PARAMETRIC ANALYSES OF ALTERNATIVE FLOW MODELS AT YUCCA MOUNTAIN, NEVADA CALIBRATIONS AND CONTROLS - STATE OF NEVADA-FUNDED RESEARCH

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ABSTRACT

The controls on the potentiometric surface and temperature distribution at Yucca Mountain have long been thought to be related to major fault zones. The exact way the faults influence these distributions has been somewhat elusive. The parametric studies discussed in this paper show that the fault zone x, y and z permeability tensors, as well as the alignment of the fault zone in relation to the flow field (1), are major contributing factors in the pressure and temperature distributions.

A series of runs were conducted for the State of Nevada with a 3-dimensional model utilizing the AT2VOC version of the A-TOUGH code (2),(3). The runs were conducted under steady state conditions and utilized fully coupled heat and flow conditions. The model setup and boundary conditions are fully described.

Comparisons were done with varying degrees of anisotropic permeability ratios in the fault zones. The resulting temperature and pressure profiles are compared. The model, while simple, allowed us to examine the relationship of the head and temperature distributions to the position and permeability of major fault zones. It is our conclusion that the major faults included in this model do significantly affect the observed head and temperature distributions.

Performance Assessments currently may not reflect actual doses at the Compliance boundary due to the potential for radionuclide flow to be captured in the Ghost Dance Fault and be transported primarily south with little dilution and dispersion.

INTRODUCTION

In conducting performance assessments for Yucca Mountain, an accurate view of the groundwater flow field is essential. The velocity of groundwater is one of the most sensitive parameters in the transport equation. The direction of the groundwater pathway is also important as it dictates the hydrologic and geochemical character of the pathway and influences sorption and ingestion rates, other important variables in the calculation of dose.

It has been known for some time that the Yucca Mountain ground water system has a range of temperatures associated with it. It also has been hypothesized that certain features in the water table surface (embayments) are coincident with major faults. In hydrogeologic assessments of ground water pathways in complex systems, such as exist at Yucca Mountain, heat may be used as a flow path tracer. Analyses utilizing heat, along with hydraulic head and chemistry measurements, serve to constrain the results of analyses which have non-unique solutions. Heat and chemical tracers, when used as collaborating evidence, can give a more reliable result for ground water flow directions in a complex system than the use of hydraulic head alone. Unfortunately, the latest performance assessments and technical modeling of Yucca Mountain have not included all relevant geologic structure, temperature, or many chemical parameters in their determination of saturated zone ground water flow paths and consequently, dose.

The Department of Energy (DOE) has not performed coupled flow and heat analyses to assess the ambient flow field, and has not yet demonstrated that the temperature field nor specific features of the actual potentiometric surface can be matched by their flow model. We also believe that further differences in interpretation exist with respect to the distribution of infiltration through the unsaturated zone. It is our contention that all relevant data must be used to determine ground water flow paths to receptors, not just selective data sets. A comprehensive model, which includes knowledge of all relevant processes including hydraulic, thermal, chemical and tectonic, needs to be developed. These pieces of information need to fit together in the analyses of repository safety.

The State of Nevada has funded independent technical reviews of DOE flow models under non-isothermal conditions, including the latest modeling efforts described in this paper. The State-funded numerical model is three-dimensional, uses fully coupled flow and heat equations, and explicitly considers geologic structures as controls on the flow field. The latest model results indicate differences exist in flow path direction and potentially velocity when compared to the latest DOE analyses and reports. These differences may influence the calculated dose received at the compliance boundary.

ALTERNATIVE SATURATED ZONE CONCEPTUAL MODEL

The conceptual model upon which our numerical model is based postulates that faults and fractures dominate the flow of groundwater through the volcanic tuffs underlying Yucca Mountain. Fracture zone intersections play a key role in the distribution of recharge, hydraulic head, pathways and velocity fields as does position of the fault in the flow field. The flow field is also transient rather than static, and has the potential to change rapidly due to tectonic movements or recharge events.

