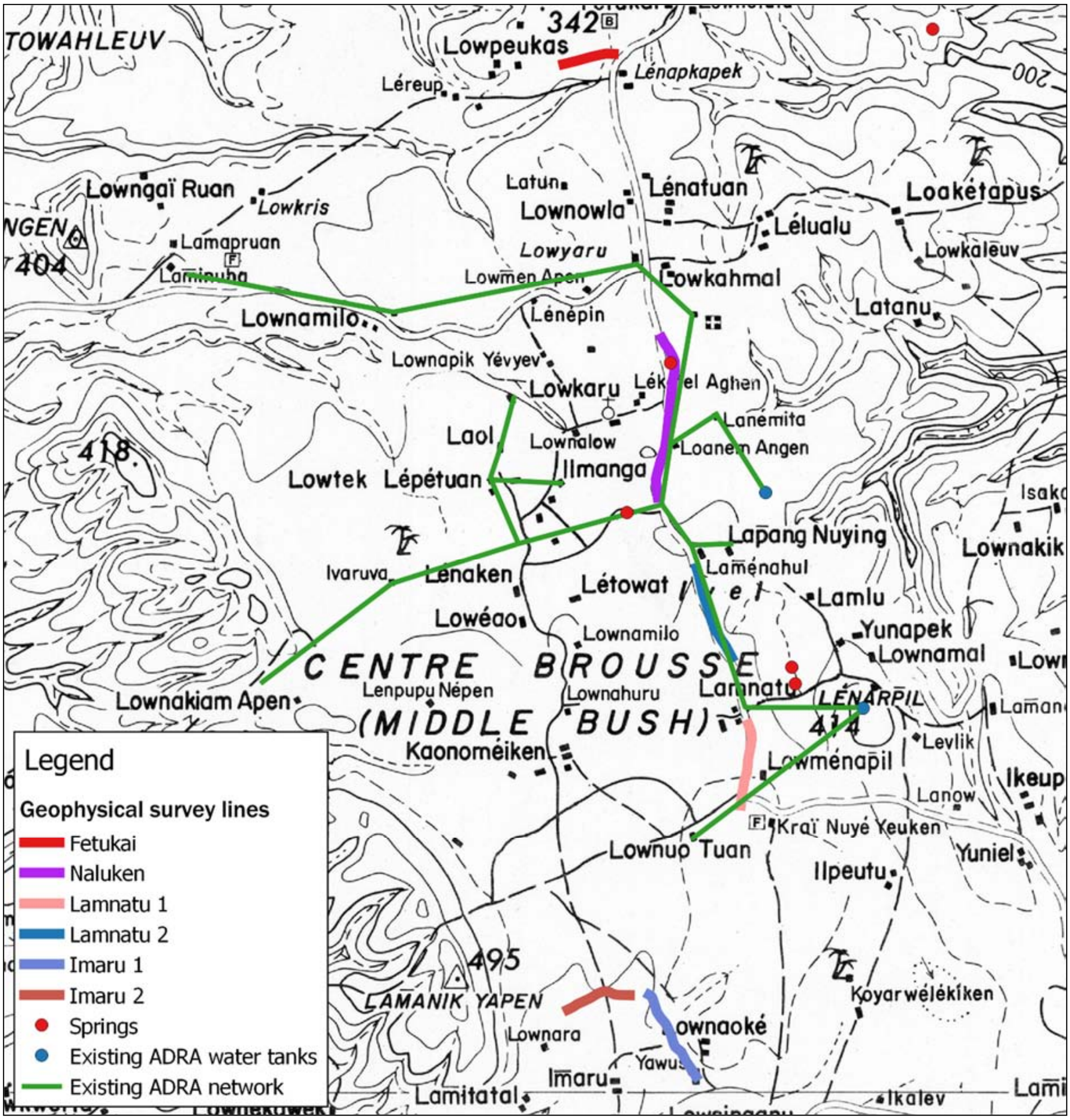

Figure 2. Adventist Development and Relief Agency (ADRA) water pipeline connecting water tanks with communities. In reality, the network is only able to serve communities at close proximity to the Lenarpil water tanks with the current water supply.

2.4 Geology and geomorphology

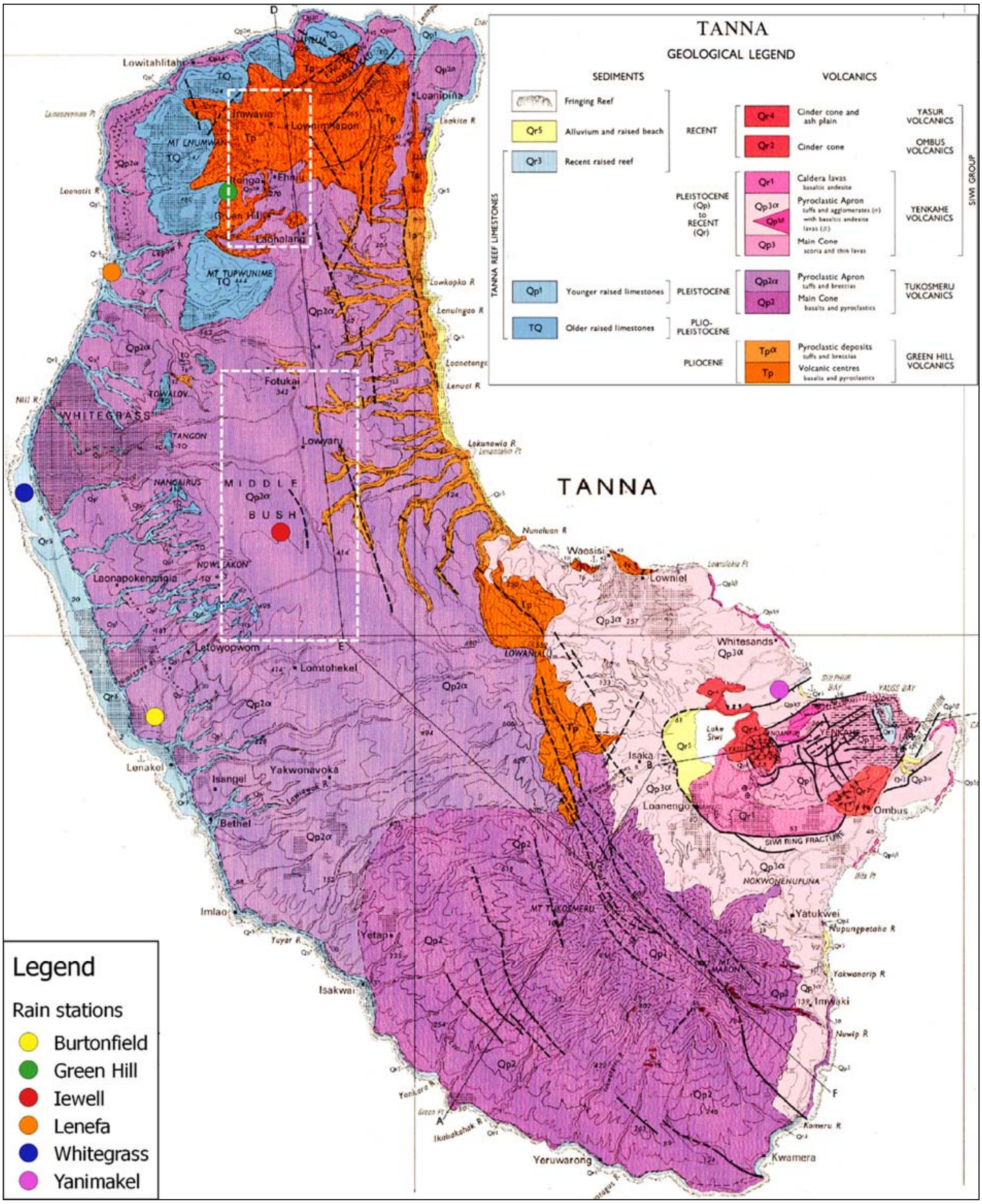

Figure 3. Geological map of Tanna with rain stations and the two study areas marked (Directorate of Overseas Surveys, Great Britain) and Department of Geology, Mines and Rural Water Supplies, Vanuatu, 1971).

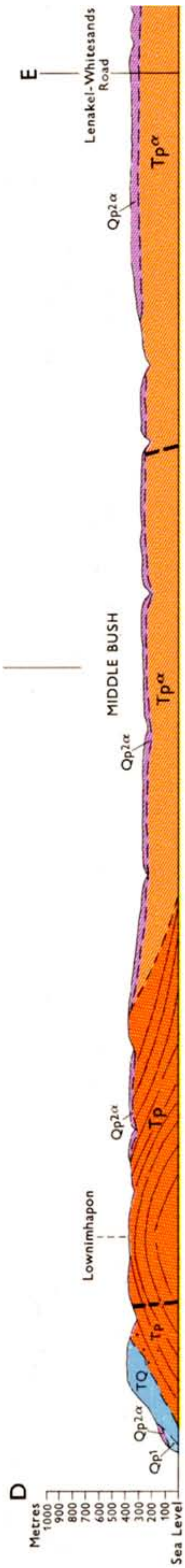

Figure 4 North-South geological cross section along North Tanna and Middle Bush (Carney and MacFarlane, 1976).

