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TEMPERATURE PROFILE ANALYSIS FOR AMARGOSA VALLEY WELLS LWS–A, ASH–B, AND MSH–C

DOE UGTA RI/FS GEOTHERMAL GRADIENT STUDY RESULTS FY 1995

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EXECUTIVE SUMMARY

Temperature distribution in the borehole fluid within a well is one of the simplest measurements to obtain. Problems produced by cross-flow within the wellbore can be eliminated by completion of the well with casing cemented to the surface and with completion zones open to a single hydrologic horizon. Fluid movement in the formations penetrated by the wellbore produce measurable changes in the temperature profile. Analysis of these changes permit the estimation of vertical fluid flux rates.

Since many of the same factors (i.e., porosity, grain composition) that affect the thermal conductivity of lithologic units also affect other geophysical logs (i.e., gamma-ray, resistivity), gradient profiles are useful in identifying and correlating lithologies. Significant variations in thermal conductivity may be evident in the thermal profile of a well where slight or no changes in the resistivity or gamma profiles may be detected. Thus, the gradient profile of a well, in conjunction with other geophysical logs (i.e., resistivity, gamma-ray) is useful in the identification of lithologic contacts and estimation of lithologic characteristics.

In this investigation, temperature profiles were obtained from three wells, LWS-A, ASH-B, and MSH-C, located south of the NTS. Comparison of thermal gradient, gamma, resistivity, and lithologic logs from the three wells, in general, show excellent correlations. In some instances, distinct changes were present in the thermal gradient profile, indicating the contacts between lithologic units. These contacts were not apparent on the gamma and resistivity profiles. The use of thermal gradient profiles can be a useful addition to gamma and resistivity profiles in determining the position of lithologic contacts. Due to the low thermal conductivity of water, compared to average rock-forming materials, thermal gradient profiles are also useful in estimations of porosity.

One of the three wells, MSH-C, displayed prominent curvatures in the upper portion of the temperature profile, indicating vertical fluid flux both upward and downward from a zone of apparent high horizontal flow at a considerably lower temperature than would be expected. Downward flow from this zone appears to converge with possible slight upward flow from below at a basalt unit. Temperature profiles from the other two wells, ASH-B and LWS-A, did not indicate the presence of vertical flow.

The traditional conceptual model for discharge in the southern portion of the Death Valley Groundwater Basin involves the upwelling of fluid from the deep carbonate aquifer along fault and fracture systems beneath the playas and discharge areas located along the Nevada-California border south of the NTS. Given this conceptual model, major ion chemistry of the water from well MSH-C should be of the Ca-Mg-HCO_3 type associated with the deep carbonate aquifer to the north. Major ion chemistry for water from well MSH-C indicates the water from the upper interval of the well (73.1 to 125.6 m) to be characteristic of carbonate waters or mixed carbonate and volcanic water types such as found in alluvium aquifers composed of carbonate and volcanic

rock fragments; however, water from the lower interval of the well (451.1 to 510.2 m) appears to be of the type ($Na\text{-}K\text{-}HCO_3$) associated with volcanic rock aquifers.

A possible explanation for the distribution of temperature and water chemistry in well MSH-C may be that the water moving up from depth to the basalt unit originates in volcanic units, overlying the deep carbonate aquifer, located below the total depth of the well. The water moving upward and downward from the interval of horizontal fluid flow may be of local origin in the carbonate mountains near well MSH-C, with discharge from the deep carbonate aquifer underflowing the location of well MSH-C to discharge areas south of the well. The discharge to the surface of water from a shallow flow system of local extent would be an important consideration in determining discharge rates from the Death Valley Groundwater Basin groundwater-flow system which underlies the NTS.

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INTRODUCTION

The purpose of this investigation is to estimate vertical fluid flux rates in saturated units penetrated by selected wells at the Nevada Test Site (NTS) using geothermal gradient data. Estimates of vertical fluid flux rates are critical in developing models for contaminate flow within, recharge potential to, and discharge from the groundwater system at the NTS.

One of the simplest measurements to obtain in a borehole is the temperature distribution in the borehole fluid. If temperature in the well is in equilibrium with the surrounding rocks, it is possible to detect the vertical flow of groundwater from the well's thermal profile. Heat in the subsurface is transported by conduction through the rock and by advection caused by subsurface water movement. Units in which vertical flow is occurring will produce a curve in the thermal profile within the well. In the case of downward flow, the curve will be concave upward (Figure 1a); in the case of upward flow, the curve will be concave downward (Figure 1b).

Prior to the implementation of the Underground Test Area Remedial Investigation/Feasibility Study (UGTA RI/FS), investigation of thermal data from wells at the NTS was hindered by the completion of wells as open holes or without casing cemented in place. The open-hole type of completion allows cross-flow within the wellbore which can yield information about relative pressures between connected aquifers (Lyles et al., 1995), but which renders thermal gradient data essentially useless, or at best highly suspect for interpreting *in situ* groundwater movement. Wells recently completed in the Department of Energy (DOE) Environmental Restoration (ER) Program have been completed with casing cemented to the surface (to prohibit cross-flow between units in the annular space between the casing and the wellbore) and with completion zones open to a single hydrologic horizon. This type of completion results in temperature gradient profiles more representative of actual thermal conditions in the units penetrated by the well.

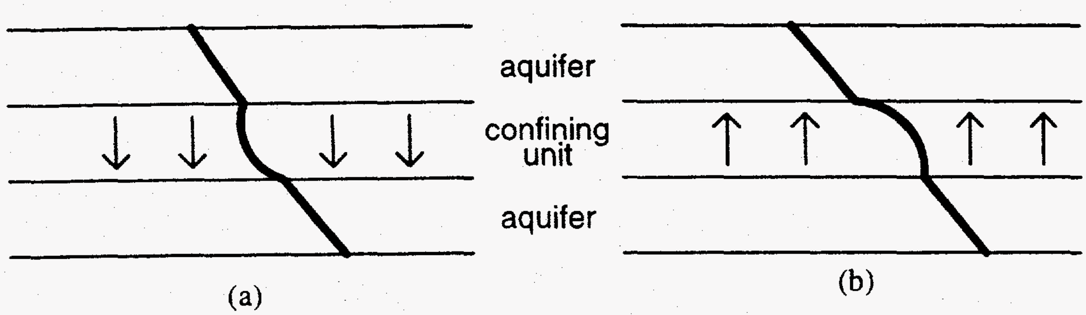


Figure 1. Idealized thermal profiles.

