Pacific Community
Communauté du Pacifique

Strengthening water security of vulnerable island states

Groundwater investigation Aitutaki, Cook Islands

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Anesh Kumar and Peter Sinclair

NEW ZEALAND
FOREIGN AFFAIRS & TRADE

GEM
Geoscience,
Energy and
Maritime
Division

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GROUNDWATER INVESTIGATION

AITUTAKI, COOK ISLANDS

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Geoscience, Energy and Maritime Division of the Pacific Community

Suva, Fiji 2018

Original text: English

Pacific Community Cataloguing-in-publication data

Antoniou, Andreas

Strengthening water security of vulnerable island: groundwater investigation - Aitutaki, Cook Islands / Andreas Antoniou, Aminisitai Loco, Anesh Kumar and Peter Sinclair

(SPC Technical Report SPC00058)

1. Sea level — Climatic factors — Cook Islands.
2. Floods — Cook Islands.
3. Water — Cook Islands.
4. Climatic changes — Management — Cook Islands.
5. Climatic changes — Environmental aspects — Cook Islands.
6. Climate change mitigation — Cook Islands.

I. Antoniou, Andreas II. Loco, Aminisitai III. Kumar, Anesh IV. Sinclair,

Peter V. Title VI. Pacific Community VII. Series

577.220 99623 AACR2

ISBN: 978-982-00-1152-6

Prepared for publication at SPC's headquarters, B. P. D5, 98848 Noumea Cedex, New Caledonia, 2018

www.spc.int
Printed by Quality Print Limited, Suva, Fiji, 2018

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Acknowledgements

This work was part of Pacific Community’s ‘Strengthening Water Security of Vulnerable Island States’ project, which is funded by the New Zealand Ministry of Foreign Affairs and Trade, to support Pacific Island governments and communities to build the skills, systems and basic infrastructure to better anticipate, respond to, and withstand drought and its impacts on supplies of safe and adequate drinking water. Key partners and stakeholders that contributed to the implementation of this mission include:

- Pa Enua Division, Office of the Prime Minister
- Infrastructure Cook Islands
- Cook Islands Meteorological Office
- Ministry of Health
- New Zealand Aid Programme and the New Zealand Ministry of Foreign Affairs and Trade
- Aitutaki Island Government
- Aitutaki Water Works Division

The community members of the Aitutaki Island Council, as well as the island mayor and deputy mayor played a key role by participating in community meetings and sharing their views on the proposed work.

Aitutaki airport authorities are acknowledged for allowing resistivity surveys to be conducted along the runways.

1. Introduction

1.1 Project background

The project, ‘Strengthening Water Security of Vulnerable Island States’, is supported by the New Zealand Ministry of Foreign Affairs and Trade and implemented by the Disaster and Community Resilience Programme (Geoscience, Energy and Maritime Division). The five-year (2014–2019) NZD 5 million project is being carried out by the Pacific Community in the Cook Islands, Kiribati, Republic of the Marshall Islands, Tokelau and Tuvalu, supporting atoll countries to build the skills, systems and basic infrastructure to better anticipate, respond to, and withstand the impacts of drought.

1.2 Mission objectives and outcomes

The main purpose of this investigation was to identify fresh groundwater resources that could complement existing water supplies or serve as a backup during dry periods. Additional objectives included assessing existing water supply schemes in conjunction with current and projected water demand, reviewing existing monitoring infrastructure, investigating fresh groundwater discharge around the coast, and analysing rainfall and groundwater quality.

The development of new groundwater resources requires: 1) investigating groundwater resource potential and optimal drilling targets; 2) drilling and constructing boreholes and assessing the yield and quality of groundwater; and 3) equipping boreholes with pumps and storages that are aligned with the resource potential and the community’s needs and resources. The current work focused on the first component. This was achieved through the use of geophysics to better understand the local hydrogeology and the groundwater flow and storage potential. Recommendations are given on potential drilling locations, expected yields and expected groundwater quality. Recommendations are also given as to how to optimise the current water supply scheme so as to maximise efficiency in the use of existing resources, and in combination with new resources becoming available through this study.

2. Background

2.1 Geographical location and land use

Aitutaki is a low volcanic island with a total area of 16.8 km^2 and is the main island of Aitutaki Atoll, which comprises 15 other islets in the southern Cook Islands. Two of these islets are also volcanic while the rest are made of coral and coral sands. Aitutaki Atoll is located at 18° 51' 0.00" S, 159° 47' 24.00" W, and is approximately 250 km north of Rarotonga, the capital of the Cook Islands. Aitutaki has a maximum elevation of 123 m (Maunga Pu hill) and a total population of approximately 2000. Coral sands extend on the lower areas around its perimeter, and particularly in the northern part of the main island. Alluvial flats and swampy depressions are also found around the coast.

The main land-use activities, besides housing and tourism, are related to agriculture. A number of crops (cabbages, tomatoes, bananas and cassavas) are cultivated in many parts of the island. Taro is grown in swamps around the edge of the island. Small household piggeries and free-grazing goats are occasionally found.

Aitutaki is subdivided in 8 districts, which are further subdivided into 19 *tapere* (subdistricts), a form of traditional land subdivision existing in the southern Cook Islands. Most *tapere* lands are subdivided among the minor lineages.

Figure 1. Map of Aitutaki showing districts and subdistricts. Source: www.ontheworldmap.com

2.2 Climate summary

Climate in the Cook Islands and the long-term distribution of rainfall are largely determined by the South Pacific Convergence Zone (SPCZ), the Southern Hemisphere's most expansive and persistent rain band, extending from the equatorial western Pacific Ocean southeastward towards French Polynesia. During the wet season, the SPCZ is active, bringing unsettled weather and rain over the Cook Islands. However, during the dry season the SPCZ is weak and brings dry trade winds from the southeast over the group (Rongo and Dyer 2014). The SPCZ's position varies with the El Niño Southern Oscillation (ENSO), moving a few degrees northward during moderate El Niño events, and southward during La Niña events. It has been observed that El Niño years tend to bring cool and dry conditions to the southern Cook Islands while during La Niña years the southern Cooks experience warm and wet conditions (Vincent et al. 2011).

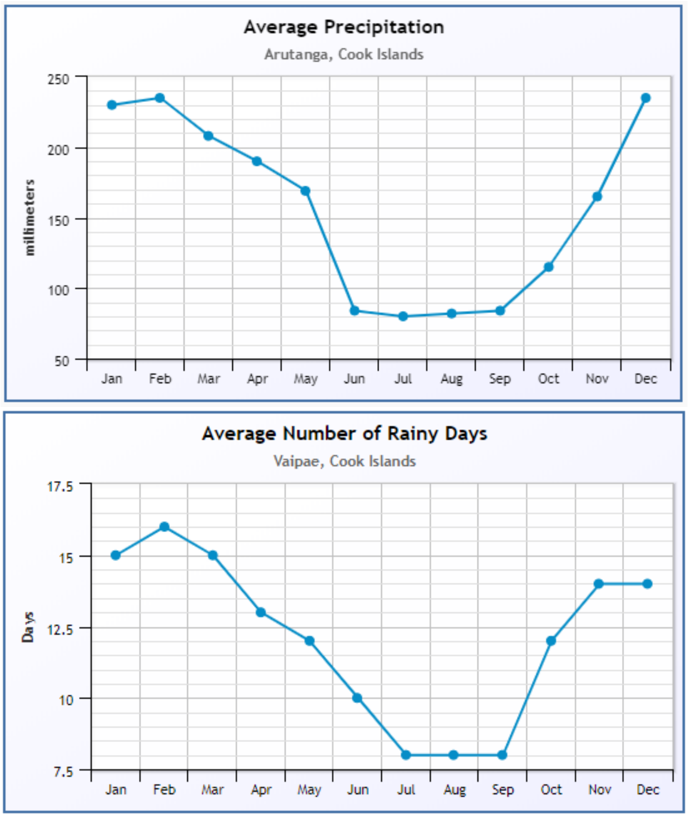

Figure 2. Monthly average precipitation and number of rainy days as recorded at the Arutanga (66 years on record) and Vaipae (29 years on record) rainstations, respectively.

On average, 1877 mm of precipitation falls annually on Aitutaki, as recorded in the Arutanga rain station over the last 66 years, with the wet period being between November and May and the dry period between June and October. The wettest month is February, with 16 rainy days on average over the last 29 years. The months of July, August and September had, on average, eight rainy days over the same period. The average annual temperature is 25°C, with an annual range of ±2 degrees.

Rainfall records for Aitutaki airport (18^0 49' 46.31" S 159^0 46' 00.17" W, elevation 7 m) extend for 94 years (1924–2018), with a mean annual rainfall over that period of 1872 mm. There is a distinctive dry season of five months from June to October. During this five-month period, the lowest rainfall on record was 131 mm, recorded in 1932.

The coefficient of variation (CV) for rainfall is used as an index of climatic risk as it describes the variability of rainfall that can be expected from the average. It is calculated as the standard deviation over the mean rainfall and often expressed as a percentage. The higher the CV of rainfall, the more likely that the rainfall over the specific period will vary from the average. The annual coefficient of variation for rainfall in Aitutaki is 23.8%, and taking into account the average annual rainfall of 1872 mm, this suggest low to moderate climate risk. However, when considered with respect to the dry season (June to October) where the average rainfall of 437 mm over five months is realised, the CV for rainfall increases to 46.6%, which indicates that during the dry months and lower rainfall and higher rainfall variability, the climatic risk is moderate to high.

A statistical analysis of meteorological droughts on Aitutaki's rainfall levels reveals that, while droughts are more common during an El Niño phase than during a La Niña, it is in the neutral phase of ENSO that meteorological droughts are more likely to occur. A rainfall index is commonly used to classify drought over different time periods, where meteorological droughts correspond to the lowest 10% of rainfall recorded for that rainfall index (i.e. within the driest 10% of all previous such months of rainfall totals). A three-month index is obtained by first summing the month's rainfall and that of the preceding two months, and ranking this relative to other three-month sums over the same period for the entire record. Based on a three-month index, meteorological drought periods on Aitutaki range from 2 to 28 months, with an average duration of 6 months, and a drought is expected to occur, on average, every 18 months.

Rainwater harvesting as a water source requires regular rainfall to maintain supply. Periods of greater than a few weeks of low rainfall, as has been experienced during the dry season, have implications for water security on Aitutaki where there is a reliance on rainwater harvesting. During these periods, rainwater harvested water sources are at risk. Groundwater has the potential to provide drought resilience during these periods as these water sources are less dependent on recent rainfall.

2.3 Previous investigations

The hydrogeology of Aitutaki has been investigated a number of times over the last 50 years. In 1969, a number of holes were drilled in the volcanic hills to study the lithology and investigate for groundwater (as cited in Waterhouse and Petty 1986). Some of these holes served as production wells but eventually became blocked. Additional holes were drilled in 1979 (as cited in Waterhouse and Petty 1986) but the results were not satisfactory from a community supply perspective. Part of these drilling programmes are described by Waterhouse and Petty (1986) who summarised the hydrogeological information available for the entire country.

Earlier in 1978, Waterhouse and colleagues, investigated existing groundwater sources for quantity and quality as well as possible drilling sites. Binnie and Partners (1984) evaluated the water resources of Aitutaki and investigated the possibility of well drilling. In 1987, Dale and colleagues investigated, through the use of geophysics, the groundwater resource potential in the areas along the old and new airport runways. They concluded that these areas hold significant volumes of fresh groundwater that could supplement existing water resources on Aitutaki.

Falkland (1994) began a new series of investigations that mainly focused on the Vaipeka area, and investigated the extension of the existing Vaipeka gallery associated with increasing water supply needs. As part of this project, a number of monitoring bores were drilled in three different parts of the island, five of which were drilled in the Vaipeka area to allow for the monitoring of groundwater salinity and to improve the management of abstraction.

These studies served as a baseline for planning the current investigation and interpreting the obtained results. More information obtained from these studies is presented in the following chapters.

2.4 Geology and groundwater occurrence

Aitutaki is generally subdivided into three major geological units (Fig. 3). The northern hilly area is mainly composed of basaltic volcanic lavas and pyroclastics (Binnie and Partners 1984). The presence of coral fragments found in basaltic scoria indicate that this area was formed upon a pre-existing reef (Wood and Hay 1970). Exposures of nepheline basalts, tuffs, scoria and breccias are present in the area surrounding Maunga Pu hill. Lithological logs from two boreholes drilled at Akataaia and Amuri School (Table 2 and Table 3) describe a weathered profile containing clay and extending up to 13 m in depth. Weathered alluvial volcanic strata, forming a series of flat topped terraces, are predominantly present in the southern part of the island (Waterhouse and Petty 1986). Cemented beach rock and coral sands are found along the coasts and particularly in the southern and northern coastal margins.

Groundwater in boreholes drilled in the northern hilly area (Table 1) occurs at depth, indicating the presence of a basal aquifer where groundwater accumulates. The presence of coastal springs at various locations around the island indicates that groundwater from the basal aquifer discharges into the sea. Thin aquifers occur in the coral sands where fresh groundwater floats on top of seawater, forming a shallow freshwater lens, particularly in the area along the airstrip, which shows similar characteristics to coral islands found in atolls.

Table 1. Summary of selected boreholes.

Borehole	Year	Depth (m)	Elevation (m)	Depth to water (m)
Piraki	1969	76	84	43.4
Teaupana	1969	44	47	21.5
Akataaia	1979	43.9	42	37.1
Amuri school	1979	12.6	12	10.9

Source: Waterhouse and Petty 1986

Table 2. Lithological field description of the Akataaia borehole.

Elevation (m)	Depth (m)	Lithology
41.5	0	Dark purple brown firm clay, very weathered scoria, black iron and some whitish-yellow fragments
39.5	2	Same as above, but with some red iron and plentiful pale yellow fragments
36.5	5	Same as above but harder with scoriaceous breccia and calcite
32.5	9	More red, still very weathered volcanics, whitish calcareous fragments
28.5	13	Yellow coral and grey volcanics
26	15.5	Dark grey, reddish grey scoria, plentiful white yellow coral
24	17.5	Yellow, very fine, non-calcareous mudstone, plentiful black staining and soft brown clay; scoria
22	19.5	Same as above but with no clay. Fresh hard orange yellow baked non-calcareous mudstone, black staining, grey hard friable scoria
14.5	27	Medium-dark grey moderately hard friable fresh scoriaceous basalt
2.5	39	Firmer drilling, some water loss
-2	43.5	Same as above but with more fractured red scoria. Core description: very dark grey vesicular basalt. Yellow vesicles some ‘washed out’. Yellow and orange fine-grained vein material. Green olivine crystals
-2.1	43.6	Core description: dark grey vesicular basaltic breccia, plentiful reddish veins, vesicles, black staining. Bottom fragments almost all red
-2.3	43.8	End of borehole

Source: Waterhouse and Petty 1986

Table 3. Lithological field description of the Amuri School borehole.

Elevation (m)	Depth (m)	Lithology
12	0	Medium tan-brown clay, some black iron fragments
9	3	Yellow light brown clay, black iron lumps
7	5	Whitish, red and pink very weathered basalt. Gritty white clay

The area surrounding the Vaipeka galleries was studied in detail by Turner and Falkland (1996) through the drilling of monitoring boreholes undertaken during the extension of the existing gallery in 1996. Five boreholes were installed and valuable lithological logs were recorded during the drilling operations (Table 4). From these studies, a three-layer geological model was generally observed in the Vaipeka area, with the top layer reflecting transported volcanic sediments sitting on top of residual volcanic material (Layer 2) formed from the intensive in situ weathering of basaltic rock formations. The third layer represents the basal volcanic rock with varying degree of weathering and a much higher permeability compared with the upper two layers. According to salinity measurements (Table 9) undertaken during the drilling, as well as at later times (including during this work), indicate that a relatively thick (15–25 m) fresh groundwater body occurs in the area, overlying brackish water. Lithological logs obtained during the drilling of monitoring boreholes AIT4 and AIT5 indicated that very low permeability volcanic sediments are located to the east of the Vaipeka galleries acting as a protecting barrier from seawater intrusion from the lagoon and vice versa reducing the loss of fresh groundwater towards the lagoon.

An additional borehole (AIT6) was drilled on the southeastern side of the eastern airstrip, offering valuable lithological information (Table 5) in this fairly different, from a geological perspective, part of the island. It was concluded that a reasonably thick (~10 m) freshwater lens overlies seawater, and its thickness is dictated by the depth to the high-permeability limestone layer encountered at 11 m depth according to the lithological log.

