Determining Fault Permeability from Subsurface Barometric Pressure

By Ning Lu, Member, ASCE, Edward M. Kwicklis, and Joe P. Rousseau

Abstract: Measured barometric pressure fluctuations in a borehole drilled 600 m into the unsaturated zone at a site on the eastern slope of Yucca Mountain, Nevada, are used to compute pneumatic diffusivities and air permeabilities of layered tuffaceous rocks. Of particular interest is the occurrence of increasing pressure amplitude and decreasing phase lags observed at several deep stations. The pressure amplitude increases by 13% and the pressure peak arrives 65 to 72 h earlier as the depth of the unsaturated zone increases from 407 to 436 m. This observation is inconsistent with a conventional 1D downward pressure decay model, but can be explained by hypothesizing the existence of a lateral pneumatic flow path from a nearby fault. A 2D numerical model has been constructed to test this lateral flow hypothesis. The modeling results indicate that a leaky-fault hypothesis can reconcile the measured barometric data with other geologic mapping and permeability measurements at the site. The inferred fault permeability ranges from $0.6 \times 10^{-12}$ to $0.12 \times 10^{-9}$ m$^2$, and that of the surrounding tuff layers ranges from $0.4 \times 10^{-13}$ to $0.8 \times 10^{-12}$ m$^2$. Our analysis also demonstrates that although the larger-amplitude, longer-period synoptic signals lack coherence and periodicity, determination of air permeability in deep unsaturated zones must rely on these longer-period oscillations of barometric pressure whose periods are on the order of weeks to months because the shorter-period diurnal and semi-diurnal barometric oscillations generally are not detectable at deep depths.

Introduction

It is well known that barometric pressure fluctuations can propagate to deep depths in the unsaturated subsurface. For example, Stallman (1967) first suggested that the histories of pressure differences between the surface and subsurface could be used to infer the pneumatic diffusivity of porous media. Later, Stallman and Weeks (1969) computed hydraulic conductivities in the unsaturated zone by using the observed atmospherically induced pressure fluctuations. Another notable example of pressure propagation in the subsurface is the fluctuation of water levels in wells in response to barometric pressure changes at the land surface. These fluctuations result from an imbalance in the pressure head between the well and its surroundings [for example, Weeks (1979); Hsieh et al. (1987); Rojstaczer (1988)]. Generally, as pressure variations propagate into the unsaturated zone, the amplitude of the pressure wave will decay and its phase will lag with respect to the barometric pressure wave.

Amplitude attenuation and phase lag of the barometric pressure signal in the subsurface can be used to determine the pneumatic properties of soils or rocks. For example, Weeks (1978) devised an in situ measurement method to record these changes and demonstrated that these depth-dependent changes can be used reliably to determine the vertical air permeability of layered soils. Rojstaczer (1988) and Rojstaczer and Tunks (1995) used the response of water levels in wells to atmospheric loading to determine fluid flow properties of aquifers and the pneumatic properties of the overlying unsaturated zone. Recently, Shan (1995) presented analytical solutions for determining vertical air permeability in unsaturated soils and demonstrated that these solutions can be applied to the interpretation of field pneumatic pressure measurements in layered soils. A new theoretical framework was developed by Lu (1999) that can be used both to determine the vertical air permeability and to predict subsurface time-series air pressure responses.

While the previous studies on barometrically induced air flow provide general methodologies and important insights into the physics of the interactions between aquifers and unsaturated zones, most of them focused either on 1D or radial flow problems. Furthermore, these studies were restricted to shallow unsaturated soils with relatively thin layers less than 50 m thick and permeabilities greater than $1 \times 10^{-11}$ m$^2$.

