Strengthening Water Security of Vulnerable Island States

Groundwater Investigations
Atafu, Nukunonu, Fakaofo Atolls, Tokelau

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Antoniou, Andreas

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

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Executive Summary

Before the 1970s, the communities of Tokelau traditionally relied on groundwater for all their water needs, including potable water supply. With the widespread introduction of rainwater tanks and the perception that groundwater was contaminated with bacteria, groundwater stopped being considered as a water supply option and nowadays only rainwater is used, even for secondary needs, such as washing, gardening, animal feeding and toilet flushing.

As part of the Strengthening Water Security of Vulnerable Island States project, supported by the New Zealand Ministry of Foreign Affairs and Trade, the Pacific Community's Disaster and Community Resilience Programme in the Geoscience, Energy and Maritime Division conducted groundwater assessment surveys on all three atolls of Tokelau. Due to time constraints, a first-pass reconnaissance was conducted, using a ground penetrating radar, allowing for quick data collection.

The results suggest the presence of fresh groundwater supplies which, albeit limited, could have a significant role if they were used conjunctively with rainwater for primary (potable) and secondary needs to assist in water source reliance diversification. In other words, groundwater could be useful to offset rainwater-harvesting needs and provide greater resilience and security to water supplies and to the communities.

The first-pass assessment presented in this study would benefit from additional electrical resistivity tomography surveys to identify and quantify the exact extent and volume of fresh groundwater lenses and better inform the installation of groundwater production infrastructure. The potential benefits of using groundwater should be thoroughly presented and discussed during community consultations and the infrastructural requirements necessary to incorporate groundwater into daily life should be clearly understood to ensure alignment with community considerations and expectations.

1. Introduction

1.1 Project background

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

As part of this project, groundwater investigations were conducted in all project countries at prioritised islands identified by the country governments, based on the recorded frequency of droughts, water demand, and other parameters relevant for each country. The groundwater assessments were conducted in collaboration with staff from the national governments, as well as with water technicians at the island level, to ensure the development of capacities and country ownership of project outputs at local and national levels. Tokelau was the last country to be assessed during this project.

1.2 Mission objectives and outcomes

The main purpose of this investigation was to assess the groundwater resources on Atafu, Nukunonu, and Fakaofo atolls and investigate their potential to complement existing water supplies or serve as a backup during dry periods. Additional objectives included installing automatic rain gauges on each atoll and conducting community consultations regarding the development of a national water and sanitation policy and a drought management framework for Tokelau.

The development of new groundwater resources in atoll environments generally requires: 1) investigating the groundwater resource potential and identifying optimal locations for groundwater production; 2) constructing groundwater production infrastructure (horizontal infiltration galleries) and assessing the yield and quality of the abstracted water; 3) equipping galleries with suitable pumps and constructing storage tanks that are in line with the resource potential and the community's needs; and 4) formulating operational, maintenance and management guidelines – in agreement with the community – that promote ongoing operation and sustainability. The current work focused on the first component, which was completed through the use of geophysics to better understand the local hydrogeology and groundwater storage potential. Recommendations are given regarding potential locations where groundwater production infrastructure could be installed, expected yields, and expected groundwater quality.

2. Background

2.1 Geographical location and history

Tokelau consists of three coral atolls, Atafu, Nukunonu and Fakaofo, with an area of 3.5, 4.7, and 4 km^2, respectively. Their elevation does not generally exceed 2 m above sea level during high tide. The atolls are located north of Samoa and east of Tuvalu, between latitudes 8^{o}-10^{o} S and 171-173^{o} W. The capital rotates yearly between the three atolls. As of October 2016, Tokelau had a total population of 1499, with 519, 484 and 448 inhabitants living in Atafu, Fakaofo and Nukunonu, respectively.

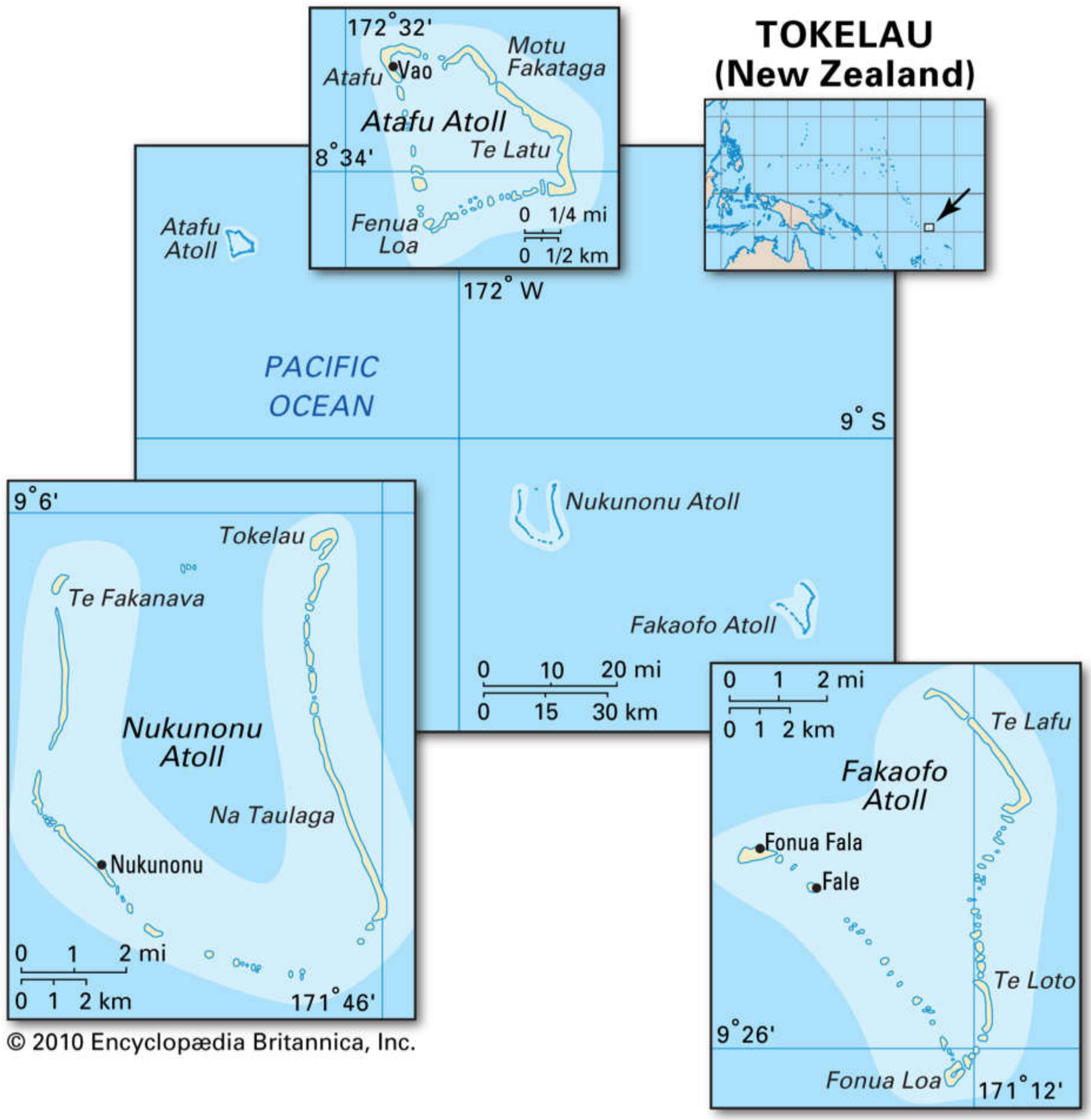

Figure 1. Map of Tokelau

2.2 Climate

The Tokelau group of atolls is located in the Southwest Pacific Ocean within the extensive trade wind belt and the influence of the South Pacific Convergence Zone. In Tokelau, a La Niña event results in drier conditions, while during El Niño events more than average rainfall is generally observed. Cyclones also tend to occur more frequently during El Niño events (Australian BoM and CSIRO 2011). A severe drought was experienced in 2011 during the last La Niña event, resulting in the declaration of a national emergency.

There appears to be no systematic rainfall recording in the three atolls since 1996 (White 2019b). According to White (2019b, Table 1), the average annual rainfall for the period 1948−1996 in Tokelau was 2,821 mm per year, with the months between October and March accounting for about 60% of the total annual rainfall due to the influence of the north-west monsoon (Thompson 1987). The wind direction is predominantly from the east, suggesting that all inhabited islets in Tokelau are situated on the leeward side of the three atolls.

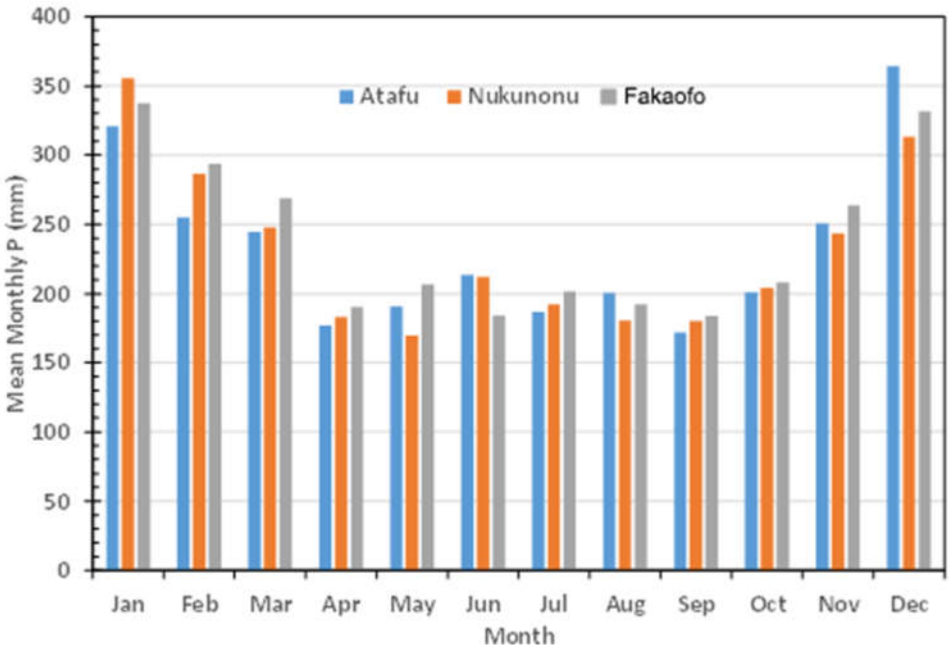

Figure 2. Mean monthly precipitation

Table 1. Rainfall statistics

Atoll	Period	Missing Data (%)		Mean Annual Rain (mm/year)	Coefficient of Variation	Minimum annual rainfall (mm/year)	Maximum annual rainfall (mm/year)
		Monthly	Annual				
Atafu	1949-96	7.5	27.1	2774	0.207	1399	4221
Nukunonu	1948-96	4.4	18.4	2773	0.196	1385	3838
Fakaofo	1948-96	8.5	26.5	2916	0.184	1569	3976

2.3 Vulnerability to climate change

Dixon-Jain et al. (2014) have undertaken a first-pass regional assessment of relative potential vulnerability of groundwater on islands of the Pacific region (covering 15 Pacific Island countries and territories) to the impacts of: (i) lowest mean annual rainfall during ENSO phases; and (ii) mean sea-level rise in two projection periods (2050 and 2085). The vulnerability of the assumed principal aquifer on each island to current and future climate was assessed through a groundwater vulnerability framework, which considered the components of sensitivity, exposure and adaptability of the groundwater system. The study found that the majority of assessed low-lying carbonate islands in the Pacific region have higher relative vulnerability. Tokelau was ranked particularly high in terms of groundwater vulnerability due to the islands being of low-lying carbonate nature.

As mentioned in the implementation plan for the *National Strategy for Enhancing the Resilience of Tokelau to Climate Change and Related Hazards, 2017-2030* (Lefale et al. 2017), it is recognised that integration of climate change and disaster risks intelligence into development planning and decision-making needs to be strengthened. Implementing water resources management, installing new climate and weather monitoring infrastructure, and conducting an updated assessment of drought risk were identified as priority actions to achieve this outcome.

2.4 Current water supply

Rainwater is currently the only source of potable water in Tokelau. It is also predominantly used for all other purposes, including the flushing of toilets. Groundwater is rarely used nowadays, mostly for building purposes during dry periods and rainwater shortages. This has not always been the case; groundwater was regularly used for drinking and cooking purposes before the widespread introduction of rainwater tanks and western amenities and lifestyle with increased water requirements. Groundwater use was abandoned in the 1970s due to faecal contamination, and all wells were sealed by the New Zealand Navy (White 2019c). The common perception nowadays is that groundwater is contaminated by septic systems discharge. There have not, however, been any dedicated studies assessing the quantity and quality of fresh groundwater in Tokelau and its potential for development as a secondary freshwater supply. This would lessen pressures on stored rainwater supplies, allowing them to last longer for primary purposes and increase the resilience of communities against droughts.