Tanna Island is part of a large volcanic complex that is mainly subsided below sea level. Carney and MacFarlane (1979) divided Tanna's volcanics into three groups of lavas and pyroclastics: two ancient groups of Late Pliocene and Pleistocene age, the Green Hill and Tukosmeru groups, and the younger Late Pleistocene to Present Siwi group, which includes the presently active Yasur cone in the southwestern part of the island. The authors described outcrops observed along the eastern coast of the island around Lenuingao. They recognised a complex series of ash flow deposits, scoria-rich pyroclastic flow deposits and massive, poorly welded bomb-rich pumice flow deposits, associated with fallout tephra, overlying lava flows and pyroclastics from the older Green Hill and Tukosmeru groups.

Little literature information exists on geological profiles in the two study areas of North Tanna and Middle Bush districts. Carney and MacFarlane (1979) produced a generalised cross section (Figure 4) depicting the sequence of the main formations and their approximate thicknesses. In North Tanna, the Green Hill volcanic centre, composed of basalts and pyroclastics, is generally exposed and occasionally (towards the south) covered with tuffs and breccias that comprise the pyroclastic apron of the more recent Tukosmeru volcanics. Farther south in the Middle Bush District, pyroclastic deposits (tuffs and breccias) belonging to the Green Hill volcanics are fully covered by the same 30–60 m thick, pyroclastic apron of the more recent Tukosmeru volcanics. The older Green Hill volcanics are only visible along stream drainage valleys where erosion has accelerated their exposure.

The Green Hill volcanics, being 1.8 million years older than the Tukosmeru volcanics according to radiometric dating performed by Dugas and colleagues (1976), are thought to have undergone a higher degree of weathering. This older formation is, therefore, characterised by increased porosity and by the presence of fractures. Older fractures, however, when they occur at depth, are predominantly clay bound and do not always form useful aquifers (Acworth 2001). The location of such older fracture trends can be inferred by examining fractures in outcrops.

According to bathymetric data obtained from northeast of Tanna (Eissen et al. 1991), the crescent-shaped island belongs to a Plio-Pleistocene volcanic complex, about 40 km wide and about 1800 m high, relative to the arc basement. Field observations revealed that the exposed Green Hill volcanics and part of the Tukosmeru lava flows along the eastern coast form the western slope of a large edifice, now collapsed below sea level northeast of Tanna.

3. Field survey methodology

3.1 Resistivity survey

The basic principle of operation in electrical resistivity methods is the injection of direct current into the ground using a pair of electrodes. This current causes a potential voltage difference in the ground, which is measured by a separate pair of electrodes. The voltage measured can then, using the parameters of the survey, be converted into an apparent resistivity value. This value can provide a range of information regarding the survey site. Different types of soil and geological formations have different resistivity responses as a function of the soil and rock depth, porosity, permeability, ionic content of pore fluids, and clay mineralisation. Resistivity is useful in determining the depth, thickness and extent of groundwater bearing zone(s). The depth of investigation is a function of the electrode spacing and the Earth's resistance; in general, the greater the electrode spacing, the deeper the investigation.

To get as much ground information as possible, resistivity should be measured in many positions. By using several multi-electrode cables, it becomes possible to measure the resistivity variation along a survey line. The ABEM Terrameter LS was used with four electrical cables, each with 21 electrode take-outs. The 'roll-along' technique was employed to create seamless profiles longer than the four-cable spread along the survey lines. The multiple gradient array was chosen as the electrode configuration protocol because it offers a good signal-to-noise ratio and good resolution to horizontal and vertical structures.

The electrical resistivity of basalts has been described with varying range in the literature. Marzan (2005) for example proposed a rather high resistivity range of 400–550 Ohm.m for weathered basalts potentially holding groundwater in the Afar Region in Ethiopia. Kebede (2001) indicated a range of 100–300 Ohm.m for saturated, rather dense basalts encountered in the Krísuvík geothermal area of Reykjanes Peninsula in Iceland. D'Ozouville et al. (2008) identified a resistivity range of 50–200 Ohm.m as hydrogeologically interesting in terms of groundwater potential in the Galapagos Islands. In the Raigad District of India, Gupta et al. (2016) interpreted a resistivity range of 30–110 Ohm.m as saturated fractured basalt. Marsan et al. (2017) proposed a resistivity range of 30–95 Ohm.m for saturated and weathered tuffs in the Cililin District in West Java. A more detailed classification was proposed by Chaturvedi et al. (1979) for the Deccan Trap basalts in India, differentiating between different degrees of weathering and saturation (Table 3). According to this classification, resistivities between 15 Ohm.m and 50 Ohm.m are considered to be ideal targets, whereas anything above 50 Ohm.m was generally assumed to be inadequately weathered to hold any substantial groundwater supplies. A similar classification that looks at degree of weathering only was proposed by Rai et al. (2013) (Table 4).

As supported by the authors mentioned above, anything below 15 Ohm.m was considered to be clay-rich, indicating low-permeability and, therefore, low-yielding formations. The high storage capacity of such clay-rich formations was, however, taken into account, especially when these formations superimpose zones with resistivity ranges, which could imply fractured, high-permeability formations. It should also be noted that the Green Hill volcanics are a mixture of basalt and pyroclastic deposits, the latter generally having a higher resistivity, especially when they are devoid of water.

Table 3. Resistivity ranges in Ohm.m for Deccan Trap basalts in Maharashtra, India

Resistivity range (Ohm.m)	Basalt type
5–15	Weathered with clay
15–30	Highly weathered/fractured saturated with water
30–50	Moderately weathered/fractured saturated with water
50–70	Slightly weathered/fractured that may contain some water OR highly weathered/fractured devoid of water
70–100	Weathered dry
>100	Massive

From: Chaturvedi et al. 1979

Table 4. Resistivity ranges in Ohm.m for Deccan Trap basalts in India

Resistivity range (Ohm.m)	Basalt type
5–10	Bole beds (interbasaltic clay)
20–40	Weathered/fractured vesicular saturated basalt
40–70	Moderately weathered/fractured vesicular saturated basalt
>70	Massive basalt

From: Rai et al. 2013

A post-processed kinematic (PPK) elevation survey style was used to determine the absolute elevation at 20-m intervals along each survey line. PPK surveys require data from at least two receivers: a base (reference) receiver and a rover (moving) receiver. Base receivers were installed at two central locations in the two study areas to allow for good communication with the rover receiver. The elevation data were then used to simulate the surface topography during the processing of the resistivity data obtained in the field.

Model inversions were performed with RES2DINV (Loke 2000). The program automatically creates a two-dimensional model by dividing the subsurface into rectangular blocks, and subsequently calculates the apparent resistivity of these blocks using either a finite difference or finite element method, and compares these to measured data. The resistivity of the model blocks is adjusted iteratively until the calculated apparent resistivity values of the model agree with the actual measurements. A uniform colour bar was used to allow comparisons between the inverted profiles. Colour classes were carefully selected to allow the identification of the major formation types, as presented in (Table 3).

3.2 Selection of survey locations

Survey locations were selected based on prioritised areas of water demand, potential groundwater occurrence, geomorphology, existing infrastructure and accessibility.

The villages of Imafin, Ehniu, Laketam, Lawithal and Green Hill in North Tanna were indicated as highly populated communities facing severe freshwater issues during dry periods. The areas around these villages were visited to identify geological structures that indicated enhanced groundwater recharge and occurrence. Simultaneously, the location of existing water tanks and water supply systems was considered to provide additional resilience and links to existing infrastructure, which may support future water supply schemes developed after the installation of boreholes. Finally, the existence of roads was considered to facilitate the surveys and eventual drilling operations and provide access to eventual pumping stations to be constructed in the future.

In Middle Bush, the investigations were focussed along the main road mainly due to the presence of the existing pipeline connecting the various communities (Figure 2). The existence of three 22,500 L water tanks in Lenarpil was considered to be important infrastructure. In addition, conducting the surveys along the S–N oriented main road aimed at targeting the major lineament features that cross the island in a WSW–ENE direction. These lineaments are mainly revealed by the location and direction of main stream drainage valleys on the eastern slopes of the island, exposing the pyroclastic deposits of the older Green Hill volcanics (Figure 3). The location of springs was additionally considered to be an important indication of groundwater discharge (Figure 2). Finally, the village of Imaru was indicated as a high priority community, and two survey lines were conducted in close vicinity to investigate groundwater potential.

Twelve survey lines were performed, six in North Tanna and six in Middle Bush. A 5-m electrode spacing was normally used as the results are well balanced in terms of detail, distance and depth covered. On two occasions, an electrode spacing of 3 m was used to provide additional detail. Longer survey lines investigated as much ground as possible along easily accessible roads, whereas shorter lines targeted specific geological features.

Table 5. Summary of resistivity lines

Line	Line code	District	Location	Direction	Length (m)	Electrode spacing (m)
1	TA-NT-L1	North Tanna	Green Hill	E-W	1200	5
2	TA-NT-L2	North Tanna	Imafin	W-E	1100	5
3	TA-NT-L3	North Tanna	Ehniu	SW-NE	240	3
4	TA-NT-L4	North Tanna	Ehniu	SW-NE	360	3
5	TA-NT-L5	North Tanna	Lawital	SW-NE	700	5
6	TA-NT-L6	North Tanna	Laketam	SW-NE	400	5
7	TA-MB-L1	Middle Bush	Imaru	SE-NW	700	5
8	TA-MB-L2	Middle Bush	Imaru	E-W	500	5
9	TA-MB-L3	Middle Bush	Lamnatu	S-N	600	5
10	TA-MB-L4	Middle Bush	Lamnatu	S-N	700	5
11	TA-MB-L5	Middle Bush	Naluken	S-N	1200	5
12	TA-MB-L6	Middle Bush	Fetukai	E-W	400	5

The survey lines in North Tanna were partly performed on exposed Green Hill volcanic centres and partly on tuffs and breccias of the younger Tukosmeru group. Groundwater occurrence near the volcanic centres was expected to be mainly in the form of small, perched aquifers and fractured aquifers, both possibly associated with vertically intruded dykes that can impound groundwater (Acocella and Neri 2009; Pryet et al. 2012; Underwood et al. 1995) and fracture the country rock (Gudmundsson et al. 2003; Singhal 1973). In areas covered with younger pyroclastic flows (Tukosmeru volcanics), groundwater occurrence was expected to be near, or in contact with, the older and more weathered Green Hill volcanics. This is due to the impervious character that volcanic rocks acquire when they become weathered. Weathering tends to reduce the permeability of volcanic rocks due to the presence of clayey secondary minerals such as montmorillonite, a product of weathered basalt.

