The Geophysical Exploration for Groundwater at the Kakuma Refugee Camp and the Proposed Kalobeyei Refugee Camp in Turkana County, Kenya

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UNHCR
THE GEOPHYSICAL EXPLORATION FOR GROUNDWATER AT THE KAKUMA REFUGEE CAMP AND THE PROPOSED KALOBEYEI REFUGEE CAMP IN TURKANA COUNTY, KENYA
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1. ACKNOWLEDGEMENTS

This program was funded largely by the Society of Exploration Geophysicists (SEG) Geoscientists Without Borders Program (GWB), whose mission statement is: “The mission of Geoscientists WithoutBorders® supports humanitarian applications of geoscience around the world.” Not only did the GWB provide funding, but they expressed complete and enthusiastic support before, during, and after the execution of the program. Rhonda Jacobs and Bernadette Ward, in particular, were very supportive and patient over the long interval between conception and execution of this program. All of the work was completed under the management of a small Israeli NGO, IsraAID, whose mission statement is “…helping people all over the world overcome extreme crises and has provided millions with the vital support needed to move from destruction to reconstruction, and eventually, to sustainable living.” This water exploration program in this remote refugee camp certainly conformed to both of the above mission statements. Without IsraAID’s involvement in the WASH (Water, Sanitation, and Hygiene) program at the UNHCR administered Kakuma Refugee Camp, this work would not have been possible. All of the geophysical equipment and equipment repairs were provided for this program, at no cost to the program, by Paul Bauman Geophysics Ltd.

The geophysicists below received no remuneration for their services, and participated in this field portion of this project during their “vacation” time. The geophysical field program, including conceptualization, preparation, mobilization, demobilization, processing, and reporting was carried out by six geophysicists from Advisian WorleyParsons, and a Ph.D. student from the University of Calgary. Advisian WorleyParsons staff included Paul Bauman, Erin Ernst, Doug McClean, Colin Miazga, Randy Shinduke, and Landon Woods. Franklin Koch, who was also a student intern at Advisian WorleyParsons, participated from the University of Calgary. Dr. Alastair McClymont, from Advisian WorleyParsons, assisted in planning and data processing. Naama Gorodischer, Alex Theran, and Jack Jones provided extensive logistical and communications support before, during, and after the field program. Alex, Jack, or both were with us in the field on a daily basis. The refugee and Turkana field crew received remuneration to the full extent as allowed by UNHCR’s work incentive payments. The field crew was completely staffed by 28 refugee and Turkana students from the IsraAID eight month WaMTech (“Water Management and Technologies class taught in the Refugee Camp and four Turkana from the village of Kalobeyei. Michael Gatriay, an incentive worker with IsraAID, also assisted with some logistical elements of the program, especially with the initial site reconnaissance within the Camp. The full names of the refugee and Turkana crew are provided in Table A. Brendan O’Brien of RedVan Studio and Josie Bauman documented the field program, including with film, still photography, and interviews. Oscar Nabiswa, UNHCR’s Assistant WASH (water, sanitation and hygiene) Officer in Kakuma, was our main UNHCR contact before, during, and after the field program. Alfred Kapoko, the village leader of Kalobeyei, oriented us to the Kalobeyei area, and provided meaningful input regarding preferred exploration areas and line locations. Despite the remoteness and harshness of the area, the support we received from IsraAID, UNHCR, and the village of Kalobeyei allowed us to proceed with the program with virtually no significant logistical delays.
2. ABSTRACT

The Kakuma Refugee Camp is located in the semi-arid Turkana County of Northwestern Kenya. The Camp is home to 187,867 refugees (UNHCR, March 16, 2016) who are entirely dependent on groundwater pumped from 12 wells. The average water use per person, per day in the Camp is estimated at 19 litres (UNHCR, March 16, 2016). The principal concern regarding water quality is fluoride, which is naturally present, sometimes in concentrations necessitating the abandonment of otherwise productive and good quality water wells.

The goals of this program were to: 1. Provide drilling targets for new water wells in the Camp, 2. Introduce a new approach to water exploration in Kakuma by combining extensive surveys of electrical resistivity tomography with seismic refraction, 3. Provide water well drilling targets for the semi-nomadic Turkana in close proximity to a proposed new 60,000 person refugee Camp at Kalobeyei, 20 km west of Kakuma, 4. Add to the overall understanding of the hydrogeology of the area, and 5. Engage and train the 28 students of the IsraAID WaMTech (Water Management and Technologies) in a practical water exploration program.

11.4 km and 5.8 km of electrical resistivity tomography (ERT) and seismic refraction data, respectively, were collected, respectively. ERT was used to differentiate granular overburden from clay, weathered rock from fractured rock, and fresh water from saline water. ERT was particularly successful in identifying interpreted faults in the Kalobeyei area. Seismic refraction was used to delineate, with confidence, the top of competent bedrock.

Possible water well drilling targets are identified in the Conclusion. In Kakuma, proposed targets of drilling include areas of thicker granular overburden and weathered rock. Overburden zones of very low resistivities, say <20 ohm-m, are suggested to be avoided as being clayey and/or saline. Bedrock zones of high resistivities, say >60 ohm, are suggested to be massive and of lower groundwater yield potential. Targeting zones of thicker, granular overburden may minimize fluoride concentrations. The area described here as The Northern Well Field appears to be particularly promising in terms of laterally extensive, thick, saturated, granular overburden.

In Kalobeyi, Elelia and Esikiriait lagas are saline and/or clayey, with no good drilling targets. In the four lines collected in Laga Kangura and in proximity to the existing Kalobeyei Well, a number of targets between a likely fault and a laga, and within a conspicuous interpreted fault block, are identified.

The geology and hydrogeology of Kakuma and Kalobeyei are complex. While the combination of ERT and seismic refraction are a vast improvement over the typically run vertical electrical soundings (VES), there remains considerable uncertainty in providing drilling targets. Given the shallow nature of water wells in the area, nuclear magnetic resonance (NMR) soundings are recommended as an additional survey to prioritize drilling sites, as NMR is sensitive only to water.
3. BACKGROUND INFORMATION

3.1 Kakuma Refugee Camp and Project Location

The Kakuma Refugee Camp is located in the semi-arid Turkana County of northwestern Kenya (Figure 1), at an elevation of approximately 600 m above mean sea level (masl). The Camp is jointly managed by the Office of the United Nations High Commissioner for Refugees (UNHCR) and the Kenyan Government. The Camp was originally opened in 1992 to receive the “Lost Boys of Sudan,” who were refugees from the Second Sudanese Civil War, which ended in 2005. The Camp, which presently provides asylum to 187,867 refugees from about 16 countries in East Africa, was designed for a maximum Camp population of 100,000. After the declaration of a new state in South Sudan in 2013, the population of the Camp dwindled to about 30,000 persons. However, ensuing conflict in South Sudan resulted in more than 46,000 Nuer and Dinka refugees coming to Kakuma since December, 2013. As well, the Camp continues to host refugees from other countries who are fleeing from famine, drought, “cattle wars,” and other conflict zones in East Africa.

The Camp is divided into four residential sections (Figure 2), with Kakuma 1 being the original area where the Lost Boys settled, and Kakuma 4 being the living area of the most recent arrivals. UNHCR is preparing to receive an additional 60,000 refugees in the near future, more than doubling the initial design capacity of the Camp. The plan is for many of these new arrivals to live in a newly constructed Camp about 20 kilometres west of Kakuma, called Kalobeyei (Figure 3). Kalobeyei will be unique among presently operating UNHCR camps in that residents will be encouraged to practice agriculture rather than to simply rely on UNHCR rations. In addition, significant interaction with the host community (i.e. the semi-nomadic Turkana) will be facilitated rather than avoided.

Kakuma town, located immediately east of the refugee camp, has a population of approximately 120,000 persons, including the semi-nomadic Turkana population in the immediate area. Kalobeyei town site, located about 30 km west of Kakuma, is a small village of a few permanent houses. Neither Kakuma nor Kalobeyei have grid connected power or water.

Turkana County is Kenya’s largest county, with an area of about 71,598 km², and a population of 855,399 (2009), both statistics being very similar to those of the Canadian Province of New Brunswick.

The climate and landscape of Kakuma is semi-arid, essentially desert. The average annual temperature in Kakuma is 27.6°C, with temperatures very rarely dropping below 21°C. Annual precipitation averages 32.1 cm. Most precipitation falls as a few intense rain events in April and November.

3.2 Project Goals

This geophysical program is intended to improve the water supply of the Kakuma Refugee Camp as well as the water supply in the Kalobeyei area south and west of the proposed new Kalobeyei Camp. Exploration near the proposed Kalobeyei Camp is designed to improve the water situation for the Turkana people in the area, both nomadic and permanent inhabitants, and in this manner assist in avoiding likely water conflicts with the UNHCR camp. In addition, an improved understanding of the
aquifer systems of the area, geophysical field training for refugees and local Turkana, and training for Kenyan professionals, are all intended consequences. Geophysical surveys were carried out with the intent of delineating saturated, fresh water sand and gravel aquifers, weathered bedrock (including saprolite), zones of elevated groundwater salinity, and significant possible water bearing structures including faults.