In 2013, a survey of all rainwater harvesting systems in Tokelau was conducted by SPC's Geoscience Division (Koroisamanunu et al. 2014). The survey concluded that the total storage capacity in Tokelau was 27.5 ML or 18,300 L per person (Table 2).

Table 2. Survey of rainwater harvesting systems in Tokelau (Koroisamanunu et al. 2014).

Data collected	Atafu	Nukunonu	Fakaofo
Total buildings surveyed	193	146	202
Rainwater harvesting systems	127	104	130
Total population	390	302	382
Total storage capacity (kL)	11,100	8,876	7,526
Storage per household (kL)	87	93	50

A survey of roof rainwater catchment areas of households and community buildings would provide additional insights on whether an adequate supply of rainwater can be provided to the existing tanks or whether additional roof areas are required. Such calculations would also require a fair estimate of per capita water requirements, as well as long-term rainfall records to derive statistics on rainfall frequency and average drought duration. Despite the absence of long-term rainfall records, White (2019a) used the existing historic rainfall data (Nukunonu 1954–1982), assuming that they are representative of current rainfall conditions in Tokelau, to estimate storage requirements and roof areas necessary to survive historic droughts. Assuming a water demand of 120 L/person/day and non-leaking tanks, White (2019a) estimated that the existing rainwater storages in Atafu, Nukunonu and Fakaofo should last for 185, 148, and 125 days, respectively. White's analysis (2019a) further identified the need for additional rainwater catchment areas to effectively fill the existing tank volumes through drought periods.

2.5 Geology and groundwater occurrence

Atolls are geologic structures derived from basaltic volcanoes that have subsided. Reef growth results in a cap of calcium carbonate minerals, extending from the sea surface to the top of the submerged volcano. Chemical alteration and weathering of these carbonate minerals, induced by precipitation and sea-level changes, have governed the shallow subsurface geology, which is generally described by the following two-layer model (Figure 3): (i) upper sediment unit composed of unconsolidated and well-sorted coral sand and gravel of Holocene age; and (ii) well-consolidated karstified limestone of Pleistocene age, which formed during subaerial exposure and recrystallisation to calcite. The unconformity between the younger sediments and the underlying Pleistocene limestone (Thurber Discontinuity) is typically encountered at depths ranging between 5 m and 25 m.

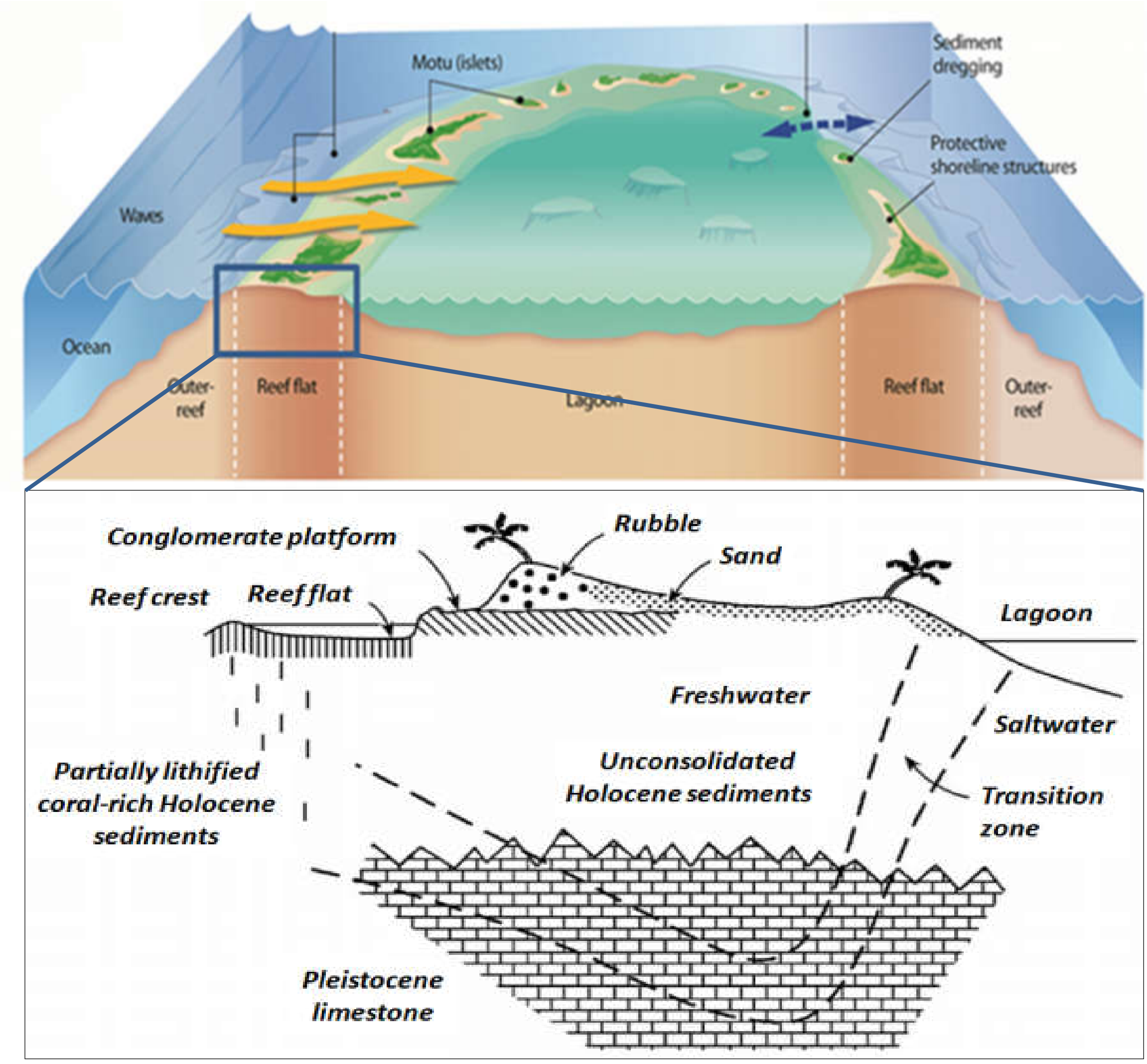

Figure 3. Schematic illustration of the hydrogeology of carbonate atolls (after Garcin et al. 2011 and Woodroffe 2008)

Fresh groundwater occurs in an atoll as a thin lens, buoyantly supported by dense underlying saline water. A freshwater lens is formed within the unconsolidated sediments due to suitable hydraulic conditions. Generally, on wider islands (> 1000 m) that receive an appreciable amount of rainfall, the base of the freshwater lens can reach the Thurber Discontinuity. The higher permeability of the underlying limestone cannot support the formation of a lens that is truncated at that point, due to immediate mixing with the underlying saltwater (Hamlin and Anthony 1987; Hunt 1997). The thickness of the freshwater lens across the width of the island depends on the recharge rate, the island's width, the hydraulic conductivity (K) of the upper sediment units, the depth to the Thurber Discontinuity, and the presence or absence of a reef flat plate (Bailey and Jenson 2012). A zone of transitional salinity typically exists between the infiltrated rainwater and the underlying saltwater. This zone is formed by the mixing of the two water types, which is promoted by tidal forces; the thickness of this transitional zone largely depends on the hydraulic properties of the aquifer sediments.

Recent and ongoing geophysical investigations conducted on an increasing number of atolls in the Pacific are revealing that island width does not necessarily reflect a proportional freshwater lens thickness. It appears that hydraulic conductivity of the Holocene sediments, in combination with the depth to the karstified Pleistocene limestone, which sets a limiting factor for freshwater lens development, are the two main parameters controlling the thickness of a freshwater lens. Both parameters may vary between atoll islets, as well as within the same islet. For example, shallow seismic investigations conducted on Pingelap atoll, Pohnpei (Ayers and Vacher 1986) have revealed that the depth to the karstified Pleistocene limestone can vary, even within the same island, controlling spatially the potential for freshwater lens development.

The hydraulic properties of freshwater lens aquifers can strongly depend on the island's position with respect to the prevailing winds (Bailey 2010). Freshwater lens aquifers tend to acquire a coarse sediment structure on islands that are in the direct path of the prevailing winds and their associated high-energy waves. In contrast, aquifers on the partially protected leeward side of atolls tend to acquire a finer sediment structure. Considering that the prevailing direction of the tradewinds in Tokelau is from the east, it is expected that islets on the western parts of the atolls may offer more suitable hydraulic conditions for the development of thick freshwater lenses.

2.6 Threats to groundwater

Threats to freshwater lenses may be naturally occurring or anthropogenic and can negatively affect groundwater quantity and quality. In the case of freshwater lenses, these two characteristics (quantity and quality) are interrelated as a reduction in volume (quantity) is accompanied by a reduction in quality (increase of groundwater salinity). This is because of the nature of freshwater lenses, which shrink upwards through the upward movement of the fresh/saltwater interface instead of a decline in the groundwater table, as happens in conventional aquifer settings. Instead of wells running dry, the salinity of abstracted groundwater gradually increases. Shrinking of a fresh groundwater lens may occur due to naturally occurring processes, such as droughts, or due to anthropogenic impacts, such as over-abstraction. Salinisation of a freshwater lens may also occur due to seawater inundation, another naturally occurring event resulting from storm surges, which can result in shallow saline plumes contaminating the freshwater lens for periods that range from a few months to several years (Werner et al 2017).

Anthropogenic threats to fresh groundwater lenses include land-use changes and contamination deriving from anthropogenic activities. Land-use changes, such as the clearance of trees and vegetation, may affect groundwater recharge and evapotranspiration patterns, many times positively in terms of groundwater storage. On the other hand, the shallow groundwater tables encountered in atoll settings render the freshwater lenses particularly prone to contamination from sources such as sanitation systems, landfills and agricultural activities. Leaking sanitation systems are the main source of virus and bacterial pathogens contaminating shallow freshwater lens systems. Nitrogen (predominantly in the form of ammonium and organic nitrogen) and phosphorus, deriving from wastewater and agricultural activities, are also commonly found in fresh groundwater lenses, particularly in urban and peri-urban areas.

3. Field survey methodology

3.1 Ground penetrating radar

To gain a better appreciation of the quantity of fresh groundwater supplies within the areas of interest, geophysics using a ground penetrating radar (GPR) was employed. Time constraints and limited manpower necessitated employing the GPR technique due to its short data acquisition time. Only two days could be spent on each atoll, constraining the available options as electrical resistivity tomography (ERT) surveys would have taken considerably longer, meaning that the surveys would have covered limited areas. It was decided to employ the GPR technique to conduct a first-pass groundwater assessment covering as big an area as possible to guide additional, more detailed assessments in the future.

GPR is a technique that employs high-frequency radio electromagnetic waves, usually between 10 MHz and 2000 MHz, to acquire subsurface information and to map metallic/non-metallic structures/features buried in the ground. Buried objects or boundaries with an abrupt change in electrical properties create a reflection from the electromagnetic signals. The radio waves are reflected back to the antenna with amplitudes and arrival times that are related to the electrical conductivities (equivalently, dielectric constants) of the material layers. Across the interfaces, part of the energy is reflected and part is absorbed, depending on the dielectric contrast of the materials. The propagation velocity of the radio wave through a subsurface layer is related to the electromagnetic behaviour of the layer: $v = {}^{c}/_{\sqrt{\varepsilon_r}}$

where: ε_r = dielectric constant (permittivity) of layer and c = speed of light in vacuum (30 cm/ns). The permittivity depends on material properties, including water content, porosity and, to a lesser extent, mineral composition of the grains (Topp et al. 1980). Propagation velocities are required in order to transform travel times into depths. Interpretation therefore requires the development of a velocity model to derive the exact location of features and the spatial distribution of layers and horizons in the subsurface.

GPR has civil engineering, geotechnical, environmental, archaeological and military applications. Under the right conditions, GPR can also provide useful information on shallow hydrogeology in coastal zones, including the identification of the depth to the water table, the depth to the freshwater/saltwater interface, and the mapping of hydrostratigraphic units. GPR waves are immediately attenuated once they hit clay layers and saltwater-saturated sediments, due to their high electrical conductivity causing the wave to get ‘scattered’ before it can return to the antenna. These high conductivity layers/interfaces can therefore be indirectly identified by the attenuation of the GPR signal.

