Summary of Findings from PTA Drilling and Testing Program
Under Cooperative Agreement W9126G-17-2-0001
Remaining Work to be Completed
Recommendations for Development of a Water Supply Well
August 2019

Executive Summary: Two small diameter test holes were drilled on USARPAC lands in the Humu'ula Saddle region of Hawaii Island in an effort to better define the underlying hydrogeology of the south flank of Mauna Kea volcano. The **PTA-2** test hole was drilled in the cantonment of Army Garrison PTA to a depth of 5786' (1764 m) below ground surface (bgs); the **KMA-1** test hole was drilled in the Keamuku Maneuvers Area to a depth of 5024' (1531 m) bgs. Both test holes encountered groundwater at substantially higher elevations than had previously been anticipated. **PTA-2** documented two significant aquifers; testing on the deeper (1800'; 549 m bgs) aquifer demonstrated both quality and productivity sufficient to serve as a drinking water source. **KMA-1** identified a series of confined aquifers and a stable water table at a depth of ~3300' (1000 m) bgs. Both test holes also documented evidence of underlying geothermal activity within Mauna Kea.

Based on the findings of the test holes, a recommendation is made to proceed to the development of a production well to meet the needs of Army Garrison PTA. If testing can demonstrate that the upper aquifer has the capacity and quality sufficient to the needs of PTA, then development of that aquifer is recommended; alternatively, drilling into the deeper aquifer would still provide sufficient capacity and manageable quality to serve as a water source. It is also recommended that the **PTA-2** borehole be maintained as a monitoring well to allow the Army and the State of Hawaii to track and manage any impacts of developing either aquifer as a drinking water source.

Background

The objective of the Humu'ula Saddle Drilling Project was to determine whether a significant, accessible groundwater resource was present in the Humu'ula Saddle region below lands occupied by the Pohakuloa Training Area. The overall strategy applied was to drill two small-diameter test holes using diamond wireline coring technology and to conduct a limited sampling and testing program on each well to determine quality of the water as well as other parameters relevant to the long term viability of the identified water resources as a potable water source for the Pohakuloa Training Area.

Drilling Program

The first borehole drilled, designated **PTA-2**, is located within the cantonment of Army Garrison PTA (Figure 1). The elevation of the well site is 6375' (1943 m) above mean sea level (amsl) and the depth drilled was 5786’ (1764 m) for a bottom hole elevation of 589’ (179 m) amsl. In order to stabilize the shallow interval of the hole, a PQ casing string was installed at a depth of 2918’ (889 m) below ground surface (bgs).

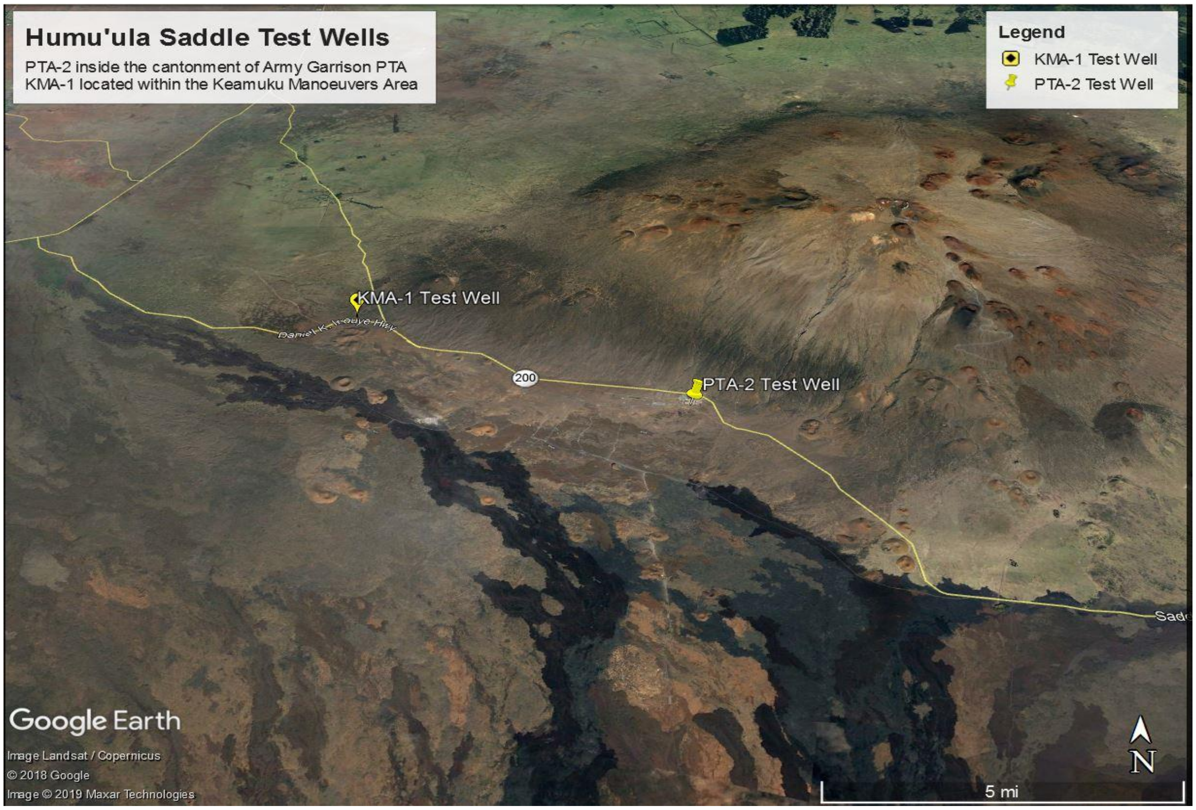

Figure 1. Showing the approximate locations of the two test borings conducted in the Humu’ula Saddle of Hawaii Island

The second test hole, designated **KMA-1**, was drilled from an elevation of 5290’ (1612 m) amsl to a total depth of 5024’ (1531 m) for a bottom hole elevation of 266’ (81 m) amsl; for this hole, PQ casing was set at a depth of 1008’ (307 m) bgs. Both test holes were drilled using diamond wireline core drilling technology with continuous recovery of core. Core recovery for both holes was in excess of 95%.