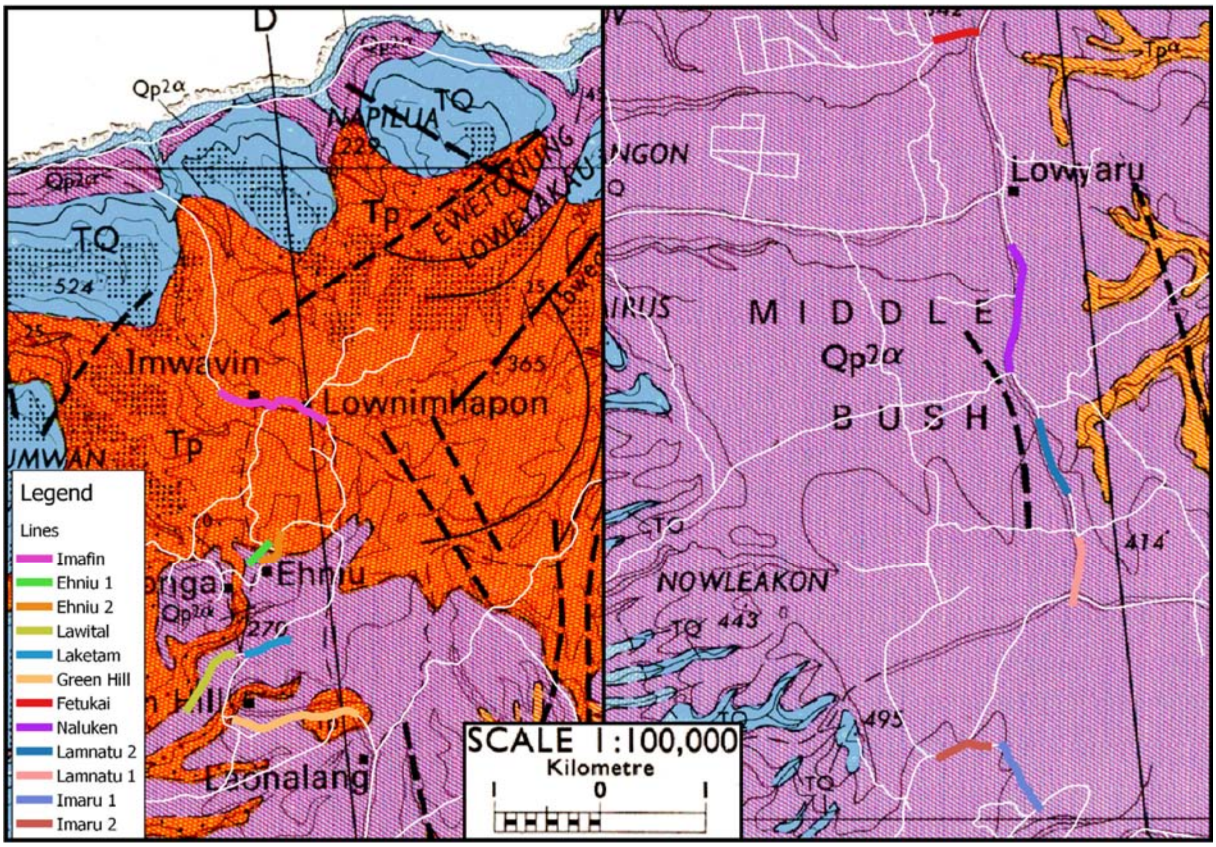

Figure 5. Location of survey lines in North Tanna (left) and Middle Bush (right). Modified after Directorate of Overseas Surveys (Great Britain) and Department of Geology, Mines and Rural Water Supplies (Vanuatu), 1971. For geological legend, refer to Figure 1.

4. Results and discussion

4.1 Geophysical results and interpretation

When interpreting modelled resistivities, a number of considerations must be taken into account because geophysical results are non-unique. Generally, electrical current prefers to follow the path of least resistance, so when low-resistivity layers exist in the shallow subsurface, these may mask the real resistivity distribution of deeper formations. In addition, resolution decreases with depth, and hence model accuracy is expected to do the same. Modelling iterations were forced to continue until the modelled absolute error could not be reduced any more with the given dataset. The presence of 'negative resistivities' in the dataset, which is an error message that indicates the electrode's inability to read a realistic difference in electrode potential, contributes substantially to the total absolute error. This is usually related to poor electrode contact, misplaced electrodes, the presence of human-made objects in the ground (e.g. cables or pipes) and above the ground (e.g. metal fences), and noise from electrical fences or power lines. Other reasons are related to incorrect transmitter and/or receiver settings, with respect to field conditions, and finally to highly variable geological conditions in two or three dimensions, forcing the electrical current to travel in unexpected ways and cause negative readings (Fredrik Nykvist, Product manager, Guideline Geo Group MALÅ/ABEM, 2017, pers. comm.).

Line 1: North Tanna – Lownaleng and Green Hill

Survey line 1 was carried out along the road between the villages of Lownaleng and Green Hill in an E–W direction. A total distance of 1200 m was covered using the largest available electrode spacing of 5 m. The location was selected because of the exposed Green Hill volcanics, possibly expressing an old eruptive dome, which could mean the potential for perched and impounded groundwater conditions, as interpreted for West Ambae by Loco and colleagues (2017). In addition, the intention was to cross the boundary between these exposed basalts and pyroclastics, and the younger tuffs and breccias, of the Tukosmeru volcanics to determine whether there was a significant resistivity contrast and to obtain insights on expected resistivities for these two formations.

The entire profile is dominated by a 40–50 m thick, low-resistivity formation (5–20 Ohm.m) that is mostly exposed to the surface up to a distance of 440 m from the start point of the survey line (Figure A1). This low-resistivity range is indicative of weathered basalt with clay, as shown in Table 3 and Table 4. Indeed, on many occasions, the electrodes were hammered into very shallow, clay-rich soil, testifying to the resistivity values found in the literature. The high clay content is expected to gradually decrease with depth and to be replaced by highly weathered saturated basalt. Past the 440-m mark, a thin (5–10 m) formation of 50–125 Ohm.m covers the low-resistivity formation, possibly representing the pyroclastic deposits of the Tukosmeru group and gradually covering the Green Hill volcanics.

Below the thick, low-resistivity formation, the basalts progressively become less weathered and their groundwater-bearing potential increases, especially considering the large storage capacity of the overlying low-resistivity formation. This moderately weathered layer is not continuous, possibly suggesting fractures at distances of 320–410 m and 720–760 m along the profile. The second interval, in particular, could reflect a fracture associated with the vertically oriented high-resistivity (100–750 Ohm.m) feature observed right next to it. This vertical feature could represent an intrusive dyke that has caused fracturing of the country rock due to thermal effects and differences in mechanical properties (Gudmundsson et al. 2003).

Line 2: North Tanna – Lownimhapon and Imafin

Survey line 2 was conducted in a W–E direction between the villages of Lownimhapon and Imafin. A total distance of 1100 m was covered, and an electrode separation length of 5 m was applied. Based on the geological map, the entire line was run on exposed basalts and pyroclastics from the Green Hill formation. Again, the intention was to explore the subsurface for potential fractures formed by intrusive dykes associated with the volcanic centres in the area. It should be noted here that the model inversion has a relatively high absolute error (20.8%), probably related to the large number of negative resistivities recorded along the profile, not allowing for an accurate simulation of resistivity distribution by the modelling software. The interpretation should, thus, be treated with caution.

Similarly to survey line 1, a low-resistivity layer of varying thickness is encountered at shallow depths, suggesting highly-weathered and possibly clay-rich basalts (Figure A2). At least one intrusive dyke is observed at 260–310 m along the profile, which may have caused fracturing of the neighbouring rock. Fractured and/or weathered basalt with relatively good groundwater potential is possibly observed at 510–560 m along the profile. The deep, high-resistivity zones, which generally extend along the entire profile, suggest the absence of groundwater in the geological formation. This could either be due to the compact and impermeable character of basalts or to the highly porous character of scoriaceous basalts, which do not allow groundwater to be held within their pores. It is, therefore, very probable that the shallower, low-resistivity zone contains some groundwater that is held within the clay by capillary forces. These groundwater bodies are not expected to yield substantial water supplies.

Line 3: North Tanna – Ehniu

Survey line 3 was performed in SW–NE direction in the village of Ehniu along the open space provided by the football field. The line was stretched uphill to potentially make use of the existing water tank if any boreholes will eventually be developed. Considering the short planned length of the line (240 m), an electrode separation length of 3 m was used to explore the value of a detailed resistivity survey in this type of geology. Because the line would cross between Tukosmeru and Green Hill volcanics, according to the geological map, a large investigation depth was probably not required and a higher resolution may had given additional insights. The maximum investigation depth attained in the central section of the survey line was 53 m.

