Characterization Of Amchitka Island Subsurface: Groundwater Modeling In The Vicinity Of The *Long Shot* Test Shot[1]

SUMMARY

Groundwater flow modeling was carried out to estimate the groundwater flow patterns from the *Long Shot* test site to discharge through the ocean floor. New data from the magnetotelluric (MT) studies described in Chapter 6 were used in combination with data from earlier studies to calibrate the model. In addition, the following assumptions were important differences from previous groundwater flow modeling: i) actual topography was used across the island instead of assuming symmetry across Amchitka's long axis, ii) cases assuming subsurface geological homogeneity or the presence of an andesite sill layer (non-homogeneous) were compared. The questions to be addressed by this effort are:

1. What is the impact of the new MT data and case assumptions on the estimated locations for discharge of groundwater originating from near the *Long Shot* test site?
2. What is the impact of the new MT data and case assumptions on the estimated time for groundwater to travel from near the *Long Shot* test site to the point of discharge through the ocean floor?

Only the *Long Shot* test site was examined because of the limited time available from completion of the MT data analysis.

Results of these groundwater modeling efforts indicate

1. Groundwater travel times from the *Long Shot* test shot to discharge through the ocean floor into the marine environment will take very long times. Estimates of travel times range from 1,400 to 4,700 years assuming a homogeneous subsurface for likely scenarios, and from 400 to 1,400 years assuming the influence of an andesite sill layer. Contaminant transport travel times will be longer than groundwater travel times because of contaminant retardation processes (e.g., adsorption and diffusion).
2. Including the presence of subsurface heterogeneity (i.e., andesite sills), actual topography, and the knowledge gained from the MT studies can have a significant impact on the estimated travel times and discharge locations for contaminants from the test shots to the marine environment.

The above results indicate that further groundwater modeling is warranted that considers the full range of geophysical information gained through this CRESP study. Factors to be considered should include subsurface fresh to salt water transition zones, subsurface heterogeneity, porosity variation, and actual island and off-shore (marine floor) topography. These modeling studies would

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[1] The results presented in this chapter are a condensation of Appendix 7.A authored by Anna Forsstrom and David Barnes, Dept. of Civil and Environmental Engineering, University of Alaska, Fairbanks, Alaska. Although not considered here, the possibility exists that the subsurface disruption due to the nuclear explosions significantly disrupted the groundwater flow for an extended period of time following the test shots.

result in reduced uncertainty in the travel times and discharge locations of groundwater from the test shots to the marine environment.

INTRODUCTION

The objective of this study is to characterize the groundwater flow through the basin in which the *Long Shot* test was conducted. The specific questions to be answered were:

1. What is the impact of the new MT data and case assumptions on the estimated locations for discharge of groundwater originating from near the *Long Shot* test site?
2. What is the impact of the new MT data and case assumptions on the estimated time for groundwater to travel from near the *Long Shot* test site to the point of discharge through the ocean floor?

A two-dimensional groundwater flow model of a cross section through the *Long Shot* site was developed. This model incorporated values from literature data and from magnetotelluric (MT) data taken in summer 2004. Several homogeneous and layered scenarios were modeled in order to calibrate the modeled data to the MT data. Results from this study will provide additional insight into the location of the sea floor discharge zones and groundwater flux rates, which will enable an improved prediction of radionuclide transport rates.

In addition, a study was initiated as part of this overall task to develop improved estimates of diffusion rates in the subsurface strata because of the influence of this parameter on contaminant transport rates. To accomplish this, an experimental study was initiated using subsurface core materials from Amchitka. That study is being completed under funding from other sources, and because only very preliminary results are available, is not being reported here.

Geology

From 1964 to 1972, beginning prior to the underground detonations, U.S. Geological Survey (USGS) performed extensive studies on the geology and hydrology of Amchitka Island. Merritt and Fuller (1977) summarize the geologic history of Amchitka Island. Amchitka Island is a part of the Aleutian Island arc consisting of a curving submarine trench as deep as 7,600 m (Merritt and Fuller, 1977). The arc extends from the Gulf of Alaska across the north Pacific to Kamchatka with a parallel ridge rising to the north. The western part of this ridge is the Aleutian Islands and the eastern part is the mountainous Alaska Peninsula. A zone of convergence exists along the Aleutian arc although, most of the tectonic features are of probable tensional origin. Faulting, differential uplift, marine, stream, and glacial erosion predominant along the Aleutians have disturbed Amchitka Island (U.S. Army Corps of Engineers and USGS, 1965).

The bedrock of Amchitka Island is primarily Tertiary submarine and subaerially deposited volcaniclastic rocks with subordinate lava flows and intrusive units (U.S. Army Corps of Engineers and USGS, 1965). Carr and Quinlivan (1969) reported four major stratigraphic formations on Amchitka: older breccias and hornfels, the pillow lavas and breccias of Kirolof Point, the Banjo Point Formation, and the Chitka Point Formation. The eastern part of the island is divided into two main units; uppermost is the Banjo Point Formation which overlies the Chitka Point Formation. The formation of the southeastern half of the island is the Banjo Point formation of Oligocene or Miocene age. It is estimated to be more than 3,000 m thick and mainly composed of volcanic breccia. The porosity of the Banjo Point Formation ranges between 4 and 26 percent (Gard and Hale, 1964). The Chitka Point Formation is estimated to be in excess of 4,900 m thick (Gard and Hale, 1964). At the central and western part of the island the Chitka Point consists of sandstone, conglomerate, and volcanic breccia.

The *Long Shot* site is underlaid by 1,220 m of Banjo Point formation (Gard and Hale, 1964). Tertiary volcanic tuffs and breccias are bounded by fractures and/or fault zones on the northwest, southeast, and southwest sides (U.S. Army Corps of Engineers and USGS, 1965). At ground zero, the rocks are altered pyroclastic rocks of andesitic and basaltic composition. The trend of the lineations is generally transverse to the island (N 55°E to N 60°E) near the *Long Shot* site (Gard and Hale, 1964).