Surveys were carried out by using a combination of ERT and seismic refraction. The objective of using seismic refraction was specifically for determining depth to relatively unweathered volcanic rock. ERT was used for salinity mapping, overburden lithology descriptions, and fault mapping. Tying these surveys to existing wells of known geology, water chemistry, and yield was intended to provide interpretational ground truthing. Exploration survey locations were chosen largely based on areas of proposed water well drilling by UNHCR and the village head of Kalobeyei (Alfred Kapoko), as well as being based on the availability of existing wells with some available information, and accessibility. The ultimate goal is to provide improved access to water, as well as to improve the understanding of the local hydrogeology and the applicability of new geophysical exploration techniques.

3.3 Geological and Hydrogeological Setting, Previous Geophysical Surveys

Much background information for the general investigation area, and for Kakuma in particular, is provided by the June 2013 M.Sc. thesis by Jonathan Sottas of the University of Neuchatel, “Hydrogeological Study of the Aquifer System of Kakuma, Kenya.” This thesis provides a comprehensive review of the regional and local geological setting, along with a chemical and physical hydrogeology overview.

Very little area specific information is available regarding the Kalobeyei site, located 30 km to the west of Kakuma, though a brief overview of the geology and hydrogeology is provided by C. M. Gicheruh in the October 2015 UNHCR study of “Hydrogeological and Geophysical Investigations, Kalobeyei New Refugee Camp Water Project.”

A brief synopsis of the geology and hydrogeology, drawing heavily from the above two documents, is provided below.

3.3.1 The Kakuma Refugee Camp

Kakuma is located in the northwestern extent of the Kenyan Rift (Figure 4). The Kenyan Rift is the eastern branch of a much larger feature, the East African Rift System. The most pronounced geographic feature of the Kenyan Rift is the broad valley of the Turkana depression and Lake Turkana lying on the axis of the Kenyan Rift.

The area around Kakuma is called the Lotikipi Plains. Sottas (2013) describes the Lotikipi plains as a saucer-shaped depression bordered to the east and west by volcanic ranges (Figure 5). The “saucer” itself is filled with volcanic derived, fluvial sediments from middle Miocene to present (0–5.5 Ma), reaching a maximum thickness of 300 m. Underlying the sediments are middle to early Miocene (5.5–23.7 Ma) rhyolites, then Oligocene age (23.7–36.6 Ma) basalts underlain by sub-volcanic sedimentary rocks of Paleocene or Cretaceous (57.8–144 Ma), and finally Precambrian basement
consisting mainly of gneisses and schists. The Lotikipi Basin is heavily faulted in a horst and graben structure (Figure 6).

As the Kakuma Refugee Camp is on the southern edge of the Lotikipi Basin, numerous rhyolite outcrops occur in the exploration area. Available drilling data indicate that the sediment overburden in Kakuma reaches a maximum of approximately 40 m in thickness. Generally, underlying the overburden, various drilling campaigns encountered volcanic rock, though sedimentary and igneous rock have also been encountered.

Presently, groundwater is the only available water source for the Kakuma Refugee Camp and the surrounding area. The vast majority of successful water wells drilled in Turkana County are located along the lagas (wadis, or ephemeral river beds, UNICEF 2006). Kakuma is no exception, as the estimated presently pumping 12 wells are all located in, or in close proximity to Laga Tarach, which flows perhaps a few days each year. Sottas (2013), as well as available drilling data, suggest that both the overlying sediments and underlying, weathered (or fractured) rock serve as aquifers. The common practice of screening multiple aquifers, and interconnecting screened intervals with permeable backfill material, make it very difficult to determine the relative contribution of the bedrock versus sediment aquifer. In addition, drilling information from abandoned boreholes is rarely archived, and information that is archived is often confusing or contradictory. Sottas concluded that most boreholes draw from both aquifers.

The shallow, alluvial aquifer is generally associated with higher yields and greater storage, with lower fluoride concentrations, but greater vulnerability to bacterial contamination. The deeper bedrock aquifer is associated with lower yields, high fluoride concentrations, and lower vulnerability to bacterial contamination. Many water wells in the area are brackish to saline. Increasing salinity in water wells has been observed during prolonged periods of drought. As no borehole geophysical information is available, and a general practice in East Africa is the screening of any and all zones of water production, more confident and detailed descriptions of the water quality of the individual aquifer systems is challenging.

The main geochemical constraints on water potability are elevated salinities and elevated fluoride concentrations. Elevated fluoride concentrations in groundwater are common in rift valley environments (Essentials of Medical Geology 2005). Sottas concluded that the high concentrations of fluoride are likely associate with the weathered volcanic rock aquifer system.

Aquifer recharge at the Camp is likely associated with indirect recharge from Wadi Tarach during flooding events (i.e. the lagas flood, and aquifers are recharged from the lagas). Sottas concluded that rainwater acts as a secondary but direct source of recharge.

Sottas carried out 19 ERT (electrical resistivity tomography) surveys varying in length from 65 m to 350 m, and varying in depth of investigation from 10 mbgs (metres below ground surface) to 40 mbgs (Figure 7). A total of about 5 km of ERT data were collected, processed, and interpreted. Sottas concluded that, essentially, the data were uninterpretable “as the presence of magnetite interferes with the electrical signals of ERT.” We believe that while Sottas presented a very sound approach, the execution of his surveys suffered from too many lines of too short a line length, with too shallow a depth of investigation. As such, he was not able to survey to significant depth in the bedrock, nor
completely through the overburden, nor over great enough survey lengths to recognize variability within both the bedrock and the overburden. Sottas did recognize that “the use of non-electrical geophysical methods might be recommended.” Also, Sottas (as did we) clearly suffered from a sparseness of good well control data, as well as a complete absence of borehole geophysical data. Of note, of course, is that our 2016 program tremendously benefitted from the information presented in Sottas’s geophysical exploration efforts, and we were able to improve upon some shortcomings identified in Sottas’s geophysical campaign.

### 3.3.2 Kalobeyei

Gicheruh (Hydrogeological and Geophysical Investigations, 2015) describes the geology and hydrogeology of the Kalobeyei area as being very similar to Kakuma, with clayey alluvium overlying Tertiary lavas, with sand lenses being present in proximity to the major lagas (Figure 8). Gicheruh suspected that weathered rhyolites underlay most areas of alluvium. Underlying the Tertiary rhyolitic lavas, are interbedded basalts, sedimentary rocks, and Precambrian basement.

The Kalobeyei borehole, drilled in 2011, is believed to be the only producing water well within 5 km of our exploration area. This well has a recorded yield of 5.02 m³/hr, and a total depth of 68 mbgs. No geological information related to the well was available.

Gicheruh concluded that possible aquifers in the area would include alluvial deposits, weathered and fractured volcanic rock, fault zones, contacts between fluvial/colluvial deposits and lava flows, contacts between lava flows of various ages, and within fractured basement rock. He estimated that “the prospects for sufficient groundwater for domestic purposes are good.”

In September 2015, Gicheruh carried out a 9 km resistivity profile, a 5 km resistivity profile, and 44 1-D VES as part of a water exploration program for the proposed Kalobeyei camp (Figure 9). The results and interpretations of these surveys can be found in “Hydrogeological Study of the Aquifer System of Kakuma, Kenya.” Six drilling locations were recommended, based on the VES interpretations. The two most promising sounding locations, VES4 (Figure 10) and VES5 (Figure 11) were drilled to depths of 130 mbgs and 150 mbgs, respectively. Both wells tested for less than 1 m³/hr of water production. VES4 had small water flows at 32 mbgs, 80 mbgs, and 112-118 mbgs. The well drilled at VES5 encountered extensive clays (UNHCR, email communication, April 2016).

### 3.4 Geophysical Need

Turkana County is the largest and most impoverished county of Kenya, with a present population of about 1,000,000. The Camp, which presently provides asylum to approximately 187,867 refugees (UNHCR, March 16, 2016) from about 16 countries in East Africa, was designed for a Camp population of 100,000. The conflict in South Sudan resulted in more than 46,000 refugees from South Sudan alone coming to Kakuma since December, 2013. UNHCR is preparing to receive an additional 60,000 refugees in the near future, more than doubling the initial design capacity of the Camp.

Water supply, of course, is perhaps the critical material constraint on sustaining the Camp population, as well as expanding for the increasing population. UNHCR’s target provision of potable water is 20 litres per person. Presently, refugees are provided an average of 19 litres per person (UNCHR,
March 16, 2016) from an estimated 12 operating pumps. After chlorine treatment, water quality from a microbiological perspective is considered to be good, though fluoride concentrations are generally high. Some boreholes with high yields and otherwise good water quality have been abandoned due to fluoride concentrations being several times World Health Organization (WHO) guidelines. Additionally, the Camp water supply is faced with the challenges of increasing salinity during drought conditions, an uneven geographical distribution of water wells, failures in the pumping or water delivery systems, dry or saline exploratory boreholes, and an incomplete understanding of the aquifer systems of the area.