THEORY AND GOVERNING EQUATIONS

Lithologic Correlation Using Gradient Profiles

Beck (1976) demonstrated the usefulness of thermal gradient profiles (thermal resistivity logs) for stratigraphic correlation. A thermal gradient profile is computed from the temperature log obtained in a borehole. The thermal gradient profile of a well is equal to the change in temperature divided by the change in depth in the well (Gradient = Δ Temperature / Δ Depth) usually expressed in °F per foot or °C per meter.

The thermal gradient observed through a particular lithology relates to the thermal conductivity of the unit. Since, in most cases, the amount of heat flow is constant, the gradient (G) profile will vary linearly with the thermal conductivity (K) of the lithology penetrated (Heat Flow = K × G). Since many of the same factors (i.e., porosity, grain composition) which affect the thermal conductivity of lithologic units also affect other geophysical logs (i.e., gamma-ray, resistivity), gradient profiles are useful in identifying and correlating lithologies.

Estimation of Vertical Flux

Stallman (1963) derived a basic equation (Equation 1) for the simultaneous transfer of heat and water in porous media:

$$\partial^2T/\partial x^2+\partial^2T/\partial y^2+\partial^2T/\partial z^2-C_oP_o/K[\partial(V_xT)/\partial x+\partial(V_yT)/\partial y+\partial(V_zT)/\partial z]=CP\partial T/K\partial t \qquad (1)$$

where T = temperature at any point in time t
C_o = specific heat of fluid
P_o = density of fluid
C = specific heat of solid-fluid complex
P = density of solid-fluid complex
K = thermal conductivity of solid-fluid complex
V_x,V_y and V_z = components of fluid velocity in the x,y and z directions
x,y and z = Cartesian coordinates
t = time since flow started

Bredehoeft and Papadopulos (1965) showed that under one-dimensional (vertical) and steady flow conditions, equation (1) reduces to equation (2):

$$(\partial^2T/\partial z^2)-(C_oP_oV_z/K)\partial T/\partial z = 0 \qquad (2)$$

Bredehoeft and Papadopulos (1965) then solved equation (2) by applying boundary conditions $T_z = T_0$ at z = 0 and $T_z = T_L$ at z = L, giving the solution:

$$(T_z-T_0)/(T_L-T_0) = f(\beta,z/L) \qquad (3)$$

where

$$f(\beta, z/L) = [\exp(\beta\, z/L) - 1] / [\exp(\beta)\ 1] \quad (4)$$

and

$$\beta = C_0 P_0 V_z L/K \quad (5)$$

The dimensionless number β defines the curve in the temperature gradient observed in the thermal profile from the well. Bredehoeft and Papadopulos (1965) presented type curves generated by plotting z/L against $(T_z - T_0)/(T_L - T_0)$ for different values of β. Ratios of $(T_z - T_0)/(T_L - T_0)$, calculated from measured temperature data, are plotted against depth factor z/L and compared to the type curves to determine a value for β.

Using the value of β obtained by matching the type curves, and the known values for C_0, P_0, L, and K, the equation $\beta = C_0 P_0 V_z L/K$ can then be solved for V_z (the groundwater velocity).

Sass et al. (1988), Sass and Lachenbruch (1982), Sass et al. (1980), and Lachenbruch and Sass (1977) in investigations at Yucca Mountain, Nevada, by the U. S. Geological Survey (USGS) showed that the vertical conductive heat flow (q) is defined by:

$$q = K(\partial T/\partial z) \quad (6)$$

then

$$(\partial^2 T/\partial z^2) - (C_0 P_0 V_z/K)\partial T/\partial z = 0 \quad (7)$$

(equation 2 above) equates to:

$$\partial q/\partial z - (C_0 P_0/K) V_z (\partial T/\partial z) = 0$$

An approximate solution to equation (7) at any depth z is given by Sass and Lachenbruch (1982) as:

$$q(z) = q_0\, e^{-Az} \quad (8)$$

where

$$A = C_0 P_0 V_z/K \quad (9)$$

To obtain an estimate of A, heat flows q(z) are plotted as a function of depth and a regression curve of the form $y = a \times e^{bx}$, where b is equal to A, is determined. V_z is then calculated by rearrangement of equation (9), given known or assumed values for C_0, P_0 and K.

In a more recent investigation, Reiter et al. (1989) have shown that by approaching the problem from the conservation of energy:

$$E = -K(\partial T/\partial z)+C_0P_0V_z(T-T')$$ (10)

where

$$E = \text{total energy}$$

Equation (10) was then rewritten in the form:

$$q = C_0P_0V_z(T-T')-E$$ (11)

From equation (11) it can be seen that plots of q versus T will have slopes (m) of $P_0C_0V_z$. Using known values for C_0 and P_0, V_z can then be determined.

The principal advantage of determining V_z using the methods described by Sass and Lachenbruch (1982) and Reiter et al. (1989), as compared to that given by Bredehoeft and Papadopulos (1965), is the ability to include variations in thermal conductivity (K) of the rock unit(s) in which vertical flux occurs.

CONVECTIVE FLOW WITHIN THE BOREHOLE

It is well known that a fluid column in a vertical tube will become unstable when the temperature gradient exceeds a critical value which depends on the properties of the fluid and the size of the tube. This relationship has been formulated by Krige (1939) as given below:

$$G_c = g\alpha T/C_p + Cvk/g\alpha a^4$$ (12)

where G_c = the critical gradient
g = acceleration of gravity
T = absolute temperature
α = coefficient of thermal expansion
C_p = specific heat
v = kinematic viscosity
k = thermometric conductivity (diffusivity)
a = radius of the tube
C = constant (which is 216 for a tube whose length is great compared with its diameter)

The first term in the equation is the adiabatic gradient, which is about 0.2°C/km for water and is exceeded in almost all water-filled holes. The second term is particularly sensitive to the effect of hole diameter; as hole diameter increases, the thermal gradient required to produce instability decreases exponentially. From the above equation, it is obvious that almost all water-filled holes of diameters greater than approximately 3 to 6 cm should be unstable. However, temperature surveys are routinely obtained in boreholes with gradients and diameters that exceed the parameters for stable thermal conditions. These logs are repeatable and apparently do not display features characteristic of unstable thermal conditions (oscillations in temperature due to convection of fluid).

