The role of ground penetrating radar and geostatistics in reservoir description

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Interpreters are routinely required to develop a continuous model of the subsurface through the integration of available data. One of the issues commonly encountered is how best to "fill in" the region between data points, or describe the region at a scale less than the scale of the sampling. We take this opportunity, as part of the Near-Surface Geophysics issue, to describe research currently underway that can assist in the development of geologic models. A near-surface geophysical method, ground penetrating radar (GPR), provides high resolution images of near-surface sedimentary packages that can be used to obtain an improved understanding of both the large-scale and sub-meter scale architecture found in a variety of depositional environments. In addition, the GPR images can be analyzed to obtain a geostatistical representation of the depositional environment that could be used in generating stochastic models of the subsurface.

In this paper we present GPR images from selected deltaic, coastal, and fluvial environments and show both the detailed sedimentology that is imaged and the information that is both captured and lost through the geostatistical characterization.

GPR images of selected depositional environments. GPR studies of both modern and ancient systems can provide a large amount of information that can improve the understanding of the lithologic variation and internal structure of ancient reservoirs. A number of recent studies have used 2-D and 3-D GPR data to characterize sedimentary units and different depositional environments.

In a GPR survey, electromagnetic energy in the frequency range 1-1000 MHz is transmitted into the ground. Changes in the dielectric properties of the subsurface cause reflections of energy which are detected on the surface. The result of a GPR survey, the radar image, is a map of reflections marking interfaces across which there are changes in dielectric properties. GPR data are commonly collected by using a single transmitter antenna and a single receiver antenna and moving these two, at a constant offset, along the survey line. Station spacing (i.e., trace spacing on the final GPR section) is usually on the order of tens of centimeters to a meter, depending on the survey's objective.

GPR data provide remarkably good images of coarse sedimentary packages. An excellent example of GPR data collected over a deltaic environment is shown in Figure 1. These data were collected in the Brigham City Sand and Gravel Company pit floor and show the late Pleistocene Box Elder Creek delta. A picture of a nearby outcrop is shown on the cover of this issue. This is a classic Gilbert-type fan-foreset delta dominated by steeply inclined beds of sand and gravel. The dipping reflections seen in the GPR data exhibit a high degree of continuity and are interpreted as steeply dipping strata. As GPR records changes in the dielectric properties of the subsurface, it is most likely in this environment that we are seeing the boundaries across which there are changes in grain size.

Figure 2 is an example of GPR data collected over a sandy coastal barrier spit, a regressive modern barrier spit at Willapa Bay, Washington which is 38 km long and up to 5 km wide. The dipping reflections in this section, are interpreted as beachface/upper shoreface beds indicating a shingle-like accretionary depositional pattern. In the strike profile shown in Figure 3, these same boundaries are seen as a subhorizontal, nearly continuous bedding pattern.

Figure 4 shows an example of GPR data from a Late Pleistocene braided fluvial deposit from the Embarras Airfield, northeastern

