



REPORT

Geophysical reconnaissance of the western basin of the Plaine du Nord aquifer, Haiti

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Abstract

A geophysical reconnaissance was conducted to support aquifer characterization and evaluate groundwater potential in the western portion of the Plaine du Nord aquifer to provision the growing water demands of the city of Cap-Haitien in the Republic of Haiti. Hybrid-source audio-magnetotelluric (HSAMT) soundings and gravity measurements were collected to support the Government of Haiti in sourcing additional water supplies for the city. The Plaine du Nord aquifer is poorly characterized considering it is one of Haiti's largest aquifers, few drilling logs are available, and only one borehole has investigated the deeper extents of the aquifer. HSAMT supports depth profiling of subsurface resistivity, which supports interpretations of geological strata and groundwater conditions. Gravity measurements allow for complementary mapping of Earth density anomalies and contrasts, which assist in interpreting aquifer thicknesses or depth to bedrock. Pairing HSAMT and gravity methods permitted both an estimation of aquifer thickness and relative changes in sediment characteristics. Gravity results allowed for the mapping of aquifer thickness across the study area, with interpreted thickness greater than 300 m in the coastal zone. HSAMT results cross correlated with available well records and enabled the delineation of zones with increased groundwater potential. The results of the combined methods indicate groundwater storage potential of freshwater in deeper alluvium and emphasize the importance of strengthening resource characterization, modelling and monitoring to guide sustainable resource development and management.

Keywords Haiti · Geophysical methods · Alluvial aquifer · Groundwater exploration · Unconsolidated sediments

Introduction

Like many hydrographic basins of the developing world, the study area is data scarce and subject to expedited groundwater development in order to meet growing water demands. This study trained local technicians and applied two cost-efficient and low-impact geophysical methods to improve the understanding of a critical aquifer system to evaluate

resource potential and guide exploratory drilling to characterize the aquifer and evaluate its sustainability.

A geophysical reconnaissance was conducted to evaluate the groundwater potential and alluvial thickness of the western portion of the Plaine du Nord alluvial aquifer in the vicinity of the city of Cap-Haitien in the Nord Department of the Republic of Haiti. The western portion of the Plaine du Nord alluvial aquifer is the primary source of water for public supply, domestic, agricultural, and commercial uses throughout the plain. Cap-Haitien is the second-largest metropolitan area in Haiti with a population of over 170,000 (IHSI 2015) and straddles the NW perimeter of the plain along the North Atlantic coast. Population growth and international investments to modernize water infrastructure and service levels require supplemental water supplies. The Government of Haiti (GoH) and the Inter-American Development Bank (IDB) have been considering options to meet the projected municipal water demands, estimated at 35,338 m³/day for the year 2035 (Sergio Perez Monforte, IDB, personal communication, 2018).

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A well field currently serves Cap-Haitien and is located approximately 4 km SE of the city center in the suburban community of Balan. In its current configuration, the pumping capacity is 10,500 m³/day from four wells that are spaced between 200 and 700 m apart, and approximately 2 km from the coast (Fig. 1). The well depths range from 74 to 88 m and specific capacities range from 5 to 7 m³/h/m (Adamson and Miner 2018a).

Increasing abstraction from the Balan area with additional wells has long been considered an augmentation strategy; however, recent hydrogeological analyses have indicated potential risks of saltwater intrusion and local drawdown impacts (Adamson and Miner 2018b; Arnaud 2018; Arnaud et al. 2022, this issue). In this context, the GoH and partners have prioritized groundwater exploration of the deeper alluvium and the evaluation of groundwater potential in less developed areas of the aquifer. The depth to the bottom of the aquifer and the nature of alluvial sediments across the plain were not known or documented. Aquifer thicknesses have been estimated up to 300 m (UNDP 1991); however, the groundwater resource potential in the deeper alluvium had not been confirmed as the deepest known boreholes are around 100-m depth (Adamson and Miner 2018a; Logan 1962; UNDP 1991).

In order to better understand the potential of the western Plaine du Nord alluvial aquifer to support Cap-Haitien, the

GoH and various international financial institutions (IFIs) have commissioned a series of studies in the past decade. The studies have improved the understanding of the shallow aquifer and its water quality and renewable capacity; however, specific recommendations for groundwater exploration and development are necessary. In order to support water supply augmentation and guide groundwater exploration, the GoH and IDB commissioned a geophysical reconnaissance to (1) estimate the thickness of alluvium, (2) improve understanding of the deeper alluvial strata below 90 m, and (3) define criteria from which to recommend areas of interest for groundwater exploration.

Ground-based reconnaissance geophysical surveys in areas with limited geologic information and constrained budgets are best approached with methods that are able to investigate a wide range of depths and provide sufficient resolution for location of useful and cost-effective exploratory wells. Gravity geophysical methods support mapping of Earth density anomalies and contrasts that assist in interpreting the aquifer thicknesses, or depth to bedrock units. Hybrid-source audio-magnetotellurics (HSAMT) methods are cost-effective, available in Haiti, and well-suited for characterizing subsurface resistivity to interpret hydrogeological conditions. In combination, the gravity and HSAMT geophysical methods provide a cost-effective and logistically simple way to investigate from the near surface to depths

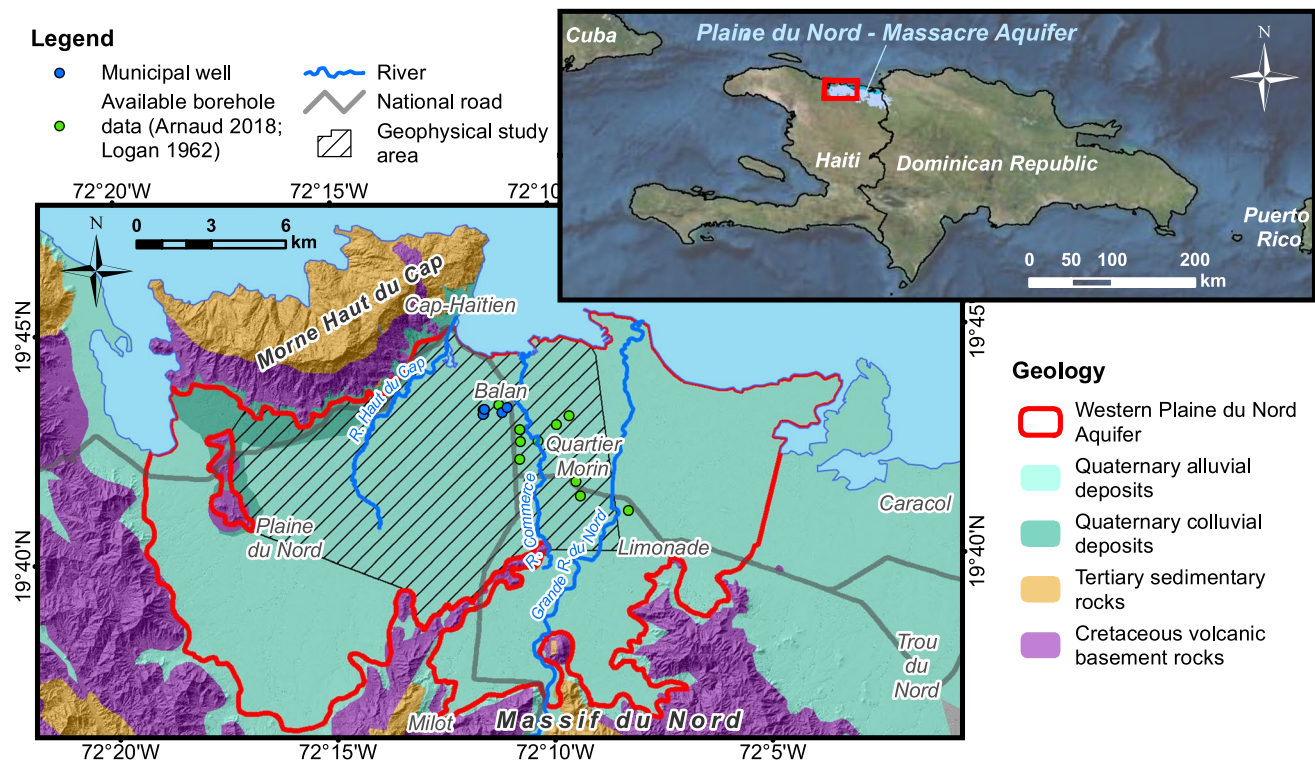


Fig. 1 Map of study area

greater than 1 km with results suitable for areas that contain two-dimensional (2D) structures such as the alluvial plains with buried structure and variable stratigraphy.

The geophysical reconnaissance serves as an initial step for investigating groundwater resource potential in data-scarce areas such as the western Plaine du Nord aquifer. Prior to this study, the deepest known well in the study area was 103 m (UNDP 1991). A recent (2021) exploratory well was drilled in Balan to 200 m depth, based on the geophysical results presented in this study, confirming the presence of deeper fresh groundwater beneath the shallow aquifer zone. The positive drilling results and correlation to geophysical data show the value in combined gravity and HSAMT methods in supporting groundwater characterization and development in data-scarce alluvial basins across the globe. This study is a preliminary phase in guiding the development of groundwater resources for the western Plaine du Nord aquifer. Sustainable management of the groundwater resources rely upon expanding aquifer characterization with exploratory drilling and aquifer testing, strengthening groundwater modeling to guide low-impact pumping schemes, and long-term monitoring of abstraction, water levels, and water quality.