Geologic Results

The most notable features of the core recovered from the **PTA-2** borehole showed that the near surface geology is made up of dominantly alluvial material (e.g glacial outwash from the Mauna Kea slope) underlain by in-place lava flows and ash beds. One significant feature encountered was a thick (~95’; 29 m) sill – a dense intrusive body of rock – within a cinder/tephra bed believed to be part of the Pu’u Pohakuloa cinder cone located NW of the drill site. The underlying lava flows were mixed pahoehoe and a’a flows with occasional ash beds interspersed among the flows. The flow units were intensively fractured and few solid cores were recovered with a length more than 3 feet (1 m); cores from other areas of Hawaii Island have not shown this degree of internal fracturing in the shallow formation. These flows and ash beds showed greater and lesser degrees of weathering with some apparently having sufficiently weathered to have significant amounts of clay within the ash matrix. At increasing depths, the flows became progressively compacted – with some of the massive units showing evidence of high horizontal stresses by fragmenting into thin plates (disking) as they were drilled. Below about 3500' (1067 m) the rock matrix appeared to be fully compacted with the clinker zones (associated with a'a lava flows) having become pancaked with a nearly complete loss of macro-pores larger than ~1 mm.

The cores recovered from the **KMA-1** test hole did not encounter the alluvial layer that was present at the **PTA-2** site and went directly to a sequence of pahoehoe and a'a lava flows interspersed with ash beds. The relative frequency of pahoehoe and a'a flows in **KMA-1** was significantly lower (30% vs 51%) than was found in the **PTA-2** test hole; this is likely due to the greater distance between the KMA site and former caldera of Mauna Kea than that for the **PTA-2** site. Other relevant features were that the lavas beneath this site showed significantly lower (slightly less than half) the number of intrusive (dike) intervals than the **PTA-2** site, but did show evidence that a long-lived dike may have passed nearby resulting in intensive oxidation of a long interval of flows. It is possible that the source of this dike was the Pu'u Ke'eke'e cinder cone complex since this zone still showed mild residual thermal activity.

Hydrologic Results

The hydrologic findings were distinct for each test hole. The **PTA-2** hole entered its first saturated interval at a depth of approximately 700' (213 m) below ground surface or about 5675' (1730 m) amsl; saturation continued to a depth of about 1200' (366 m) depth (5175' [1577 m] amsl) where a clay-rich ash interval was breached and the water level in the borehole progressively dropped until there was no standing water level in the drill string. As coring continued, a second saturated interval was encountered at a depth of 1800' (549 m) depth (4575' [1394 m] amsl) that continued to the total depth drilled (**Figure 2**).

Prior geophysical surveys (**Figure 3**) conducted across the Humu'ula Saddle had measured the electrical resistivity of the subsurface rocks across the Saddle region; the results of those surveys showed a broad conductive zone several hundred meters below the ground surface that extended across much of the Saddle with a narrow low-resistivity ridge immediately below PTA. We interpret our water level and resistivity findings to indicate that the narrow ridge-like resistivity low was associated with the shallower perched aquifer whereas the deeper saturated zone is part of a much larger aquifer that produced the deeper broad conductive region detected by the resistivity surveys. Another aspect of the geophysical survey results relevant to the hydrogeology of this region was that the measured resistivities continued to decrease with increasing depth below the ground

