The Use of Radar Methods to Determine Moisture Content in the Vadose Zone

Principal Investigator: Rosemary Knight
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EXECUTIVE SUMMARY

Water content is a critical parameter affecting both liquid-phase and vapor-phase contaminant transport in the vadose zone. This means that accurate estimates of *in situ* water content must be obtained in order to design for the appropriate handling or remediation of a contaminated region of the vadose zone. Traditional methods of sampling the subsurface by drilling and/or direct sampling are very time consuming, limited in terms of spatial coverage, and have the associated risk of contacting and increasing the size of the contaminated area. One solution is to use geophysical methods which can provide a high-resolution, non-invasive means of sampling or imaging the subsurface.

Radar methods provide an image of the variation in the dielectric constant of subsurface materials. The dielectric constant of a volume is largely determined by the water content. As a result, radar images potentially provide a non-invasive means of “mapping out” water content in the vadose zone. In our research we focused on two specific aspects of the link between radar images and water content, defined in terms of the two following questions:

1) Can we use a measure of the dielectric constant of a volume of the subsurface to determine the water content of that volume?
2) Can we use the spatial distribution of radar reflections as a means of characterizing the spatial distribution of water content in the subsurface?

Can we use a measure of the dielectric constant of a volume of the subsurface to determine the water *content of that volume?*

In addressing this first question, our focus was on determining the optimal way to transform a 3-D map of dielectric constants, derived from surface or borehole radar data, into a 3-D map of water content. Specifically, we explored the relationship between the measured dielectric constant κ of a volume of the subsurface, and the water content θ of the volume. Understanding the correct transform to use between the geophysical parameter that is measured, κ , and the hydrogeologic parameter of interest, θ, is clearly a critical step in the use of radar information.

Through theoretical modeling, we investigated the way in which the spatial heterogeneity within a volume of the subsurface will control the relationship between the measured value of κ and the total water content of the volume. We were able to quantify the errors that can result in water content values, derived from radar data, if the $\kappa-\theta$ relationship that is used does not correctly represent the heterogeneity that exists below the scale of measurement of κ. It is important to recognize that it is highly unlikely that we will ever have sufficient knowledge to be able to produce perfectly accurate estimates of water content from any non-invasive measurement; we therefore must develop ways of accounting for the possible levels of error in the data. For some applications involved with characterization of the vadose zone, it might be sufficient to determine the potential error or uncertainty in water content that will be introduced by use of the standard models; the uncertainty could be incorporated in models of contaminant transport. The framework that we developed can be applied to the analysis of borehole radar data from Hanford. This research forms part of the Ph.D. thesis of Stephen Moysey, graduate student in the Geophysics Department, Stanford University and is described in Moysey and Knight (2003a).

We found that one of the key parameters controlling the form of the $\kappa-\theta$ relationship is the level of anisotropy in the distribution of θ. We investigated the way in which this anisotropy affects borehole radar data, and found that significant dielectric anisotropy can result in the vadose zone, where a high contrast in dielectric properties can exist between geological materials having different textures. This research is part of the Ph.D. thesis of James Irving, graduate student in the Geophysics Department, Stanford University. The results of this research have led us to conclude that borehole radar methods could be used to determine the magnitude of anisotropy in dielectric measurements. This, in turn, could be used to improve the accuracy of θ estimates obtained from borehole radar data.

Can we use the spatial distribution of radar reflections as a means of characterizing the spatial distribution of water content in the subsurface?

Our ability to use the radar image to quantify the spatial distribution of water content is highly dependent on the quality of the radar image. We therefore included in our research the development of a new processing method to improve the resolution of the radar image. An improved image provides a closer link between the water variation in the subsurface, the related dielectric variation, and the location, continuity and amplitude of reflections. This research was part of the M.Sc. thesis of James Irving, when he was a graduate student at the University of British Columbia, and was continued when he transferred to Stanford as a Ph.D. student in the Geophysics Department. This work is described in the publication by Irving and Knight (2003).

To use a radar image as the basis for quantifying the magnitude or distribution of water content in the subsurface, we first divide our model of the subsurface into regions over which water content can be assumed to be approximately homogeneous. In our approach, we make these divisions according to the natural geologic boundaries that are seen as separate regions in the radar image and are referred to as “radar facies”. The division of the radar image into radar facies provides us with a model of the large-scale structure or architecture of the subsurface. In our work we have used artificial neural networks as a tool to improve the interpretation of radar images into radar facies models. This research forms part of the Ph.D. thesis of Stephen Moysey, graduate student in the Geophysics Department, Stanford University and is described in Moysey and Knight (2003b).

A reflection in a radar image corresponds to the location of an interface in the subsurface across which there is a change in water content. We therefore suggested, in our proposal, that we could use an analysis of the structure seen in the radar reflection image to obtain information about the subsurface distribution of water content. We worked in collaboration with researchers at Pacific Northwest National Laboratory, Eugene Freeman, Chris Murray and Mark Rockhold, and conducted a field study at the Hanford site to test this idea; this research is described in Knight et al. (2003a, b). We collected surface-based radar data at the Sisson and Lu test site where we had available two sets of water content data derived from neutron probe measurements that had been made to a depth of ~18 m in 32 wells. The comparison of neutron probe-derived water content data, synthetic radar data, and the acquired radar data indicated a good correspondence between the changes in water content and the location of reflections in the radar data. Geostatistical analysis was conducted of the two sets of water content values and the amplitudes of the reflections in the radar section. Our interpretation of the geostatistical results is that there is a structure in subsurface θ at Hanford with a correlation length on the order of 10 to 14 m that we see in both the water content and radar data sets. We concluded that surface-based radar data from the Hanford site can provide valuable information about the spatial distribution in θ.

The ability to determine the spatial variability in water content using non-invasive surface-based radar would represent a significant advancement in current approaches to characterization at DOE sites. The key practical limitation to the use of this method at Hanford is the limited depth (~15 m) to which we could image with the surface-based radar. The scientific limitation is our lack of understanding of the link between the spatial heterogeneity of the subsurface and what is captured in the radar data. Research completed as part of this project, and still ongoing, has focused on the role of the resolution of the radar measurement.