Study area

The geophysical study area encompasses the north-central portion of the western Plaine du Nord alluvial aquifer within the communes of Cap-Haitien, Plaine du Nord, and Quartier Morin (Fig. 1). The western portion of the Plaine du Nord aquifer is approximately 270 km² in spatial extent, thickening northward towards the coast (Adamson and Miner 2018c; Arnaud 2018; UNDP 1991; V3 Companies and Northwater International 2016). The aquifer is the westernmost extension of the regional Plaine du Nord - Massacre Aquifer (PNMA) system that is one of four Transboundary Aquifer Systems shared by Haiti and the Dominican Republic, and is considered Haiti's largest aquifer by spatial extent (950 km²). Along the 60-km width of the PNMA, it is bound between the Massif du Nord mountain range and the North Atlantic Ocean, and spans from the Dominican Republic to its westward limit near Cap-Haitien (Adamson 2018b; UNDP 1991). At the western extent of the aquifer, it is also bounded by the Morne Haut du Cap ridge and the city of Cap-Haitien.

Land surface elevation across the study area ranges from sea level to 60 masl (CNIGS 2017). Three primary rivers flow through the western portion of the plain and are the origin of most of the alluvial sediments. Grande Riviere du Nord bounds the eastern study area, Riviere Haut du Cap bounds the western study boundary and Riviere Commerce flows through the center of the study area near the existing

well field in Balan. Precipitation across the western Plaine du Nord aquifer averages 1,500 mm/year, ranging from 1,350 mm/year near the coast up to 1,620 mm/year along the southern higher elevations (Fick and Hijmans 2017; UNDP 1991). A majority of the rainfall occurs during two wet seasons between April to June and September to December (Fick and Hijmans 2017).

There is limited knowledge of the aquifer stratigraphy due to a lack of well drilling records, the shallow nature of most wells and limited number of geophysical investigations (Peragallo 1980; Radstake 1992). In the areas of Balan and Quartier Morin, the few drilling records that are available indicate the upper 90 m of the aquifer consists primarily of fine to coarse sands with occasional fine gravels with a silty to clayey matrix (Adamson and Miner 2018a; Logan 1962). Several logs (Logan 1962; STEACI 2006), downhole geophysical records in Balan, and a hydrochemical study indicate that discontinuous layers of clay and semiconsolidated siltstone promote semiconfined conditions at depths as shallow as 15 m (Gutierrez et al. 2012) and confined conditions at depths below 60–80 m (Adamson and Miner 2018a). Based on analysis of recently collected gamma logs from the four production wells in Balan, alluvial strata in the Balan area are interpreted to dip in the NE direction, in alignment with basin morphology (Adamson and Miner 2018a). A majority of wells in the Plaine du Nord are believed to source groundwater from the unconfined and semiconfined zones in the upper 80 m of the alluvium (Adamson and Miner 2018a; Gutierrez et al. 2012) which, despite sediment heterogeneity, appear relatively well mixed based on stable isotope analysis (Gourcy et al. 2022, this issue).

The basin-fill deposits are believed to be predominately underlain by Cretaceous-age rocks of volcanic, intrusive and volcano-sedimentary origin, primarily consisting of andesite, turbidite, diorite, and tonalite (Boisson and Pubellier 1987; Radstake 1992; UNDP 1991; Woodring et al. 1924). Recent mapping by Montheil et al. (2013) indicated that Eocene-age granitoid intrusives may be present in the vicinity of Morne Haut du Cap and that a substantial portion of the plain may be underlain by Cretaceous-age volcano-sedimentary turbidites rather than andesites. These varying hypotheses for what underlie the plain introduce uncertainty in the analysis and interpretation of the geophysical data and require deep exploratory drilling to resolve. Several faults have been mapped along the boundaries of the study area including a thrust fault along the northwestern edge of the plain which is responsible for the uplift of Morne Haut de Cap, and the regional Septentrionale strike-slip fault which traverses the coast of northern Haiti and into the Dominican Republic (Montheil et al. 2013). Buried faults certainly exist beneath the basin-fill; however, limited data exist to support their location and influences on hydrogeology and groundwater potential.

Recharge to the alluvial aquifer has been estimated between 114 and 364 mm/year (Arnaud 2018; Arnaud et al. 2022; Adamson and Miner 2018b; Miner and Adamson 2017; Tomasi 1990). Across the western portion of the PNMA, this equates to between 38.9 and 124 Mm³/year. The potentiometric surface ranges from sea level near the coast to 15 m above sea level near the southern extent of the geophysical study area (Adamson and Miner 2018b; Arnaud 2018; Arnaud et al. 2022; UNDP 1991). Several flowing artesian wells are documented between the town of Plaine du Nord and Balan (Haiti Outreach 2017) and between Balan and Quartier Morin (Gutierrez et al. 2012; UNDP 1991).

Alluvial groundwater is typically of calcium-magnesium bicarbonate hydrochemistry (Adamson and Miner 2018a; Gutierrez et al. 2012; Tomasi 1990; UNDP 1991). Total dissolved solid concentrations of groundwater are generally less than 600 mg/L and electroconductivity less than 1,000 μ S/cm (Gutierrez et al. 2012; Haiti Outreach 2017; UNDP 1990). Increased salinity has been documented in shallow wells near the coast (Haiti Outreach 2017; UNDP 1990) with saltwater mixing in the shallow aquifer identified north of the Balan well field by Gutierrez et al. (2012) via stable isotope analysis. Hardness concentrations are considered high to very high (Haiti Outreach 2017; Adamson and Miner 2018a,c). Stable isotope, CFC and SF₆ testing indicated that alluvial groundwater is generally well mixed (Gourcy et al. 2022) and that groundwater pumped from the Balan well field was recharged from precipitation at least 60 years prior to sampling (Gutierrez et al. 2012).

Methods

In basin-scale studies similar to Plaine du Nord, gravity methods have been used with a high degree of success to determine sediment thickness (Chandler 1994; Zaenudin 2020) and have provided useful information on fracturing within the basement rock (Murty 2002). Gravity models must be constrained by borehole records or other geophysical methods in order to limit uncertainty. In the absence of

such data, gravity methods are paired with complementary geophysical methods in order to simultaneously characterize basin-fill thickness and sediment variations related to groundwater potential (Santos 2006; Araffa 2013). Audio-magnetotelluric (AMT) and HSAMT electromagnetic methods have been extensively applied with positive results in the USA, Caribbean (including Haiti), China, and Africa to interpret subsurface conditions and optimize the success of well drilling (Adamson et al. 2016a, b; Carlson et al. 2011; Fu et al. 2013; Nolan 1998; Northwater International and Rezodlo 2017 and 2019; Northwater International 2014).

Combining HSAMT and gravity methods overcomes many of the spatial, logistical, or analytical limitations of other geophysical methods in a cost-effective way. Those two methods allow correlation of sediment thickness, structure and interpretation of stratigraphy in data sparse and logistically constrained areas. Other ground-based geophysical methods are limited in various ways—for example, electrical resistivity tomography (ERT) is limited in its investigation depth (typically less than 100 m), and requires large areas without cultural interferences such as power lines, metal fences, and buildings and is logistically difficult over a regional study area such as the western Plaine du Nord. Other methods such as time domain or transient electromagnetics (TEM) do not provide 2D results and field survey logistics can be complicated. For the study area, HSAMT methods were able to investigate to at least 500 m and required only two perpendicular 15-m electric dipoles with magnetometers located slightly farther away, thus an approximate survey setup diameter of a little more than 15 m, which also easily accommodated the gravity measurements. This compact footprint makes it possible to acquire quality data much closer to any existing infrastructure and to not incur any access difficulties with the local population.

A team of Haitian geoscientists were trained in equipment operation and data acquisition and conducted a majority of the field work under the supervision of licensed geologists and geophysicists (Fig. 2). A total of 75 HSAMT soundings and 50 gravity readings were conducted and were modeled into eight 2D resistivity lines