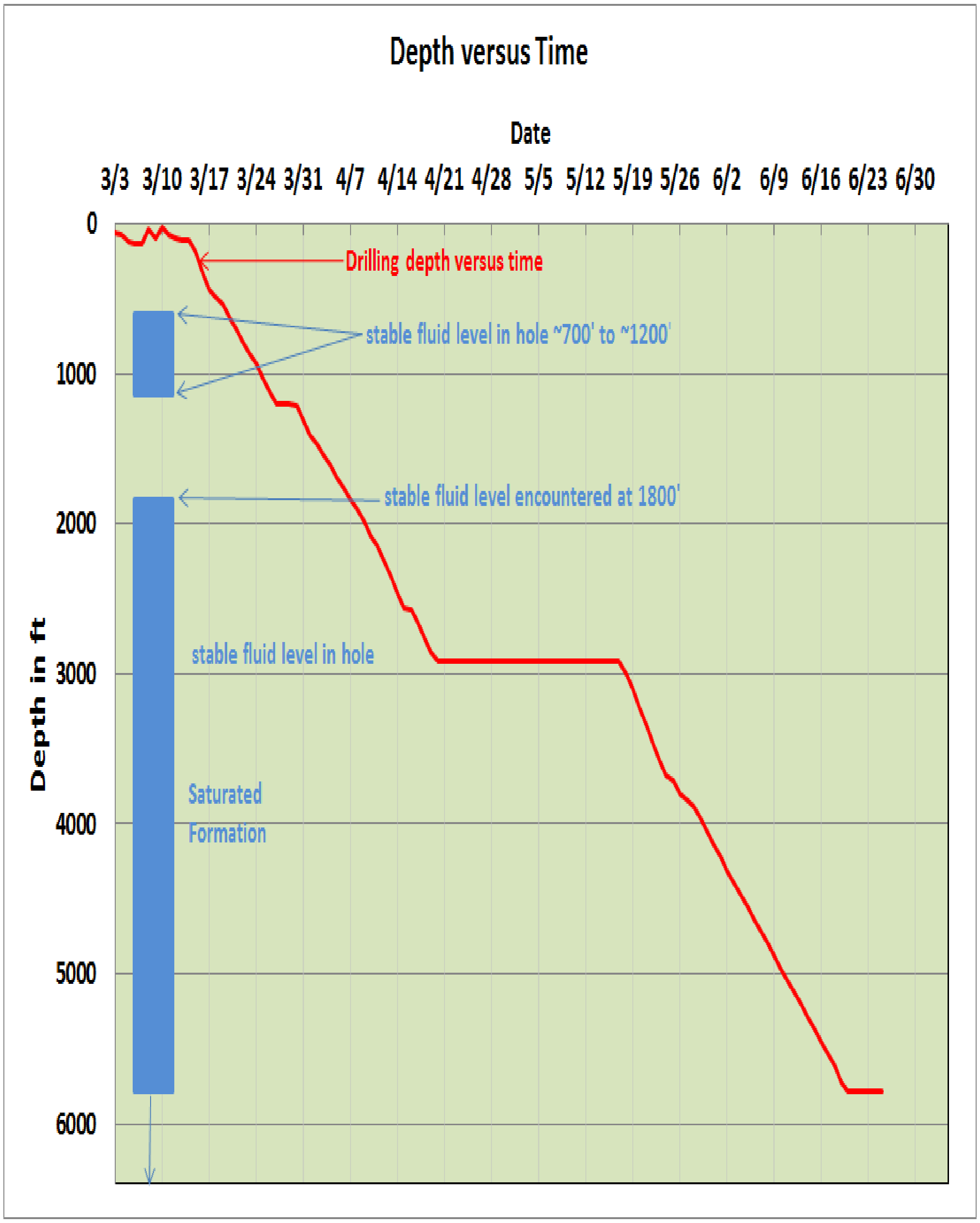

Figure 2. Drilling progress and observed fluid levels in the **PTA-2** borehole

surface. Those findings correspond to progressively increasing temperatures that were encountered as the hole was deepened. Although drilling was terminated when the maximum temperature (during drilling) measured in the borehole reached 210 °F (99 °C), the equilibrium temperatures in the borehole later reached a maximum of 280 °F (140 °C) at bottom hole.

The hydrologic findings in the **KMA-1** borehole were both similar and dissimilar to those in the **PTA-2** hole. They were similar in the sense that we found saturated formations at

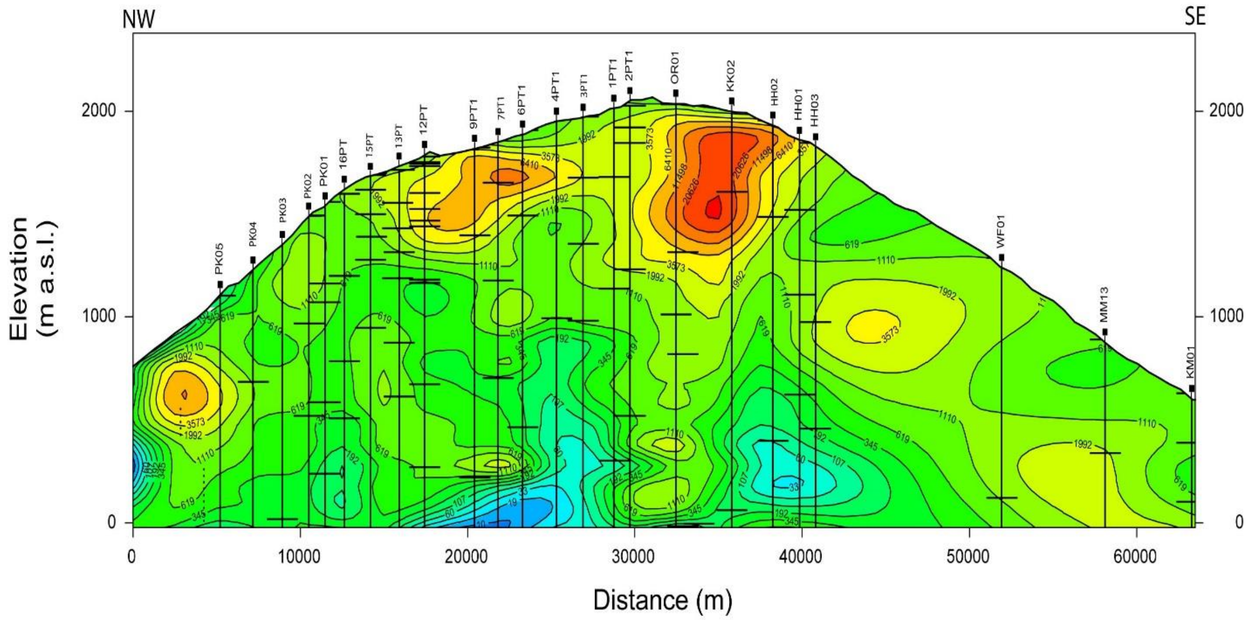

Figure 3. Presents a resistivity cross section of the Humu'ula Saddle from surface to sea level. The warm colors are highly resistive, the cooler colors are less resistive. The less resistive formations are those most likely to be saturated with water.

much higher elevations in the **KMA-1** hole than previous models had indicated would be found: the first saturated formation was encountered at a depth of ~1050' (320 m) or 4240' (1292 m) amsl. However, the water in that saturated interval was under significant hydrostatic pressure, and that pressure sent water up the drill string by ~600' (183 m), but was present over a much shorter interval of drilling. These pressurized aquifers are formed when the geology has low permeability layers interspersed with more permeable layers; often these layers extend to higher elevations and, as water accumulates at the higher elevations, pressures increase within the permeable layers confined by the (upper) capping and (lower) perching zones. After drilling another 70', the perching layer was breached and the water levels in the borehole dropped to the bit and remained absent until we reached a depth of ~2000' where a second pressurized interval was encountered. From that depth to the bottom of the hole, water levels successively rose and fell in the borehole as confining formations (e.g. ash beds) were penetrated (**Figure 4**). At one point, we observed water levels to rise as much as 3500' (1067 m) above the depth of the formation penetrated and,

