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ATTACHMENT 1

Conceptual Site Model Topics

Item 1. Basalt Strike and Dip

The geometry of lava flows affects the transport of LNAPL, groundwater, and dissolved contaminants. This is particularly true for vadose zone transport of LNAPL. Characterizing the geometry of lava flows – in particular, the predominant strike and dip values and variations about these predominant values – is critical to assessing the risk the Red Hill facility poses to potential groundwater receptors.

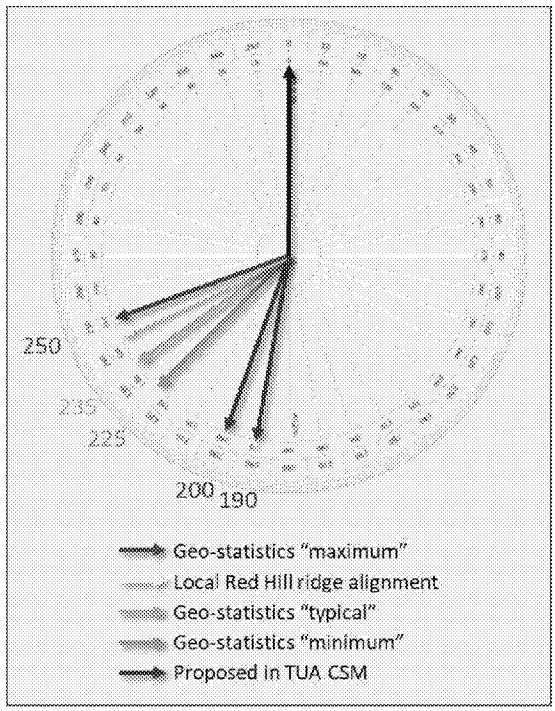


Figure 1.1 Estimated Dip Directions in and Around Red Hill

The values for the strike and dip of the lava flows reported by consultants to the Navy (CSM Report, page 5-2: "*True dip in the vicinity of Red Hill has been measured at angles of 10–12 degrees, with a strike of 190–205 degrees*") differ from values that were obtained independently by the regulator SMEs via field observation and measurement and geostatistical analysis of barrel log data, which consistently exhibit lower dip values of about 5 degrees and more westerly strike values (Inset Figure 1.1). Although these differences may appear subltle, they are consequential for groundwater flow and potential contaminant transport paths. This is illustrated in Inset Figure 1.2, which presents pathlines calculated using the interim groundwater model, with values for the direction of anisotropy that differ by 10 degrees (particles depicted in red were computed with a more westerly direction of anisotropy reflecting a more westerly assumed dip direction).

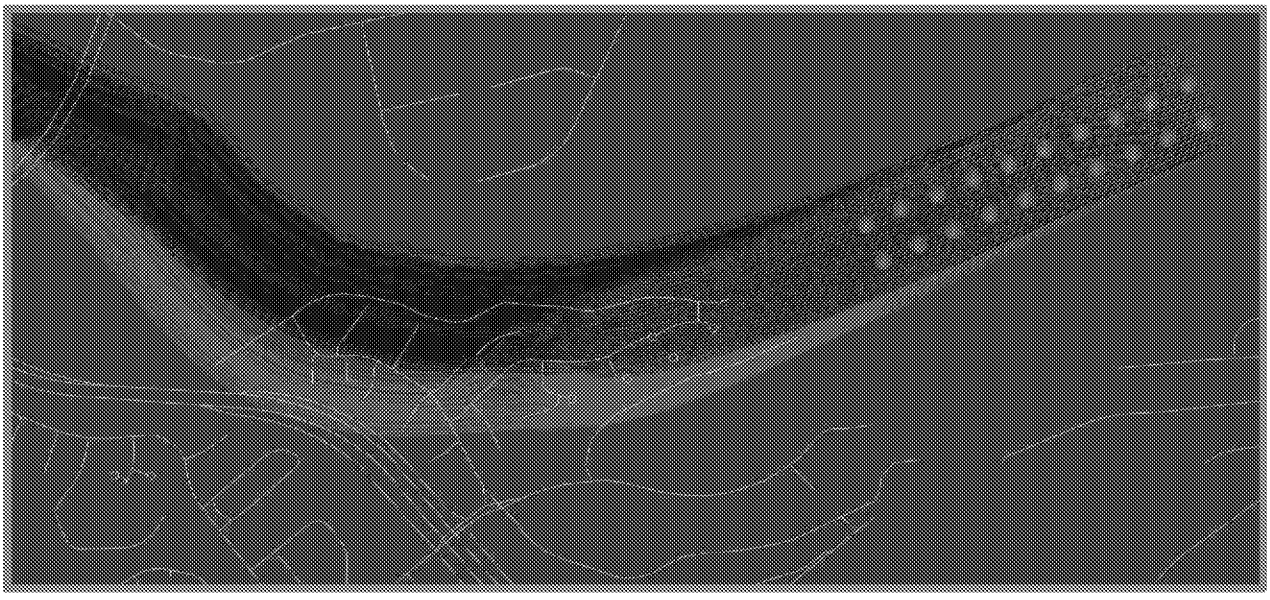


Figure 1.2 Illustration of Particle Path Sensitivity to Assumed Principal (Long-Axis) Direction of Anisotropy

Two difficulties are often encountered obtaining best estimates of dip and strike. First, measurements made at an outcrop face, where the scale is on the order of inches to feet, may not be directly applicable or accurate indicators at the scale over which fluid transport may occur, where distances of hundreds to thousands of feet must be considered. Second, there is likely to be variability in dip and strike values throughout an area, as a function of paleotopography, flow volume, and other factors.

Because there is a variety of data sources for dip and strike at Red Hill, it is appropriate to combine the data while considering their representative scales and quality to obtain a best-estimate at the scale of most interest to the fate-and-transport evaluation. Data sources at Red Hill include (a) close-quarters outcrop measurements such as obtained with a compass-clinometer, (b) surveys of visible outcrop from a distance that allow the geometry of a continuous bed-set to be followed for many tens or hundreds of feet, and (c) geostatistical analysis of the barrel log data. The resulting best-estimate derived from combining these lines of evidence can be to some extent corroborated by intersecting the derived plane with a digital elevation model for comparison with features observed in the field (Inset Figure 1.3).

Figure 1.3 Example of Extensive Correlatable Units Viewed from a Distance using a Theodolite Application for a Camera

References:

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "CSM Report")

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "GPEC Report")

Item 2. Saprolite Extents

The saprolite (chemically and physically weathered basalt) is a critical hydrostratigraphic unit (HSU) that affects contaminant transport upon the water table and within groundwater. The saprolite typically exhibits a lower hydraulic conductivity than surrounding basalts and where present beneath the water table, it likely acts as a barrier to contaminant transport, causing groundwater and contaminants to migrate around or beneath it. The depth of the saprolite/basalt interface is important in many areas of the site, but the point up-valley where the saprolite/basalt interface rises above water table is a critical feature in assessing the risk the Red Hill facility poses to drinking water sources.

Review of the representation within the interim groundwater flow model files provided for courtesy review by the Navy of the saprolite/basalt interface depths and general trends (i.e., slopes) relative to the axis of the North and South Halawa Valleys suggests the saprolite is likely deeper down-valley and shallower up-valley than represented in the interim model. One consequence is that the point up-valley where the saprolite/basalt interface rises above water table may be more downslope than currently represented. If this is true, the role of the saprolite as a barrier to flow between valleys – particularly in up-slope areas – may be less protective than the current conceptual model indicates (Inset Figure 2.1).

There are at this time insufficient available data regarding the depth of the saprolite/basalt interface relative to the water table (particularly in North and South Halawa Valleys) to accurately and uniquely represent them in the model. Characterizing the three-dimensional (3D) extent and hydrogeological properties of the saprolite in each valley, including North and South Halawa Valleys, is difficult. Available data include a general CSM regarding basalt weathering and valley infilling; seismic geophysical analysis conducted along several transects; and a single detailed borehole geologic log that crosses the saprolite/basalt interface. Though the seismic data are very informative, ground-truthing is costly and only very localized. Available data from borings – such as the Halawa deep monitoring well – provide specific stratigraphic logs, but even these are accompanied by uncertainty regarding the appropriate depth to pick the interface (inset Figure 2.2). Consequently, uncertainty remains regarding the depth at which to represent the saprolite/basalt interface within North and South Halawa Valleys in particular, and regarding the protection afforded to Halawa Shaft by the saprolites acting as a barrier.

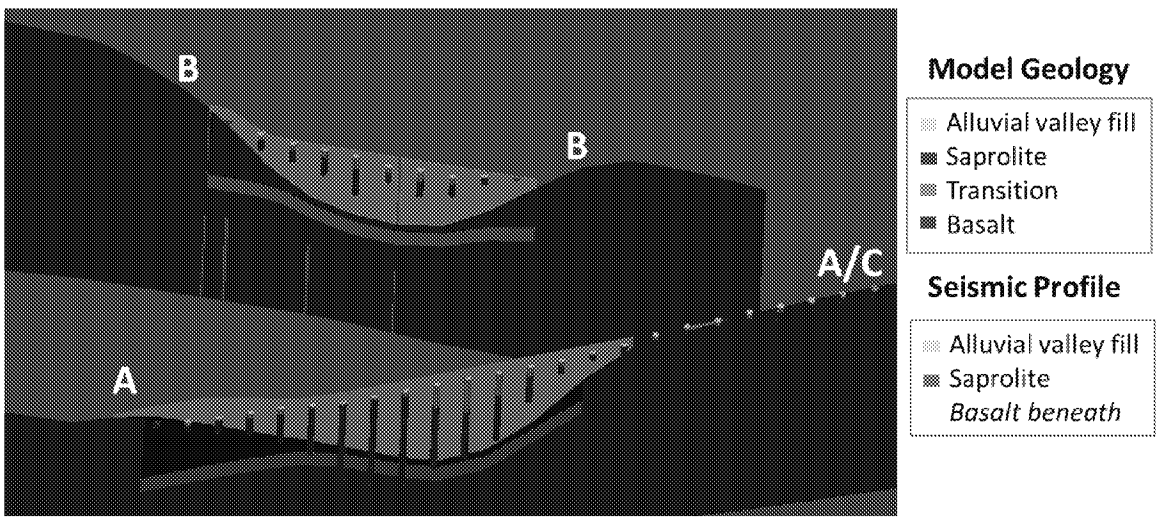


Figure 2.1 Example Comparison of Seismic Profiles and Representation in the Interim Model