Table 4. Lithological field description of AIT1, AIT2, AIT3 and AIT7 monitoring boreholes (Turner and Falkland, 1996). Site elevations: AIT1: 1.35 m, AIT2: 1.64 m, AIT3: 1.52 m, AIT7: unknown.

Depth AIT1 (m)	Depth AIT2 (m)	Depth AIT3 (m)	Depth AIT7 (m)	Lithology
0–10.3	0–8.3 (k=2.6 m/day)	0–6 (k=0.61 m/day)	0–4.2	Transported volcanic sediments (slope wash): clays, clayey gravel, sandy clayey gravel
10.3–22.9	8.3–13.3 (k=4.3 m/day)	6-13 (k=0.02 m/day)	4.2–9.0	Residual volcanic material: silty clays and clayey gravels formed from the intensive in-situ weathering of the basaltic rock formations
22.9–25.0	13.3–19.2	13–21	9.0–14.7	Volcanic rock: basalt with varying degree of weathering and fracturing

Table 5. Lithological field description of AIT6 monitoring borehole, site elevation: 3.3 m.

Depth (m)	**Lithology**
0–11	Coral sands and gravel: fine to coarse grained, loose to medium density
11–019.8 (k=16.9 m/day)	Limestone (older): cemented coral and coral sands
19.8–23.0	Completely weathered basalt, seen as gravelly silty clay: either transported or residual volcanic material

Source: Turner and Falkland 1996

2.5 Current water supply

Aitutaki relies mostly on rainwater for its potable water needs, with households collecting rainwater and storing it in tanks. In addition, there are a number of community tanks that collect rainwater from the roofs of community buildings. These are located in central locations around the island, and in recent times the water from these community buildings has been treated using UV technology and made available to the community through community filling stations for drinking water purposes.

The non-potable water supply is sourced from six groundwater infiltration galleries. These are located at Vaipeka, Vaipae, Tautu, Vaimaru, and Vaitekea (Fig. 3). The biggest proportion of the non-potable water supply is produced in Vaipeka where two galleries exist at close distance to each other. The original Vaipeka gallery (gallery 1) is equipped with two pumps (pump station 1 and 2) at ~110 m distance from each other, while gallery 2 was constructed during the Australian-funded Vaipeka gallery extension program in 1999 and was equipped with a single pump (pump station 3). Groundwater produced from pump stations 2 and 3 is piped to the Punganui tank while groundwater produced from pump station 1 is piped to the Piraki tanks from where the water is distributed to households via a piped reticulation network. The three pumps operate at a nominal flow of 3 L/sec each, and while pump station 1 operates continuously, abstraction alternates between pump station 2 and pump station 3 normally every three hours. All galleries are operated by the island council. A number of private galleries also exist on the island, which are mainly used by resorts to cover their water needs. During dry periods, some villages such as Vaipeka, Tautu and Vaipae suffer from reduced flows in their reticulated supply. Water with a salinity above 1500 µS/cm EC is generally unsuitable for drinking water purposes, but may be suitable for secondary purposes.

3. Field survey methodology

3.1 Electrical resistivity tomography survey

Electrical resistivity tomography (ERT) geophysics was used to assess, visualise and identify the lateral and vertical variability in electrical resistivity response within the different geological units around the island. The method works on the principle of injecting 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. Resistivity of the subsurface is a function of porosity of geological medium, hydraulic permeability, electrical conductivity or salinity of pore fluids, and clay mineralisation, and can provide insight into the underlying geology and hydrogeology.

The ABEM Terrameter LS2 from GuidelineGeo Inc. was used in combination with the multiple gradient array as the preferred survey protocol, offering a high horizontal and vertical data resolution (Darlin and Zhou 2006). 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. An electrode separation range of 2–5 m was selected, depending on the permissible survey space, to investigate depths ranging from 30 m to 80 m, respectively. The orientation of the survey profiles and traverse distance was guided by the review of geological maps, satellite photos, and existing groundwater drilling and gallery development records so as to adequately investigate the groundwater potential of either the inferred fractures within the multiple-flows volcanics or the shallow coastal sediments.

Table 6 shows the different geological materials that may be encountered on Aitutaki and the corresponding resistivity range that is likely to be measured.

Table 6. Resistivity ranges for different rocks and sediment types.

Rock and sediment type	**Resistivity (Ohm.m)**
Clay containing brackish to saline water	< 3
Clay containing brackish to fresh water	5–8
Clay, silty sand, and some gravel saturated with fresh water	11–25
Weathered basalt containing fresh water	30–60
Fresh basalt saturated with saline water	30–40
Fresh basalt saturated with fresh water	300–700
Dry coral sediments	500–1000

Source: Zohdy and Jackson 1969

3.2 Model inversion methodology

Model inversions were performed using RES2DINV software (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 resistivity colour bar was used to allow comparisons between the inverted profiles.

Prior to running the model inversions, the raw exported database was first treated to remove any 'negative resistivity' readings that might affect the accuracy and reliability of the inversion. These erroneous readings indicate the electrode's inability to read a realistic difference in electrode potential, and contribute 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 Nyqvist, Product manager, Guideline Geo Group MALÅ/ABEM, 2017, pers. comm.). The presence of seawater with very low resistivity along the coastal survey lines is another factor that can contribute to noisy datasets. After removing the negative values, a preliminary inversion was carried out using all of the remaining data points. Then, using the 'RMS error statistics' option that displays the distribution of the percentage difference between the logarithms of the measured and calculated apparent resistivity values, bad data points having an error of 100% and above were further removed. A final inversion was then carried out using the new filtered dataset, allowing for a much lower absolute error compared to the first run, providing improved confidence in the datasets.

The inversion process of some of the coastal survey lines became unstable due to large resistivity contrasts. This necessitated increasing the damping factors to allow for a stable completion of the inversion process. In these cases, both initial and minimum damping factors were increased and allowed the program to automatically calculate the value to increase the damping factor with depth.

Finally, for a number of inversions and particularly the coastal ones, the 'severe reduction of the effect of side blocks' option was selected in RES2DINV to obtain a more realistic resistivity distribution along the edges of the inverted profiles.

3.3 Selection of ERT survey locations

As per the objective of the mission, detailed assessment work was undertaken around the island into the three major geological units as proposed and mapped by Binnie and Partners (1984) (Fig.3), considering all the historical geological and hydrogeological information, relevant data from existing water supply infrastructure, and the need to explore supplementary groundwater sources that are capable of meeting projected increases in water demand and withstand extreme climate conditions. These geological units include:

- The coastal sands and beach deposits that are already developed mainly as private groundwater gallery systems from Amuri beach and extending into both the old and current airstrips. The assessment here was aimed at identifying areas of appreciable freshwater lens development that can be utilised for public water supply. The survey lines undertaken in this area include: Golf course, Old Runway, Vaipeka and the six lines along the new runway (Runway-1 to Runway-6). The areas around the golf course and along the airport runways have been suggested by Dale et al (1987) as suitable areas for the installation of groundwater galleries which would be able produce small but consistent fresh groundwater volumes. The area along the Vaipeka galleries was selected due to the importance of these galleries, which currently provide 60% of Aitutaki's reticulated water supply. According to drilling logs (Turner and Falkland 1996) the Vaipeka area is underlain by shallow coastal sediments and weathered volcanics. There are instances of increased salinity, as reported by the Aitutaki Water Works Department, which prompted this assessment to consider the cause of groundwater deterioration, be it overabstraction or blocked gallery arms causing the infrastructure to perform as a single well and thus accelerating upconing and saline intrusion.

- The younger volcanics unit located between Piraki and Maunga Pu hills and the contiguous rugged terrain and a caldera around the northwest. The assessment aimed at investigating the presence of exploitable groundwater-bearing fractures or fissures that were identified from satellite images and may be used to supplement existing water supply or be used as emergency sources. The survey lines undertaken in this area include: Piraki-1, Piraki-2, Maunga Pu and Crater. Previous investigations (Waterhouse and Petty 1986) have suggested the presence of groundwater potential in this geological unit. The survey lines Vaimokora, Vaikoa-1, Vaikoa-2 and Vaipeka were conducted along the edge between the younger volcanics and the coastal sands.
- The older volcanics unit which according to Binnie and Partners (1984) are composed of multiple volcanic flows capped by thick clay formations around Vaipae and Vaitekea. Here the investigation targeted possible weathered or fractured volcanics that can be developed as a water supply source and piped to a 1 ML storage tank that is planned to be constructed near the hospital. The survey lines undertaken in this area include: the three lines in Vonnias, Vaipae and Vaitekea. Infrastructure Cook Islands also requested that the assessment extend into a proposed gallery development site, located in Vaitaparoro, in the Taravao area (Fig.1 and Fig. 3). The proposed Vaitaparoro site, situated in a moderately vegetated and confined valley, is aimed at supplementing the water supply around the area, where excessive water disruption is reported to be caused by reduced water pressure in the existing distribution system. The national government has already committed resources for this infrastructural development as is evident through the successful land acquisition, vegetation and land clearance around the area, and the installation of several test pits and hand-auger sites to provide guidance on location and installation depth of the gallery. Advice was received from the geotechnical team that the area is underlain by thin strata of coastal sediments that overlay thick clay derived from completely weathered basalt. Salinity levels in the test pits demonstrated acceptable levels, although they slightly increased towards the southeastern end due to proximity to the lagoon. Thus, the resistivity survey was conducted with the following objectives:
    - investigate the spatial variability of the thickness of the coastal sediments (both lateral and vertical) to determine the thickness of the aquifer materials, which in turn will guide the placement of gallery wells and arms; and
    - establish areas of reduced resistivity response within this target formation that may suggest saline intrusion.

A submarine groundwater discharge (SGD) study was also undertaken amid the interest around understanding the dynamics of groundwater discharge and flow patterns into the lagoon as evident by the numerous coastal springs. This assessment also considered the health of groundwater-dependent ecosystems and impacts of poor water quality into the lagoon should wastewater follow similar flow paths. This assessment, undertaken in front of Vaporia Beach House at Amuri beach where a number of known SGD points were observed, was initially designed to be conducted over a 24-hour period to capture a complete tidal cycle and to determine the variation in SGD during this period. A four-cable spread was set up along the beach parallel to the shoreline, with a 2-m interval between electrodes to allow for a detailed visualization of resistivity in the shallow subsurface. The intention was to obtain a resistivity ‘screenshot’ every two hours to visualise the tidal effect on the salinity in the existing fresh groundwater conduits. Due to technical difficulties, however, only two resistivity screenshots could be obtained separated by a two-hour interval.

Table 7. Summary of survey lines.

Survey line	Distance (m)	Electrode spacing (m)	Start point	End point
Crater	1000	5	18°50'36.74"S 159°46'19.22"W	18°50'9.93"S 159°46'24.34"W
Golf course	225	3	18°49'40.18"S 159°46'13.12"W	18°49'33.47"S 159°46'10.10"W
Maunga Pu	900	5	18°50'35.19"S 159°46'55.30"W	18°50'51.46"S 159°46'32.67"W
Old runway	720	3	18°49'39.51"S 159°46'30.10"W	18°49'45.99"S 159°46'6.48"W
Piraki-1	900	5	18°51'11.89"S 159°47'13.54"W	18°50'46.05"S 159°47'2.82"W
Piraki-2	400	5	18°50'50.28"S 159°47'3.00"W	18°50'56.53"S 159°46'52.19"W
Runway-1–5	160	2	18°49'52.40"S 159°45'52.99"W	18°50'38.83"S 159°45'29.15"W
Runway-6	400	5	18°50'15.75"S 159°45'40.67"W	18°50'27.44"S 159°45'34.69"W
Paradise cove (SGD)	160	2	18°50'10.88"S 159°46'58.54"W	18°50'14.33"S 159°47'2.60"W
Vaikoa-1	500	5	18°50'38.92"S 159°47'27.59"W	18°50'30.55"S 159°47'13.04"W
Vaikoa-2	360	3	18°50'15.16"S 159°47'0.36"W	18°50'9.25"S 159°46'49.87"W
Vaimokora	400	5	18°49'56.45"S 159°46'24.44"W	18°50'1.13"S 159°46'11.85"W
Vaipae	600	5	18°52'9.52"S 159°47'4.04"W	18°52'13.40"S 159°46'43.97"W
Vaipeka	900	5	18°51'13.62"S 159°46'44.56"W	18°50'49.12"S 159°46'31.75"W
Vaitekea	1000	5	18°52'21.47"S 159°47'46.95"W	18°52'31.59"S 159°47'15.00"W
Vonnias-1	700	5	18°51'48.61"S 159°47'49.65"W	18°51'50.17"S 159°47'26.07"W
Vonnias-2	365	5	18°51'50.43"S 159°47'23.92"W	18°51'50.59"S 159°47'11.65"W
Vonnias-3	400	5	18°51'50.27"S 159°47'10.28"W	18°51'47.88"S 159°46'56.88"W
Vaitaparoro-1	150	2	18°53'20.15"S 159°47'16.65"W	18°53'23.44"S 159°47'12.97"W
Vaitaparoro-2	68	2	18°53'24.09"S 159°47'14.87"W	18°53'22.30"S 159°47'13.52"W
Vaitaparoro-3	80	2	18°53'23.41"S 159°47'15.89"W	18°53'21.00"S 159°47'14.87"W

3.4 Assessment of tidal and abstraction influences on groundwater

Existing infrastructure allowed for adequate monitoring of groundwater throughout the entire study period. Groundwater was monitored through the existing monitoring wells, production galleries and existing test pits.

All sampling tubes installed inside each monitoring well were measured for electrical conductivity (EC) and temperature. To ensure that the measurement was representative of that depth, prior to recording the measurement each sampling tube was pumped using a 12-V FLOWJET pump until the EC value of the pumped groundwater was stabilised. Three loggers (Schlumberger Divers) were installed in the selected production wells in Vaipeka gallery 1 and gallery 2 (Fig. 3), and in an investigation pit situated along survey line Vaitaparoro-3 to record temperature, pressure and conductivity changes in the groundwater over a 10-day period, from 6 to 16 March 2018. The objective was to determine the hydraulic connection between the geological formations and oceanic influences as a guide to determining the tidal influence on the aquifer because tidal fluctuations have a significant influence on groundwater levels and salinity. For the Vaipeka gallery, being a major water supply source, the effects of abstraction in relation to periods of accelerated salinity increase was of great interest.

The loggers were suspended on stainless steel wire at a depth that ensured they were submerged below the water table at all times. A barometric logger was installed in the study area to compensate for barometric influences. The loggers were set up to record data every six minutes. Manual water level and EC readings were taken at the beginning and at the end of the 10-day monitoring period in order to validate the readings recorded by the loggers.

Ten unfiltered groundwater samples and one rain water sample were collected and analysed for major ions and metals (e.g. Fe, Mn). The samples were analysed at Hill Laboratories in Hamilton, New Zealand.