Diment (1967) investigated this phenomenon in detail; a summary of his conclusions are paraphrased below:

Temperatures in water-filled holes exhibit oscillations at all depths where temperature increases downward. However, this instability manifests itself in vertical water movements of short periods (several minutes to several hours) that do not exceed several diameters of the hole, and are limited to oscillations in temperature of several hundredths of a degree.

This instability results in a limit to which thermal data can be applied to investigating small-scale features within a well, such as the identification of detailed stratigraphy. However, in the examination of large-scale thermal features, small-scale thermal instabilities within the borehole become averaged over the larger interval and, if detected at all, can be ignored.

DETERMINATION OF THERMAL CONDUCTIVITY OF ROCK UNITS

Construction of Thermal Conductivity Measurement Device

It is possible to refine estimates of vertical fluid flux rates by determining the effects of any variations in the thermal conductivity of lithologic units on the thermal profile. To determine the thermal conductivity of units penetrated by the wells investigated in this study an apparatus was constructed after the type described by Reiter and Hartman (1971). This apparatus (Figure 2) utilizes a steady-state absolute method for determining the thermal conductivity of rock specimens (cores or cuttings).

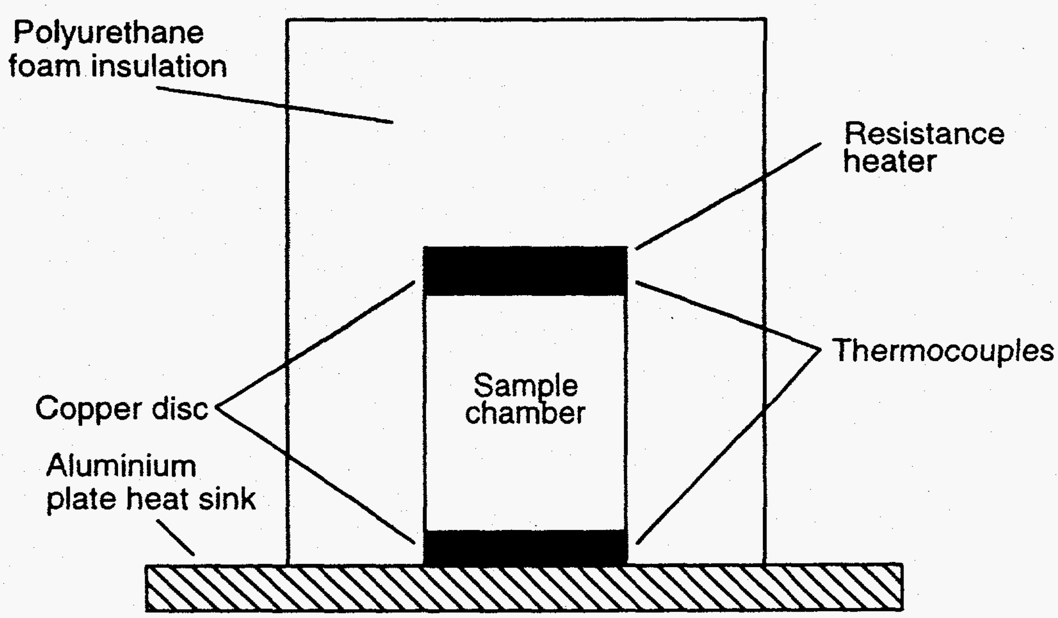


Figure 2. Schematic diagram of thermal conductivity measurement device.

The technique consists of placing a known quantity of heat into a specimen with a resistance heater and determining the thermal gradient across the specimen with thermocouples. A heat sink (high thermal conductivity material) is placed at the opposite end of the specimen from the heater, and the heating element and specimen are insulated with polyurethane to reduce thermal losses. Because the sample is radially insulated, the heat flow through the specimen is essentially axial from the heater into the heat sink through the specimen. Thermal conductivity of the specimen can then be calculated from the expression $K = q/(\Delta T/\Delta z)$, where q is the flux of heat (heat flow per unit area per unit time) into the specimen, K is the thermal conductivity of the specimen, and $(\Delta T/\Delta z)$ is the thermal gradient across the specimen.