The overall objective of our research, defined at the start of this project, was to advance the usefulness of radar methods (ground-based and borehole) as a means of characterizing water content in the vadose zone. We have met this objective by providing research results that can be used to 1) improve the accuracy of water content estimates from radar measurements; 2) provide estimates of the potential error in water content estimates from radar measurements; 3) improve the clarity of radar images; 4) develop large-scale models of the subsurface "architecture" using radar images; 5) develop ways of quantifying the spatial heterogeneity of the subsurface through analysis of radar images. We have also been able to identify the critical areas where more research is needed in order to be able to use radar methods most effectively as an accurate means of subsurface characterization.

Relevance, Impact and Technology Transfer: Water content is a critical parameter affecting contaminant fate and transport in the subsurface. Therefore accurate information is needed about the spatial distribution of water content in order to design effective strategies for the long term management of DOE sites. Our research has shown a very close tie between radar images and water content at Hanford. If radar technology can be improved so as to “see” to greater depths at Hanford, this would provide an efficient means of obtaining the information needed about subsurface water content for accurate hydrogeological modeling. An important part of our research was the development of a quantitative framework for estimating the potential error in water content that can result from the interpretation of radar data. In addition to the relevance of our research to DOE site characterization needs, our research dealt with fundamental issues involving measurement scale and heterogeneity that are of importance in advancing our basic understanding of the ways in which geophysical measurements can be used to image and study complex geologic systems.

RESEARCH OBJECTIVES

Water content is a critical parameter affecting both liquid-phase and vapor-phase contaminant transport in the vadose zone. Any attempt to model the behavior of a contaminant in the vadose zone, in designing for the handling or remediation of a contaminated region, must adequately account for the spatial variation in water content. The variation in water content must therefore be determined with a high level of accuracy at the relevant scale or scales, given the governing transport processes. Obtaining such accurate estimates of *in situ* water content is a challenge. Traditional methods of drilling and direct sampling are very time consuming, limited in terms of spatial coverage, and have the associated risk of contacting and increasing the size of the contaminated area. One solution is to use geophysical methods which can provide a high-resolution, non-invasive means of sampling or imaging the subsurface.

Of specific interest in our research is the use of radar methods - both surface and borehole - as a means of determining *in situ* water content. Radar methods produce an image of the subsurface in terms of its dielectric properties. The large contrast between the dielectric constant of water (~80), and that of air (~1) and the minerals forming the rocks or soils in the subsurface (~5) means that a measurement of dielectric constant can be highly sensitive to water content. As a result, radar methods have become increasingly popular for obtaining information about water content in regions of the subsurface, as shown in a number of recent studies (Greaves et al., 1996; Hubbard et al., 1997; Eppstein and Dougherty, 1998; Parkin et al., 2000; Binley et al., 2001; Tsoflias et al., 2001; Alumbaugh et al., 2002; Hubbard et al., 2002; Stoffregen et al., 2002). The overall objective of our proposed research was to further develop the usefulness of radar methods as a means of characterizing water content in the vadose zone.

Our research was focused on two specific aspects of the link between radar images and water content. The first aspect or question we addressed was: *Can we use a measure of the dielectric constant of a volume of the subsurface to determine the water content of that volume?* Surface or borehole radar data can be used to obtain a model of the variation in the dielectric constant of the subsurface. Obtaining this dielectric model from surface and/or borehole data is a topic currently being addressed by other research groups (e.g., Cai and McMechan, 1999; Clement and Knoll, 2000; Tronicke et al., 2001; Holliger and Maurer, 2002), and was not an objective of our research. Our focus was on determining the optimal way to transform the 3-D map of dielectric constant κ into a 3-D map of water content θ. We first explored the way in which heterogeneity, below the scale at which the dielectric constant is measured, controls the $\kappa-\theta$ relationship. Having determined the form of the $\kappa-\theta$ relationship for a wide range of systems, we then quantified the level of error or uncertainty that can occur in estimates of water content if heterogeneity, in both water content and dielectric properties, is not correctly accounted for.

The second question which we addressed was involved specifically with the issue of spatial heterogeneity. Rather than using radar data to get estimates of water content at specific locations, can we use the radar data to obtain information about the way in which the level of water content varies spatially? Given that dielectric properties are closely related to water content, the basic assumption we made was that the spatial heterogeneity that is captured in the radar image contains information about the spatial heterogeneity in water content. The second question we addressed in our research was: *Can we use the spatial distribution of radar reflections as a means of characterizing the spatial distribution of water content in the subsurface?* In this aspect of our research we built on earlier work, completed by ourselves (Rea and Knight, 1998; Tercier et al., 2000) and others (Olhoeft, 1994; Young, 1996) , and used geostatistical methods as the framework for quantifying the correlation structure of the reflections in a radar image. A key consideration was the importance of the scale-dependent nature of heterogeneity in natural systems and the scale of the radar measurement. The focus in this aspect of our research was on obtaining information directly from the radar reflection image, so included research involved with both processing of the radar data, and classifying, in terms of radar facies, regions of the image.

The ability to obtain accurate estimates of *in situ* water content is a critical step in developing accurate models of the behavior of contaminants in the vadose zone. Our research project was designed to improve the accuracy of the information we can obtain from radar data about both the magnitude of water content and its spatial distribution in the vadose zone.

METHODS AND RESULTS

I. Can we use a measure of the dielectric constant of a volume of the subsurface to determine the water content of that volume?

Modeling the $\kappa-\theta$ Relationship

Surface and borehole ground penetrating radar (GPR) methods provide a way of measuring the dielectric constant of a region of the subsurface. The measured dielectric constant is very sensitive to the presence of water (κ_{water}~80, κ_{air}=1, $\kappa_{mineral}$~5-10). Determining water content from dielectric constant measurements is typically accomplished using semi-empirical volumetric mixing formulas (e.g., Roth et al., 1990) or purely empirical calibrations, such as the well known Topp equation (Topp et al., 1980). A common approach for calibrating these relations for site-specific conditions, such as lithology or porosity, is to perform measurements of both dielectric constant and water content on core-sized samples in the laboratory. Although these lab-scale measurements provide useful information, the dielectric constant derived from GPR data is also influenced by the geometric distribution of water in the subsurface at a scale that cannot be captured by lab-scale measurements alone.