The rapid change in moisture content upon reaching the water table produces a distinct GPR reflection, especially where the capillary zone is thin relative to the length of the emitted wave. According to Kruse et al. 2005, the water table is not readily apparent at frequencies > 200 MHz. The freshwater/saltwater interface is generally thicker than the radar wavelength and does not cause a reflection. Identification of the extent of a freshwater lens is inferred by the signal attenuation associated with the high conductivity of the underlying seawater-saturated sediments. Signal attenuation should always be interpreted with care, as surficial obstacles (e.g. concrete) and shallow geological layers (e.g. mudflats) may impede the radio wave penetration. It is strongly recommended that the interpretations are always calibrated for the depths to the water table and saltwater/freshwater interface locally, through existing shallow wells and monitoring boreholes.

GPR surveys were conducted on all three atolls in Tokelau on a total of eight islets. A total of 20, 14, and 14 survey lines were conducted on Atafu, Fakaofo and Nukunonu atolls, respectively. The main objective of these surveys was to approximate the lateral variation of the vertical extent of the freshwater lenses along the width of the surveyed islands. The absence of monitoring boreholes and of accessible shallow wells did not allow for the in situ calibration of GPR results. A preliminary survey was conducted in a similar low carbonate island setting to test the capability of GPR to identify the groundwater table and the freshwater lens thickness and to calibrate against the electrical resistivity tomography (ERT) method, which has so far been considered a more accurate method. Nukulau island, off the coast of Suva, Fiji, was chosen as a suitable coral islet where a freshwater lens has developed and a number of piezometers have been installed to monitor the lens behaviour.

The Mala Easy Locator Pro WideRange GPR (dual frequency, 160 and 670 MHz) was used to undertake the surveys. The dual frequency allowed a greater appreciation of the subsurface, as each frequency has pros and cons and the combination of both allowed for a more complete insight.

For the interpretation, signal propagation velocities of 12–15, 5.5–6.5 and 1 cm/ns were assumed for unsaturated coral sands, saturated sands with freshwater, and saturated sands with seawater, respectively (Table 3*Table 3*). This allowed converting travel times into depths and, in the absence of distinctive/continuous horizons indicating the groundwater table, approximating the depth to the groundwater table through the hyperbole fitting method. The freshwater lens extent with depth was approximated by the signal attenuation with depth, acknowledging the fact that surficial factors may also contribute to signal attenuation. The results presented in this study provide, therefore, a conservative approximation of freshwater lens depths and calibrating them against ERT surveys or against real groundwater salinity observations obtained through piezometers is strongly recommended.

Table 3. Propagation velocities in relevant materials

Material	**Propagation velocity (cm/ns)**
Unsaturated sand	12–15
Saturated with freshwater	5.5–6.5
Seawater	1

4. Results and discussion

4.1 Calibration of GPR

Two perpendicular GPR profiles were conducted along Nukulau island, following existing tracks which cross the island (Figure 4). A 440 m survey line (Line 1) was conducted from west to east and a 215 m line (Line 2) was conducted from north to south. Additionally, an ERT survey line was also conducted along Line 1. The two GPR profiles were conducted twice, first during a dry period (October 2018) and a month later during a wet period to evaluate any changes in the thickness of the freshwater lens. Unfortunately, topographical surveys could not be conducted along the survey lines due to dense vegetation obstructing the satellite signal necessary for a real time kinematic survey. The results are therefore presented assuming a flat topographical surface. The limitations of this assumption are addressed later on.

Figure 4. Test GPR profiles conducted on Nukulau island, Fiji

Figures 5, 6 and 7 illustrate the different stages followed during the interpretation of the high frequency GPR Line 1, conducted in October 2018 during a dry period. Figure 5 illustrates the identification of the groundwater table, using the appropriate signal gain factor. The reflection is less obvious along the first half of the survey line but becomes clearly visible along the second half. The depth to the interface is in good accordance with groundwater table measurements in existing wells along the survey line. It should be noted that the unusual concave shape of the interpreted groundwater table is due to the absence of topography which, if incorporated, would have resulted in a relatively flat and slightly convex groundwater table shape. Figure 6 illustrates the approach followed to approximate the freshwater lens thickness through the use of a high signal gain factor to reveal the maximum penetration depth of GPR signal before it dissipates in a highly conductive brackish water environment. Although the groundwater table is less visible with these gain settings, the signal attenuation with depth reveals a concave shape, which is interpreted as the extent of the freshwater lens. The zones in between the delineated surfaces are assigned a propagation velocity of 6.5 cm/ns based on Table 3 and time (ns) is converted to depth (m) along the y-axis in Figure 7, revealing a freshwater lens extent up to 3.5 m depth with a thickness of 1–1.5 m. A similar procedure was followed using the low frequency profile of the same survey line to identify a sharper and clearly visible reflection for the groundwater table along the entire profile, as well as a slightly deeper signal penetration depth (up to 4 m depth). The lateral variation in the penetration depth between the two frequencies was comparable but the high frequency profile resulted in a clearer illustration of maximum penetration depth compared to the low frequency profile. The low frequency profile (Figure 8) revealed a second reflection below the groundwater table towards the end of the survey line, possibly illustrating the presence of a reef plate, a geological feature often present in low carbonate islands. The presence of a reef flat along the western part of the island has been observed during the drilling of piezometers.

Of particular interest is the high frequency GPR profile conducted along Line 1 in November 2018 during a wet period (Figure 9). The groundwater table is barely visible, producing a very weak reflection, probably due to higher moisture levels in the unsaturated zone and the greater thickness of the capillary zone relative to the length of the emitted wave. The low frequency GPR profile is still capable of identifying the groundwater table, albeit with a less distinct reflection compared to the October 2018 profile. The same observations were made for the north-south profile (GPR Line 2), although the groundwater table could not be clearly identified anywhere along the high frequency profiles.

The ERT profile conducted along Line 1 revealed a more accurate representation of the freshwater lens extent and of the transition zone from freshwater- to saltwater-saturated sediments, compared to the GPR (Figure 10). Although there is no multi-screen piezometer on the island to allow for monitoring of the groundwater salinity at different depths, calibration of ERT results was conducted in a similar geological setting in Laura, Majuro atoll, Republic of the Marshall Islands (Antoniou et al. 2019), where a groundwater monitoring network of boreholes exist. This allowed matching electrical resistivity values against real groundwater salinity measurements at different depths. Coral sands saturated with groundwater having an electrical conductivity of 2,500 µS/cm (5% seawater) were matched with an electrical resistivity of around 20 Ohm.m and the same value was used to infer the freshwater lens extent in Nukulau. The ERT profile in Nukulau revealed a freshwater lens extent of up to 12 m, demonstrating the sensitivity of GPR to slightly increased groundwater salinity. The GPR-inferred freshwater lens extent is similar to the 60 Ohm.m electrical resistivity contour modelled in Figure 10 which represents coral sands saturated with fresh groundwater having an EC of around 800 µS/cm, according to the calibration exercise performed in Laura, RMI. It should be noted that the low frequency electromagnetic signal emitted by the GPR is expected to reach a maximum penetration depth of around 10 m under suitable conditions (dry sand/gravel or saturated with very fresh water), strengthening the conclusion of quick signal attenuation with slightly increased groundwater salinity. Nevertheless, the lateral distribution of the GPR signal penetration depth can give relatively good approximation of a freshwater lens shape and potentially identify the areas where a freshwater lens might be thicker. Another point worth mentioning, observed in Figure 6, is the fact that a deeper penetration depth is observed along the second half of the profile, despite the thinning of the unsaturated zone, supporting the conclusion that this increased penetration depth is due to a thicker freshwater lens.

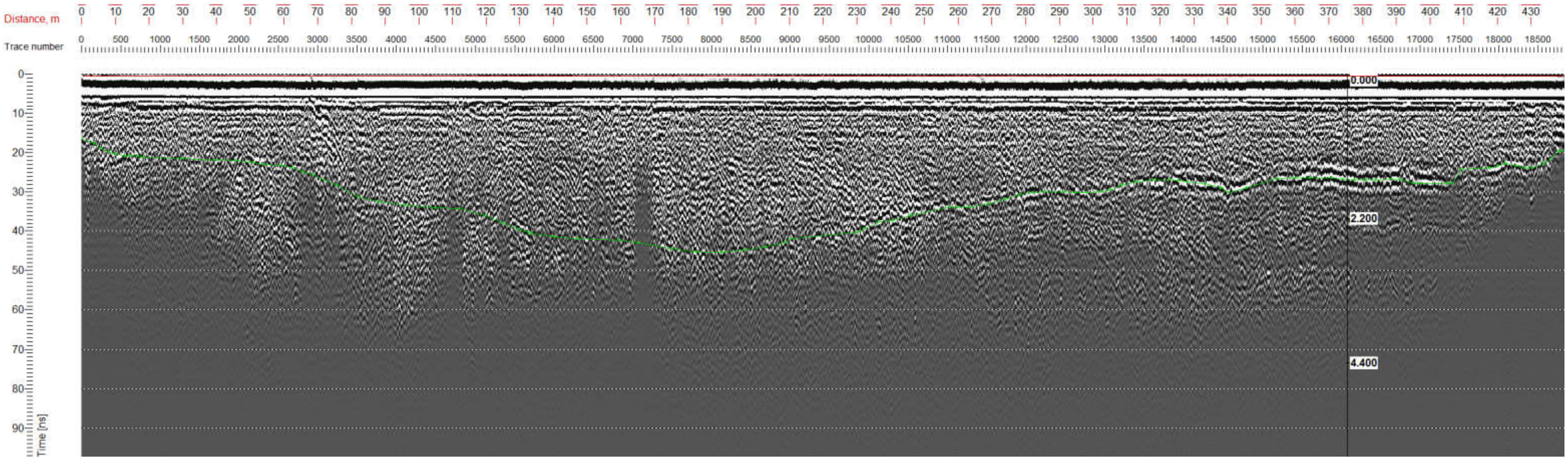

Figure 5. GPR Line 1 (W-E) high frequency (670 MHz) conducted in Nukulau in October 2018 – identification of groundwater table (green line)

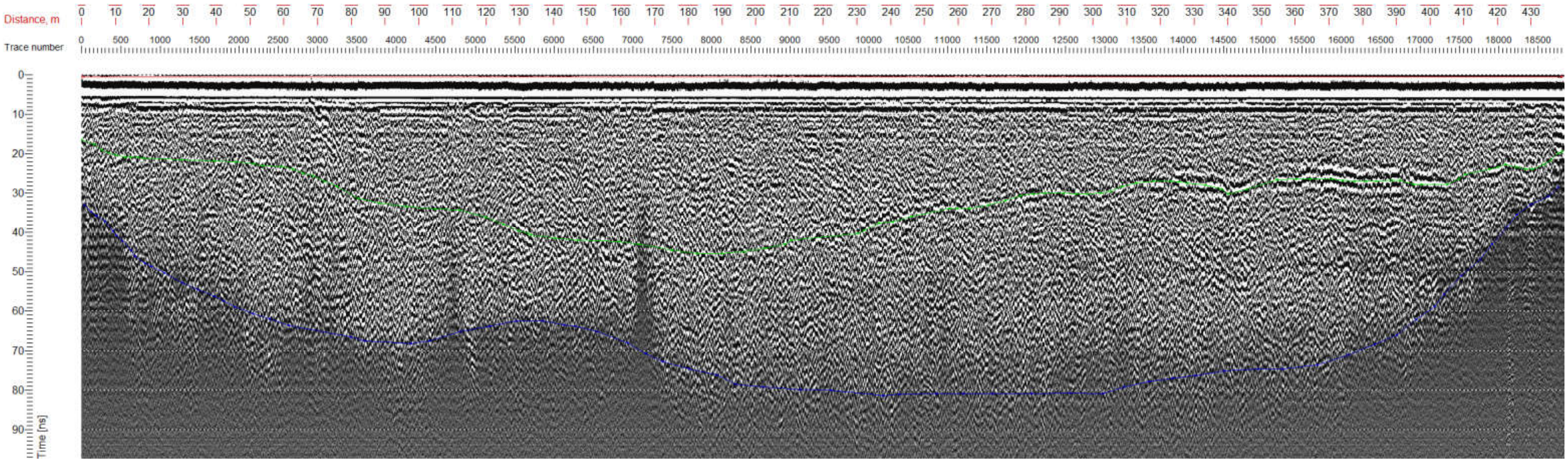

Figure 6. GPR Line 1 (W-E) high frequency (670 MHz) conducted in Nukulau in October 2018 – identification of freshwater lens extent (blue line)