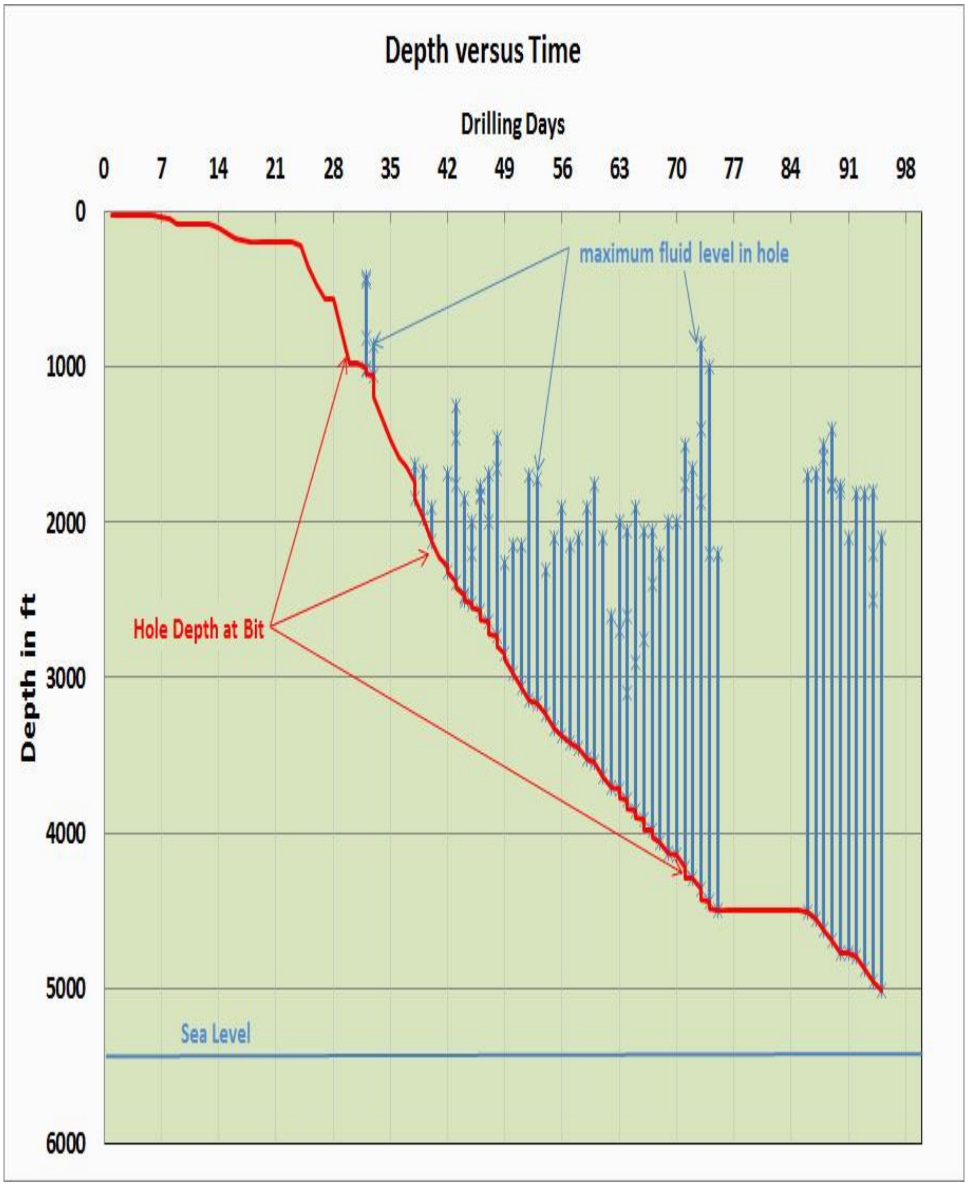

Figure 4. Showing drilling progress and borehole water levels during drilling. The red line represents the depth of the hole on a given drilling day; the vertical blue lines show the measured water level in the borehole. The gap between day 75 and 85 was a break in the drilling when water level measurements were not made.

hence, had an excess hydrostatic pressure of about 1500 psi. These confined, pressurized aquifers appeared to have been relatively small as pressures did bleed off. After drilling had been suspended for several months, we returned to collect water samples and found that the shallowest stable water table was at a depth of ~3,300' (1006 m) or an elevation of about 1990' (606 m) amsl.

Well Testing Results

After confirmation of accessible water in the **PTA-2** hole, a testing program was designed to allow us to determine whether water was suitable as a potable drinking water source. It should be understood that collection of formation fluid samples during a drilling program can be problematic: substantial volumes of water are injected into the borehole during drilling (to flush cuttings away from the bit and to cool the bit). That injected water will mix with the formation fluids and any downhole sampling will need to first purge those mixed fluids from the hole by pumping. A second issue for this well was that, because the shallow formation was extremely unstable, we were unable to pump water from the hole until a casing string had been installed. Hence, the testing program was designed to collect data from the deeper formations first and the shallower formations afterward. As noted in the discussion of the drilling program, casing was set in the **PTA-2** hole to a depth of 2918' (889 m) bgs with open (uncased) hole below that depth.

The following results were obtained by the testing program on the **PTA-2** borehole:

Temperature: Temperatures were measured during drilling using a recording temperature tool that was installed in the core tube. These measurements were initiated as soon as it became apparent that temperatures were increasing in the hole (this area had never been identified as having potential geothermal resources and the increasing temperature was one of the significant discoveries of this borehole). Although these measurements were recognized as having been affected by circulation of drilling fluids, it was a method of insuring that temperatures were low enough to allow drilling to safely continue. **Figure 5** shows a plot of the borehole temperatures collected during drilling as well as temperatures measured weeks to months after drilling was terminated and sufficient time had been allowed for the borehole temperatures to come to equilibrium. In an abundance of caution, a decision was made to terminate drilling when the drilling temperature approached the boiling point of water (212 °F/ 100 °C); at the depths and hydrostatic pressures involved, there was no chance that the water would spontaneously boil at these temperatures, but, in the unlikely event that a pressurized aquifer could have sent water up the wellbore, we believed that the boiling pressures at this temperature would be easily handled by injection of quench water from the surface. After termination of drilling and a period of stabilization of the borehole temperatures, the maximum temperature at the bottom of the hole was estimated to be ~280 °F (140 °C). (Again, in an abundance of caution, we injected a dense drilling fluid into the bottom of the hole to preclude any unmonitored internal circulation in the deeper formations; that dense drilling fluid gradually became more viscous and so we were not able to conduct temperature surveys over the entire depth of the hole.) The temperature gradient over the lower 2130' (650 m) of the borehole was approximately 165 °C/km (10°F/100'); this is about 10 times the (non-volcanic) temperature gradient in Hawaii's basalts. We interpret these results to indicate