Air diffusivities or permeabilities inferred from shallow and permeable unsaturated zones in the previous studies relied heavily on the diurnal and semi-diurnal barometric fluctuations. However, based on the previously developed theories of air pressure propagation under the harmonic components of the barometric excitations [for example, Weeks (1978); Hsieh et al. (1987); Rojstaczer (1988); Nilson et al. (1991)], it can be concluded that the diurnal and semi-diurnal oscillations cannot be detected in the deep and less permeable unsaturated zones—say, greater than about 100 m—where permeability is less than $0.1 \times 10^{-12}$ m$^2$. This is because the diurnal and semi-diurnal signals usually have amplitudes less than 300 Pa and can decay to a level less than the measurable value of 10 Pa in the deep and less permeable unsaturated zones. On the other hand, the synoptic and seasonal pressures, though less regular in nature, can fluctuate on the order of 1 to 3 kPa. Therefore, these long-term fluctuations with larger amplitudes and longer time periods can propagate much deeper into the unsaturated zone. Few case studies under thick and less permeable unsaturated zone conditions have been documented to date. In this work, measured barometric pressure fluctuations from a 660 m borehole are used to infer pneumatic permeability of a fault and its host rocks.

Site Description

Borehole USW SD-12 was drilled 660 m into the tuffaceous rocks within the central block of the proposed repository area (Fig. 1) at Yucca Mountain, Nevada, between January 1994 and August 1995. Packer air injection tests were conducted in the upper 350 m between January and May 1995 by the U.S. Geological Survey (LeCain 1997) in order to determine air permeabilities of the tuffaceous rocks. SD-12 is located on the eastern slope of Yucca Mountain and is strategically located...
because of its close proximity to the Ghost Dance Fault (~200 m apart), which is the most significant structural feature within the boundaries of the main repository area. The fault lies within the middle of the repository area (Fig. 1) and crosses almost the entire Central Repository Block from north to south. The length of the fault along the north-south direction is about 5 km and the cross section (Fig. 1) is at about the middle (that is, 2.5 km from the north end). It dips to the west about 84° and extends nearly vertically to an unknown depth below the water table, which is located about 594 m below the ground surface at SD-12.

For years, the hydrogeologic significance of the Ghost Dance Fault has been a major concern and the focal point of some research activities. Because faults are broken and intensely fractured, they can potentially act as preferential pathways for either water or air. Therefore, understanding the hydrologic structure and behavior of the Ghost Dance Fault is important in evaluating the performance of a geologic repository under both natural and post-waste-emplacement conditions.

The lithology and hydrostratigraphy of the bedded tuffaceous rocks in the area of SD-12 are shown in Fig. 2. The tuff layers consist of five major hydrogeologic units identified here in descending order as follows: Tiva Canyon Tuff, Paintbrush Nonwelded Unit, Topopah Spring Tuff, Calico Hills Formation, and Prow Pass Tuff. Previous geologic and hydrologic investigations (Scott and Bonk 1984; Buesch et al. 1996) indicate that the Tiva Canyon Tuff is densely welded and intensely fractured; the Paintbrush Nonwelded Unit is sparsely fractured and its intergranular porosity is high (about 0.45); the Topopah Spring Tuff—which contains the layers from the crystal-rich to the crystal-poor vitric—is moderately to densely welded and its fracture density is high; and the Calico Hills Formation and Prow Pass Tuff are nonwelded and sparsely fractured and their porosity is medium to high (about 0.3).

Sixteen instrument stations were established in SD-12 in November 1995. A ground surface station to reference temperature and barometric pressure was established at each site. Each downhole station was instrumented with two pressure transducers, two thermistors, and two thermocouple psychrometers (Rousseau et al. 1999).

**OBSERVATION AND HYPOTHESIS**

The observed barometric pressure variations at selected depths during a 104-day period for SD-12 from November 27, 1995, to March 19, 1996, are presented in Fig. 3. Several pressure variation patterns can be identified. At the depth of 25 m (station 1691 located within the Tiva Canyon Tuff), air pressure exhibits the largest pressure fluctuation, from 87,875 Pa (January 12, 1996, 1,550 h) to 85,540 Pa (January 16, 1996, 1,650 h). Therefore, the amplitude at the depth of 25 m (called the 25 m station hereafter) is 2,335 Pa.