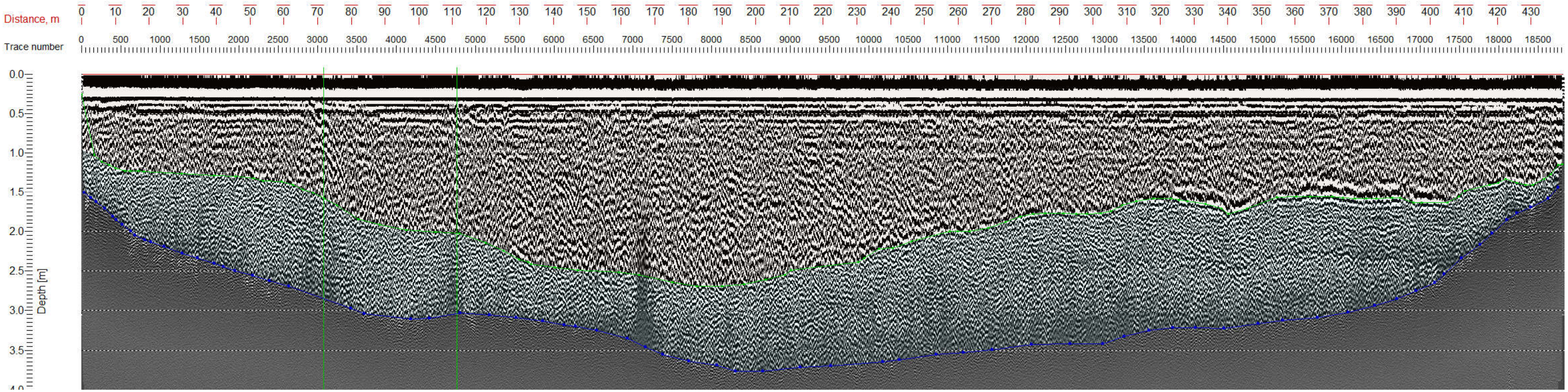

Figure 7. GPR Line 1 (W-E) high frequency (670 MHz) conducted in Nukulau in October 2018 – depth model depicting unsaturated zone (light brown), freshwater lens (light blue) and saltwater saturated sediments (dark blue)

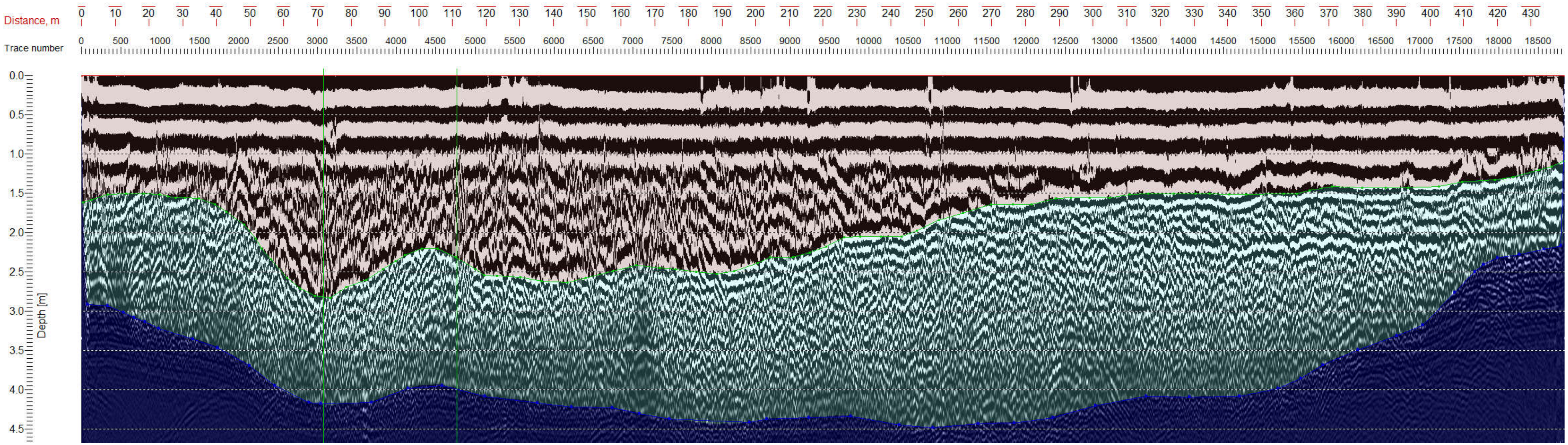

Figure 8. GPR Line 1 (W-E) low frequency (160 MHz) conducted in Nukulau in October 2018 – depth model depicting unsaturated zone (light brown), freshwater lens (light blue) and saltwater saturated sediments (dark blue)

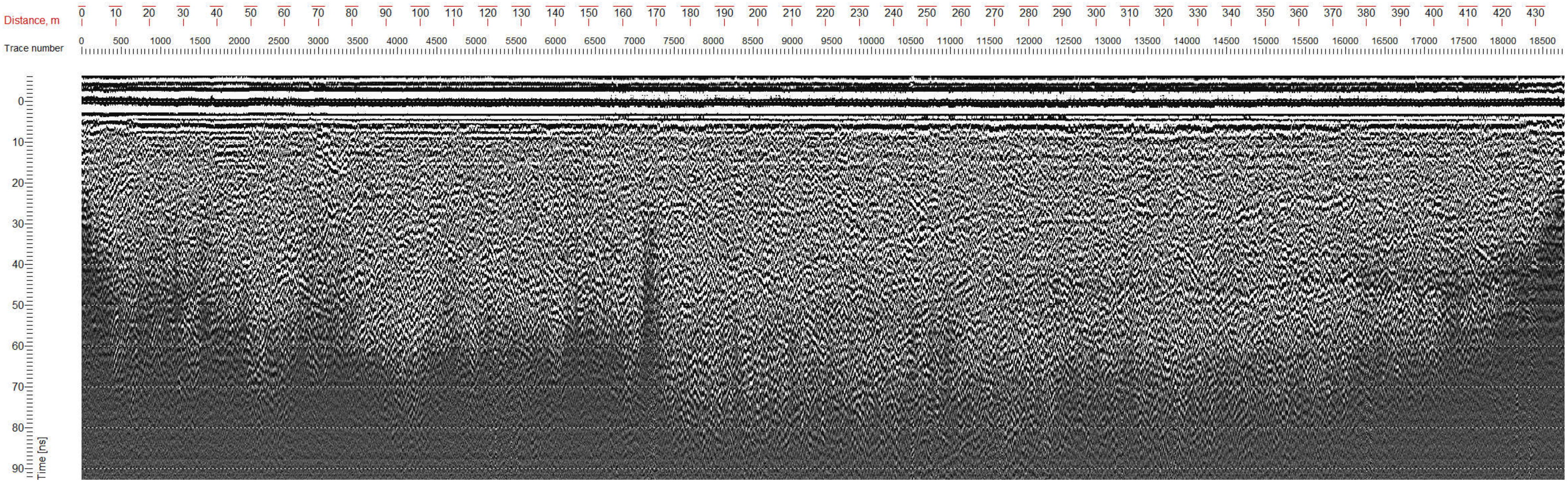

Figure 9. GPR Line 1 (W-E) high frequency (670 MHz) conducted in Nukulau in November 2018 (wet period)

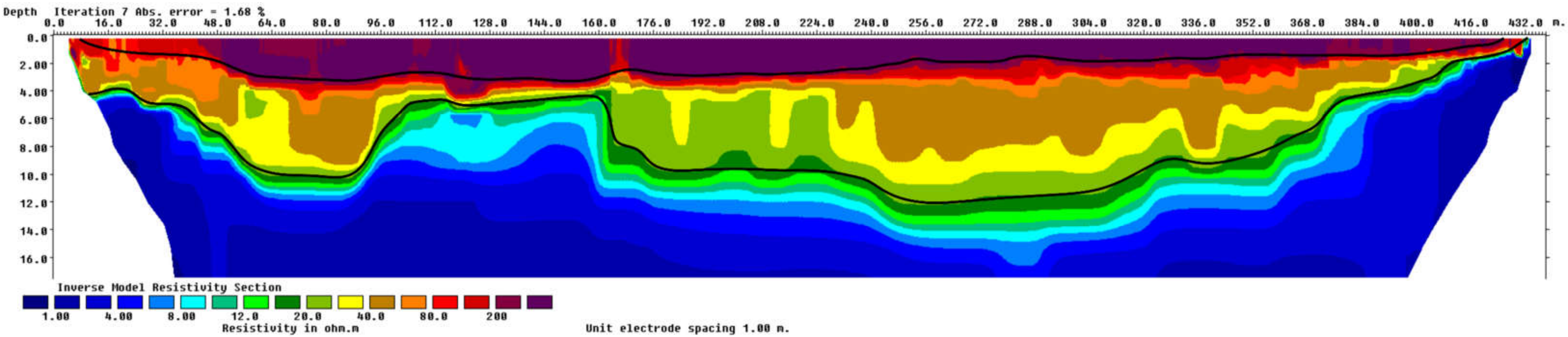

Figure 10. ERT Line 1 (W-E) conducted in Nukulau in November 2018 (wet period)

4.2 Geophysical results and interpretation

The survey locations and interpreted results are presented in Figures 11, 12 and 13 and are summarised in Table 4. Supported by the calibrated results obtained during the preliminary survey on Nukulau island and assuming a flat topography along the survey lines, the penetration depth of the GPR signal was used as a proxy to approximate the thickness of the freshwater lens. The areas with the thickest freshwater lens, as suggested by the GPR surveys, were delineated as areas with higher groundwater development potential. It is, however, strongly recommended that, prior to installing any groundwater production infrastructure, additional ERT surveys are conducted within the areas identified from this first-pass investigation, to confirm the GPR results and to identify the exact locations for the infrastructure to be installed.

Table 4. Estimated thickness of freshwater lenses through GPR

Atoll	Islet	Indicative freshwater lens thickness (m)	Indicative groundwater development potential
Atafu	Atafu	< 5	High
	Te Oki	< 1	Low
	Na Utua	< 1	Low
Fakaofo	Fenua Fala	< 2.5	Medium
	Fale	< 1	Low
Nukunonu	Nukunonu	< 5	High
	Motuhaga	< 5	High
	Motu Akea	< 1	Low

Atafu

The GPR results suggest the presence of a slightly thicker freshwater lens in the western part of Atafu island, extending between the solar farm and the southern tip of the village. The freshwater lens thickness is not expected to be greater than 5 m. Due to the presence of households along the southern part of the delineated area, groundwater development should be focussed on the northern part, preferably in the area between the solar farm and the endpoint of survey line 45 (Figure 11) where there are no households. This would provide for a safer distance between potential contamination sources (septic tanks) and the groundwater production infrastructure. GPR surveys conducted on the other islets (Te Oki and Na Utua) suggest the absence of any substantial fresh groundwater supplies and thus no further investigations are recommended.

Nukunonu

A similar freshwater lens with a maximum thickness of 5 m was also observed in the islets of Nukunonu and Motuhaga in Nukunonu atoll. No surveys were conducted through the village but the ones conducted northwest of the village, especially around the football field, suggested the presence of potentially useful groundwater supplies with a thickness of < 5 m.

Fakaofo

Low to medium groundwater development potential is suggested by the GPR surveys in Fakaofo atoll, conducted on the islets of Fale and Fenua Fala. Some limited potential is suggested for the village area on Fenua Fala, possibly allowing for groundwater production which could be useful for secondary purposes, such as the flushing of toilets.

4.3 Groundwater resource development

The fresh groundwater resources identified through this survey are expected to be very thin and prone to salinisation due to the underlying saltwater-saturated sediments and the mixing promoted by the tidal movement. It has been demonstrated in the past that thin freshwater lenses can be successfully developed through the use of horizontal infiltration galleries, able to skim the top – the freshest part of the lens – while preventing the mixing with underlying saltwater and delaying the onset of salinity in the abstracted water. As trialled during the EU-funded KIRIWATSAN project (Loco et al. 2015), it is proposed that infiltration galleries be equipped with variable-speed submersible pumps and be solar-powered. Raised reservoirs and appropriately sized pipes will be required to provide enough gravity-induced flow to serve the community purposes.