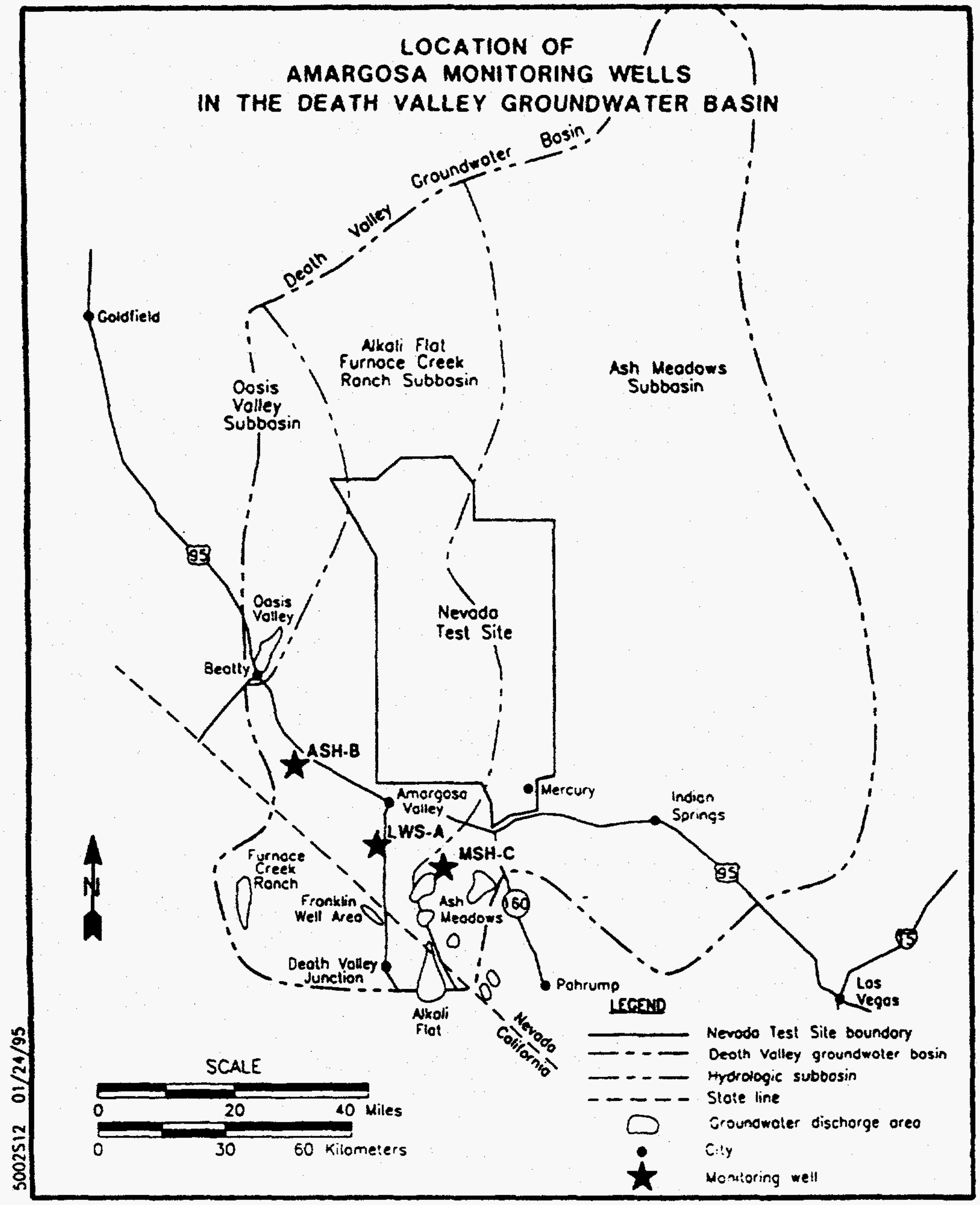
Accuracy of this apparatus is dependent on the thermal conductivity of the material being measured. Lower thermal conductivity materials permit greater heat loss from the apparatus than higher thermal conductivity materials during measurements. This type of apparatus is considered to have an accuracy of ± 4 percent over the range of thermal conductivities for most rock types.

Unfortunately, insufficient quantities of cuttings (approximately 50 cm^3 required) were collected during drilling of wells LWS-A, ASH-B, and MSH-C to permit determination of thermal conductivities in the laboratory using the apparatus described earlier. Without measured thermal conductivities of the units penetrated by the wells it is not possible to determine precisely the variations in heat flow with depth which would permit use of the methods described by Sass et al. (1988), Sass and Lachenbruch (1982), Sass et al. (1980), Lachenbruch and Sass (1977) or Reiter et al. (1989). However, the method described by Bredehoeft and Papadopulos (1965), in which a uniform thermal conductivity is assumed for the unit in which vertical flux occurs, may be employed.

WELLS INVESTIGATED

Temperature profiles from three wells (LWS-A, ASH-B, and MSH-C) located south of the NTS were obtained in FY1995 for this investigation (Figure 3). The three wells are located in the southern portion of the Death Valley Groundwater Basin. Wells ASH-B and LWS-A are within the Alkali Flat/Furnace Creek Ranch subbasin. Well MSH-C is in the Ash Meadows subbasin and located near discharge areas for groundwater flow through this subbasin (Winograd and Thordarson, 1975; Waddell et al., 1984).

These wells were drilled as mineral exploration boreholes by U.S. Borax. Following construction of the three 14.3-cm-diameter boreholes, the wells were completed by the DOE ER UGTA program as groundwater monitoring locations with the installation of deep and shallow piezometer tubes in each well (Figure 4). These piezometer tubes were gravel packed over their slotted intervals and cemented to surface within the borehole. The deeper piezometer tube in each borehole contains a Moyno stator used in pumping water from the well. Temperature logs were obtained in the deep piezometer tube of all three wells from the fluid level within the well to a point immediately above the Moyno stator (Table 1). No attempt was made to obtain temperature logs below the Moyno stator. High quality temperature logs were obtained for all three wells.



(provided by IT Corp.)

Figure 3. Location of Amargosa wells from which termperature profiles were obatined.