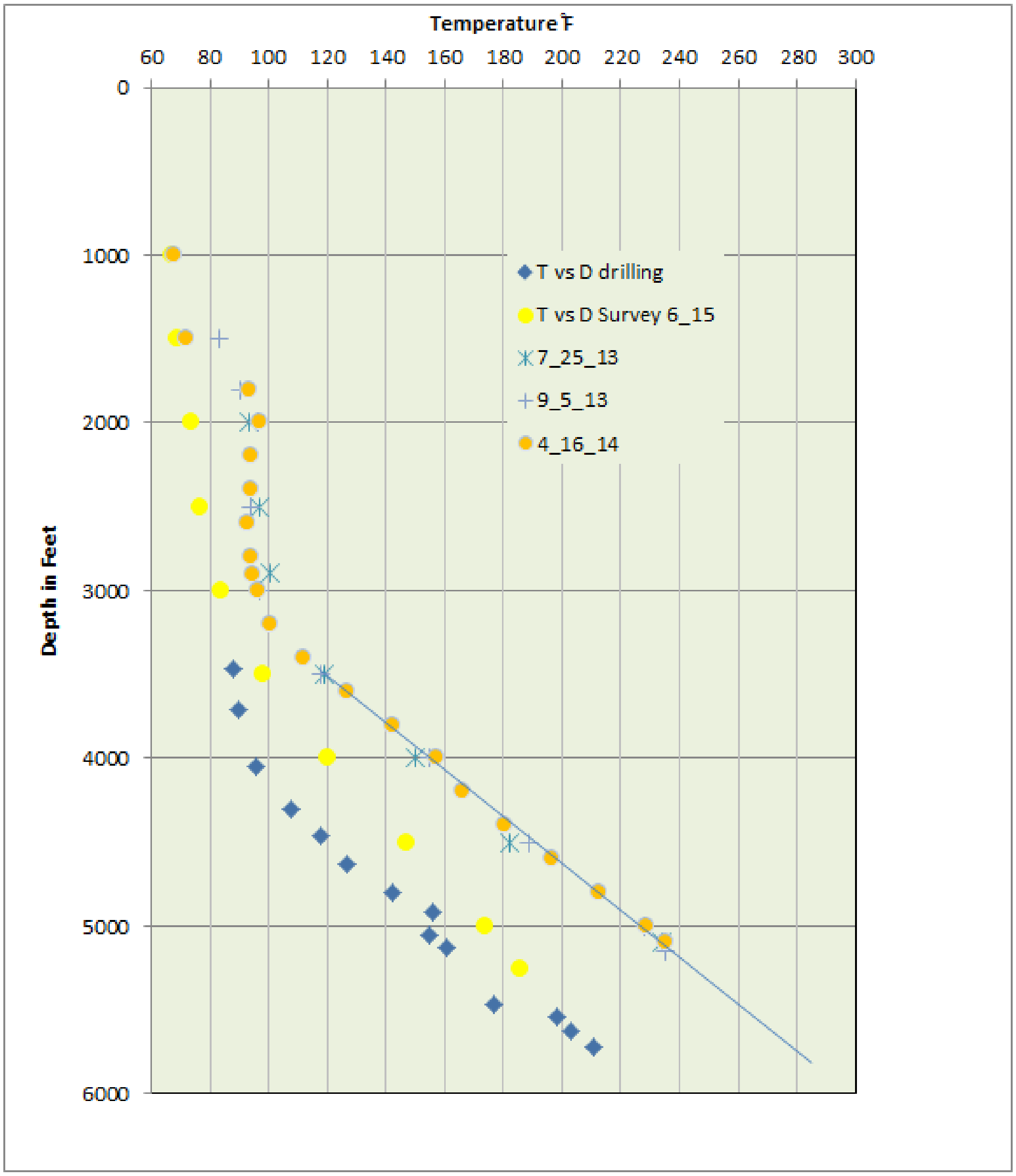

Figure 5. Temperatures measured in the **PTA-2** test hole during drilling and as thermal equilibrium was re-established in the borehole. The blue diamonds were temperatures measured nearly daily below 3500' depth; the yellow diamonds were measured the day after drilling was terminated; the blue line is a projection of the temperature gradient to the borehole depth based on the temperature gradient computed for the shallower temperatures measured.

that an additional 1 km of drilling would enable a borehole to reach temperatures approaching those present in the Puna geothermal resource area. This was the first time deep subsurface temperatures in this range have been identified outside of Kilauea and suggest that Mauna Kea may host a substantial geothermal system.

The **KMA-1** borehole did not show as clear signs of temperature and was surveyed only once at the conclusion of the drilling program after the borehole had reached thermal equilibrium. The temperatures there were significantly lower than those found at the **PTA-2** borehole, reaching a maximum of only 122 °F.