Halawa Deep Monitor Well No. 2253-~~01~~ 03
Geologic Log by Glenn Bauer

Depth (ft.)	Description
0-50	Very weathered gray, tan, and red rock; cuttings are rounded and angular
50-70	Same as above, however cuttings are redder and clay present
70-80	Weathered tan cuttings, some of the vesicles lined with Mn
80-100	Weathered reddish-brown friable cuttings
100-110	Same as above, though cuttings are redder
110-130	Weathered tan cuttings
130-140	Weathered red cuttings with clay
140-150	Weathered light brown cuttings
150-170	Weathered brown aa basalt with angular vesicles some coated with Mn
170-180	Weathered dense brown, tan, and gray cuttings
180-190	Mixture of weathered brown pahoehoe and aa basalt
190-210	Weathered gray aa basalt
210-230	Friable brown-gray aa basalt ~-5 ft msl
230-250	Mixture of weathered aa and pahoehoe basalt; some of the pahoehoe has secondary minerals in the vesicles.
250-260	Weathered pahoehoe basalt with secondary minerals in the vesicles
260-270	Mixture of light gray and dark gray aa basalt with a few tachylitic cuttings present
270-280	Weathered gray aa basalt with tachylite
280-290	Dense light gray aa basalt ~-55 ft msl
290-300	Mixture of dense non-vesicular light gray and dark gray aa basalt
300-310	Mixture of weathered gray pahoehoe and non-vesicular aa basalt
310-320	Dense dark gray non-vesicular aa basalt
320-340	Mixture of light and dark gray pahoehoe and aa basalt
340-350	Slightly weathered reddish brown pahoehoe basalt with many small round vesicles

Saprolite/ Basalt Interface

Figure 2.2 Boring Log of Halawa Deep Monitoring Well

Available data which are overwhelmingly large scale and relatively low resolution (i.e., seismic profiles) must be interpreted in the context of the CSM and AOC to provide an appropriate representation for purposes of the flow and transport modeling. The solution to this problem likely lies in two parts: First, re-interpretation of the available data. When the currently seismic-inferred depths to the saprolite/basalt interface are compared to the CSM, the down-valley transects show a deeper interface depth than the current CSM would suggest while the up-valley transects suggest a shallower interface than currently believed. Interpolating between the down-valley and up-valley transects and extrapolating this trend up-slope from the most up-valley transect may help define where the saprolite is no longer beneath the water table and thus a barrier to flow and transport. Second, ground-truthing of the seismic data using test borings (this may already be planned as there is discussion of a test boring adjacent to Seismic Transect E near the Halawa Deep Monitoring Well [HDMW2253-03]). Additional ground-truthing is highly desirable, even though costly, in targeted areas with maximal information benefit to provide (a) seismic velocities needed to better constrain the depth to the saprolite/basalt reflector and (b) interface elevations at key boring locations to condition the geophysical results.

References:

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "CSM Report")

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "GPEC Report")

Item 3. Preferential Pathways.

Voids, fractures, and related features in this shield volcanic setting will potentially allow for rapid transport of both LNAPL and dissolved-phase contaminants. These include lava tubes, bedding plane structures, fractures, etc. While mentioned in the CSM, there is no discussion or quantification of site specific facets. A good framing for hard rock and fractured systems is the ITRC fractured rock CSM schematic (e.g., Figure 3.1). Some of the more important factors are the orientation of these features, the wall roughness, dip, aperture ranges, continuity and density. While some of these aspects have been discussed in the CSM, none have been quantified (excepting dip, around which there are remaining questions), which would directly assist in considerations of contaminant F&T, particularly the LNAPL migration. For instance, based on the geologic barrel logging when the Red Hill tanks were installed, lava tubes are present beneath 13 of the 20 tanks; Tanks 1, 3, 4, 6, 8, 9, 13, 15, 16, 17, 18, 19, and 20. Lava tubes are expected to be a smooth-walled and distally continuous features (personal comm, Dr. Scott Rowland, U.H., 2018) that if intersected by LNAPL in the unsaturated zone would act as essentially an open-pipe transport conduits. In-filling, collapse and other post-deposition factors can affect how these conduits might behave, as noted in the Navy CSM. However, there is no site or area specific characterization of these important transport features in the CSM, absent which, little can be inferred regarding their potential effects on transport.

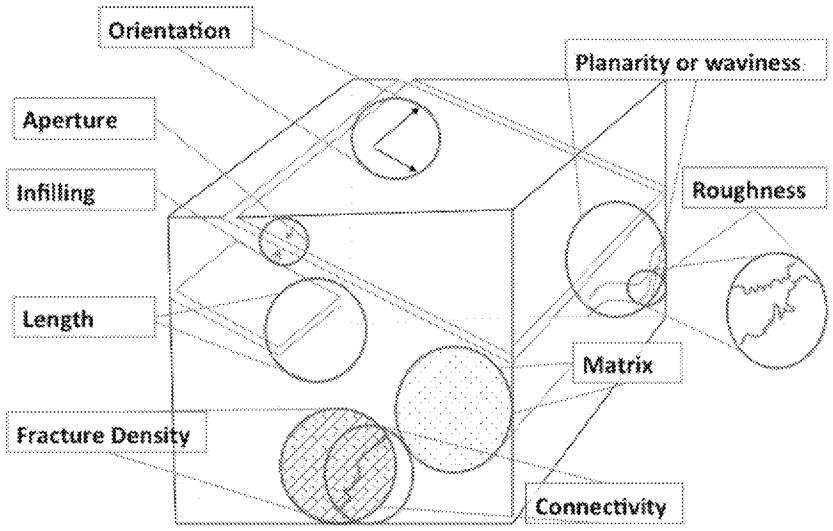


Figure 3.1 Key fracture/hard rock characteristics as defined by the Interstate Technology Regulatory Council (ITRC, December 2017). Of those shown, the most important factors are the orientation of these features, the wall roughness, dip, aperture ranges, continuity and feature density.

A portion of this issue is discussed in the bedding strike and dip discussion above. Based on the range of dip measurements by both the Navy and HDOH scientists, it is clear that there is significant variability in the dip and its azimuth. It also appears that there are changes in dip from the axis of the Red Hill Ridge to outlying areas. The Navy team does some good work in drawing analogies between current volcanic activity on the Big Island and past processes at work on O'ahu. We would simply note that on the Big

Island, recent flows have a much wider meander potential than the 30-45 degrees from the fall-line noted in the CSM. Maps of historically recent lava flows relative to the rift zone alignment show that flows can be in almost any downhill direction (Figure 3.2; USGS, 2018). Whether by preferential pathways or other mechanisms, the observed plume distribution noted previously is clearly not in the direction of the main bedding dip of 190 – 205 degrees stated in the CSM. This also affects the assumptions of the CSM LNAPL F&T evaluations discussed below.

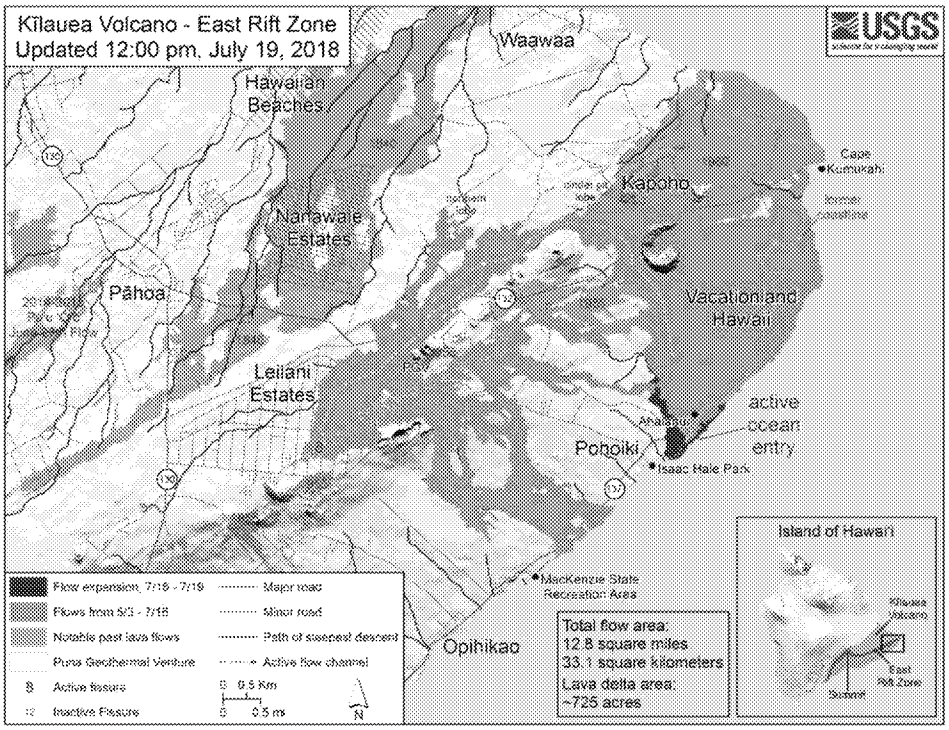


Figure 3.2 Geologic Map of recent lava flow directions from eruptions at the Kilauea Volcano, Hawaii. While the predominant downslope movement is roughly perpendicular to the East Rift Zone, there is significant variability in lava deposition pathways.

The agencies would like to see more thought and geologic features quantification with regard to preferential pathways in the CSM along with their potential effects on LNAPL and dissolved-phase F&T. We recommend such new evaluations be placed in context with the noted ITRC fractured rock framework with associated quantitative evaluations of these critical potential preferential pathways (along with other related technical literature). We also recognize that this system is not purely a fractured matrix, but rather one in which fractures, voids, bedding planes, clinker zones and other features interact as a continuum that will ultimately control LNAPL and dissolved-phase transport. Decisions regarding modeling methods, approaches, and conceptualizations will need to be made and described so the agencies can understand the assumptions and potential limitations therein.

We would also note that the Navy team may wish to consider some additional site data collection in this category using widely recognized fractured rock characterization techniques (e.g., Neumann, 2005). These include cross-hole pneumatic and hydraulic testing with tracers and a variety of other commonly

recognized field methods. Transport estimates, which are the backbone of risk evaluations will be much more reliable when coupled with these types of site specific observational data.

References:

API #4731, 2003. Light Non-Aqueous Phase Liquid (LNAPL) Parameters Database - Version 2.0 - User Guide.

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "CSM Report")

Fractured Bedrock Field Methods and Tools: Volume I, Main Report. Science Advisory Board for Contaminated Sites in British Columbia, authored by Golder & Associates, 2010.

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "GPEC Report").

Hydrogeologic characterization of fractured rock masses intended for disposal of radioactive waste DM Reeves, R Parashar, Y Zhang - Radioactive Waste, 2012.

Huyakorn, P.S., Panday, S., Wu, Y.S., 1994. A Three Dimensional Multiphase Flow Model for Assessing NAPL Contamination in Porous and Fractured Media, 1. Formulation. Journal of Contaminant Hydrology, #16 (1994), pp 109-130.