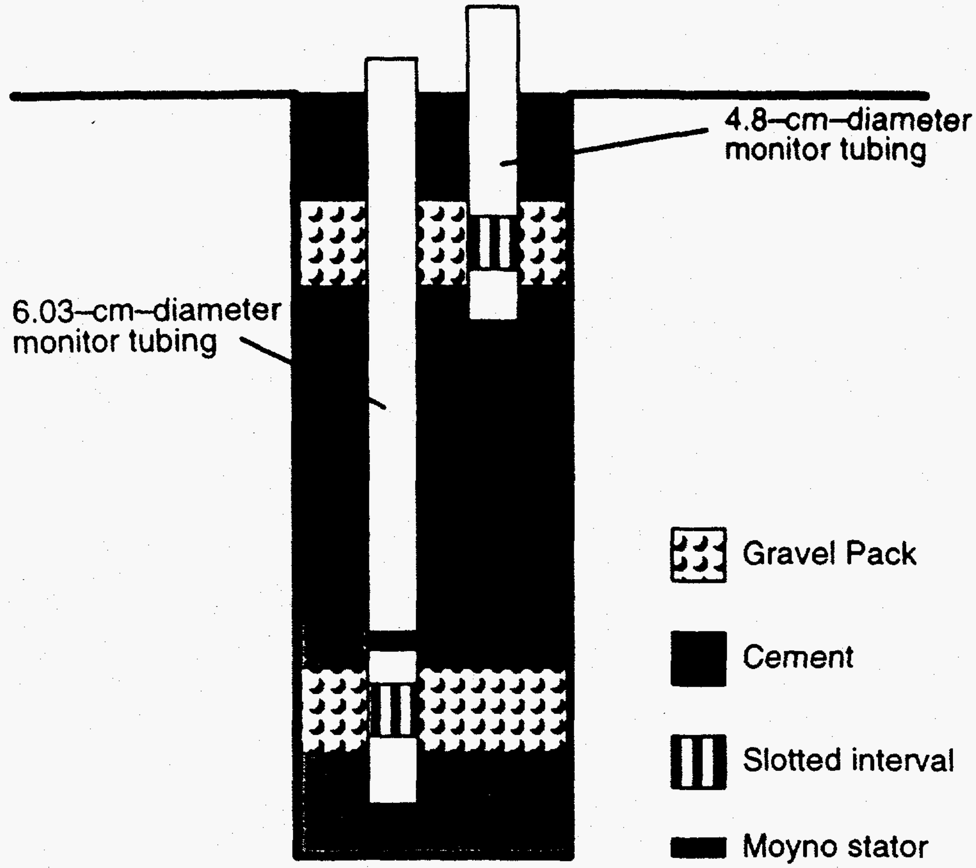


Figure 4. Generalized well construction diagram for wells LWS-A, ASH-B, and MSH-C.

TABLE 1. WELL LOGGING DATA.

Well Name	Date Logged	Land Surface Elevation	Depth to Fluid Level	Logged Interval
LWS-A	05/11/95	730.0 m	34.1 m	30.5-515.1 m
ASH-B	05/11/95	815.3 m	96 m	91.4-320 m
MSH-C	05/11/95	710.2 m	0 m	0-429.8 m

LWS-A

LWS-A was drilled to a total depth of 617.2 m on November 6, 1994. Figure 5 illustrates the relationship between lithology penetrated by the borehole and temperature, gradient, gamma, and resistivity logs obtained from the well.

There is a readily apparent correlation between the thermal gradient profile and the gamma-ray and resistivity profiles from well LWS-A. Coarser-grained/lower-porosity lithologies display a

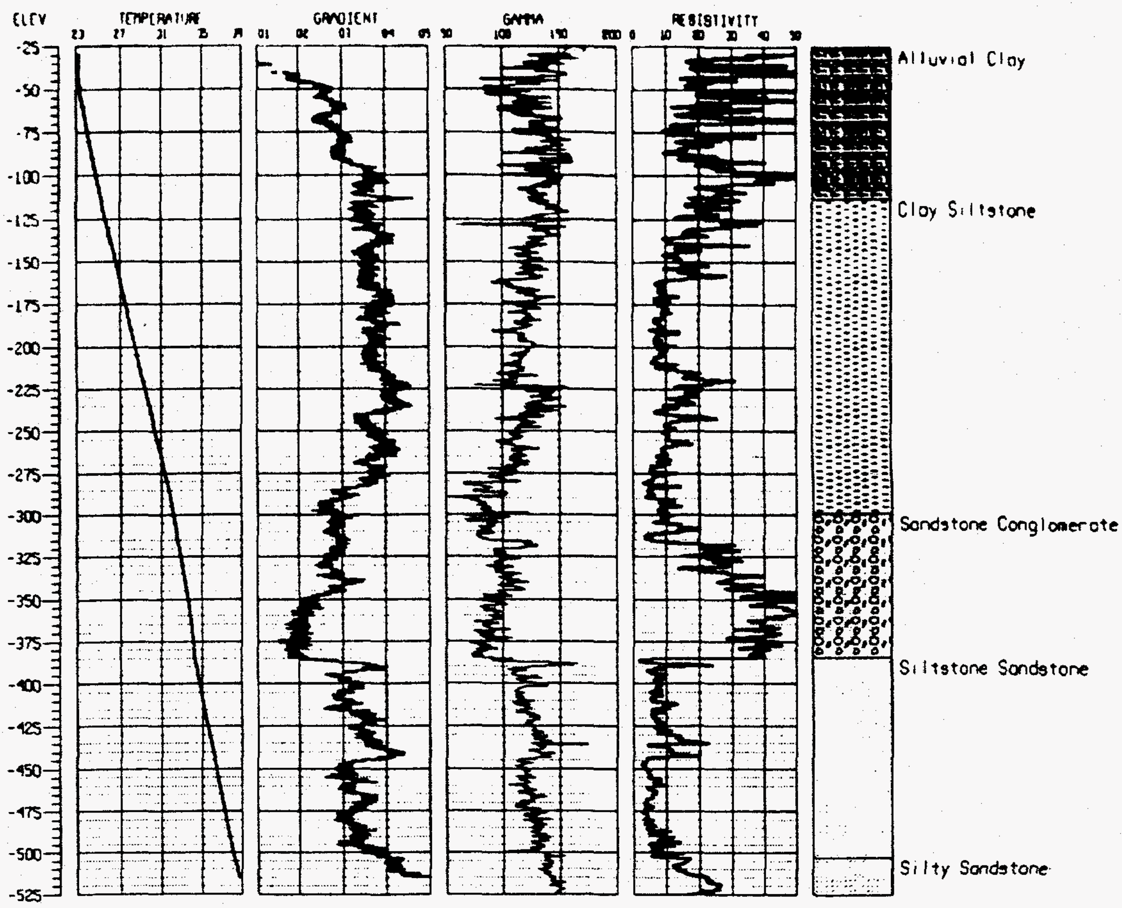


Figure 5. LWS-A geophysical logs and lithology.

decrease in thermal gradient (increase in thermal conductivity) compared to finer-grained/greater-porosity lithologies. This is expected, given the thermal conductivity of water is about 0.6 Watts meter^{-1}C (Wm^{-1}C), much lower than the thermal conductivities of most rock-forming materials (3 to 7 Wm^{-1}C). Using this relationship, the thermal gradient profile can be used to estimate the relative porosities of the units penetrated by the wells. A distinctive change in the thermal gradient occurs in the conglomerate unit penetrated by the borehole between 298.7 and 384 m. This change in gradient, apparent to a lesser extent on the gamma log, appears to indicate the lower portion of the conglomerate may be of lower porosity than the portion of the conglomerate above approximately 345 m.