This geophysical program is intended to improve the water supply of the Kakuma Refugee Camp as well as the water supply for the host community Turkana population in the area in immediate proximity to the proposed new Kalobeyei Refugee Camp. Besides increasing water availability, an improved understanding of the aquifer system of the area, training to refugees and local Turkana, and training to Kenyan professionals are intended consequences. Geophysical surveys were carried out with the intent of delineating saturated, fresh water sand and gravel aquifers. As the survey progressed, fractured and weathered bedrock were also included as targets. This is especially true near Kalobeyei where overburden was generally found to be thin or non-existent. Geophysical methods included a combination of seismic refraction and ERT for depth to rock, as well as using ERT for salinity mapping. Tying these surveys to existing wells of known geology, water chemistry and yield provides some interpretational “ground truthing”. Exploration survey locations were chosen based on areas of proposed water well drilling by UNHCR and the Village headman of Kalobeyei. Access, safety, ease of drilling rig mobilization, availability of nearby wells, sources of noise (e.g. generators, school children, etc.), driving time, Camp curfews, and other factors also influenced the chosen line locations. The ultimate goal of the project is to provide improved access to water, as well as to improve the overall understanding and means to continue the exploration and development of new water resources.

3.5 The Human Element

The geophysical field program, preparation, mobilization, demobilization, processing, and reporting was carried out by six geophysicists from Advisian WorleyParsons, and a PhD from the University of Calgary. Advisian WorleyParsons staff included Paul Bauman, Erin Ernst, Doug McClean, Colin Miazga, Randy Shinduke, and Landon Woods. Franklin Koch, who was also a student intern at Advisian WorleyParsons, participated from the University of Calgary. The two person film crew consisted of the director and camera man Brendan O’Brien, and the assistant camera man Josie Bauman. Jack Jones and Alex Theran of IsraAID managed the complex logistics of staffing the crews, feeding field staff, moving people to different locations every day, organizing transport, managing finances, organizing accommodation for the Canadians, monitoring the safety situation in a very remote but dynamic corner of the world, interacting with UNHCR and the Norwegian Refugee Council (NRC), and a variety of other tasks that went largely unseen by the field crews. Michael Gatriay, an incentive worker with IsraAID, also assisted with some logistical elements of the program, especially with the initial site reconnaissance within the Camp. Michael was a student in the 2014 IsraAID Hydrogeology and Water Exploration course taught by Paul Bauman. Oscar Nabiswa, the Assistant WASH Officer of UNHCR’s Kakuma Sub-Office, was our main contact person with UNHCR, provided our project with available background material for both Kakuma and Kalobeyei, and organized a final
Typically, field days ran approximately 12 hours from 6:30 AM to 6:30 PM. Two crews worked simultaneously, usually one crew collecting ERT data, and the second crew collecting seismic data. Three Canadian geophysicists would work with each crew, with the seventh floating between crews, processing data, or back at camp recovering from health problems. The crew itself was composed of students from the IsraAID 2015 WaMTech class, all of whom had previously participated in the November, 2015 IsraAID Hydrogeology and Water Exploration course taught by Paul Bauman. The 28 students were divided into four groups, as noted in Table A. The four groups were cycled through the 12 field days as noted in Table B. Each day, one crew would work from 6:30 to 13:00, and the second crew from 12:00 to 18:30, with both crews overlapping for lunch. Besides food and training, all Turkana and refugee crew received incentive pay to the maximum allowed by UNHCR and IsraAID guidelines. All crew participated in both seismic and ERT surveys, including in all phases of data collection and some portions of the data processing. The preliminary results of the program were presented to the 2016 WaMTech students, as well as the 2015 WaMTech students, on January 25.

In Kalobeyei, four Turkana from the village of Kalobeyei were included in the crew. The Turkana from Kalobeyei had previous experience on geophysical crews elsewhere in Turkana, and were very quick to adapt to the water exploration program. The preliminary results of the Kalobeyei exploration program were presented to the head of the village, Alfred Kapoko, on January 23, 2016.

Table A  Field crews composed of 28 students divided into 4 groups

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<td>Sabio Ohitei Galdo</td>
<td>Ngumi Toblo Ngatu</td>
<td>Tut Bol Wuol</td>
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<td>Odong Brabo Estilio</td>
<td>Ohuro Orufa</td>
<td>Loboi Paul Lino</td>
<td>Seleman Isaak Jeberel</td>
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Table B  Field schedule from January 11 to January 22, 2016

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4. FIELD STUDIES AND GEOPHYSICAL FIELD METHODS

Field work occurred over the period of January 10 to January 22, 2016. Sunday, January 10, was used to uncrate, prepare, and check equipment, as well as to carry out a reconnaissance survey at existing water points and proposed exploration areas in the Kakuma Refugee Camp. The geophysical field program was executed over the period from January 11 through January 22, 2016.

The geophysical field program was carried out by two crews working simultaneously, usually in different areas separated by several kilometres. On January 11, both crews carried out ERT surveys, with one crew using 81 electrodes and a minimum electrode spacing of 10 m for a maximum depth of investigation of about 140 mbgs, and the second crew using 81 electrodes and a minimum electrode spacing of 5 m for a maximum depth of investigation of about 70 mbgs. From January 12 through January 21, one crew carried out ERT surveys with either 5 m or 10 m minimum electrode spacings, while the second crew carried out seismic refraction surveys. On January 22, one crew began cleaning and crating equipment for transport back to Nairobi and onward to Calgary, while the second crew carried out an ERT survey within the LWF Compound.

All positioning was carried out with Trimble Geo7X Handheld GPS units. A Geo7X GPS base station was set up within the World Food Program (WFP) Compound over the entire survey period. As such, georeferenced positions are, generally, recorded in X, Y, and Z positioning to sub-metre accuracy. All positioning data were collected in the coordinate system of UTM 36 North, and with the datum of WGS84. Generally, field notes were recorded on the Geo7X units as well as in field notebooks. Each field area was intensively photographed.

The investigation areas have been grouped into four areas (Figure 12):

1. **Laga Tarach South** (LWF and UNHCR Compound, Figure 13);
2. **Northern Well Field** (Figure 14);
3. **Central Well Field** (Figure 15);
4. **West of Kakuma 1** (Figure 16); and
5. **Kalobeyei** (Figure 17).

**Laga Tarach South** is an area close to the UNHCR and LWF compounds, has some borehole control, has wells of variable yield and water quality, and is in, or close to the main channel of Laga Tarach. Laga Tarach South is immediately south and east of the longest inhabited (since 1992) portion of Kakuma 1. Survey objectives here included overall testing of the survey approach, locating potential drilling sites with potential superior yield and lower fluoride concentrations as compared to existing wells, and identifying if there is a geoelectric signature of the reported high salinity in the Construction Borehole in the LWF Compound.

**The Northern Well Field** is the area of the highest yielding wells, has some borehole control, and is also close to Laga Tarach, which likely functions as a source of indirect recharge. The Northern Well Field is essentially outside and to the north of the Camp itself, and is in an area of Turkana villages and
family compounds. Survey objectives here included locating potential drilling sites with potential superior yield and lower fluoride concentrations as compared to existing wells.

The Central Well Field is approximately midway between Laga Tarach South and The Northern Well Field, and is also in close proximity to Laga Tarach. There are a number of wells in this area; however, well control is poor as most wells are hand dug or have very limited accompanying geological and hydrogeological descriptions. The Central Well Field is on the north edge of densely populated Kakuma 1. Survey objectives here included locating potential drilling sites with superior yields.

The area West of Kakuma 1 has no producing water wells. However, numerous abandoned wells have been drilled in this area, including the “Kakuma 1 VES 1 Borehole” which tested for 110 m³/hr, though with elevated salinity and a very high fluoride concentration. Limited geologic control exists in this area due to an absence of available archived information. The high tested yield from the noted borehole makes this an interesting area for exploration. Also, as there are no producing wells in this area, a successful water well in the area West of Kakuma 1 would bring a water source considerably closer to Kakuma 3 and 4, and possibly avoid water delivery disruptions during flooding in the lagas (buried pipelines are often damaged by flood waters).

The Kalobeyi area has only a single producing water well which has been tested at 5 m³/hr. The surficial geology in this area appears considerably different in the Kalobeyi exploration area as compared to Kakuma, as in Kalobeyi there is considerable rock outcrop, and the nearby lagas are much smaller than Laga Tarach. Exploration in the Kalobeyi area occurred in proximity to the existing Kalobeyi borehole (Figure 18), and south of the Lokichogio Road (Figure 17) in three small lagas near the proposed new Kalobeyi Refugee Camp, lagas Elelia, Esikiriait, and Kangura (from east to west).

4.1 Electrical Resistivity Tomography (ERT) Method

ERT is a technique for mapping the distribution of subsurface electrical resistivity (or its inverse, conductivity) in a cross-sectional format. Resistivity data are collected through a linear array of electrodes coupled to a direct current (DC) resistivity transmitter and receiver, and an electronic switching box. The spacing between electrodes largely controls the horizontal and vertical resolution of the data (smaller spacing results in higher horizontal and vertical resolution). Similarly, the length of the array controls the depth of investigation (longer arrays yield greater investigation depths). Data collection is carried out in a sequential and automated fashion that takes advantage of all possible combinations of current injection and potential measurement electrodes. The data are downloaded to a computer for processing and analysis. The data are inverted using a two-dimensional (2-D) finite difference or finite element inversion routine. The final product is a 2-D cross-section plotting resistivity (in ohm-m), or conductivity (in millisiemens per metre [mS/m]), versus depth.