Starting in 1964, the U.S. Army Corps of Engineers did exploratory drilling for the *Long Shot* detonation. Vertical and directional holes EH-1, EH-3, EH-5, EH-5a, EH-6, and EH-6a were successfully cored and logged (U.S. Army Corps of Engineers and USGS, 1965). The emplacement hole for the *Long Shot* detonation, EH-5, was drilled vertically to a depth of 750 meter below sea level (mbsl). At 183 m northwest and southwest from EH-5, holes EH-3 and EH-6 were directionally drilled to cross hole EH-5 at 640 mbsl. Hole EH-1 was located 335 m north of EH-5 and close to a possible fault. This hole was drilled to a depth of 490 mbsl.

One notable stratigraphic feature in this region of the island is the two layers of andesite encountered in EH-3, EH-5, EH-5a, and EH-6a between depths of 679 and 771 mbsl. The “main andesite” is about 76 m thick overlaid by a 4.6 m thick layer, referred to as the “first andesite”. A layer of tuff and siltstone is embedded in between the andesite sills. When looking at overlying gross units, general correlations can be made but there is no certainty where top or bottom of such a unit is located. The andesite encountered in holes EH-3 and EH-5 nearly corresponds to andesite found in the quarry at Hill 165 located 2.7 km northwest of *Long Shot*. There are both similarities and dissimilarities in petrographical and chemical studies between the andesite in EH-5 and the quarry outcrop, however a correlation between the locations cannot be proved or disproved. The andesite at the quarry dips 12° to 16° southeast. A dip of 14° would carry the andesite to the same depth as the main andesite at EH-5. Sea-cliff strata in this area show a southeast dip of 5° to 15°. A lithologic correlation can be made between core holes EH-3, EH-5, and EH-6 but not with core hole EH-1 (U.S. Army Corps of Engineers and USGS, 1965).

Hydrology

A hydrologic network was established on Amchitka Island in 1967 and continued through August 1974. The hydrologic studies were prompted by the potential of using Amchitka Island as a location for high yield testing. Surface water gauging stations and groundwater observation wells were installed at potential sites for possible high yield emplacement holes. Groundwater investigations performed during this investigation included water level monitoring in test wells and other holes. Furthermore it included a detailed testing of deep exploratory holes at actual and potential test sites across the island. The investigation also integrated surface study of hydrologic features such as springs, terrestrial seeps, and perennial lakes and streams.

Because of the Island's remoteness, little data were collected before and after the long-term hydrologic network in the late 60's. Reported mean annual precipitation for February 1943 through June 1948, and from October 1967 through June 1972 was 828 and 953 mm respectively. Gard and Hale (1964) computed a recharge rate to range between 4 and 12 percent of 889 mm annual precipitation. This rate was based on flow net model, head distribution, and estimated hydraulic conductivity for *Long Shot*.

The lower plateaus of Amchitka Island are composed of small drainage basins and hundreds of small lakes and ponds (Gonzalez, 1977) with bottoms of low permeability materials (Merritt and Fuller, 1977). Precipitation temporarily stored in the lakes and mantle of tundra and peat moves directly to the stream channels or laterally to the stream courses and thereafter discharge into the ocean (U.S. Army Crops of Engineers and USGS, 1965). The upper few meters to a few hundred meters beneath the surface of Amchitka Island consist of permeable materials such as tundra, soil, peat, and fractured and weathered volcanic rocks (Merritt and Fuller, 1977). At shallow observation wells a rapid response in water levels could be seen during precipitation events. This response indicates a high infiltration rate in the top few meters of the subsurface. Moreover, a clay zone is present at the base of the tundra and peat in some areas across the island, which retards the recharge to the bedrock (U.S. Army Corps of Engineers and USGS, 1965). These two observations lead to the conclusion that a large fraction of precipitation infiltrates and flows through shallow aquifers and discharges to surface bodies. Gonzalez (1977) and Merritt and Fuller (1977) performed a comparison between precipitation and runoff altitude relationships and concluded that most precipitation results in surface water runoff. At several test holes the water level was within few meters of the land surface which implies that the sediment of the lowland parts of the island is saturated essentially to land surface. Gonzalez (1977) and Merritt and Fuller (1977) also suggest that the water table is at or very near surface over most of Amchitka Island.

The overall direction of groundwater flow beneath most of Amchitka is downward (Gonzalez, 1977). The groundwater is most likely flowing from approximately the central part of the island towards the coast as is consistent with island groundwater hydrology (U.S. Army Corps of Engineers and USGS, 1965). This groundwater flow pattern could be changed by the inclined bedding of the sediments and intrusive rocks, which would result in a diversion of the flow to the coast within a few kilometers of a recharge area by the numerous cross-cutting, permeable, and near vertical fracture zones. In addition, hydraulic testing has also shown that primary avenues for fluid movement are fractures such as joints and faults. Fracture intensity decreases with depth due to a tendency of fracture closing under greater lithostatic loads (Gonzalez, 1977 and Merritt and Fuller, 1977). These features decrease the transmissivity with depth (Merritt and Fuller, 1977).

Long Shot was detonated at a depth of 701 m below land surface (mbls) and within the Banjo Point Formation. The site is divided by linear features (faults or lineations) that express probable near-vertical permeable fracture zones (U.S. Army Corps of Engineers and USGS, 1965). Two northeast-trending linear features are located at 610 m apart on each side of the *Long Shot* site. Hazleton-Nuclear Science Corporation (1964) estimated a hydraulic conductivity of these features to be 3.53×10^{-4} m/s. Furthermore, a north-trending feature cuts the two northeast-trending features about 2,410 m from the coast (U.S. Army Corps of Engineers and USGS, 1965).

Both the Banjo Point formation and the andesitic sill have very little interstitial permeability (U.S. Army Crops of Engineers and USGS, 1965). The andesite sills encountered between 679 to 771 mbsl contain cooling joints and tectonic features. When compared with the bulk of the bedrock, the sills are of moderate hydraulic conductivity and, thus affect the overall groundwater flow. The hydraulic conductivity of the fractured sill units is from 4.72×10^{-8} to 4.72×10^{-7} m/s, which is slightly greater than the hydraulic conductivity of the Banjo Point bedrock. A bulk hydraulic conductivity of the Banjo Point formation is approximately 3.53×10^{-8} m/s (Hazleton-Nuclear Science Corporation, 1964). In summary, the most permeable of the Banjo Point formation is the fracture zones followed by a moderate permeability in the sills and the bulk of the formation is poorly permeable. Considering the thickness of the sills in comparison to the fractured zones, the sills are more transmissive and, thus constitute the major pathway for groundwater flow. The principal recharge to the system at the *Long Shot* site is most likely along the fracture zones.