The focus of our research was the problem of determining the appropriate relationship to use between dielectric constant and water content in determining water content from dielectric measurements obtained from GPR data. The results of this research are described in detail in the publication by Moysey and Knight (2003a). To address the problem, we developed a framework to upscale lab-scale $\kappa-\theta$ relationships to the field scale, which is relevant to GPR measurements. We used this framework to derive an analytical expression to predict the field-scale $\kappa-\theta$ relationship based on a calibrated lab-scale relationship. We used a geostatistical description of the medium given by a spatial correlation function. This approach is valid in the effective medium limit, which applies when the GPR wavelength is much greater than the length scale of the spatial heterogeneity.

Figure 1 illustrates how small-scale spatial variability of water content affects the field-scale $\kappa-\theta$ relationship. In this figure, we have shown the specific case where the Topp equation (approximated by the expression given in Ferre et al., 1996) relates θ and κ at the local scale (shown in Figure 1 as the heavy solid line). Also shown in the figure are the limits resulting from the Wiener bounds, which are the bounding relationships obtained in the arithmetic and harmonic average limits for a perfectly layered system (shown in Figure 1 as heavy dashed lines). The remaining lines, marked with symbols, show how the $\kappa-\theta$ relationship relevant to field-scale GPR measurements differs from the Topp equation for a variety of geologic conditions. In this example, different geologic conditions are differentiated by the coefficient of variation (ξ), which controls variance (σ_θ^2), and statistical anisotropy (A is the ratio of correlation lengths) of the subsurface water content distribution in a transversely isotropic medium. Shown in this figure is an example of the error that results when a field-scale measurement of κ is transformed to an estimate of θ using the lab-scale $\kappa-\theta$ relationship. In this case (as is generally the case) the lab-scale relationship does not account for the spatial heterogeneity that exists at the field scale, so the estimate of θ is inaccurate. This result clearly shows the importance of the distribution of local (below the scale of the measurement) water content in determining the macroscopic $\kappa-\theta$ relation.

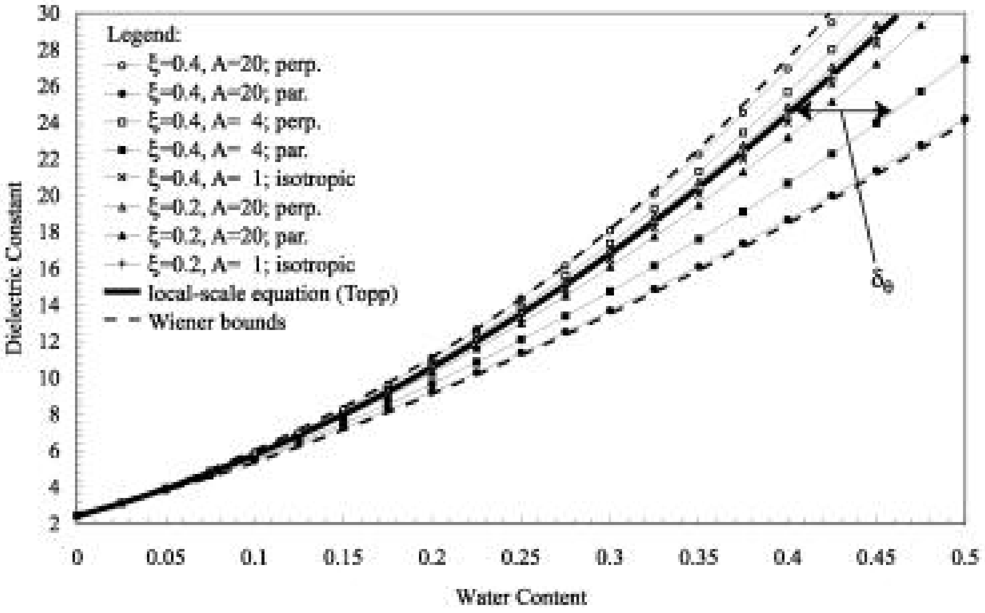

Figure 1: The field-scale relationship between dielectric constant and water content depends on the structure of the subsurface, i.e., the coefficient of variation (ξ) and statistical anisotropy (A) of the θ field. The notation “perp.” and “par.” in the legend indicate the case for wave propagation perpendicular or parallel, respectively, to the maximum direction of correlation. An example of the estimation error (δ_θ) is shown as the difference between water content estimated from a field-scale dielectric constant measurement using the lab-scale vs. field-scale relationship.

We have also performed our analysis numerically for the case where the GPR wavelength is much less than the scale of the heterogeneity (i.e., ray theory limit). In this case, we use the first arrival time of a wave between two known locations to determine the apparent velocity v of an electromagnetic wave through the subsurface; v is proportional to $1/\sqrt{\kappa}$. The first arrival time, however, corresponds to the fastest path that a wave can take between a source and receiver location and, therefore, follows a route through the medium that preferentially samples high velocity zones and bends around slow zones. This preferential sampling of high velocity means that for a given mean water content, the apparent dielectric constant is much lower than would be predicted based on lab-scale $\kappa-\theta$ relationships. In practice this means that in systems where ray theory behavior is dominant, water content will always be underestimated if lab-calibrated $\kappa-\theta$ relationships, such as the Topp equation, are used to interpret field-scale measurements made using surface or borehole radar methods.

The Effect of Anisotropy on Borehole Radar Data

The results of our study of the effect of heterogeneity on the $\kappa-\theta$ relationship suggest that we could improve the accuracy of our estimates if we could better describe the true structure of the subsurface. One of the key parameters affecting the form of the $\kappa-\theta$ relationship is the anisotropy of the subsurface. We have investigated the way in which anisotropy affects borehole radar data, the idea being that we might be able to quantify dielectric anisotropy using borehole radar methods.

Simple numerical modeling of 1-D coarse/fine layered systems under the assumptions of effective medium theory and capillary equilibrium indicates that, in the saturated zone, dielectric anisotropy is likely unimportant because changes in dielectric constant between layers result largely from porosity differences, which are relatively minor. In the vadose zone, however, our modeling shows that significant dielectric anisotropy can result due to the strong dependence of dielectric properties on saturation, and the pronounced saturation heterogeneity that can exist between layers.

As the overall saturation in the vadose zone decreases, fine-grained layers preferentially retain water while coarse-grained layers preferentially drain; this process enhances the dielectric contrast between the layers.