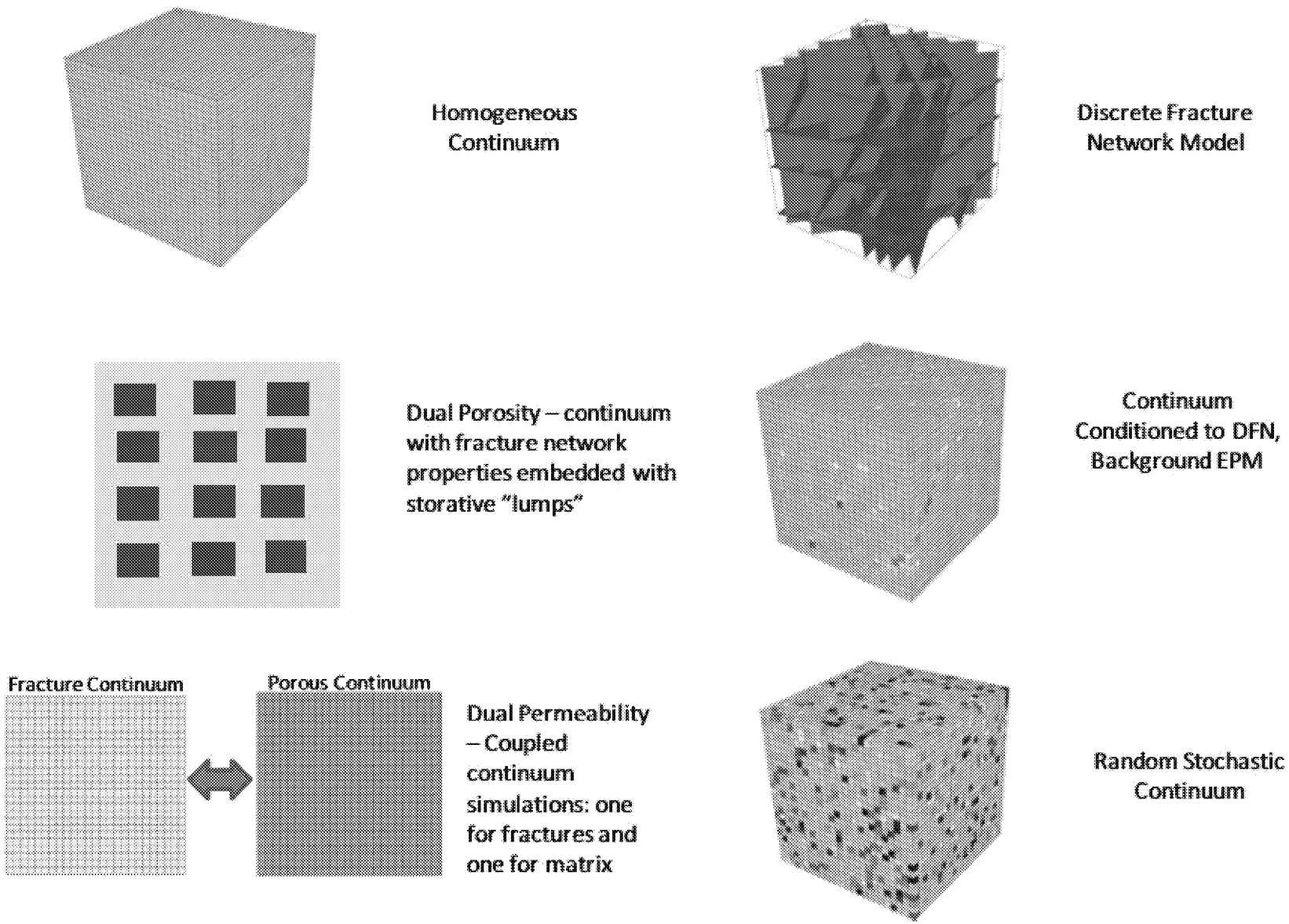
Characterization and Remediation in Fractured Rocks. Online publication: https://fracturedrx-1.itrcweb.org/ ITRC, 2017.

Neuman, S. P., 2005. Trends, Prospects and Challenges In Quantifying Flow And Transport Through Fractured Rocks. Hydrogeology Journal, March 2005, Volume 13, Issue 1, pp 124–147.

Attachment 1 - Appendix

Figure 3. Representations of fractured media.

For Red Hill, the CSM would benefit by conceptualizing and quantifying key systemic features and their potential behavioral characteristics, as well as deciding on the transport framework that is most representative.



(source: Fractured Bedrock Field Methods and Analytical Tools, Volume 1, Main Report, Submitted to the Ministry of Environment Canada, April 2010.

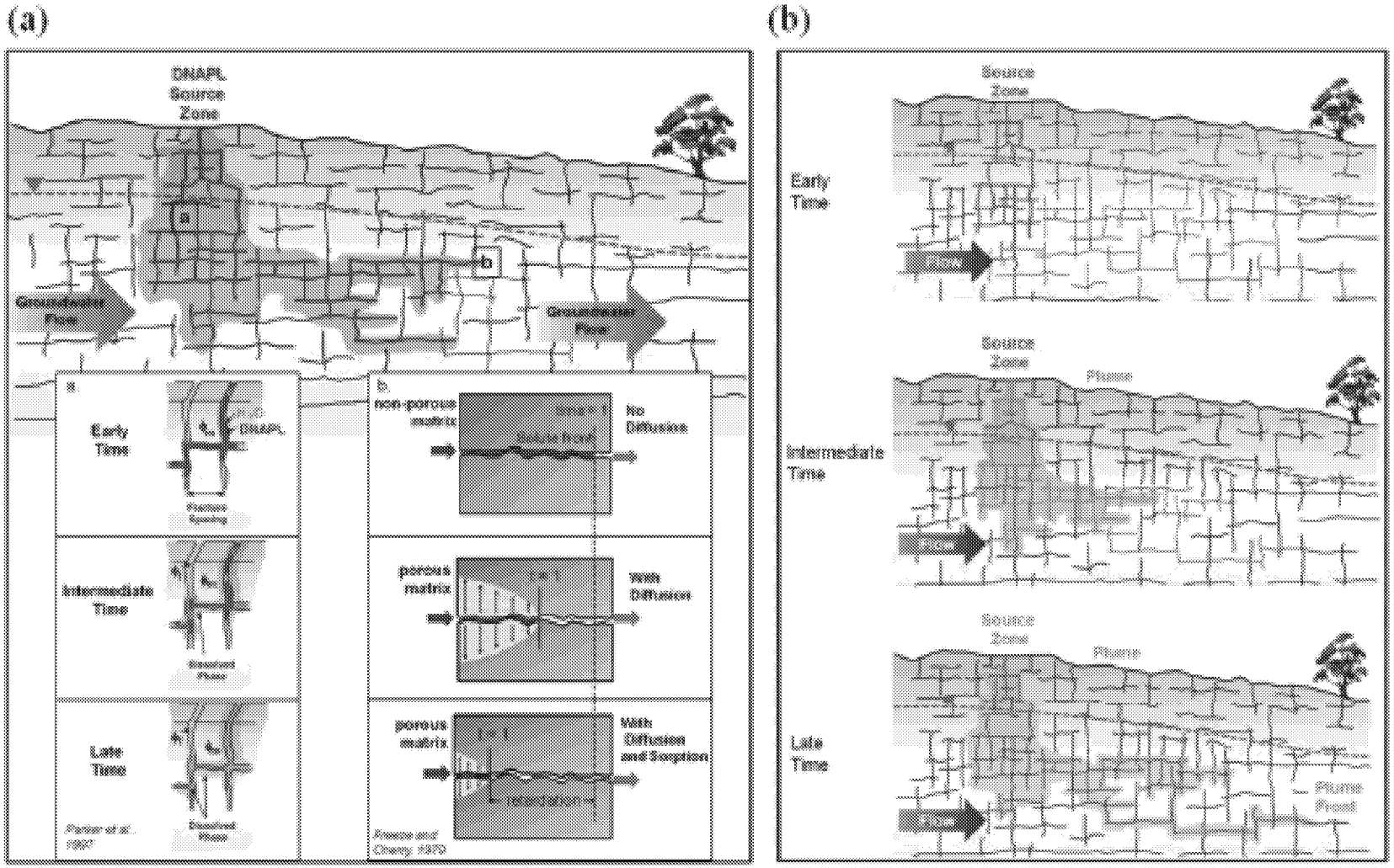
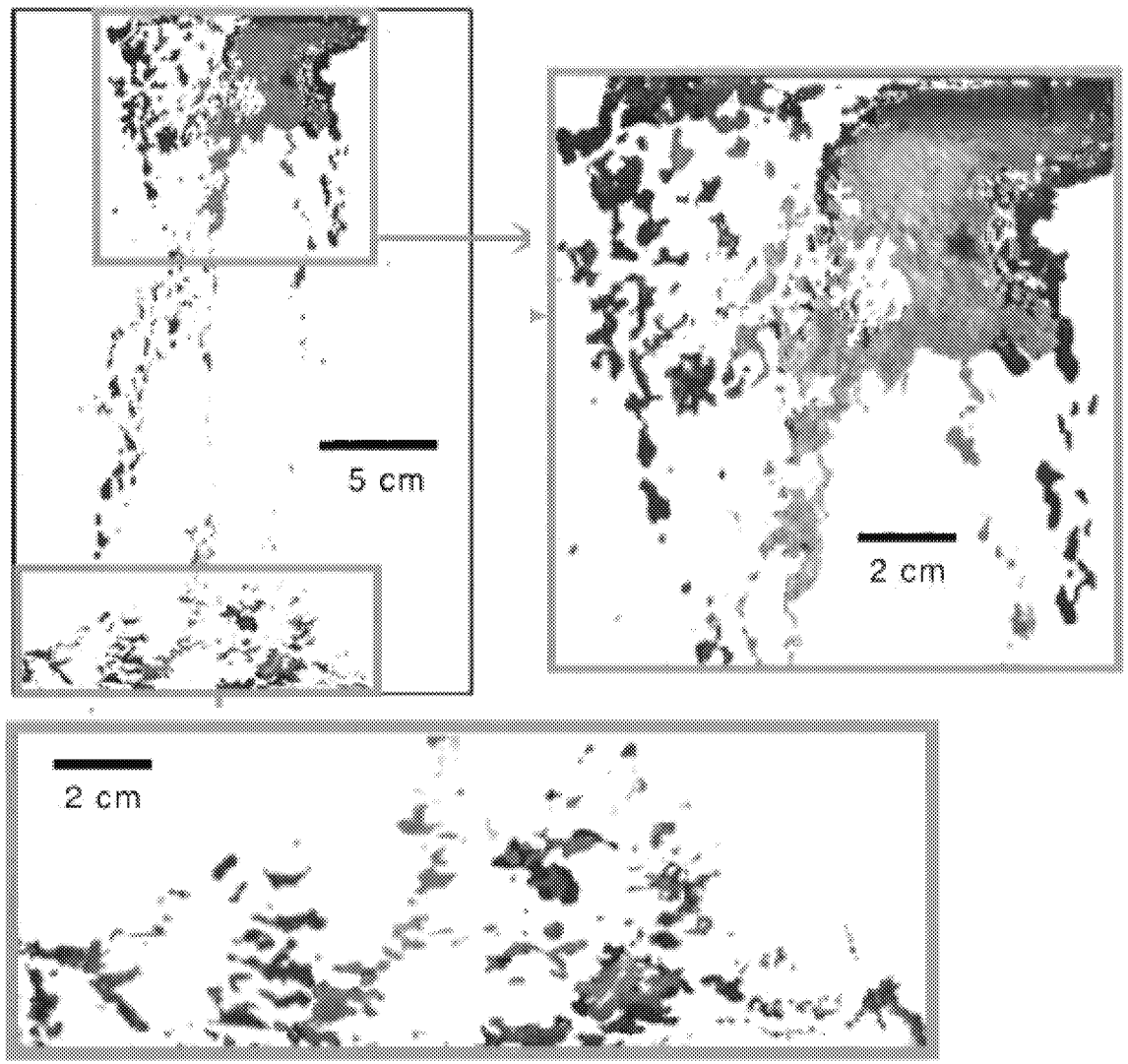