Fig. 2 a HSAMT data collection, b gravity data collection



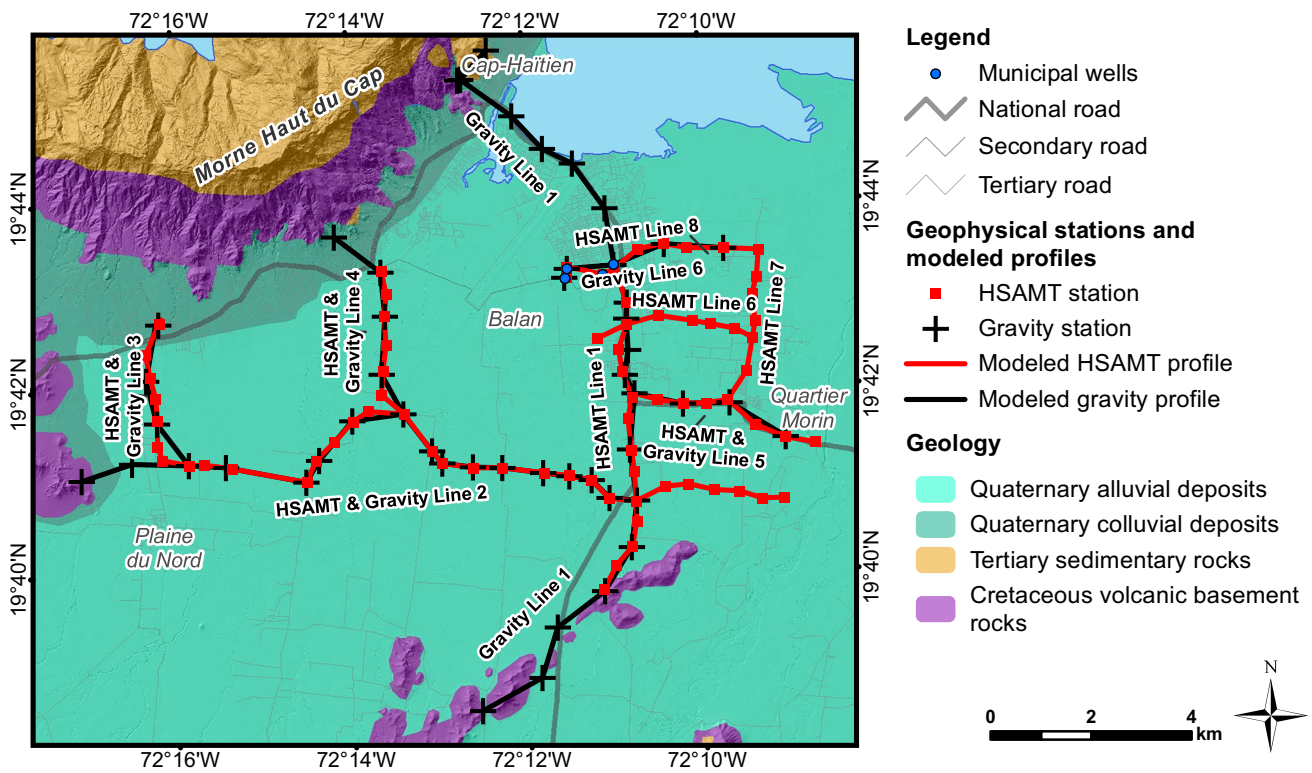


Fig. 3 Geophysical survey location map

and six 2D gravity lines. Figure 3 shows the locations of all the geophysical stations and the respective modeled profiles. The locations of the stations were selected to generate profiles that transected the aquifer. Some areas had higher data density as they were identified as areas of interest based on a review of historical drilling records. The geophysical data collection was performed from June 5 through June 15, 2018. Transport between data stations was assisted with 4x4 vehicles, and hiking was sometimes required to reach desired locations.

Borehole data

Limited borehole lithology or downhole geophysical data were available for calibrating the HSAMT and gravity geophysical results. Thirteen borehole records were utilized, which included borehole yield, specific capacity or lithology (Fig. 4). Lithological interpretation based on gamma logs was utilized for two of the Balan production wells as original lithology records were not available (Adamson and Miner 2018a), the remaining logs were compiled by Logan (1962) with additional specific capacity data from Arnaud (2018) and Arnaud et al. (2022). Lithology and well data were used in interpreting the HSAMT results in order to estimate variations in aquifer materials and groundwater potential. Due to the lack of data regarding the deeper aquifer, a significant degree of

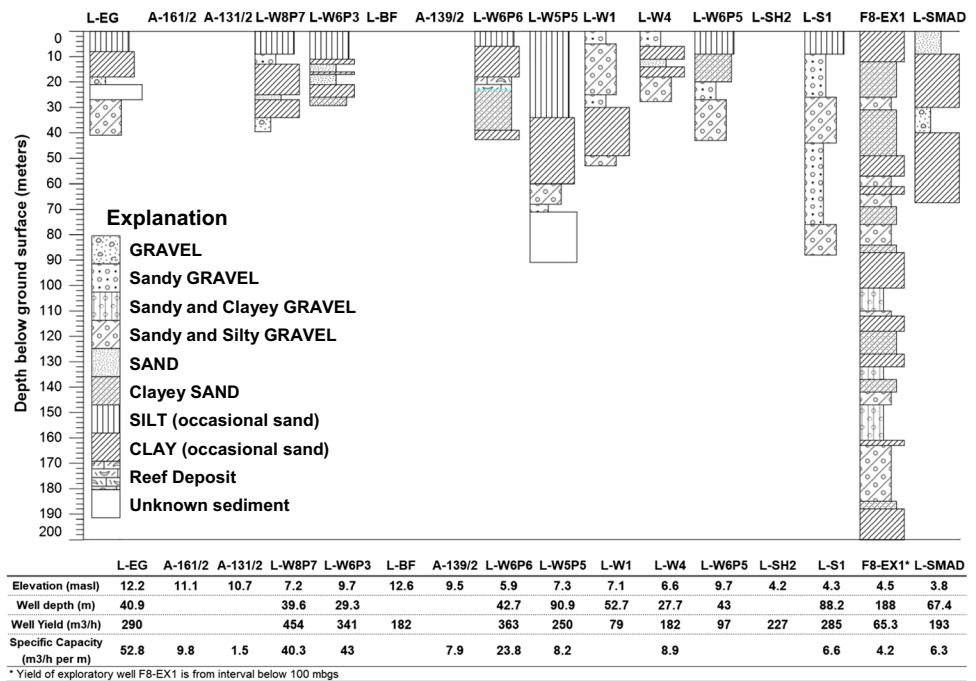
uncertainty is associated with interpretation of the resistivity results below depths of existing wells.

HSAMT data acquisition, processing and modeling

Hybrid-source audio-magnetotellurics is an electromagnetic geophysical method commonly applied in the groundwater exploration industry. It determines the Earth’s subsurface electrical resistivity distribution by measuring time-dependent variations of the Earth’s natural electric (*E*) and magnetic (*H*) fields from worldwide thunderstorm activity (spherics) and solar wind interacting with the Earth’s magnetic field (micro-pulsations of the ionosphere), as well as the electric and magnetic fields resulting from high frequency transmitted signals (Cagniard 1953; Vozoff 1991; Zonge and Hughes 1991; Rodi and Mackie 2001; Berdichevsky and Dmetriev 2002). HSAMT measurements are made with two electric dipoles (*E_x* and *E_y*) and two horizontal magnetometers (*H_x* and *H_y*) and are used to assess surface impedance and estimate subsurface resistivity at various frequencies. Surface impedance (*Z*) is the ratio of electric to magnetic fields calculated as:

$$Z_{ij} = \frac{E_i}{H_j} \tag{1}$$

Fig. 4 Available borehole data for high-capacity wells in western Plaine du Nord Aquifer, arranged from southeast (left) to northwest (right)



where i and j are component directions, and are the basis for defining apparent resistivity (ρ) and impedance (φ) from the real (Re) and imaginary (Im) components of the surface impedance (and f stands for frequency):

$$\rho_{ij} = \frac{0.2}{f} |Z_{ij}|^2 \tag{2}$$

$$\varphi_{ij} = \tan^{-1} \left[\frac{\text{Im} (Z_{ij})}{\text{Re} (Z_{ij})} \right] \tag{3}$$

Two apparent resistivity values are computed (ρ_{xy} and ρ_{yx}) for the two orthogonal pairs of E and H sensors thus the data can be modeled and interpreted in two dimensions.

Field data consist of sounding curves that are logarithmic plots of apparent resistivity versus frequency with lower frequencies and/or higher resistivities corresponding to deeper investigation depths and vice versa with higher frequencies and/or lower resistivities corresponding to shallower investigation depths. The true resistivity of Earth materials is dependent upon several factors including physical characteristics, composition, grain size, degree of saturation, and water quality. In general, fine-grained materials such as clays and silts have lower resistivities than coarse-grained materials such as sands and gravels. Unweathered and unfractured hard rocks such as lithified sedimentary rocks (limestone, dolomite, sandstone, chert, etc.), volcanic rocks, plutonic rocks, and some metamorphic rocks generally have high resistivities. The

presence of fracturing and weathering lowers the resistivity of these rocks, while the occurrence of groundwater will greatly reduce the resistivity of all rocks and sedimentary materials (through electrolytic conduction).

Data were acquired with a StrataGem EH4 HSAMT system manufactured by Geometrics Inc. of San Jose, California, USA. With the StrataGem EH-4, time-series of the four components of data were recorded for three overlapping frequency bands: 10 Hz to 1 kHz, 500 Hz to 3 kHz, and 750 Hz to 92 kHz. The lowest frequency band recorded only natural signals, the middle band encompassed both natural signals and about five separate transmitted frequencies, and the highest band recorded signals from 15 separate transmitted frequencies in addition to any natural signals present. The StrataGem EH-4 is a broadband instrument and as such will record signals of any frequencies within its operating range. The transmitter is used to augment the typically lower amplitude signals in the middle and highest frequency bands. For each HSAMT station, or sounding, the magnetic sensors and 15-m-long electric dipoles were oriented with a geologic compass so that both components in each direction were parallel. The E_x and H_x components were oriented approximately parallel to the assumed geoelectric strike of the study area, while the E_y and H_y components were oriented perpendicular. If geoelectric strike (which may or may not be the same as geologic strike) is known, then measured resistivities with the E field oriented parallel to strike (i.e., current flow along strike) are referred to as transverse electric (TE) mode measurements, while

resistivities with the E field oriented perpendicular to strike (i.e., current flow across strike) are referred to as transverse magnetic (TM) mode measurements. The data from each sounding were stored on the instrument's compact flash drive and downloaded to a laptop PC at the end of each field day. The location of each sounding was surveyed using a Trimble Juno 3B GPS receiver and the elevations were derived from the 1.5 m LiDAR MTN dataset (CNIGS 2017).