The determination of subsurface dielectric anisotropy from borehole radar data could allow us to improve the transformation from dielectric properties to water content. Extremely important, however, is the fact that we must account for anisotropy (when it exists) during the tomographic inversion of borehole radar data in order to avoid serious inversion artifacts. False heterogeneity in the recovered image of dielectric properties can be produced if we attempt to fit an anisotropic medium with a series of isotropic cells. It is thus important to understand under what conditions we must account for dielectric anisotropy with borehole radar methods.

We have completed one set of field experiments to investigate the magnitude of dielectric anisotropy. Crosshole radar data were collected at a site near Abbotsford, British Columbia during the summer of 2002. These data were acquired between two wells located 5.89 m apart and 26 m deep, and the water table at the time of the survey was 17.5 m below the surface. As a result, the experiment provided adequate ray coverage of both the vadose and saturated zones. Our initial interpretation of these data suggested the presence of significant dielectric anisotropy in the vadose zone. We have since found that borehole deviation was responsible for this apparent anisotropy. Our research on this topic continues with analysis of data sets acquired by other research groups.

II. Can we use the spatial distribution of radar reflections as a means of characterizing the spatial distribution of water content in the subsurface?

The second aspect of our research addressed the use of the radar image for quantifying the spatial distribution of water content in the subsurface. That is, rather than focusing on extracting the magnitude of water content at specific locations, we wanted to determine the form of variability in water content that exists throughout an area. Our research is described below in five parts. We first describe the method that we developed to correct for a form of attenuation in the radar data that affects the clarity of the radar reflection image. We then describe our approach to developing a model of the large-scale architecture of the subsurface, our assumption being that different subsurface units will have different forms of spatial heterogeneity. In the third section we describe a field experiment conducted at Hanford to test the idea that we can use geostatistical analysis of a radar image to characterize the spatial variability in water content. The last two sections describe our most recent and ongoing research. This includes studying the effect of the resolution of the radar measurement on the determined spatial variation in water content, and the development of numerical models for both surface and borehole radar data.

Correcting for Wavelet Dispersion in Radar Images

The first completed research in our project, described in the publication by Irving and Knight (2003), was to improve the clarity of radar images by developing an effective methodology for the estimation and correction of wavelet dispersion in GPR data. Wavelet dispersion results from the frequency-dependent attenuation of electromagnetic (EM) waves and causes a characteristic "blurriness" in the GPR image that increases with depth. Correcting for wavelet dispersion allows us to obtain the highest resolution radar images possible and is a necessary step for the determination of subsurface electrical properties.

In examining attenuation versus frequency curves for a wide range of geological materials, we found that, over the bandwidth of a GPR pulse, the attenuation could be reasonably approximated by a linear function of frequency. As a result, wavelet dispersion in these materials could be adequately described using a single parameter, Q*, related to the slope of the linear region. To estimate subsurface Q* from GPR data, we developed a technique that builds on the frequency shift method of Quan and Harris (1997). We compute Q* from the downshift in the dominant frequency of the radar signal with time using a relatively new time-frequency analysis tool called the S-transform (Stockwell et al., 1996). Once Q* has been obtained, we correct for wavelet dispersion in GPR data by inverse Q filtering. Our filtering algorithm, which we developed using a Bayesian approach to inversion, allows for the recovery of absorption-free models that are both sparsely distributed and temporally correlated. In the first year of this project we had tested a similar methodology using the wavelet transform. We subsequently found that the S-transform is superior for Q* estimation because it yields a true measure of frequency, rather than scale, and it avoids the challenge of choosing a mother wavelet function for the analysis.

Radar Facies Analysis

Our interest is in quantifying the spatial variability in water content in the subsurface. In regions of the subsurface where large-scale structure is present, we must first develop a model of the large-scale architecture of the subsurface. The approach we take to characterize the complex structure of the subsurface is to divide a radar image into distinct architectural units referred to as radar facies. Individual radar facies units can be distinguished by characteristics such as: (i) reflection amplitude, (ii) reflection continuity, (iii) reflection configuration, and (iv) external form (i.e., geometry) (van Overmeeren, 1998). Accurate reproduction of the large-scale architecture of the subsurface is a critical step in building a model when prediction of contaminant fate and transport are of interest. Therefore, a major contribution of our work has been the use artificial neural networks as a means to quantify the uncertainty in the interpretation of a radar image to obtain a radar facies model (Moysey et al., 2003b).

We use the neural network as a pattern recognition device, which takes the radar image as input and provides a map of the probability of distinct facies units as output. In Figure 2 we provide an example using GPR data from the Borden Aquifer (CFB Borden, Ontario, Canada). Figure 2a shows the original GPR image of a region of the subsurface at Borden overlain by a manual interpretation of the radar facies units. Figure 2b shows probability maps interpreted by the neural network for each of the four facies types identified at the site. Finally, the resulting neural network facies model, which would be obtained by choosing the most likely facies type at each location, is shown in Figure 2c. The agreement between the manual and neural network interpretations of the facies model is quite variable, with high success in identifying Facies 1, but very poor success in identifying Facies 4.

Because we have taken a stochastic approach to interpreting radar facies, we are able to use geostatistical techniques to combine our radar facies interpretations with other available data, such as might be available at borehole locations; the best possible estimates of hydrologic processes will result when multiple data types can be integrated in models that are maximally constrained by all available data. Another major advantage of our stochastic approach is that we are able to propagate the uncertainty in the resulting radar facies interpretations to estimates of hydrologic processes, such as flow and transport. These ideas are illustrated in Moysey et al. (2003b) for a simple conservative contaminant transport problem in a medium composed of two distinct facies types. In general, we find that the relative worth of radar compared to other data and the resulting reduction of uncertainty obtained will depend on the quality of the radar data available, which is highly dependent on the geologic environment.

Geostatistical Analysis of a Radar Reflection Image to Characterize Spatial Variability in Water Content

A radar reflection corresponds to an interface in the subsurface across which there is a change in the dielectric constant. Given the relationship between water content and dielectric constant, we tested the idea that the correlation structure seen in a radar reflection image captures information about the correlation structure of subsurface water content. This work was done in collaboration with Eugene Freeman, Chris Murray, and Mark Rockhold at Pacific Northwest National Laboratory and is described in detail in Knight et al. (2003).