Fig. 1: *Conceptualization of source zone and plume evolution in fractured sedimentary rock: (a) schematic cross-section showing DNAPL release with formation of a downgradient plume, with insets showing source zone evolution (adapted from Parker et al., 1997) and diffusion effects on contaminant migration (adapted from Freeze and Cherry, 1979), and (b) conceptual stages of source zone and plume evolution (adapted from Parker et al., 2010).*

Similar to the Hunt (1996) lithologic schematic, these authors discuss the quantification of such a network for the purposes of understanding the nature of contaminant F&T. The features of Hunt's model need to be bounded by quantifying the various parametric apsects of those features and their impact on transport.

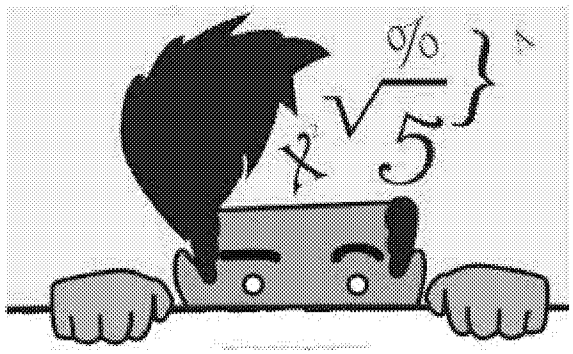
NAPL Distribution in a Fracture



Geller et al., 2000

Heterogeneity of transport is the expected norm in a fractured/hard rock system such as Red Hill and the complexity of the LNAPL CSM needs to comport with the actual complexity of the system.

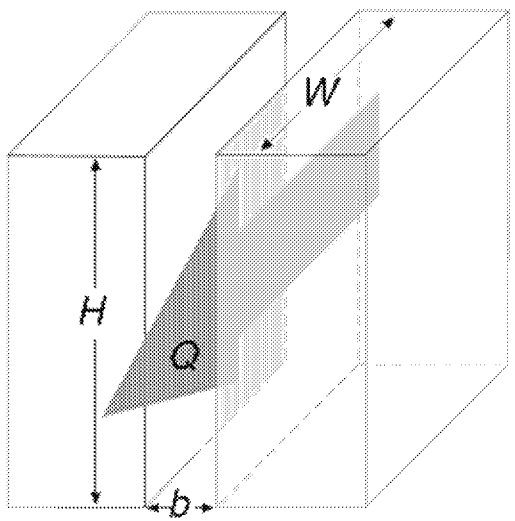
Just a Little Math... Cubic & Quintic Flow



$$Q = -\frac{\rho g}{12\mu} b^3 \partial h$$

$$K = \frac{2b^2 \rho g}{12\mu}$$

For "simple" fractures



Holy exponential cow!

Suggested for "real" fractures with aperture/length correlations

$$Q = -\frac{4\rho g}{3\mu(\pi\alpha)^2} b^5 \partial h$$

after Climczak et al., 2009 From a transport quantification point of view, fractures and voids of larger apertures and connectivity will allow for very rapid transport of LNAPL. These features need to be understood and quantified so the implications for transport may be understood and constrained.

ATTACHMENT 2

Interim Groundwater Flow Model

Item 4. Caprock, Tuffs and Sediments

The CSM that underlies the interim and final numerical groundwater and LNAPL models needs to represent, albeit in an approximate manner, the principle features and processes that affect groundwater flow and contaminant migration. The configuration and properties of the caprock, tuffs and sediments are collectively an important feature of the hydrogeologic system. The interim groundwater model terminates the saprolites a short distance down-valley of Red Hill; represents the caprock as a wide-reaching uniform and continuous layer; and does not appear to represent older Honolulu volcanics or surrounding finer sediments. These areas were evaporative "lakes" at one time, exhibiting strongly artesian fresh-water conditions, and they may form a barrier to flow influencing groundwater flow and contaminant transport.

Gradients simulated by the interim flow model, as presented in the GPEC Report and determined from the interim model files provided for courtesy review by the Navy, do not comport well with gradients determined from synoptic data in and around Red Hill facility. While this is in part related to conditions local to Red Hill, analyses conducted using the interim model exhibit high sensitivity to conditions downgradient of Red Hill - specifically, in the area broadly represented by the caprock (GPEC Report Section 5.9). This suggests that although uncertain, because there are insufficient data available to uniquely and accurately specify the distribution and properties of downgradient geologic units, it is important to represent the hydrostratigraphy downgradient of the Red Hill facility as accurately as possible, using as one basis the overarching CSM regarding the distribution and properties of these features (Inset Figure 3.1).

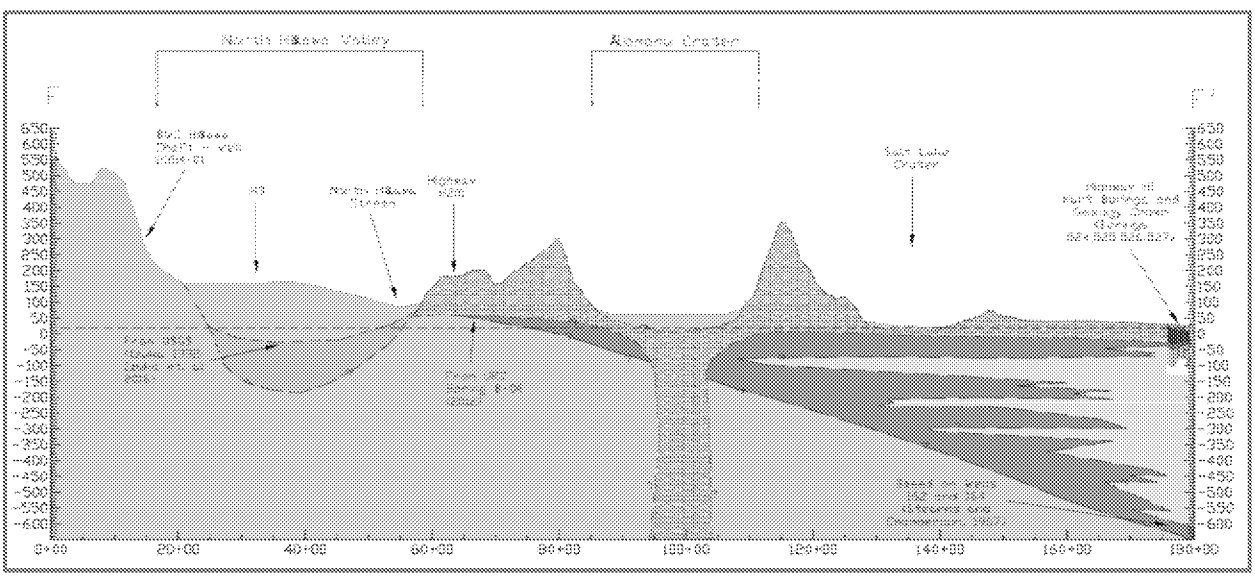


Figure 3.1 Example Figure Illustrating Hydrostratigraphic Features

Available information must be interpreted in the context of the CSM and AOC to provide an appropriate representation for flow and transport modeling. The solution to this problem likely lies in two parts: First, re-interpretation of the available data, and expanded use of sensitivity analysis and model calibration to help identify probable geometries and properties, including for example extending the saprolites down-valley, and differentiating Honolulu volcanics from surrounding sediments. Second, based on the anticipated results of sensitivity analyses conducted with this updated representation of

these features, consideration should be given to methods of data collection to better constrain the likely presence, extent and properties of these features. For example, other sources of information and data collection – such as airborne gravity surveys – may provide further evidence for the extents of some of these features.

References:

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "CSM Report")

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "GPEC Report")

Item 5. Calibration – Tunnel Inflows

The role of Red Hill shaft as a mitigating hydraulic containment measure in the event of a contaminant release depends on its ability to develop a capture zone that encompasses the area impacted by a release. As a Hawaii-style water supply, Red Hill shaft does not function as a simple vertical well: it gains water via seepage along the quasi-horizontal tunnel that extends broadly eastward from the vertical shaft. One role of the interim and final groundwater models is to demonstrate the likely extent of capture (zone of contribution) of Red Hill shaft under a range of plausible conditions.

The interim groundwater flow model does represent Red Hill shaft as a linear quasi-horizontal feature rather than at a single vertical point, which is appropriate. However, the distribution of inflows to the eastern tunnel extension simulated by the interim model as determined from the model files provided for courtesy review by the Navy does not appear to match the inflow pattern encountered during tunnel construction (Inset Figure 5.1). During construction, a clinker zone was encountered that contributed more than 60% of the flow to the tunnel whereas the interim model simulates uniform inflow along the tunnel. This difference highlights two issues: first, there is heterogeneity present on a scale of many tens to hundreds of feet that is not well understood nor represented in the interim model; second, the extent of capture developed by the tunnel may be more head-dependent than represented in the interim model. That is, the capture zone under high water level conditions may be dominated by seepage from this clinker at the end of the east tunnel, but under low water level conditions may be dominated by drawdown within the vertical shaft itself. Sensitivity analyses conducted with the interim model indicate that the model exhibits sensitivity to the potential presence of a clinker zone (GPEC Report Section 5.9).