Hybrid-source audio-magnetotelluric measurements may be made in either the tensor or scalar mode. Tensor measurements use all four impedance components and are best utilized in areas where the structure is very complex, when soundings are far apart relative to the size of geologic features under investigation, or where regional anisotropy is strong. Scalar measurements use only two components and are generally adequate in one-dimensional (1D) layered environments or more complex areas if measurements are dense. Electromagnetic noise from cultural features (e.g., power lines, grounded metal fences, metallic objects, etc.) may degrade the quality of the data from some of the components, and in such cases processing of the data in the scalar mode is necessary.

For this project, 2D depth sections were modeled in the scalar TE mode along profiles through a combined use of Geometrics' ElectroMagnetic Array Profile (EMAP) transform software that calculates the Bostick transform resistivities from the HSAMT data and Schlumberger's WinGLink software. The smooth model inversion routine of WinGLink is based on Rodi and Mackie (2001); the routine finds Tikhonov regularized solutions (Tikhonov and Arsenin 1977) to the 2D inverse problem for magnetotellurics or HSAMT data, using the method of nonlinear conjugate gradients (NLCG) and the forward model simulations, are calculated using the finite difference method (FDM). The method of Rodi and Mackie solves each step of a Gauss-Newton iteration incompletely using a truncated conjugate gradients technique. In their use of incomplete solutions of the linearized inverse problem, the Rodi and Mackie inversion method departs from the strict approach of iterated, linearized inversion. The use of conjugate gradients is a well-established optimization technique (Fletcher and Reeves 1959; Polak, 1971) and was suggested for nonlinear geophysical inverse problems by Tarantola (1987). Resistivity data inversion to 2D profiles uses an average resistivity half-space starting model with data rotated to the assumed geoelectric strike. Each depth section consists of logarithmic resistivity versus depth along relatively straight lines. Subsequently, values for each sounding were converted into a format compatible with the Tecplot Focus computer program and presented as 2D and 3D cross-sections in depth format.

Gravity data acquisition, processing and modeling

The force of the Earth's gravity field is not constant everywhere and its measurement changes based upon many known and predictable factors including elevation, latitude, instrumentation drift and tides. Additionally, gravity changes are related to lateral differences in the densities of subsurface rock. Lateral density changes are useful in exploration because many types of rocks have characteristic densities and thus are distinct from other rock types. By taking very careful measurements of the Earth's gravity field at the surface and then removing all the predictable effects, subsurface density variations can be modeled into a meaningful geologic picture of the subsurface.

Gravity data for this project were acquired with the LaCoste & Romberg Model G gravity meter capable of highly accurate readings (± 0.01 milliGals [mGals]). A local gravity base station was established at station 1001 and data were acquired between base readings at times generally less than 8 h apart, depending upon logistics. That is, a reading was taken at the local base, several new station readings were taken within a period of less than 8 h, and then another reading was taken at the local base. The repeated base readings allowed for calculation of the instrument drift which was applied to the data. The instrument drift rates for this survey were nominally 0.04 mGals over approximate 8-h periods with no tares (an instantaneous variation in reading if the gravity meter is jarred).

The gravity data were processed using the GravMaster computer program from Geotools Corporation following standard processing procedures with terrain corrections calculated from compartment elevation differences estimated in the field for Hammer zones B and C (2.0–53.3-m radius), while Hammer zones D–M (53.3–21,943 m) compartment elevation differences were determined from high-resolution digital elevation models. From previous surveys conducted in similar areas in the Caribbean, a Bouguer slab density of 2.67 g/cm^3 was chosen to process the data. Using data from all the Hammer zones and a Bouguer slab density of 2.67 g/cm^3 , complete Bouguer gravity values were calculated. Modeling of the gravity data was conducted using Interpex Ltd.'s IX2D-GM computer program that is capable of interactive forward and inverse modeling in 2½-dimensions (i.e., the models can extend both along and perpendicular to profiles) based upon polygonal models. The modeled gravity data were converted into a format compatible with Golden Software's Grapher computer program and are presented as 2D depth sections along each line.

Results and discussion

HSAMT results

Hybrid-source audio-magnetotelluric data collection was predominately within the alluvial plain, although some stations were located on bedrock outcrops along the perimeter

of the alluvium. Resistivity data inversion utilized EMAP and WinGLink software as described in the methods; 2D profiles were modeled using a 25- Ω -m half-space smooth starting model with a fine mesh and the data were rotated 40° to the assumed geoelectric strike. The resulting RMS errors between observed and calculated resistivity ranged from 4.6 to 5.2%. Resistivity values ranged from less than 5 Ω -m to greater than

Fig. 5 HSAMT modeled lines fence diagram using lines H1–H8

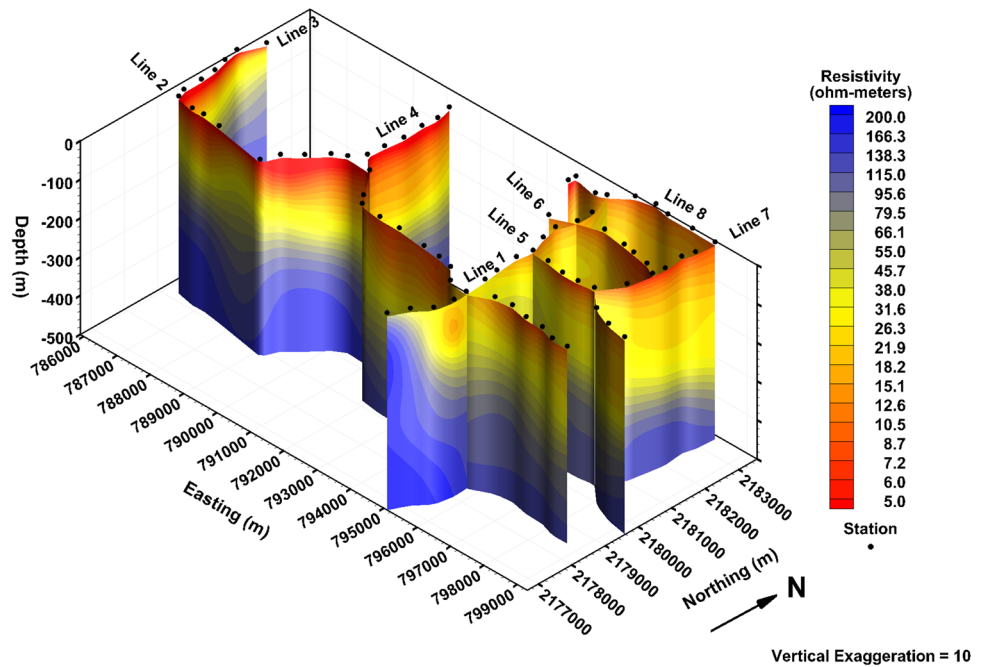
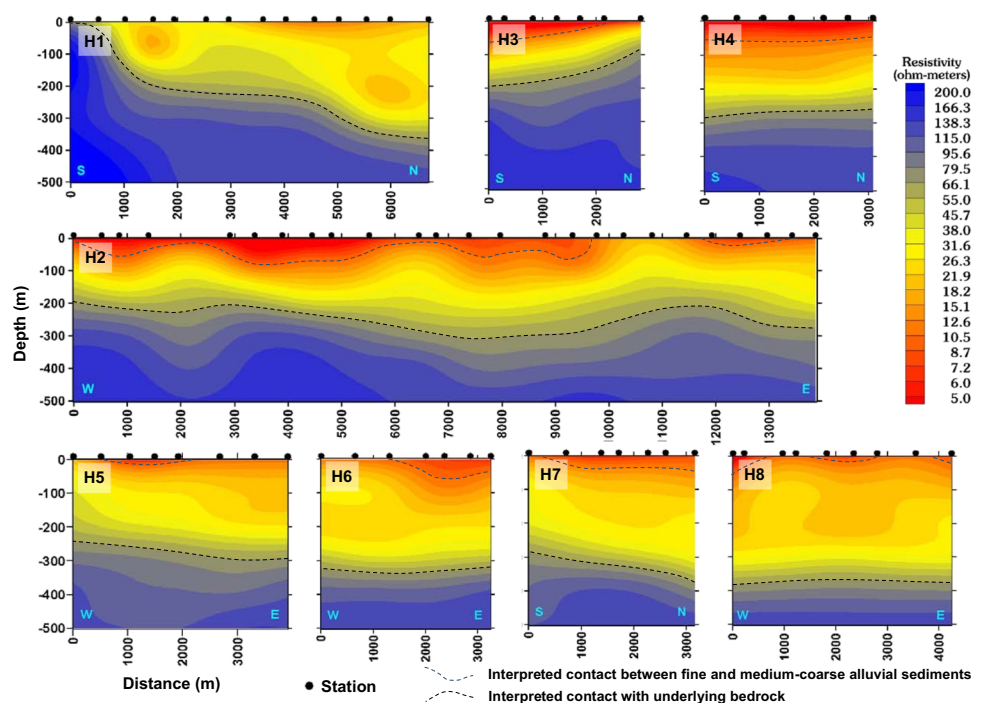


Fig. 6 Modeled 2D HSAMT lines along eight transects



200 Ω -m in the study area. Figure 5 shows a fence diagram of all eight HSAMT lines and Fig. 6 shows the eight modeled HSAMT lines individually. The higher resistivity values are believed to correlate to bedrock units, and the very low values correlate to fine-grained clays and silts. Intermediate values between 10 and 35 Ω -m are believed to correlate to productive sands and gravels, with increased clay and silt on the lower range, and cleaner gravels on the higher range. These resistivity ranges are relatively similar to those found by Radstake (1992) and other researchers for unconsolidated alluvial materials (Keller 1966; McNeil 1980; Telford et al. 1976).