On the lithologic log for LWS-A, as determined from cuttings recovered from the borehole, the contact between the clay siltstone and sandstone conglomerate is placed at 298.7 m. Neither the gamma nor the resistivity logs from the well display a definitive contact between these units. The thermal gradient profile for the well shows a distinct change in gradient (thermal conductivity) at approximately 285 m, indicating a more likely position for the contact between the two units. This is also true for the contact between the alluvial clay and the clay siltstone penetrated by the well. The lithologic contact is placed at 112.8 m, however, the thermal gradient profile indicated a distinct change in thermal conductivity at approximately 95 m. The contact between the sandstone conglomerate and the underlying siltstone sandstone is clearly evident on the gradient, gamma and resistivity profiles and is placed at approximately 385 m on the lithologic log.

ASH-B

ASH-B was drilled to a total depth of 372 m on December 7, 1994. Figure 6 illustrates the relationship between lithology penetrated by the borehole and temperature, gradient, gamma-ray, and resistivity logs obtained from the well. As with LWS-A, there is a good correlation between the thermal gradient profile and the gamma-ray and resistivity profiles from well ASH-B. The relatively uniform thermal gradient observed in all units except between 210.3 to 222.5 m may indicate the gravel and coarse sand unit present above 167.6 m contains a large amount of matrix material and has low porosity.

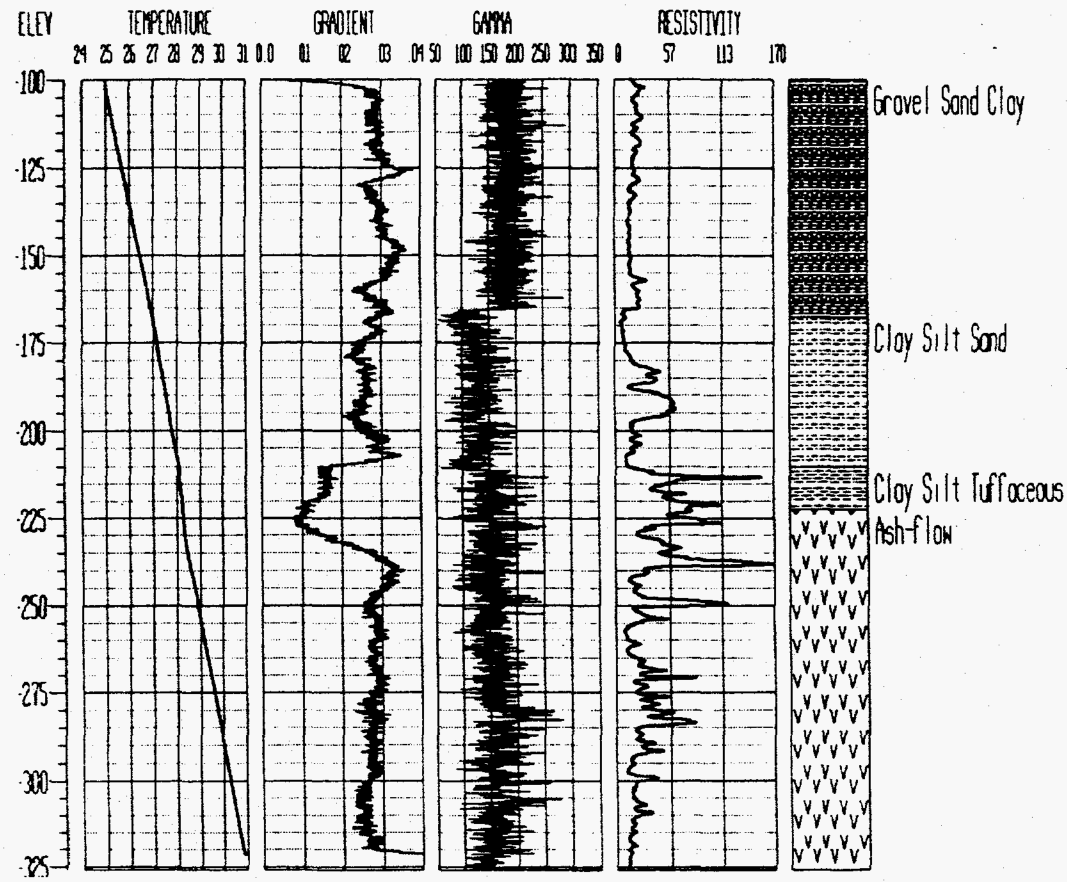


Figure 6. ASH-B geophysical logs and lithology.

The unit from 210.3 to 222.5 m is described as clay and silt, some tuffaceous, possibly weathered. This unit displays a substantially lower thermal gradient than the other units penetrated by the wellbore. This low gradient (high thermal conductivity) may indicate low porosity or the presence of mineralization produced by weathering which has increased the thermal conductivity of the unit. The thermal gradient profile displays a relatively sharp upper contact for the clay/silt/tuffaceous unit. The lower contact between this unit and the ash-flow tuff below is gradational and is not readily apparent from an examination of the gamma and resistivity logs. The thermal gradient profile indicates the contact between the clay/silt/tuffaceous unit and the underlying ash-flow tuff to be several meters deeper (at approximately 240 m) than indicated on the lithologic log.

MSH-C

MSH-C was drilled to a total depth of 710 m on November 16, 1994. Figure 7 illustrates the relationship between lithology penetrated by the borehole and temperature, gradient, gamma-ray, and resistivity logs obtained from the well. As with LWS-A and ASH- B, there is a good correlation between the thermal gradient profile and the gamma-ray and resistivity profiles from well MSH-C.