4.2 Electrical Resistivity Tomography Field Survey

16 ERT sections were collected for a total of 11.4 km of line. Line lengths varied from a minimum of 400 m for ERT6, ERT14, and ERT16, to 1600 m for ERT3. Both 10 m minimum electrode spacings (140 m maximum depth of investigation) and 5 m minimum electrode spacings (70 m maximum depth of investigation) were used. Greater depths of investigation were used in areas of expected thicker
overburden or saprolite. An ABEM LS system was used for all data collection. A GradientPlus Array was used for all data collection so as to provide the best compromise of horizontal and vertical resolution, as well as to be able to optimize the 12 measurement channel capabilities of the ABEM LS system. The GradientPlus Array protocol uses a gradient array.

In the investigation area of Laga Tarach South (Figures 13 and 19), ERT lines ERT1, ERT3, and ERT16 were collected. Lines ERT1 and ERT3 used a 10 m minimum electrode spacing, while ERT16 used a 5 m minimum electrode spacing.

In the investigation area of the Northern Well Field (Figures 14 and 19), ERT lines ERT4 and ERT7 were collected. ERT4 used a 10 m minimum electrode spacing, and ERT7 used a 5 m minimum electrode spacing.

In the Central Well Field (Figures 15 and 19), ERT lines ERT5, ERT6, and ERT8 were collected. All lines used a 5 m minimum electrode spacing.

In the area West of Kakuma 1 (Figures 16 and 19), only ERT15 was collected. ERT15 used a 10 m minimum electrode spacing.

In Kalobeyei, six ERT lines were collected (Figures 12 and 18). ERT lines ERT9, ERT14, and ERT11 were collected in lagas Elelia, Esikiriait, and Kangura, respectively. The above three locations are all south of the A1 Highway (Lokichogio Road). ERT12 was collected in close proximity to the only existing well in the area, the Kalobeyei Well. ERT13 was collected approximately 100 m north of ERT12. ERT10 was collected approximately 100 m south of ERT12, and south of the A1 Highway (Lokichogio Road).

4.3 Seismic Refraction Method

The seismic refraction method uses the propagation of compressional waves in the subsurface to determine the velocity structure of the earth. Seismic energy is produced by a source (e.g. sledge hammer, weight drop or dynamite), and spreads downwards and laterally through the earth. An array of receivers (geophones) measures the arrival of that energy at points (geophone positions) on a line. Increasing vertical velocity gradients with depth will cause seismic energy to refract back to the surface. Decreasing vertical velocity gradients are rare but, where present, will bend rays away from the surface and create shadow zones that cannot be imaged. The travel path that the energy takes from each shot to each receiver (geophone) can be represented by a curved ray path. Typically, seismic energy that has propagated through bedrock material will arrive with faster apparent velocities along the seismic array than seismic energy that has travelled through overburden.

The picked travel times of the first-arriving energy can be used as input to seismic inversion software (e.g. Rayfract), which solves for the velocity model of the subsurface that best fits the observed travel times. The accuracy of each travel-time pick is determined by the frequency of the first-arriving energy and the signal-to-noise (S/N) ratio. Factors that can reduce the frequency and/or S/N ratios include soft or spongy soils, wind noise, traffic noise, and the distance between the shot and the receiver (signal strength will reduce proportionally with increasing length of the ray path). The maximum depth of
investigation of a velocity model is determined by the deepest refracted ray path. As a general rule, the longer the horizontal offset between a shot and a receiver, the greater the depth of penetration.

**4.4 Seismic Refraction Field Survey**

10 seismic refraction lines were collected for a total of 5.8 km of line length. Individual sections ranged in length from 355 m for Seismic3, to 720 m for Seismic1. All lines were shot with 40 Hz vertical component geophones, with a single geophone in each group, and with a 5 m geophone spacing. Geometrics Geode 24-channel networked seismographs were used for all surveys. Most lines were shot with 144 channels (6 networked seismographs), though some lines used fewer channels due to space constraints. Generally, a Propelled Energy Generator (PEG) was used as a seismic source. A PEG-40 was mounted to the back of an open pickup truck as the main seismic source. The PEG-40 uses an industrial strength elastic band to propel a 40 kg steel beam into an aluminum strike plate. Generally, the source frequency is between 10 Hz and 250 Hz. Where the truck could not gain access, a 16 pound sledge hammer was used as the seismic source.

**4.5 Soil Cell**

Resistivity measurements were made on a number of hand samples using a soil resistivity test box and an ABEM SAS1000 resistivity meter. Soils were packed into the test box with electrodes configured in a Wenner Array. The box dimensions are such that the meter reads in ohm-cm directly, which can then be converted to ohm-m by dividing by 100.
5. GEOPHYSICAL SURVEY RESULTS AND INTERPRETATIONS

The geophysical results and interpretations will be addressed through the five spatial subsets as described earlier. Though limited, all available borehole data were used, and are referenced in the interpretations. Through a combination of well ties and physical properties assumptions, certain broad interpretive assumptions are assigned to each area. These broadly applied interpretive assumptions include:

1. depth to competent bedrock, as derived from the P-wave refraction results, generally correlates with the 2000 m/s velocity contour;

2. the delineation of more massive bedrock with lower groundwater yield potential, is based on relatively higher bedrock resistivities (greater than approximately 60 ohm-m);

3. the delineation of fractured to highly weathered bedrock with higher groundwater yield potential, is based on relatively lower bedrock resistivities (less than approximately 60 ohm-m);

4. saline and/or clay overburden, is based on very low resistivities (less than approximately 10 ohm-m);

5. fresh water saturated or partially saturated granular overburden is interpreted as being between approximately 30 ohm-m and 100 ohm-m;

6. saturated overburden, with a significant percentage of clays or elevated salinity, is between 10 and 20 ohm-m;

7. saturated saprolite (very highly weathered bedrock) is between 10 ohm-m and 30 ohm-m; and

8. granular, dry overburden is greater than 100 ohm-m.

5.1 Kakuma Refugee Camp (Figure 19)

5.1.1 Laga Tarach South: LWF (Lutheran World Federation) and UNHCR compound

Data sets in this area include ERT1, Seismic 1 (Figure 20), ERT3, Seismic 2 (Figure 21), and ERT16 (Figure 22). Boreholes in close proximity to the geophysical lines include UNHCR Borehole, Construction (saline water) Borehole 1, Water Supply Borehole 1, Borehole 10, and Borehole 11. This area was chosen as the beginning of the field investigation due to available geological control at the UNHCR Borehole, shallow bedrock, easy logistical access, and proximity to the WFP compound.

Regarding the interpretations of the results, the top of bedrock (bottom of overburden) is interpreted to be at about the 2000 m/s P-wave velocity contour. Overburden resistivities less than 10 ohm-m are interpreted to be saline and/or clay, and water saturated. Overburden resistivities greater than 30 ohm-m are interpreted to be granular and fresh water saturated or partially saturated.
Rock resistivities above 60 ohm-m are interpreted to be, generally, massive and of lower groundwater yield potential. Rock resistivities below 60 ohm-m are interpreted to be, generally, fractured to deeply weathered, with higher groundwater yield potential by comparison.

**ERT1 and Seismic1**

The interpreted resistivity section of ERT Line 1 and the processed seismic P-wave velocity section of Seismic Line 1 are presented in Figure 20. The P-wave velocity contour of 2000 m/s is interpreted as the top of bedrock, and overlain on to the ERT section. This velocity contour falls about 4 m below the top of rhyolite identified in the UNHCR Borehole which is located approximately 80 m from the ERT and seismic lines. The low overburden resistivities (<10 ohm-m) at the UNHCR Borehole are supportive of the cuttings description of mostly clay overburden. The UNHCR Borehole is one of the few boreholes screened entirely in bedrock. The moderately high resistivities of the rock may be indicative of the relatively low yield of the UNHCR Borehole (5 m³/hr; 1999).

The UNHCR Borehole is reportedly very high in fluoride concentration (8 mg/l; 1999). This may be a result of the well being screened only in rock, with no dilution from groundwater in the overlying alluvial (laga) deposits. Given the shallow and high resistivity rock; low resistivity, clayey overburden; and high fluoride concentrations, the geophysical data in proximity to the UNHCR Borehole are notable for their counter indications of a high yielding borehole (i.e. the geophysical results suggest low yield).

Following the 2000 m/s velocity contour to the north delineates the proposed rock surface along the top contacts of the high (>70 ohm-m) rock resistors. The rock surface deepens to the north (i.e. overburden thickens to the north). The position of the rock surface is unclear north of 1050 m.

The two massive resistive bodies in rock, and continuing to depth, are interpreted to be rock zones of poor yield. The lower resistivity zones centered around 575 m North and north of 1050 m are interpreted to likely provide greater water yield from rock.

ERT1 and ERT3 sections correlate well at their tie point.

As overburden thickness increases to the north, overburden yields may increase to the north. However, overburden resistivities are generally very low (<10 ohm-m), and may be indicative of significant salinity and/or clay content. Construction Borehole 1, located about 100 m west of ERT1, produces reportedly saline water (sulphate 400 mg/l, chloride 110 mg/l; tested 26 April, 2011), hence this well located in the LWF compound is used only for construction water.