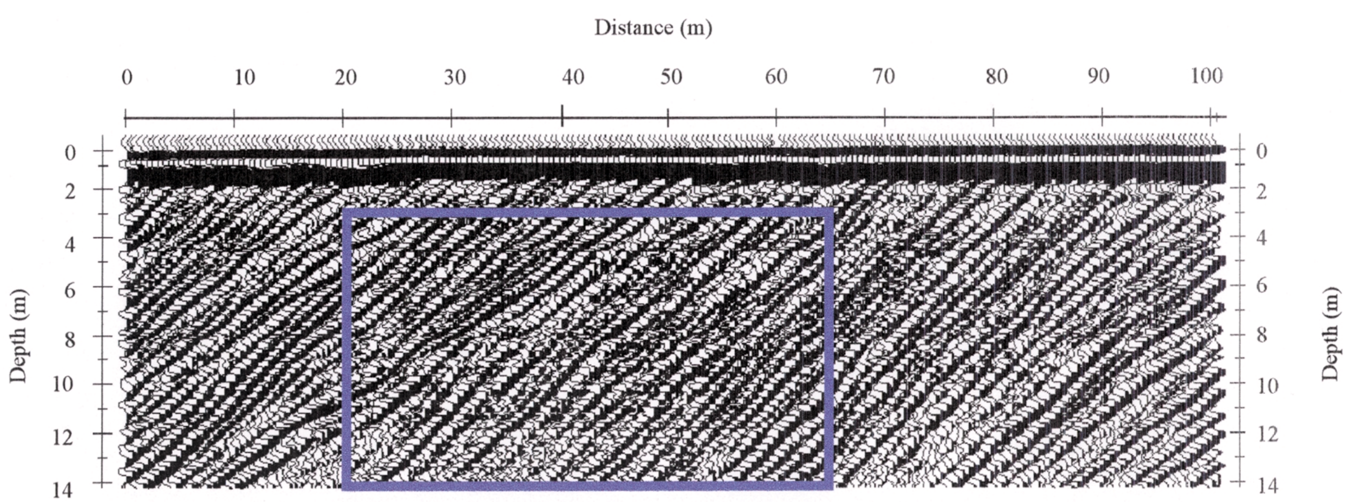

Figure 1. GPR data collected over the Box Elder Creek delta (modified from "Ground-penetrating radar investigation of a Lake Bonneville delta, Provo level, Brigham City, Utah" by Smith and Jol, *Geology*, 1992). The steeply inclined beds of sand and gravel in this classic Gilbert type fan foreset delta are seen in the GPR profile. The data inside the blue lines were used in the geostatistical analysis of the GPR section.

Alberta. The short, discontinuous reflections in the GPR section are interpreted as cut and fill structures, caused by changes in stream course. The boundaries often observed in GPR profiles probably represent bounding discontinuities which may include contacts between beds and sedimentary structures, channel scours, and the base and top of stratigraphic units.

These examples illustrate the value of GPR studies in imaging the internal structure of modern and ancient deposits. This allows us to better understand the nature of the spatial heterogeneity that is found at all scales in these types of environments.

Geostatistics from GPR data. In developing a model of the subsurface, an approach commonly taken is to describe the spatial variability using geostatistics. In the same way that geostatistical analysis of data from analog outcrops is presently used in generating stochastic models of the subsurface, we suggest that *analog GPR sections* can also be used as a means of characterizing small-scale heterogeneity. When we use geostatistical methods to analyze the GPR images, we obtain a geostatistical representation of the image in the form of a semivariogram. It is informative to see what information about the internal structure in the GPR images is actually captured in the geostatistical representation.

Geostatistics is a mathematical framework that allows us to describe the spatial relationship between data values in a region. In our work we use the semivariogram, a plot which illustrates the way in which the difference between data values is related to the distance between the data values.

Let us consider some parameter of interest z, where the value of z varies throughout a region of the subsurface. To construct our experimental semivariogram, that will describe the way in which z varies throughout this region, we select two locations, separated by a distance h and we compute the difference between z at these two locations. We do this for all data pairs separated by h and then repeat this exercise for h equal to many other distances. The semivariogram is a plot of semivariogram function γ (defined in the Appendix) versus h, and is a way of showing the difference between data points as the distance between them increases. In our geostatistical analy-

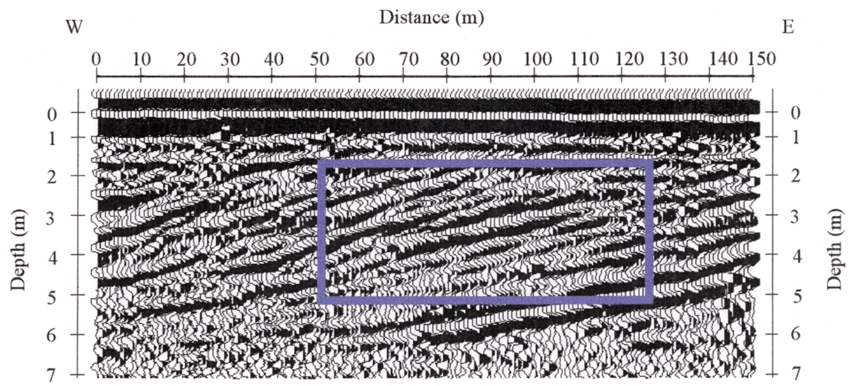

Figure 2. GPR data collected over the Willapa Bay coastal barrier spit (modified from "A detailed ground penetrating radar investigation of a coastal barrier spit, Long Beach, Washington, U.S.A." by Jol et al., 1994 SAGEEP *Proceedings*.) The dipping reflections are interpreted as beachface/upper shoreface beds indicating a shingle-like accretionary depositional pattern. The data inside the blue lines were used in the geostatistical analysis of the GPR section.