Gravity results

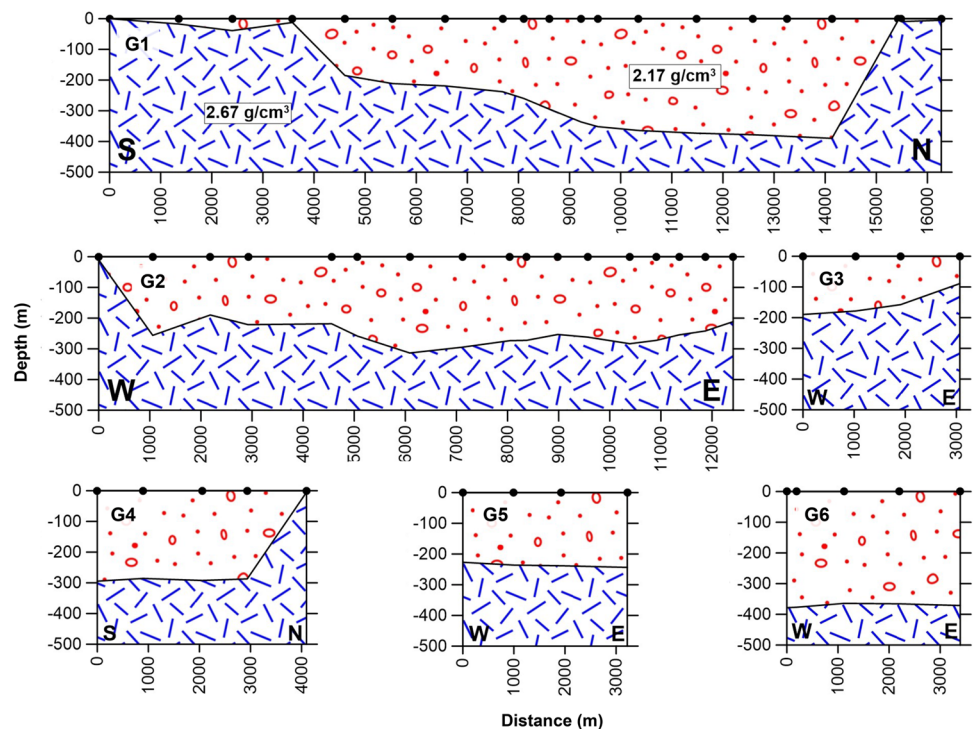
Station spacing of the gravity stations were variable between 500 and 1,000 m in order to evaluate regional changes in sediment thickness. Similar to the HSAMT data, gravity stations were predominately within the alluvial plain with some stations located on bedrock outcrops. Gravity exploration is a potential field method and as such modeling of the data produces a nonunique solution. Consequently, variations in density contrasts and thicknesses of subsurface bodies can result in the same model fit to the field data. Therefore, without geologic data from wells, there can be several models that fit the data. Because of limited or no wells that intersected bedrock within or near the study area and the nonunique solutions of gravity modeling, stations along several lines either began or ended on bedrock so as to have at least one known depth to bedrock to enable accurate

modeling. Gravity lines with stations only within the alluvial plain had modeling constrained at intersecting points along lines that had station(s) on bedrock outcrop. The data were modeled as two layers with lower density materials (2.17 g/cm^3) interpreted as alluvium or perhaps weathered bedrock, volcano-sedimentary or semiconsolidated units, while the higher density materials (2.67 g/cm^3) were interpreted to be denser bedrock such as basalt and andesite. Gravity modeling used an Inman-style Ridge Regression (Inman 1975) for nonlinear least-squares fitting technique with up to five iterations. Convergence was achieved when error between modeled and observed data was less than 1 mGal or the decrease in error from the previous iteration was less than 3%. No regularization algorithm was used in the gravity modeling; however, using the ridge regression method, it was possible to calculate an accuracy of fit between modeled and observed data which was between zero and 0.12 mGal. Correlation to the HSAMT data was strong and indicated confidence in the nonunique gravity results. Figure 7 presents the modeled sediment thicknesses along all six gravity profiles. Similarities are present between the gravity lines and the HSAMT lines (Fig. 6).

Correlation between techniques

There is strong correlation between the two geophysical methods on all modeled lines throughout the study area. The overlapping segments of HSAMT Lines H1, H3–H5 and H8 (Fig. 6) and gravity lines G1 and G3–G6 (Fig. 7)

Fig. 7 Modeled sediment thicknesses based on gravity measurements along six lines. All lines used a density of 2.17 g/cm^3 for basin-fill sediments and 2.67 g/cm^3 for hard bedrock



show excellent agreement and correlation, with the gravity results suggesting that a resistivity value of approximately 66 Ω -m could be a potential indicator of the transition between alluvium and dense, hard bedrock. Agreement between HSAMT line H2 and gravity line G2 is also generally good, divergence does occur along several intervals. This may be explained by the presence of geological units other than the binary alluvium or bedrock used in gravity modeling, such as semiconsolidated or volcano-sedimentary tertiary rocks, or the presence of thick fractured or weathered zones within the bedrock. Weathered bedrock, and other sedimentary or volcano-sedimentary bedrock beneath the alluvium may have lower resistivities and as a result, the thickness of productive alluvium could be less than the depth to bedrock indicated by the gravity modeling.

Geologic interpretation

Based on the authors understanding of the study area, an analysis of past literature, and a review of historical drilling records, a framework to correlate resistivity to lithology and aquifer properties in the study area was produced. Using this framework, *target* ranges of resistivity can be considered when interpreting the results and guiding recommendations for groundwater exploration. Table 1 presents ranges of resistivity based on Radstake (1992) which were modified to accommodate the newly acquired geophysical data combined with the analysis of well records in Balan and Quartier Morin that are located adjacent to or in close proximity to HSAMT soundings. The lower range for sands and gravels suggests that silts and clays may be mixed and interbedded.

The interpreted thickness of alluvial sediments increases in the central portion of the basin and toward the coast. Resistivities in the upper 200 m tend to be lower in the western portion of the study area, while the eastern and coastward sections indicate a significant thickness of resistivities between 15 and 35 Ω -m. This thicker zone of intermediate resistivity corresponds to

the region in which a majority of the high-capacity wells have been historically located (Logan 1962) and may also indicate that the Riviere Commerce and Grande Riviere du Nord are the sources of coarser basin sediment. Based on both the HSAMT and gravity data, the long west–east transect (lines H2 and G2) indicates the possibility of several buried bedrock valleys or other anomalies. There is an abrupt basin edge on the northern edge of line G1 near the City of Cap-Haitien which possibly corresponds to a thrust fault mapped by Monthel et al. (2013).

Aquifer geometry

Groundwater exploration and development must consider aquifer thickness as it is an important criterion to improve drilling success and target areas of greater storage potential. Alluvial thickness and depth to bedrock were estimated with the gravity analysis and the corresponding 66 Ω -m resistivity isoline, which is interpreted to be the contact with dense, hard bedrock beneath the alluvium and generally corresponds to the modeled gravity depth. Figure 8 presents the modeled thickness of the aquifer in the study area based on the gravity results. The results at each station were statistically analyzed and interpolated using Golden Surfer and ArcGIS software.

It is important to note that weathered bedrock, and other sedimentary and volcano-sedimentary bedrock beneath the alluvium may have lower resistivity and density and as a result, the depth to bedrock/alluvial thickness could indeed be less than indicated. Radstake (1992) suggested that hard volcanic basement rock had resistivity values starting at 90 Ω -m in the nearby Trou du Nord portion of the PNMA. The gravity and HSAMT results indicate that the lower limit of volcanic basement rock could be slightly lower in the western Plaine du Nord. While seawater intrusion processes are affecting shallow wells between Balan and Cap-Haitien, the sediment thickness estimates are primarily based on the gravity results which would not be impacted by the lowered resistivity caused by saltwater intrusion in the shallow aquifer.

Table 1 Average resistivity of various lithologies for the Northern Plain (modified from Radstake 1992)

Lithology	Average resistivity
Sediments with high TDS groundwater (~10,000 mg/L)	0.5–4.5 Ω -m
Compact wet clays	<5 Ω -m
Clays	5–10 Ω -m
Clayey and silty sands	5–12 Ω -m
Sands and gravels	10–66 Ω -m
Weathered bedrock, sedimentary rock, semiconsolidated rock	35–90 Ω -m
Denser bedrock, based on correlation with gravity data	>66 Ω -m
Harder/dense sedimentary rock, volcanic basement rock	>90 Ω -m