Groundwater quality should be ensured through adequate testing prior to use. Groundwater could be monitored automatically through on-line salinity meters or manually, at predefined time intervals, by local water technicians. It is possible that bacteriological contamination of groundwater is also present close to pigpens and septic systems. Coliform contamination has been observed (Parsons Brinckerhoff 2010) in groundwater samples in Atafu and Fakaofo but sample preservation methods were not strictly followed. It is recommended that any installation of groundwater development infrastructure be conducted at a distance of at least 100 m from any potential contamination source to allow contaminants to be removed through natural attenuation processes during aquifer passage. These processes consist of a combination of physical straining, adsorption due to surface complexation and die-off of microorganisms (Schijven et al. 2017). Crennan (2001) conducted tracer experiments on Lifuka island in the Kingdom of Tonga to establish whether contaminants were likely to move from point sources of pollution to water supply sources, and whether pathogens would survive that rate of movement. Crennan's experiments indicated that diffusion through the water table of disease-causing micro-organisms could occur at a minimum rate of 0.4 m per day in all directions. This suggests that certain pathogens could theoretically travel up to 100 m before their die-off.

Even though groundwater quality is of primary importance for the potability of the groundwater resources, it becomes less relevant when these resources are used for secondary purposes, such as washing, gardening, animal feeding, and toilet flushing. In Tokelau, these secondary needs are also currently covered by collected rainwater, putting additional pressure on rainwater supplies, particularly during droughts. The communities of Tokelau could reconsider groundwater as an excellent resource to cover secondary needs and alleviate some of the pressure on the potable rainwater supplies. In other words, groundwater development and use could increase the resilience of the communities against droughts by indirectly contributing to an increase in potable freshwater supplies and allowing rainwater supplies to be exclusively used for drinking water purposes.

Developing groundwater resources in Tokelau would require a community consultation process in order to bring about behavioural change after communities have exclusively used rainwater for both primary and secondary needs for 50 years. The potential benefits of using groundwater should be discussed, in conjunction with the infrastructural improvements necessary to incorporate groundwater as a daily supply, or drought supply, to cover secondary and even primary water needs.

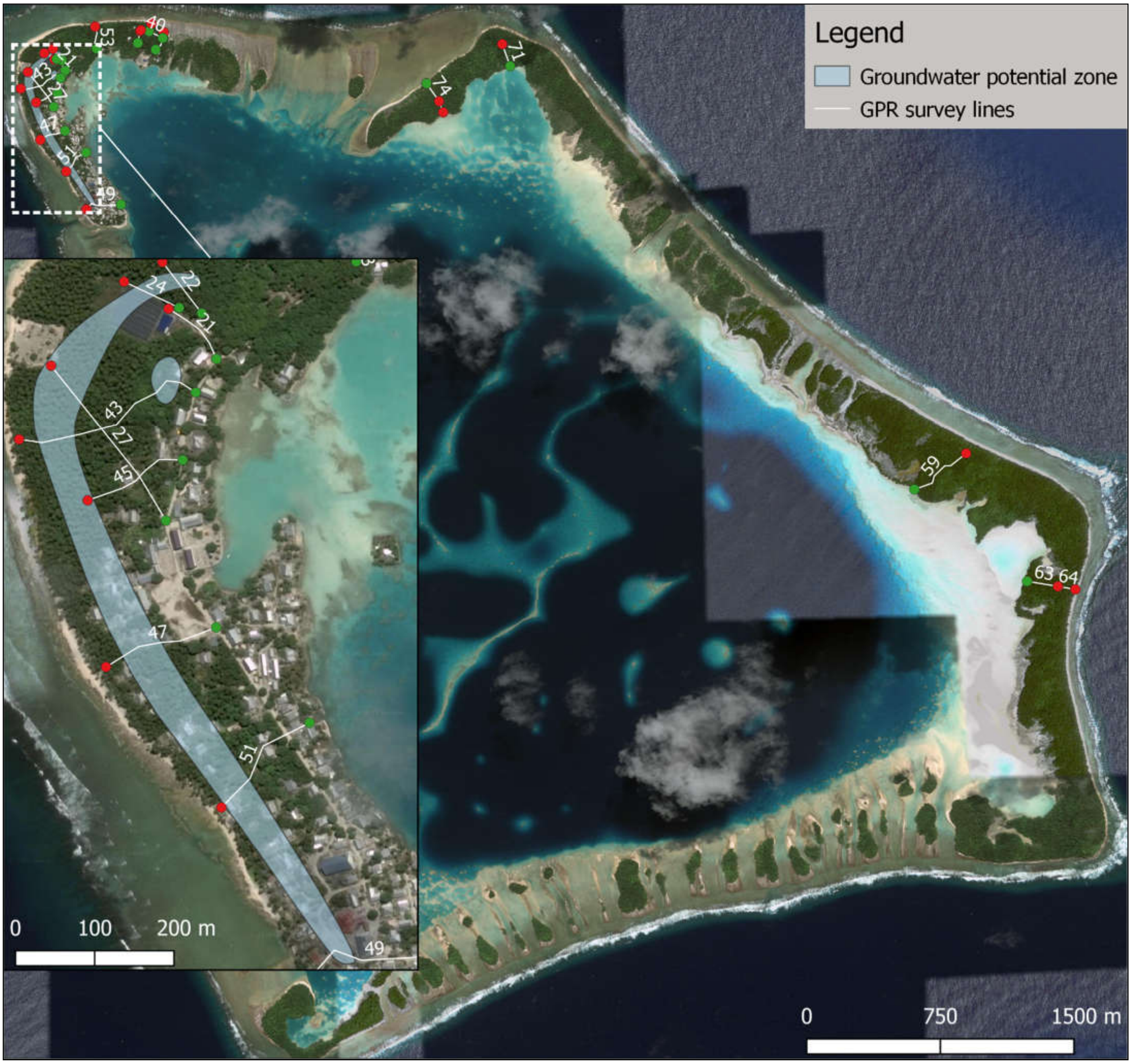

Figure 11. Atafu atoll - GPR survey lines and approximation of area with increased groundwater development potential

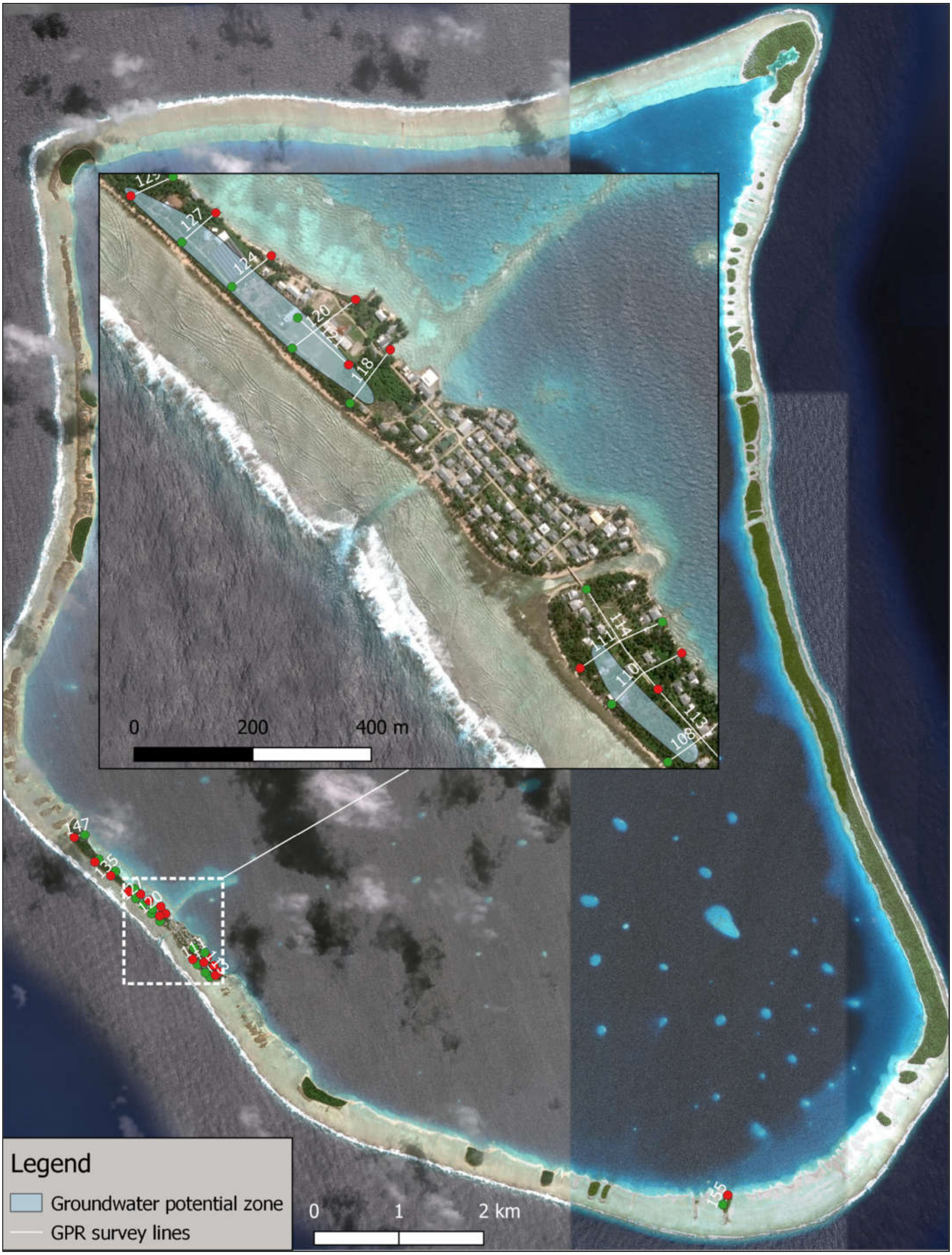

Figure 12. Nukunonu atoll - GPR survey lines and approximation of area with increased groundwater development potential

Figure 13. Fakaofo atoll - GPR survey lines and approximation of area with increased groundwater development potential

5. Conclusions and recommendations

The groundwater assessments conducted in Atafu, Nukunonu and Fakaofo atolls revealed the presence of fresh groundwater supplies which, albeit limited, could have a significant role if they were to be used conjunctively with rainwater for primary (potable) and secondary needs to assist in water source reliance diversification. In other words, groundwater could be useful to offset rainwater-harvesting needs and provide greater resilience and security to water supplies and to the communities.

The survey results presented in this study should be considered as a first-pass groundwater assessment and would benefit from additional electrical resistivity tomography (ERT) surveys, able to identify and quantify the exact extent and volume of fresh groundwater lenses and better inform the installation of groundwater production infrastructure. ERT surveys are more time-consuming, something that should be taken into consideration in a follow-up mission. Consultation with the communities would be the logical next step to decide how to utilise the resource. The potential benefits of using groundwater should be thoroughly presented and discussed and the infrastructural requirements necessary to incorporate groundwater into daily life should be clearly understood. If groundwater development takes place, this should be in line with community considerations and expectations.

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Annex 1 – Selected GPR survey profiles