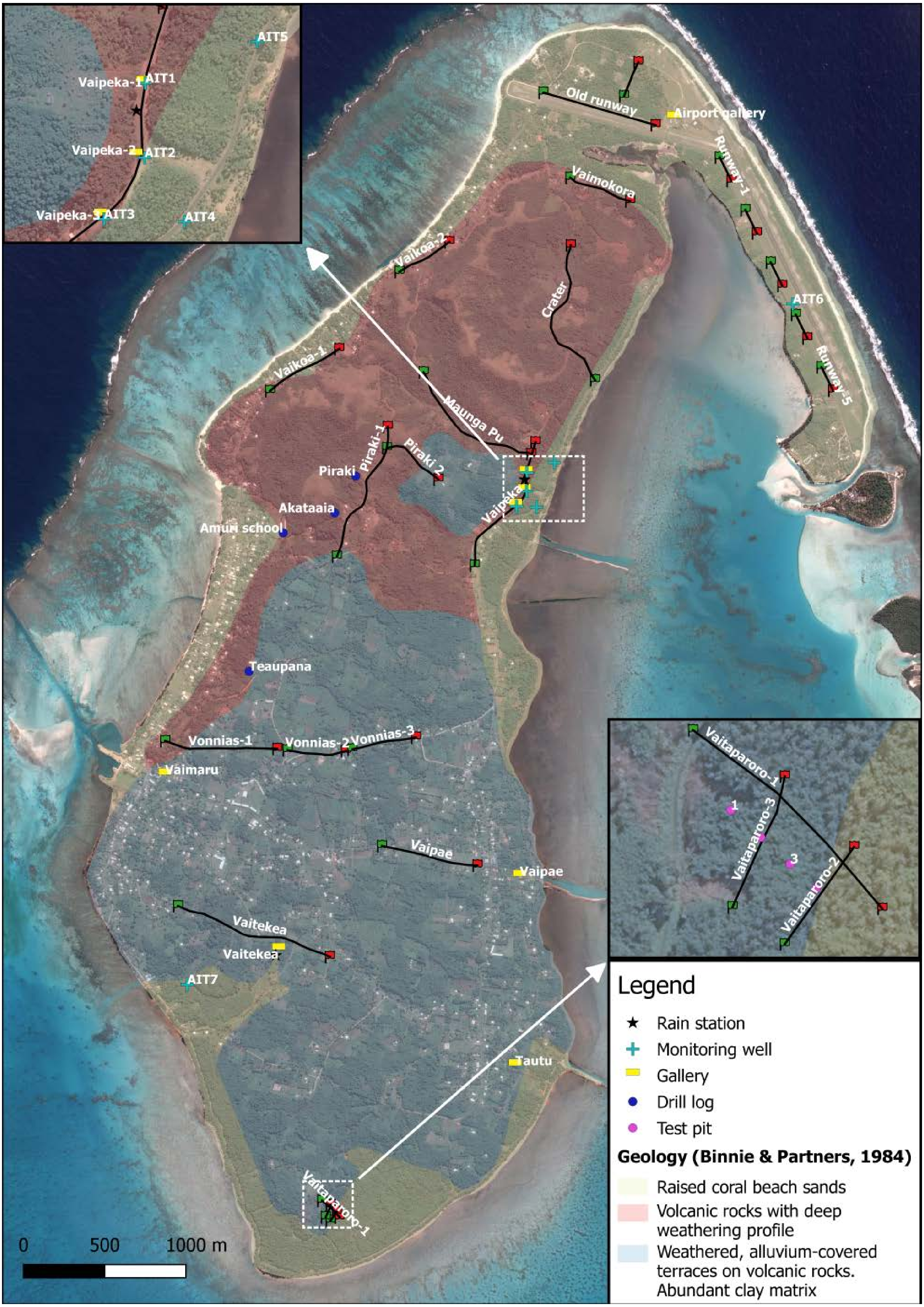

Figure 3. Geological map of Aitutaki (based on Binnie and Partners 1984) with locations of ERT profiles. Basemap: Google maps

4. Results and discussion

4.1 Geophysical results and interpretation

In this section, a general interpretation of the geophysical results is given for the three geological units present on the island. The modelled resistivity profiles are presented in Annex 1.

4.1.1 Raised coral beach sands unit

The first group refers to the lines that were run in the northern part of the island along the airport runways and next to the golf course. The interpretation of these survey lines is fairly straightforward as the observed distribution of resistivity displays a gradual decrease in resistivity with depth, reflecting the typical shape of a freshwater lens floating on top of seawater and separated by a transition zone.

Lithological changes with depth in this area have been documented by Turner and Falkland (1996) during the drilling of monitoring borehole AIT6 located approximately 700 m from the southern end of the new runway and approximately half way between the road and the runway (Fig. 3). According to the lithological log for AIT6 (Table 5), the first 11 m consist of fine to coarse-grained coral sands and gravels that become cemented to form a consolidated coral limestone extending up to 20 m in depth. Below this, completely weathered basalt is encountered (present as gravelly silty clays), believed to be either transported or residual volcanic material.

The observed resistivity changes are due to an increase in groundwater salinity with depth. According to groundwater salinity as measured in monitoring well AIT6 (Table 9), the freshwater limit occurs somewhere between 10 m and 14 m, matching with the depth to the limestone and suggesting that the limestone poses a limitation to the maximum freshwater thickness due to its higher permeability (14.4–16.9 m/day, Turner and Falkland 1996) compared with the overlying coral sands and gravels. In other words, the freshwater lens is truncated due to the higher permeability of the limestone.

In all survey lines located in the coral beach sands, the water table seems to be located at ~2.5 m in depth and the freshwater lens seems has a thickness of 7.5–12.5 m. The resistivity range of coral sands and gravels saturated with freshwater seems to be 50–150 Ohm.m while the higher resistivity (150–250 Ohm.m) features observed within this layer probably represent coral boulders or cemented sands with low volume of pore water present. The resistivity of unsaturated coral sands seems to be 500–1000 Ohm.m, in line with the literature values in Table 6. A thin (1–4-m thick) transition zone seems to underlie the freshwater lens represented by a sharp decrease in resistivity towards values, indicating saltwater saturation of the sediments. There are no indications of resistivity profiles of the interface (~20 m) between the limestone and the underlying weathered volcanics, probably due to the major influence of seawater on resistivity, masking any other lithological influence.

A similar pattern was observed along the Vaimokora line (Fig. A13), along the edge between the younger volcanics and the beach sands. Along the first 120 m, the very low resistivity layer encountered at shallow depth (~5 m) probably suggests the presence of seawater. This is likely due to the presence of an estuary extending inland towards the start of the survey line, possibly influencing the salinity of shallow groundwater. The presence of a freshwater spring located in-between the second half of the survey line and the estuary reinforces the interpretation of a relatively thick (30–40 m) freshwater body that seems to exist from 120 m onwards along the profile. It is believed that the spring is fed by fresh groundwater flowing from the volcanic hills towards the estuary via preferential pathways.

4.1.2 Younger volcanics unit

The ERT assessment was undertaken around the younger volcanics unit, extending from Piraki hill through the valley adjoining Maunga Pu hill, as well as the crater-like landform to the east. The aim was to investigate identified lineaments that may represent fractures and fissures that are potentially groundwater bearing. Two profiles were completed in the elevated topography of Piraki, and the other two traverses went through the relatively low elevation areas near Maunga Pu and through the crater.

The resistivity profiles revealed a three-layer geological model in the Piraki and Maunga Pu areas whereas the profile crossing the crater showed a rather different picture. Layer 1 is present in Piraki-1 (Fig. A5) and Maunga Pu (Fig. A3) profiles but is absent in the Piraki-2 area (Fig. A6) and is believed to represent in situ weathered volcanics consisting of clays and regolith, and exhibiting a low to intermediate resistivity response (30–100 Ohm.m). Below these surficial deposits lies a higher resistivity (150–500 Ohm.m) layer that may represent the scoriaceous volcanics that were intercepted by the Akataia bore between 5 m and 9 m below ground level (Table 2). The profound and extensive high resistivity may suggest compact and low permeability volcanics with negligible weathering. Water loss observed during the drilling of the old Akataaia bore (Table 2) suggests the presence of a shallow aquifer perched on semi-permeable deposits. This semi-permeable formation that essentially represents the younger volcanics crops out along the entire Piraki-2 profile where the capping weathered regolith is absent probably due to high-relief topography (also along the second half of Piraki-1). Layer 3 shows high lateral and vertical variability in resistivity and is characterised by a number of contrasting features. The contrasting resistivity may represent older volcanics with varying degrees of weathering and fracturing that may lead to increased permeability and potential groundwater occurrence. Very low resistivity zones (5–25 Ohm.m) represent most probably the clay-infilled fractures with the possibility of some groundwater occurring around them. High resistivity, vertically oriented features such as the one observed along the Piraki-1 profile (Feature 1) may represent vertically intruded dykes (Acocella and Neri 2009; Pryet et al. 2012; Underwood et al. 1995). During their upward intrusion, these dykes tend to fracture the country rock, sometimes creating favourable conditions for groundwater accumulation. Two low-resistivity features (Feature 2 and Feature 3) are observed on each side of the volcanic dyke, which may represent fractured volcanic rock. These dykes represent more recent volcanic activity, which resulted in the unweathered flows observed along most of the survey profiles (Layer 2).

Along the Maunga Pu profile, the deeper part of Layer 3 is dominated by a very low resistivity area, which could suggest the presence of brackish water, considering the negative elevation and the proximity to the lagoon towards the end of the profile. As re-inforced by the drilling records along the Vaipeka profile (which is intersected at the end of the Maunga Pu profile, Fig. 3), the resistivity profile suggests that the fractured basal volcanic rock, saturated with brackish water, is indeed encountered at depth.

The crater-like landform on the east of Maunga Pu hill (Crater profile, Fig. A1) presents a different pattern as high-resistivity, unweathered volcanics are generally absent except at the crater rim. This suggests that this crater forms part of an older volcanic center that has undergone significant weathering over time. Most likely, this was the source of the older volcanics, which are identified along most of the profiles as Layer 3. It is suggested that only Layer 3 is present along the Crater profile, showing advanced weathering of volcanic frameworks having high clay content. Weathering progressed slower on the crater rim due to the high-relief topography there. There is a strong possibility of basal saline water dominant at greater depth. Observations at the nearby quarry revealed the presence of moderately fractured volcanics with a number of spring-fed creeks with no evidence of clay formations at depth.

Vaipeka survey

The survey in Vaipeka was conducted along the existing galleries crossing the three monitoring wells for which drilling records are available (Table 4). The main observation from the resistivity profile (Fig. A15) is that the semi-permeable, younger volcanic layer (Layer 2) observed in the resistivity is not present in the area surrounding the galleries. Based on the resistivity and observations in the monitoring bores, it is suggested that fresh groundwater flows from the hills in the west forming a fairly thick groundwater body of relatively low salinity, as observed via the three monitoring boreholes (Table 9). The groundwater salinity distribution with depth, as recorded in the monitoring wells, indicates a substantial thickening of the freshwater body between AIT3 and AIT2, and this thickness is maintained up until AIT1 and possibly farther. It is suggested that the higher resistivity features identified near pump station 2 and 1 at depths of 5–25 m depth, coupled with the monitoring bore data, indicate a possible fresher groundwater flow along preferential pathways. Drilling records indicate that the basal volcanic rock is encountered at greater depth (23 m) in AIT1 as opposed to AIT3. The basal volcanic rock is expected to have varying degree of fracturing and the resistivity profile suggests that unweathered volcanic rock underlies AIT2 (Feature 1, Fig. A15) as opposed to weathered rock underlying AIT1 and AIT3.

4.1.3 Older volcanics unit

The three survey lines of Vaitekea, Vonnias and Vaipae were undertaken in the older volcanics unit. The resistivity profiles again show a three-layer geological model, with the top layer having a thickness of ~5 m and a resistivity of 35–100 Ohm.m, representing the in situ weathering of the younger volcanics deposits, which are clearly observed (Layer 2) below this surficial layer along all three profiles. Layer 1 consists of clays and regolith with variable porosity and moisture storage capacity.

Layer 2, having a high resistivity response of 100–500 Ohm.m and around 10 m thickness, may represent scoriaceous basaltic flows with no clear evidence of fracturing or weathering. The higher resistivity probably indicates a semi-permeable layer that can act as a hydrogeological constraint resulting in perched aquifer conditions in certain locations, but which may be more permeable at depth. At the time of the survey, the Vaitekea gallery (Fig. A16) recorded a water level of 1.5 m below ground and, with a total depth of 5.7 m, is probably situated at the base of Layer 1 with Layer 2 creating perched groundwater conditions, as suggested by Falkland (1994). Also, even though the Vaipae survey line did not extend all the way to the Vaipae gallery, it is expected that Layer 2 is still present at the location of the gallery, which pumps fresh groundwater from the base of the shallow perched aquifer.

Layer 3, with a resistivity range of 5–100 Ohm.m probably represents the older underlying volcanics with the low resistivity zones, demonstrating in situ weathering of basalts, similar to the residual volcanics recorded during the drilling of monitoring well AIT7 (Table 4). The varying resistivity responses could suggest varying degrees of weathering and/or fracturing occurring in the volcanics, and most importantly the difference in infilling materials. Clay-dominated zones would generate extremely low resistivity responses (5–20 Ohm.m) whereas zones having a resistivity range of 30–60 Ohm.m may represent a saprolitic or highly weathered composite and may be conducive for groundwater occurrence. High resistivity responses (75–600 Ohm.m) may represent fresh volcanic flows and vertical intrusive dykes (such as Feature 1 along the Vaitekea profile) with negligible weathering and limited groundwater potential. These dykes represent more recent volcanic activity which is considered contemporaneous with the unweathered flows observed along most of the survey profiles (Layer 2).

Vaitaparoro survey

Three survey profiles – Vaitaparoro-1, Vaitaparoro-2 and Vaitaparoro-3 – were completed on a proposed gallery site that had undergone vegetation clearance and in which four exploratory pits had been excavated. Results from the excavation exhibit shallow (2–3 m thick) strata of unconsolidated coral beach sand underlain by bluish grey clay, the weathered composite of the mapped volcanics. The marine deposits appeared to be a potential shallow aquifer (water quality measurements in the test pits are illustrated in Table 8).

Table 8. Water levels and salinity of groundwater in test pits aligned in a northwest to southeast direction at the Vaitaparoro site.

Test pit	Depth (m)	Static water level (m)	EC top (µS/cm)	EC bottom (µS/cm)
Pit 1	3.7	0.3	682	732
Pit 2	4.7	0.45	622	778
Pit 3	3.3	0.54	863	1032
Pit 4	1.6	0.36	774	777

The ERT profiles were performed using a 2-m electrode spacing to investigate in detail the thickness of the unconsolidated beach deposits atop weathered residual volcanics represented by clays. All three profiles revealed two layers of contrasting resistivity responses. Layer 1 having a resistivity response of 30–60 Ohm.m was interpreted as consisting of shallow and recent unconsolidated beach deposits, with the likelihood of groundwater storage. Layer 2, on the other hand, exhibits a very low resistivity response (5–25 Ohm.m), representing a clay layer with a thickness of at least 20 m. The ponding of water in the area suggests that fresh groundwater is perched on top of the low permeability clay layer.

The profile Vaitaparoro-1 was undertaken in a northwest to southeast orientation (Fig. 3) to assess the variation in thickness of potential aquifer materials and the possibility of saline intrusion towards the coast, as implied by elevated salinity readings in test pit 3 close to the southeastern end of the line. Layer 1 recorded an increasing thickness up to 5 m towards the southeastern end of the profile (Fig. A18). Profiles Vaitaparoro-2 and Vaitaparoro-3 were performed along a southwest to northeast orientation and revealed a uniform thickness of 2–3 m of shallow unconsolidated beach deposits.

4.2 External influences to groundwater

The electrical conductivity of groundwater was measured in all existing monitoring wells (Table 9) to obtain insight on the freshwater extent with depth. For comparison, the measured salinities are tabulated against measurements done during previous years (February 1996 and September 2015). As previously stated, a fairly thick fresh groundwater body exists in Vaipeka and particularly around gallery 1 (monitoring wells AIT1 and AIT2). Based on measurements performed in the wet season during this study, groundwater up to a depth of 25 m in AIT1 and AIT2 had an EC of <1100 µS/cm, whereas the EC did not exceed 1500 µS/cm in measurements performed at the end of the dry season (September 2015). In AIT3, groundwater was substantially more brackish, with EC values exceeding 1000 µS/cm at 3-m depth during the wet season (March 2018) and approaching 2000 µS/cm in the dry season (September 2015).

Table 9. Electrical conductivity (EC) of groundwater as measured in the monitoring wells in 1996 (Falkland 1996), 2015 (Tukua Upokomanu, Supervisor, Water Works Division, Aitutaki Infrastructure 2015, pers. comm.) and 2018.

Monitoring well	**Depth**	**EC (µS/cm)**			**Monitoring well**	**Depth**	**EC (µS/cm)**		
		Feb 1996	Sep 2015	Mar 2018			Feb 1996	Sep 2015	Mar 2018
AIT1-1	3	970	693	617	AIT4-1	3	-	1543	692
AIT1-2	6	590	689	718	AIT4-2	6	-	1678	1235
AIT1-3	9	560	646	583	AIT4-3	9	-	10250	5080
AIT1-4	12	545	789	669	AIT4-4	12	-	17240	8640
AIT1-5	15	685	924	950	AIT4-5	15	-	17520	11020
AIT1-6	18	729	1050	904	AIT4-6	20	-	11530	10860
AIT1-7	21	780	1389	1061	AIT5-1	3	3690	3450	1951
AIT1-8	24.5	730	1425	1068	AIT5-2	6	2370	1274	969
AIT2-1	3	1240	1297	1068	AIT5-3	9	6930	1050	883
AIT2-2	6	975	1300	785	AIT5-4	12	-	1364	1084
AIT2-3	9	855	1205	686	AIT6-1	4	870	-	466
AIT2-4	12	610	987	733	AIT6-2	7	1130	-	616
AIT2-5	15	700	1334	850	AIT6-3	10	1220	-	1127
AIT2-6	19	930	1468	708	AIT6-4	14	11050	-	8387
AIT3-1	3	970	1959	1195	AIT6-5	18	38700	-	37167
AIT3-2	6	1110	2213	1372	AIT6-6	22.3	46400	-	27867
AIT3-3	9	990	2420	1607	AIT7-1	3	570	-	-
AIT3-4	12	960	2653	1527	AIT7-2	6	460	-	-
AIT3-5	15	980	2599	1622	AIT7-3	9	510	-	-
AIT3-6	20.9	1010	4760	3403	AIT7-4	12	360	-	-

The automatically recorded changes in water level in Vaipeka pump station 3 (gallery 2, Fig. 4) indicate that the pump turns on and off every three hours (alternating with pump station 2 installed in gallery 1), except on certain occasions when the pump shuts down for nine hours, allowing the water level and the EC to recover during this period. These prolonged periods of shutdown allow for the EC in gallery 2 to drop just below 1000 µS/cm; however, upon starting up of the pump, the EC rises immediately and then gradually increases up to 1400 µS/cm before the next shutdown. During the regular three-hour shutdown periods, the EC drops to around 1100 µS/cm.