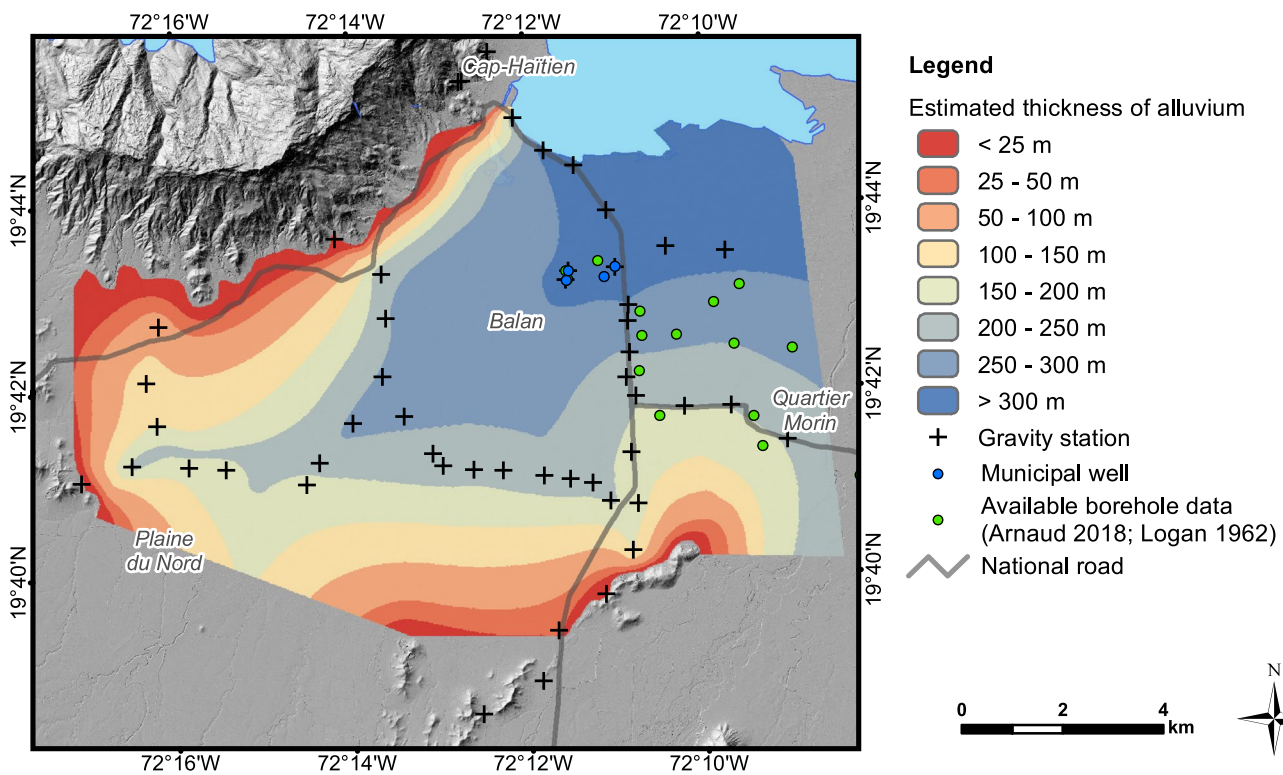


Fig. 8 Modeled thickness of alluvium based on gravity data

Hydrogeological interpretations

The geophysical data suggest that groundwater potential is laterally and vertically variable throughout the study area. Successful wells can be drilled throughout the aquifer; however, the yields and specific capacities can be highly variable depending on the aquifer thickness and composition of the alluvium beneath a particular location or area. It is also important to note that aquifer recharge rates and water balance must be considered in order to avoid local overexploitation which could adversely impact water quantity and quality of existing wells and perhaps increase seawater intrusion risk.

Stratigraphy

The upper 20–75 m of the alluvium throughout the study area are typically lower to moderate resistivity, indicative of sands and finer-grained strata. Resistivity generally increases with depth prior to the interpreted contact with underlying bedrock, indicating the potential for coarser sediments below the zone exploited by existing wells (100 m). This trend across the study area suggests the possibility that deeper sediments may store and yield significant groundwater resources where only limited exploration has occurred to our knowledge. The subsurface resistivity varies laterally across

the study area, likely due to the complex nature of alluvial deposition and erosion, the presence of buried channels, deltaic deposits, and transgression and regression sequences. Values of higher resistivity, especially within the alluvial deposits may indicate buried channels or depositional facies where coarser-grained gravels and sands are more prevalent. Lower resistivity in the alluvium is interpreted to be finer-grained strata such as clays, silts, and fine sands. Targeting zones in the aquifer with gravels and coarser sands will result in higher yields and specific capacity, and will ultimately result in less drawdown, well interference impacts, and seawater intrusion.

Groundwater exploration target ranges

Based on the reconnaissance, the recommended targets for groundwater exploration appear where the alluvium is thicker, and a *target range* of subsurface resistivity is represented above the inferred bedrock contact. Twelve historical well records were available which recorded a specific capacity from pump testing and were nearby an HSAMT sounding. Figure 9 plots bulk subsurface resistivity from 20 to 150 m depth against the specific capacity; wells with bulk resistivity between 15 and 25 Ω -m are interpreted to have the highest specific capacity and thus yield potential. At this first stage of exploration, *good potential* for high-capacity

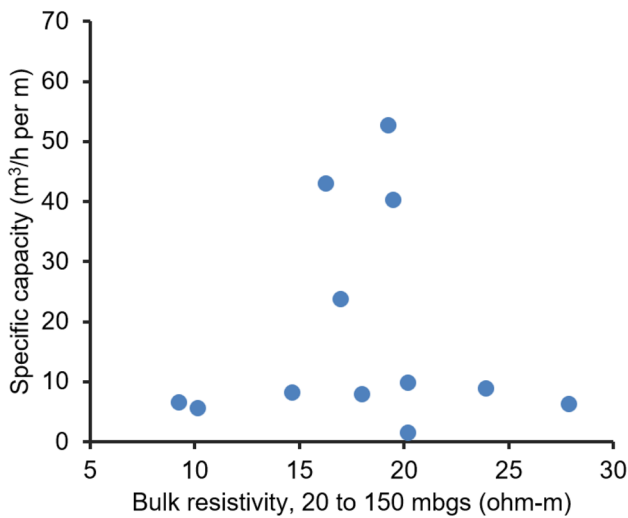


Fig. 9 Plot of bulk subsurface resistivity from 20 to 150 m below ground surface (mbgs) vs well specific capacity; the limited data indicates that the resistivity range of 15–25 Ω-m may be representative of aquifer materials with higher specific capacity

groundwater exploration could be considered where target resistivities range from 15 to 25 Ω-m. *Moderate potential* for high-capacity groundwater exploration may be considered on either side of this target range (10–15 Ω-m and

25–35 Ω-m). These target ranges are in agreement with the previously derived resistivity-lithology relationships (Table 1) which generally correlate to sands and gravels with small amounts of silt or clay, particularly at the lower resistivity values. The suggested exploration targets are where these resistivity ranges are present at depths below 20 m. Locations that have thicker strata within these ranges are also considered more favorable.

Figure 10 shows the median resistivity between 20 and 150 m depth for all 75 HSAMT soundings symbolized according to the target resistivity ranges. Viewing resistivity statistics spatially provides a means to illustrate the variability of subsurface resistivity and provides a screening tool to identify areas that fall within target ranges at key depths. The HSAMT results indicate a zone between Balan and Quartier Morin that may have good potential for high-yielding wells, which corroborates with available well data.

Seawater intrusion

Seawater intrusion has been documented in shallow wells north of Balan (Gutierrez et al. 2012) and modeled to increase during periods of low precipitation or increased abstraction from irrigation (Arnaud et al. 2022). The resistivity data (HSAMT) collected for this study did not extend into the area of documented impact, however,