Water moves primarily from north to south, with some movement from west to east via northwest trending shear zones. In this conceptualization, flow in the carbonates is upward and then discharges to the south of the Yucca Mountain block. Flow in the volcanics is downward in the northern reaches of the block and also discharges south of Yucca Mountain where the volcanics are pinched out by the carbonates or alluvium.

The distribution of temperature at the site and surrounding areas indicates that there are alternating bands of heat running from north to south. The highest temperatures seem to be associated with block bounding faults such as the Solitario Canyon Fault and the Bow Ridge Fault. The intrablock faults contain cooler water as can be seen in the Ghost Dance and Forty Mile Wash zones.

Hotter water has also been encountered by the Nye County Early Warning Drilling Program (EWDP) and seems to be coincident with the northwest trending Highway 95 Fault (Carerra Fault) or other north northeast trending extensions of normal faults in this location.

Structural Controls on Flow

The conceptual model is that of a fracture flow system, where flow paths and velocities are controlled by the existing fracture networks. A significant upward component of flow is possible on the west side of Yucca Mountain due to the high temperatures noted at the water table at wells WT-10 and WT-7 along the alignment of the Solitario Canyon Fault. Other extensional fault zones, such as the Bow Ridge, also may allow upwelling of warm water from the carbonates when hydraulic pressures are favorable.

The Solitario Canyon Fault also influences the hydrology in a lateral sense by potentially creating a “medium hydraulic gradient” from west to east near the repository block. Measured heads range from about 775 meters to the west of the fault and drop abruptly to about 730 meters on the eastern side. The Solitario Canyon Fault is a major north-striking scissors fault, which to the south is down-thrown on its western side and to the north is down-thrown on the eastern side and may exhibit differing hydraulic properties along its length.

Northwest trending strike-slip faults also seem to play a role in influencing the hydraulic potentials at the site. Strike-slip faulting may provide vertical conduits to flow and in some cases barriers to horizontal flow. Strike-slip faulting has been linked to tectonic activity in the Walker Lane Belt, a large northwest-trending structural zone that parallels most of the southwestern border of Nevada. Some water movement occurs across the mountain block from west to east, primarily via discrete northwest trending fracture zones.

Colder flow also enters the Yucca Mountain block from the north and northwest across a very steep hydraulic gradient. This gradient is equal to over 300 meters of head change across 2500 meters distance. The northwest trending faults in the Drill Hole Wash region no doubt play a role in the transport of water across this steep hydraulic gradient. Where the Drill Hole Wash Fault or those near it, intersect the northern extension of the Solitario Canyon Fault, a potential breach may occur and allow the colder water north of the steep gradient to move across this fault zone and subsequently into the Ghost Dance and Bow Ridge faults. The potentiometric surface also suggests that another fault zone exists just to the south of the repository footprint. This zone may also be transporting water from the west side of the Yucca Mountain block in Crater Flat toward the east.

Fracture zone intersections also play a key role in the distribution of recharge, pathways and velocity fields. Areas of fault intersections may act as drains in the northern regions and conduits for upwelling water in the southern regions of the mountain block and intercept eastward flow.

Hydrostratigraphic Units

The hydrostratigraphic section was modeled as three layers in these exercises. The first layer represents the aquifer series of upper Miocene tuffs. Layer 2 represents the lower Miocene volcanic confining units. Layer 3 represents the Paleozoic carbonate aquifer.

NUMERICAL MODEL

In order to evaluate an alternative conceptual model of saturated zone flow for the area around and including Yucca Mountain, a numerical model was assembled and tested. This model covers a larger area than our previous modeling work (4), due to the necessity of including regional discharge areas and most likely affected populations.

Modeling Objectives

A major goal in developing the larger numerical model was to be able to use this model as a framework for testing alternative hypotheses and flow paths. The model should not be thought of as an exact replica of Yucca Mountain, but one which closely resembles it and can therefore be used to test structural and hydraulic controls on flow.

The first step was to calculate a steady state flow field in which the calculated heads and temperatures are matched as closely as possible to those measured at Yucca Mountain.