The general groundwater flow pattern is from the central part of the island towards the coast. Many features such as fractures and inclined bedding of sediments will influence this pattern. The fractured andesite sill units with higher hydraulic conductivity compared to the average hydraulic conductivity of the Banjo Point formation is an important feature that needs to be taken into consideration when looking at the groundwater flow pattern. The U.S. Army Corps of Engineers and USGS (1965) suggest three different cases of groundwater circulation at the Long Shot site.

Case 1 assumes that the andesite sill is the only water transporting unit and that the andesite unit is continuous with the andesite that was encountered at the quarry 2.7 km north of EH-5. The circulation pattern would be northward to the sea from the outcrop area towards EH-5. More permeable fracture zones and vertical faults intercepting the andesite sills are not taken into account which makes this pattern unlikely.

Case 2 assumes that no groundwater flows in the bedrock block between the fracture zones and that that no recharge occurs to the bedrock. The andesite sill is assumed continuous. Water should then move from the fracture zones into the sills at the *Long Shot* site. Movement of water near shore and seaward will occur from the sills to the fracture zones and discharge in the ocean.

Case 3 assumes permeability of the bedrock block above and below the sills and between the fracture zones approximately the same as the sills. This would result in a somewhat less travel time for the water to move from EH-5 to the ocean compared to case 2. Also, a larger volume of water would discharge to the ocean.

In this study, a two dimensional combination of case 2 and 3 was investigated. It was assumed that the andesite sill unit is continuous. The permeability of the bedrock block above and below the andesite sills and between the fracture zones is smaller than the sill. Recharge occurs to the bedrock and groundwater flows in the fractured bedrock.

Freshwater saltwater interface

Beneath oceanic islands, a lens of freshwater sits above relatively denser saltwater. In the ideal case of a homogeneous and isotropic island, the freshwater body assumes a lenticular (lens-like) shape bounded at its base by a concave-upward surface. The infiltrating water flows laterally and thereafter upward exiting in seepage zones along the shoreline. The freshwater lens is therefore thickest under the central part of the island. In the central part of the island close to the *Long Shot* site, U.S. Army Corps of Engineers and USGS (1965) estimated the interface between freshwater and saltwater at deeper than 760 mbsl.

Several methods have been formulated to estimate the freshwater interface with saltwater in coastal and island aquifers. Assuming the fresh water and saltwater to be immiscible and the liquids are hydrostatic, the freshwater-saltwater interface can be found by using the Ghyben-Herzberg relationship (Fenske, 1972). This relationship results in an interface between the freshwater and saltwater at a depth of 40 times the elevation of the water table above sea level. Considering the ground surface elevation at the *Long Shot* site to be 43 m (U.S. Army Corps of Engineers and USGS, 1965) an interface depth of 1707 mbsl at the working point of *Long Shot* is calculated. However, in actuality a sharp interface between the two fluids does not exist instead a mixing or dispersion zone through the action of ocean tides, seasonal fluctuations of the water table, diffusion in response to salinity, density gradient of saltwater, and temperature gradients. The assumption of hydrostatic fluids eliminates discharge of the fresh water, instead the actual lens extends out under the sea floor and provides a discharge area for the fresh groundwater. In addition, there is also a head loss due to friction from the fresh groundwater that seeps through the rocks. The assumptions that make up this relationship results in an overestimation of the interface between the freshwater and saltwater.

A second method, the potential method, can also be used in order to locate the freshwater saltwater interface (Fenske, 1972). By using piezometer wells at different depths throughout the system, the potential distributions in the lens can be found. From potential data at EH-1 and EH-5 Fenske (1972) estimated the bottom of the fresh water lens to 1,120 mbsl at the working point of *Long Shot*.

Chemical analysis of groundwater samples taken at various depths give a total dissolved-solids (salinity) distribution, which provides an independent estimate of the interface. In EH-5, the water contained between 300 and 500 ppm chloride at a depth of 671 to 792 mbsl (Fenske, 1972). This result implies a freshwater saltwater interface close to this depth.

In summer 2004, magnetotelluric measurements were performed in order to locate the freshwater saltwater interface depth as part of this CRESP study (Unsworth et al., 2005). It was concluded that increasing salinity is approximately between 600 and 1,700 m at the *Long Shot* site, defining a transition zone between the fresh and saltwater. Due to non-uniqueness of the data analysis the top and base of the transition zone could be in the range 500 to 1,000 m and 1,500 to 2,000 m respectively. The transition zone (TZ) used in the groundwater modeling performed in this report was chosen to range between 700 and 1,600 m, which reflects preliminary results found by Unsworth et al. (2005). Future simulations will be calibrated to final depths determined by Unsworth et al. and reported in Appendix 6.A. The travel time to be determined using a transition zone between 600 and 1,700 m will most likely not be significantly different from results reported here.

Previous groundwater models of *Long Shot*

Several groundwater models of the *Long Shot* site have been developed by others. Wheatcraft (1995) modeled the groundwater system of Amchitka Island with the finite element program SUTRA. The island was assumed as isotropic and homogenous system. Furthermore, the recharge was assumed to be spatially and temporally constant from the island surface. It was concluded that, the dimensionless recharge/hydraulic conductivity ratio is $6.88 \cdot 10^{-3}$ in order for a freshwater saltwater interface at 1,200 m to be modeled. Wheatcraft (1995) used a recharge of 0.1 m/year which resulted in a hydraulic conductivity of the rock matrix as $4.63 \cdot 10^{-7}$ m/s. He estimated the longitudinal dispersivities to 33.3, 66.7 and 133 m and transverse dispersivity was chosen as a tenth of the longitudinal dispersivity.

Hassan et al. (2002) modeled groundwater flow and transport of radionuclides at Amchitka. The finite element program “Finite Element Subsurface Flow system” (FEFLOW) was used and this model is referred to below as the Desert Research Institute (DRI) model. The island was modeled as homogenous, anisotropic, and no spatial variability except at the cavity and chimney. Head and concentration data were used to find the hydraulic conductivity and recharge values. Different random values of hydraulic conductivities were selected in a Monte Carlo fashion. For *Long Shot*, their calibration resulted in a hydraulic conductivity of $1.83 \cdot 10^{-7}$ m/s and a recharge of 10^{-4} m/day. The recharge/hydraulic conductivity ratio was thus $6.3 \cdot 10^{-3}$. Estimated longitudinal and transverse dispersivities were 100 and 10 m respectively.