Dry sand in Laga Tarach, near the bridge, was tested in the soil cell. The sample was infinitely resistive (i.e. could not pass current). A saturated sample was tested from the bottom of a “scoop hole” used for drinking water near the bridge. The resistivity of the sample was 73 ohm-m.

**ERT3 and SEISMIC2**

ERT3 passes close to water supply boreholes 1, 10, and 11 (Figure 21), as well as crossing ERT1 at approximately line position 1250 North of ERT1 and 200 of ERT3. Seismic2 passes in close proximity to boreholes 10 and 11.
Unfortunately, due to noise from the water pump generators, the seismic refraction data are of poor quality in proximity to boreholes 10 and 11. Nevertheless, the refraction velocities suggest that the top of rock runs below the near surface resistive layer (>90 ohm-m) northwest of position 850 Northwest. Southeast of 850 m, the top of rock is interpreted to follow along the top of the high resistivity bodies (>90 ohm-m). In proximity to where ERT1 crosses ERT3, the depth to top of rock is unclear.

Geologic descriptions from boreholes 10 and 11 were not located. However, both boreholes are relatively shallow (60 mbgs and 50 mbgs, respectively), and have good yields (24 m\(^3\)/hr and 36 m\(^3\)/hr, respectively). The geology at boreholes 10 and 11 is interpreted to be granular overburden (pink, high resistivity layer >90 ohm-m) overlying weathered bedrock (blue, moderate resistivity layer 10 to 20 ohm-m). Borehole 1 is positioned over a highly resistive feature (>90 ohm-m) that continues to depth, and is a low yielding borehole testing at 5.7 m\(^3\)/hr.

ERT16

Due to a lack of time, no seismic data were acquired along ERT16. Construction Borehole 1 (Figure 22) is located at about 155 m North on the section, but there was no available geological information associated with this borehole. Construction Borehole 1 is known to be saline; hence, the water from this borehole is available for construction purposes only. The well was unavailable for EC testing at the time of the water exploration program. It should be noted that the reported total dissolved solids (TDS) in the well are 591 mg/l; this low TDS contradicts the reported high salinity of the well (UNHCR, verbal communication)

The ERT data indicate a highly resistive (>90 ohm-m) and undulating surface at depth, continuing to the bottom of the section. This feature is interpreted to be generally unweathered to partially weathered volcanic rock. The borehole intersects the highest point of bedrock, as delineated in the ERT16 section, at 570 masl (27 mbgs).

ERT16 indicates the overburden sands (lithology described in Construction Water Borehole 1, drilled in 2005) to have very low resistivities (generally <5 ohm-m), strongly suggesting the presence of elevated salinity.

The Construction Borehole tested for 12 m\(^3\)/hr. The moderate yield and reported salinity of the well suggest the well is likely drawing from the overlying sands. Given its depth, the well is likely also screened in rock.

5.1.2 Northern Well Field (Figure 14)

ERT4 and SEISMIC3

Geophysical surveys ERT4 and Seismic3 (Figure 23) pass in close proximity to two high yielding boreholes, Borehole 7A and Borehole 7B, testing for 22.2 m\(^3\)/hr and 16 m\(^3\)/hr, respectively. The 2000 m/s P-wave velocity contour defines the approximate top of the “fresh biotite gneiss intrusion,” and the bottom of fractured, weathered, and altered basaltic tuffs. If the seismic refraction survey were to have extended further to the north, it is not clear whether the 2000 m/s contour would have defined the bottom of the gravels intersected in Borehole 7B, or continued to depth and delineated the bottom
of similar fractured and weathered basaltic tuffs as described in Borehole 7A. Nevertheless, it is likely that the good yields from boreholes 7A and 7B are due to the heavily weathered bedrock.

Borehole 7A is entirely screened in the weathered volcanics. Borehole 7B is screened almost entirely in the weathered volcanics, though a short section appears to be screened in overburden gravels. Borehole 7A tested for 5 mg/l fluoride. This high fluoride concentration may be associated with the heavily weathered bedrock. Borehole 7B tested for only 0.9 mg/l fluoride. The mixing of overburden water due to the shallow screen section at the bottom of granular overburden may explain the lower fluoride concentration in Borehole 7B as compared to Borehole 7A.

Although the weathered bedrock is low resistivity, generally less than 10 ohm-m, neither Borehole 7A nor Borehole 7B are saline. 7A tested for a TDS of 903 mg/l; 7B tested for a TDS of 756 mg/l. The low resistivities observed in the ERT4 section are likely related to weathering products (i.e. clay) resulting from mineral alteration in the basalts.

It should be noted that the high resistivity layer (orange to pink) intersected by Borehole 7B is likely granular alluvial sediments, and may extend between positions 220 m and 550 m in the section. If saturated, this overburden layer may provide a significant yield of water, assuming proper and effective drilling and completion methods are applied.

5.1.3 Central Well Field (Figure 15)

ERT2 and SEISMIC4

Although geophysical sections ERT2 and Seismic4 (Figure 25) intersect six boreholes, no geological information was available regarding any of the boreholes. Total depths and yields are available for Borehole 4B and Borehole 4C. Both boreholes 4B and 4C have high yields and low TDS water.

The 2000 m/s P-wave velocity contour, interpreted as the top of rock, is clearly delineated by the seismic refraction results. When overlaid onto the ERT results, the 2000 m/s contour approximately follows the upper contacts of the two large resistive bodies, and shows overburden thickening to the west. The uppermost resistive layer at surface (>100 ohm-m) is likely unsaturated granular material.
The moderately conductive underlying layer (<30 ohm-m) is likely saturated granular overburden continuing to the upper rock contact at the 2000 m/s contour. The rock is interpreted as varying from higher resistivity (>60 ohm-m) massive rock with less groundwater potential, to lower resistivity (<60 ohm-m), weathered and fractured bedrock, with interpreted higher groundwater potential.

Borehole 4B; three open, hand dug wells; and a well with a broken hand pump are all likely completed in the overburden. Groundwater (static water level [SWL]) was measured at about 7 mbgs in one open borehole. Borehole 4B was drilled to 25 mbgs with an SWL of 7.7 mbgs. Refugees using the hand dug wells for agriculture claim that the wells have been excavated through the saturated sands until refusal at a stiff clay layer.

Borehole 4C has a Total Depth of 60 mbgs, tested for a high yield of 40 m³/h, and has a TDS of 282 mg/l. Borehole 4C is drilled immediately west of a large, high resistivity body. As the screen intervals are not known, it is unclear from where water is being produced in Borehole 4C, though it is assumed that production is coming from both overburden and rock.

ERT5

ERT5 was collected through Borehole 4D, and crossing ERT6 (Figure 26). No seismic survey was shot along ERT5. The top of rock is determined through the correlation of the cuttings log to the lower contact of the high resistivity layer imaged by the ERT (Figure 26). This resistive surface layer is interpreted as granular material (alluvial and pyroclastic) as described in the driller’s log. Rock is described as being mixed volcanics.

Borehole 4D tested for 17 m³/h, with a TDS of 280 mg/l. During drilling, water was encountered in the shallow, granular aquifer (between 6 and 12 mbgs) that is in the high resistivity overburden, and in the weathered trachytes that are in the low to moderate resistivity bedrock. However, Borehole 4D has six screen intervals including these upper two zones, and the well is gravel packed from 121 mbgs to 6 mbgs. As such, it is impossible to accurately interpret from where water is being produced from the subsurface. The measured static water level at Borehole 4D is 7.86 mbgs.

ERT5 and ERT6 correlate well at their tie position.

ERT6

ERT6 (Figure 27) has no well ties, and has no co-located seismic refraction section. However, it does intersect and correlate well with lines ERT5 and ERT2. As such, the surficial high resistivity (>100 ohm-m) layer is interpreted to be unsaturated granular overburden. The underlying lower resistivity layer is interpreted to be saturated overburden, with the very low resistivity zone to the west possible having higher salinity. The lower resistivity rock zone (230 Northeast to 280 Northeast) may be more fractured and/or weathered, and possibly a good yielding aquifer.
ERT8

Resistivity section ERT8 intersects the 45 m deep Borehole 5; however, there is no available geological or well construction information from this borehole (Figure 28). There are no accompanying seismic sections or any intersecting ERT tie lines either.

Despite the lack of correlating information, ERT8 is about 300 m south of ERT5, ERT6, and Borehole 4D. Tentatively, then, we can apply similar interpretations from those northerly lines to ERT8 (Figure 28). As such, we can interpret ERT8 showing a few metres of high resistivity (>100 ohm-m), unsaturated, granular material overlying a 20 m or so thick layer of saturated overburden, all overlying weathered rock. Borehole 5 is a moderate yielding well, testing at 12.9 m³/h, with a TDS of 926 mg/l. There is no well construction information available, so it is not known from where the water is being produced. However, it is likely that much of the water is coming from the saturated overburden, with some contribution from weathered bedrock.

5.1.4 West of Kakuma 1 (Figures 16 and 29)

ERT15 and SEISMIC9

Geophysical survey lines ERT15 and the overlapping Seismic9 traversed “Kakuma 1 VES 1 Borehole” and two unidentified abandoned boreholes (Figure 29). Both ERT15 and Seismic9 are notably different from all other lines in Kakuma as there are no moderately high resistivities in ERT15 until approximately 90 mbgs, and the 2000 m/s seismic P-wave velocity contour is also notably deep in the Seismic9 section.