Measured temperature and pressure are used as calibration targets. In addition to calculating the steady state velocity field, another objective was to ascertain which faults exhibit control on the flow field and which do not.

Model Grid

The model grid is composed of three layers each possessing 3030 cells in an 30 x 101 grid. Figure 1 represents the Layer 1 and 2 grid. Layer 1 represents the volcanic aquifer. The thickness of this unit generally decreases from north to south. In this modeling exercise, the layer is set uniformly at 500 meters in thickness At well number UE-25-p#1 the thickness is

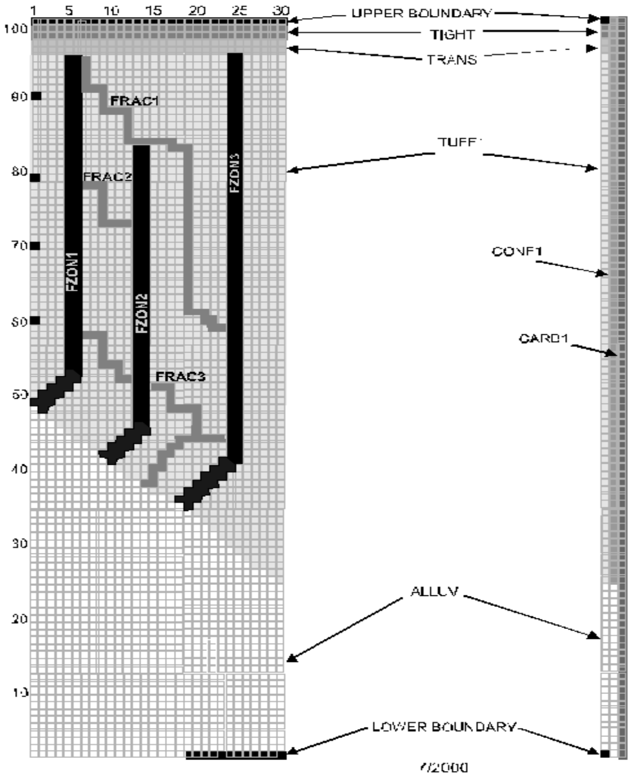


Fig. 1. Model Grid

approximately 800 meters. Permeability increases generally from north to south. A Tight Unit (TIGHT) comprises the northern boundary and creates the large hydraulic gradient conditions. The Transitional Unit (TRANS) represents a permeability transition to the generally more transmissive tuff properties (TUFF1 & 2). This unit was necessary to maintain numerical stability and to simulate the observed potentiometric surface. Based on the work done by Nye County, alluvium was added to the lower part of the new model. The Highway 95 fault forms the northern boundary of the alluvial layer. The alluvium is considered more permeable than the tuff and exists in Layers 1 and 2. The Highway 95 fault is implicit due to permeability differences.

Fault hydraulic properties range from less permeable than, to more permeable than the tuffs, in some cases causing barriers and in others conduits. In this layering, a few of the faults are explicitly included and specific hydrologic properties have been individually assigned to them. Explicitly included in Layers 1 and 2 are the Solitario Canyon, the Ghost Dance and the Bow Ridge and Forty Mile Wash faults. Three northwest trending strike-slip faults are included as Drill Hole Wash, Sun Dance and a third fault zone (name unknown) just south of the repository horizon.

Initially, all fault zone permeabilities, vertical and horizontal were set equal, as there is no information available to indicate differences. These differences in anisotropy were explored in the calibration process.

Layer 2 has the same number of elements (3030) as does Layer 1. This layer represents the lower volcanic confining unit. This unit is about 400 meters in thickness at UE-25-p#1. In these simulations Layer 2 is held constant at 500 meters in thickness. Layer 2 represents the Lithic Ridge and older tuffs down to the Tertiary/Paleozoic contact. The volcanic system appears to be acting as an aquitard at its lower boundary with the carbonates, as interpreted from UE - 25p#1 data. The head increases slightly in the Lithic Ridge Tuff and significantly increases in the older tuffs beneath the Lithic Ridge, to a potential of 752.2 meters Above Sea Level (ASL). At UE - 25p#1 this aquitard lies at a depth of 873 meters. The Tertiary/Paleozoic contact is at a depth of approximately 1,200 meters.