Pump station 1, installed in Vaipeka gallery 1, operates continuously. The recorded water level, however, reflects a similar behavior as pump station 3 (gallery 2, Fig. 5). This is due to the influence of the intermittent operation of pump station 2 installed in the same gallery. When pump station 2 stops operating, the water level in pump station 1 recovers despite the continuous abstraction from pump station 1, reflecting the high groundwater production capacity of gallery 1 in general. Only when both pumps installed in gallery 1 abstract simultaneously does the water level drop.

The EC in pump station 1 has an average value of 800 µS/cm due to the presence of a thicker fresh groundwater body as observed through the monitoring bore AIT1. The variation in EC observed in the logger is rather strange as the EC increases when the water level recovers and decreases when the water level drops. This behaviour is probably related to the influence of pump station 2, which shows increasing salinity levels during abstraction. Because no logger was installed in pump station 2, it was not possible to fully assess its behaviour. However, based on previous studies, salinity at pump station 2 has consistently been higher than at the other pumps, and the EC has frequently exceeded 2500 µS/cm (Falkland 1999). It is believed that when pump 2 stops operating, higher salinity water flows through the gallery towards pump station 1, thus increasing the salinity of the abstracted water. Considering that monitoring bore AIT2 suggests the presence of a thick fresh groundwater body at depth, it is possible that pump station 2 has induced localised intrusion of near surface brackish water. Groundwater produced from pump stations 2 and 3 is piped to the Punganui tank where mixing results in end-member EC values between 800 µS/cm and 1550 µS/cm (Falkland 1999). Rainfall does not seem to affect the water level or EC (as observed during the relatively strong rainfall event on 10 March 2018), which are primarily governed by abstraction patterns.

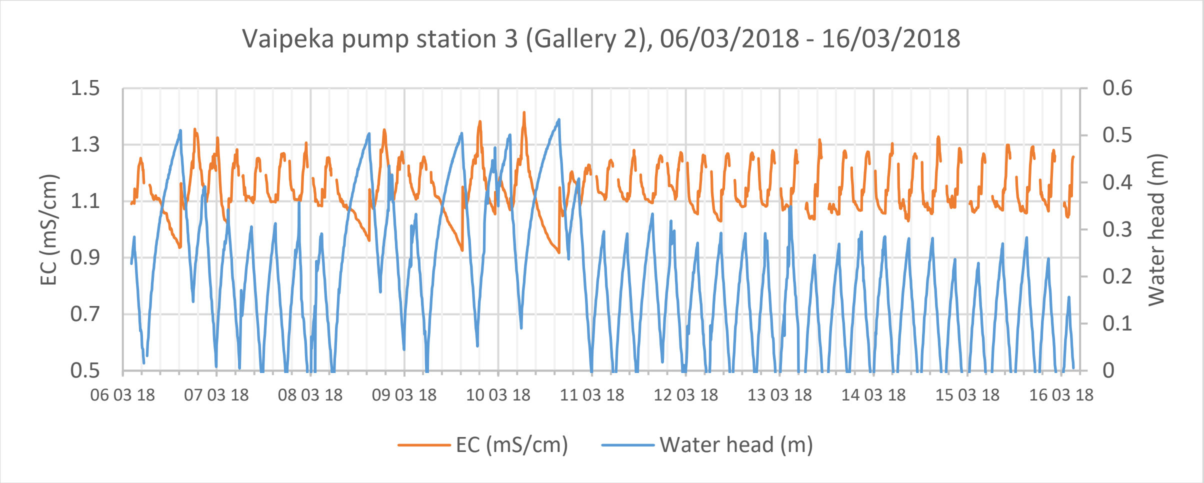

Figure 4. Variation in electrical conductivity and groundwater head above logger installed in Vaipeka gallery 2.

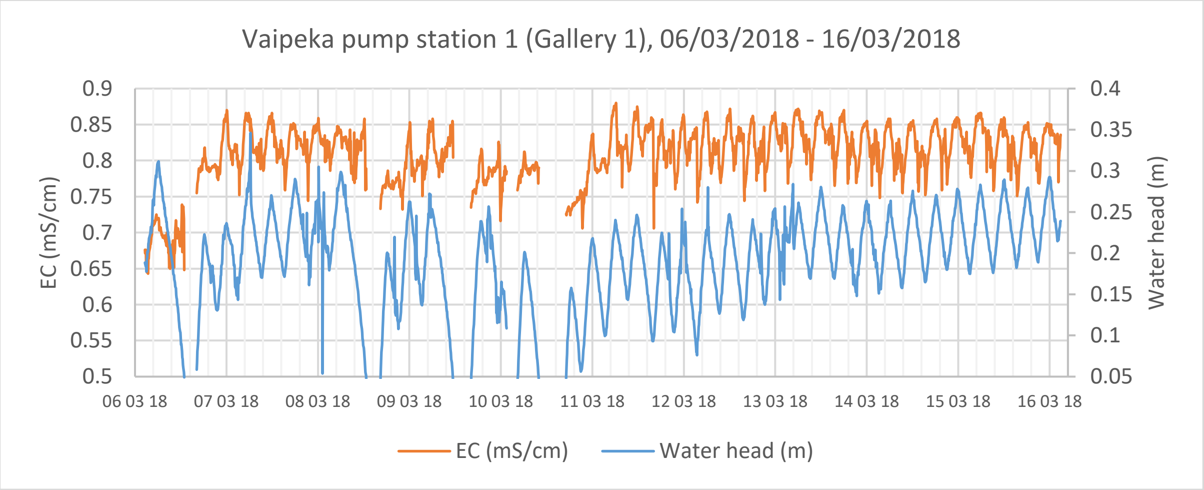

Figure 5. Variation in electrical conductivity and groundwater head above logger installed in Vaipeka gallery 1.

The variation in EC and water head recorded in the Vaitaparoro test pit 1 are presented in Fig. 6. The cumulative daily rainfall is also plotted to assess its impact on groundwater. Both water level and EC are influenced by the relatively strong rainfall event recorded on 10 March 2018 (33 mm recorded at the Vaitekea rain station). The water table showed an increase of 20–25 cm, which gradually decreased to normal levels (~0.3 m below ground level) within five to six days. The EC showed a small decrease of 65 µS/cm in response to the rainfall recharge; after a few days, salinity gradually increases, probably due to mixing with in-flowing groundwater and evaporation. Tidal impacts are not observed in the water level of the shallow groundwater.

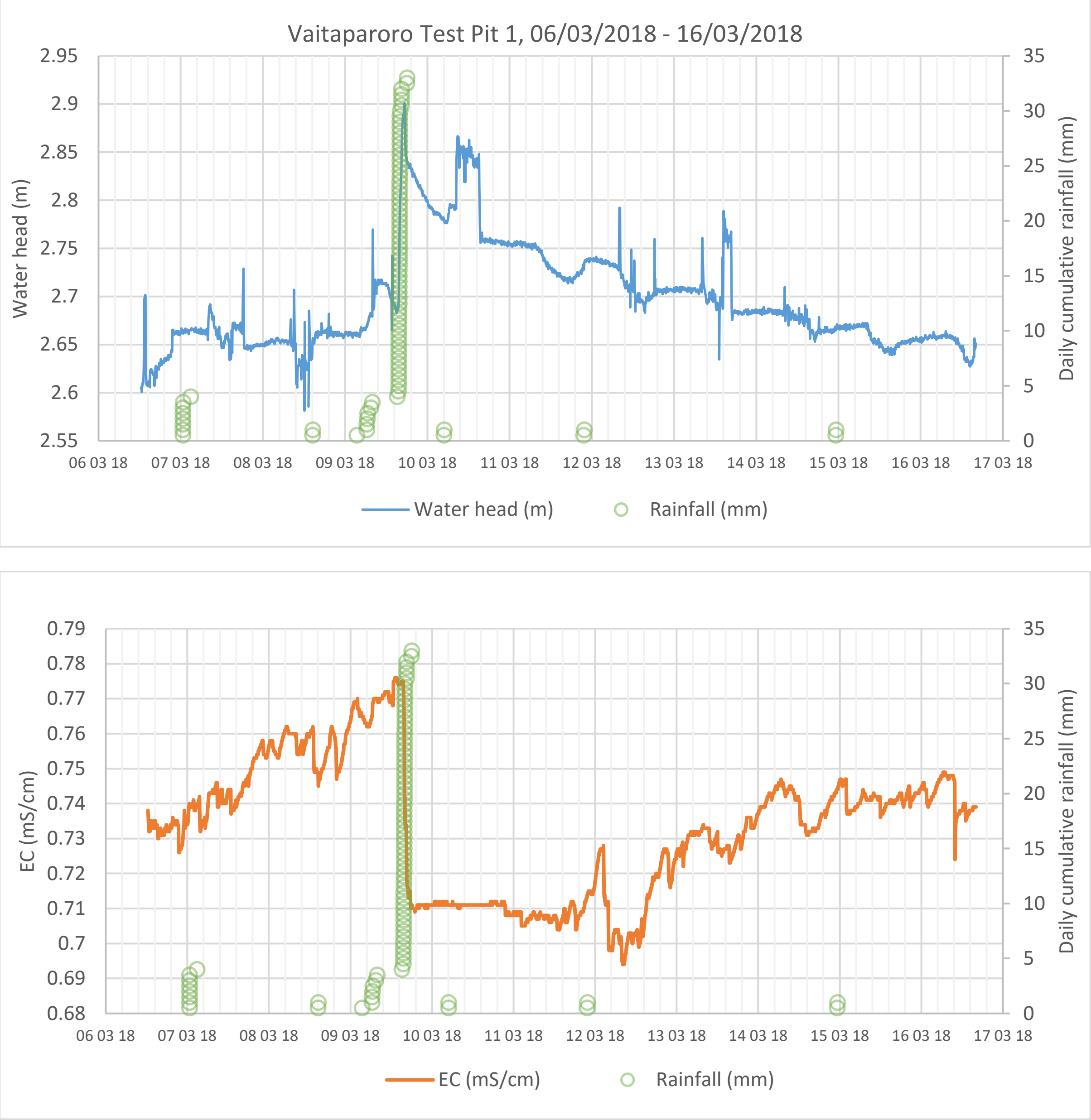

Figure 6. Variation in electrical conductivity and groundwater head above logger installed in Vaitaparoro test pit 1 plotted against observed tides.

4.3 Groundwater quality

Besides salinity, ten unfiltered groundwater samples and one rain water sample were collected and analysed for major ions and metals (e.g. Fe, Mn). The purpose was to assess the quality of the water for drinking purposes and to obtain some further insights on the hydrogeochemical processes that may be occurring. The quality of the analysed samples is summarised in Table 10.

The saturation index of the water samples with respect to carbonate minerals (calcite, aragonite and dolomite) – which are potentially present in the beach sands – was calculated using PHREEQC software (Parkhurst and Appelo 2013). Both samples obtained from the airport gallery and monitoring well AIT6-1 were oversaturated with respect to the three minerals, indicating a tendency for carbonates to precipitate. Although rainwater was highly undersaturated with respect to these minerals, the positive saturation index of shallow groundwater indicates that carbonate dissolution probably occurs in the unsaturated zone until an equilibrium between infiltrating rainwater and aquifer matrix is attained. All the other samples were undersaturated with respect to carbonates, indicating the absence of mineral dissolution processes in the volcanic aquifer matrix.

The samples were plotted on a Piper diagram to characterise the hydrogeochemical facies and obtain further insight on the underlying processes influencing the water. Groundwater samples obtained from the airport gallery and Vaimaru gallery and monitoring well AIT6-1 are characterised as Ca-HCO$_3$ type waters, representing recharge water whose chemistry is controlled by the dissolution of calcium carbonates. The remaining samples are characterised as Na-Cl types, which suggests the influence of underlying seawater.

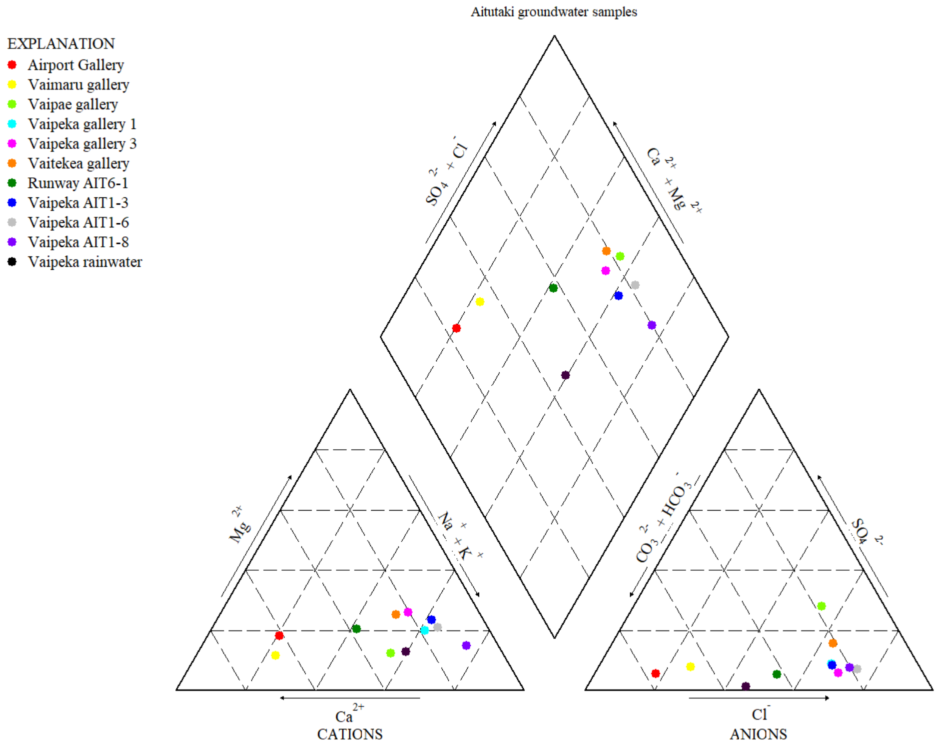

Figure 7. Piper diagram of the major cation and anion chemistry.

None of the elements analysed in the samples exceeded any drinking water guidelines although from an aesthetic point of view, water with an EC above 800 µS/cm may become unpalatable, and water with an EC above 1500 µS/cm is generally not recommended for drinking water purposes. Water produced in the Vaipae, Vaitekea, Vaimaru and airport galleries is, therefore, of good quality and could be used for drinking water, provided they are devoid of bacterial contamination.

Table 10. Quality of one rain water and ten groundwater samples.