According to the inverted profile, a 10–20-m thick, low-resistivity, and possibly clay-rich, layer exists (more or less) along the entire length, possibly discontinued at the 54–69 m interval by highly weathered and saturated basalt (Figure A3). Below the clay-rich layer and especially in the central section (i.e. the interval at 110–140 m) the gradual increase in modelled resistivity suggests a decreasing degree of weathering. Again, whether this suggests increasing or decreasing groundwater potential depends on the porosity and degree of permeability and whether the higher resistivities reflect massive basalts or porous unsaturated scoriaceous basalts. If they represent massive basalts then the groundwater development potential is high, especially considering the large storage capacity of the overlying clay-rich formation. The contact between Green Hill and Tukosmeru volcanics was not clearly observed.

Line 4: North Tanna – Ehniu

The second survey line in Ehniu was conducted along the road leading to the village in a SW–NE direction. A 3-m electrode spacing was again applied in order to explore the lateral extent of features identified in the previous line, considering the two Ehniu lines were parallel.

The inverted profile shows some well-defined features with large resistivity variations (Figure A4). The top (5–15 m thickness) layer of 50–150 Ohm.m is observed along the first 144 m of the profile, suggests unsaturated tuffs and breccias, and matches well with the contact between the younger (and thus less weathered) Tukosmeru and the older Green Hill volcanics. Deeper in the profile, the survey line shows low resistivity, suggesting clay-rich weathered basalts, as observed on the surface. The interval at 90–150 m shows a good resistivity range (20–40 Ohm.m) from a groundwater development potential point of view. Farther along the profile at 280 m distance, a distinct, vertically oriented, high-resistivity (>750 Ohm.m) massive feature is observed. The minimal weathering that the feature has undergone, reflected by the sharp resistivity interface with the surrounding formations, suggests the massive character of the feature, which was probably formed by vertical lava intrusion. Rising magma that does not erupt at the land surface cools within fissures and forms thin, near-vertical sheets of massive rock that intrude existing permeable lava flows. Possible fracturing of the country rock may be present but no clear indications are given by the resistivity distribution.

Line 5: North Tanna – Lawital

Line 5 was carried out in a SW–NE direction along the road in Lawital. About 700 m were covered using a 5-m electrode spacing. According to the geological map, the area is covered by the shallow pyroclastic deposits of the Tukosmeru group overlying the older Green Hill basalts and pyroclastics.

The top layer has an average thickness of 10 m and a resistivity of 40–125 Ohm.m, which probably indicates the shallow Tukosmeru volcanic, as indicated on the geological map. Below that, a 20–30 m thick layer of low resistivity exists along the first 400 m of the profile, reflecting moderately to highly weathered saturated basalt with good groundwater potential. This formation appears to be overlying a fresher layer with lower groundwater potential, either due to its higher porosity (if it is scoriaceous basalt) not allowing groundwater to be held within the pores, or due to its more impermeable nature (if it is massive basalt). Past the 400-m mark, the groundwater-bearing layer extends throughout the entire profile depth until 520 m, where a very low-resistivity feature suggests the possible presence of clay, interpreted as lower groundwater potential.

Line 6: North Tanna – Laketam

Line 6 was performed around Laketam Village, a relatively busy area considering the popular *nakamal* (kava bar) and football field nearby. A distance of 400 m was covered along a SW–NE direction.

According to the inverted profile, a layer 10–20 m thick sits on top of a lower-resistivity layer that extends until the maximum investigation depth of ~90 m (Figure A6). Again, these two layers are interpreted as representing the younger and less weathered Tukosmeru volcanics overlying the older Green Hill volcanics, and this is supported by the geological map (Figure 3) and the generalised geological cross section (Figure 4). At this stage, tentative resistivity ranges of 40–150 Ohm.m and 5–40 Ohm.m can be assigned to the Tukosmeru and Green Hill volcanics, respectively. In terms of groundwater development, the central section between 175 m and 210 m should preferably be targeted in order to avoid some possible low-yielding clay formations indicated by the lower-resistivity values.

Line 7: Middle Bush – Imaru

Survey line 7 was the first line performed in the Middle Bush area. According to the geological map and geological cross section, the Tukosmeru pyroclastic deposits are rather thick in this area and it was questionable whether the contact with the Green Hill volcanics would have been caught by the survey. Nevertheless, a 700-m section was covered using the maximum electrode spacing of 5 m to investigate at depth. A large number of negative resistivities were recorded, and as a consequence, the model simulation resulted in high absolute error (24.6%).

The prevailing resistivity range is 50–100 Ohm.m, possibly indicating the Tukosmeru group extending to ~90 m (Figure A7). Small aquifer systems seem to be present where the resistivity range is between 15 Ohm.m and 50 Ohm.m, and constrained between high-resistivity (125–500 Ohm.m) massive features that are able to withstand weathering. These block-shaped higher-resistivity features are probably large pyroclastic rocks. The high-resistivity feature at 365–415 m could be related to an intrusive dyke although no volcanic centres have been identified in this area. Possible fractures seem to be present on either side of the dyke-like feature, with favourable resistivity ranges (30–50 Ohm.m) in terms of groundwater potential. The deeper part of the central section of the profile, between 220 m and 360 m, suggests groundwater potential.

Line 8: Middle Bush – Imaru

Survey line 8 was performed within 200 m and parallel to survey line 7 in an E–W direction. The inverted profile and resistivity variations look very similar to survey line 7 (Figure A8). The prevailing resistivity ranges between 50 Ohm.m and 125 Ohm.m, and the block-shaped, high-resistivity pyroclastic features were again observed. The second half of the section (275 m onwards) is governed by somewhat lower resistivity in the range of 50–75 Ohm.m; therefore, if drilling is to be undertaken along this survey line, this part should be preferred.

Line 9: Middle Bush – Lamnatu

Survey line 9 was carried out in a S–N direction along the main road south of Lamnatu Village and not far from the Lenarpil water tanks. About 600 m were covered using a 5-m interval between electrodes to increase efficiency and depth.

The profile reveals two distinct resistivity layers overlying each other (Figure A9). A 10–20 m thick layer, with a resistivity range between 50 Ohm.m and 125 Ohm.m, overlies a lower-resistivity (15–50 Ohm.m) layer, extending all the way to the bottom of the profile. According to the general geological profile (Figure 4), the Tukosmeru deposits are expected to be thinner in this area and moving towards the north, as compared with the Imaru area. The two layers observed in the modelled profile probably represent the younger and less weathered Tukosmeru deposits overlying the older Green Hill deposits. Moderately- to highly-weathered volcanics present good groundwater development potential along the entire profile. These are expected to be intercepted at 20–30 m depth. Drilling should preferably be performed in the section between 230 m and 380 m along the profile due to especially favourable resistivity ranges (15–20 Ohm.m).

Line 10: Middle Bush – Lamnatu

This 700-m survey line was performed along the same road past Lamnatu Village using a 5-m electrode spacing to target the possible extent of the main lineament, which cuts the eastern slopes in an ENE–WSW direction.

The resistivity distribution resembles the previous survey line, although there is a more pronounced presence of the younger and more resistive Tukosmeru pyroclastic deposits with noticeable block-shaped pyroclastic rocks (Figure A10). In terms of groundwater potential, the section between 110 m and 275 m distance along the profile presents higher potential due to a favourable resistivity range (20–40 Ohm.m).

Line 11: Middle Bush – Naluken

Survey line 11 followed the same concept as the previous two lines and was performed between the villages of Naluken and Lowyaru. It covered a distance of 1200 m with an electrode spacing of 5 m. The presence of a subsurface spring, in conjunction with an E–W lineament feature, was a decisive factor in exploring the groundwater potential.

The hydrogeological model conceptualised so far for Middle Bush, with the younger Tukosmeru deposits overlying the older Green Hill volcanics, was again present (Figure A11). High development potential generally exists along the entire profile at depths greater than 15–20 m below the surface. The section between 200 m and 620 m along the profile seems to offer the most ideal conditions in terms of resistivity range.

An interesting, high-resistivity (250–750 Ohm.m) feature exists at shallow depth at 1040 m along the profile, coinciding with the location of the subsurface spring. This geophysical feature could represent a subsurface conduit, such as a volcanic tube or void feature, supporting the existence of the spring.

Line 12: Middle Bush – Fetukai

The last survey line covered 400 m in an E–W direction close to Fetukai Village. The line ran across a N–S running dry stream in order to explore the groundwater potential associated with the presence of this lineament. The line also aimed at providing geographical coverage for the northern part of Middle Bush.

Again, good groundwater potential exists and is associated with the presence of weathered and possibly fractured volcanics of the Green Hill group, which are encountered at 15–20 m depth (Figure A12). The section between 210 m and 270 m along the profile offers good potential for groundwater development.

4.2 Hydrogeological conceptual model

Consolidating the findings from the different survey lines, it is concluded that groundwater in North Tanna and Middle Bush occurs mainly within the Pliocene Green Hill volcanic deposits. These basaltic and other pyroclastic deposits, partly exposed in North Tanna and covered in the Middle Bush by the more recent, Pleistocene Tukosmeru volcanics, have undergone sufficient weathering to offer suitable conditions for groundwater occurrence.