APPROACH FOR THIS STUDY

For the study reported here (Appendix 7.A), the *Long Shot* site groundwater flow pattern was modeled with the finite element program FEFLOW. FEFLOW is a three-dimensional density dependent, mass and heat transport model available from Water Resources Planning and Systems Research Ltd. (WASY). Several scenarios were modeled by using literature values for recharge and hydraulic conductivities. The *Long Shot* site was modeled in 2-D with a cross section perpendicular to the long axis of the island. This profile is the same as the profile along which the magnetotellurics data was collected and will be referred to as the *Long Shot* profile (Unsworth et al., 2005). The model was built with bathymetry data from the Amchitka Expedition in 2004 (Appendix 5.A) and the topography data was obtained from Space Shuttle Radio Topography (SRTM, 2005).

Earlier conceptual models (Fenske, Wheatcraft, and DRI) assumed the groundwater divide in the middle of the island and, thus, only modeled half of the island. This current modeling incorporates actual topography and the andesite sills necessitating modeling of the entire cross section from the North Pacific coast to the Bering Sea coast. In order for the freshwater lens not to be affected by the finite element model boundaries, a total cross section width of 16 km was used. The highest surface elevation at the *Long Shot* profile is 47 m above sea level and the lower boundary condition was at 3,000 mbsl.

A constant flux (recharge) was used for the boundary on the island. The ocean was modeled as a hydrostatic pressure boundary condition. A no-flow boundary was specified for the bottom of the model. Lateral boundaries were established at a sufficient distance from the subsea discharge zones resulting in a cross section width of 16 km.

In the model, recharge estimation from Gard and Hale (1964) was used and calculated from average annual precipitation in Merritt and Fuller (1977). Hydraulic conductivities for the Banjo Point formation, the fractured andesite sill units, and the units above the andesite sill were obtained from U.S. Army Corps of Engineers and USGS (1965) and used in the modeling. In addition, hydraulic conductivities of the aquifer at *Long Shot* site reported by Gard and Hale (1964) were also used in the simulations.

Transverse and longitudinal dispersivities have not been determined for Amchitka Island. In a different aquifer (other than Amchitka) Gelhar et al (1982) reported a longitudinal/transverse ratio of 0.6 for brecciated basalt interflow zone. Again at a different aquifer, a longitudinal/transverse ratio for basaltic lava and sediments was documented by Robertson, (1974) as 910/1370. Wheatcraft (1995) used a longitudinal dispersivity from 133 to 33.3 m the transverse dispersivity was a tenth of the longitudinal dispersivity for the groundwater model developed for the *Long Shot* site. Hassan et al.(2002) used a longitudinal and transverse dispersivity for the *Long Shot* site of 100 and 10 m respectively. In the simulations presented in this report, longitudinal and transverse dispersivities (α_L and α_T) were altered until a freshwater saltwater transition zone was reached that matched the MT results.

Scenarios investigated

Scenarios investigated in this study are summarized in Table 7.1. A summary of scenarios used for previous groundwater modeling studies is provided in Table 7.2 for comparison.

Homogeneous scenarios

A homogeneous subsurface were used in six scenarios. Two scenarios used literature values for the recharge and four scenarios used literature values for the hydraulic conductivity of the rock matrix. For the first scenario a literature value of recharge was used. The hydraulic conductivity of the subsurface was thereafter changed until a freshwater saltwater transition zone was located at 700 to 1,600 m and matching the MT results. The reader should note that this location of the freshwater saltwater interface reflects preliminary results reported by Unsworth et al. (2005) and not the final depths provided in Appendix 6.A. Once the first scenario was calibrated a recharge/hydraulic conductivity ratio, N_{rk}, was calculated to aid in finding the hydraulic conductivity or the recharge for the other scenarios. For the scenarios where a literature value for recharge was used, the hydraulic conductivity was found by dividing the recharge with N_{rk}. Similarly, for the scenarios where reported values for hydraulic conductivities were used, the recharge was calculated by multiplying the hydraulic conductivity with N_{rk}.

Andesite sill layer scenarios

At the *Long Shot* site, the andesite sill layer was recognized by the U.S. Army Corps of Engineers and USGS (1965) as an important feature for groundwater flow. The depth of this layer is between 678 and 771 mbsl (U.S. Army Corps of Engineers and USGS, 1965). The lateral extent and width of this layer are not known. Thus, both the width of the andesite sill layer and the lateral location were adjusted iteratively until the shape and location of the transition zone matched the MT results. Due to time constraints two scenarios with a layer representing the andesite sills were modeled. This layer had a higher hydraulic conductivity compared to the rock matrix. These two scenarios used literature values of recharge and the hydraulic conductivity of the rock matrix, and the andesite sill layer as well as the extent of the layer were adjusted to match the MT results.

RESULTS

Results of the groundwater flow simulations carried out in this study are summarized in Tables 7.3 and discussed below. Analogous results from previous studies are summarized in Table 7.4 for comparison.

Scenarios assuming Homogeneous Subsurface Stratigraphy

Calibration of the model to the MT results with a transition zone at 700 to 1,600 mbsl at the *Long Shot* working point considering homogeneity in hydraulic conductivity was done by changing hydraulic conductivity and recharge within reported or reasonable ranges. For a dispersion thickness of 900 m to be modeled, the longitudinal and transverse dispersivities were also changed. Longitudinal and transverse dispersivities were adjusted to calibrate the model to the transition zone measured by MT.