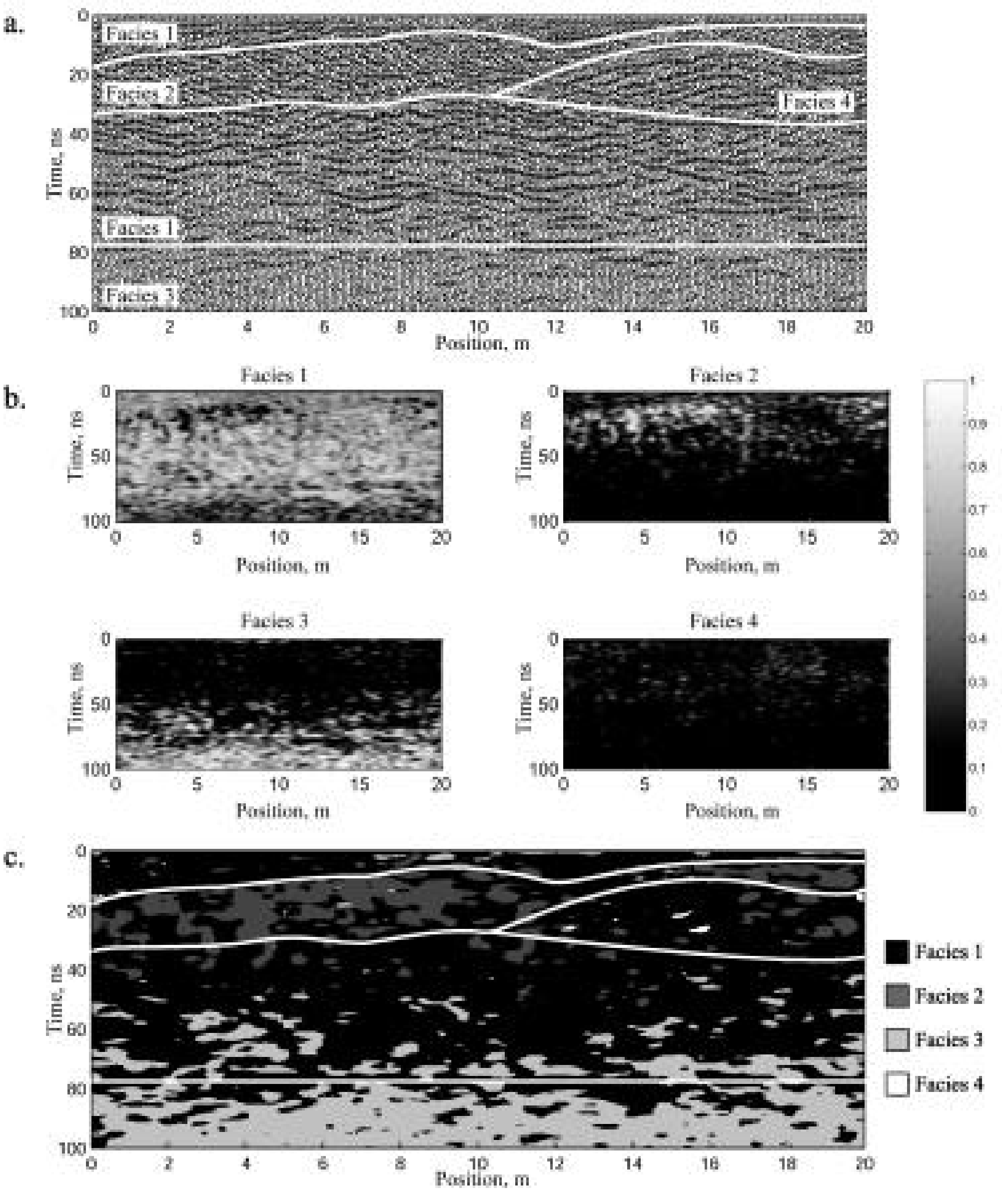

Fig. 2. Example of neural network facies identification for the Borden Aquifer: a) Radar response and manual facies interpretation, Facies 1: flat reflections, Facies 2: dipping reflections, Facies 3: massive, Facies 4: complex reflections, b) Facies probabilities estimated by the neural network, c) Facies classification. (Moysey et al., 2003b)

Ground-penetrating radar data were collected at the Sisson-Lu Injection Test Site, located in the south-eastern corner of the area referred to as the 200 East Area at Hanford. The test site consists of 32 wells, 18 to 19 m deep, surrounding a central injection well that is 5 m deep. The GPR profile started at well D8 and extended 30 m in the northwest direction. Water content data were available from the interpretation of neutron probe measurements made during two field tests conducted at the Sisson and Lu site in 1980 and 1995. (More recent neutron probe measurements were made at the site in the summer of 2000, but the water content data from these measurements are not yet available.)

Comparison of the radar reflection image and the probe-derived water content data indicated a good correspondence between the location of changes in water content and the location of the reflections in the radar data. Semivariogram analysis in the horizontal direction was completed on the radar data using the program gam found in GSLIB (Deutsch and Journel, 1998). The data values that were used were the recorded amplitudes of received energy, as done in the study by Rea and Knight (1998); more details on the geostatistical analysis of radar data can be found in that reference. Semivariogram analysis was completed on the two water content data sets using the program gamv found in GSLIB (Deutsch and Journel, 1998). The lag vector was in the horizontal plane for all sampled depths and set parallel to the northwest direction of the radar line. The semivariogram for the radar data was best fit with a nested exponential model containing a dominant long-range structure with a correlation length of 14 m, and a smaller-scale structure with a correlation length of 0.3 m. The semivariograms for the water content data were best with single exponentials with a correlation length of 10 m.

The results of the semivariogram analysis were considered in terms of the scale of measurement of both the radar and neutron probe data. We used the concept of the scale triplet, defined by Western and Bloschl (1999), where the three relevant scales of measurement are the extent, the spacing and the support of the measurement. Our interpretation of the geostatistical results is that there is a structure in subsurface θ with a correlation length on the order of 10 to 14 m that we see in both the neutron probe and radar data sets. The limited horizontal extent of both the neutron probe data and radar data, relative to the correlation length, suggests that the true correlation length of the subsurface water content may be underestimated in modeling the semivariograms of both data sets. The radar data suggest that a sub-meter correlation structure may also be present, but its correlation length cannot be quantified. We conclude that surface-based radar should be further explored for use at Hanford and at other sites where measurements obtained in wells are insufficient to provide the required detailed information about spatial variability in θ.