	Sample	**Vaipeka rainwater**	**Vaipeka Gallery 1**	**Vaipeka Gallery 3**	**Vaipeka AIT1-3**	**Vaipeka AIT1-6**	**Vaipeka AIT1-8**	**Airport Gallery**	**Runway AIT6-1**	**Vaipae Gallery**	**Vaitekea Gallery**	**Vaimaru Gallery**
pH	pH Units	5.9	7.5	7.5	7.5	7.5	7.5	7.9	8	6.4	6.3	7.2
EC	µS/cm		1104	1183	583	904	1068	570	466	246	212	396
Alkalinity$_{(tot)}$	mg/l as $CaCO_3$	4.1	93	142	72	83	88	220	195	17.8	14.5	130
HCO_3	mg/l at 25°C	5	113	173	87	101	107	270	240	22	17.7	158
Hardness$_{(tot)}$	mg/l as $CaCO_3$	3.2	143	270	111	161	105	230	270	45	35	153
Ca$_{(diss)}$	mg/l	0.88	28	48	17.1	26	15.9	71	71	13	6.8	52
Ca$_{(tot)}$	mg/l	0.88	28	46	16.8	25	15.3	72	71	13.4	6.5	51
Fe$_{(tot)}$	mg/l	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.04
Mg$_{(diss)}$	mg/l	0.25	17.9	37	16.5	23	15.8	12.7	23	3	4.3	5.5
Mg$_{(tot)}$	mg/l	0.24	16.8	34	15.6	21	14.2	12.2	21	3	3.9	5
Mn$_{(tot)}$	mg/l	0.0032	0.0007	0.0012	<0.0005	<0.0005	<0.0005	<0.0005	0.0153	0.04	0.0138	0.0158
K$_{(tot)}$	mg/l	0.172	2.7	5.3	2.5	3.5	3.7	4.5	2.7	1.22	0.44	1.25
Na$_{(tot)}$	mg/l	2.1	104	142	81	134	151	25	88	25	16.1	20
Br	mg/l	<0.05	0.56	0.99	0.46	0.83	0.77	<0.05	0.52	0.18	0.11	0.15
SO_4	mg/l	< 0.5	31	32	23	31	32	15.6	24	27	10.4	14.7
Cl	mg/l	2.5	175	289	137	241	224	36	173	38.5	31.5	37

4.4 Submarine groundwater discharge

The submarine groundwater discharge study undertaken in Amuri resulted in the two resistivity screenshots shown in Fig. 8. The resistivity distribution suggests the presence of three larger and two smaller fresh groundwater conduits, responsible for the submarine groundwater discharge observed at close distance offshore. The first screenshot was obtained at high tide while the second was obtained one hour later. The higher resistivity in conduits observed in the first screenshot suggests a higher freshwater proportion also indicative of more localised discharge, focused on the preferential flow paths. This preliminary exercise was useful in proving and identifying the existence of fresh groundwater conduits at depths between 2 m and 15 m, responsible for the submarine groundwater discharge observed from springs in the ocean side of the island. Although not performed in the present study, discharge rates can also be calculated by following a mass and salt balance approach (Dimova et al. 2012) using resistivity data of pore water collected through piezometers along the profile.

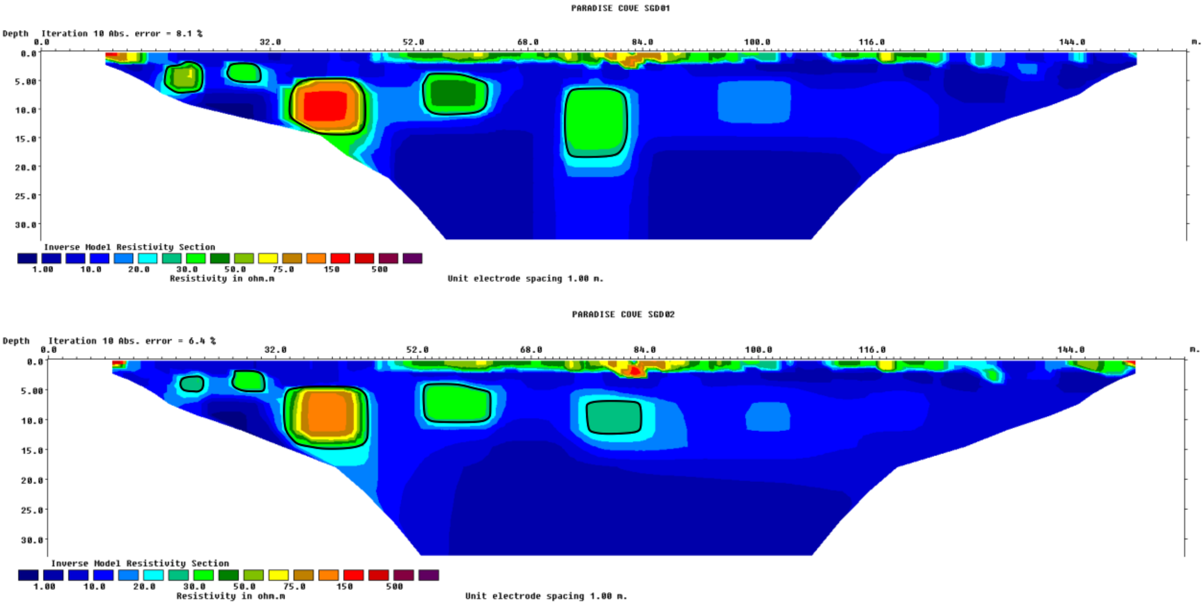

Figure 8. Resistivity profiles at Paradise Cove separated by a one-hour interval depicting fresh groundwater conduits (upper profile: high tide).

4.5 Hydrogeological conceptual model

Assessing all observations collected during this study and including the available literature, a hydrogeological conceptual model was derived. A three-layer hydrogeological model seems to be dominant in most parts of the island, which are composed of volcanic deposits. Below the thin (5–7 m thickness) surficial layer that represents in situ weathered volcanics (regolith and clay) lies a higher-resistivity layer that probably represents the less weathered part of a recent lava flow able to create conditions for development of perched groundwater conditions on the top layer, as re-inforced by observations around the Vaitekea gallery. North of Vaitekea (between the Vaitekea and Vonnias survey lines), groundwater seepage and surface runoff over the main road was observed along an extended sloping area, indicating overflow of the shallow perched aquifer due to recent wet conditions. These perched aquifers can apparently yield substantial groundwater volumes as reported by Falkland (1994) for the Vaitekea gallery (2.4–2.9 L/sec) and for the Vaipae gallery (1.4–2.0 L/sec). The presence of perched aquifers is also suggested by the drilling record of the old Akataaia bore around the Piraki area where water loss was experienced upon reaching the base of the semi-permeable layer. Closer to the coast, the semi-permeable volcanic layer disappears and fresh groundwater mixes with more brackish water. Especially in the Vaipeka area, the absence of the semi-permeable layer and the large volumes of fresh groundwater flowing from the hills in the west, along preferential pathways, cause a substantial accumulation of fresh groundwater, which creates incursions into the brackish water resulting in slightly higher salinity groundwater, as observed through the existing monitoring wells when moving closer to the coast. The suggested preferential flows at the Vaipeka gallery contribute to the substantial volumes of groundwater, observed even during drier conditions; however, due to this mixing the salinity is slightly higher (up to 1350 µS/cm measured during this study) than in the other galleries, which tap the fresh perched aquifers. The salinity in the Vaipeka galleries is also influenced by abstraction as it gradually increases until the pump is stopped when the groundwater is then replenished and the salinity drops.

Underneath the recent volcanic layer lie the older volcanic deposits, which show varying degrees of weathering with very low resistivity zones, which suggests the presence of clay, either in the form of extensive weathering or as infilling material of fractures and fissures formed in the basalt. Fractured zones in this layer may have groundwater exploitation potential, which should be further investigated through targeted drilling (see section 4.6). The water loss experienced during the drilling of the Akataaia bore suggests that, for the hilly areas, the presence of an unsaturated zone underneath the semi-permeable layer of the younger volcanics and of a deeper groundwater table encountered at 37 m and 43 m depth in the Akataaia and Piraki boreholes, respectively (Table 1). The depth to groundwater is expected to show considerable lateral variation as it can be significantly influenced by structural features (e.g. fractures) present in the rock. The presence of high-resistivity, vertically oriented features cutting through the older volcanic deposits suggest recent volcanic activity, which has resulted in surficial, less-weathered volcanic deposits.

In summary, from a geological perspective, two volcanic units are observed through the ERT results in most parts of the island, with the top unit representing the recent volcanic deposits and consisting of a more weathered and a less weathered layer (Layer 1 and Layer 2, respectively) and the deeper unit representing the older and more weathered volcanics (Layer 3). In high-relief areas, such as the Piraki hills, the top weathered layer (Layer 1) may be absent due to slower weathering processes and possible slope wash.

Fresh groundwater discharge from various submarine springs around the coast indicates the presence of preferential flow paths discharging groundwater along fractures and fissures found within the weathered volcanic framework.

In the areas consisting of raised coral beach sands, resistivity results suggest that groundwater develops as a freshwater lens floating on top of higher density seawater and separated by a brackish transition zone. The depth of the freshwater lens is generally between 10 m and 14 m, matching with the depth to the limestone encountered during the drilling of monitoring bore AIT6 and suggesting that the limestone poses a limitation to the maximum attainable freshwater thickness due to its higher permeability.

4.6 Groundwater resources development

4.6.1 Shallow perched aquifers

On Aitutaki, the shallow perched aquifers seem to be able to yield substantial volumes of fresh groundwater considering that the existing galleries have been pumping these aquifers since the 1960s (Vaitekea gallery, Falkland 1994). These systems also recorded drastic decline in yield in the recent prolonged dry periods, indicating their rapid response and heavy reliance on rainfall. Although no resistivity survey lines crossed the Vaipae and Vaimaru galleries, it is expected that these galleries also pump the shallow perched aquifer and are able to produce substantial groundwater volumes. Particularly the Vaipae gallery, which according to Falkland (1994) has the potential to be extended to allow for increased groundwater production without compromising water quality. This is mainly due to the presence of the underlying semi-permeable layer (Layer 2) that protects the shallow aquifer from saltwater intrusion. If, however, groundwater production from the existing galleries cannot be increased during dry periods, consideration of additional galleries should be explored in areas where adequate thickness (5–7 m) of possible perched systems were observed. Thus, the installation of galleries will be made at the base of the shallow perched aquifer in areas such as:

- along the Maunga Pu profile (Fig. A3),
- the first half of the Piraki-1 profile (Fig. A5),
- the first and the last 120 m along the Vaipae profile (Fig. A14),
- the entire Vaitekea profile (Fig. A16), and
- parts of the Vonnias profile (Fig. A17).

These shallow systems, albeit relatively cheap to excavate and having the capacity to supplement existing water supplies, can be vulnerable to reduced yield during prolonged dry periods and anthropogenic contamination from surface land-use practices.

In the Vaipeka area, the impermeable base layer is absent, and water quality deterioration due to the mixing with brackish water is a possible threat to groundwater development activities. In fact, the Vaipeka galleries have always recorded higher salinities, particularly after prolonged abstraction, despite the substantial thickness of the fresh groundwater body as measured by monitoring bores AIT1, AIT2 and AIT3 (Table 9). Nevertheless, the Vaipeka galleries and particularly pump station 1 are capable of producing groundwater that is of acceptable water quality that covers the majority of secondary water needs (e.g. washing, cleaning, flushing toilets) on Aitutaki. The investigation of further development of the Vaipeka galleries to the north of gallery 1 should be considered for additional water supplies.

4.6.2 Vaitaparoro area

The Vaitaparoro area was identified prior to this study as a suitable area to host a new gallery due to its proximity to Tautu Village, which during drought periods, suffers the most due to the poor performance of the existing gallery and the distance to other galleries. The top layer (Layer 1), which seems to be perched on top of a low-permeability clay-rich formation, recorded an increasing thickness up to 5 m towards the southeastern end of the Vaitaparoro-1 profile (Fig. A18). Profiles Vaitaparoro-2 and Vaitaparoro-3 were performed along a southwest to northeast orientation and revealed a uniform thickness of 2–3 m of the shallow unconsolidated beach deposits. It is, therefore, suggested that the new gallery be installed in a southwest to northeast direction and towards the southeastern end of the Vaitaparoro-1 profile (at around 135 m distance along the profile, Fig. A18). An installation depth of around 4 m depth towards the base of the top layer should be chosen to prevent the gallery running dry due to a possible decrease in the water table during dry periods. Salinity should, however, be carefully monitored because it may increase during dry periods and with continuous pumping from the gallery triggering lateral brackish water intrusion possibly from the lagoon in the southeast. The shallow and perched nature of groundwater in this area also suggests heavy dependence on rainfall, and a decline in yield can be expected during rainfall-deficient periods. This will require regular monitoring of groundwater levels, salinity and rainfall in the immediate and long term.

4.6.3 Coral beach sands

In areas covered by coral beach sands, development potential of the existing freshwater lens exists by means of horizontal galleries skimming the fresh groundwater just below the water table. It should be noted that the principle in this hydrogeological setting is fairly different because the shrinking of the fresh groundwater body occurs by means of the upward movement of the transition zone. Galleries installed in these areas should therefore be installed just below the groundwater table whose depth is fairly stable and should consider the sensitivity of freshwater lens thickness to tidal processes and rainfall events. While all of the resistivity profiles around the coastal sediments showed encouraging results, the golf course area should be promoted as a priority development option for infiltration galleries. This is due to the following reasons:

- substantial lens thickness indicated in the ERT profile;
- the good performance of the existing airport gallery; and
- its close proximity to residential areas, being the potential beneficiaries of this system.

However, a suitable site and appropriately sized storage tank will be required which, in turn, will have implications on infrastructure costs. The current runway, albeit relatively isolated, can be considered as a possible alternative source for nearby resorts around the northeast. The water resources development on the current runway, however, should also consider any impact on the civil aviation authority. The old runaway, while more accessible, might be difficult and more costly to excavate due to the level of historical reclamation and/or filling and compaction it has undergone resulting in more limited groundwater potential than elsewhere. Finally, the promising results along the second half of the Vaimokora profile should be considered as an alternative groundwater source for nearby residents.

4.6.4 Old weathered volcanics

The final option is deeper drilling into the older, weathered volcanics targeting fresh groundwater within fractures and forming the theoretical basal aquifer. This may require a number of exploratory holes to confirm the resistivity results, before constructing a water supply borehole. A water supply bore with a yield of 0.5–1.0 L/sec, however, could be considered as a suitable and resilient source for drought supply purposes compared to the shallow perched aquifers where the current galleries are installed.

The weathered volcanics (Layer 3) along the Piraki-1 profile (Fig. A5) may also offer a number of potential groundwater development options. The zone extending between 320 m and 480 m distance along the profile and between 20 m and 35 m in depth may reflect a localised aquifer perched on top of the high-resistivity, vertically oriented feature, which may represent a vertically intruded dyke (Feature 1). During their upward intrusion, these dykes tend to fracture the country rock creating sometimes favourable conditions for groundwater accumulation. Two features (Feature 2 and Feature 3) are observed on each side of the volcanic dyke, which may represent fractured volcanic rock. The very low resistivity measured in Feature 2 probably reflects a fracture infilled with clay material whereas Feature 3 does not seem to be filled with clay and, thus, may offer better groundwater development potential. It is recommended to drill three exploratory holes, one in each zone (Feature 3, Feature 1, and above Feature 2) to confirm the resistivity results, before constructing a water supply bore. The close proximity of these possible targets to the existing reservoirs means that no additional storage tank will be required and less piping-related costs.

The older volcanics (Layer 3) along the Maunga Pu profile (Fig. A3) may offer a good option for groundwater development, as suggested by the distribution of resistivity along the profile. Layer 3 suggests that there is a relatively thick fresh groundwater body, probably directly recharged through Layer 2, which seems to be discontinuous in the area. Drilling however should terminate above the underlying low-resistivity zone which, considering its absolute elevation and resistivity values, may be saturated with brackish water. Considering that the main Vaipeka–Piraki pipe runs through the survey area, it will be relatively easy to connect the Maunga Pu bores into the existing piping network.

Another option along the Vaitekea profile (Fig. A16) could be drilling through the semi-permeable layer to investigate the potential presence of a deeper aquifer perched on top of the high-resistivity vertical feature (Feature 1). Potential fracturing of the country rock may have developed on the western side of this possible volcanic dyke, although the low absolute elevation (around sea level) poses concerns regarding groundwater quality.

The Crater profile (Fig. A1) also indicates resistivity features, which may suggest groundwater potential, including a potential drilling target between 720 m and 730 m profile distance. This should be further investigated through exploratory drilling down to 15 m to test groundwater potential around this resistivity anomaly. If sufficient groundwater volume is found, then the bore should be fully constructed as a production bore and completely secured. Considering the absence of households in this area, an eventual groundwater source could be used as an emergency supply during extreme climatic periods. Other resistivity anomalies that suggest geological anomalies and potential for groundwater include the feature at 260 m and 40 m depth.

5. Recommendations and conclusions

5.1 General recommendations

A number of potential groundwater targets were identified in the volcanic rocks, which could potentially yield fresh groundwater volumes for a drought-resilient supply. Such targets could potentially be present along the Maunga Pu, Piraki and Vaitekea areas. If drilling is to be undertaken in the volcanic rocks, it is highly recommended that exploratory pilot bores should be drilled first to verify the resistivity results and confirm the presence of adequate groundwater volumes. Logging the lithology of the cuttings during the drilling operations is critical to calibrating the resistivity results and guiding the subsequent holes and drilling process in general. When a suitable pilot bore is drilled, it can then be enlarged using larger diameter drill bits (see drilling recommendations).