Scenario 1 (R_{min})

The calculated minimum recharge of 9.07×10^{-5} m/day was kept constant in this scenario and hydraulic conductivity was varied to obtain a match to the MT results. To fit the MT results, several simulations resulted in a hydraulic conductivity of 2.3×10^{-7} m/s which is in the same order of magnitude as the hydraulic conductivity (3.5×10^{-7} m/s) estimated for the *Long Shot* site by Gard and Hale (1964). Also, the longitudinal and transverse dispersivities were 120 and 10 m respectively. These values resulted in a transition zone between 680 to 1,560 mbsl. On the east side of the island, the freshwater discharges up to 20 m off the shore-line. The transition zone ends (where the salinity of the water approaches the salinity of seawater) approximately 1,360 m from shore. The groundwater travel time from the working point of *Long Shot* to the marine environment is approximately 4,700 years. It should be noted that this travel time changes with porosity. The fracture porosity is not known on Amchitka Island. In these simulations a porosity of 0.1 was used. Increases in porosity (relative pore volume of water) will increase the travel time, while decreases in porosity will result in decreased travel times. The minimum recharge scenario resulted in a recharge/hydraulic conductivity ratio of 4.56×10^{-3}. This ratio was used in the homogeneous simulations to find approximate values of the recharge or hydraulic conductivity in order to model a transition zone from 700 to 1,600 mbsl.

Scenario 2 (R_{max})

For the maximum recharge scenario a calculated maximum recharge of 3.13×10^{-4} m/day was kept constant while varying hydraulic conductivity of the rock matrix. A hydraulic conductivity of 7.9×10^{-7} m/s was calculated from the recharge/hydraulic conductivity ratio of 4.56×10^{-3}. This hydraulic conductivity is in the same order of magnitude as estimated by Gard and Hale (1964) for the aquifer at *Long Shot* site and resulted in a transition zone from 680 to 1,560 mbsl. Longitudinal and transverse dispersivities were 120 and 10 m respectively. On the east side of the island, the freshwater discharges 20 m off shore. The transition zone ends approximately 1,360 m from the shore line on the Bering Sea side of the island. Groundwater travel time from the working point of *Long Shot* is approximately 1,400 years.

Scenario 3 (K_{Banjo})

A homogeneous hydraulic conductivity of 3.53×10^{-8}m/s, which corresponds to the reported value for the Banjo Point Formation was used in this scenario. The recharge value for this scenario was calculated from the recharge/hydraulic conductivity ratio of 4.56×10^{-3}. The resulting value of 1.4×10^{-5} m/s is in the same order of magnitude as the minimum recharge calculated from precipitation and the minimum recharge estimation of 4 % by Gard and Hale (1964). Longitudinal and transverse dispersivities of 120 and 10 m respectively were assigned in order for a transition zone of 680 to 1,560 mbsl to be modeled. On the east side of the island, the freshwater discharges 20 m off shore. The transition zone ends approximately 1,360 m from shore on the Bering Sea side of the island. The groundwater travel time from the working point (Ground Zero) of *Long Shot* is 30,700 years.

Scenario 4 ($K_{Abovesill}$)

In this scenario the reported hydraulic conductivity of the rock matrix above the sills (4.72×10^{-9} m/s) was assigned as the homogenous hydraulic conductivity and recharge (1.9×10^{-6} m/day) was obtained from the recharge/ hydraulic conductivity ratio. The recharge value is one order of magnitude less than the recharge calculated from the minimum precipitation and the 4 % recharge that was estimated by Gard and Hale (1964). This resulted in a transition zone between 680 and 1,560 m when a longitudinal and transverse dispersivity of 120 and 10 m respectively were used in the model. Freshwater discharged 20 m off shore on the Bering side of the island. The transition zone ended approximately 1,360 m from shore on the east side of the island. Groundwater travel time from the working point of *Long Shot* is in this scenario 230,000 years.

Scenarios 5 and 6 (K^{min}_{LS} and K^{max}_{LS})

The homogenous value of 1.06×10^{-7} m/s for hydraulic conductivity used in scenario 5 represents the minimum value in the range in hydraulic conductivity for the *Long Shot* aquifer reported by Gard and Hale (1964). The maximum value of this range, 3.53×10^{-7} m/s, was used as the homogeneous hydraulic conductivity in scenario 6. The resulting recharges values for scenarios 5 and 6 calculated from recharge/hydraulic conductivity ratio were 4.2×10^{-5} m/d and 1.4×10^{-4} m/d, respectively. These recharge values are in the same order of magnitude as the recharge calculated from the 4% recharge estimation by Gard and Hale (1964). Longitudinal and transverse dispersivity values of 120 m and 10 m were used in both scenarios. A transition zone ranging from 680 to 1560 mbsl was generated from the values used in scenario 5. In scenario 6, the resulting transition zone ranges from 680 to 1,560 mbsl. On the east side of the island, the freshwater discharges 20 m off shore in both scenarios 5 and 6. The transition zone ends 1,360 from shore at the Bering Sea side in both scenarios 5 and 6. Groundwater travel time for scenario 5 and 6 are 10,200 and 3,100 years respectively.

Summary of homogeneous results

Scenarios 1 and 2 both resulted in hydraulic conductivities in the same order of magnitude as compared to literature values. The hydraulic conductivity for scenario 1 falls within the range of literature values whereas the hydraulic conductivity of scenario 2 is slightly higher than reported values. If the assumption that the hydraulic conductivities at the *Long Shot* site are greater than the swabbing and pump test results indicate as discussed, then the results generated in both scenario 1 and scenario 2 are likely. The longitudinal dispersivities for these two scenarios are higher but in the same range as Wheatcraft (1995) and Hassan et al. (2002) used in their modeling efforts. Transverse dispersivities are the same as Wheatcraft (1995) and Hassan et al (2002) used. The thicker transition zone measured by MT can explain this result.

Scenarios 3 through 6 were modeled with literature values of hydraulic conductivity and the recharge value was changed in order for the location and thickness of the transition zone to correspond to the MT results. Scenarios 3, 5 and 6 resulted in recharge values in the same order of magnitude as reported literature values of recharge. For both scenarios 2 and 5, the recharge values were lower than reported values for recharge. Scenario 6 is within the same range as reported values. Scenario 4 resulted in a recharge value being one order of magnitude lower than calculated from the 4 % recharge estimation by Gard and Hale (1964).