This section is also notable as Kakuma 1 VES 1 Borehole tested at a very high yield of 110 m³/h, though the well was not completed with a pump due to a reported very high fluoride concentration of 10.22 mg/l, and a high TDS concentration of 4377 mg/l. Nevertheless, water zones were encountered between 12 and 18 mbgs, and a “major strike” at 66 mbgs, while saline water was encountered only at 78 mbgs.

Unlike other boreholes drilled into rock, Kakuma 1 VES 1 Borehole drilled through 48 m of alluvium and 36 m of sedimentary rock before encountering volcanic rock (basalt). The combination of alluvium, mudrock, claystone, and siltstone likely explains the moderate to low resistivities recorded through the entire section ERT15. The top of basalt may be indicated by the 2000 m/s velocity contour, while the sedimentary rocks recorded by the driller likely have P-wave velocities less than 2000 m/s, possibly due to weathering or poor lithification.
5.2 Kalobeyei (Figure 17)

5.2.1 Laga Elelia

ERT9

ERT9 has no accompanying seismic line (Figure 30). ERT9 intersects an abandoned well for which there is no available information. However, immediately north of the Lokichogio Road, Earth Water Ltd. of Nairobi carried out 11 vertical electric soundings (Gicheruh, 2015) in Laga Elelia for UNHCR (Figure 8). This work was done from September 11 to 25, 2015. The soundings were carried out to AB/2 spacings approaching 300 m, providing an approximate depth of investigation likely exceeding 100 mbgs. The 11 soundings showed no prospective water well targets, and generally showed decreasing resistivity with depth, indicating increasing salinity and/or clay content with depth. No bedrock outcrop was observed at surface.

ERT9 shows low resistivity values along the entire section, and to depth. Only south of 400, below a depth of 40 mbgs, do resistivity values rise above 10 ohm-m. No prospective water well drilling targets are evident.

5.2.2 Laga Eskiriait

ERT14 and SEISMIC6

There were no available wells or drilling information to correlate with the geophysical data (Figure 31). However, 15 vertical electric soundings were carried out in Laga Eskiriait (Figure 8) in 2015 by Earth Water Ltd (Gicheruh 2015). No potential water well drilling targets were identified, and the soundings generally showed decreasing resistivity with depth, indicating increasing salinity and/or clay content with depth. Rock outcrop was observed at surface.

The 2000 m/s seismic velocity contour indicates that competent rock will be encountered at depths of between 20 and 40 mbgs. However, similar to the 2015 soundings carried out by UNHCR, resistivities are low along the entire section, and to depth, indicating high salinity and/or clay content. No prospective water well drilling targets are evident.

5.2.3 Laga Kangura

ERT11 and SEISMIC7

There were no available wells or drilling information to correlate with the geophysical data (Figure 32). However, Earth Water Ltd. (Gicheruh, 2015) identified a drilling target in Laga Kangura, immediately north of the highway, in the interpretation of their vertical electric sounding VES7 (Figure 9). The possible aquifer was interpreted as a fractured basalt of 25 ohm-m.

Rock outcrop was observed along the geophysics line. However, competent rock is interpreted to follow the 2000 m/s seismic P-wave velocity contour, which generally lies between 10 and 20 mbgs. At
250 m North on ERT11, there is a velocity low over what is clearly a vertical conductor. This feature is likely a fault, and may provide a good drilling target. As the interpreted fault is electrically conductive, drilling near the fault in possibly fractured rock, toward Laga Kangura, may be preferable to directly drilling in the fault. Overall, the resistivity values in ERT11 are moderate as compared to the low resistivity values in Elelia and Eskiriait lagas, suggesting that lower clay content and salinity makes the Kangura area a better prospect for water well drilling. Resistivities through the ERT11 section generally range between 10 and 30 ohm-m.

5.2.4 Kalobeyei Well (Figure 18)

ERT12

ERT12 crosses the Kalobeyei Well (Figure 33). The well is 68 m deep, and has a tested yield of 5 m$^3$/h. The well has reportedly been also tested at 22 m$^3$/h. Nothing is known about the geological descriptions from drilling of this well. Nor is there available information regarding the well construction. The Kalobeyei Well supplies water to local herders as well as the community of Kalobeyei. Outcrop appears along the survey line, including in the laga. In the laga, a clay likely derived from weathered volcanics was tested with the soil cell and the resistivity meter to be very conductive (i.e. very low resistivity) at 3 ohm-m.

At 350 m East, a vertical, moderately conductive feature immediately east of the laga is imaged. This feature is likely a fault associated with the laga. The large, higher resistivity feature at depth (orange to red, >55 ohm-m), is interpreted to be competent though possibly fractured rock. The Kalobeyei Well appears to have drilled an elevation low in the rock block. This elevation low may indicate a “blind” fault within the block. Blind faults do not come to surface. Lithologies with resistivities in the range of 20 to 50 ohm-m (light blue to yellow) are interpreted to be weathered volcanics, possibly saturated. The low conductivity, blue, near surface layer is interpreted to be clayey, weathered volcanics.

ERT10 and SEISMIC8

There are no wells located along this survey line (Figure 34). Outcropping rock is visible along the survey line.

ERT10, collected 90 m south of the Kalobeyei Well (Figure 18), and 120 m south of ERT12, is very similar in appearance to ERT12. The large, higher resistivity (>70 ohm-m, red to pink) feature in the center of the section is interpreted to be a block of more competent rock. This is supported by the 2000 m/s velocity high determined from the seismic P-wave velocity survey. As along ERT12, the resistive bedrock block appears to be split by a lower resistivity depression, possibly a fractured or weathered zone, and possibly associated with a fault.

The possible fault identified in the ERT12 and ERT13 survey lines appears to be much wider in ERT10; we have extrapolated this fault to be continuing immediately west of the interpreted resistive bedrock block and associated with the seismic velocity low. Lithologies with resistivities in the range of 20 to 50 ohm-m (light blue to green) are interpreted to be weathered volcanics, possibly saturated. The undulating, low velocity (blue, <10 ohm-m) layer is interpreted as clayey, weathered volcanics.
ERT13 and SEISMIC10

The resistivity section from this survey line (Figure 25), located about 120 m north of ERT12, and 240 m north of ERT10, appears similar to these other two cross-sections. The large, higher resistivity (>70 ohm-m, red to pink) feature in the center of the section is again interpreted to be a block of more competent rock. A seismic velocity high is associated with the west portion of this block. As in ERT10 and ERT12, the resistive bedrock block appears to be split by a lower resistivity depression, possibly a fractured or weathered zone, and possibly associated with a fault.

The possible fault identified in the ERT10 and ERT12 survey lines is very clear in ERT13, and located at 350 m East. This feature dips steeply to the west. Lithologies with resistivities in the range of 20 to 50 ohm-m (light blue to green) are interpreted to be weathered volcanics, possibly saturated.

The undulating, low velocity (blue, <10 ohm-m) near surface layer is interpreted as clayey, weathered volcanics, and is approximately sitting on the 2000 m/s seismic velocity contour.
6. CONCLUSION: POSSIBLE DRILLING TARGETS

Proposed drilling targets described below are referenced to the line positions of the referenced figures (with associated georeferenced positions on the maps and in Tables C and D). The locations, line positions, and georeferenced positions of proposed drilling targets in both lat/long and UTM coordinates are summarized in Tables C and D.

In the Kakuma area, targeting locations with thick, granular overburden, and minimizing or eliminating penetration into bedrock, may help reduce fluoride concentrations. However, the precise source of elevated fluoride concentrations, while presumed to be volcanic rock, is uncertain. In Kalobeyei, depths of drilling may be expected to be similar to the Kalobeyei Well, about 70 m depth, or when a sufficient yielding aquifer is intersected, or when drilling has completely drilled through the weathered and/or fractured rock.

6.1 Kakuma

In the area of the Kakuma Refugee Camp, preferred drilling locations are based on:

1. thick overburden with moderate to high resistivities (>15 ohm-m); and
2. interpreted weathered or fractured rock.

All noted possible drilling locations are referenced to the ERT lines. Possible drilling locations include:

1. Laga Tarach South, ERT1 (Figure 20): 950 to 1175 m North, thicker overburden and weathered rock.
2. Laga Tarach South, ERT3 (Figure 21): 160 to 280 m Northwest, 750 to 1300 m Northwest, weathered rock.
3. Northern Well Field, ERT7 (Figure 24): Granular overburden at 60 m South; thick overburden at 325 m and 405 m South; seismic velocity low and granular overburden from 550 m to 675 m South.
4. Northern Well Field, ERT4 (Figure 23): 275 to 350 m, 400 m to 625 m, thick, granular overburden and weathered rock.
5. Central Well Field, ERT2 (Figure 25): 150 to 650 m West. Saturated overburden thickness likely increases moving west. Zones between 150 and 250 m West, and west of 400 m West may be preferred areas due to interpreted greater extent of weathering in rock.
6. Central Well Field, ERT5 (Figure 26): 75 to 130 m North, and 200 to 300 m North target thicker, saturated, granular overburden overlying interpreted weathered volcanic rock. The moderately resistive (between 50 and 60 ohm-m), interpreted basalt body at depth may be an aquifer if it is weathered or fractured, but this is not at all clear from the results; nor is there any available drilling information into this body.
7. Central Well Field, ERT6 (Figure 27): 225 m to 280 m East will likely penetrate weathered volcanics. Saturated, granular overburden thickness is thinner than on ERT5. As with ERT5, it is speculation whether or not the moderately resistive (between 50 and 60 ohm-m), interpreted basalt body at depth may be a weathered or fractured rock aquifer.