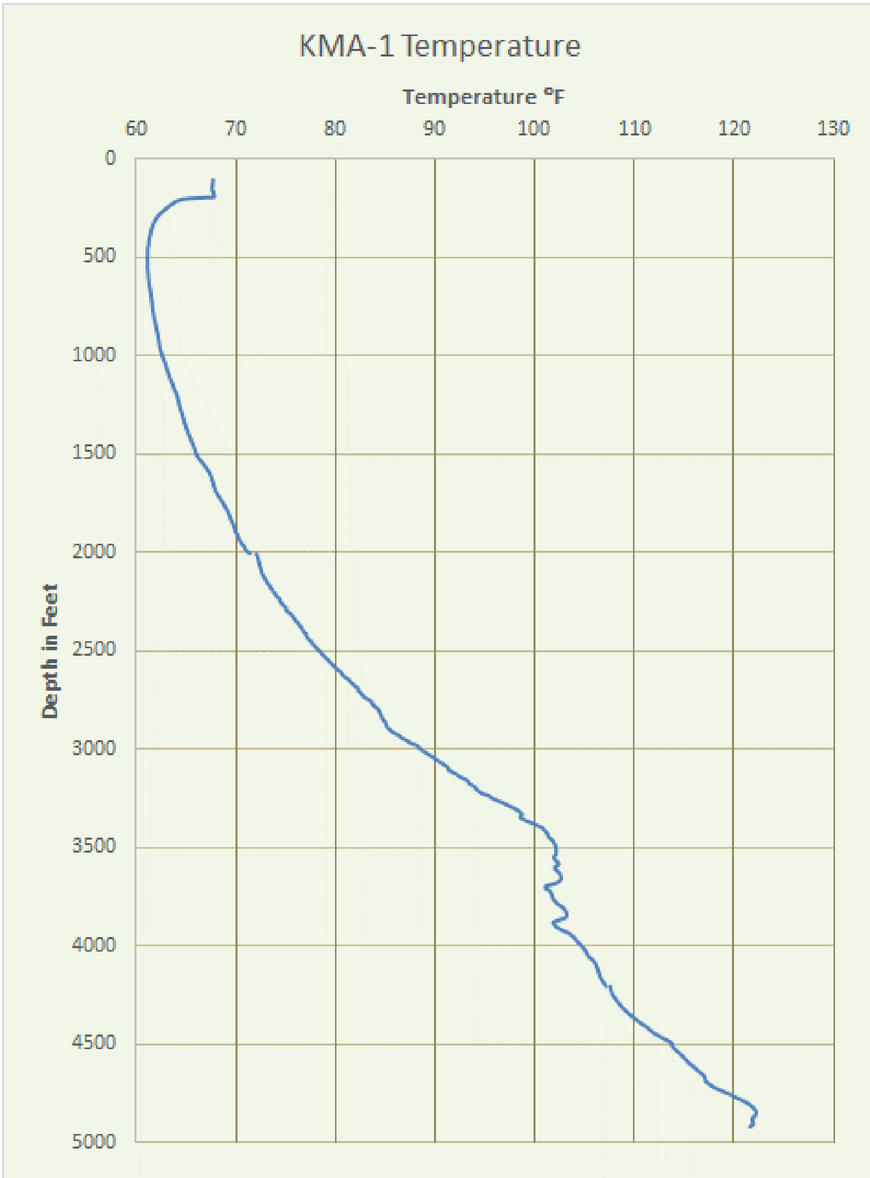

Figure 6. Temperatures measured in the **KMA-1** test hole. The temperatures, and temperature gradients here were significantly lower than those in the **PTA-2** test hole.

Water Chemistry: As noted above, downhole water samples were collected from the borehole after completion of drilling and as part of the pump testing of the deeper aquifer (to be discussed below). In general, the dissolved ion concentrations were fairly modest: the total dissolved solids (TDS) values (the combined mass of dissolved ions) were below ~500 mg/kg (see Table 1 below) for the deepest downhole sample and less than 300 mg/kg for water collected at the end of the production test. The latter would be most representative of what a production well from this aquifer would provide.

Table 1: Dissolved Ion Concentrations in **PTA-2** Borehole Samples

	Cation Concentrations					
	Sodium	Potassium	Calcium	Magnesium	Silica	TDS
PTA 1/27/15 2100'	105.9	17.87	0.691	0.1341	105	355
PTA 1/13/15 4500'	99.9	5.12	1.59	0.0620	215	431
PTA 2/19/15	70.33	9.92	3.35	2.14	102	276
	Anion Concentrations			Trace Elements		
	Fluoride	Chloride	Sulfate	Arsenic	Lead	
PTA 1/27/15 2100'	2.40	83	40.3	< 0.12	< 0.050	
PTA 1/13/15 4500'	1.72	67	40.2	< 0.12	< 0.050	
PTA 2/19/15	1.16	44.9	42.7	< 0.11	< 0.080	

The dominant dissolved cations present in all samples were sodium and silica with substantially lower values for potassium and calcium. The deeper downhole sample shows the highest silica values which is reflective of the underlying geothermal system below this aquifer. Whereas chloride ion is the most enriched dissolved anion, sulfate is also present at significant concentrations: in typical Hawaii ground waters, sulfate concentrations are about 15% of those for chloride. The elevated sulfate values here are likely also to be associated with the underlying geothermal system.

A much more detailed analysis, that is applied to drinking water wells, was conducted on the water produced during the pumping test. Those tests measure levels of more than 60 potentially hazardous or toxic compounds that are routinely tested for in drinking water. The results of that test were non-detects or no-results for all compounds for which the water was tested.

Light stable isotopic analysis of the water yielded values indicating that the zone of recharge had an average elevation of about 8,000' to 10,000' (2440 m to 3050 m) amsl. Analysis of radiocarbon in the dissolved carbon dioxide present in the water yielded an apparent age of about 10,000 years. Analysis of the ^{13}C of the dissolved carbon dioxide shows that a significant fraction of the dissolved CO_2 in the deep water is derived from magmatic (^{14}C-free) carbon dioxide. Hence, the apparent ages are as much as twice the true age of the water itself.

A much more limited testing program was undertaken for the **KMA-1** test hole. The primary intent of the **KMA-1** borehole was to test the western extent of the regional aquifer identified in the **PTA-2** borehole. Because of land access issues (authorization to drill on State-owned lands leased to USARPAC would have required more time than was available in the contract), we located the **KMA-1** borehole further west than the geophysical data suggested that the regional aquifer extended. We did not drill directly into the regional aquifer but found, instead, a sequence of confined aquifers as described above. Additionally, the stability of the **KMA-1** borehole was significantly more challenging than that in the **PTA-2** borehole and, hence, pumping was not a viable option for that borehole. Hence, we were restricted to conducting a relatively few downhole samples from the stable water table in the hole some months after drilling was concluded there. A representative analysis is presented below:

Table 2: Dissolved Ion Concentrations in **PTA-2** Borehole Samples

Well Name	Na	K	Ca	Mg	SiO_2	Cl	SO_4
KMA-1	53.24	7.69	11.52	16.88	74	17	50.7

These values bear some resemblance to the chemistry of the **PTA-2** borehole, having elevated concentrations of sodium, silica, and sulfate relative to other ions, but there is limited interpretation that we can do since we have no way of knowing the degree of mixing of these formation fluids with the drilling water that was used in this hole.