To better compare resulting values of hydraulic conductivity and recharge for each scenario with measured values reported in literature, precipitation was calculated from recharge values using reported ranges of likely recharge to precipitation ratios. For example, if the modeled recharge is 1.4×10^{-5} m/day it would result in a daily precipitation of 3.5×10^{-4} m/day or 0.128 m/year for the 4 % recharge estimation. For scenario 3, the modeled recharge would result in an average yearly precipitation of 43 to 128 mm when using the 4 to 12 % recharge estimation by Gard and Hale (1964), which is much lower than measured values of 828 to 953 mm. These values would be even lower for the rock matrix above the sill scenario (scenario 4) because of the lower recharge that was used in the model. *Given these results, scenarios 3 and 4 are not very probable.*

Scenarios 5 and 6 modeled recharge values are in the same order of magnitude as the minimum recharge estimated by Gard and Hale (1964). Similar precipitation calculations as was made for scenarios 3 and 4 were performed. If the 4 to 12 % recharge estimation by Gard and Hale (1964) is used, the modeled recharge of the scenario 5 would result in a yearly precipitation range between 128 and 383 mm. Once again these values are lower than historically measured values causing questions about the validity of this scenario. For scenario 6 the yearly precipitation would range between 426 and 1288 mm when using the 4 to 12 % recharge estimation by Gard and hale (1964). This scenario is thus a very likely scenario because it compares to the measured precipitation values. From this comparison it appears that scenario 1, 2 or 6 are most likely reasonable models of groundwater flow through the *Long Shot* site. This conclusion is further validated when one compares the magnitude of measurement error in hydraulic conductivity to precipitation. Point measurements of hydraulic conductivity were basically obtained in bore holes at the *Long Shot* site. Considering the highly heterogeneous nature of fractured rock and the error associated with the measurement, one can discern that reported values may be off by as much as an order of magnitude. This is not to say that precipitation measurements do not have error associated with them, especially in locations with high wind speeds such as Amchitka. In general, for hydraulic conductivity measurements to be off by one order of magnitude is more likely than for precipitation measurements to be off by an order of magnitude.

The distance on the east side of the island where the transition zone ends is approximately 1,360 m (offshore). All scenarios model the freshwater discharge to 20 m off shore on the east side of the island.

The groundwater travel time ranges from 1,400 to 230,000 years with the longest travel time for the above the sill scenario (scenario 4) and shortest for the maximum recharge scenario (scenario 2).

Scenarios examining the influence of Andesite sills on the groundwater flow

The limited number of core logs at the *Long Shot* site provides little information about the subsurface. However, one prominent stratigraphic difference is the two andesite sill layers encountered in EH-5 at a depth 678 to 771 mbsl (U.S. Army Corps of Engineers and USGS, 1965). This layer was recognized by the U.S. Army Corps of Engineers and USGS (1965) as an important feature that influences the groundwater flow due to moderate hydraulic conductivity when compared to the main units at *Long Shot* site. Because a hydraulic conductivity was only given for these sills as a whole, one layer of sill from 678 to 771 mbsl was modeled. From the core logs, it is not possible to distinguish its lateral extent. The width of this layer was therefore varied in the cross section so that the depth and shape of the modeled transition zone would fit the magnetotelluric measurements.

Two scenarios were chosen to be modeled with an andesite sill layer. One scenario was with the minimum recharge value and the other scenario was with the maximum recharge value as constant while changing the hydraulic conductivity of the andesite sill layer and the rock matrix in order to match the MT results. According to U.S. Army Corps of Engineers and USGS (1965), the hydraulic conductivity of the andesite sills were one to two orders of magnitude greater than the rock formation. In the modeled scenarios where reported values of recharge were used and hydraulic conductivities of the rock matrix and the andesite sill layer were modeled, the hydraulic conductivity of the andesite sill layer was chosen as two orders of magnitude greater than the hydraulic conductivity of the rock matrix. Only scenarios with a two orders of magnitude difference between the andesite sill layer and the rock matrix were chosen due to time constraint. In order to duplicate the top of the transition zone as MT results show, several simulations resulted in a best fit to the magnetotelluric data with the location of the andesite layer at 1,000 m and 1,000 m west and east of *Long Shot* respectively. The thickness of the layer was from 679 to 771 mbsl. This positioning does not suggest that this location of the sill is the only location, but because of time constraints, this was the only location used in these simulations.

Scenario 7 (R^{min}_{sill})

The calculated minimum recharge (9.07×10^{-5} m/day) was held constant in this scenario and the hydraulic conductivity was varied to calibrate the model to the MT results. This resulted in a modeled hydraulic conductivity for the rock matrix and andesite sill layer of 1.9×10^{-7} m/s and 1.9×10^{-5} m/s, respectively. The transition zone was located between 740 to 1,560 mbsl. Longitudinal dispersivity and transverse dispersivities were 120 and 10 m, respectively. The bump in the upper transition zone shown in the MT results for *Long Shot* located at approximately 1,000 m west of *Long Shot* was duplicated in the model. The dip of the upper transition zone that can be seen to the east in the MT results could not be duplicated. This dip is most likely due to other subsurface heterogeneities not yet included in the modeling effort. Freshwater discharges 30 m off shore on the Bering Sea coast. The transition zone ends 1,360 m off shore-line. The groundwater travel time from the working point of *Long Shot* is approximately 1,400 years. In the homogeneous minimum recharge scenario (scenario 1) the groundwater travel time was approximately 4,700 years. This shows that the groundwater travel time changes significantly when an andesite sill layer is included in the subsurface. The hydraulic conductivity of the rock matrix is in the same order of magnitude as estimated by Gard and Hale (1964) and similar to the hydraulic conductivity that was simulated in the minimum recharge scenario (scenario 1), a decrease from 2.3×10^{-7} m/s to 1.9×10^{-7} m/s. The groundwater divide was at 890 m west of *Long Shot* which is approximately 250 m west of mid-island compared to only approximately 20 m as was modeled in the homogeneous minimum recharge scenario (scenario 1).

Scenario 8 (R^{max}_{sill})

Similar to scenario 7, hydraulic conductivity was varied in this scenario while keeping the recharge constant (R_{max} = 3.13×10^{-4} m/day). Hydraulic conductivity of the andesite sill and the matrix rock were chosen to 7.3×10^{-7} m/s and 7.3×10^{-5} m/s respectively in order for a transition zone at 700 to 1,600 mbsl to be modeled. Longitudinal and transverse dispersivities were the same as for scenario 7. The transition zone was located between 790 and 1,520 mbsl. Freshwater discharges at 30 off shore-line in the Bering Sea and the transition zone ends at 1,500 m. Groundwater travel time is approximately 400 years. This is a decrease in groundwater travel time when compared to the homogeneous maximum recharge travel time of approximately 1,400 years. The hydraulic conductivity of the rock surrounding the sills is in the same order of magnitude as was estimated for the aquifer at the *Long Shot* site by Gard and Hale (1964) but decreased from 7.9×10^{-7} to 7.3×10^{-7} m/s when compared to the homogeneous maximum recharge scenario (scenario 2).