In North Tanna where this group is generally exposed, weathering is significantly progressed to form a layer that is 40–50 m thick of what is believed to be clay-rich weathered basalts. This is observed at very shallow depths along survey line 1 close to Lownaleng Village. The presence of these weathering products may complicate groundwater development due to their low permeability. These low-resistivity formations are underlain by higher-resistivity formations that represent low to zero groundwater content. This could either be due to the compact and impermeable character of the formation (i.e. massive basalts) or due to the highly porous character not allowing groundwater to be held within the pores (i.e. scoriaceous basalts). It is, therefore, difficult to interpret the groundwater potential near the contact between the two zones. Drilling operations in these areas may need to extend beyond these clay-rich formations, which in many cases appear to be present at depths up to 55 m below the surface. Moreover, groundwater occurrence in North Tanna, where volcanic activity has been intense as evidenced by the presence of eruptive cones, may be dictated by the presence of intrusive dykes, which can compartmentalise groundwater and fracture the neighbouring massive rock, creating suitable conditions for groundwater accumulation. Groundwater occurrence zones are distinct and limited to the width of geological features (fractures). Drilling should, therefore, be targeted to exact locations, as proposed in the next section.

In Middle Bush, the Green Hill deposits are located at 20–30 m depth and groundwater occurrence below this depth is expected to be relatively homogeneous. This suggests better development potential compared with North Tanna, and more flexibility when selecting drilling locations. Based on the modelled resistivity profiles, clay appears to be less extensive in the Green Hill deposits in Middle Bush, suggesting that weathering did not progress as far as it did in North Tanna, probably because of the more recent Tukosmeru protective cover. In the southern Middle Bush (Imaru), the Tukosmeru volcanics become significantly thicker, and the Green Hill deposits could not be identified in the resistivity profiles. Groundwater occurrence in these pyroclastic deposits is limited to small, probably low-yielding, aquifers.

4.3 Groundwater resources development

A large number of drilling targets with increased groundwater potential were identified in the two study areas (Table 6). Nine targets are proposed for North Tanna and eight targets are proposed for Middle Bush. It is not expected that all targets will be required to be drilled, and the final selection and prioritisation of targets should be made by the Department of Water Resources after communication with local communities. This chapter serves to facilitate the selection process. It should be noted that although the coordinates refer to specific locations along the survey lines, it is generally accepted that the actual drilling location be selected within close proximity to the nominated target, unless otherwise stated. It is also recommended during investigative drilling to drill to nominated drilling depths and acceptable airlift yield of groundwater is achieved, as monitored with the V-notch weir during drilling. The airlift yield is purely realised by the pressurised air used during the drilling for the removal of cuttings and is, therefore, only a rough and conservative indication of the actual borehole yield, as calculated with the pumping test once the borehole is complete.

Along survey line 1, three sites are proposed (Figure A1). Sites TA-NT-GHL1 and GHL2 target features interpreted as potentially fractured basalts. The proposed sites indicate good potential to produce useful yields considering the large storage capacity expected in the thick overlying clay-rich weathered layer. Drilling through clay-rich formations should be expected until the productive formation is encountered. Site TA-NT-GHL1 could suit the needs of Lownalag Village, which was identified as a priority village by local communities. Sites TA-NT-GHL2 and TA-NT-GHL3, being conveniently located close to Green Hill Village, also indicate good groundwater potential, providing an important water supply for the inhabitants who currently, during dry periods, have to walk a long distance downhill to fetch stream water.

Table 6. Proposed drilling targets

Site	Location	Longitude	Latitude	Distance along profile	Elevation (m)	Expected depth to water-bearing zone (m)	Expected total depth (m)
TA-NT-GHL1	Green Hill	169.307217°	-19.376061°	90	390	10	70
TA-NT-GHL2	Green Hill	169.304438°	-19.376645°	390	380	10	70
TA-NT-GHL3	Green Hill	169.299179°	-19.377586°	975	334	10	70
TA-NT-IMF1	Imafin	169.296736°	-19.349146°	107	430	10	60
TA-NT-IMF2	Imafin	169.303260°	-19.350114°	885	428	10	60
TA-NT-ENU1	Ehniu	169.298938°	-19.362827°	63	327	5-10	30-40
TA-NT-ENU2	Ehniu	169.300527°	-19.362895°	101	298	5-10	40-50
TA-NT-LWT1	Lawital	169.295173°	-19.371976°	515	295	10	60
TA-NT-LKT1	Laketam	169.299940°	-19.370465°	197	309	10	60-70
TA-MB-IMR1	Imaru	169.309195°	-19.492503°	345	360	25	80
TA-MB-IMR2	Imaru	169.308952°	-19.491860°	423	360	10	70
TA-MB-IMR3	Imaru	169.303818°	-19.489845°	277	355	65	100
TA-MB-LMT1	Lamnatu	169.314361°	-19.475453°	223	388	25	80
TA-MB-LMT2	Lamnatu	169.314501°	-19.474419°	340	378	20	80
TA-MB-LMT3	Lamnatu	169.312777°	-19.466715°	120	360	20	60
TA-MB-NLK1	Naluken	169.308499°	-19.454547°	300	342	25	80
TA-MB-NLK2	Naluken	169.308893°	-19.452453°	540	340	20	80
TA-MB-FTK1	Fetukai	169.304150°	-19.428039°	127	328	15	55
TA-MB-FTK2	Fetukai	169.303149°	-19.428275°	238	332	15	70

Survey line 2 is considered to be the less promising survey line in terms of groundwater potential due to the high absolute error and, thus, higher uncertainty, the general absence of zones in the good resistivity range with regards to groundwater potential (i.e. 15–50 Ohm.m). Two targets are proposed along survey line 2 (Figure A2). Again, the exposed Green Hill volcanic deposits are considered to have undergone substantial weathering, resulting in a thick, clay-rich weathered layer forming below the surface. Water-bearing formations may be expected at depths > 25 m, depending on the location, and drilling through clay and saprolite should generally be expected. In case high-permeability formations are encountered and groundwater from the overlying clay-rich formation is lost, back-filling with cement should be considered. Site TA-IMF1 is located close to the edge of the inverted profile and the resistivity distribution with depth is not easily interpreted. Nevertheless, the site is proposed as the only location that is conveniently located to serve the purposes of the much-in-need Lownimhapon communities. Site TA-NT-IMF2 is proposed in potentially fractured weathered basalts and is conveniently located to supply water to Imafin communities.

For Ehniu Village, two targets were identified along survey lines 3 and 4. The water-bearing formation is expected to be encountered at 5 m depth. The proposed sites could conveniently feed the existing water tank to manage droughts more efficiently.

One drilling target is proposed along survey line 5 in Lawital Village. Target TA-NT-LWT1 could potentially provide high groundwater yields, and the water-bearing formation should be encountered at ~10 m depth.

A promising target is proposed in Laketam Village along survey line 6. Improved groundwater yields are indicated by the geophysics at site TA-NT-LKT1. The water-bearing formation should be encountered within ~10 m. The location is conveniently located in the village and close to the popular *nakamal* and football field.

Survey lines 7 and 8 revealed a complex geology with moderate groundwater potential. Nevertheless, due to the water shortages that the Imaru community frequently faces, three potential drilling targets with the greatest potential for a useful groundwater supply have been identified. The proposed sites along line 7 target either side of a near-vertical, high-resistivity feature that was interpreted as a possible intrusive dyke. Although the sites are within close distance of each other, the massive high-resistivity feature is expected to act as a boundary to groundwater flow, preventing the two boreholes influencing each other. The aquifer is expected to be encountered at 15-20 m depth at site TA-MB-IMR1 and at ~5 m depth at site TA-MB-IMR2. Especially at site IMR2, it is recommended to keep as close to the identified coordinates as possible. A third target was proposed at 278 m distance along survey line 8. Although the main water-bearing formation is expected to be encountered at great depth (65 m), the resistivity distribution suggests the presence of a rather large groundwater body with good groundwater potential.

Survey line 9 indicates good promise in terms of groundwater potential from the resistivity results. The entire line seems to be underlain by high-yielding groundwater bearing deposits starting at 15–20 m depth. The proposed sites TA-MB-LMT1 and TA-MB-LMT2 are based on low-resistivity zones encountered along the profile. Boreholes drilled along this profile, if of sufficient yield, could be pumped to the existing water tanks in Lenarpil to support the current water supply network, which presently does not operate at full capacity due to insufficient surface water sources.

Useful yields are also expected at proposed target TA-MB-LMT3 along survey line 10 and the main groundwater-bearing formation should be encountered at ~15 m. Similarly to the previous line, this target could also pump into the Lenarpil water tanks and support the existing water supply system.

Survey line 11 presents good groundwater potential based on resistivity results, and two drilling targets are proposed. Both targets – TA-MB-NLK1 and Ta-MB-NLK2 – indicate useful groundwater volumes, with the aquifer expected to be encountered beyond 15–25 m depth.

Finally, two targets are proposed along survey line 12 to cover the northern part of the Middle Bush area. Sites TA-MB-FTK1 and TA-MB-FTK2 are identified in locations with good groundwater potential.

4.4 Drilling recommendations

It is recommended drilling 10” (inch) boreholes in order to allow for the installation of no less than 5” of PVC casing with at least 2” annular thickness on either side. This is considered the minimum annular thickness to allow for the proper placement of the gravel pack material. Such casings will allow the placement of a 4” submersible pump capable of producing adequate flow rates to serve the purposes of a community production well. It is also important that the pump is powerful enough to lift groundwater from the large depths indicated in Section 4.3, and possibly to higher elevations where water tanks may be present. If a 4” casing is installed, this will limit the pump size to 3”, which will restrict the flow rate to 0.3–0.4 L/sec for 50–70 m of total head pressure (indicative of an average 3” solar submersible pump).