Considering the work already carried out by Infrastructure Cook Islands in the Vaitaparoro area, it is recommended to develop the proposed gallery, noting the increasing groundwater salinity and thickness of coastal sediments towards the southeastern part of the area. The expected EC of groundwater produced in the northwest of the area is expected to be close to 800 µS/cm while in the southeast it is likely to close to 1100 µS/cm. Considering the small aquifer thickness (3–5 m), production yields are expected to be relatively low and it is advisable to install the gallery towards the bottom of the productive aquifer layer, close to the top of the underlying impermeable clay layer. Considering the somewhat higher expected yields associated with the higher aquifer thickness towards the southeast, it is recommended installing the gallery in that part of Vaitaparoro (at a southwest–northeast orientation) if the water is to be used for secondary purposes. If, however, potable water quality is desired, it is recommended to install the gallery towards the northwest. In any case, stringent salinity monitoring should be carried out once the gallery becomes operational in order to derive conclusions on permissible abstraction rates and suitability of groundwater for specific purposes.

Gallery construction in freshwater lenses involves excavating a trench approximately 1 m below the lowest level of the water table (to ensure no tidal impact), and installing horizontal PVC-slotted pipes that lead to a central pumping station. The horizontal wells are backfilled with suitably sized rounded gravel to help develop a gravel pack before being backfilled with the excavated sand. It is suggested that during the excavation of the trench for the gallery, if reef rock is encountered and remains weathered to moderately weathered, trench construction should continue. A practical approach during construction may be that if the trench excavation can continue relatively easily through the reef rock, then trench construction should continue. If the reef rock is hard or well cemented or thick reef rock is intercepted, then the continued construction of the trench should be assessed. In the areas where thick and unweathered reef rock is encountered, it is expected that the recharge may be reduced and/or delayed, thereby reducing the effectiveness of the horizontal gallery.

5.2 Water resources protection and management

The integrated and coordinated development and management of freshwater resources around Aitutaki will be key to the island’s long-term health and security. Thus, it is critical to:

1. Have an audit of water supply systems, including the usage and demand, abstractions, and infrastructure, to provide an insight into how much water is required by local communities under normal and extreme climatic conditions.
2. Install water resources monitoring technologies, such as flow meters and salinity meters, in galleries and around the main reservoirs to allow the assessment of groundwater abstraction, water usage and leakage, and allow the assessment and management of water across the different reservoirs and to the end users.

3. Undertake regular rainfall analyses from existing stations in Vaipeka and Vaitekea to determine the temporal and spatial variability of rainfall and to capture the periodical island-wide groundwater recharge. This will require the strengthening of the links between the island government and the national weather office on the compilation, archiving and sharing of rainfall data and climate forecast.
4. Identify appropriate trigger levels for groundwater salinity and rainfall to support water resources management during prolonged dry periods.
5. Establish and/or strengthen appropriate water restriction actions with communities during extreme climatic conditions.
6. Develop a drought awareness and action plan that considers different climatic conditions and the practical solutions required and how this might impact the major water users within the community.

In view of the numerous geological formations and their proposed development options, it will be imperative that sound management strategies, including the installation of appropriate technologies and subsequent monitoring of groundwater level and salinity, are considered and adopted to ensure the safety and availability of freshwater resources at all times. Appropriate protection measures against improper land-use activities are equally important and will be required to safeguard groundwater bodies for water supply purpose.

5.3 Specific drilling recommendations

If drilling in volcanic rocks, 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 or 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 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, although commercial water well screens are preferable and will help to optomise yields. The gravel pack should consist of washed, well-rounded gravel. A gravel pack is required when the water-bearing formation sediments are fine and will assist in maintaining 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 to use a casing advancement system in loose geological formations such as scoriaceous basalt. This is to protect the borehole walls from collapsing 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 conduct a pump test for a minimum of eight hours, followed by a two-hour recovery phase, with the water table and flow logging at time intervals that increase logarithmically.

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Annex 1 – Inverted resistivity profiles