8. Central Well Field, ERT8 (Figure 28): Due to a lack of well control; ERT tie lines; an absence of a companion seismic refraction line; a highly speculative bedrock contact; and an absence of thick, granular overburden, possible water well locations along ERT8 are highly speculative. Nevertheless, a preferred zone may be between 300 and 350 m North where the interpreted overburden (i.e. top 40 m) is slightly more resistive (and therefore possibly lower clay content) than elsewhere along the line.

9. West of Kakuma 1, ERT15 (Figure 29): Given the very high water well production test yield at 305 m North (Kakuma 1 VES1 Borehole), and the very thick section of weathered bedrock described in the driller’s description, as well as both the low resistivities of the ERT section and the low P-wave velocities of the seismic section, attempting to again install a water well near this location may be considered. Borehole geophysical logging with gamma and resistivity tools, and halting drilling before reaching the saline aquifer at depth, may significantly improve water quality. It is not certain where in the section is the source for the very high fluoride concentrations. On site fluoride analyses at Kakuma could greatly assist in determining whether to complete or abandon a productive borehole, as well as assist in determining the geologic source of high fluoride concentrations. Salinity monitoring of returning drilling mud, while drilling, is also recommended.
Table C  Possible Drilling Targets in Kakuma Exploration Area (Datum: WGS84, Zone: 36 N)

<table>
<thead>
<tr>
<th>Area</th>
<th>ERT Line #</th>
<th>Line Position</th>
<th>Georeferenced Pairing Coordinates</th>
<th>Geologic Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lat/Long</td>
<td>UTM (Easting/Northing)</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>Laga Tarach South</td>
<td>ERT1 (Figure 20)</td>
<td>950 to 1175 m North</td>
<td>3.713446/34.85862 to 3.715445/34.85842</td>
<td>706423/410670 to 706400/410891</td>
</tr>
<tr>
<td>Laga Tarach South</td>
<td>ERT3 (Figure 21)</td>
<td>160 to 280 m Northwest</td>
<td>3.715932/34.858682 to 3.716693/34.857919</td>
<td>706429/410945 to 706344/411029</td>
</tr>
<tr>
<td></td>
<td></td>
<td>750 to 1300 m Northwest</td>
<td>3.719557/34.854846 to 3.722937/34.85128</td>
<td>706002/411345 to 705605/411718</td>
</tr>
<tr>
<td>Northern Well Field</td>
<td>ERT7 (Figure 24)</td>
<td>60 m South</td>
<td>3.77845/34.829055</td>
<td>703123/417852</td>
</tr>
<tr>
<td></td>
<td></td>
<td>325 m South</td>
<td>3.776108/34.829131</td>
<td>703132/417593</td>
</tr>
<tr>
<td></td>
<td></td>
<td>405 m South</td>
<td>3.775411/34.829175</td>
<td>703137/417516</td>
</tr>
<tr>
<td></td>
<td></td>
<td>550 to 675 m South</td>
<td>3.774082/34.829136 to 3.772952/34.829196</td>
<td>703133/417369 to 703140/417244</td>
</tr>
<tr>
<td>Northern Well Field</td>
<td>ERT4 (Figure 23)</td>
<td>275 to 350 m</td>
<td>3.771159/34.830381 to 3.771846/34.8304</td>
<td>703272/417046 to 703274/417122</td>
</tr>
<tr>
<td></td>
<td></td>
<td>400 to 625 m</td>
<td>3.772244/34.830374 to 3.774024/34.83108</td>
<td>703271/417166 to 703349/417363</td>
</tr>
<tr>
<td>Area</td>
<td>ERT Line #</td>
<td>Line Position</td>
<td>Georeferenced Pairing Coordinates</td>
<td>Geologic Targets</td>
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<td>-----------------------</td>
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<td>-------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Central Well Field</td>
<td>ERT2</td>
<td>150 to 650 m West</td>
<td>Lat/Long: 3.755719/34.836902 to 3.75344/34.84138, UTM: 704000/415340 to 704498/415089</td>
<td>Interpreted greater extent of weathering in rock in zones between 150 to 250 m West and west of 400 m West</td>
</tr>
<tr>
<td>Central Well Field</td>
<td>ERT5</td>
<td>75 to 130 m North</td>
<td>Lat/Long: 3.753207/34.835798 to 3.753696/34.835664, UTM: 703878/415062 to 703863/415116</td>
<td>Thicker, saturated, granular overburden overlying interpreted weathered volcanic rock</td>
</tr>
<tr>
<td>Central Well Field</td>
<td>ERT6</td>
<td>200 to 300 m North</td>
<td>Lat/Long: 3.754248/34.835476 to 3.755081/34.835127, UTM: 703842/415177 to 703803/415269</td>
<td>Will likely penetrate weathered volcanics (Thinner than on ERT5)</td>
</tr>
<tr>
<td>Central Well Field</td>
<td>ERT8</td>
<td>225 to 280 m East</td>
<td>Lat/Long: 3.755096/34.836387 to 3.755511/34.836667, UTM: 703943/415271 to 703974/415317</td>
<td></td>
</tr>
<tr>
<td>Central Well Field</td>
<td>ERT15</td>
<td>Near Kakuma 1 VES 1 Borehole</td>
<td>Lat/Long: 3.742763/34.831627 to 3.747743/34.832951, UTM: 703417/413906 to 703563/414457</td>
<td>Interpreted overburden is slightly more resistive</td>
</tr>
<tr>
<td>West of Kakuma 1</td>
<td></td>
<td></td>
<td></td>
<td>See Kakuma Results section #9</td>
</tr>
</tbody>
</table>
6.2 Kalobeyei

In the area of Kalobeyei, rock is interpreted to be close to surface, though it may be highly weathered. Both Elelia and Eskiriait lagas appear to be too low resistivity, and therefore too high in either salinity or clay content, to offer likely water well drilling targets. As such, possible drilling targets are identified by:

1. faulting (not necessarily drilling into faults, but into possible fractured zones near faults, and in proximity to possible recharge from a laga), including drilling into the saddle of the same fault block into which the existing Kalobeyei Well is drilled;

2. zones of thicker weathering or fracturing, but with resistivities exceeding 15 ohm-m so as to avoid zones with very high clay content and/or salinity; and

3. the low velocity and low resistivity zone in the saddle of the same fault block into which the existing Kalobeyei Well is drilled, and which appears on all three sections collected close to the Kalobeyei Well, along with drilling near the fault zone highlighted in Figure 18.

All noted possible drilling locations are referenced to the ERT lines. Possible drilling locations include:

1. Kangura Laga, ERT11 (Figure 32): 270 m to 300 m South. This zone is characterized by a likely fault at 250 m South. A preferred drilling target may be 20 or so metres south of the fault, say between 270 m and 300 m South, between the likely fault and Laga Kangura, but close enough to the fault to take advantage of likely fracturing. It is not clear if the fault itself would be a good target as it is very low resistivity, and therefore likely clayey (i.e. low hydraulic conductivity) and potentially saline. Moderate resistivity zones (green) should be targeted.

2. Kalobeyei Well area, ERT12 (Figure 33): 130 to 150 m East, and 370 m East. The preferred drilling target may be the moderate resistivity zones (green) at around 370 m East (in close proximity to the interpreted fault), and between 130 and 150 m East (immediately west of the interpreted fault block). The existing Kalobeyei Well may be drilled into a “blind” fault (i.e. a fault that does not come to surface) in the resistive block as suggested by Figure 33. This interpreted fault may explain the water yield in the Kalobeyei Well.

3. Kalobeyei Well area, ERT10 (Figure 34): 260 m and 355 m East. 260 m East is a target immediately east of the fault, but near the possible recharge provided by the laga. 350 m East targets the resistivity low in the interpreted fault block.