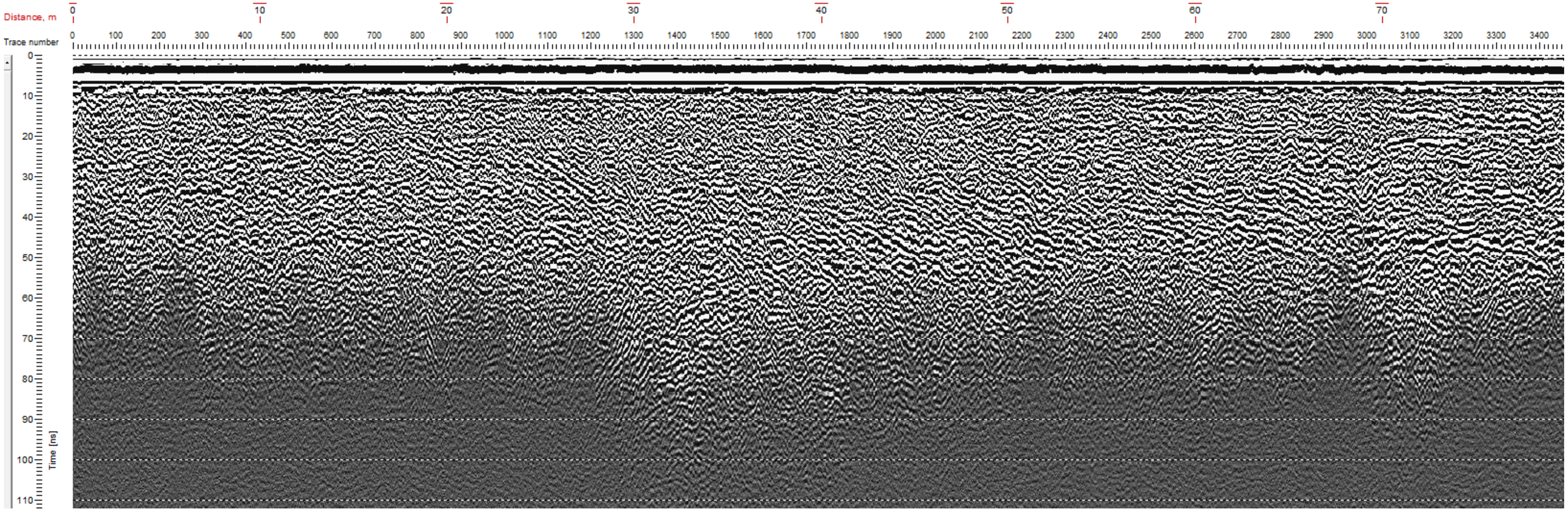


Figure A1. GPR profile 22 - Atafu

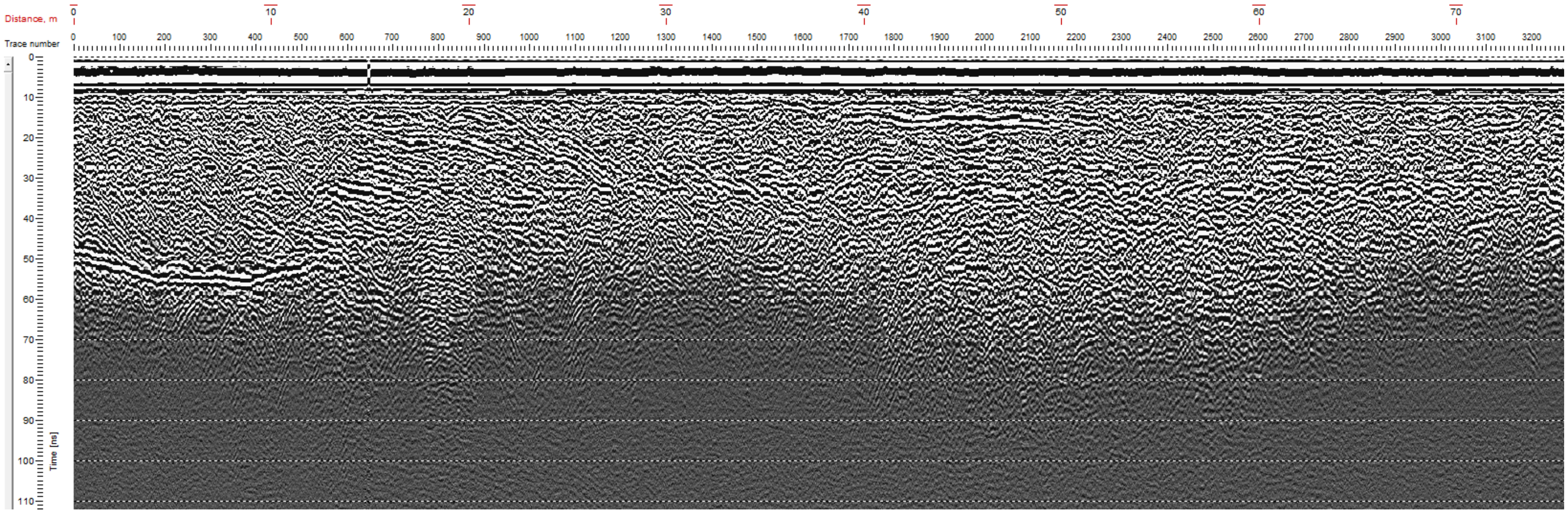


Figure A2. GPR profile 24 – Atafu

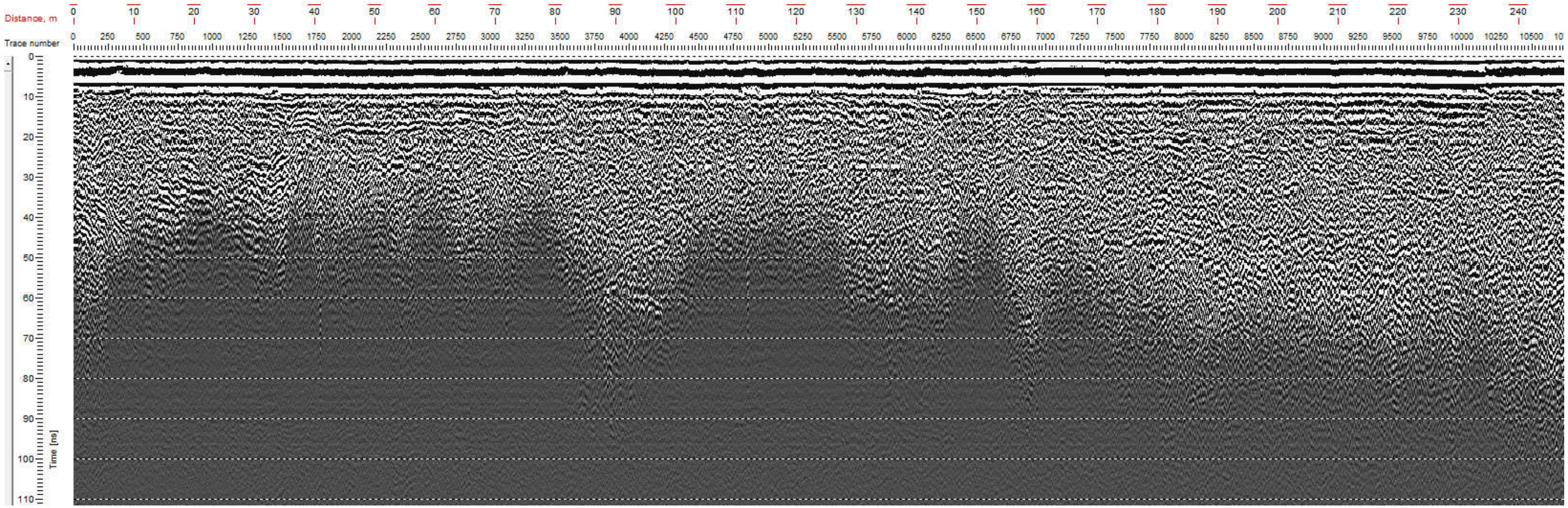
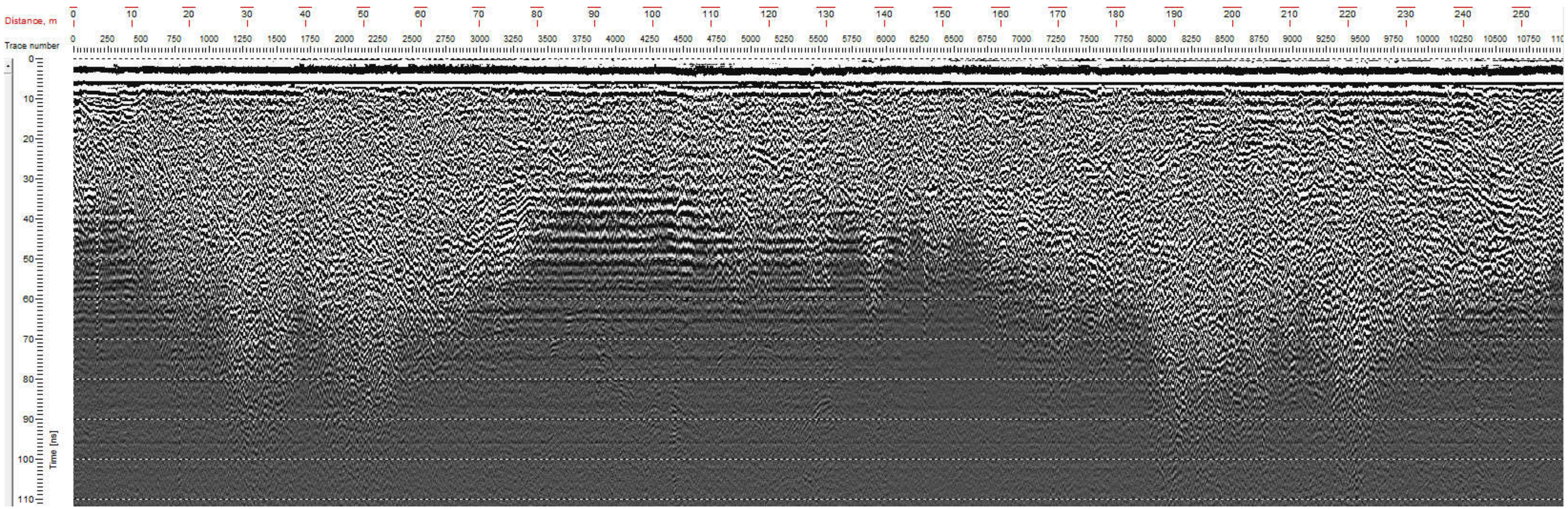


Figure A3. GPR profile 27 - Atafu



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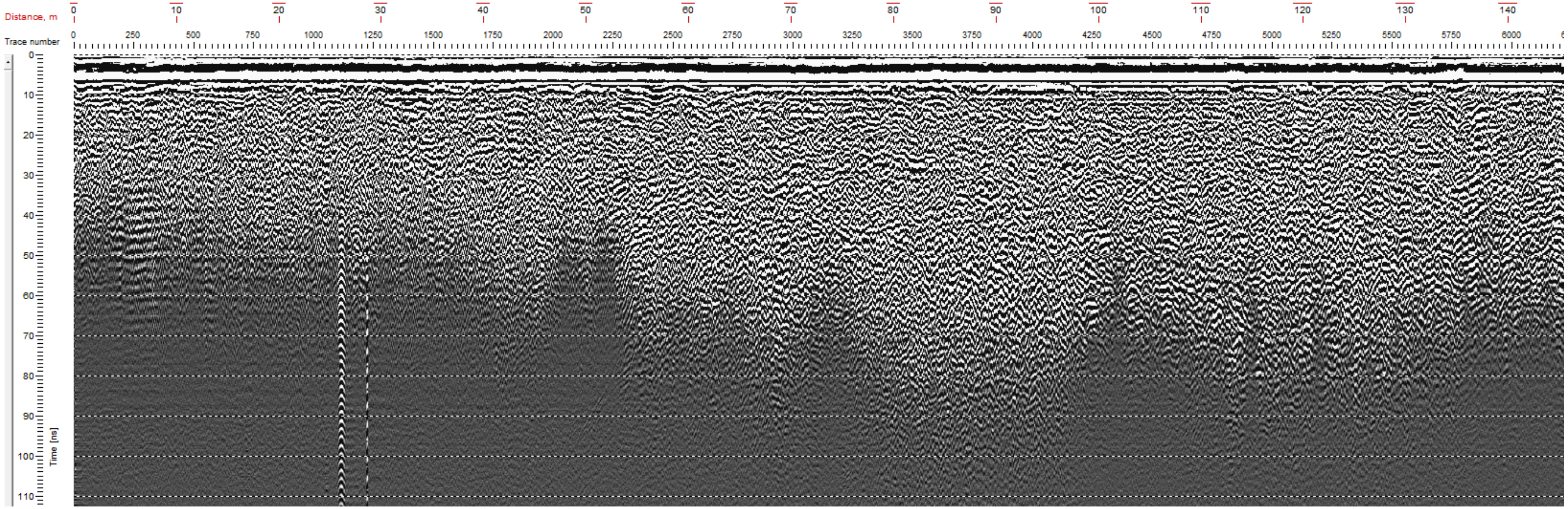