Rock properties assigned to this layer were initially the same for the fault zones in Layer 1, but the rest of the grid was assigned a lower permeability (Conf1). Bredehoeft (5) indicates that this confining unit must be quite tight in order to sustain earth tides. This permeability was adjusted to best match measured head and temperature values in the lower volcanic confining units. No boundary conditions are assigned to this unit and it is allowed to float, or equilibrate naturally.

Layer 3 is the carbonate aquifer which apparently discharges in Ash Meadows and generally to the south, south east and possibly southwest of the Yucca Mountain block. As mentioned earlier, it is simulated via constant temperature and head boundary nodes of 752 meters and 57 degrees

C, and does not actually exist as a separate layer. Flow will therefore be upward from the carbonates into the tuffs over most of the entire grid, where higher heads along the northern boundary are not present. It is 20 meters above that in the volcanics at UE -25-p#1.

Other boundary conditions are head and temperature on the northern boundary (1000 m and 29 degrees C) and head and temperature at two positions along the southern boundary as measured by Nye County (720 m) In a few simulations, points for head and temperature were also placed along Solitario Canyon to the west of the mountain, near WT-7 and WT-10 (775 m and 32 degrees C). The eastern boundary is east of Forty Mile Wash and has no boundary nodes. These boundary conditions can be seen in Figure 1.

Calibration Targets and Data Sets

There are several sets of data which may be used in calibrating steady state and transient flow models. The steady state data sets include the potentiometric surface, hydraulic head with depth in 10 wells, calculations of fault zone permeability and upward groundwater flux by Bredehoeft (5), temperature distributions and heat flux calculations of Sass (6) and chemistry analyses of the US Geological Survey (USGS) and Los Alamos National Laboratory. Calibration of a transient model is more difficult, but water table fluctuations over time are available as are various water level studies in Pahrump, Nevada. The Nye County Alluvial Tracer test complex results and C-Well complex tests could be utilized for these purposes.

Potentiometric Surface and Other Potentiometric Data

In 1994, the USGS published a Water Resources Investigations Report (7). In this report, the USGS has undertaken to correct the earlier water level measurements by re-surveying the elevations of the well-heads and by correcting for temperature and density. The report contained the actual revised data, so we were able to plot the potentiometric surface utilizing all the new data. Embayments are clearly visible. There are three major embayments, which appear to be coincident with the NW-SE trending strike-slip Drill Hole Wash Fault, Sundance Fault and an unnamed fault just south of the repository footprint. Figure 2 shows the potentiometric surface we are using as a calibration target.

Other data are available in terms of hydraulic head on which to calibrate model outputs. There are 10 sites which have been measured at multiple depth intervals. Many of these wells exhibit increasing head with depth, especially when the lower volcanic confining unit is reached.
At well number UE-25 p#1, upward flux rates and fault permeabilities have been derived from earth tide calculations. Upward movement of hot water was thought coincident with major