4. Kalobeyei Well area, ERT13 (Figure 35): 230 m to 265 m East, and 330 to 340 m East. 230 m to 265 m East targets the low resistivity “saddle” in the bedrock block at 250 m East; 330 m to 340 m East targets the zone immediately east of the fault block, but in close proximity to possible recharge provided by the laga.
Table D  Possible Drilling Targets in Kalobeyei Exploration Area (Datum: WGS 84, Zone: 36 N)

<table>
<thead>
<tr>
<th>Area</th>
<th>ERT Line #</th>
<th>Line Position</th>
<th>Georeferenced Pairing Coordinates</th>
<th>Geologic Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elelia</td>
<td>ERT9 (Figure 30)</td>
<td>N/A</td>
<td>N/A</td>
<td>No Targets</td>
</tr>
<tr>
<td>Eskiriait</td>
<td>ERT14 (Figure 31)</td>
<td>N/A</td>
<td>N/A</td>
<td>No Targets</td>
</tr>
<tr>
<td>Kagura</td>
<td>ERT11 (Figure 32)</td>
<td>270 to 300 m South</td>
<td>3.752147/34.703427 to 3.751876/34.70348</td>
<td>Fractured rock close to fault, between fault and Laga Kangura</td>
</tr>
<tr>
<td>Kalobeyei well, North of Highway</td>
<td>ERT12 (Figure 33)</td>
<td>130 to 150 m East</td>
<td>3.755926/34.66658 to 3.755889/34.666751</td>
<td>Moderate resistivity zone West of fault block</td>
</tr>
<tr>
<td></td>
<td></td>
<td>370 m East</td>
<td>3.755488/34.668685</td>
<td>Moderate resistivity zone East of interpreted fault, straddling fault in proximity to laga</td>
</tr>
<tr>
<td>Kalobeyei well, South of Highway</td>
<td>ERT10 (Figure 34)</td>
<td>260 m East</td>
<td>3.754495/34.6679</td>
<td>Proximity to fault with possible recharge from laga</td>
</tr>
<tr>
<td></td>
<td></td>
<td>355 m East</td>
<td>3.754294/34.668746</td>
<td>Low resistivity saddle of fault block</td>
</tr>
<tr>
<td>Area</td>
<td>ERT Line #</td>
<td>Line Position</td>
<td>Georeferenced Pairing Coordinates</td>
<td>Geologic Targets</td>
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<td>-------------------------------------------</td>
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</tr>
<tr>
<td>Kalobeyei well, north of Highway</td>
<td>ERT13 (Figure 35)</td>
<td>230 to 265 m East</td>
<td>Lat/Long: 3.756937/34.667635 to 3.756828/34.667932</td>
<td>UTM (Easting/Northing): 685196/415437 to 685229/415425</td>
</tr>
<tr>
<td></td>
<td></td>
<td>330 to 340 m East</td>
<td>Lat/Long: 3.756646/34.66849 to 3.756618/34.668571</td>
<td>UTM (Easting/Northing): 685291/415405 to 685300/415402</td>
</tr>
</tbody>
</table>
7. RECOMMENDATIONS

1. The geology and hydrogeology of Kakuma and Kalobeyei are complex. While the combination of ERT and seismic refraction are a vast improvement as an exploration approach as compared to the typically run vertical electrical soundings (VES), there remains considerable uncertainty in providing drilling targets. Given the shallow nature of water wells in the area, the almost complete absence of electrical noise generating infrastructure, and the substantial cost of drilling water wells, nuclear magnetic resonance (NMR) soundings are recommended as an additional survey to prioritize drilling sites, as NMR is sensitive only to water.

2. In future drilling programs, screening of selective aquifers instead of screening and interconnecting all aquifers would assist in developing an improved geochemical, hydrogeophysical, and overall hydrogeological understanding of the aquifer systems.

3. Borehole geophysical logging to characterize the physical properties (e.g. electrical resistivity, electrical conductivity, seismic velocity, etc.) of aquifers, aquitards, various volcanic lithologies, saline zones, etc., would greatly improve the understanding of the aquifer systems of the Kakuma and Kalobeyei areas, provide physical properties information to improve interpretations and designs of surface geophysical surveys, and assist in understanding the hydrochemical and hydraulic behaviour of existing and future wells.

4. The use of PVC casing instead of steel casing would allow cased hole logging with induction and magnetic susceptibility logging tools, as well as completely avoid problems with well corrosion. If PVC casing were used, induction (i.e. formation conductivity) logging would allow cased hole monitoring of changes in formation salinity as well as physical properties logging of abandoned holes. Cased hole logging has the advantage over water quality testing of monitoring salinity changes behind the blank pipe as well as along the screened intervals.

5. The use of borehole camera logging to inspect and monitor well completions would be particularly important if problems with some low producing wells are, in fact, due to problems with the well, rather than the formation. Borehole camera logging would also provide information on the extent of corrosion to steel pipe and screens. Finally, borehole camera logging would provide a means of verifying screen intervals.

6. The improvement of archiving of drilling, completion, and geochemical data is strongly recommended. More information from existing and future wells would greatly enhance the ability to interpret nearby geophysical surveys, plan drilling programs, plan screen intervals, understand the aquifer system, and cost-effectively manage ongoing exploration programs.

7. Developing a consistent and meaningful well nomenclature would greatly assist in confidently interpreting the proper well data for the correct well. There is significant confusion in well identification.

8. The maximizing of information from abandoned wells, and the capping rather than the destruction of abandoned wells, would facilitate the maximizing of information gathering at little
risk. For instance, abandoned wells could continue to be geophysically logged or have their water levels monitored. Water chemistry could be monitored at abandoned wells.

9. More reliable and rapid hydrochemical analyses would provide significant improvements to the hydrochemical, hydrogeophysical, and hydrogeological understanding of the area. For instance, on-site fluoride analyses could provide immediate certainty to water quality where otherwise a high production well might be needlessly abandoned, or water production might be postponed until two or more matching fluoride analyses were produced. On-site water chemical analyses would allow multiple tests to be rapidly performed so as well completion decisions could be made in a timely manner, even while a drilling rig was still on site.
8. REFERENCES


IsraAID. http://www.israaid.co.il/


UNICEF. April 2006. Map 3A, Turkana District, Spatial Distribution of Water Sources.
Figures
Note: Figure from Sottas, 2013
a) General structures of the region of interest and location of the Turkana Depression.

b) Focus on the eastern branch of the EARS, the Kenyan rift and location of Kakuma.

Vetel et al., 2005

Note: Figure from Soltas, 2015
Note: Figure from Sottas, 2013
Moglia Range  
Lotikipi Basin  
Lokwanamoru Range

- Volcanic derived fluvial sediments
- Rhyolites and Olivine basalts with interbedded tuffaceous rocks
- Possible sub-volcanic sedimentary rocks
- Precambrian crystalline basement

Note: Figure from Sottas, 2013
Note: Figure from Sottas, 2013
Note: Figure from Gicheruh, 2015
<table>
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<th>Resistivity (Ωm)</th>
<th>Latitude (N)</th>
<th>Longitude (L)</th>
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Note: Figure from Gicheru, 2015
Note: Figure from Gicheruh, 2015
WEST

EAST

ERT LINE 12

BEDROCK OUTCROP
KALOBEYEI WELL
DEPTH: 50 MEGS
TESTED YIELD: 5.02 m³/h
LAGA - ROCKY SLOPE

POSSIBLE BLIND FAULT

INTERPRETED FAULT ZONE

ELEVATION (m)

560
580
600
620
640
660
680

5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95

ERT LINE 12

ELECTRICAL RESISTIVITY
(ohm-m)

LEGEND

ERT survey line positions in UTM Zone 36N / WGS84 Datum
Water well location
Site feature intersection or close to survey line

Inset Map

Water Well Location
Observed locations of outcrop outside of lagas
Laga location based on GPS mapping
ERT survey line locations with distance in metres (m)
Seismic survey line path
Interpreted fault zones from ERT and seismic

FIELD PARAMETERS:

Coordinates Referenced to UTM NAD83, Zone 36N

Scale 1:2000

GEOGRAPHY AND LANDSCAPE:

KARIMA AND KALOBEYEI

2016 GEOPHYSICAL INVESTIGATION AT KALOBEYEI, KENYA

ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT)

KALOBEYEI WELL: ERT LINE 12

FILE: KEN030DGKJKMA.Kenya EGS GEM Geophysics Program 3D/3DRegmap/Kalob/ERT12.fm.PDF
Photographs
Note: ERT Line 1, South End near UNHCR Borehole

Note: Seismic Line 1, PEG-40 Seismic Source, South of Kakuma Bridge
Note: ERT Line 2, Central Well Field, Laga Tarach

Note: Seismic Line 4, PEG-40 Seismic Source, Near Hand Wells in Laga Tarach
Note: West End of ERT Line 3, Near Boreholes 10 and 11
Note: Seismic Line 3, GPS Data Collection near Borehole 7A
Note: ERT Line 5, Near Borehole 4D
Note: ERT Line 6, Near Hand Pump, Facing Borehole 4B
Note: ERT Line 7, Northern Well Field, Near Borehole 12

Note: Seismic Line 5, PEG-40 Seismic Source, West of IOM Borehole
Note: ERT Line 8, South of Borehole 5
Note: ERT Line 9, Near Laga Elelia
Note: ERT Line 10, Kalobeyei Well, South of Highway

Note: Seismic Line 8, Hammer and Plate Seismic Source, Kalobeyei Well, South of Highway
Note: ERT Line 11, Laga Kangura, Facing North

Note: Seismic Line 7, Seismic Laptop, Laga Kangura, Facing South
Note: ERT Line 12, Kalobeyei Well, North of Highway
Note: ERT Line 13, North of Kalobeyei Well

Note: East End of Seismic Line 10, GPS Data Collection

GEOSCIENTISTS WITHOUT BORDERS IN COOPERATION WITH THE UNITED NATIONS AND ISRAAID
2016 GEOPHYSICAL INVESTIGATION AT KALOBEYEI, KENYA
ERT LINE 13 AND SEISMIC LINE 10
(Figure 35)
Note: ERT Line 14, Laga Esikirait
Note: ERT Line 15, South of Borehole 110

Note: Seismic Line 9, Near Borehole 110