Summary of results from the andesite sill layer

The calibration of scenarios 7 and 8 resulted in a hydraulic conductivity of the rock matrix in the same order as estimated by Gard and Hale (1964). The freshwater discharges approximately 30 m to the east of the island for both scenarios 7 and 8. This is close to the modeled values for the homogeneous scenarios. This result is also true for the location where the transition zone ends which was modeled to 1,350 and 1,500 m respectively for scenario 7 and 8. As for the shape of the upper transition zone shown in the MT results, the bump located at approximately 1,000 m west of *Long Shot* was the only feature that could be duplicated. The groundwater travel time was determined to approximately 1,400 and 400 years for the minimum and maximum recharge, respectively. This is a significant decrease in travel time when compared to the homogeneous minimum and maximum scenarios (scenarios 1 and 2) showing the importance of modeling heterogeneities in the subsurface.

DISCUSSION AND CONCLUSIONS

Homogeneous

The parameters used in scenarios 1, 2, and 6 to calibrate the *Long Shot* model (permeability and recharge) are close to the values reported in the literature discussed in the previous section. Parameters used to calibrate scenarios 3, 4 and 5 do not compare well with literature values. Thus, scenarios 3, 4 and 5 should not be considered in further modeling.

Scenarios 1, 2, and 6 model a distance from shore to the end of the transition zone at approximately 1,360 m. The freshwater discharges 20 m off shore on the east side of the island for all modeled scenarios. Wheatcraft (1995) did not document where the freshwater discharge ended nor where the transition zone ended. An approximation was made from a figure presented in Wheatcraft (1995) in the report and which illustrated that the freshwater discharged at about 335 and that the transition zone ended at about 400 m. These distances were not documented by Hassan et al (2002).

There are no reported values for porosity on Amchitka Island. Unsworth assumes a linear relationship between porosity and depth ranging from 0.3 at the surface and decreasing to 0.02 at a depth of 3000m. For the *Long Shot* groundwater model a constant value for porosity of 0.1 was assumed. This value was selected from the results provided by Unsworth, which indicate that the porosity is approximately 0.1 at the depth of the *Long Shot* working point. Using this value for porosity will result in shorter estimated of travel time, since the porosity of the media above the working point will most likely be greater than 0.1 as indicated by Unsworth. The resulting groundwater travel time for the *Long Shot* working point to the sea floor ranges between approximately 1,400 and 4,700 years for the most likely scenarios (scenarios 1,2 and 6) modeled. The shortest travel time was calculated in scenario 2, which used the maximum documented recharge and the longest travel time was for scenario 6 that used the higher range of hydraulic conductivity reported by Gard and Hale (1964).

Both Wheatcraft and Hassan et al. (2002) assumed the groundwater divide at mid-island and, thus only modeled half the island. In scenario 1 (R_{min}) the groundwater divide is shifted approximately 20 m to the east. This suggests that for a homogeneous island it should be sufficient to model only a half island and assume that the groundwater divide is in the middle of the island.

It should be noted that these scenarios are assuming a homogeneous stratigraphy. This is most likely not the case. The following section examines the influence heterogeneity in hydraulic conductivity (i.e., the presence of andesite sills) has on the groundwater dynamics.

Andesite sills influence on groundwater flow

Due to time constraints only the minimum and maximum recharge scenarios were modeled with an added andesite sill layer. These two scenarios were chosen due to the most likelihood scenarios modeled in the homogeneous simulations. The hydraulic conductivity of the andesite sills was modeled as two orders of magnitude higher than the hydraulic conductivity of the rock matrix. In general it can be seen that when an andesite layer is added to the model, the hydraulic conductivity of the rock matrix surrounding the sill is in the same order of magnitude as was chosen in the calibration for the homogeneous scenarios. This can be seen when comparing scenarios 1 and 7 and also when comparing scenarios 2 and 8. The results of the hydraulic conductivities are in the same order of magnitude as was estimated by Gard and Hale (1964). The relatively more permeable layer of andesite will influence the travel time to the ocean from the working point of *Long Shot*. When an andesite sill layer was added to the minimum recharge scenario (scenario 1) the travel time decreased from approximately 4,700 to 1,400 years. This was also shown in the maximum recharge scenario where the travel time decreased from approximately 1,400 to 400 years.

The distance to where freshwater discharges in the Bering Sea and the distance to where the transition zone ends does not show a large difference when comparing the homogeneous scenarios with the andesite sills scenarios. It should be noted though that the east location of the upper transition zone (200 mg/l salinity isolines) is not known but is indicated by the MT result to be further east than what has been modeled in these scenarios. This will need further study in order to locate the beginning and end of the transition zone at the Bering Sea side of Amchitka Island.

The location of the groundwater divide was at approximately 250 m west of the mid-island compared to only 20 m for the homogeneous minimum recharge scenario. Thus, when modeling heterogeneities of the island the whole island should be modeled rather than half island.

While these two scenarios show only preliminary results due to time constraints, they do suggest that the andesite sills do influence the groundwater dynamics. This result is noted when comparing the shape of the upper and lower boundaries of the transition zone generated in these modeling efforts to the results obtained from the MT survey of *Long Shot*. Most notable is the slight rise and subsequent dip to the west of the working point as well as the shift in the point of maximum depth in the lower boundary of the transition zone both shown in the inversion model for *Long Shot* (figure in MT results section) and in the modeled results.

In conclusion, results of these groundwater modeling efforts indicate

1. Groundwater travel times from the *Long Shot* test shot to discharge through the ocean floor into the marine environment will take very long times. Estimates of travel times range from 1,400 to 4,700 years assuming a homogeneous subsurface for likely scenarios, and from 400 to 1,400 years assuming the influence of an andesite sill layer. Contaminant

transport travel times will be longer than groundwater travel times because of contaminant retardation processes (e.g., adsorption and diffusion).