With regards to the PVC casing, it is recommended that PN 12 PVC-U pressure pipe is used (Australian Government National Water Commission 2012). PN 6 PVC-U pipe, PVC-U sewer and drainage pipes should never be used because they have a low collapse pressure and could result in bore failure.

It is important to monitor the airlift yield during the drilling as well as logging the lithology of the cuttings coming out of the drilled hole. These two observations can give valuable insights with regards to screening or slotting the borehole casing. Sudden increases in the airlift yield, measured preferably with a V-notch weir, are indicative of fractured intervals and water-bearing zones with substantial groundwater volumes. Fractured intervals can also be inferred by careful assessment of drill cuttings. Discoloration or the presence of clays can imply the presence of fractures and joints where groundwater can flow and advance the weathering of the formation along the fracture. When adequate yield is achieved, the drilling should be stopped and the casing should be screened or slotted along the intervals which represent these water-bearing formations.

The placement of gravel pack is recommended. The screen slots should be narrow enough to keep out the gravel. The use of numerous short (~5 cm), narrow slots with a 2-cm spacing between them and covering the entire circumference is preferred. Slots should be perpendicular to the pipe and can be made in the field using a hacksaw. The gravel pack should consist of washed, well-rounded gravel.

A gravel pack is required when the water-bearing formation is so fine that no screen would be suitable to maintain the flow of water into the borehole. When developing boreholes in hard rock, a gravel pack while not required is recommended. During borehole development, settling of the gravel pack and maximum specific capacity of the bore are achieved.

When drilling through fractured rocks, it is highly recommended using a casing advancement system. This is to protect against collapsing of the borehole walls and prevent the hammer from being stuck. Moreover, the steel casing will confine the pumped air and allow for better circulation and a more effective airlift of cuttings and foam. Otherwise, in highly porous and fractured formations, the air may escape through the pores and fractures and circulation may be lost. This, in turn, will prevent the hammer from drilling farther due to inadequate back-pressure and will increase the risk of the hammer getting stuck. If a casing advancement system is not available, it is possible to backfill with cement the newly drilled part of the borehole and continue the next day by re-drilling through the cement after it has set. Care should be taken, however, to avoid cementing along productive intervals where the water-bearing formations are present.

After development, a formal pumping test should be performed to establish the indicative yield of the borehole and to determine the hydraulic properties of the groundwater system. It is recommended to pump for at least eight hours followed by a two-hour recovery phase, with water table and flow logging at time intervals that increase logarithmically.

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Annex 1 – Inverted resistivity profiles

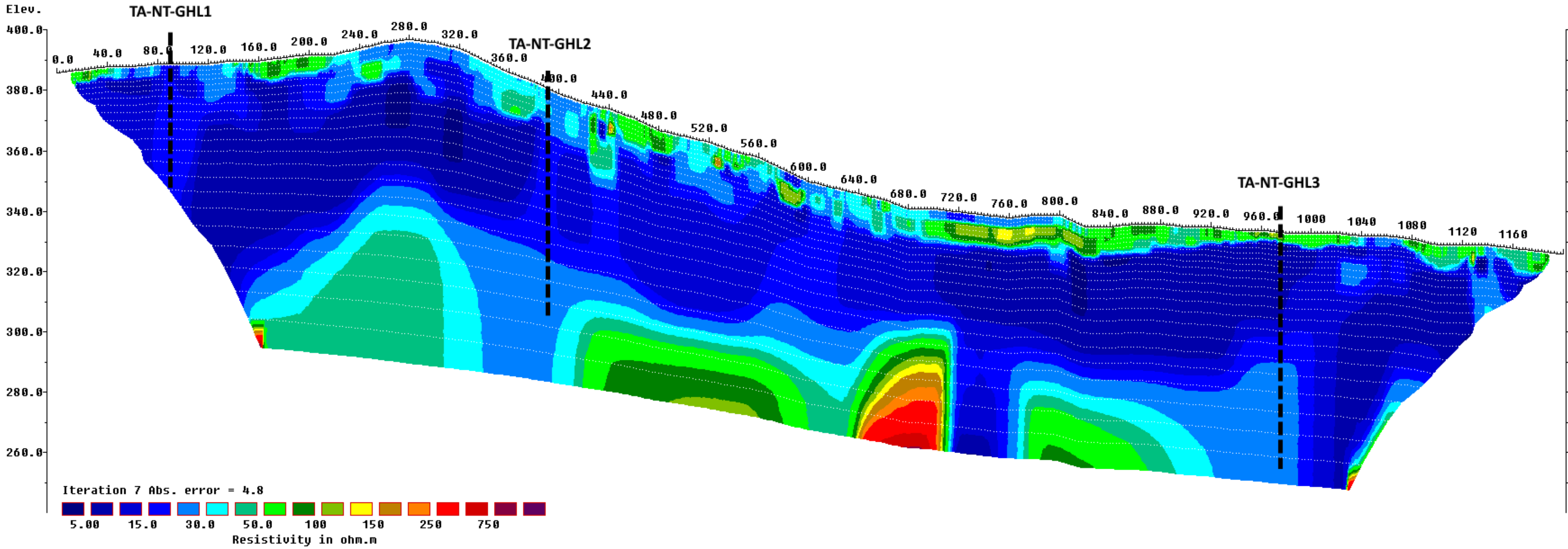

Figure A1. Resistivity profile and proposed drilling targets along survey line 1 (Lownaleng – Green Hill).

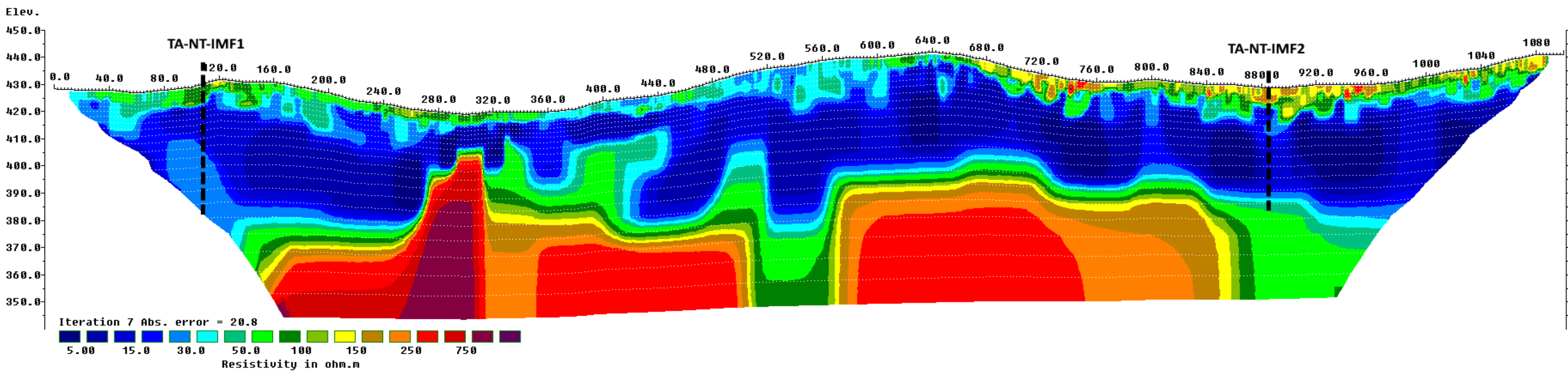

Figure A2. Resistivity profile and proposed drilling targets along survey line 2 (Lownimhapon – Imafin).

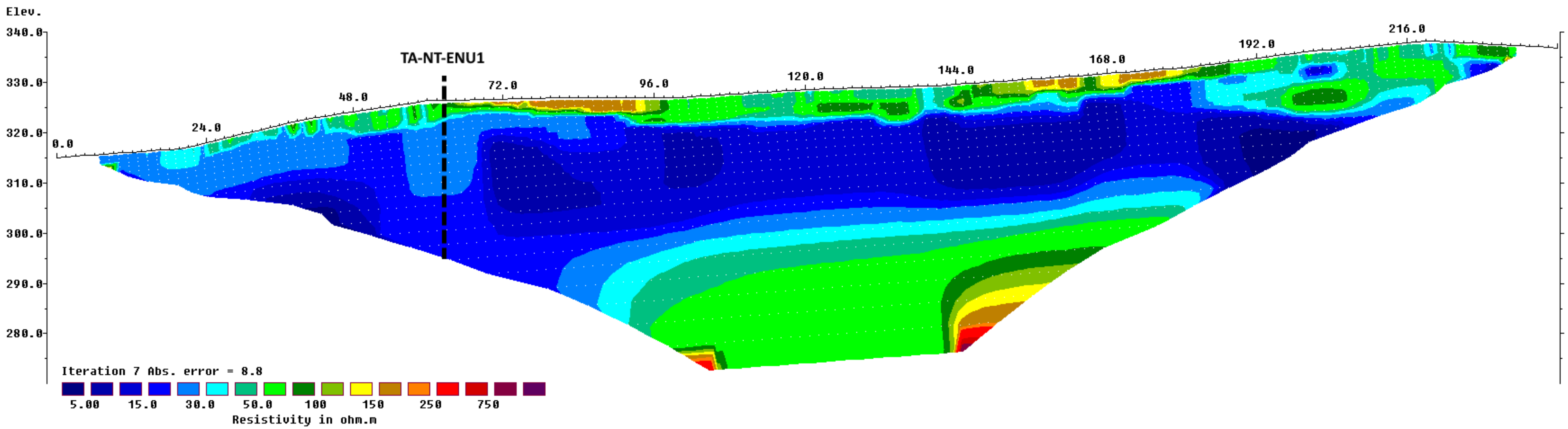

Figure A3. Resistivity profile along survey line 3 (Ehniu 1).