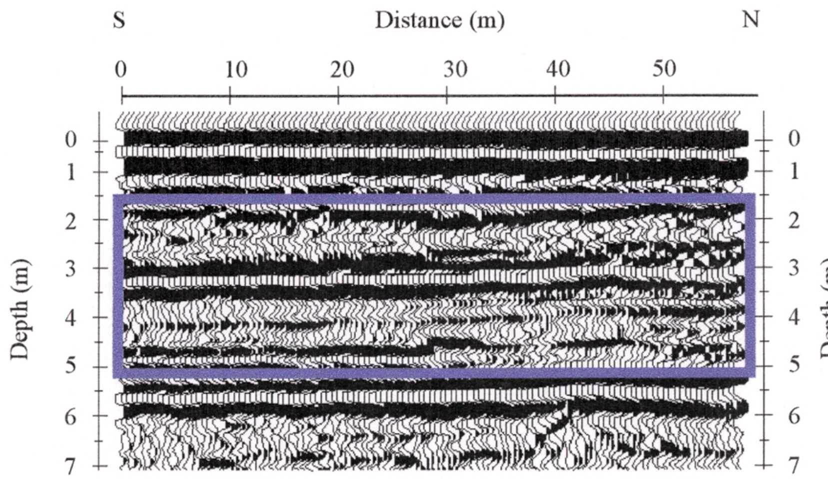

Figure 3. GPR strike profile of the Willapa Bay coastal barrier spit (modified from Jol et al.). The beachface/upper shoreface beds are seen as subhorizontal, laterally continuous reflectors.The data inside the blue lines were used in the geostatistical analysis of the GPR section.

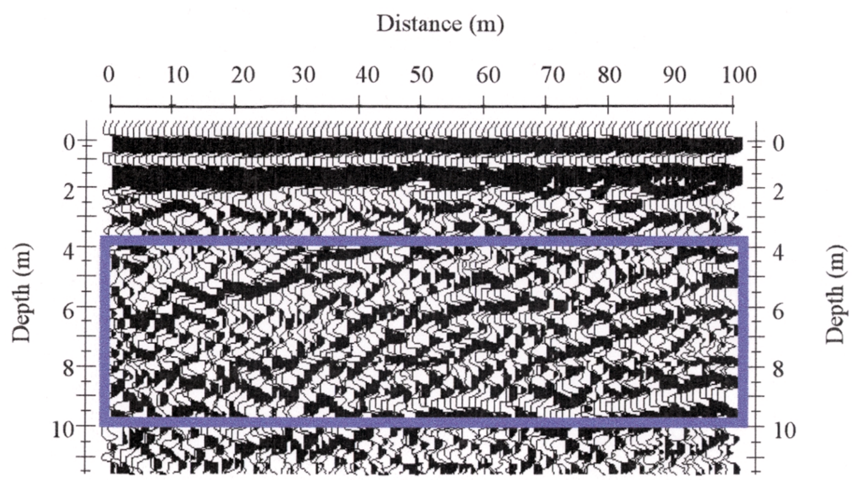

Figure 4. GPR profile of a braided fluvial deposit from the Embarras Airfield, northeastern Alberta (modified from "Ground penetrating radar: high resolution stratigraphic analysis of coastal and fluvial environments" by Jol et al., presented at the GCSSEPM Foundation 17th Annual Conference, 1996). The short, discontinuous reflections are interpreted as cut and fill structures. The data inside the blue lines were used in the geostatistical analysis of the GPR section.

sis of the GPR data, we use the amplitude values recorded in the radar traces to construct the experimental variogram using the program GSLIB.

Let us first consider the GPR image in Figure 1 from the deltaic environment. It is clear that we are seeing in this image features that are laterally continuous over many meters in the down dip direction. Our geostatistical analysis first indicates that the direction of maximum continuity is at a dip of 20°, and we construct our experimental variogram in this direction. The result, Figure 5, is a classic example of a variogram. The data points in the experimental variogram (the circles in the figure) are fit using a standard variogram model (shown as a solid line). Unlike many geostatistical studies where the lack of data points makes it very difficult to accurately define and interpret the variogram, the large number of data points in the GPR data gives us a "text book" example of a variogram. As seen in Figure 5, the semivariogram function γ increases as the distance between data points increases, and levels off when the distance becomes so large that the data values are no longer correlated. For this data set we find this distance to be 53 m. When we refer back to the GPR image we can see that our geostatistical analysis of the GPR image from the deltaic environment has captured what is seen as the dominant feature in this data set, and interpret the 53 m as a measure of the continuity of the inclined strata/ reflections.