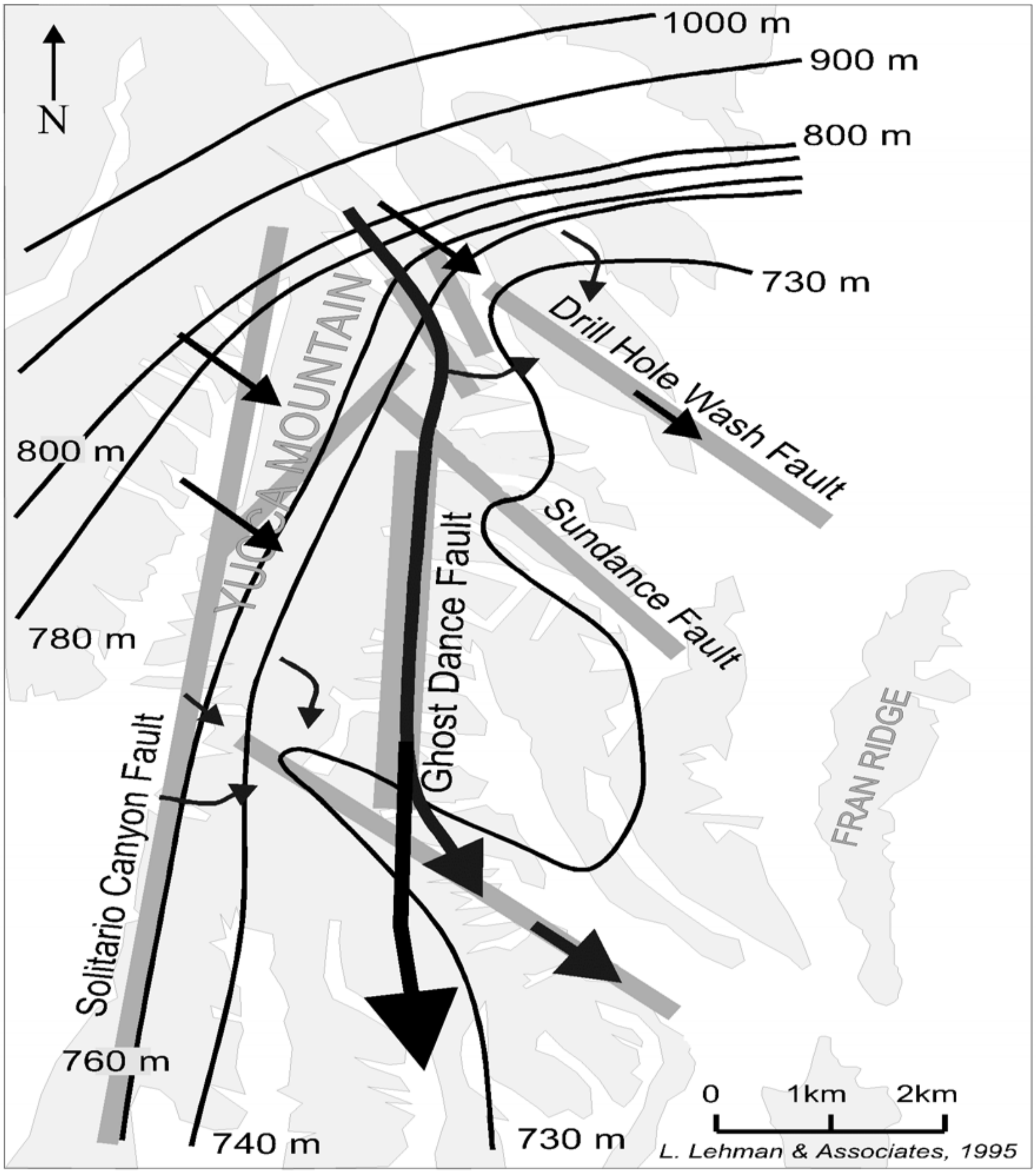


Fig. 2. Potentiometric Surface

extensional faults which breach a very tight confining unit, such as the Bow Ridge Fault in Midway Valley (5).

The Nye County EWDP maintains a data base of hydraulic information obtained during their drilling program. Recently, Nye County drilling of Well 19 D hit the carbonates. Once again an upward gradient of approximately 20 meters higher than the surficial aquifer was detected at this well.

Temperature

Additional information on the pathways for ground water movement is obtained from the temperature distributon. The data set utilized as a calibration target for this work is that of Sass (6) and is shown in Figure 3. Heat flux also calculated over the Yucca Mountain region (6). This work can also be used as guidance when applying recharge.

Large temperature gradients exist across the mountain block and also in the area of the Nye County Early Warning Drilling Program (EWDP), which also collects temperature at each borehole. These temperature data are maintained in their database.