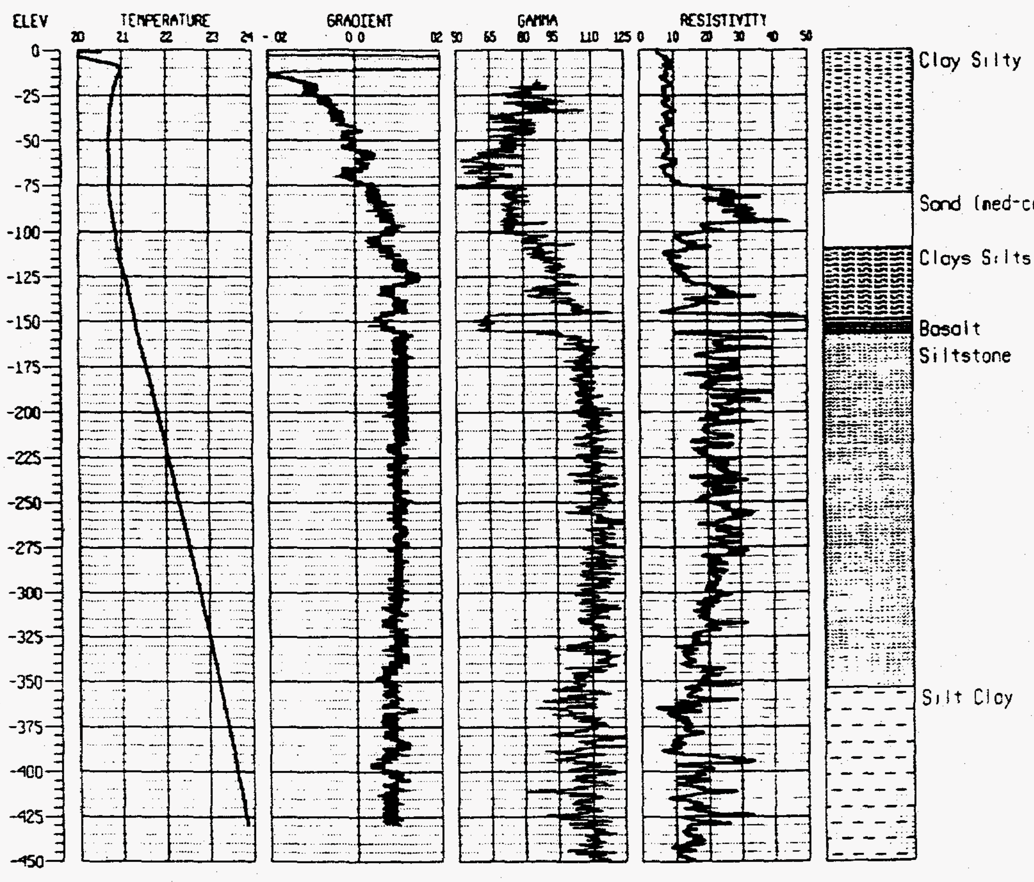


Figure 7. MSH-C geophysical logs and lithology.

The basalt unit between 148.4 and 157 m is easily correlated between the gamma-ray and resistivity logs and the thermal gradient profile from MSH-C. Due to its low porosity, this basalt unit displays a low gradient (high thermal conductivity) signature.

Hydraulic heads measured following completion of the well indicate a water level of 106.7 cm above ground level for the upper zone and a water level of 22.9 cm above ground level for the lower completion zone in the well. This head distribution indicates the potential for both upward and downward flow from the upper completion zone. Due to the artesian nature of the well, it was possible to obtain a temperature log from ground level at MSH-C. The effect of the annual temperature pulse can be observed in the upper 10 m of the temperature profile.

Unlike ASH-B and LWS-A, MSH-C displays prominent curvatures in its temperature profile indicating significant vertical fluid flux. These curvatures in the temperature profile from well MSH-C indicate both upward and downward flow from a zone located between approximately 44.2 to 70.1 m. Downward flow from this zone appears to converge with possible slight upward flow from above 359.7 m at the basalt unit located at 148.4 to 157 m.

The vertical section (thermal gradient = 0) of the temperature profile from well MSH-C, located between 44.2 and 70.1 m, is indicative of high horizontal flow rates. The fluid in this zone is of considerably lower temperature than the units above and below, indicating rapid transport from a location of lower temperature. This zone occurs near the base of a lithologic unit described as a silty clay and above a unit described as a medium-coarse sand with a clay and silt matrix. However, this zone displays gamma counts lower than any other unit penetrated by the well, with the exception of the basalt unit, indicating minimal matrix material. The resistivity log from MSH-C indicates this zone to have the lowest resistivity of any unit penetrated by the well, indicating enhanced porosity (water content). In contrast, the sand unit present from 79.2 to 109.7 m displays the highest resistivity of any other unit penetrated by the well, with the exception of the basalt unit, indicating reduced porosity (water content).

The temperature vs. depth profile obtained from MSH-C displays a uniform curvature above the interval between approximately 44.2 to 70.1 m, indicating a relatively uniform lithology (and thus thermal conductivity) over this zone of upward flow. The interval between approximately 70.1 m and the basalt unit displays a segmented curvature, indicating variation in the lithology (thermal conductivity) over this zone of downward flow. Below the basalt unit, the thermal profile appears to display a slight concave down curvature, which may be indicative of slight upward flux.

The one-dimensional diffused upward (or downward) flow model devised by Bredehoeft and Papadopulos (1965) was used to calculate the fluid flux rate for the uniform concave downward curvature section of the temperature profile in MSH-C located above approximately 44.2 m. A match of their type curves to the temperature profile resulted in an upward vertical fluid flux rate of 3.2 E-08 m/sec (3.4 ft/yr) using an assumed thermal conductivity of 2.15 $Wm^{-1}C$ (Table 2).

TABLE 2. THERMAL CONDUCTIVITY OF SEDIMENTARY ROCKS AT ROOM TEMPERATURE ($Wm^{-1}C$) (from Wright and Louden, 1989)

Rock/rock type	Thermal Conductivity
All mudstones	1.85
Calcium mudstones	1.76
Silty mudstones	2.15
Siltstone	1.91
Muddy sandstones	2.23
All sandstones	2.92
Quartz sandstone	5.09
All limestones	2.51
Dolomite	4.78

DISCUSSION AND CONCLUSIONS

Temperature distribution in the borehole fluid within a well is one of the simplest measurements to obtain. Problems produced by cross-flow within the wellbore can be eliminated by completion of the well with casing cemented to the surface and with completion zones open to a single hydrologic horizon.