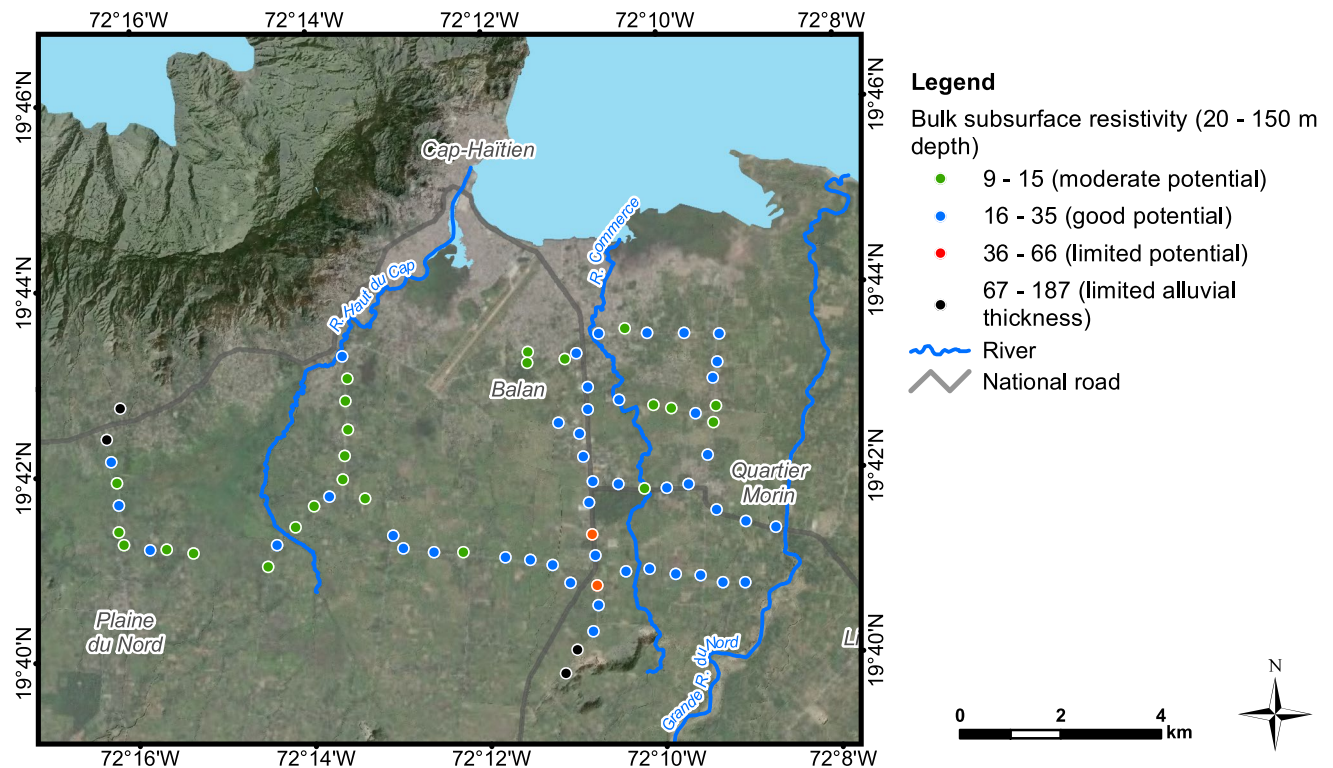


Fig. 10 Statistical representation and interpretation of HSAMT resistivity data

seawater intrusion and its impact on study results are important. Saltwater, or high TDS mixed groundwater reduces the bulk resistivity, with several studies (Goebel et al. 2017; Zohdy et al. (1993); Jurcek and Hasbrouck, Hasbrouck Geophysics, ‘Geophysical survey to identify potential production well locations at the Sand City Desalination Well Field, Sand City, California’, unpublished report, 2018) indicating a range of 0.5–3 Ω -m for sediments with very high TDS (>20,000 mg/L) and 3–4.5 Ω -m for high TDS (~10,000 mg/L). Such resistivities are present only in the shallow zones (less than 25 m depth) of lines H2, H3 and H4; however, these areas are generally farther from the coast and likely reflect the saturated and very fined grained strata rather than high TDS groundwater. A possible exception lies on the northern end of line H4, which may extend into zones where intrusion processes may occur during drought years (Arnaud et al. 2022). The potential for intrusion does not impact sediment thickness estimates, which are primarily based on gravity modeling with corroboration from broad HSAMT resistivity results distal from higher risk areas. Subsurface resistivity in the upper 200 m in the coastal areas of lines H1, H6 and H8 do not decrease with depth, as would be anticipated if a saltwater mixing were occurring. Based on the snapshot of resistivity data, it is interpreted that seawater intrusion may be limited to the shallow unconfined portion of the aquifer. This insight highlights the importance of multilayer aquifer modeling building upon the work of Arnaud et al. (2022) with downscaling supported by updated results from this study and recent exploratory drilling and aquifer testing. Calibration of such modeling would also benefit from a water level and water quality monitoring program, which would also serve as an early warning to guide water management.

Detailed well siting

Hybrid-source audio-magnetotellurics and gravity are well suited for regional or reconnaissance scale studies of groundwater potential and for locating zones for further study. However, historical records indicate that yield and groundwater potential can vary significantly over distances less than 100 m (Logan 1962). Such variability in intersecting buried high-permeability channels may warrant detailed well siting studies using higher resolution geophysical techniques, such as electrical resistivity tomography (ERT), than were employed in this regional study. Even greater discernment of sediment type would be available by pairing ERT with spectral-induced polarization (SIP); however, as noted previously, these techniques are limited in their depth of investigation to around 100 m depth.

Preliminary validation results

An exploratory well was drilled based on the presented results in late 2020, after initial submission of this report. The exploratory well (F8-EX1) was drilled in Balan with funding from the United States Agency for International Development (USAID). Drilling advanced to a depth of 200 m and the well was constructed with perforations between 98 and 110, 116–122, 134–140 and 146–182 m in order to evaluate deeper aquifer layers. Sieve analysis indicated that lithology generally fined downwards, with median grain size (D_{50}) between 2.1 to 3 mm (very fine gravel) in the coarser intervals above 100 m depth, and between 1.1 to 1.8 mm (very coarse sand) in the coarser intervals below 100 m. The coarsest sediments below 100 m were between 133 and 145 m with D_{50} between 1.4 and 1.8 mm (very coarse sand) and D_{10} of 0.5 mm (medium sand). Two thick clay layers were noted between approximately 69–76 m and 87–101 m, the upper clay layer appearing to correspond to a silty clay visible in other logs (Adamson and Miner 2018a; Logan 1962). Drilling terminated in a clay layer from 188 to 200 m with higher gamma counts and higher single point resistance, possibly indicating older, increasingly consolidated deposits.

The static water level was approximately 1.5 m above ground surface (flowing artesian). Pump testing (24 h) at a rate of 65 m³/h resulted in a drawdown of 15.5 m. The resulting specific capacity of these deeper layers (4.2 m³/h/m) is slightly lower than the F8 well of 74 m depth (5.4 m³/h/m). Analysis of pumping curves indicates a bulk hydraulic conductivity of the deeper layers on the order of 2 m/day compared to 8 m/day for the upper 90 m of the aquifer. Monitoring of nearby municipal and private wells during the F8-EX1 pump test measured almost no discernable drawdown, further indicating the hydraulic separation between the deeper layers and the previously exploited upper layers. Groundwater EC during pumping was stable around 830 μ S/cm, which is slightly higher than in the shallower aquifer at F8 (600 μ S/cm) and F9 (760 μ S/cm).

The preliminary results validate the potential of the deeper aquifer to store and yield groundwater at depth. The thick confining clay layer at around 100 m depth appears to hydraulically isolate the shallow and deep aquifers, potentially providing some degree of protection against seawater intrusion. The exploratory well encountered primarily sand size fractions in the deeper layers, likely due to distance from the sediment source. Gravel and coarser-grained materials with lower fines content may be found with an exploratory focus further inland toward the sources of sediment. Given the lithologies encountered and the downhole geophysical results for the exploratory well, it is possible that the target resistivity range for the deeper aquifer is slightly higher than for the shallow aquifer due to increased consolidation of the

sediments. Further exploratory drilling and aquifer testing is needed to better predict variations in aquifer materials, yield potential, and water quality dynamics based on the resistivity data.

Conclusions

The geophysical reconnaissance supports estimations of alluvial thickness, characterization of subsurface conditions, and the identification of subsurface features and anomalies to guide exploratory drilling. The application of gravity and HSAMT geophysical methods proved to be a suitable and cost-effective way to advance the understanding of the western portion of the Plaine du Nord aquifer and guide groundwater exploration and characterization activities in a data-scarce region. The combination of methods overcame several typical constraints of single technique studies, specifically improving sediment thickness estimation and aquifer stratigraphy beyond the individual capabilities of either method. The geophysical results supported the development of exploratory well siting criteria that corroborates with historical drilling results. The approach is widely applicable to similar data-scarce basins and the data presented provides a foundation from which to advance water supply development for the western Plaine du Nord and the city of Cap-Haitien. The interpretations of geophysical data must be considered as dynamic and be reevaluated as validation data becomes available from exploratory drilling and other geophysical methods. Due to the limited historical drilling and well testing records available for calibration, there remains uncertainty in the resistivity conditions indicative of high yield and storage potential. Reducing this uncertainty through exploratory drilling and subsequent reinterpretation of the geophysical results is an important component of successful aquifer characterization, development, and management. This study should be considered a preliminary phase in guiding the development of groundwater resources for the western Plaine du Nord aquifer. Sustainable management of the groundwater resources relies upon expanding aquifer characterization with exploratory drilling and aquifer testing, strengthening groundwater modeling to guide low-impact pumping schemes, and long-term monitoring of abstraction, water levels, and water quality.

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References

- Adamson JK, Jean-Baptiste G, Miner WJ (2016) Summary of groundwater resources in Haiti. In: Wessel GR, Greenberg JK (eds) *Geoscience for the public good and global development: toward a sustainable future*. *Geol Soc Am Spec Pap* 520:1–22. [https://doi.org/10.1130/2016.2520\(14\)](https://doi.org/10.1130/2016.2520(14))
- Adamson JK, Miner WJ, Hasbrouck JC (2016b) Groundwater assessment of the Titanyen - Cabaret corridor, Republic of Haiti. *Northwater International report 15-2013*, Northwater, Chapel Hill, NC, 52 pp
- Adamson JK, Miner WJ (2018a) Well inspection and testing report, existing wells at Balan, Cap-Haitien, Haiti. Preliminary report, Inter-American Development Bank, Washington, DC
- Adamson JK, Miner WJ (2018b) Groundwater flow model report: Hydrogeologic characterization of the aquifer and existing wells at Balan, Cap Haitien, Haiti. Preliminary report, Inter-American Development Bank, Washington, DC
- Adamson JK, Miner WJ (2018c). Geophysical reconnaissance of the Plaine du Nord alluvial aquifer, Cap Haitien, Haiti. Preliminary report, Inter-American Development Bank, Washington, DC
- Araffa S (2013) Delineation of groundwater aquifer and subsurface structures on North Cairo, Egypt, using integrated interpretation of magnetic, gravity, geoelectrical and geochemical data. *Geophys J Int* 192:94–112
- Arnaud L (2018) Modélisation hydrodynamique de la plaine alluviale du Nord (République d'Haïti) [Hydrodynamic modeling of the northern alluvial plain (Republic of Haiti)]. Final report, no. 4, BRGM/RC-67407-FR, BRGM, Orléans, France, 79 pp
- Arnaud L, Gutierrez A, Zegoulli I, Gonomy N (2022) Modelling groundwater flow in the Plaine du Nord–massacre shallow aquifer, Haiti. *Hydrogeol J*. <https://link.springer.com/article/10.1007/s10040-022-02469-6>
- Berdichevsky MN, Dmitriev VI (2002) Magnetotellurics in the context of the theory of ill-posed problems. *Investigations in Geophysics* 11, Society of Exploration Geophysicists, Houston, TX
- Boisson D, Pubellier M (1987) Carte géologique à 1/250 000 de la République d'Haïti -feuille Nord-Est (feuille de Cap-Haïtien) [1: 250,000 geological map of the Republic of Haiti - Northeast sheet (Cap-Haitien sheet)] B.M.E. [Bureau des Mines et de l'Energie] Editeur CERCg IMAGEO, CNRS, Paris
- Cagniard L (1953) Basic theory of the magnetotellurics method of geophysical prospecting. *Geophysics* 18:605–635