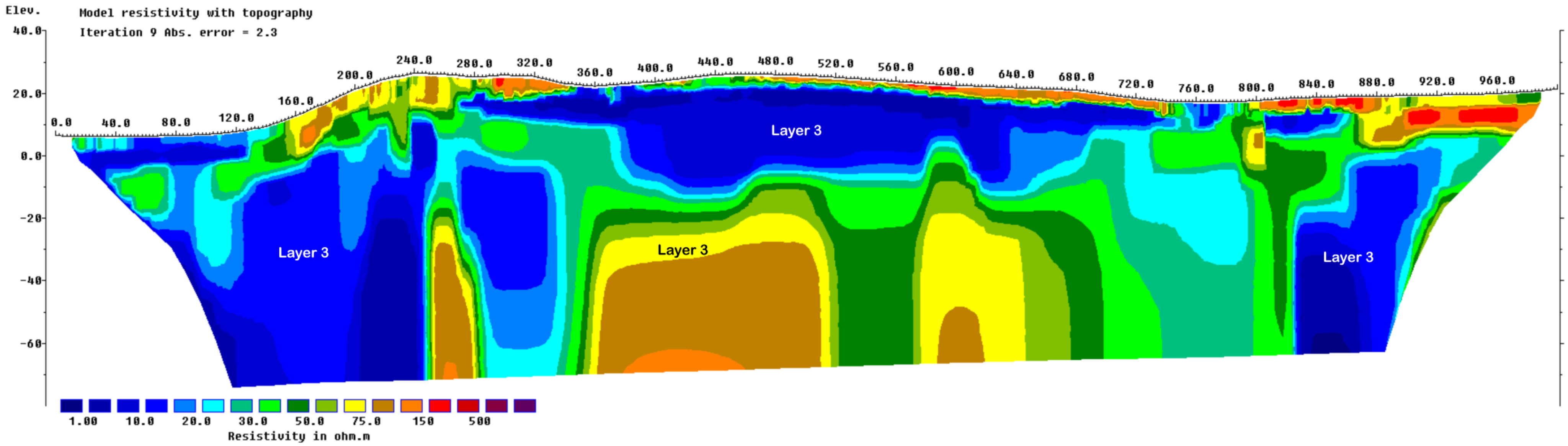


Figure A1. Crater profile

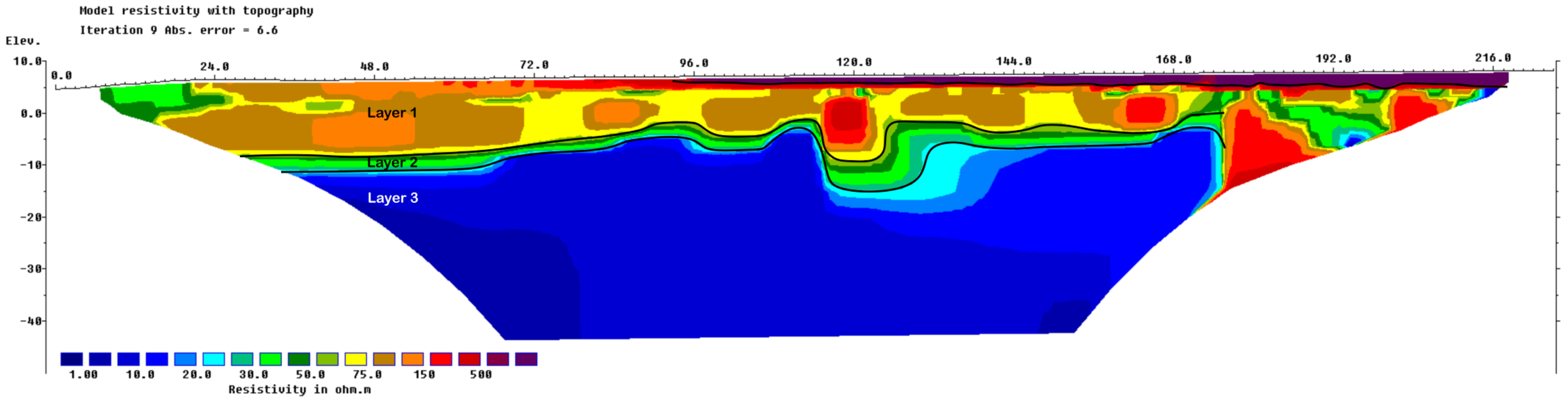


Figure A2. Golf course profile

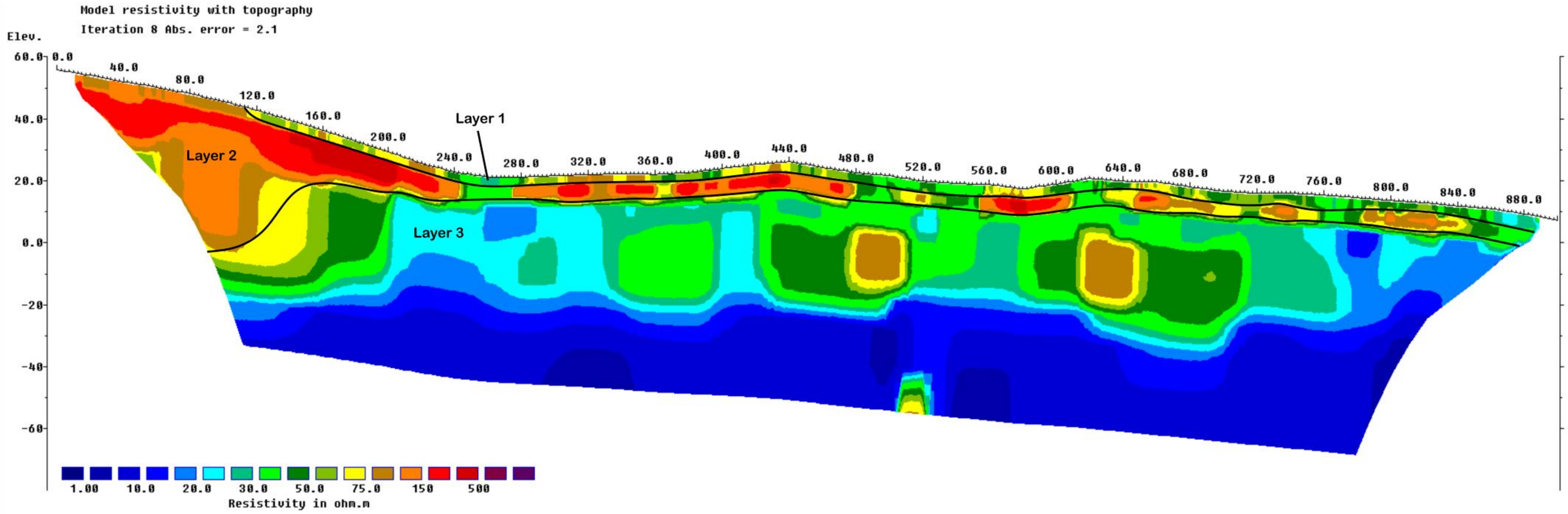


Figure A3. Maunga Pu profile

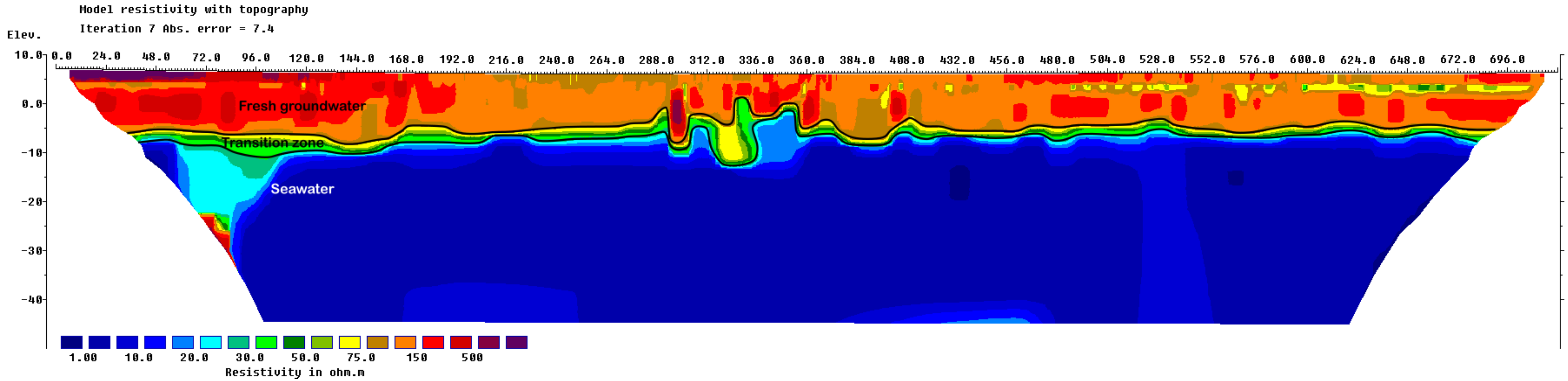


Figure A4. Old runway profile

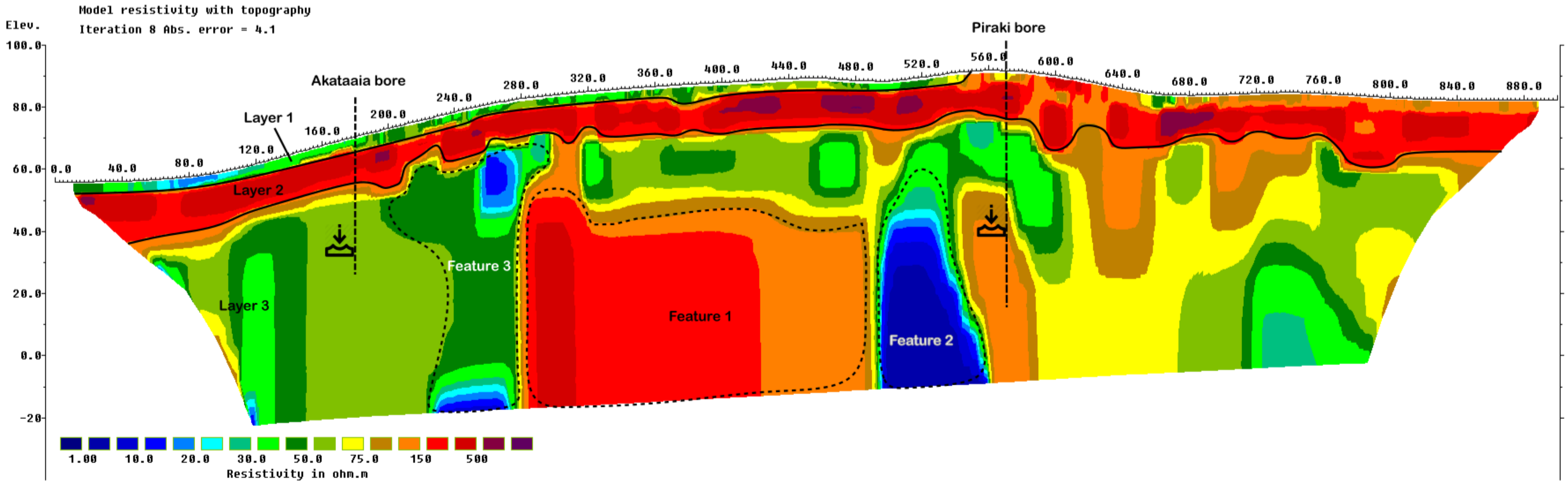


Figure A5. Piraki-1 profile

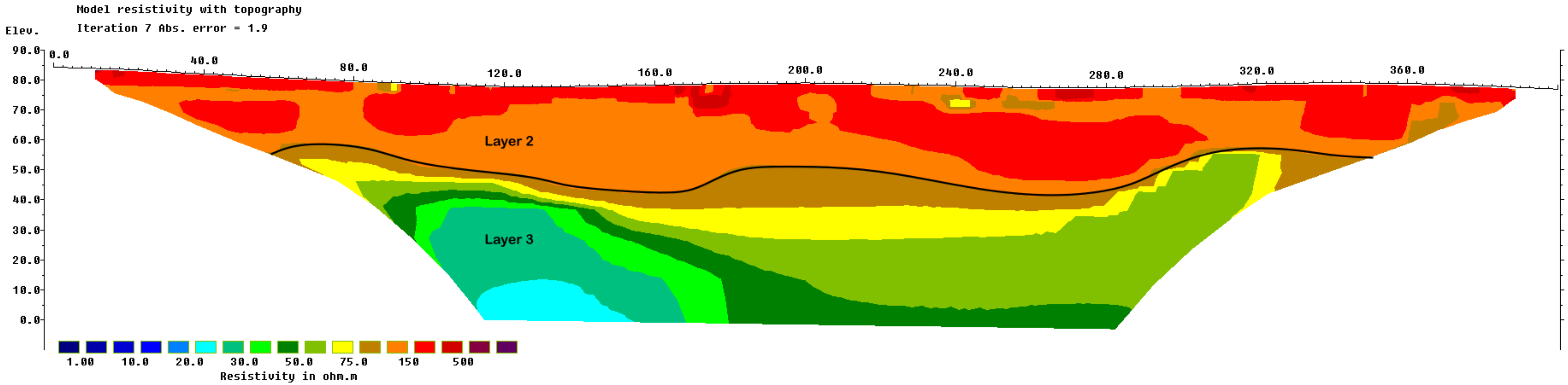


Figure A6. Piraki-2 profile

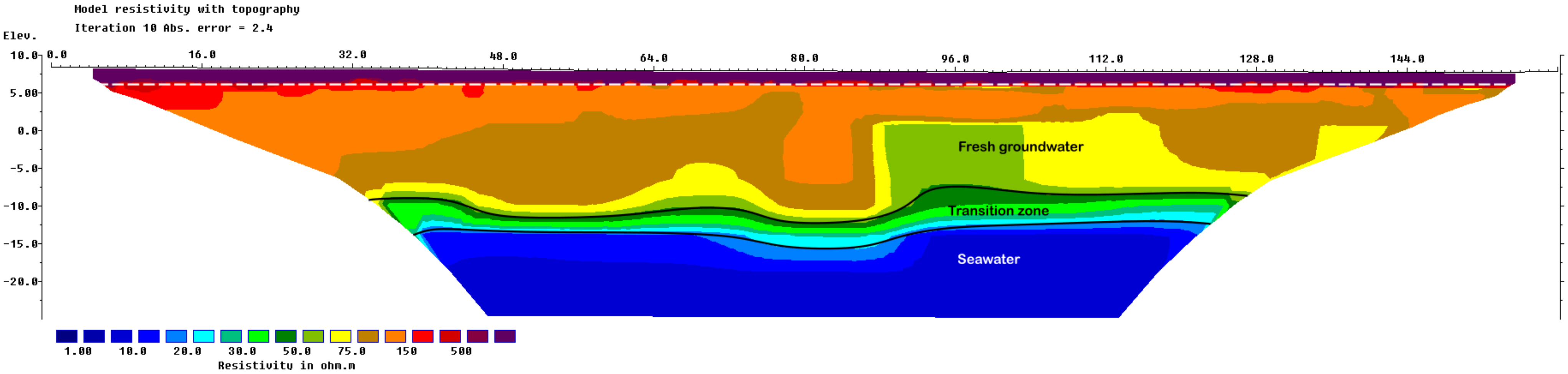
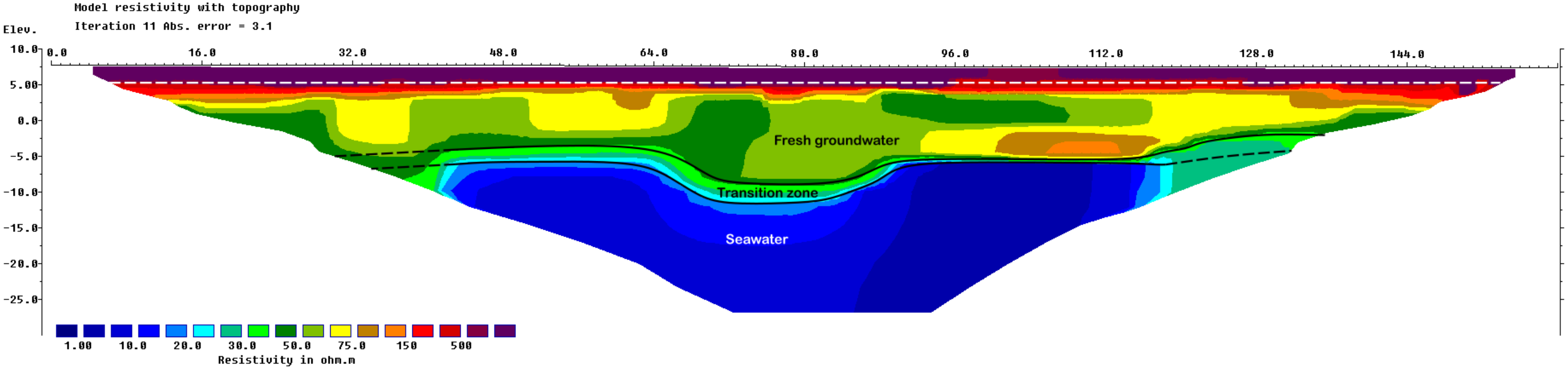


Figure A7. Runway-1 profile



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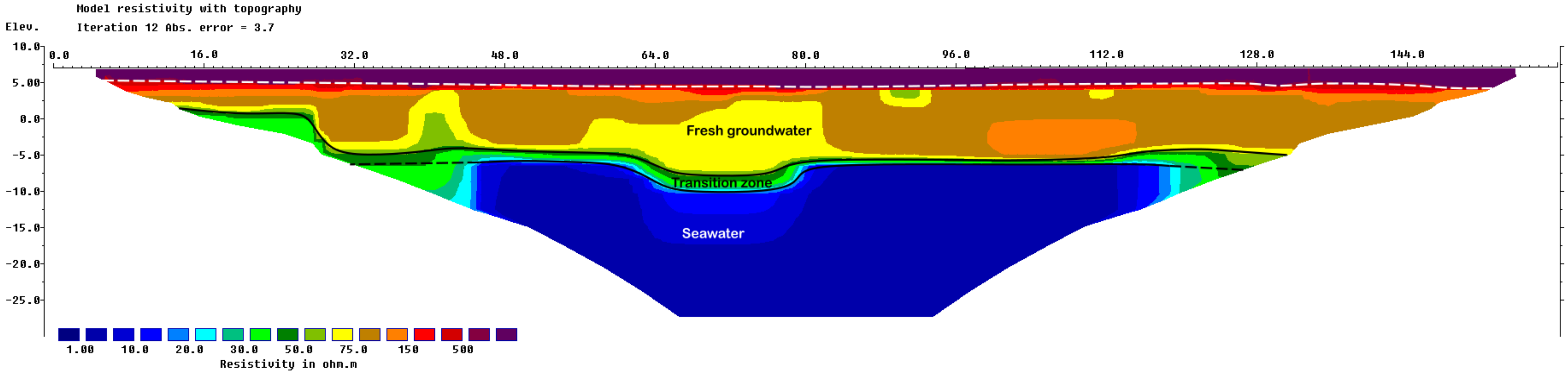