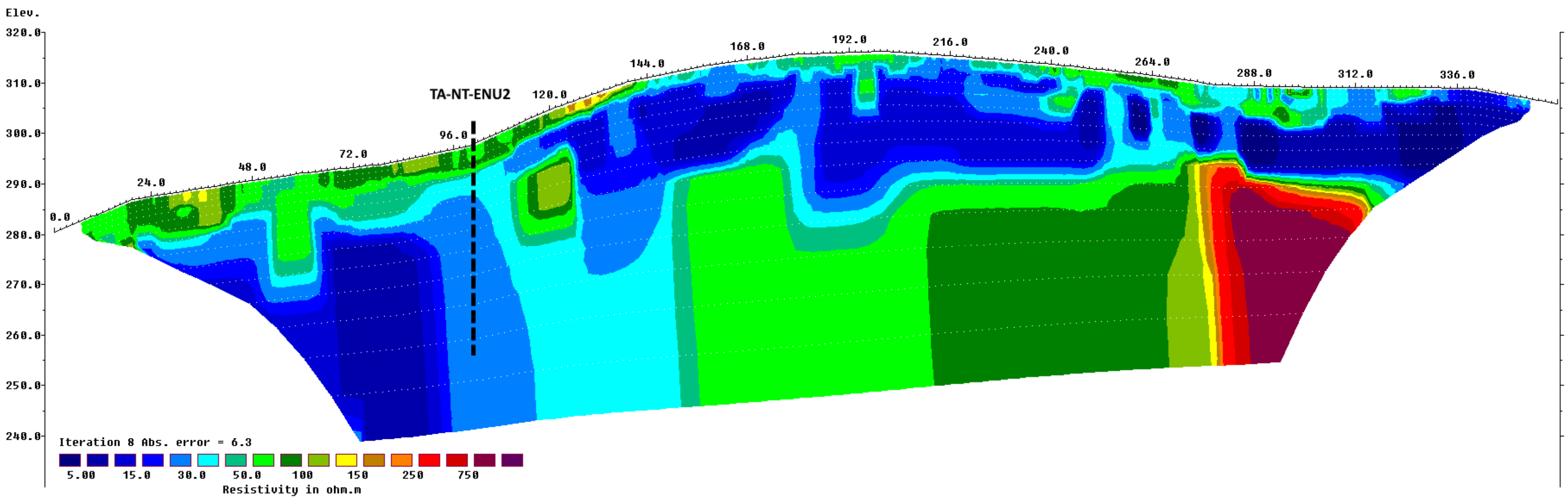

Figure A4. Resistivity profile and proposed drilling targets along survey line 4 (Ehniu 2).

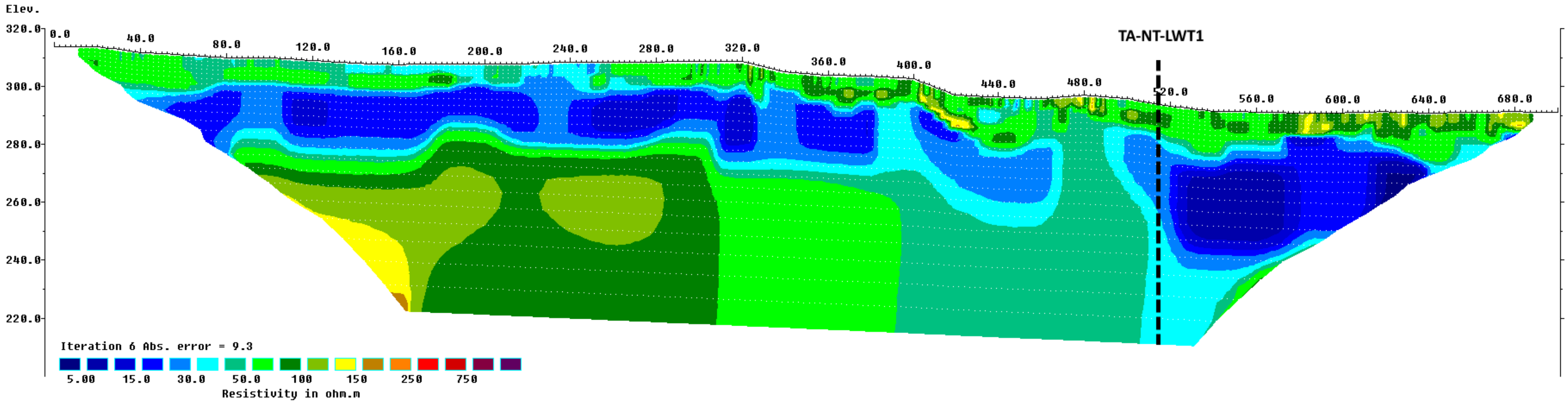

Figure A5. Resistivity profile and proposed drilling targets along survey line 5 (Lawital).

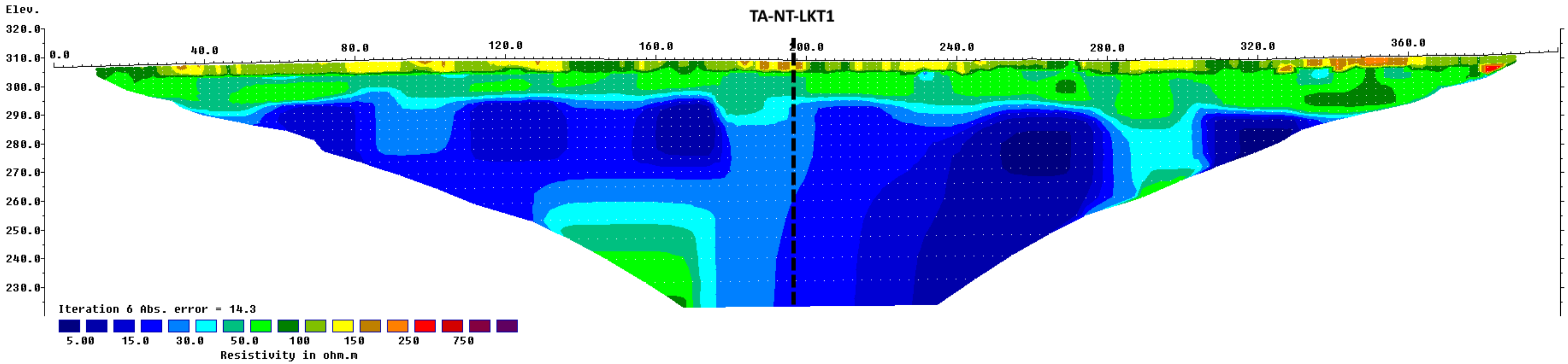

Figure A6. Resistivity profile and proposed drilling targets along survey line 6 (Laketam).

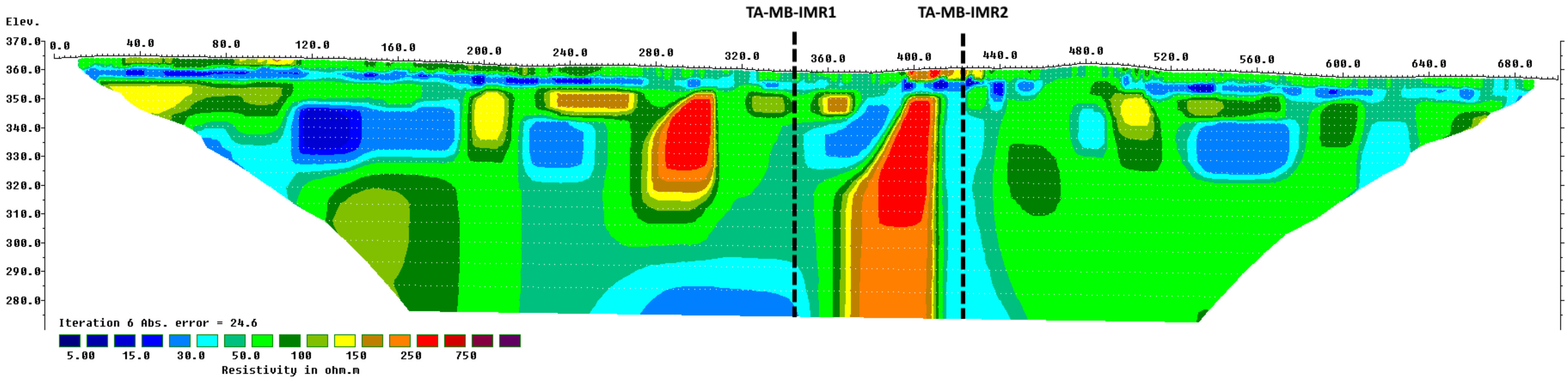

Figure A7. Resistivity profile and proposed drilling targets along survey line 7 (Imaru 1).