Significant attenuation of the pressure amplitude and shift in the phase can be observed at the depth of 107 m (station 1661, which is about 107 m below the ground surface, or 82 m below the 25 m station) and is located in the upper non-
FIG. 2. Location of Pressure Sensors and Lithology of Tuff Layers near SD-12. Topopah Spring Unit Includes Subunits of Crystal-Rich Vitric Upper Nonlithophysal, Upper Lithophysal, Middle Nonlithophysal, Lower Lithophysal, Lower Nonlithophysal, and Crystal-Poor Vitric lithophysal subunit of the Topopah Spring Tuff. The pressure amplitude at the 107 m station for the same synoptic pressure signal is 1,258 Pa and is about 45% of the amplitude at the 25 m station. The time lag for the peak pressure arrival between the 25 and 107 m stations is about 23 h. The large amplitude attenuation and phase-lag shift imply that the pneumatic diffusivity of the Paintbrush Nonwelded Unit is very low, reflecting a combination of moderate-to-low permeability and highly drained porosity. Another phenomenon is the apparent extinction of the higher-frequency barometric fluctuations, that is, the diurnal and semidiurnal modes at the 107 m station (Fig. 3), consistent with the aforementioned damping of diurnal and semidiurnal oscillations.

At greater depths, pressure fluctuation patterns are very similar for all stations within the Topopah Spring Tuff except the 390 m station (station 1613, located in the lower nonlithophysal subunit at the bottom of the Topopah Spring Tuff—see the pressure fluctuations at the 107, 285, and 390 m stations in Fig. 3). There are two possibilities for the similar pressure responses observed in these deeper stations: either (1) the entire Topopah Spring Tuff is very permeable and uniform throughout; or (2) the source of the pressure fluctuation is located at a nearly equal distance from all these stations.

Previous air permeability tests in this borehole indicate that air permeability in the Topopah Spring Tuff ranges between $10^{-11}$ and $10^{-13}$ m$^2$ (LeCain 1997). Therefore, if the barometric pressure propagation is predominantly vertical, we should expect to see a progressive decay in the amplitude and a progressive shift in the phase lag of the pressure signal with increasing depth over the 283 m interval between the uppermost (the 107 m station) and lowermost (the 390 m station) Topopah Spring instrument stations. Because the Ghost Dance Fault is between 185 m (western trace) and 225 m (eastern trace) away directly east from SD-12 (Fig. 1), it seems logical to suspect that the fault may be the pressure source for all the observed pressure fluctuations in these stations.
FIG. 3. Barometric Pressure Fluctuations at (a) Different Stations; (b) 413 m Station (within Vitric Zone of Topopah Spring Unit) and 443 m Station (in Upper Part of Calico Hills Unit) between November 9, 1995, and March 13, 1996, in USW SD-12

Deeper in the borehole, there is a dramatic decrease in amplitude from 1,450 Pa at the 390 m station to 77 and 92 Pa at the 413 and 443 m stations, respectively. See Fig. 3 for the pressure variations at the 390, 413, and 443 m stations, which are located in three very different hydrogeologic subunits: the lower nonlithophysal subunit of the Topopah Spring Tuff (the 390 m station); the crystal-poor, densely welded vitric zone of the Topopah Spring Tuff (the 413 m station); and the non- to partially welded Calico Hills Formation (the 443 m station).

An interesting phenomenon is the increase in pressure magnitude and the decrease in phase lag between the 413 and 443 m stations. The pressure amplitude increases by 13%, and the pressure peak arrives 65 to 72 h earlier as the depth increases from 413 to 443 m [Fig. 3(b)]. This phenomenon is inconsistent with a vertical 1D downward pressure decay model. It also suggests that the barometric pressure wave may propagate laterally from the fault toward these stations because vertical pressure propagation would result in smaller amplitudes and later arrivals of the pressure peak at the lower station at 443 m than at the higher station at 413 m. Because the distance between the 390 and 413 m stations is 23 m and between the 413 m station and the fault is 152 m, air pressure fluctuations observed at the 413 m station should be dominated by vertical pressure propagation unless the air permeability of the vitric zone is highly anisotropic with a very large horizontal to vertical permeability ratio.

Based on the above observations, we propose the following conceptual pneumatic model in the area of borehole SD-12 and the Ghost Dance Fault. In the Tiva Canyon Tuff the barometric pressure fluctuation propagates vertically with little attenuation and phase lag until it encounters the Paintbrush Nonwelded Unit, where the amplitude begins to decay rapidly but the direction of propagation remains vertical. The Ghost Dance Fault acts as a preferential pneumatic pathway for barometric pressure, and therefore little attenuation of the pressure signal occurs inside the fault zone.