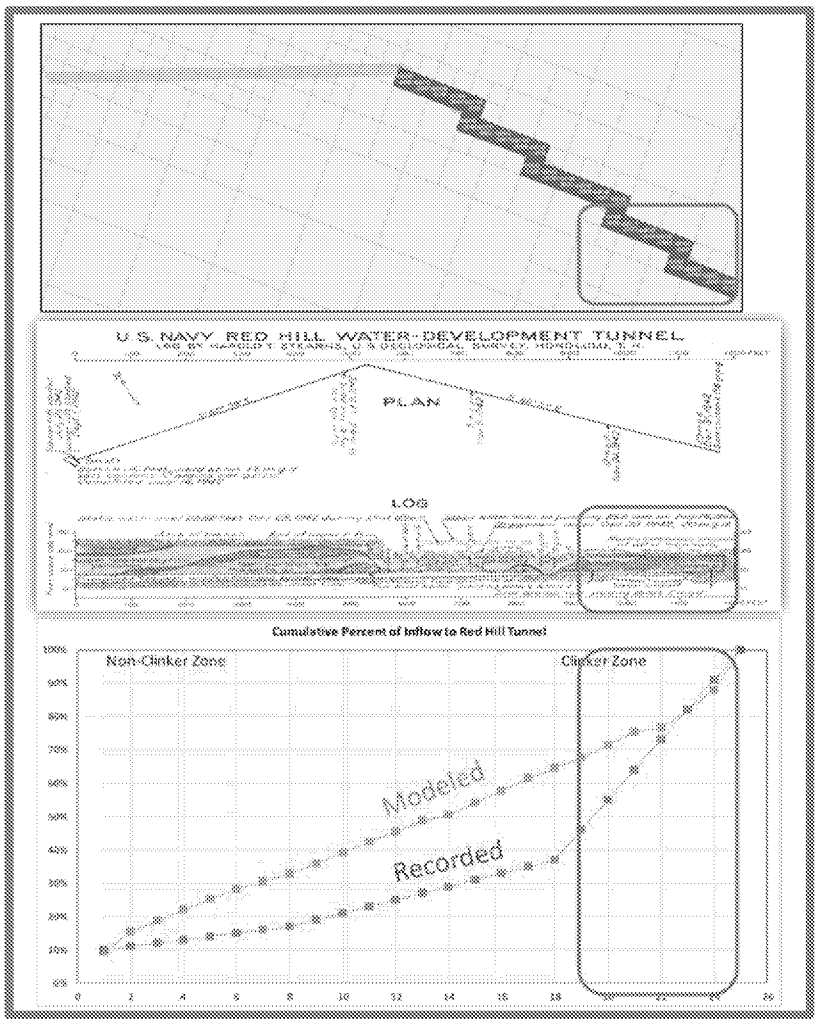


Figure 5.1 Schematic of Recorded and Simulated Inflows

The presence of large-scale heterogeneity is documented: however, the distribution and properties of these heterogeneities are not well known and cannot be perfectly represented in models. Despite this, consideration must be given to the role they may play in the

calibration of the groundwater model, and any inability to reasonably match heads and gradients; the zone of contribution to Red Hill shaft and tunnel system under different conditions; and, the transport and fate of constituents in groundwater.

The final CSM and model should make a greater effort to evaluate the possible role of these heterogeneities – in particular, as an illustrative example, the Red Hill tunnel clinker – on calibration, zones of contribution, and contaminant transport. This may be accomplished for example by evaluating the zone of contribution under high water level conditions dominated by tunnel seepage, and under low water level conditions dominated by active pumping at the Red Hill shaft.

References:

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "CSM Report")

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "GPEC Report")

Item 6. Calibration Heads and Gradients

Groundwater flow and contaminant migration are, under most circumstances, determined or strongly influenced by hydraulic gradients. A groundwater model developed to predict the transport and fate of contaminants from a release should present reasonable correspondence with hydraulic gradients determined using site-specific measurements, to provide confidence the model will reasonably predict contaminant transport.

Hydraulic gradients determined from measured data are generally flat in and around Red Hill. On most occasions, gradients are to the southwest at a low slope, but occasionally they appear to be to the northwest and possibly north. The interim model outputs presented in the GPEC Report do not closely reproduce the magnitude or direction of these gradients. Flow in the calibrated interim model is dominantly Mauka-to-Makai, and most of the sensitivity-derived alternative models demonstrate flow toward Red Hill shaft at gradients that are 10 to 100 times higher than measured values. Although the sensitivity analyses do present a range of simulated gradients c(GPEC Report Section 5.9), the distribution of simulated gradients across all models that were provided for courtesy review by the Navy does not match closely values derived from the synoptic data (Inset Figure 6.1).

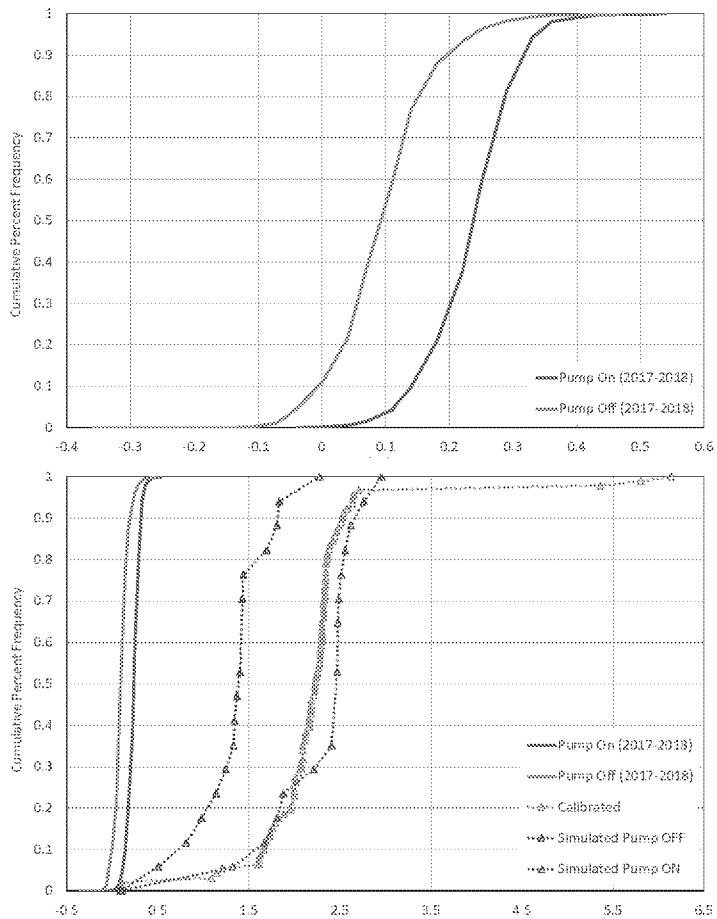


Figure 6.1 Example Comparison of Pairwise Head Differences from Synoptic Data with Simulate Head Differences from All Interim Models

Historical data had shortcomings (frequency, reference elevations, lack of pumping knowledge) that they were not easily amenable to rigorous analysis. Recent synoptic data provide improved frequency and quality. These data suggest that certain aspects of the CSM incorporated into the interim flow model may prevent the model from reproducing these gradients, including the saprolite distribution; basalt strike and dip; the "keying" of saprolites into down-valley Honolulu volcanics, older sediments and cap rock; and recharge distribution and rates.

The final CSM and model should focus on analyzing recent high-quality synoptic data to the extent possible, and down-weight analyses based on older data. Despite difficulties preparing water level maps, pairwise head-difference plots can show the effects of pumping on gradients and the frequency and magnitude of gradient reversals. Steady-state model calibration should focus on demonstrating a match

with regional patterns and with representative local gradients under pumping and non-pumping conditions. This combination is required to demonstrate that the model is useful for near-field transport to understand the available groundwater data, and for developing predictions of capture zones for Red Hill shaft and Halawa shaft to help evaluate risk and mitigating responses or strategies. Transient calibration will provide information on T, S, anisotropy, and possibly on the geometry of features such as the saprolite but is not a substitute for obtaining reasonable mean-centered correspondence to the measured gradients (or pairwise head differences).

References:

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Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "GPEC Report")

Item 7. Coastal Submarine Discharge

The CSM that underlies the interim numerical groundwater and LNAPL models and will underlie the final versions needs to represent the principle features and processes that affect groundwater flow and contaminant migration. There is uncertainty regarding the downgradient outflow boundary, which as currently represented in the model may lead to a bias toward discharge occurring in the northeast Pearl Harbor area. All groundwater that is not extracted by wells or discharged to streams or springs flows to the saline water bodies: how the model distributes groundwater between the Pearl Harbor Estuary and offshore (submarine) discharge areas can affect upslope flow patterns including the Red Hill area.

Gradients simulated by the interim flow model do not comport well with measured gradients in and around Red Hill facility. While this is in part related to conditions local to Red Hill, the interim model exhibit high sensitivity to conditions downgradient of Red Hill. The interim model represents the downgradient discharge (outflow) from the model to the saline water bodies (Pearl Harbor Estuary and offshore areas south of Pearl Harbor) via a general head boundary (GHB) with some areas exhibiting intervening high-conductivity cap rock (GPEC Report Section 4.4). The GHB allows flow based upon an ascribed elevation and an intervening resistance between the boundary and the aquifer. In this configuration, groundwater is simulated to preferentially flow to the eastern part of Pearl Harbor Estuary. However, muds and volcanic ash on the bottom of Pearl Harbor may impede flow leading to more flow from Moanalua Aquifer to the Waimalu Aquifer. Flow from the Moanalua Aquifer to the Waimalu Aquifer where spring systems and large pumping centers create significant drawdown could result in a flow path beneath the Red Hill facility to the northwest.

Thus, though there are insufficient available data regarding the distribution and properties of downgradient discharge outflow boundary to accurately and uniquely represent it in the groundwater model, sensitivity analyses indicate this area is important to regional flow patterns (GPEC Report Section 5.9). Therefore, available information must be interpreted in the context of the CSM and AOC to provide an appropriate representation for purposes of the flow and transport modeling.