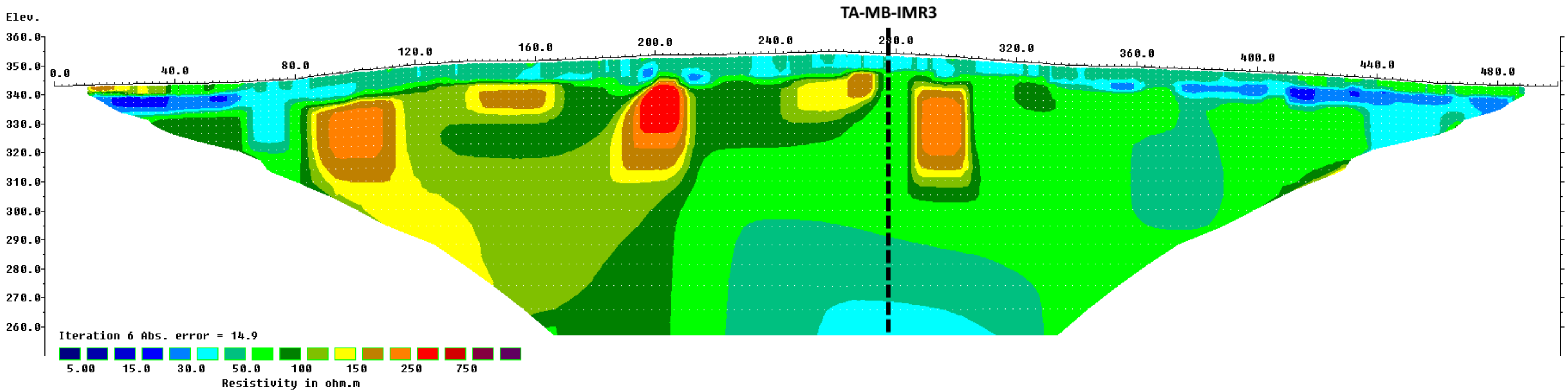

Figure A8. Resistivity profile along survey line 8 (Imaru 2).

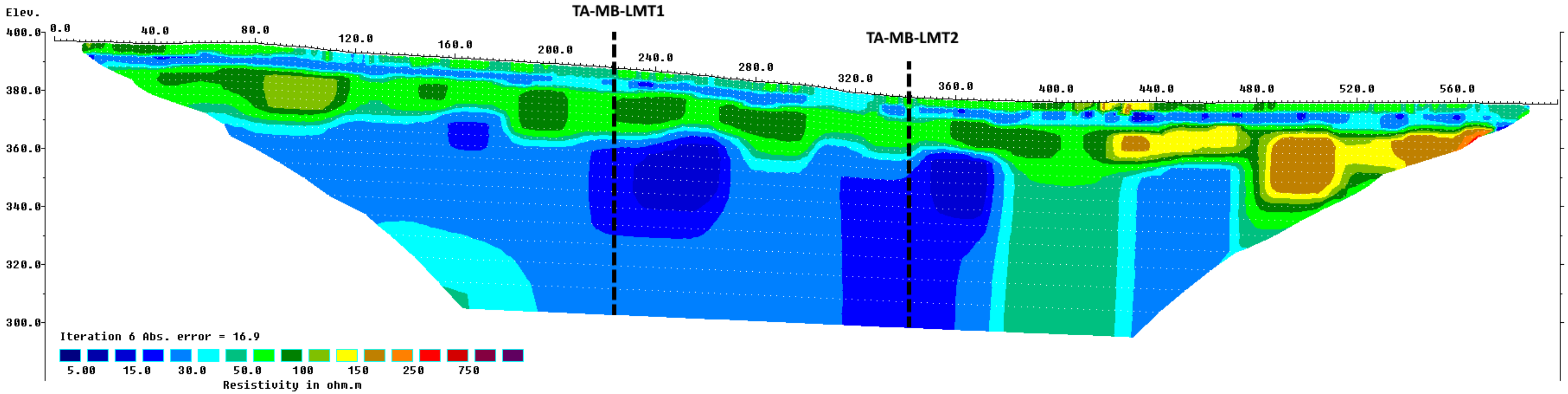

Figure A9. Resistivity profile and proposed drilling targets along survey line 9 (Lamnatu 1).

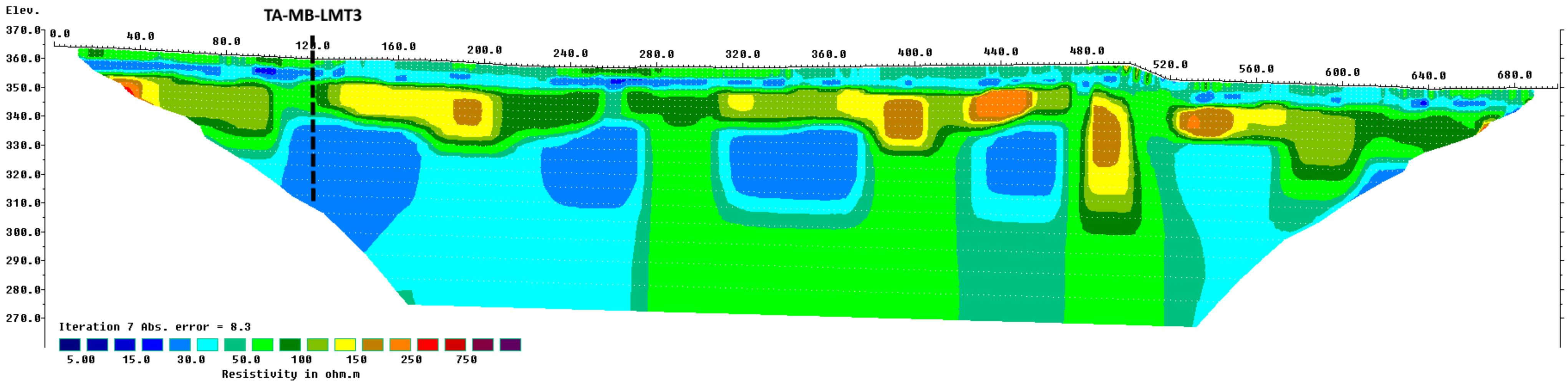

Figure A10. Resistivity profile and proposed drilling targets along survey line 10 (Lamnatu 2).

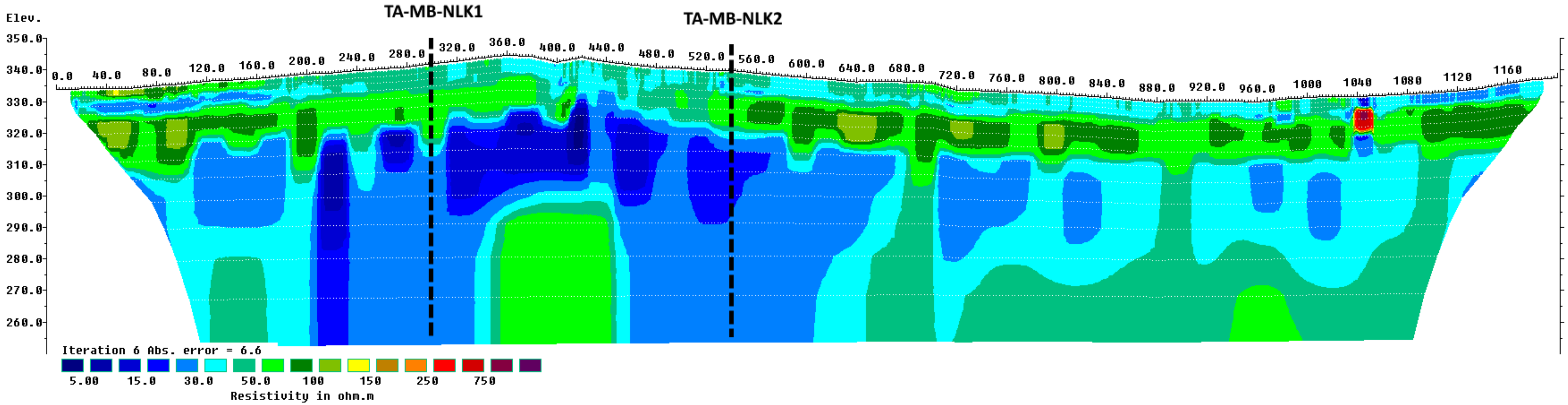

Figure A11. Resistivity profile and proposed drilling targets along survey line 11 (Naluken).

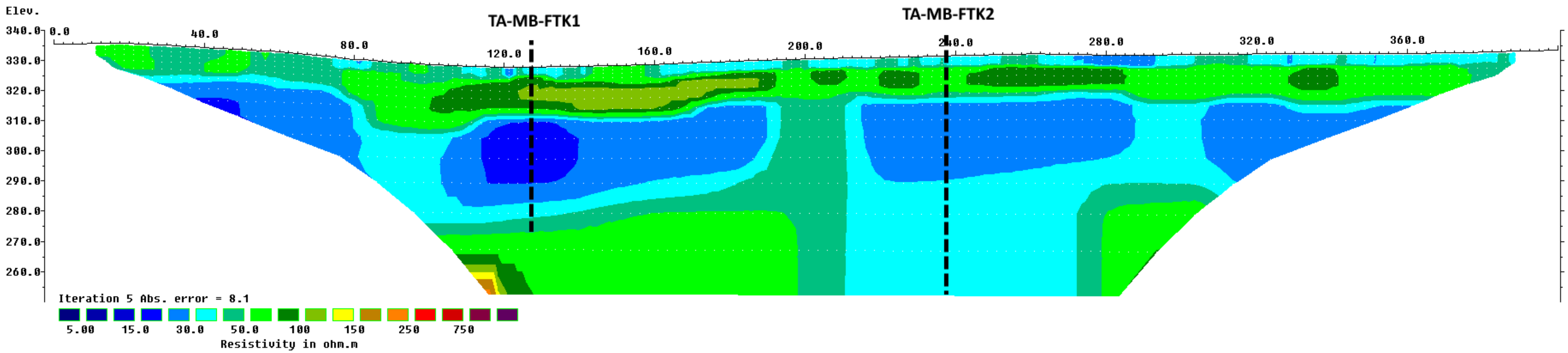

Figure A12. Resistivity profile and proposed drilling targets along survey line 12 (Fetukai).

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