Barometric pressure changes propagate rapidly down the fault zone and then laterally into the formations adjacent to the fault (Fig. 1). The lateral propagation is relatively fast in the permeable formations, such as the Topopah Spring unit, and slow in the less permeable formations, such as the Calico Hills and Prow Pass units. A 2D pneumatic flow model accounting for all these features is illustrated in Fig. 1. This model was used to test the lateral flow hypothesis and estimate the permeabilities of the fault zone, the upper part of the Calico Hills Formation, and the crystal-poor vitric zone of the Topopah Spring Tuff.

GOVERNING EQUATION AND INITIAL AND BOUNDARY CONDITIONS

In general, the equation governing air flow in unsaturated porous media is nonlinear and can be expressed as [for example, Weeks (1978) and Lu (1999)]

\[
\frac{\partial P}{\partial t} = \alpha_x \frac{\partial^2 P}{\partial x^2} + \alpha_z \frac{\partial^2 P}{\partial z^2}
\]

(1)

where \( P \) = square of the air pressure \( P \), and \( \alpha_x \) and \( \alpha_z \) are respectively the diffusivity of gas in the horizontal \( x \)- and vertical \( z \)-directions and are defined as

\[
\alpha_x = \frac{kP}{\Phi \mu}; \quad \alpha_z = \frac{kP}{\Phi \mu}
\]

(2)

where \( \Phi \) = air-filled porosity, \( \mu \) = air viscosity, and \( k_x \) and \( k_z \) = intrinsic permeabilities in the horizontal \( x \)- and vertical \( z \)-directions, respectively. Eq. (1) is a second-order nonlinear partial differential equation. The nonlinearity arises because of the dependency of the air diffusivities \( \alpha_x \) and \( \alpha_z \) on pressure, as depicted in (2). However, because seasonal and daily atmospheric pressure fluctuation are usually much less than 10% of the mean pressure, the pressure in the diffusivity terms can be treated as a constant, as has been done in many previous studies. Therefore, for many practical problems that involve analysis of barometric pressure responses in the subsurface, (1) can be linearized by setting a constant pressure in the diffusivity terms to yield satisfactory results [for example, Weeks (1979) and Lu (1999)].

The hydrostatic equilibrium condition is used to define the initial pressure distribution:

\[
p(x, z) = P_0 e^{\frac{z}{mRT}}
\]

(3)

where \( P_0 \) = mean annual atmospheric pressure at \( z = 0 \); \( M \) = molecular weight of air; \( g \) = acceleration of gravity; \( R \) = gas constant; and \( T \) = temperature. Because Calico Hills and Prow Pass are of low permeability (LeCain 1997) and the water table is within Prow Pass, a no-flow boundary is applied at the bottom boundary. The right boundary is set at about 500 m west of SD-12 because it is below the crest of Yucca Mountain. The 500 m also provide a large distance so that the uncertainty due to the boundary effect can be minimized. By way of the mountain symmetry, the left boundary is treated as a no-flow boundary. The right boundary is located along the approximate symmetric center line of the Ghost Dance Fault, and therefore a no-flow boundary should be a reasonable physical representation. Note that the Ghost Dance Fault itself is simulated as a permeable column (Fig. 4).

Due to the limitation on the number of boreholes available...
The permeability of the Topopah unit is densely welded and intensely fractured (Scott and Bonk 1984; Buesch et al. 1996), and the permeability of the Topopah Spring unit has been previously identified as a much more permeable layer than Calico Hills (LeCain 1997; Rousseau et al. 1999—see Fig. 1 and a detailed discussion in the previous section), air pressure travels laterally much faster from the Ghost Dance Fault to the stations within the Topopah Spring unit than from the Ghost Dance Fault to the stations within the Calico Hills unit. Previous geologic and hydrologic studies showed that the Topopah Spring unit is densely welded and intensely fractured (Scott and Bonk 1984; Buesch et al. 1996), and the permeability of the Topopah Spring unit is $2.0 \times 10^{-11}$ m$^2$, about 20 times higher than that of the Calico Hills unit (LeCain 1997). On the other hand, significant phase lag and amplitude attenuation have been observed between the Topopah Spring and Calico Hills units. Based on these considerations, the boundary condition along the top is approximated as a time-varying pressure. The time-varying upper boundary condition is simulated using the measured pressure fluctuation data at the 390 m station.