Since many of the same factors (i.e., porosity, grain composition) that affect the thermal conductivity of lithologic units also affect other geophysical logs (i.e., gamma-ray, resistivity), gradient profiles are useful in identifying and correlating lithologies. Significant variations in thermal conductivity may be evident in the thermal profile of a well where slight or no changes in the resistivity or gamma profiles may be detected.

Fluid movement in the formations penetrated by the wellbore produce measurable changes in the temperature profile. Analysis of these changes permit the estimation of vertical fluid flux rates. Analysis of vertical fluid flux rates from temperature profiles requires the determination or estimation of the thermal conductivity of the unit, or units, through which the vertical flow occurs. Estimates of vertical fluid flux rates may be refined with the determination of thermal conductivities of the lithologic units through laboratory analysis of cuttings or core samples.

In this investigation, temperature profiles were obtained from three wells located south of the NTS. Comparison of thermal gradient, gamma, resistivity, and lithologic logs from the three wells, in general, show excellent correlations. In some instances, distinct changes were present in the thermal gradient profile, indicating the contacts between lithologic units. These contacts were not apparent on the gamma and resistivity profiles. The use of thermal gradient profiles can be a useful addition to gamma and resistivity in determining the position of lithologic contacts. Due to the low thermal conductivity of water, compared to average rock forming materials, thermal gradient profiles are also useful in estimations of porosity.

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The traditional conceptual model for discharge in the southern portion of the Death Valley Groundwater Basin involves the upwelling of fluid from the deep carbonate aquifer along fault and fracture systems beneath the playas and discharge areas located along the Nevada-California border south of the NTS. Given this conceptual model, major ion chemistry of the water from well MSH-C should be of the Ca-Mg-HCO_3 type associated with the deep carbonate aquifer to the north. Major ion chemistry for water from well MSH-C (Table 3) indicates the water from the upper interval of the well (73.1 to 125.6 m) to be characteristic of carbonate waters or mixed carbonate and volcanic water types such as found in alluvium aquifers composed of carbonate and volcanic rock fragments; however, water from the lower interval of the well (451.1 to 510.2 m) appears to be of the type (Na-K-HCO_3) associated with volcanic rock aquifers.

TABLE 3. MAJOR ION CHEMISTRY FOR WATER FROM MSH-C (UNPUBLISHED DATA PROVIDED BY USGS-LAS VEGAS; SAMPLES COLLECTED JANUARY 19, 1995).

Interval	Date	Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2	pH
lower	3/28/95	3.4	0.6	220.0	7.0	33.0	140.0	430.0	25.0	8.90
upper	3/28/95	13.0	15.0	75.0	9.5	20.0	59.0	250.0	15.0	8.3

A possible explanation for the distribution of temperature and water chemistry in well MSH-C may be that the water moving up from depth to the basalt unit originates in volcanic units, overlying the deep carbonate aquifer, located below the total depth of the well. The water moving upward and downward from the interval of horizontal fluid flow may be of local origin in the carbonate mountains near well MSH-C, with discharge from the deep carbonate aquifer underflowing the location of well MSH-C to discharge areas south of the well. The discharge to the surface of water from a shallow flow system of local extent would be an important consideration in determining discharge rates from the Death Valley Groundwater Basin.

Although heat flow rates could not be determined for the wells investigated in this study, a comparison of temperature profiles from wells LWS-A, ASH-B and MSH-C (Figure 8) yields an interesting observation. If basement rocks are taken to be an isothermal lower boundary, then temperature logs in areas of thicker sedimentary sections will display lower heat flows, i.e., steeper temperature vs. depth profiles (lower gradients). Comparison of the temperature profiles from wells LWS-A, ASH-B and MSH-C indicates that well MSH-C displays a significantly lower overall gradient (lower heat flow) than either LWS-A or ASH-B. This suggests that well MSH-C is located in an area with a substantially thicker sedimentary section that the other wells. A fault down-thrown to the east separating wells LWS-A and ASH-B from MSH-C could explain this heat-flow anomaly.

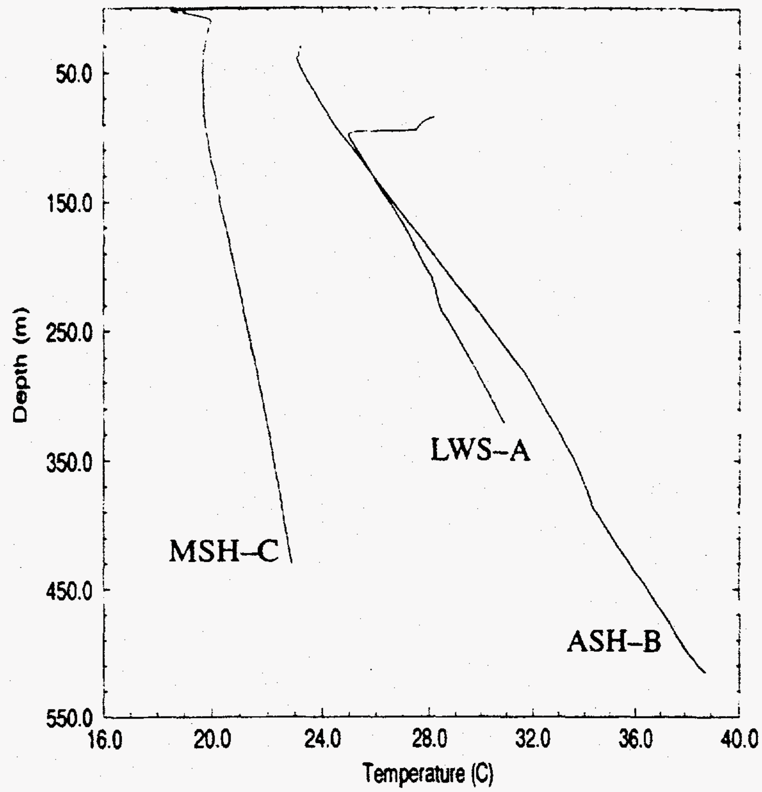

Figure 8. Comparison of temperature profiles from wells LWS-A, ASH-B and MSH-C.

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