Figure A5. GPR profile 47 – Atafu

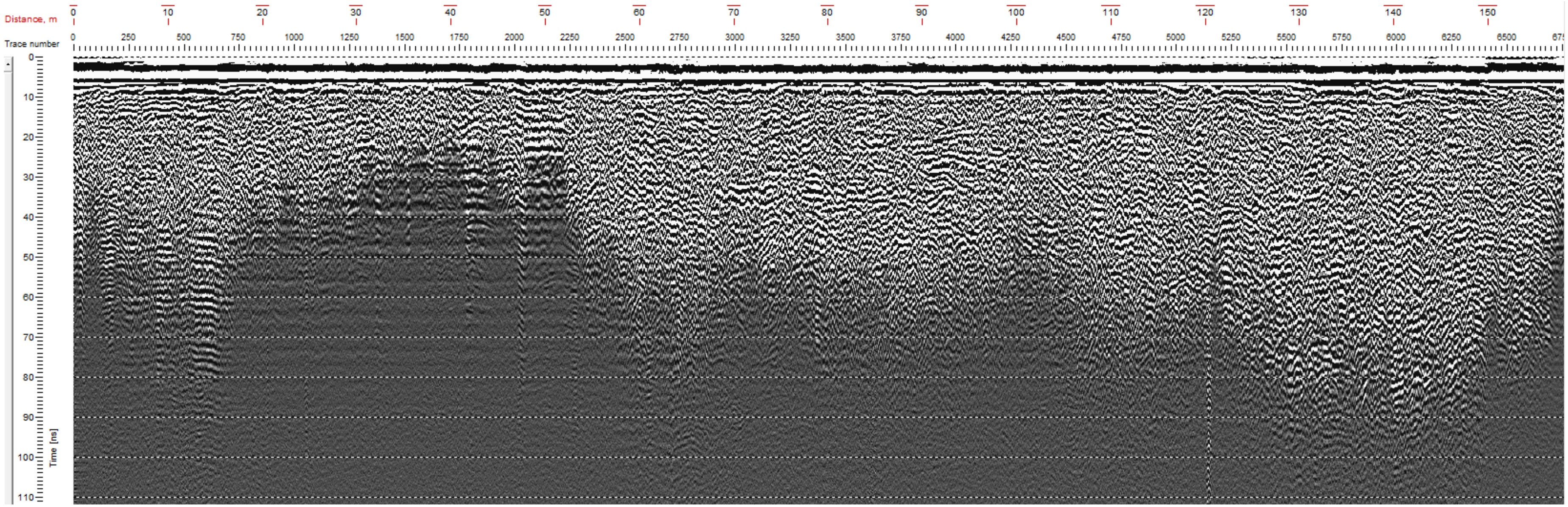


Figure A6. GPR profile 51 - Atafu

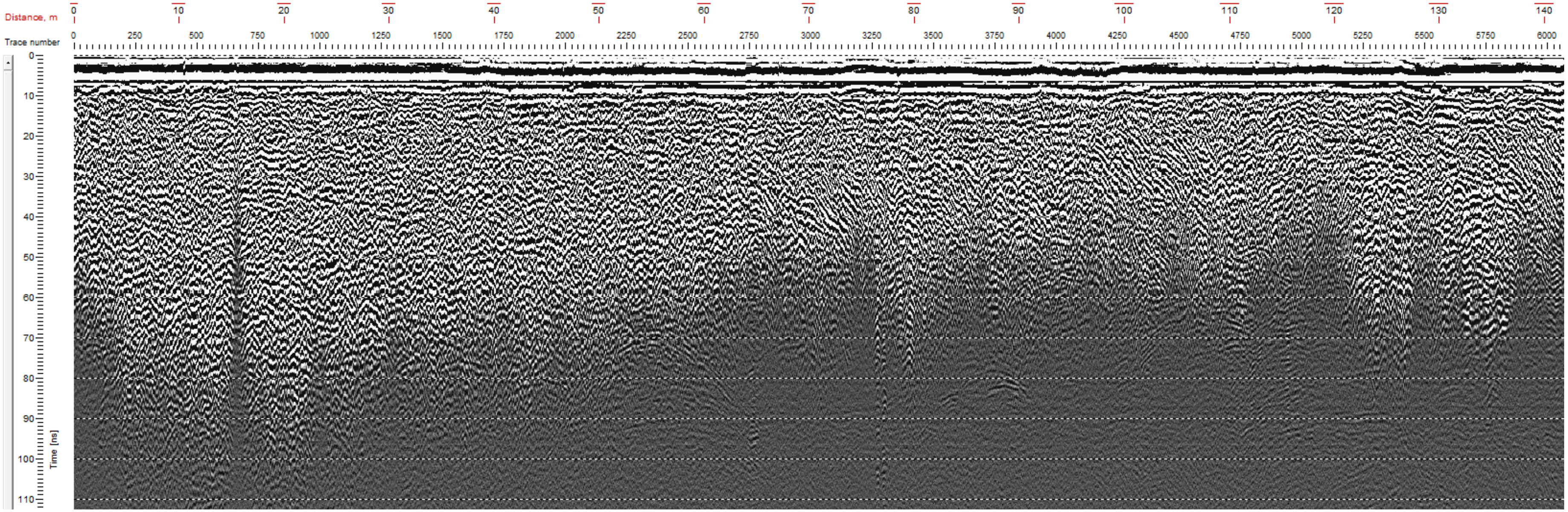


Figure A7. GPR profile 110 - Nukunonu

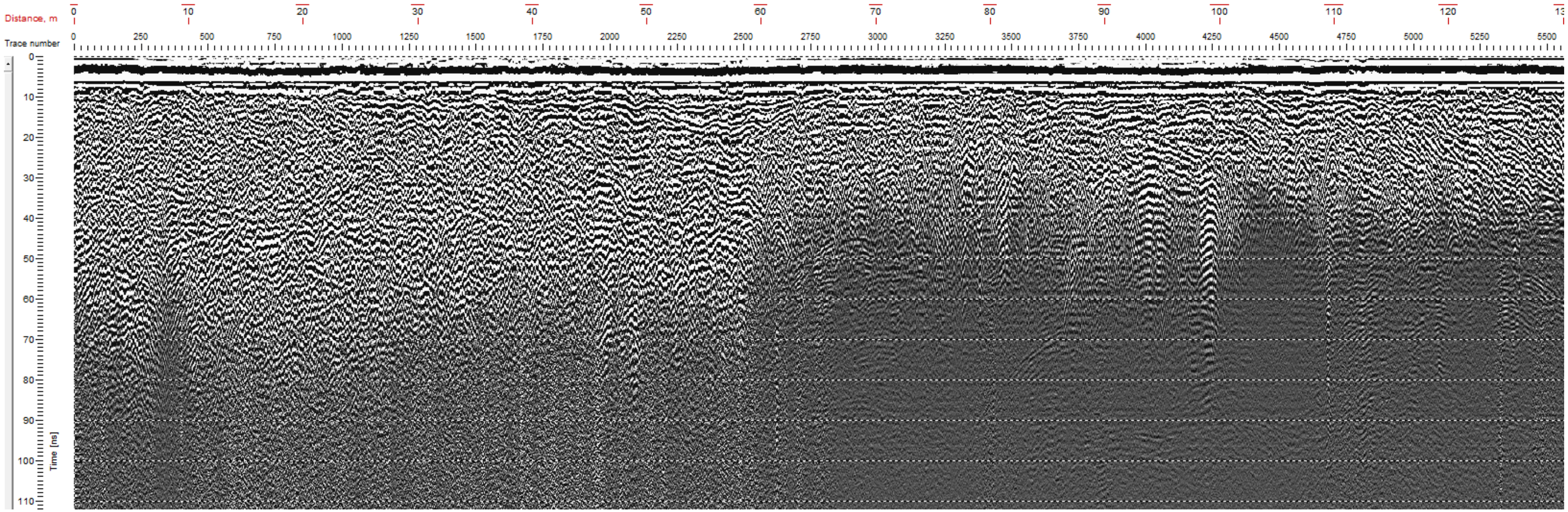
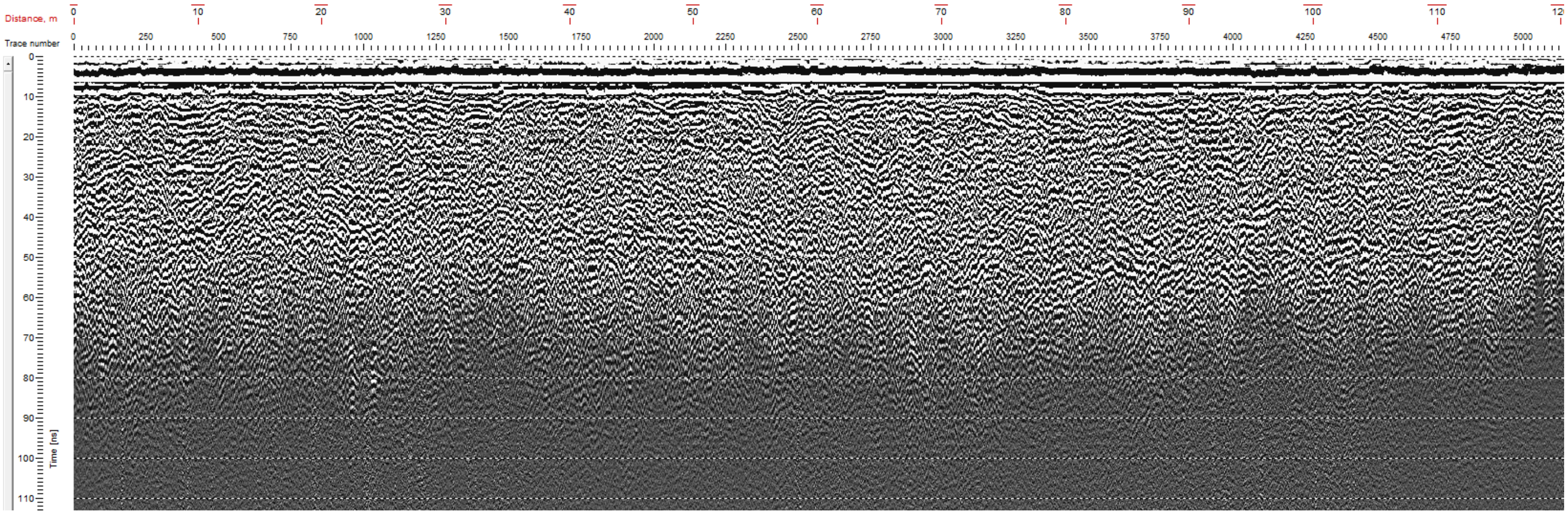


Figure A8. GPR profile 120 – Nukunonu



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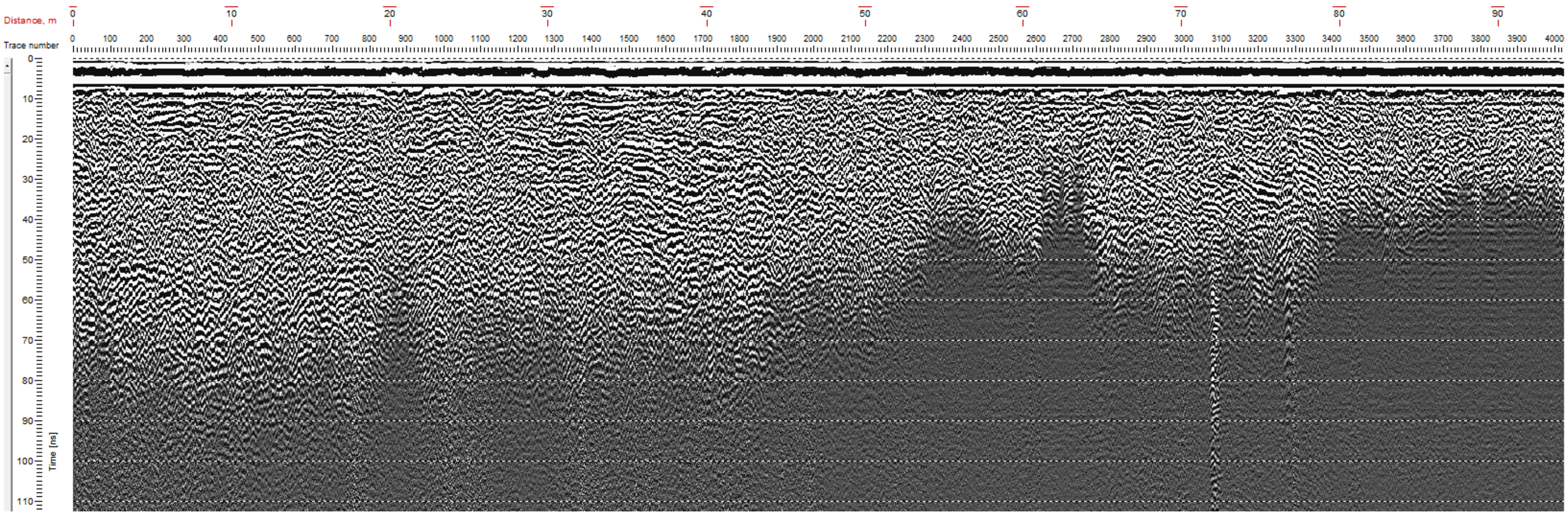