Pump/Drawdown Testing: In order to test the capacity of the deep aquifer to produce the needed volume of water required to supply the PTA facility, a limited step drawdown test was conducted on the **PTA-2** borehole. Because of the small diameter of the borehole, and the requirement that water be lifted from 1800' depth, a specialized high-capacity, limited volume, pump was lowered into the well and driven by a line shaft from the surface. Production of water at an average rate of 22 gpm (~31,680 gallons per day) resulted in a stable drawdown of approximately 13.2 inches. After production of approximately 45,000 gallons over the course of the test, recovery of the water level to pre-pumping conditions was 95% complete within about two hours. With this limited drawdown and rapid recovery, we can, with a high degree of confidence, conclude that a larger production well would be able to produce at least twice the above volume rate of water (~60,000 gallons per day) without inducing an unacceptable degree of drawdown in the deep aquifer.

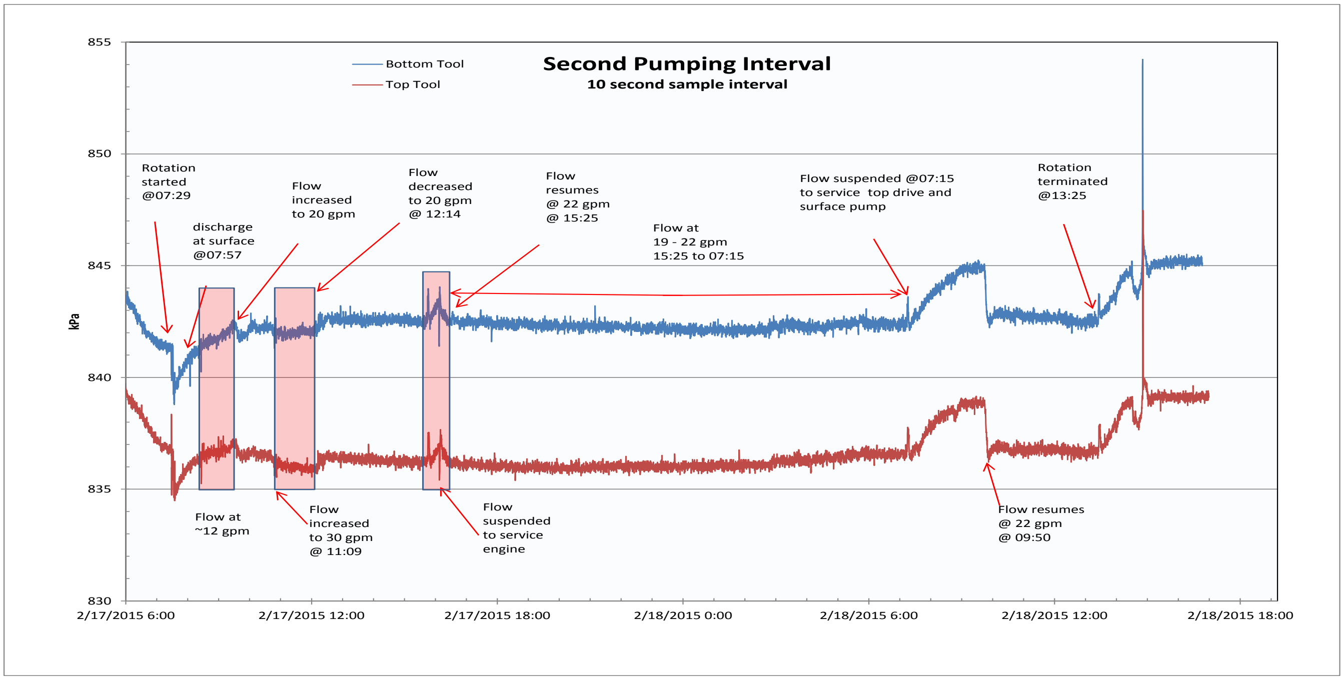

Figure 7. Pressure results for the pump-drawdown test in the **PTA-2** borehole. The left-hand scale is in kPa. The horizontal axis is time/date at 6 hr intervals. The total drawdown is ~13 inches of water.