In the next example, we analyze the data shown in Figure 2 from the sandy coastal barrier spit. The direction of maximum correlation was found to be along depositional dip, at an angle of 3° to the west. In Figure 6 is shown the experimental variogram which is modeled to obtain a correlation length of 24 m. In referring to the GPR image, we conclude that in this case the geostatistics contains information about the dip direction and the continuity of the beachface/upper shoreface beds. While other more subtle, smaller scale features can be seen in the GPR data, the reflections from these beds are such dominant features that our geostatistical analysis is only sensitive to this structure in the data set.

In the GPR data in Figure 3 we see the near-horizontal orientation in the beachface/upper shoreface beds, continuous over most of the section, when imaged in the strike direction.

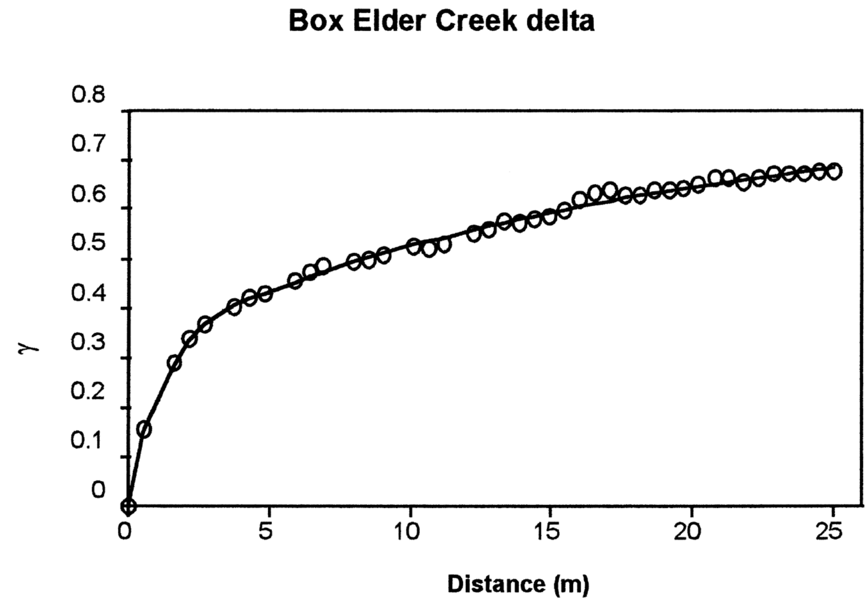

Figure 5. Semivariogram obtained through analysis of the GPR data (shown in Figure 1) from the deltaic environment. The data points are the circles; the model of the semivariogram is the solid line. The geostatistical results give a correlation length of 53 m in a dip direction of 20°. This is a measure of the distance over which the inclined strata are continuous.