Figure A10. GPR profile 124 – Nukunonu

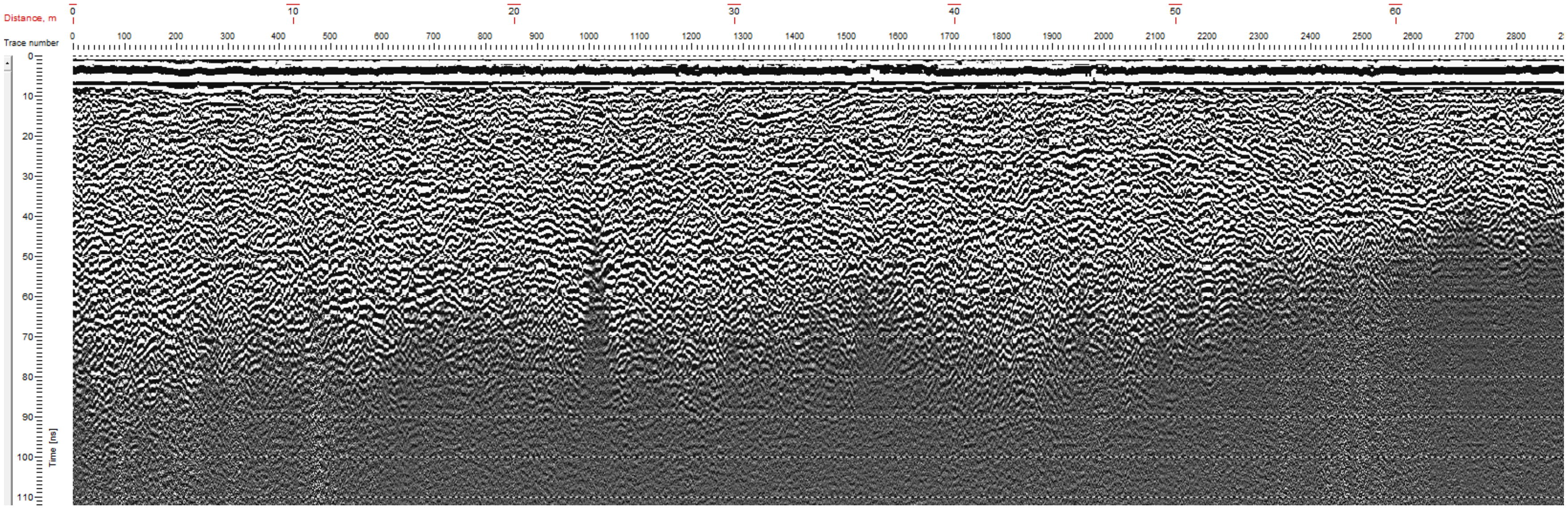


Figure A11. GPR profile 127 – Nukunonu

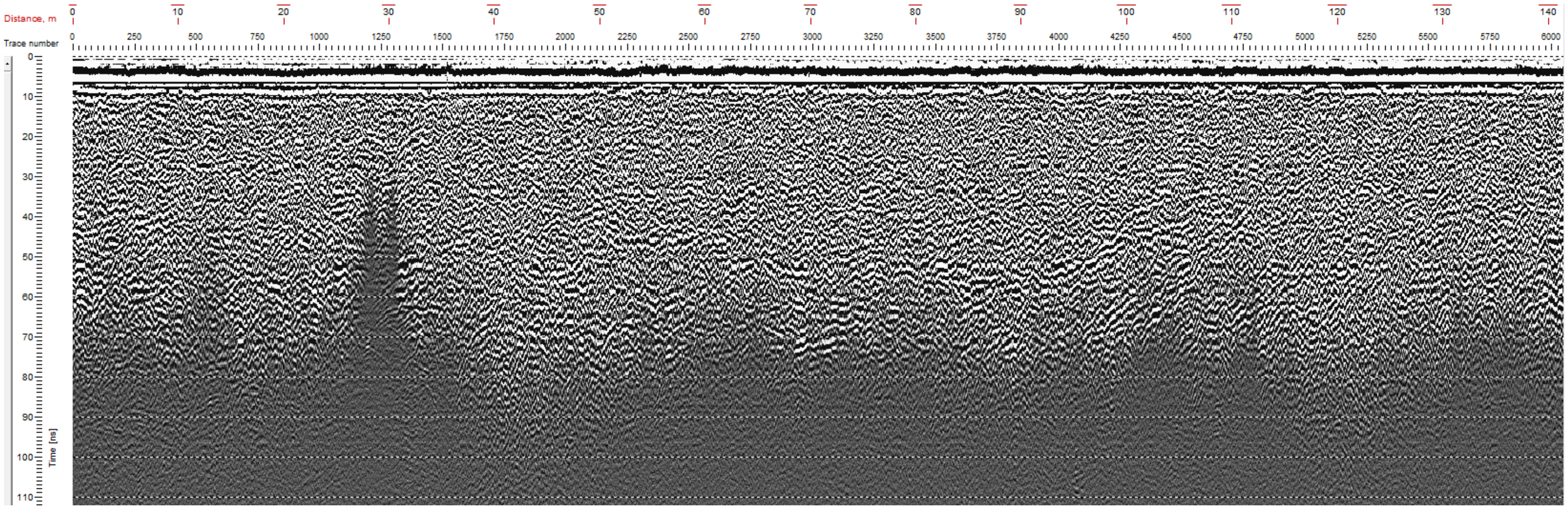


Figure A12. GPR profile 163 – Fakaofo

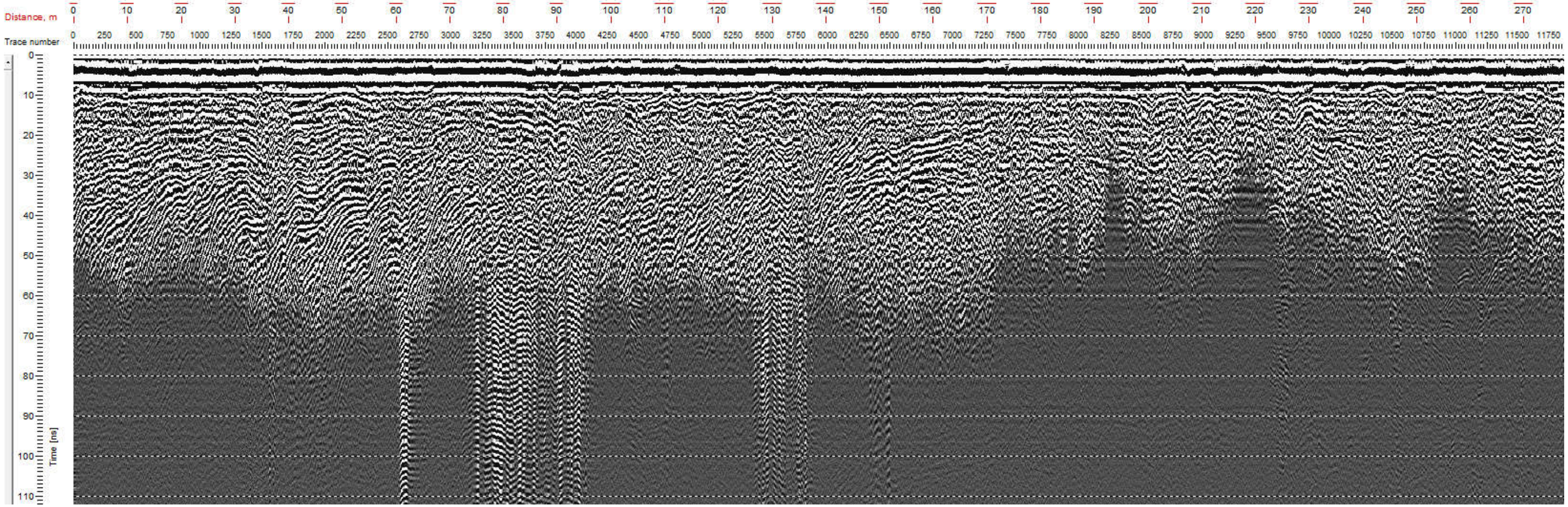


Figure A13. GPR profile 172 - Fakaofo

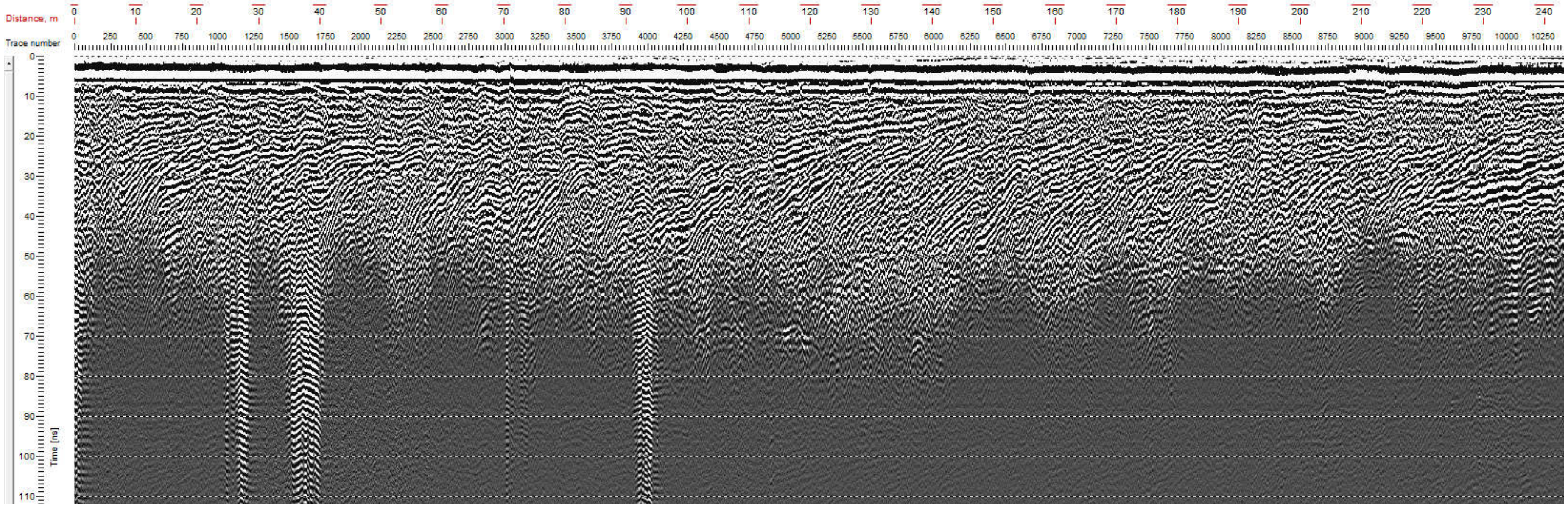
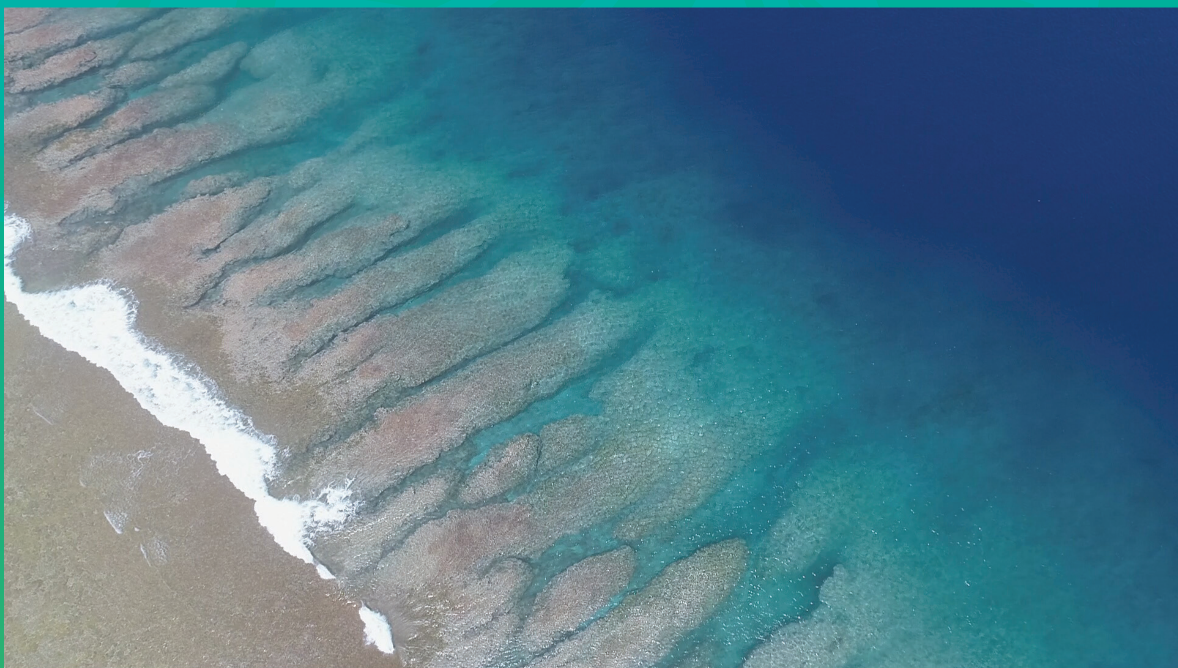


Figure A14. GPR profile 174 - Fakaofo



Pacific Community
spc@spc.int | www.spc.int
Headquarters: Noumea, New Caledonia