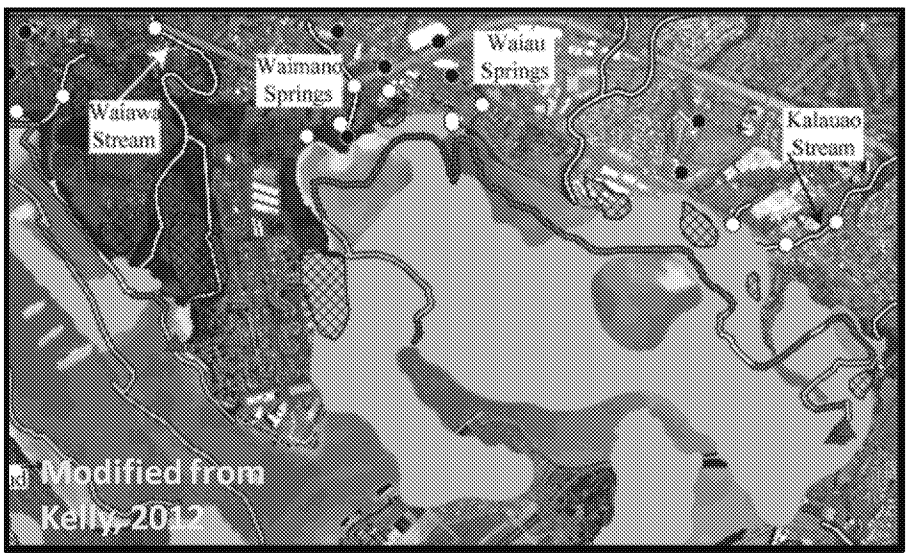

Figure 10.1 Example Figure Illustrating Variable Discharge to Pearl Harbor

The approach to simulating the groundwater flow to the Pearl Harbor Estuary and the southern offshore regions needs further work. Although uncertain in extent and character, it is important to represent the downgradient outflow conditions as accurately as possible, using as one basis the CSM regarding the distribution and properties of these features, and also other sources of information (Inset Figure 10.1).

The solution likely lies in two parts: First, re-interpretation of the available data, with expanded use of sensitivity analysis and model calibration to help identify probable geometries and properties. Model refinements may include using multiple layers to simulate the caprock and include older alluvial sediments and the muds and tuffs that blanket the floor of Pearl Harbor. Second, based on the anticipated results of sensitivity analyses conducted with this updated representation of these features, consideration should be given to methods of data collection to better constrain the likely presence, extent and properties of these features.

References:

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "CSM Report")

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "GPEC Report")

Attachment 2 – Appendix

ATTACHMENT 3

Interim Fate and Transport Analyses

8. LNAPL Fate and Transport.

The following set of comments pertain to the contaminant transport aspect of the CSM and related modeling and evaluation approaches taken by the Navy's technical team. Conceptually, contaminant transport will depend on a suite of facets starting with the LNAPL migration that will occur following its release to the subsurface and the cumulative effects of multiple releases over time. While the LNAPL is mobile and moving in the environment, it poses a potential threat to receptors as a free-phase contaminant. Once the LNAPL ceases to move, the residual along the transport pathways presents a longer-term source of contaminants to groundwater that may be transported some additional distance within the aquifer system. Combined, these two aspects of fuel F&T represent the primary threat pathways to the sole-source groundwater resource. The Navy team's conceptualization of these processes would benefit from additional technical work and data collection to be more consistent with observed site data discussed in prior comment sections.

It is unclear how the Navy's current CSM will effectively represent LNAPL transport as indicated in Section 7.4 of CSM document that states: *"..to estimate LNAPL migration for current and potential future releases, including the fraction expected to be immobilized in the vadose zone, and the fraction expected to reach groundwater. The modeling effort will also include an assessment of the potential migration of LNAPL within the saturated zone."* The primary component of the Navy's LNAPL current modeling approach is a *"statistical LNAPL holding model"* that accounts for only the residualization of some fraction of an assumed LNAPL release within an assumed release geometry. This results in a source zone for the dissolved phase transport model that is rather arbitrary in nature since no active LNAPL transport calculations have been done to account for primary and preferential pathways, pore volume already occupied by past releases or infiltrating water, or the characteristics of different release rates. While perhaps useful for some general framing, this non-dynamic form of LNAPL modeling cannot determine critical aspects of risk determinations and potential mitigation approaches. The Navy team's CSM and contaminant fate and transport evaluation should be able to address questions, such as:

- What range of LNAPL releases might reach groundwater (and how quickly) as a function of release rates, locations, fuel types, and other characteristics? Transport in each area of the tank farm can reasonably be expected to behave differently based on the boring and barrel logging of the ridge. How do geologic distribution differences affect the transport outcomes?
- How do chronic low-rate releases behave in comparison to large-scale sudden events? How can the release event ranges be confidently bracketed and what are those ranges?
- Related, what is the fraction of residual capacity already taken up by pre-existing releases or infiltrating water, and how can that be determined from existing data? If it cannot be determined from existing data, what conservative assumptions might be made?
- How fast and how far might LNAPL travel as a function of various release scenarios and in what directions? The approach discussed by the Navy teams assumes a southwest direction that does not seem to comport well with observed detections of petroleum related compounds and depletion of natural attenuation parameters to the northwest.
- How can hydraulic capture be achieved for LNAPL containment in context with the

estimated LNAPL transport rates and under what kinds of pumping regimes?

- How far would an LNAPL release need to propagate to create potential detections at the Halawa Shaft and/or other groundwater resource areas and with what release volume and scenario could that occur?

As the regulatory agencies SME's LNAPL screening modeling shows, a release that exceeds the formation's residualization capacity, which is presently undefined in the CSM or by any correlative data, could potentially reach the water table zone at a rapid rate. This rapid downward transport may result in LNAPL gradients that exceed the shallow groundwater gradient resulting in LNAPL migration in unexpected directions and distances. This is an area that needs more development prior to submitting a revision to the fate and transport model, since the area covered by LNAPL plumes is the source zone for the dissolved phase transport model.

Defining specific LNAPL transport parameters will be a significant challenge in this environment. The Navy should consider what additional efforts can be taken to characterize these parameters. Unfortunately, core-scale testing in petrophysical labs (CSM Chapter 5.2.3) may be of limited value. As evidenced through the results of the API LNAPL Parameters Database compilation (API 4731, 2003), capillary centrifuge testing has also been shown to be suspect where residual saturation is over-estimated compared to field studies and other soil properties databases (e.g. U.S. Salinity Lab and others). It has also been observed in work at the IDPP OU1-C area in Honolulu that the residual saturations determined in the lab are unreliable and non-conservative. The Navy needs to develop an approach to better constrain the residualization capacity of the formation. Briefly, in situ samples collected by continuous coring in free-phase LNAPL zones generally test at or below residual saturation values in site areas of significant free product LNAPL. Since LNAPL cannot flow into a well if it is below residual in the formation, these lab-derived values conflict with site LNAPL observations. The same limitations may be expected for the Red Hill petrophysical testing program and we recommend the Navy team develop alternate bench and field testing and data collection methods to more realistically constrain these important LNAPL F&T parameters.

Absent additional source zone characterization data, the LNAPL residual capacity will remain unconstrained along with other important elements to the LNAPL transport regime. As noted, this is one of several critical factors in the dynamic evaluation of LNAPL transport and potential risks to the groundwater system. Where measurements and data are absent, a greater degree of conservatism in the estimation approaches is necessary to allow for that uncertainty.

<u>References:</u>

API #4731, 2003. Light Non-Aqueous Phase Liquid (LNAPL) Parameters Database - Version 2.0 - User Guide.

Considerations on LNAPL Transport at the Navy Red Hill Facility, February 2018. G.D. Beckett, a presentation to interested Red Hill parties.

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "CSM Report")

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "GPEC Report").

Nonaqueous-Phase-Liquid Dissolution in Variable-Aperture Fractures: Development Of A Depth-Averaged Computational Model With Comparison To A Physical Experiment. Detwiler, R.L., Rajaram, H., 2001. Water Resources Research, December 2001.

Neuman, S. P., 2005. Trends, Prospects and Challenges in Quantifying Flow and Transport Through Fractured Rocks. Hydrogeology Journal, March 2005, Volume 13, Issue 1, pp 124–147.

Item 9. Groundwater Data

Groundwater flow and contaminant migration pathways beneath the Red Hill facility are poorly understood. Analysis of groundwater chemistry data can help constrain flow paths. The interim and final groundwater flow models should present reasonable correspondence with available water level and gradient data, so they can underpin the transport model (developed to predict the fate of contaminants from potential releases) which in turn should present reasonable correspondence with available water quality data. This includes contaminant data and other data that may evidence groundwater impacts (e.g., terminal electron acceptors [TEAs]), or of migration directions and mixing of water from different sources (e.g., isotopic data and other quality indicators).

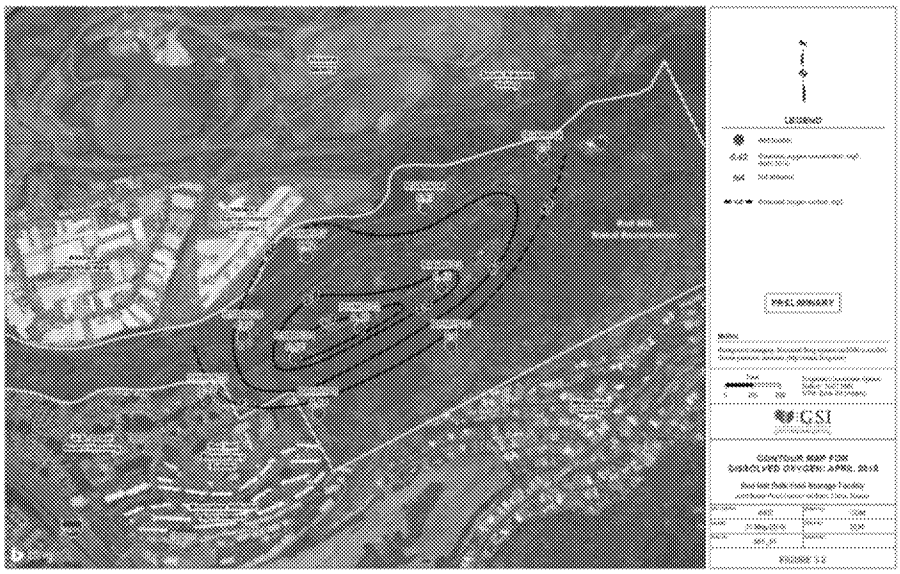

Figure 9.1 Example Terminal Electron Acceptor (TEA) Map – Dissolved Oxygen

Interpretations of water quality data presented in the CSM Report and GPEC Report are in places non-conservative, and conflict with other lines of evidence and with conclusions reached by regulator SMEs. Example 1: The Navy consultants dismiss some detected results out of concerns for data quality (CSM Report Section 7.2 and Appendix B.7). Though in some instances justified, these concerns do not address all detected results, and from the regulatory perspective, any reported detections that are not qualified are evidence of impacts. Example 2: Independent analyses of TEA data presented and discussed in CSM Report Section 7.3.2 and Appendix B.4 and GPEC Report Figure 6.3 as indications of natural attenuation (e.g., Inset Figure 9.1), dissolved phase contaminant detection frequency and distribution (inset Figure 9.2), and hydraulic gradients, suggest transport occurred not just to the southwest but also to the northwest and possibly northeast of the facility. Example 3: The distribution and concentrations of general chemistry data (i.e. major ions, specific conductivity, and pH) show a poorly-mixed system inconsistent with the Navy CSM of robust flow from upslope recharge areas to Red Hill Shaft. The chemistry is highly variable with chloride concentrations spanning over an order of magnitude and is more suggestive of sluggish down-slope flow and compartmentalization (inset Figures 9.3 and 9.4).