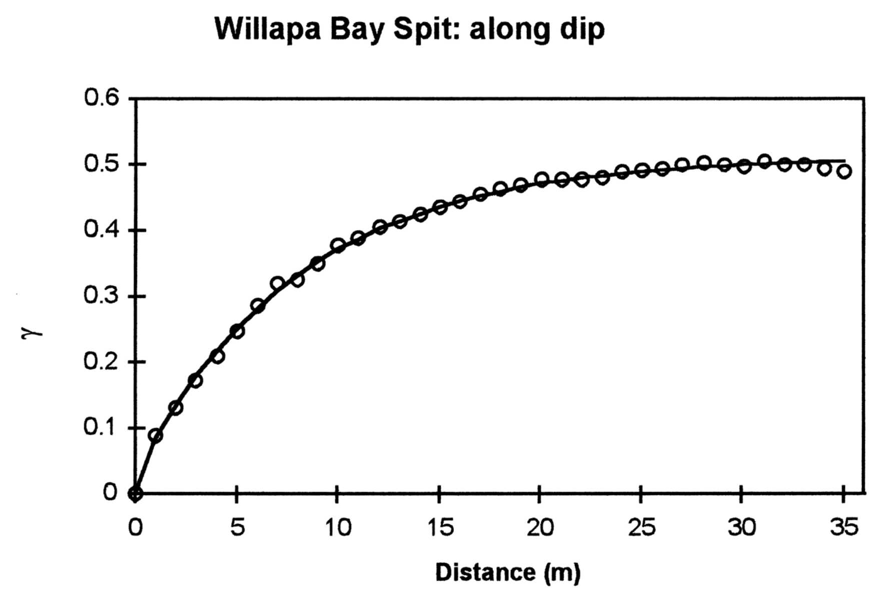

Figure 6. Semivariogram obtained through analysis of the GPR image of the coastal barrier spit. The data points are the circles; the model of the semivariogram is the solid line. Referring to the GPR data in Figure 2, this variogram was constructed at an angle of 3° to the west and indicates that the reflections from the beachface/upper shoreface beds have a correlation length of 24 m. This can be taken as a measure of the spatial continuity of these reflections.

The experimental variogram obtained from this data set is shown in Figure 7, and is found from the modeling to be dominated by a correlation length of 46 m. Again we find that the large scale structure of the beachface/upper shoreface beds is the main feature contributing to the semivariogram. The continuity of these beds is found to be twice as long in the strike direction as in the dip direction. The anisotropy present in most depositional systems can be well documented through the collection and analysis of 3-D GPR data sets.

Figure 4 shows an example of GPR data from a braided river. The experimental variogram in Figure 8 quantifies the spatial heterogeneity seen in this environment. Again, we obtain a very high quality variogram which can be modeled with a correlation length of 6 m. We find in this depositional environment short, discontinuous reflections, unlike the coastal environment which tends to produce continuous features over tens of meters. The length scale of 6 m is interpreted as a measure of the scale of the variability associated with erosion and deposition of channels and bars. Geostatistical analysis of GPR data appears to be a very effective means of describing the observed structure in the image.

The link between GPR images and material properties. GPR data give us an excellent way of imaging and describing spatial variability in the subsurface. The critical issue which must still be addressed is the relationship between the GPR image and the properties of the subsurface. Determining this link, between the GPR image and the "geological reality" is a key part of our research. The approach that we are taking is to conduct cliff face studies: GPR data are collected along the top of the cliff and the imaged section can be seen and sampled. This offers an outstanding opportunity to determine what is really imaged in the GPR section; i.e. to "ground truth" the GPR data.

In one cliff face experiment we compared the geostatistical analysis of a photographic image and a GPR image of a sequence of alternating coarse sand, and fine sand and silt. The digital photograph of the face captured information about the spatial distribution of coarse grained and fine grained beds on the basis of gray scale. There was excellent agreement between the variograms from the photograph and the radar data, in determining both the maximum correlation direction and the correlation length. These results led us to conclude that the GPR data did in fact image the spatial distribution of these two lithologies and could be used to quantify both the correlation direction and length in this sedimentary unit. In this example the spatial variation in dielectric properties in the subsurface was closely related to the spatial variation in grain size; this is very reasonable given what is known about the relationship between dielectric properties and sedimentary properties.