The Role of Scale of Measurement in Subsurface Characterization

In our research, described above, we explored the idea that we can use the structure seen in radar images to characterize the spatial heterogeneity of the subsurface. An important issue that needs to be considered is the scale of the radar measurement. Radar data are collected at a set frequency; this frequency has a corresponding spatial resolution. As frequency decreases, the spatial resolution or support volume of the radar measurement increases. The key question for our research: How does the spatial resolution or support volume of the radar data affect the correlation length determined for these radar images?

Multi-frequency radar datasets (50, 100 and 200 MHz) were collected along the top of a cliff-face of unconsolidated sediments in the Fraser Valley, British Columbia. Experimental semivariograms were obtained for each of the radar reflection images and modeled to determine the dominant correlation length. We found that as the frequency of the radar data decreased (and the support volume increased) the corresponding correlation length generally increased. The change in correlation length can be attributed to the change in the support volume with the change in frequency. It has been well documented that, in general, as support size is increased the correlation length will also increase (Western and Bloschl, 1999; Collins and Woodcock, 1999). Also collected at this site were digital photographs of the cliff-face.

To better understand the relationship between support volume and correlation length we studied digital photographs of various natural and man-made structures. Correlation lengths were determined for the original photograph and were assumed to represent the true correlation structure. Spatial averaging was used to change both the horizontal and vertical dimension of the support volume and correlation length was then determined. For all examples we found a range of support dimensions where as support increased the determined correlation lengths also increased.

The specific way in which the determined correlation length was affected by the dimensions of the support volume depended upon the original structure and on the type of spatial averaging that was used. Many near-surface geological environments are highly anisotropic. In these systems, we found that a change in the vertical length of the support volume can have a much greater affect on the horizontal correlation length than a change in the horizontal length of the support volume. We concluded that when analyzing radar reflection images of anisotropic systems, it is the vertical resolution which has the greatest affect on the determined horizontal correlation lengths.

Numerical Modeling

Over the past year, we have developed 2-D numerical models for both crosshole and surface-based ground-penetrating radar using the finite-difference time-domain (FDTD) technique. These forward models are playing a key role in our current research by allowing us to create synthetic data sets on which we can test and evaluate our methods before applying them to field data. Although synthetic data sets could feasibly be created using simpler forward models based on ray theory, models based on the electromagnetic wave equation are more accurate, and allow for investigation into resolution issues associated with wave phenomena such as scattering.

The FDTD technique is by far the most commonly used method for GPR simulation. Reasons for this include the method's conceptual simplicity, and the ease with which realistic antenna designs and features such as dispersion can be incorporated into the modeling process. With this method, Maxwell's curl equations are discretized using a staggered grid for the electric and magnetic field components in both space and time (Yee, 1966). The propagation of waves from an initial excitation source is then computed by alternating back and forth between updating the electric and magnetic fields. The FDTD codes described in the literature for GPR simulation vary greatly in their level of complexity depending on the application at hand (e.g., Bergmann et al., 1998; Wang and McMechan, 2002; Radzevicius et al., 2003). The 2-D models that we have developed for surface and borehole GPR assume a line electric field source, and allow for variations in dielectric permittivity, magnetic permeability, and electrical conductivity throughout the simulation grid. These modeling codes were initially written in MATLAB, but were then written to interface MATLAB with C-code in order to significantly increase the speed of the field updating loops. The codes also incorporate the perfectly matched layer (PML) absorbing boundary technique (Berenger, 1994; Fang and Wu, 1996; Chen et al., 1997), which is the most effective method known for the absorption of waves at the edges of a simulation grid at any angle of incidence. Finally, we are in the process of implementing the codes on a 16-node parallel computing cluster at Stanford, which will significantly decrease the time needed for modeling.

RELEVANCE , IMPACT AND TECHNOLOGY TRANSFER

1) How does this new scientific knowledge focus on critical DOE environmental management problems?

Water content is a critical parameter affecting contaminant fate and transport in the subsurface. Therefore accurate information is needed about the spatial distribution of water content in order to design effective strategies for the long term management of DOE sites. We have found that reflections in surface-based radar data at the Hanford site closely corresponded to the location of changes in subsurface water content. Surface-based radar data could therefore prove to be very useful in mapping out changes in water content between, or away from, well locations. We also found that geostatistical analysis of radar images can provide very useful information about the spatial distribution of water content. With the costs and risks associated with drilling wells at many DOE sites, non-invasive surface-based radar surveys could complement, or replace, measurements in wells.

Borehole radar methods can provide measurements of the dielectric constant κ of regions of the subsurface at a submeter scale. These dielectric constant measurements are commonly interpreted to obtain estimates of water content θ using relatively simple relationships between κ and θ. We have quantified the way in which heterogeneity below the scale of the field measurement of κ can introduce significant error into the estimate of θ. In particular we present a framework that could be used at a site such as Hanford to include estimates of potential error in water content derived from dielectric measurements.

2) How will the new scientific knowledge that is generated by this project improve technologies and cleanup approaches to significantly reduce future costs, schedules, and risks and meet DOE compliance requirements?

Our research has shown a very close tie between radar images and water content at Hanford, clearly illustrating that radar imaging could be an effective means of accurately determining the variation in subsurface water content. Our research has also shown that a key limitation in the use of radar at Hanford is the limited penetration depth of the radar. Given the potential value of radar measurements for vadose zone characterization, our work should provide the incentive for others to improve radar imaging technology so as to acquire images to greater depths, without sacrificing the resolution. If radar technology can be improved for use at Hanford, this would provide a very efficient means of obtaining the information needed for accurate hydrogeological modeling.

An important part of our research was the development of a quantitative framework for estimating the potential error in water content that can result from the interpretation of radar data. In order to reduce costs, schedules and risks it is essential that potential error is carefully determined for all forms of subsurface measurement. Error analysis needs to become a standard part of using any form of data in designing long-terms strategies for management of sites. We hope that the scientific knowledge that has been generated in our project will be adopted as part of the DOE approach to site characterization.

3) To what extent does the new scientific knowledge bridge the gap between broad fundamental research that has wide-ranging applications and the timeliness to meet needs-driven applied technology development?