2. Including the presence of subsurface heterogeneity (i.e., andesite sills), actual topography, and the knowledge gained from the MT studies can have a significant impact on the estimated travel times and discharge locations for contaminants from the test shots to the marine environment.

The above results indicate that further groundwater modeling is warranted that considers the full range of geophysical information gained through this CRESP study. Factors to be considered should include subsurface fresh to salt water transition zones, subsurface heterogeneity, porosity variation, and actual island and off-shore (marine floor) topography. These modeling studies would result in reduced uncertainty in the travel times and discharge locations of groundwater from the test shots to the marine environment.

Table 7.1. Summary and comparison of scenarios modeled in this study.

	Scenarios 1 and 2 (R_{min} and R_{max})	**Scenarios 3 through 6 (K_{Banjo}, $K_{Abovesill,}$ K^{min}_{LS} and K^{max}_{LS})**	**Scenarios 7 and 8 (R^{min}_{sill} and R^{max}_{sill})**
Primary Assumptions and Approach	Whole island modeled as homogeneous. 2-D based on MT results, fixed recharge, varied hydraulic conductivity to match MT prediction of transition zone.	Whole island modeled as homogeneous. 2-D based on MT results, fixed hydraulic conductivity, varied recharge to match MT prediction of transition zone.	Whole island modeled as heterogeneous considering the andesite sills. 2-D based on MT results, fixed recharge, varied hydraulic conductivity to match MT prediction of transition zone.
Recharge, R (m/day)	9.1×10^{-5} and 3.1×10^{-4}	1.9×10^{-6} to 1.4×10^{-4}	9.07×10^{-5} and 3.13×10^{-4}
Hydraulic conductivity, K (m/s)	2.3×10^{-7} and 7.9×10^{-7}	4.7×10^{-9} to 3.5×10^{-7}	Rock matrix: 1.9×10^{-7} and 7.4×10^{-7} Sill: 1.9×10^{-5} and 7.4×10^{-5}
N=R/K	4.56×10^{-3}	4.56×10^{-3}	N/A
$\square_{L}$	120	120	120
$\square_{T}$	10	10	10

Note: The range of recharge for scenarios 3 – 6 is modeled values. Also, the range of hydraulic conductivity for scenarios 1 – 2 is modeled. It should be noted that the cross section of the whole island used was the cross section where the MT measurements were taken. This resulted in a half-island length of 2,385 m.

Table 7.2. Summary and comparison of previous groundwater models for Amchitka.

	DRI (Hassan et al. 2002)	Wheatcraft (1995)
Primary Assumptions and Approach	Groundwater-divide at half island. 2-D homogeneous subsurface. Monte Carlo simulations in FEFLOW. Calibrated to head data and chloride concentration.	Groundwater-divide at half island. 2-D homogeneous subsurface Several simulations in SUTRA calibrated to a freshwater lens of 1,200 m (from water table to middle of transition zone) at mid-island.
Recharge, R (m/day)	2.22×10^{-5} to 3.86×10^{-4}	2.7×10^{-4}
Hydraulic conductivity, K (m/s)	1.83×10^{-7}	4.6×10^{-7}
N=R/K	6.3×10^{-3}	6.88×10^{-3}
□$_L$	100	133 to 33
□$_T$	10	13 to 3

Note: Wheatcraft modeled half-island with a width of 2,000 m. DRI used 2,224 m as the half-island width Hassan et al.(2002)

Table 7.3. Summary of results from scenarios modeled in this study.

Homogeneous scenarios

Scenario	1	2	3	4	5	6
Distance to off-shore edge of freshwater discharge (m)	20	20	20	20	20	20
Distance to off-shore edge of transition zone (m)	1,360	1,360	1,360	1,360	1,360	1,360
Location of freshwater/saltwater transition zone (mbsl)	680 – 1,560	680 – 1,560	680 – 1,560	680 – 1,560	680 – 1,560	680 – 1,560
Travel time for groundwater from working point of *Long Shot* to the Bering Sea (years)	4,700	1,400	30,700	2.3×10^5	10,200	3,100

Note that scenarios 1, 2, and 6 are the most likely scenarios found in the current modeling effort.

Andesite sills scenarios

Scenario	7	8
Distance to off-shore edge of freshwater discharge (m)	30	30
Distance to off-shore edge of transition zone (m)	1,350	1,500
Location of freshwater/saltwater transition zone (mbsl)	740 – 1,560	790 – 1,520
Travel time for groundwater from working point of *Long Shot* to the Bering Sea (years)	1,400	400

Table 7.4. Summary of results from previous groundwater modeling studies for the *Long Shot* test shot at Amchitka.

Previous Studies

Scenario	Fenske (1972)	Wheatcraft (1995)	DRI (Hassan et al. 2002)
Distance to off-shore edge of freshwater discharge (m)	Not reported[a]	335[b]	580 to 1380[c]
Distance to off-shore edge of transition zone (m)	Not reported[a]	400[b]	1,380 to 3,280[c]
Location of freshwater/saltwater transition zone (m)	1,120[a]	1,200[b]	1,120
Travel time for groundwater from working point of *Long Shot* to the Bering Sea (years)	Not reported[a]	880	10 to >2,200[d]

Notes:

a) The 1,120 m is for the top of the freshwater/saltwater transition zone. Distance to off-shore edge of freshwater discharge, distance to off-shore edge of transition zone, and travel times were not reported for *Long Shot*.

b) Wheatcraft calibrated the freshwater distance to 1,200 m measured from the water table to the middle of the transition zone (at the center of the island). The distance to off-shore edge of freshwater discharge and the distance to off-shore edge of transition zone were not stated by Wheatcraft; the values were read off of one of the figures and are thus estimated distances.

c) The location of the left and right edge of the plume from the cavity of *Long Shot* were reported but not the freshwater/saltwater transition zone. Location of the left edge of the mass plume was between 580 and 1,380 m from the shore-line. The right edge of the mass plume was approximately between 1,380 and 3,280 m from the shore-line.

d) DRI used a fracture porosity of undisturbed rocks of 5.0×10^{-4} which is lower than what was reported by Unsworth et al. (2005). The lower value of porosity will decrease the ground-water travel time (Hassan et al. (2002)

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