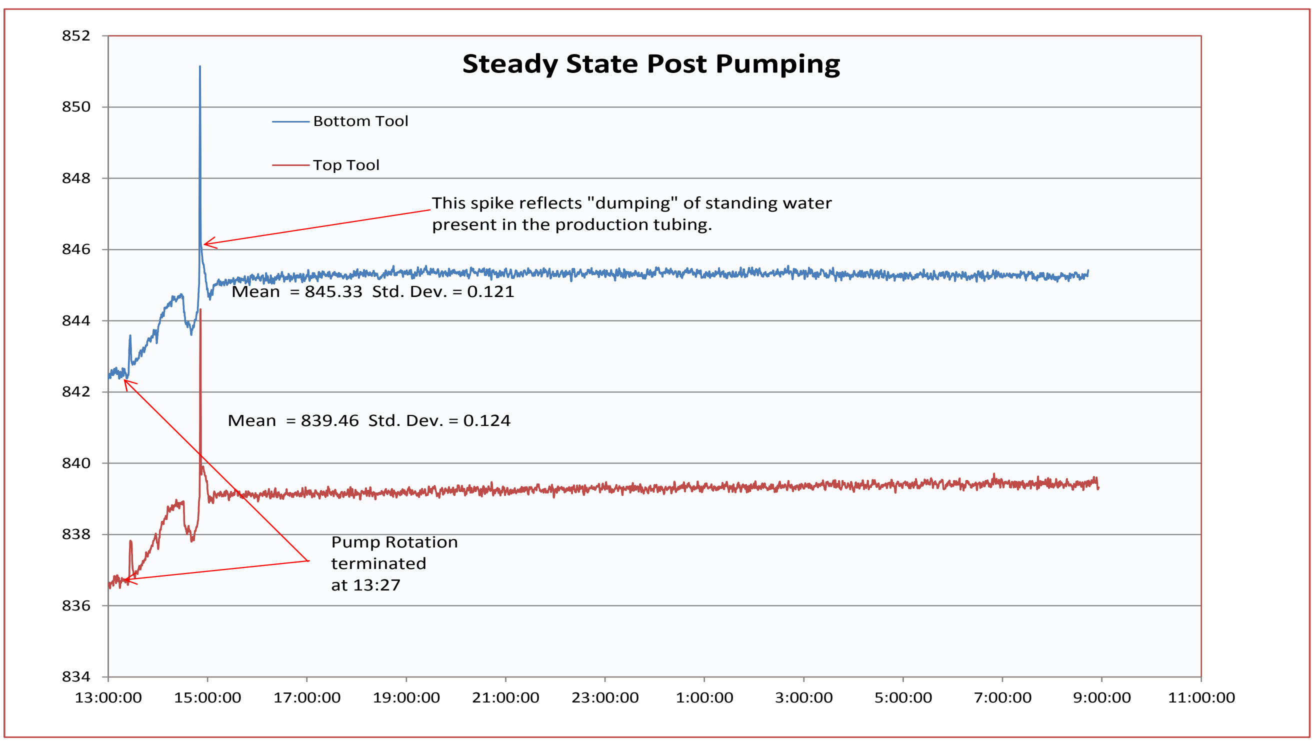

Figure 8. Pressure results showing recovery after pumping the **PTA-2** borehole. The left-hand scale is in kPa. The horizontal axis is time/date at 2 hr. intervals. Nearly full recovery occurred in two hours.

Follow-on Testing Program: Additional testing was planned for the **PTA-2** test hole that would have conducted draw-down testing and sampling of the shallow perched aquifer. In order to conduct this testing, it was necessary to cement the bottom of the **PTA-2** hole to isolate the upper perched aquifer from the deeper aquifer. As part of that program, the casing in the hole was perforated at appropriate intervals to allow cement to be forced into the casing annulus and fully seal the bottom of the perched aquifer where it was penetrated by the initial drilling program. The cementing operation was successfully completed in mid-2018 and pressure transducers were installed to monitor water level recovery. Although some water level recovery was observed, it was slow and sporadic and did not recover fully to the 700' bgs level where the saturation zone was initially encountered during drilling. We are uncertain whether that slow recovery is due to the fact that we did not achieve a complete annular seal with our cementing work, or if the long duration (from 2013 through mid-2018) of drainage of water from the perched aquifer will require additional time for complete recovery.

Status of the PTA-2 and KMA-1 Test Holes

It was our intent to continue monitoring the **PTA-2** borehole for continued recovery of the water table; however, due to an administrative oversight, the project was allowed to lapse at the Fort Worth Office of the Army Corps of Engineers and further work on the well had to be suspended until a new contract can be established. At the current time, instruments are in the borehole and were left recording but it is unknown whether they continue to be operational.

As part of the well modification and completion of the **KMA-1** borehole, our permits required that that hole be plugged and abandoned when research operations were completed on the hole. That work was completed in July, 2018 and no further work will be done in that borehole.

Recommendations based on the Findings to Date from the Humu'ula Research Drilling Effort

The drilling and testing program confirmed the presence of two prospective aquifers below the cantonment of the Army Garrison PTA. The deeper aquifer has been demonstrated to be capable of producing sufficient quantities of water (~60,000 gallons per day) with acceptable drawdown, to meet the foreseeable needs of the Pohakuloa Training Area. Although this aquifer is clearly affected by the underlying geothermal system within the Saddle region, the overall quality of the water is good; the sulfate concentration is of minor concern as to aesthetic considerations, but these can be addressed by implementing a low cost treatment program for the water. Chemical contaminant testing of the water did not find any compounds of concern that would preclude its use as a drinking water source.

We were unable to conduct the planned tests on the shallow aquifer due to its slow recovery. There is reason to expect that this aquifer will have somewhat better water quality and, if sufficient capacity can be demonstrated, it could serve as a preferred source of water to supply the PTA training facility: the cost of drilling will be significantly less and the cost of pumping will likewise be less due to the shallower lift required to bring the water to the surface.

Our recommended course of action is to continue the monitoring program into the future for another 12 months or until water levels fully recover to the point where the shallow aquifer can be tested. If those tests demonstrate better quality water than that in the deeper aquifer; and if pumping can demonstrate an adequate production rate and sufficiently rapid recovery to serve as a long-term production source, then the upper aquifer would, as noted above, be the optimal aquifer to draw from.

The data available to the present date indicates that a production well can be drilled in the PTA Cantonment to supply drinking water to the PTA training facility. The location of the production well should be located within close proximity (~1000') of the **PTA-2** test well in order to have high confidence that it will enter the same aquifers identified by the test well.

If prior testing of the upper aquifer at PTA-2 cannot be done prior to the start of drilling of the production well, our recommended strategy would be to design the production well with a capacity to reach the deeper aquifer but, during drilling, test for a shallower perched aquifer. If that aquifer is encountered: suspend drilling and conduct pump testing and sampling from that aquifer to determine its suitability as a production source for Army Garrison PTA. If testing does not demonstrate the desired water quality or does not indicate that the shallow aquifer has the capacity to meet the needs of PTA, then continue drilling to access the deeper regional aquifer and complete the well to that depth as a production well.

In light of recent concerns expressed regarding groundwater resources within Mauna Kea, it is further recommended that the **PTA-2** test hole be modified, based on the disposition of the production well, to serve as a monitoring well that can be used to monitor changes in the water level and water chemistry in the aquifer tapped by the planned production hole. This would help alleviate concerns that production of water from the aquifer was having a significant detrimental impact on the groundwater aquifer being drawn from.