- Carlson NR, Feast CF, Bushner GL, Hoerth R (2011) The use of CSAMT and NSAMT in siting groundwater production wells: two case studies. Presentation to the International Workshop on Gravity, Electrical and Magnetic Methods and their Applications, Beijing, China
- Chandler V (1994) Gravity investigation for potential ground-water resources in Rock County, Minnesota. Minnesota Geological Survey, ST Paul, MN
- CNIGS [Centre national de l'Information Géo-Spatiale] (2017) LiDAR elevation dataset at 1.5 m grid spacing. Provided in ArcGIS raster format. CNIGS, Port-au-Prince, Haiti
- Fick SE, Hijmans RJ (2017) WorldClim2: new 1-km spatial resolution climate surfaces for global land areas. *Int J Climatol* 37(12):4302–4315
- Fletcher R, Reeves CM (1959) Function minimization by conjugate gradients. *Comp J* 7:149–154
- Fu C, Di Q, An Z (2013) Application of the CSAMT method to groundwater exploration in a metropolitan environment. *Geophysics* 78:201–B209. <https://doi.org/10.1190/geo2012-0533.1>
- Goebel M, Pidisecky A, Knight R (2017) Resistivity imaging reveals complex pattern of saltwater intrusion along Monterey coast. *J Hydrol* 551:746–755
- Gourcy L, Adamson JK, Miner WJ, Vitvar T, Belizaire D (2022) The use of water stable isotopes for a better understanding of hydrogeological processes in Haiti: overview of existing $\delta^{18}\text{O}$ and $\delta^2\text{H}$ data. *Hydrogeol J*. <https://doi.org/10.1007/s10040-022-02498-1>
- Gutierrez A, Gourcy L, Braibant G (2012) Etude de Faisabilité pour la Réhabilitation et l'Extension du Système AEP, la Réalisation du Système d'Assainissement des Rejets Liquides et la Supervision des Travaux de la Ville de Cap-Haïtien: Caractérisation géochimique [Feasibility study for the rehabilitation and extension of the AEP System, the realization of the liquid waste sanitation system and the Supervision of Works of the City of Cap-Haïtien: geochemical characterization]. BRGM-BRL-PC. PRET 1010/SF-HA AOI no. 26-02/10, BRGM, Orléans, France. <https://doi.org/10.13140/RG.2.2.19986.68801>
- Haiti Outreach (2017) Water point inventory of Department Nord, Haiti. Database provided in spreadsheet format. Haiti Outreach, Golden Valley, MN
- IHSI [Institut Haïtien de Statistique et d'Informatique] (2015) Population totale, population de 18 ans et plus ménages et densités estimés en 2015 [Total population, population 18 years and over households and densities estimated in 2015 Total population]. IHSI, Port-au-Prince, Haiti
- Inman JR (1975) Resistivity inversion with ridge regression. *Geophysics* 40(5):798–817. <https://doi.org/10.1190/1.1440569>
- Keller GV (1966) Electrical properties of rocks and minerals. In: Clark S (ed) Handbook of physical constants. GSA Memoir 97, Geological Society of America, Boulder, CO, pp 553–577
- Logan [USGS] (1962) Hydrology data collected by J. Logan, US 410 for wells in Haiti. US Geological Survey Library, Reston, VA
- McNeill JD (1980) Electrical conductivity of soils and rocks. Technical note TN-5, Geonics Limited, Mississauga, ON
- Miner WJ, Adamson JK (2017) Modeling the spatial distribution of groundwater recharge in Haiti using a GIS approach. Geological Society of America 2017 annual meeting, Seattle, WA. <https://doi.org/10.1130/abs/2017AM-297120>
- Monthel J, Bialkowski A, Jeah Ph, Jean-Baptiste M (2013) Cartographie géologique des villes de Cap-Haïtien, Fort Liberté et Ouanaminthe (République d'Haïti) [Geological mapping of the cities of Cap-Haïtien, Fort Liberté and Ouanaminthe (Republic of Haïti)]. Final report, BRGM/RP-61951-FR, BRGM, Orléans, France, 55 pp
- Murty B (2002) The gravity method in groundwater exploration in crystalline rocks: a study in peninsular granitic region of Hyderabad, India. *Hydrogeol J* 10:307–321
- Nolan B (1998) Depth of the base of the Jackson aquifer, based on geophysical exploration, southern Jackson Hole, Wyoming, USA. *Hydrogeol J* 6:374–382
- Northwater International (2014) Hydrogeological assessment report: Tanganika District, Katanga Province, Democratic Republic of Congo. Concern Worldwide, Northwater, Chapel Hill, NC
- Northwater International and Rezodlo (2017) An evaluation of the Plaine du Cul-de-Sac aquifer and its potential to serve Canaan: Port-au-Prince, Haiti. Technical report, Cooperative agreement no. AID-521-A-15-00010, United States Agency for International Development and American Red Cross, Washington, DC, 40 pp
- Northwater International and Rezodlo (2019) Prospection géophysique à l'est de la Plaine de L'Arbre, Commune Anse Rouge, Département de L'Artibonite [Geophysical survey of the eastern Plaine de L'Arbre, Anse Rouge Commune, Artibonite Department], Haiti. Preliminary report, DINEPA and World Bank, Washington, DC
- Peragallo J (1980) Reconnaissance géophysique des alluvions de la Plaine du Nord (Haïti). Organisme de développement du Nord [Geophysical reconnaissance of the alluvial deposits of the North Plain (Haïti). Development agency of the North]. Report BRGM 80 GPH 039, BRGM, Orléans, France, 22 pp
- Polak E (1971) Computational methods in optimization: a unified approach. Academic, San Diego
- Radstake F (1992) Electromagnetic resistivity profiling for locating buried river channels: a case study in Haiti. *Appl Hydrogeol* 2(92):7
- Rodi W, Mackie RL (2001) Nonlinear conjugate gradients algorithm for 2D magnetotelluric inversion. *Geophysics* 66:174–187
- Santos F (2006) Joint inversion of gravity and geoelectrical data for groundwater and structural investigation: application to the north-western part of Sinai, Egypt. *Geophys J Intl* 165:705–718
- STEACI (2006) Forage SNEP URSEP, Balan Cap Haïtien, Forage de puits, développement à l'air lift, pompage d'essai [Drilling report for SNEP URSEP Well, Balan Cap-Haïtien: well drilling, air lift development, pump test]. Société Technique d'Architecture et d'Ingénierie S.A., Port-au-Prince, Haiti
- Tarantola A (1987) Inverse problem theory. Elsevier, Amsterdam
- Telford WM, Geldart LP, Sheriff RE, Keys DA (1976) Typical values of electrical constants of rocks and minerals. In: Applied geophysics. Cambridge University Press, Cambridge, pp 450–457
- Tikhonov AN, Arsenin VY (1977) Solutions of ill-posed problems. Winston, New York
- Tomasi B (1990) Inventaire des points d'eau de la région Nord [Inventory of water points in the northern region]. Programme des nations unies pour le Développement (PNUD)/Ministère de l'Agriculture. Report HAI/86/003, Service Nationale des Ressources en Eau, Port-au-Prince, Haiti
- UNDP [United Nations Development Program] (1990) Carte Hydrogéologique République d'Haïti [Hydrogeologic map of the Republic of Haïti]. United Nations Development Program, New York, scale 1:250,000, 1 sheet
- UNDP [United Nations Development Program] (1991) Développement et gestion des ressources en eau. Disponibilité en Eau et Adéquation aux besoins, Rapport Technique, Volume II, Région Nord. [Water Resources Development and Management: availability of water and adequacy to water needs. Technical report, vol II, North Region]. Project HAI/86/003, UNDP, New York
- V3 Companies and Northwater International (2016) Technical results memorandum for development of hydrologic model(s) for Caracol Industrial Park. Inter-American Development Bank, Washington, DC
- Vozoff K (1991) The magnetotelluric method. In: Nabighian MN (ed) Electromagnetic methods in applied geophysics, vol 2: application, part B. Invest Geophys 03:641–712
- Woodring WP, Brown JS, Burbank WS (1924) Geology of the Republic of Haiti. Department of Public Works, Port-au-Prince, Haiti

- Zaenudin A (2020) Analysis of gravity anomaly for groundwater basin in Bandar Lampung city based on 2D gravity modeling. *J Phys Ser* 1572:012006
- Zohdy AAR, Martin P, Bisdorf RJ (1993) A study of seawater intrusion using direct-current soundings in the southeastern part of the Oxnard plain, California. *US Geol Surv Open-File Rep* 93-524, 139 pp
- Zonge KL, Hughes LJ (1991) Controlled source audio-frequency magnetotellurics. In: Nabighian MN (ed) *Electromagnetic methods*

in applied geophysics, vol 2: application, part B. *Invest Geophys* 03:713–809

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