The numerical code TOUGH2 (Pruess 1987, 1991) was used because of its capability of solving (1) by an integrated finite-difference method and easily imposing (3). In principle, we can solve the well-defined initial and boundary value problem illustrated in Fig. 4 by applying the time-dependent pressure boundary condition at the upper boundary and imposing other appropriate boundary and initial conditions. By conducting parametric sensitivity analysis or inverse modeling and using the observed air pressure fluctuations within the domain, we should be able to infer or calibrate the permeability structure. However, there are at least two practical difficulties preventing us from doing so: the limited observation period and the limited knowledge of the initial condition of the air pressure field, as discussed below.

**HARMONIC ANALYSIS OF MEASURED DATA**

Because the present study deals with a thick unsaturated zone and 2D flow problem, the initial pressure field cannot be obtained as was done in the previous studies of 1D and shallow problems. Unlike the diurnal and semidiurnal barometric fluctuations, the barometric pressure fluctuation on a monthly scale is usually less periodic. In addition, pressure propagation from one station to another may take much longer. As a result, the effect of the initial condition may have a prolonged influence on the numerical simulation of barometric fluctuation in thick zones.

To overcome the problem described above, we use harmonic analysis, which previously has been used by others to analyze the diurnal and semidiurnal signals (Hsieh et al. 1987). The basic idea is to select the desired harmonic signals from the original nonperiodic data and conduct a time-series analysis or modeling using only those selected harmonic functions. In our case, we first conduct a Fourier series or spectrum analysis on the measured data at the stations of interest. Harmonic functions with amplitudes significantly larger than the measurement error ($11 \pm 6$ Pa) are chosen for further analysis. Because of the periodic nature of the harmonic function, we can always remove the effects of inaccurate initial conditions by continuing the simulation through a sufficient number of cycles (Lu 1999).

Fig. 5(a) shows the results of the harmonic analysis of the pressure data at the 390, 413, and 443 m stations, where the amplitude of harmonic functions is a function of the frequency. At the 390 m station, it is found that the amplitude decays as the frequency increases, but at a much slower rate than those at the 413 m and 443 m stations. The amplitudes at these stations show that only the five lowest frequencies are larger than or equivalent to the measurement error (10 Pa). In fact, only the first frequency (period equal to 102 days and amplitude equal to 33 Pa) is significantly larger than 10 Pa. Fig. 5(b) shows the first five harmonic functions and Fig. 5(c) the superposition of these five harmonic functions at stations 1607 and 1601. It can be concluded that the first five harmonic functions can well represent the observed data at these two stations over the period of 102 days. It can also be concluded that, of the harmonic function observed at the 390 m station [solid line in Fig. 5(a)], the lowest frequency component dominates the signal detected at the 413 and 443 m stations. Therefore, we focus on modeling the first harmonic mode in the next section.

**INFERRED PERMEABILITY REGIMES**

As illustrated in the conceptual model, there are three subregions where permeabilities need to be determined: the Ghost
Dance Fault, the upper part of the Calico Hills Formation, and the crystal-poor vitric zone at the base of the Topopah Spring Tuff. The relationship of the permeability regimes for these subregions is depicted in Fig. 6. The logic used to assign the different permeability ranges to these subregions is described below.

Because the barometric pressure signal in the upper part of the Calico Hills Formation (the 443 m station) is larger and arrives earlier than that in the vitric zone at the 413 m station, and the horizontal distance between the 443 m station and the Ghost Dance fault (152 m) is much greater than the vertical distance between the 390 and 413 m stations (23 m), the permeability of the vitric zone can be assumed to be much smaller than the permeability of the upper part of the Calico Hills Formation. Therefore, the maximum permeability of the vitric zone is less than $k_b$. Another constraint is that the permeability of the Ghost Dance Fault is at least greater than the upper part of the Calico Hills Formation due to the broken and displaced nature of the fault. Therefore, the upper limit of permeability for the Calico Hills Formation and the lower limit of permeability for the fault are defined by $k_2$.