Chemistry

Zell Peterman of the USGS has developed plots of major ion and isotope chemistry. These plots were distributed at the Nuclear Waste Technical Review Board (NWTRB) January, 1998, meeting in Amargosa. These plots should also be helpful in delineating flow paths. Our work is consistent with these data, to the extent possible.

Ed Kwikless presented analyses done at Los Alamos National laboratory at the May 2001, DOE/USGS Death Valley Flow Model meeting (1), which used geochemistry to link potential flow paths toward Forty Mile Wash. These data may be utilized as collaborative data. Nye County also maintains water chemistry data on their database, collected through their EWDP project.

MODEL RESULTS AND CONTROLS ON POTENTIOMETRIC SURFACE AND TEMPERATUE FIELDS

A series of parametric analyses were undertaken where permeabilities of the various grid zones were varied. As mentioned earlier, the first runs were accomplished with isotropic permeability fields assigned to the fault zones. We have discovered that the model at Yucca Mountain is a balancing act. Changes which affect temperature may also affect the potentiometric surface. It was fairly easy to match the potentiometric surface, but quite another problem to keep the potentiometric surface while adjusting the parameters that affect temperature. However, during the calibrations, considerable knowledge was gained regarding the controls on flow.

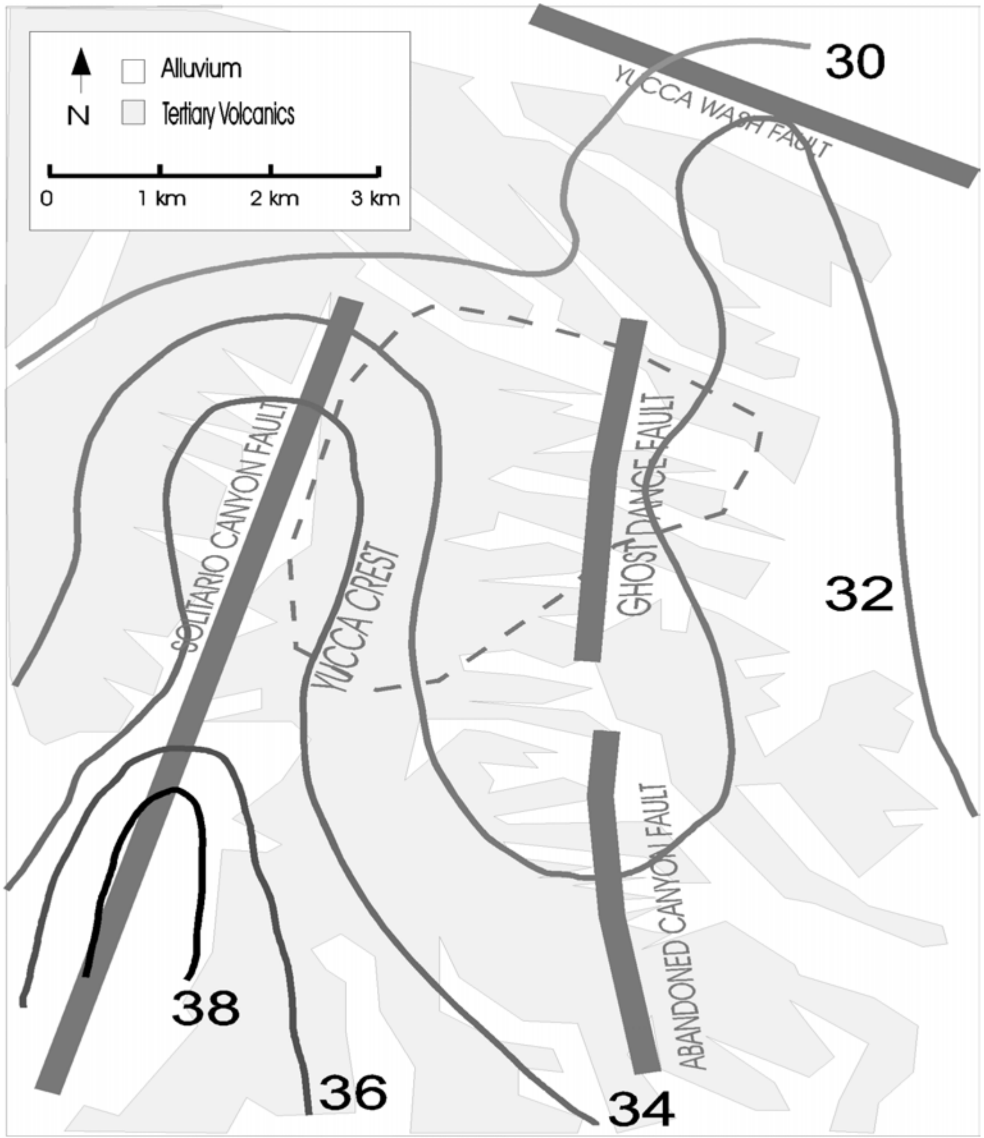


Fig. 3. Temperature Distribution

During these calibration analyses, it was found that the main control on temperature is the vertical conductivity. In areas where the hydraulic head is higher in the carbonates than in the tuff sequence, the higher heat from the lower carbonate boundary condition will dominate the temperature distribution at the water table. Water table temperatures can also be affected by limiting the amount of flow coming into the model from the north. By decreasing inflow from the north, more water upwells from the carbonates and temperatures are correspondingly higher. Likewise, by bypassing the TIGHT and TRANS units aat the Drill Hole Wash and Forty Mile Wash Faults, i.e. creating a constant head boundary condition at these locations of 1000 meters, we are able to cool these two fault zones considerably. We were able to get temperatures to within a degree or so of the target calibration set. As can be seen in our final temperature distribution, the intrablock fault zones are still a little hotter than the surrounding tuffs. We have identified several ways to cool the fracture zones, as follows:

- Add more water from the north via a slightly higher head boundary.
- Add water from surface infiltration as indicated in the heat flux analyses (6).
- Limit vertical communication of the faults under Yucca Mountain with the carbonates.
- Adjust thermal conductivities.
- Change carbonate boundary conditions under Yucca Mountain.

Future modeling work will pursue some of these options.

The controls on the potentiometric surface were more straightforward. The northwest trending shear zones of high permeability in the x and y direction control the location of the embayments.

The north-south trending faults also influence the potentiometric surface and their position within the flow field is important. For example, it had been previously assumed that the low permeability of the Solitario Canyon Fault was the main control on the "medium hydrologic gradient" seen at Yucca Mountain. In an attempt to better match the temperature distribution, we removed the Ghost Dance Fault zone completely. This run greatly affected the potentiometric surface, in that the "medium hydrologic gradient" was reduced and moved to the east, to the position of the Bow Ridge fault. It seems that the x and y permeability of the Ghost Dance had been controlling the position of the gradient, rather than the Solitario Canyon Fault. While not intuitively obvious, it does make sense when considering the position of the Ghost Dance in relation to the flow field. The flow field is oriented primarily north to south under the imposed boundary conditions, with some flow, though not as much, coming in from the northwest. The impermeable Solitario Canyon Fault, being also positioned north-south, doesn't have much affect, as flow will simply go around it and continue south. The Ghost Dance, on the other hand, would tend to capture the north to south flow since it would behave as an open channel and confine the flow to within its borders.

The final temperature distribution obtained in these analyses is shown as Figure 4. While we still have not gotten colder temperatures in the Ghost Dance fault, we are very close and have decided on the next steps to accomplish this goal. In this figure, the alluvium south of the mountain is covered. This is because the alluvial properties have not yet been calibrated or adjusted. From the Nye County explorations and well testing, it is apparent that a confining unit is also justified in the alluvium.