The relative absence of high-concentration detections within the small, widely-spaced, monitoring network around Red Hill is not proof of absence of impacts, but appears to be interpreted as such by the Navy consultants. Other data, including TEAs, TPH and individual fuel constituents suggest a broad area of impacts extending in various directions within a complex groundwater flow system that is not uniformly Mauka-to-Makai, with the possibility of LNAPL impacts at the water table as the cause.

Before developing the transport model, it is important that the CSM encompass reasonable interpretations of available water quality data. The CSM should, at this stage, allow for "alternative hypotheses" of at least equivalent likelihood of LNAPL impact to groundwater versus the current hypothesis of there having been no impacts. The final groundwater flow model, when it reasonably represents hydraulic gradient directions and magnitudes in the vicinity of Red Hill ridge, would be anticipated to underpin a contaminant transport model that demonstrates a reasonable match historical sample results (contaminants and TEAs, etc.), thereby demonstrating that the model is useful for near-field transport to understand the available groundwater data, and for developing predictions of contaminant transport and fate to help evaluate risk and mitigating responses or strategies.

Figure 9.2 Example Map of TPH-D Detections

Figure 9.3 Image of Chloride Concentrations Sampled at Wells

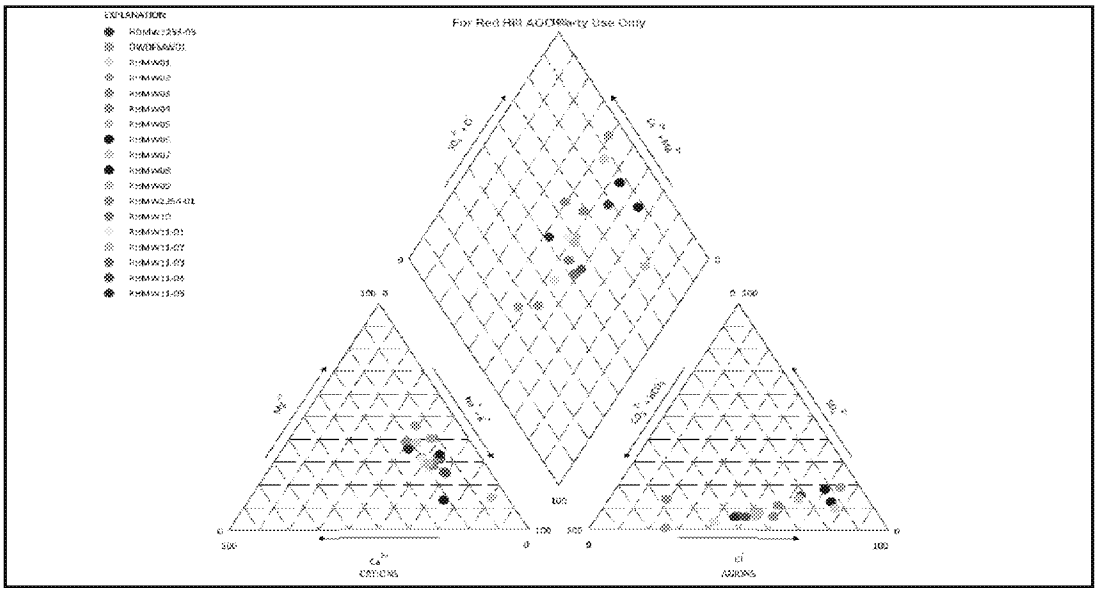

Figure 9.4 Example Piper Diagram

References:

Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "CSM Report")

Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility (dated July 27, 2018: "GPEC Report")

10. **LNAPL and Dissolved-Phase Plume Distribution**:

The LNAPL and dissolved-phase plumes are potentially more widespread and in alternate directions than the Navy team's CSM suggests. This has direct implications to the estimation of potential risks. The CSM will benefit by consideration of these observations as representative and then accommodate those implications through more thorough evaluations and possibly additional data collection/demonstration. Site specifically, there are multiple data sets that indicate there have been historic detections of interest to the west and northwest. For example, the dissolved-oxygen depletion shown in Figure 9.1 closely parallels the observed historic detections of TPHd in groundwater, as expected based on the mechanisms of degradation and transport. The CoC distribution, elevated temperature distribution (Figure 10.1), and other natural attenuation parameters also support this historic transport direction.

Much less is known with respect to the potential LNAPL distribution in the subsurface that is the source of these groundwater impacts. Simplified transport estimates suggest that for a wide range of general site parametric conditions, the expected downgradient extent of these compounds is typically less than 100-ft away from the LNAPL source zone, particularly when attenuation rates are high. Naphthenic compounds, due to their transport properties, are not generally highly transportable in aquifers. This suggests the possibility of distal LNAPL impacts relative to the Tank Farm from cumulative historic releases that have left their signature in the groundwater system. Naphthenic compounds are frequently detected at several outlying monitoring locations at low concentrations (commonly J-flagged), but detections of petroleum related compounds and depletion of natural attenuation parameters (NAPs) occur predominantly in the tunnel and northwest wells.

With regard to the CSM interpretations about the outcome of the 2014 Tank 5 release, perhaps one of the most fundamental is the estimated release volume of 27,000 gallons. The regulatory agency SMEs have not been able to find the specific release volume calculations nor the certainty bounds on that value. In our experience, release volume estimates have significant uncertainty that would affect the assumptions and conclusions in the CSM, particularly given that the release occurred during both filling and draining of Tank 5. We believe the particular details of the release estimate need to be more fully discussed in the CSM and the implications of that range considered in the evaluations. If the estimate is relatively certain, that should be documented with the appropriate background so that related interpretations are appropriately bounded.

The CSM and the underlying available data cannot (at present) reliably place the LNAPL source zone(s) in context with the observed groundwater contaminant distribution. The underlying cause for this gap is the absence of characterization around the Tank Farm. The product staining indications in historic angled-core sampling beneath various Red Hill USTs are useful, but none of those investigatory locations were intended to be sampled to groundwater. Further, it is unclear whether wells RHMW01 through RHMW03 are directly within an area of vadose zone contamination or not. At the time of their installation there were no gross indications of vadose zone fuel impacts, but groundwater was impacted, suggesting a complex relationship between release transport pathways and groundwater impacts. In other words, LNAPL impacts in the vadose and water table regions sourcing these impacts are not delineated by the available investigatory locations. This key uncertainty is not adequately discussed in the CSM, but affects all the related F&T discussions and framing.

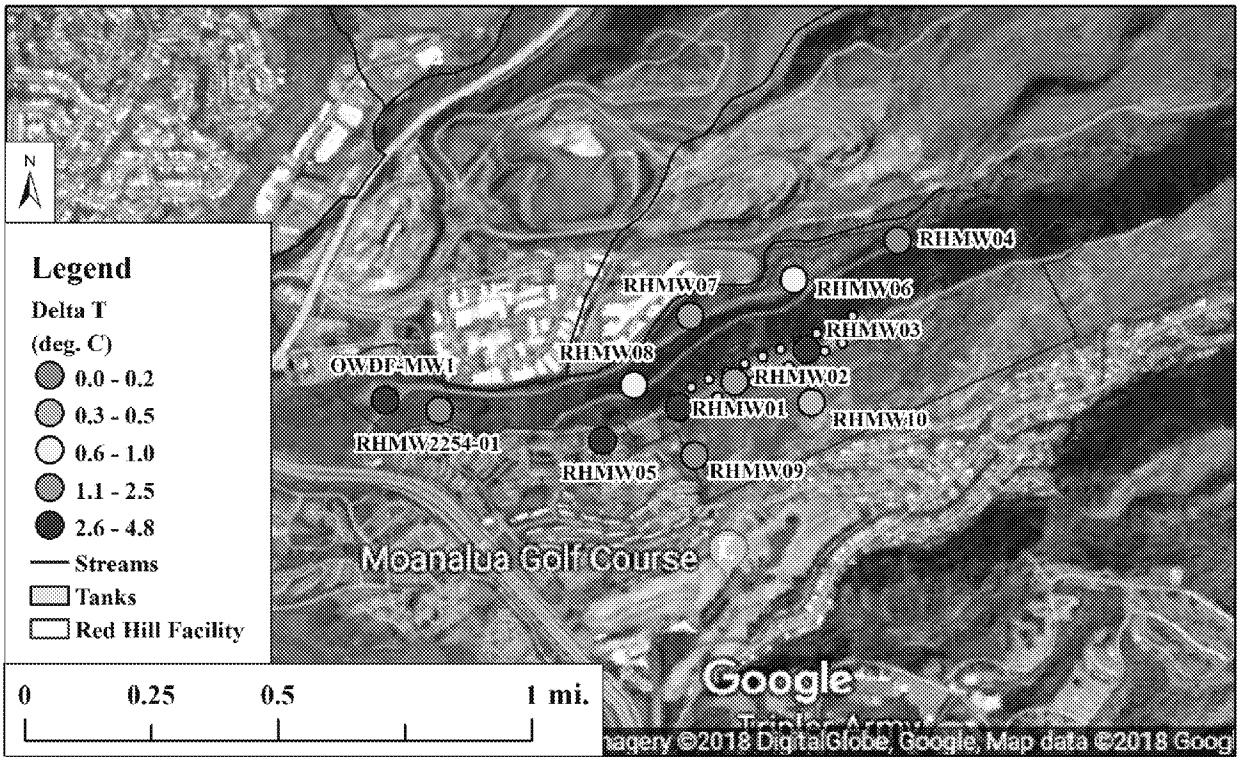

Figure 10.1 Net average temperature greater than the Red Hill Shaft (RHMW2254-01; in degrees Celsius). Like other MNA-related parameters, the elevated temperatures are generally along the Red Hill Ridge and to the west and north. Data source: USGS Synoptic Data, 2018.

The in situ vapor probe response around Tank 5 in the timeframe following the 2014 release can be interpreted as indicating that the primary vapor migration may have been to the northwest side of that tank and not in the direction of RHMW02 (see Figure 10.2 below). Actual LNAPL transport outcomes beneath Tank 5 in 2014 below the vapor probes is unknown; the conservative assumption based on this limited data is that transport was potentially to the northwest and is not represented with any certainty by the spatially limited monitoring well array.