The three permeability regimes shown in Fig. 6 are bounded by four values of permeability: a lower limit $k_4$ for the vitric zone; an interface value $k_3$ for the vitric zone and the upper part of the Calico Hills Formation (and it could be a range rather than one number); an interface value $k_2$ for the Ghost Dance Fault and the Calico Hills Formation (and it could be a range rather than one number); and an upper limit $k_1$ for the Ghost Dance Fault. Because the vertical distance between the 390 and 413 m stations is 23 m, the barometric pressure signal observed at the 413 m station is the response to the barometric signal at the elevation of the 390 m station. Therefore, the lower-limit value of permeability $k_4$ for the vitric zone can be inferred by calibrating the air permeability using the measured signal at the 413 m station.

For estimation purposes, an analytical relation among $k_1$, $k_2$, and $k_3$ can be established by using the principle of mass conservation and Darcy's law. Because the air permeability of the vitric zone is considered much smaller than the air permeability of the fault (up to four orders of magnitude less) and smaller than that of the Calico Hills Formations (up to two orders of magnitude less), the hydrologic relation between the fault and the Calico Hills Formation may be approximated by a series model [for example, Freeze and Cherry (1979), pp. 30–34]; that is, air pressure travels vertically along the fault and then horizontally along the Calico Hills unit. By applying the mass conservation principle, Darcy’s law, and the assumption that air flow across the vitric zone is zero ($Q_{\text{vmc}} = 0$), we have

$$\Delta h \approx \Delta h_0 + \Delta h_f$$

$$Q_{\text{fault}} = Q_{\text{Calico}} = \frac{k_b h_f \Delta h_f}{d_f} \approx \frac{k_b h_f \Delta h_f}{d_f} = \frac{k_c b_c \Delta h}{d_c}$$

where $Q_{\text{fault}}$ = total flux moving vertically through the Ghost Dance Fault (Fig. 4); $Q_{\text{Calico}}$ = total flux moving horizontally through the upper part of the Calico Hills Formation; $k_1$, and $k_2$ are respectively the air permeability for the Ghost Dance Fault and the Calico Hills Formation; $h_0$ and $d_f$ are respectively the width of the fault and the Calico Hills; $d_c$ is the distance over which the head losses $\Delta h_f$.
and $\Delta h_f$ for the fault and the Calico Hills are measured; and $k_{\text{eff}}, b_{\text{eff}}, d_{\text{eff}}$, and $D_{h_f}$ are respectively the effective permeability, width, distance, and total head loss for the series model depicted in (4) and (5). Solving the outside relationship of (5) for $k_{\text{eff}}$ and using the inside relationship (5) for $D_{h_f}$ and $D_{h_c}$, we obtain

$$k_{\text{eff}} = \frac{d_{\text{eff}}}{b_{\text{eff}} (d_f/k_f + d_c/k_c)} \quad (6)$$

From the previous discussion, the effective permeability $k_{\text{eff}}$ may be estimated if we could calibrate the permeability value $k_2 (= k_c; = k_f)$ and knowing all the other geometric parameters in (6). The value $k_2$ can be calibrated by setting the permeability of the Ghost Dance Fault equal to that of the Calico Hills Formation and using the observed barometric pressure data at the 443 m station:

$$k_{\text{eff}} = \frac{d_{\text{eff}} k_2}{b_{\text{eff}} (d_f/k_f + d_c/k_c)} \quad (7)$$

The relationship between the upper limit of the Ghost Dance Fault $k_1$ and the lower limit of the Calico Hills Formation $k_3$ can be established by setting $k_f = k_1$ and $k_c = k_3$ and substituting (7) into (6):

$$\frac{d_f}{k_f b_f} + \frac{d_c}{k_c b_c} = \frac{d_f}{k_f b_f} + \frac{d_c}{k_c b_c} \quad (8)$$

To illustrate the advantage and necessity of using a harmonic series analysis, we first conduct simulation directly using the observed barometric data cycled five times [Fig. 7(a)]. The known parameters are tuff density (2,380 kg/m$^3$) and air porosities (0.2 for the Calico Hills Formation, 0.04 for the vitric zone of the Topopah Spring Tuff, and 0.05 for the Ghost Dance Fault). It can be observed that a persistent difference exists even after a long simulation time of 770 days. As discussed earlier, we attribute the difference to uncertainty in the assignment of the initial pressure values, and it is hard to circumvent without using the harmonic analysis.