Much of our research addressed the fundamental issue of the way in which radar measurements sample, or capture, subsurface variation in water content. Our approach included a detailed study of the way in which heterogeneity, below the scale of a measurement, affects the interpretation of the measurement and also included an assessment of the role of measurement scale on the resulting interpretation of the data. These are fundamental issues that have wide-ranging application in the use of many forms of geophysical data for subsurface characterization. Most of our results, however, can be applied or put into practice now for characterization needs at DOE sites. We have highlighted ways in which changes to existing technology and/or current practices would greatly improve the way in which radar methods are used. These improvements would save time, money and reduce the risk that currently exists due to the way in which subsurface measurements are interpreted and the resulting data used.

4) What is the project’s impact on individuals, laboratories, departments and institutions? Will results be used? If so, how will they be used, by whom, and when?

It is too early to say the impact that this project will have as the results of our research are just now starting to appear in the literature. I am aware that Mike Powers and Dave Wright have received EMSP funding to develop a lower frequency GPR system for use at Hanford. If they are successful, the results of our project will be very useful for the application of this specific technology at Hanford.

5) Are larger scale trials warranted? What difference has the project made? Now that the project is complete, what new capacity, equipment or expertise has been developed?

We had one successful field test at Hanford, at the Sisson and Lu site. There is a real need to conduct repeat tests at other areas at Hanford. Based on the one field test, there is a great deal of interest in the hydrogeologic community in the method we used to extract information about spatial distribution of water content from non-invasive surface-based radar measurements. With the costs and risks associated with drilling wells at many DOE sites, non-invasive surface-based radar surveys could complement, or replace, measurements in wells. This project has provided a relatively simple methodology that could be put to use immediately as a way of characterizing subsurface heterogeneity. What is needed is the further research, that we are conducting, to understand in a more fundamental way the link between the correlation structure in the radar image and the correlation structure in subsurface water content.

As stated above, a very important part of the project was our emphasis on quantifying the errors that can result from the interpretation of a radar measurement when subsurface heterogeneity is not adequately accounted for.

6) How have the scientific capabilities of collaborating scientists been improved?

The collaboration with the research scientists at PNNL was very positive. It allowed us to work with scientists who are actively engaged in addressing the characterization and modeling needs at Hanford. Through the collaboration, the PNNL scientists were able to better understand the way in which we are trying to use radar methods as a new means of subsurface characterization at sites such as Hanford.

7) How has this research advanced our understanding in the area?

Our research has advanced the understanding of the relationship between radar data and subsurface water content. The first research question which we addressed was focused on developing an improved understanding of the way in which scale of measurement can affect the relationship between the measured dielectric constant and water content. We were able to quantitatively demonstrate how sub-measurement scale heterogeneity affects the relationship; and also demonstrated the errors that are likely to occur in estimates of water content if this factor is neglected. Our second research question was focused on using a geostatistical analysis of a radar reflection image to characterize the spatial variability in water content. Our field study at Hanford, and the analysis of the results led to new insights into both the potential usefulness of this method and the importance of considering the spatial resolution of the radar measurement.

8) What additional scientific or other hurdles must be overcome before the results of this project can be successfully applied to DOE Environmental Management problems?

Our work at Hanford, and the work done by Majer and others, has shown a very close link between water content and radar data at Hanford. This means that radar methods could potentially be extremely useful as a means of mapping out subsurface variation in water content. The methodologies developed in this project could be applied today, to obtain information about the top ~15m at Hanford. The main technology hurdle that must be overcome is the limited penetration depth that radar methods have at Hanford. While we would ideally like to use surface-based radar to acquire data to the depth of the water table (~50m), we were only able to penetrate to a depth of ~15 m. To overcome this hurdle requires technology development.

While the methodologies developed in this project, if applied today, could yield useful information about the subsurface, we are still not able to achieve the level of accuracy in terms of subsurface characterization that is needed at DOE sites. The main hurdles to be overcome here are scientific - the limitations we still face in our understanding of the complex interactions between the spatial heterogeneity of the subsurface and the spatial sampling of the radar methods.

9) Have any other government agencies or private enterprises expressed interest in the project? Please provide contact information.

The National Science Foundation, Hydrology Program, has funded a three-year project to continue the research that we began on using neural networks to identify radar facies. The funded project is: The Use of Ground Penetrating Radar Data in the Development of Facies-Based Hydrogeologic Models; Rosemary Knight (PI), Richelle Allen-King (Co-PI); 4/2003-3/2006.

PROJECT PRODUCTIVITY

The project accomplished the proposed goals and has provided answers to the two questions posed in the original proposal:

1) Can we use a measure of the dielectric constant of a volume of the subsurface to determine the water content of that volume?

2) Can we use the spatial distribution of radar reflections as a means of characterizing the spatial distribution of water content in the subsurface?

The project was conducted over four years, rather than the original proposed three years. A one year no-cost extension was needed as Rosemary Knight (PI) moved from the University of British Columbia to Stanford University at the end of the first year of the project. The two Ph.D. students on the project transferred to Stanford and had coursework requirements that delayed their research by one year.

There were two minor revisions to the work plan. We had proposed to conduct laboratory experiments on heterogeneous systems to assess the effect of heterogeneity on the relationship between dielectric constant and water content. When we began to design the experiments it immediately became clear that the limited cases that could be dealt with experimentally would mean that the results would have limited application. We decided instead to used analytical and numerical methods to model the effect of heterogeneity on the dielectric constant-water content relationship. This yielded very useful results, presented in Moysey and Knight (2003a).

The second revision in the work plan was our decision not to pursue the use of wavelet transforms as a possible means of characterizing non-stationary spatial heterogeneity in radar images. We came to realize that the fundamental problem that needs to be resolved is an improved understanding of when a radar image can be used as a proxy for the actual subsurface image in terms of determining its spatial statistic. As a result, we revised our work plan to spend much of the last two years investigating the effects of the spatial resolution of the radar data and the spatial structure of the subsurface on the radar-derived information about spatial variability in subsurface water content.