In terms of the depth of migration of LNAPL from the Tank 5 release in 2014, the primary analysis relied upon in the CSM is the thermal profile at RHMW02, with backup support from chemistry considerations. A net positive temperature profile indicates the effects of exothermic biologic reactions and is affected by a variety of subsurface factors. In general, that relationship can be useful to infer lateral distributions of LNAPL biodegradation (e.g., Figure 10.1 above) but is highly uncertain with respect to the LNAPL vertical distribution. In many cases, as shown in the example thermal profile in our August 15, 2018 presentation (Slide 28), the LNAPL vertical mass distribution cannot be inferred from the temperature profile. A review of data in the 2007 Red Hill investigation report (DON, 2007) shows that the rock cores were evaluated for evidence of petroleum contamination by checking for odor and by screening with a photo-ionization detector. No evidence of petroleum contamination was found. The groundwater temperature in RHMW03 measured during sampling has remained unchanged at about 26.5 °C since first sampled in 2005 to the present, indicating that the temperature profile recently measured by the Navy likely existed when RHMW03 was first drilled. As a consequence, this locally-elevated temperature does not directly relate to the migration or distribution of LNAPL arising from the 2014 release but

relates (at least, predominantly) to past releases. Also, there has been no release of consequence since 2005 that would cause LNAPL to enter the zone indicated by the thermal anomaly in RHMW03. In summary, the Navy's contention that the thermal profiles in the tunnel wells show that the LNAPL is constrained above the water table is not supported by the available data. We believe the Navy technical team needs additional data to validate its interpretation of LNAPL transport around Tank 5 from the 2014 release, as it is a fundamental cornerstone to the remainder of the LNAPL F&T considerations. At a minimum, the Navy should include several Hawai'i or equivalent geology examples where the LNAPL source distribution has been definitively interpreted by this method and independently validated through subsurface data demonstrating that actual LNAPL source distribution (e.g., core sampling, downhole investigation, etc.). Alternatively, it would be useful to consider a site specific data collection program to verify the LNAPL source distribution around Tank 5 and possibly other key locations. By whatever approach, additional lines of evidence are needed to verify the assumptions relative to fate and transport of the 2014 release.

Lastly, CoC concentrations in groundwater at RHMW02 (and occasionally other locations) have been within the expected solubility ranges for jet, diesel and other fuels stored at the facility, suggesting that LNAPL may be in direct contact with the aquifer system somewhere in the vicinity. Robert Whittier, currently at DOH, visually observed LNAPL blebs at RHMW02 when this well was sampled using a bailer, indicating residual LNAPL in the vicinity of this well. Further indicating that LNAPL reached groundwater, was the distinct increase in several CoCs at this location immediately following the 2014 release that can be interpreted as a breakthrough curve (Figure 10.3). While the Navy Team's interpretation is of simple coincident data scatter, these data could be interpreted as a new arrival of LNAPL to groundwater in the general vicinity of RHMW02 in the timeframe associated with that release. The CSM would benefit from examining these potential viable working hypotheses, though it is acknowledged that this is a spatially sparse data set.

This alternate interpretation of LANPL reaching the groundwater table following the 2014 release is consistent with site data and transport processes. The chemical analyte ratio methods used in the CSM to suggest otherwise are unbounded by site specific data of fuel compositional variability and analyte transformations. Further, we believe where chemical ratios use TPHd values, those values should also consider the native totals (without silica gel cleanup) because the parent hydrocarbons are predominantly derived from the original petroleum source(s). We also recognize the value of having both native and silica gel cleanup values for interpretation for various aspects of this investigation such as biodegradation and attenuation.

Lastly, the current deployment design for the in-situ sampling pumps below the water table within the existing monitoring wells precludes the sampling of LNAPL or any direct observation of an LNAPL plume, if present. Such measurements could however be accomplished in these wells periodically either by resetting these pumps or removing them to allow direct sampling of the top of the water table.

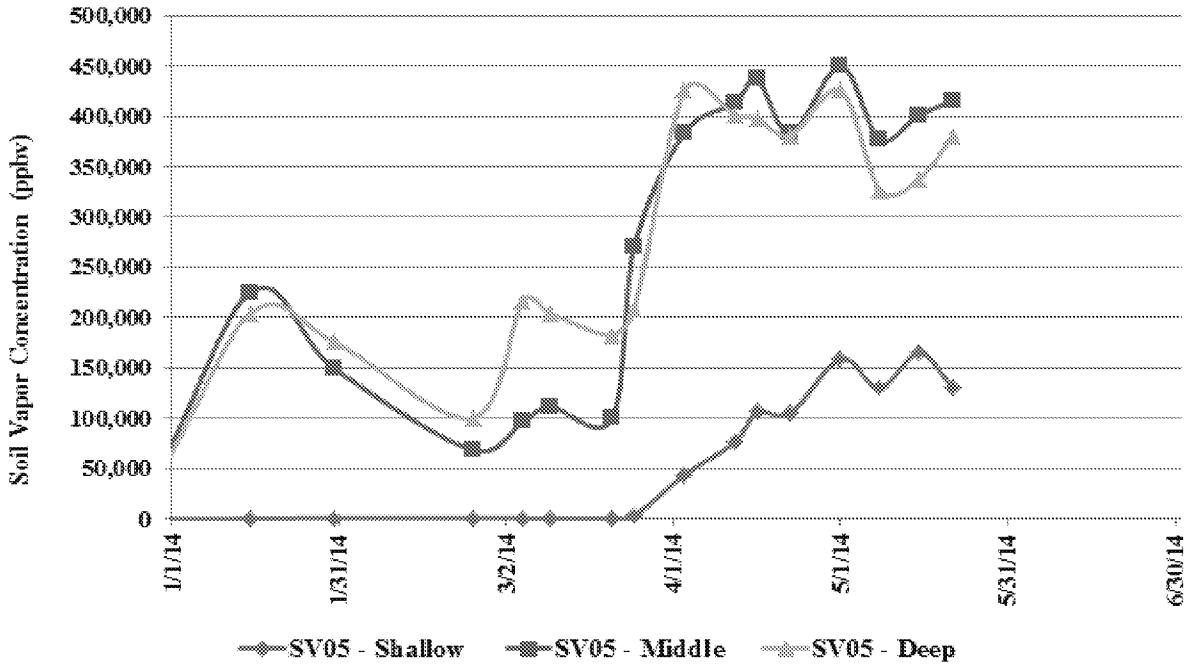

Figure 10.2 Soil vapor probe readings beneath Tank 5 following the January 2014 release. The deep probe is toward the outside of the tank corridor and the shallow probe closest to the tunnel. These data can be interpreted as initial release migration to the northwest of this Tank; note the shallow probe has low level detections that are not visible on a linear plot.

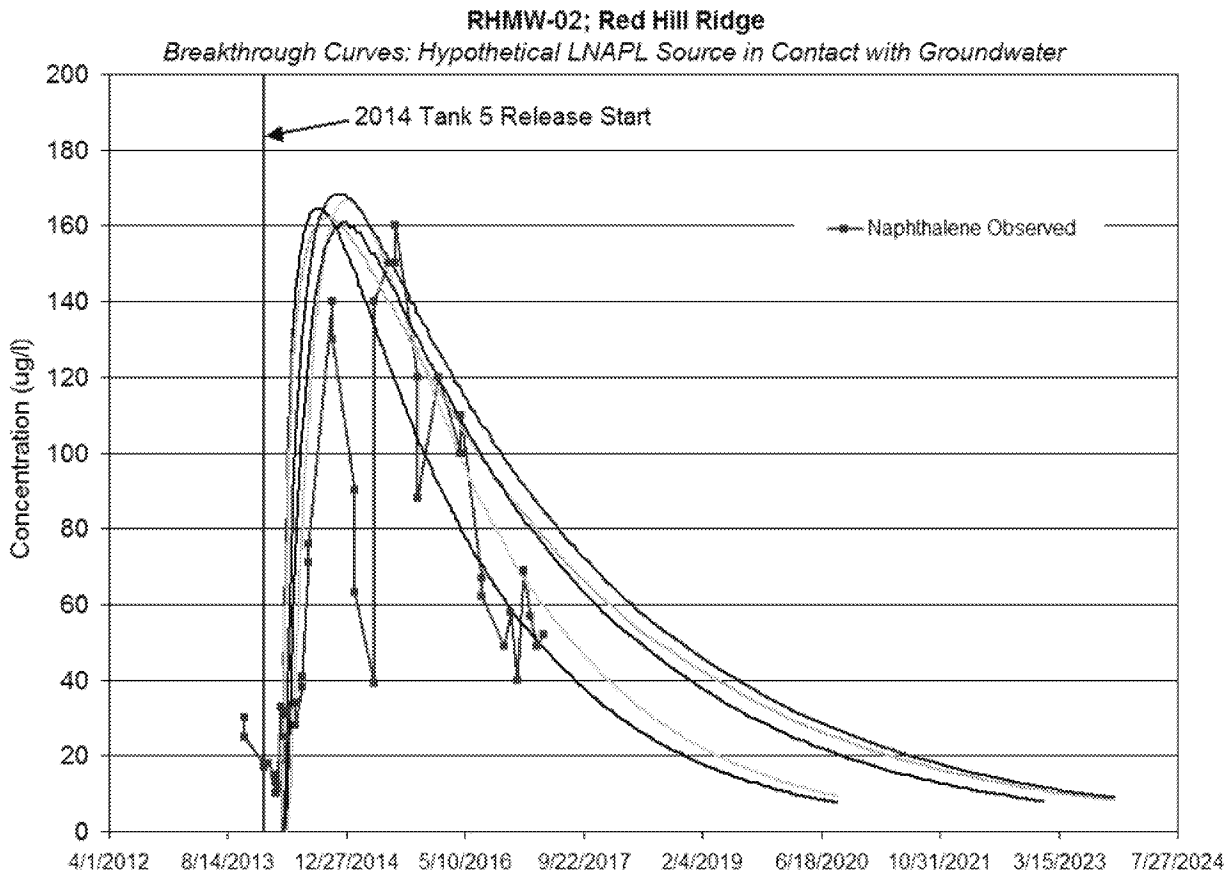

Figure 10.3 Observed naphthalene concentrations following the 2014 Tank 5 release and a family of conceptual contaminant transport breakthrough curves matching those data. Other interpretations are viable, as is the possibility of LANPL contacting groundwater near RHMW02 following that release.

References

Department of the Navy (DON), 2007. *Red Hill Bulk Fuel Storage Facility Final Technical Report, Pearl Harbor, Hawaii*. 12 Prepared by TEC Inc., Honolulu, HI. Pearl Harbor, HI: Naval Facilities Engineering Command, 13 Pacific. August