We then conduct the simulation using the time-series analysis to identify $k_2$. The first mode of the harmonic function is used based on the harmonic analysis [Fig. 5(a)]. The best fit results yield very good agreements between the simulated and measured data at both the 413 and 443 m stations, as shown in Figs. 7(b) and (c). A best-matched permeability structure is obtained for permeability value $k_2 (= k_c; = k_f)$ equal to $0.6 \times 10^{-2}$ m$^2$ [Fig. 7(b)] and the vitric zone of the Topopah Spring unit equal to $0.44 \times 10^{-12}$ m$^2$ [Fig. 7(c)].

Several observations can be made. It can be seen that even under the harmonic excitation condition, the effect of the initial value is quite significant; it takes about two cycles (204 days) to diminish. The simulated pressures at both stations match very well with the observed data in terms of both amplitude and phase, with a time lag of 3 days (72 h) between the two stations at the end of the simulations.

The upper limit of the air permeability for the Ghost Dance Fault now can be estimated from (7) if the low limit of permeability for the Calico Hills is known. For instance, if the lower limit of permeability for the Calico Hills is $0.8 \times 10^{-15}$ m$^2$, inserting the calibrated $k_2$ value of $0.6 \times 10^{-2}$ m$^2$ and the $k_3$ value of $0.08 \times 10^{-12}$ m$^2$ into (7) along with the other physical parameters ($d_f = 620$ m, $b_f = 130$ m, $d_c = 130$ m, including the thickness of both Calico Hills and Prow Pass, and $b_c = 2$ m) yields an upper-limit permeability value $k_1$ of $1.2 \times 10^{-16}$ m$^2$ for the Ghost Dance Fault.

**DISCUSSION AND CONCLUSION**

Air pressure responses to the barometric pressure fluctuation, although small in amplitude and large in oscillation period at a great depth, can be used to infer air permeability structure in thick unsaturated zone environments. As unsaturated zones become thicker, particularly if such distinct hy-
dendritic structures exist as layered tuffs and faults, pneumatic flow paths become complicated and multidimensional. Analysis of field measurements under such conditions is difficult, but can be done by numerical models and time-series analyses. Because of the complex nature of the air flow field in deep and faulted unsaturated zones, the widely used diurnal and semidiurnal barometric signals may not be detected at a large depth. Therefore, harmonic analysis must rely on modes with longer periods. Our analysis supports this assertion.

Obtaining a good guess on the initial values for the multidimensional problem is difficult and has a persistent effect on the simulated pressure variation. An alternative approach is to use the harmonic time-series analysis and use the long-period harmonic components of the measured data as the basis for model calibration. Our simulation results show that a good agreement can be achieved between the simulated and measured data; therefore, the simulation of pressure fluctuation in deep zones may depend heavily on the long-period harmonic functions.

Using the principle of mass conservation and Darcy’s law, a general analytical relationship for a series model with variable length and width of each hydrologic unit can be established. As shown in our simulation result, this relationship greatly constrains the range of the air permeability values for the individual hydrologic unit.

The depth inversion of the pressure magnitude and the phase lag observed at two deep stations indicate the existence of preferential flow paths. In this work, a leaky-fault hypothesis is proposed and a 2D numerical model is constructed to infer a plausible permeability structure near the fault. It is shown that the pressure propagation in a layered domain is different for faulted and nonfaulted domains. The modeling results show that the leaky-fault hypothesis is consistent with the measured barometric pressure data and other independent hydrologic studies.

Three distinct permeability regimes are identified and tested using a 2D air flow model. The inferred air permeability for the Ghost Dance Fault ranges from $0.6 \times 10^{-13}$ to $1.2 \times 10^{-10}$ m$^2$, the vitric zone of the Topopah Spring unit $0.44 \times 10^{-13}$ m$^2$, and the upper part of the Calico Hills from $0.8 \times 10^{-13}$ to $0.6 \times 10^{-12}$ m$^2$.

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