PERSONNEL SUPPORTED

Principal Investigator: Rosemary Knight, Professor of Geophysics

Graduate students:

Stephen Moysey - support for one year only; then supported by Stanford Graduate Fellowship

James Irving - support for two years; one year of support from Stanford Geophysics Department

Jonathan Franklin - support for one summer

Research Scientist:

Paulette Tercier – supported through related project held at the University of British Columbia

PUBLICATIONS

a) Peer-reviewed journals and books:

Irving, J.D., and Knight, R.J. (2003) Removal of wavelet dispersion from ground-penetrating radar data. Geophysics, 68, 960-970.

This paper describes the processing method that was developed to correct for frequency-dependent attenuation in radar data, and thereby enhance the resolution of the radar image.

Moysey S., J. Caers, R.J. Knight, R.M. Allen-King, Stochastic estimation of facies using ground penetrating radar data, *Stochastic Environmental Research and Risk Assessment,* 17, 306–318, 2003.

This paper described the development and testing of the use of neural networks to classify and identify radar facies. The radar facies are used to build a model of the large-scale architecture of subsurface regions.

b) Published in unreviewed publications (proceedings, technical reports, etc.)

Irving, J. and Knight, R. 2000. Estimation and correction of wavelet dispersion in GPR data, In: GPR 2000, Proceedings of the Eighth International Conference on Ground Penetrating Radar, Gold Coast, Australia, p. 123-129.

Moysey, S., R.J. Knight, R.M. Allen-King and J. Caers, The construction of stochastic facies-based models conditioned to ground penetrating radar images, 4th International Conference on

Calibration and Reliability in Groundwater Modelling, Universita Karlova, Prague, Czech Republic, ModelCARE2002 Proceedings, 344-348, 2002.

Irving, J.D., and Knight, R.J., Saturation-dependent anisotropy in borehole radar data, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, April 6-10, 2003, San Antonio, TX, 2003.

Knight, R. J., Irving, J., Freeman, E., and Tercier, P., The use of ground penetrating radar for site characterization at Hanford, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, April 6-10, 2003, San Antonio, TX, 2003.

c) Accepted/submitted for publication:

Knight, R.J., Irving, J., Tercier, P., Freeman, G., Murray, C., and Rockhold, M., A comparison of the use of radar images and neutron probe data to determine spatial variability in water content, submitted to Water Resources Research (status: in revision), 2003.

Moysey S. and Knight, R., Modeling the field-scale relationship between dielectric constant and water content in heterogeneous systems, submitted to Water Resources Research (status: resubmitted after minor revision), 2003.

INTERACTIONS

3) Participation/presentations at meetings, workshops, conferences, seminars etc

Knight, R., The Use of Radar Environmental Management Science Program (EMSP) Vadose Zone Workshop, Environmental Molecular Science Laboratory, Richland, Washington, November 16-18, 1999.

Knight, R.J., Irving, J., and Moysey, S., The Use of Radar Methods to Determine Moisture Content in the Vadose Zone, Advanced Vadose Zone Characterization/Modeling Workshop, Environmental Molecular Science Laboratory, Richland, Washington, January 19-21, 2000.

Knight, R.J., The Use of Radar Methods to Determine Moisture Content in the Vadose Zone (poster), Science Advancing Solutions, Environmental Management Science Program (EMSP) National Workshop (NWS 2000), Atlanta, Georgia, April 24-27, 2000.

Moysey, S. and Knight, R. J., Heterogeneity, Scale & Radar: Improved Hydrogeologic Characterization Through Advancements in Geophysical Interpretation. Gordon Research Conference on Modeling of Flow in Permeable Media, August 2000.

Knight R.J., G. Moret, S. Moysey and J. Irving. The use of ground penetrating radar data to quantify the scale-dependent spatial heterogeneity of the subsurface. Subsurface Flow and Transport Phenomena Workshop, Delft University of Technology, October 2000.

Knight, R.J., The Use of Radar Methods to Determine Moisture Content in the Vadose Zone, EMSP Workshop, Environmental Molecular Science Laboratory, Richland, Washington, November 28-30, 2000.

Moysey, S. and Knight, R. J., Quantifying error in water content estimates from GPR: Consideration of scale in rock physics relationships. NATO Advanced Study Institute on Hydrogeophysics, Trest Castle, Czech Republic, July 2002.

Knight R.J. and Moysey, S., From the lab-scale to the field-scale: Spatial heterogeneity in geophysical data. Inland Northwest Research Alliance Subsurface Science Symposium, Boise, Idaho, Oct.13-16, 2002.

Knight, R.J., S. Moysey and P. Tercier, The use of ground penetrating radar for the development of hydrogeologic models, EOS Trans. AGU, 82(47), Fall Meet. Suppl., Abstract F317, 2002.

Moysey S. and Knight, R. J., The effect of change in scale on water content estimates derived from ground penetrating radar data, EOS Trans. AGU, 83(47), Fall Meet. Suppl., Abstract T22B-1148, 2002.

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Irving, J., and Knight, R. J., Improving estimates of subsurface water content by accounting for saturation-related anisotropy, Eos Trans. AGU, 84(46), Fall Meet. Suppl., Abstract H31B-0446, 2003.

c) Collaborations

The field experiment at the Sisson and Lu site at Hanford and resulting study was done in collaboration with Eugene Freeman, Chris Murray, and Mark Rockhold at Pacific Northwest National Laboratory. This research is described in detail in Knight et al. (2003).

FUTURE WORK

There are a number of aspects of our work, completed with funding from EMSP, that are the focus of ongoing research. These are briefly described below:

1) Optimal strategies for the quantitative interpretation of radar facies is an ongoing focus of our work. We are continuing to investigate both pattern recognition based algorithms, e.g., cluster analysis, as well as the use of radar attributes. Neural network analysis of radar images and related information continues to be a central part of this research. This research is currently funded by the National Science Foundation.

2) Based on the work performed under this grant, we continue to develop methods for the improved estimation of water content from dielectric constant measurements made using GPR. In particular, we are currently extending the framework developed under this grant to relate water content and dielectric constant at different scales, to deal with problems that include simultaneously accounting for change of scale, measurement resolution, geologic heterogeneity and inversion artifacts. This extension of our work promises to provide a flexible method for improved estimation of hydrologic parameters from geophysical data, which applies to many types of geophysical measurements.

3) We continue to investigate the effect of the resolution of radar data on the correlation structure determined from a radar reflection image. This is a fundamental issue that must be resolved in order to determine when radar data can be used to accurately characterize the subsurface spatial variability in water content.

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