Figure A9. Runway-3 profile

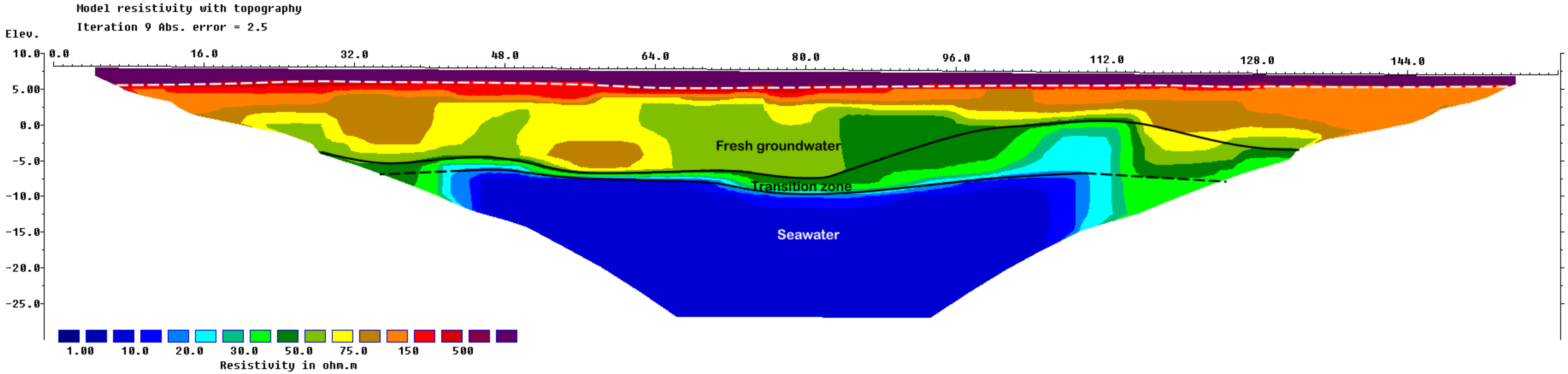

Figure A10. Runway-4 profile

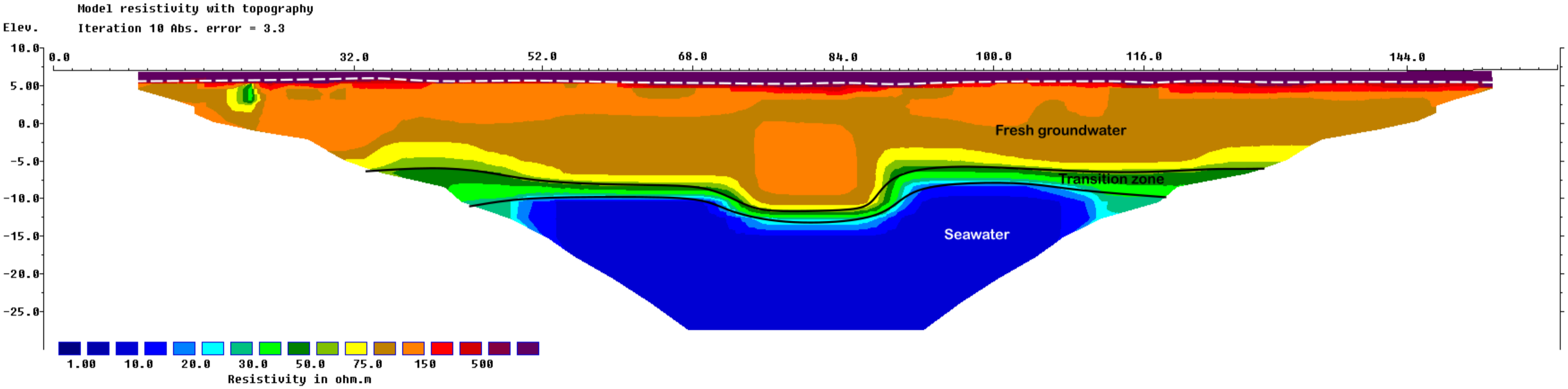

Figure A11. Runway-5 profile

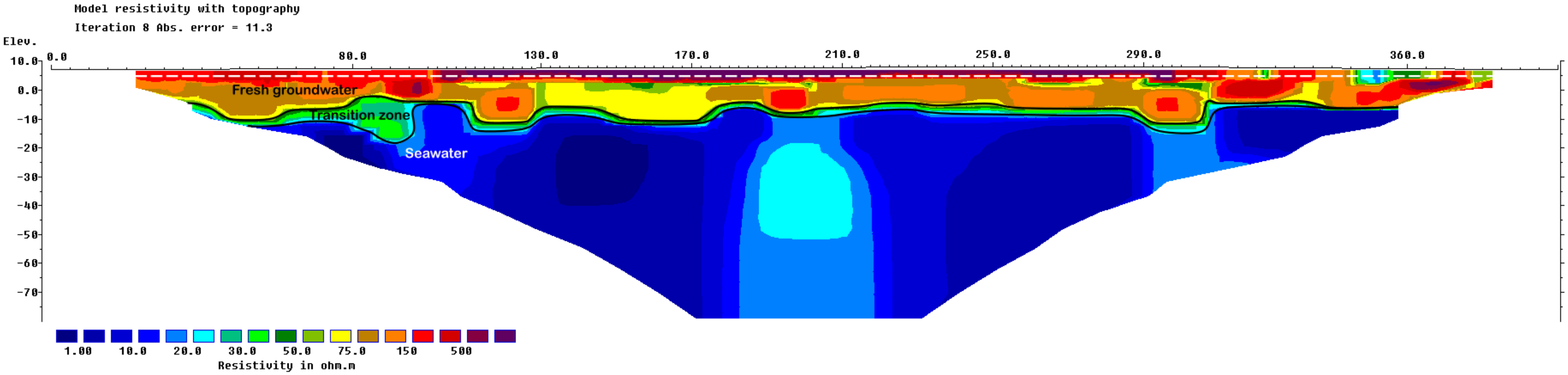

Figure A12. Runway-6 profile

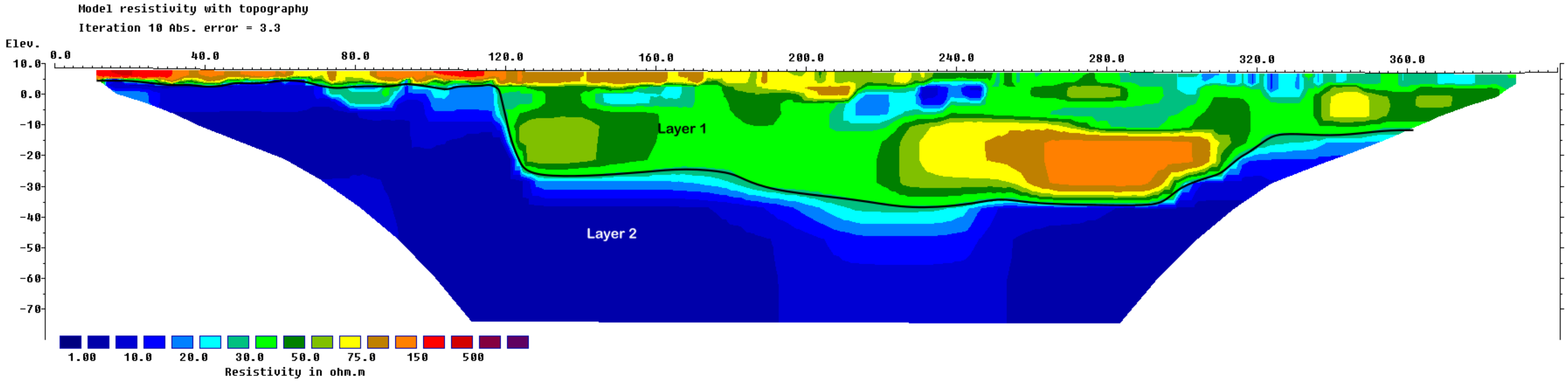

Figure A13. Vaimokora profile

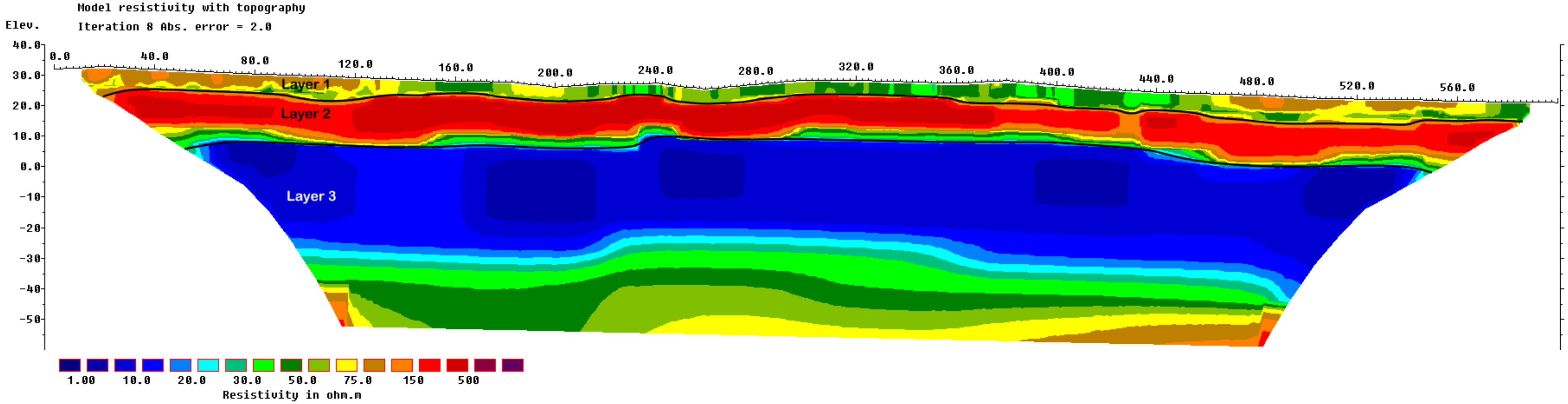

Figure A14. Vaipae profile

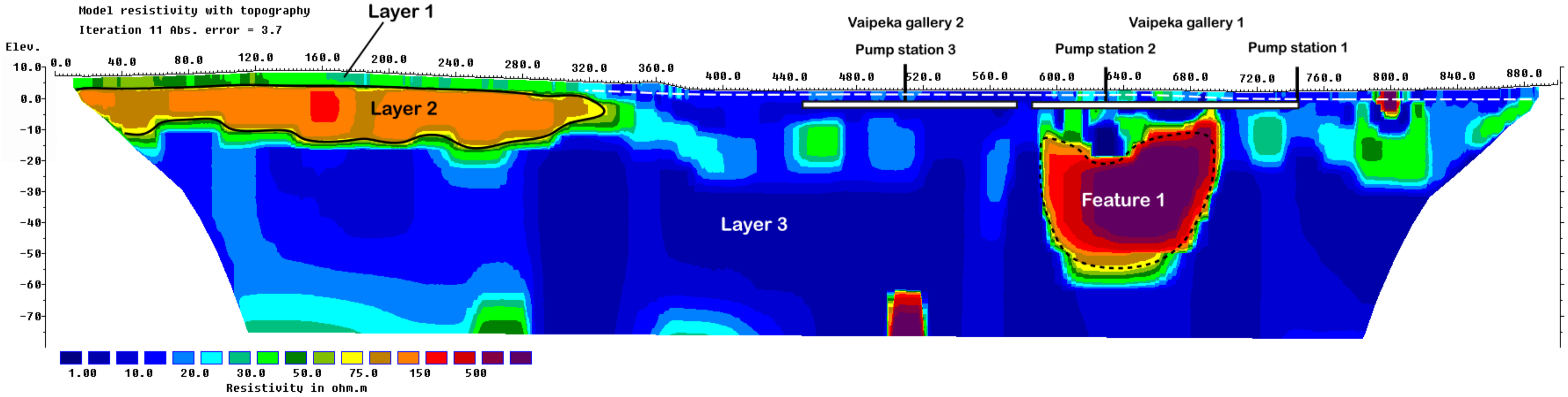

Figure A15. Vaipeka profile

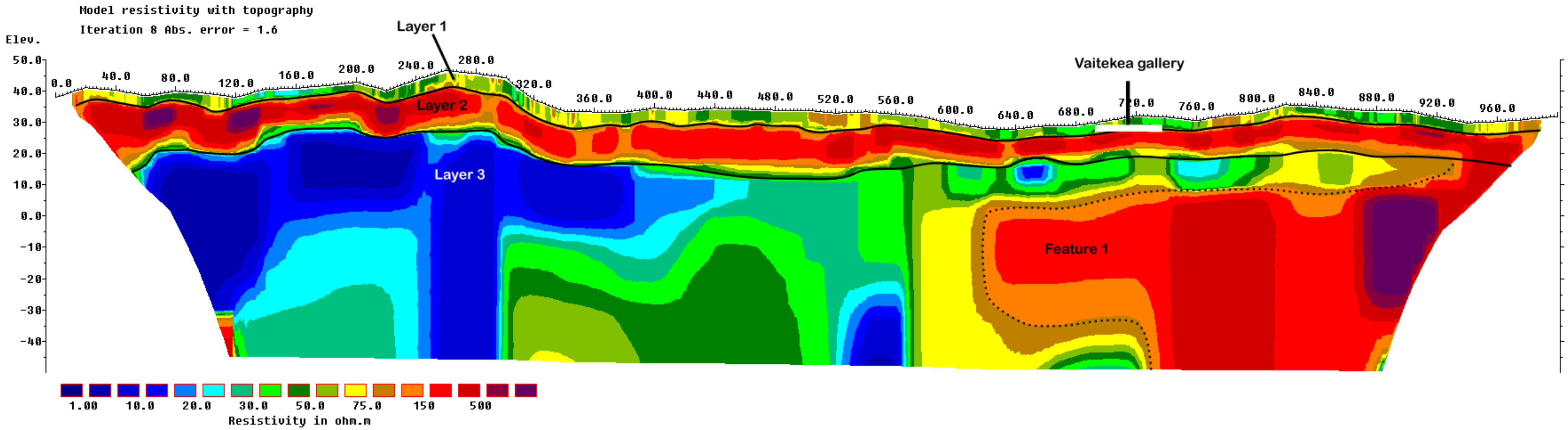

Figure A16. Vaitekea profile

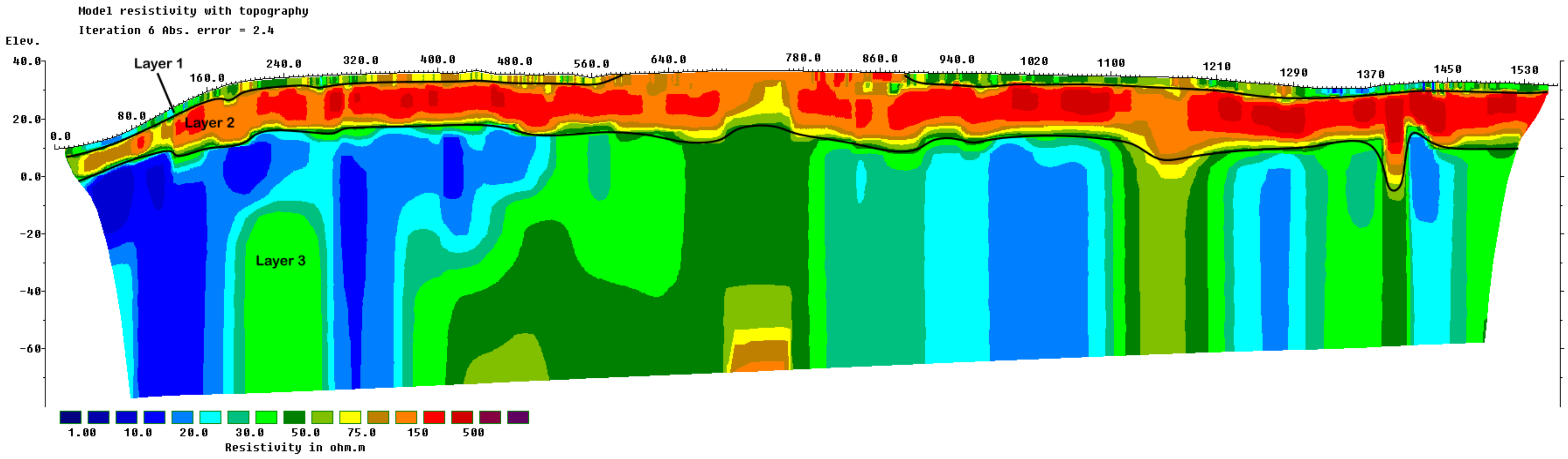

Figure A17. Vonnias (merged) profile

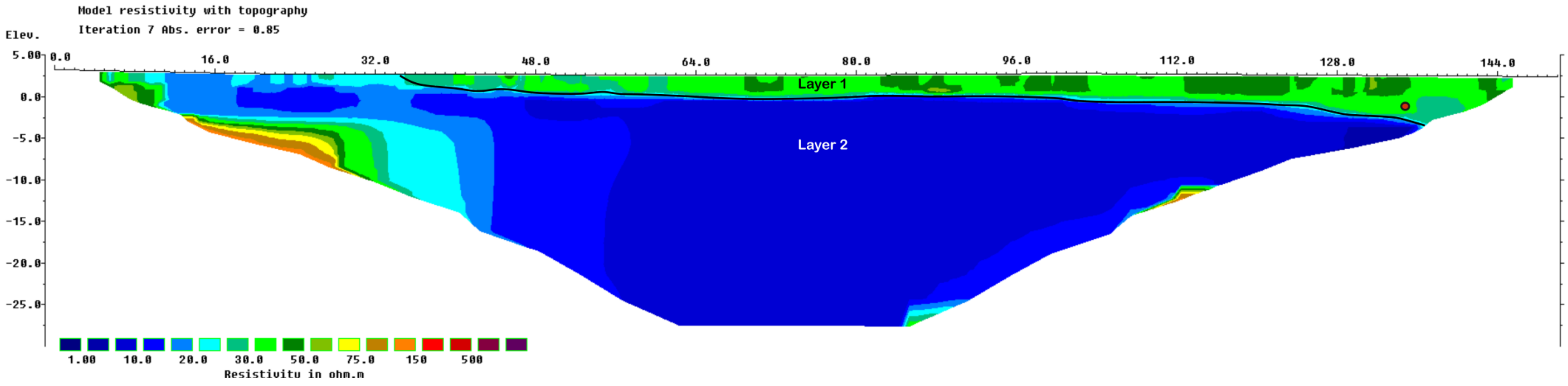

Figure A18. Vaitaparoro-1 profile with proposed location for new gallery depicted in cross-sectional view (red circle)

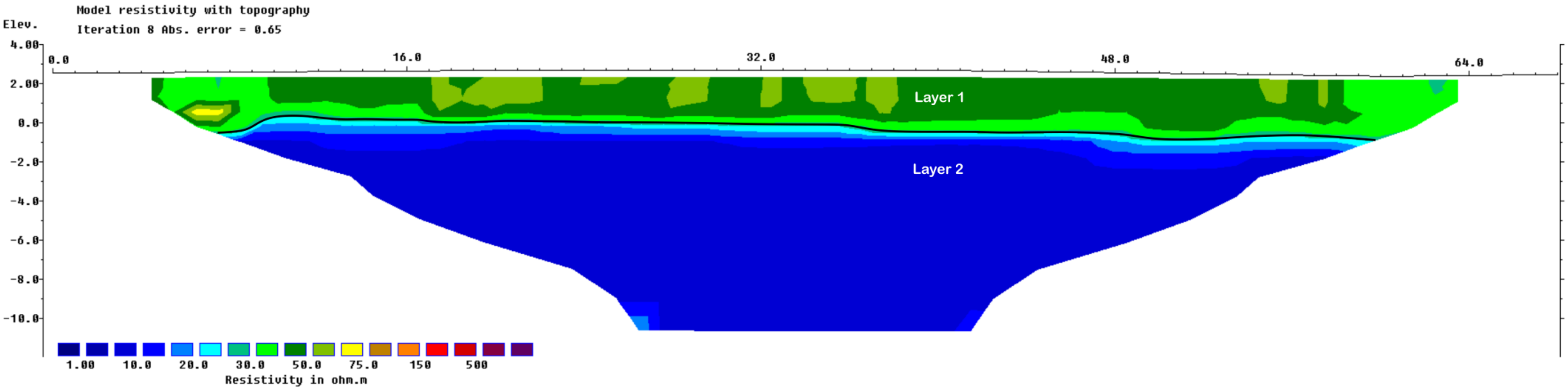

Figure A19. Vaitaparoro-2 profile

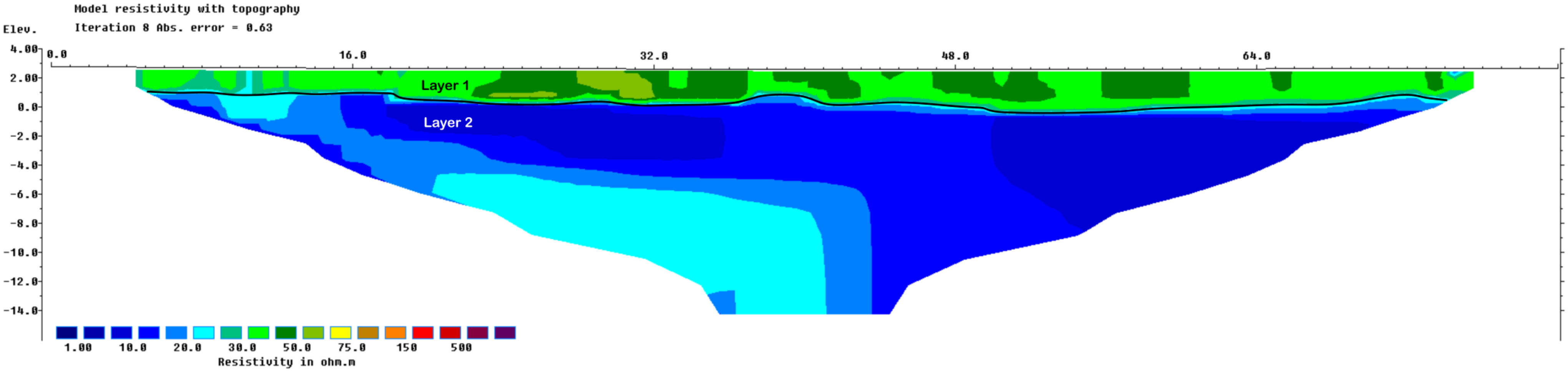

Figure A20. Vaitaparoro-3 profile

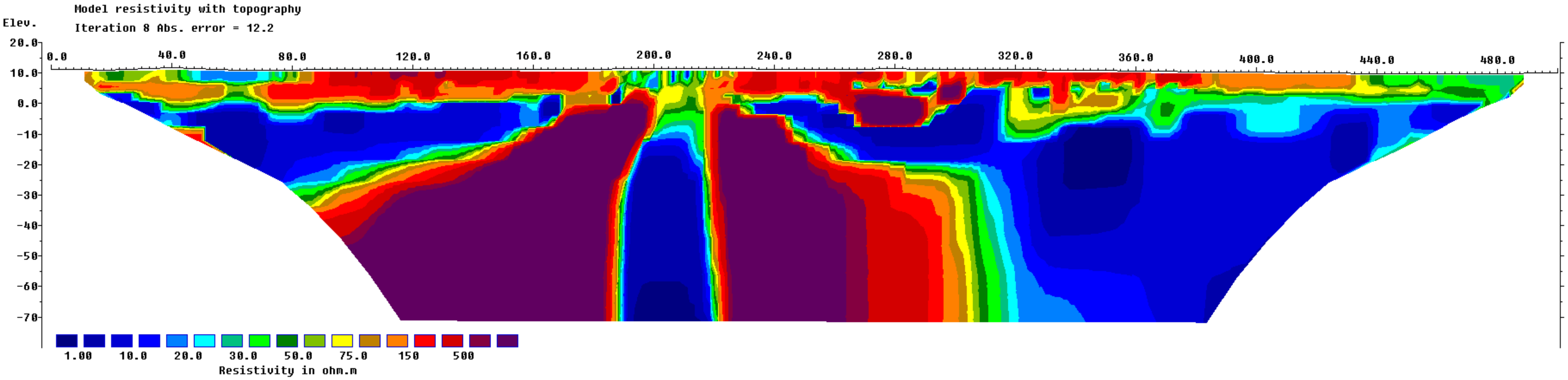

Figure A21. Vaikoa-1 profile

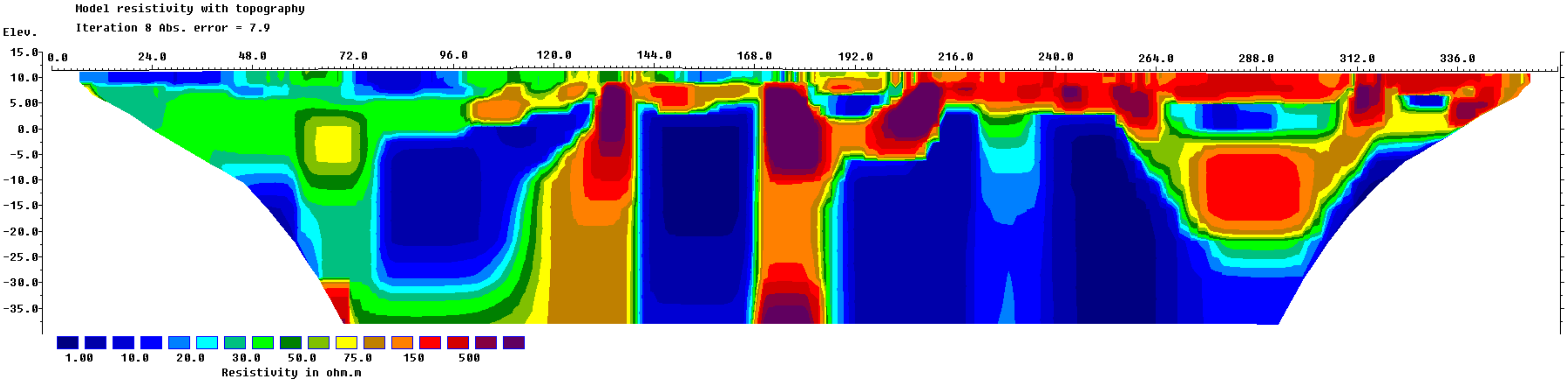

Figure A22. Vaikoa-2 profile

SUSTAINABLE PACIFIC DEVELOPMENT THROUGH
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