From these analyses we conclude that flow to the repository appears to be entering from the north and upwelling along northwest trending shears where head conditions in the lower units are higher than in the tuffs. Recharge is occuring where heads are lower than in the tuffs. Flow is predominately southward from the repository footprint. Some upstream diversion of northwest flow occurs along the north side of the repository and into the Bow Ridge in Midway Valley and Forty Mile Wash. Most of the repository block on the west side of Ghost Dance would drain into the Ghost Dance Fault.

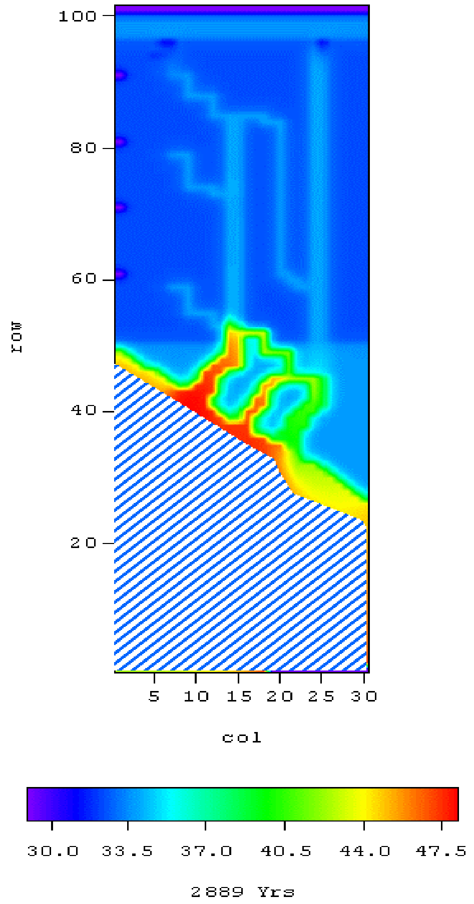
FUTURE WORK

Some future work has already started which includes the explicit addition of the Highway 95 Fault and the addition of a confining unit in the alluvium. Recharge will also be applied in the area of the low heat flux. It is also planned to limit the connectivity between the Yucca Mountain block and the carbonate aquifer. This should reverse the temperature profiles which show hot upwelling in the northern reaches of the block. Alternatively, upwelling could be reduced by adjusting the vertical permeability (Kv) in the northwest trending fault zones or adjusting the lower boundary conditions of temperature and pressure to more closely match the Nye County findings for head as measured to the southeast of the Yucca Mountain block. Runs for these conditions will continue in FY 2002. We plan to work closely with Nye County in ascertaining permeabilities and calibration data sets for the alluvium and carbonates.

SUMMARY

In the process of calibration, it was found that the temperature distribution is controlled by the distribution of $K_{v.}$ Under the circumstances tested, flow is upward and hot unless heads in the tuff are higher than the lower boundary condition of 750 m.. High temperature water comes up faults Temperature is higher in faults and lower in tuffs, unless enough water is available to move through the fault zone from cooler areas. Then faults are cooler than the tuff. This is the case from the temperature measurements of Sass (6) and from our previous model results; the Ghost Dance Fault is cooler, not hotter than the surrounding tuffs.

Two things that give us reason to think that recharge is occuring at Yucca Mountain and cooling the fractures are 1) the temperature distribution is centered on Ghost Dance Fault, and 2) heat flux is negative at the intersection of Ghost Dance and Drill Hole Wash faults.



New Run: Initials set at
Carb=50
Layer 2 = 40
Layer 3 = 29

Layer 1 Deck03

Fig 4. Modeled Temperature Distribution

Control of the potentiometric surface is based not only on the x and y permeability tensors, but also the position of the fault in the flow field This was upheld by our analysis when the Ghost Dance Fault was removed resulting in a less steep gradient.

The model, while simple, allowed us to examine the relationship of the head and temperature distributions to the position and permeability of major fault zones. It is our conclusion that the major faults included in this model do significantly affect the observed head and temperature distributions.

Current DOE Performance Assessments may not reflect actual doses at the compliance boundary due to the potential for radionuclide flow to be captured in the Ghost Dance Fault and be transported primarily south with little dilution and dispersion.

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