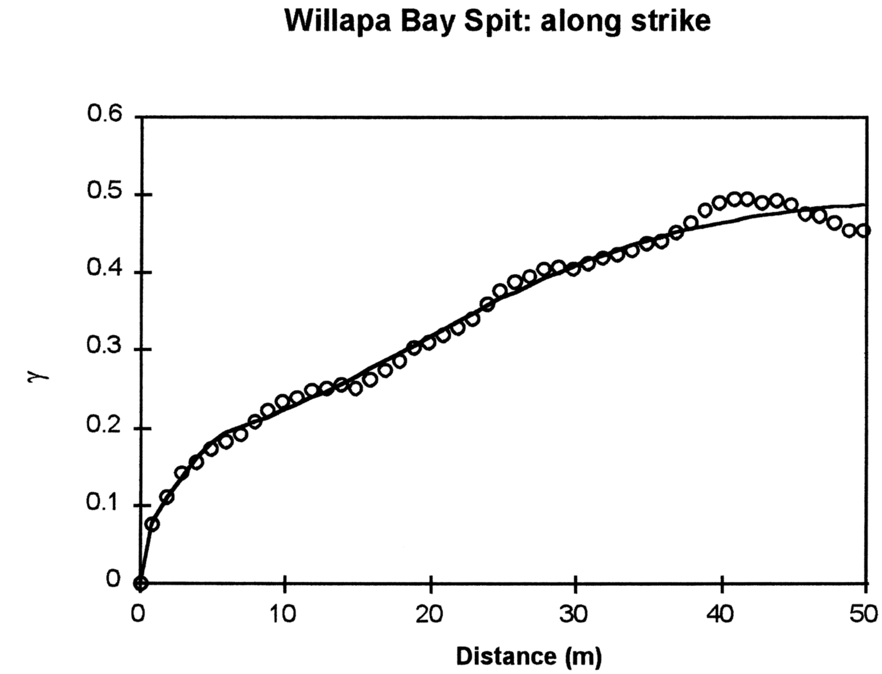

Figure 7. Semivariogram obtained through analysis of the GPR strike profile of the coastal barrier spit, shown in Figure 3. The data points are the circles; the model of the semivariogram is the solid line. When imaged in this direction the near-horizontal reflections from the beachface/upper shoreface beds are found to have a correlation length of 46 m.

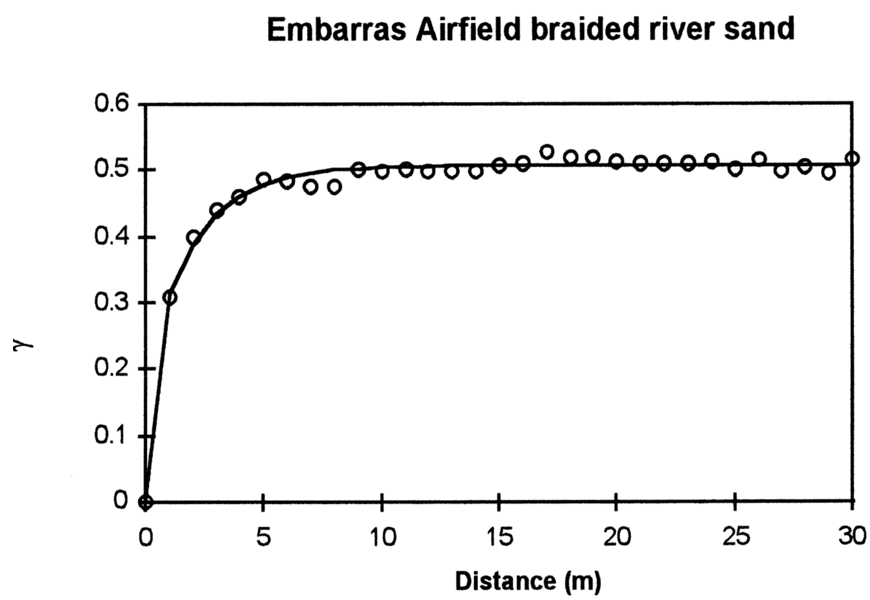

Figure 8. Semivariogram obtained for the GPR profile (Figure 4) of a braided river sand. The data points are the circles; the model of the semivariogram is the solid line. The short, discontinuous reflectors, which likely represent the erosion and deposition of channels and bars, have a correlation length of 6 m.

Conclusions. Ground penetrating radar is a high resolution geophysical technique that can provide outstanding image of sedimentary packages. We can use these GPR images of selected depositional environments to further our understanding of both depositional processes and the resulting structure and heterogeneity that will exist in the subsurface.

We find that geostatistical analysis of GPR images can be used to obtain a geostatistical representation of the different depositional environments. This geostatistical analysis captures information about the spatial distribution of the dominant sedimentological features, but inevitably loses information about much of the detailed sub-meter scale variability that can be seen in the image. Our long-term objective in this research is to collect and analyze GPR data from a wide variety of depositional environments to determine whether there exists a characteristic geostatistical "signature" associated with specific environments. The variograms from the GPR data could then be used to help extrapolate in areas where the depositional environment is known, but there is a shortage of hard data. In this way, GPR studies of near-surface, modern and ancient deposits, can assist in the integration of data to obtain a more realistic and accurate model of the subsurface.

Suggestions for further reading. A number of recent studies have used 2-D and 3-D GPR data to characterize sedimentary units and different depositional environments. Some examples of these are: "Ground penetrating radar: high resolution stratigraphic analysis of coastal and fluvial environments" by Jol et al. (SEPM, 1996); "Response of ground penetrating radar to bounding surfaces and lithofacies variations in sand barrier sequences" by Baker (*Exploration Geophysics*, 1991); "Anatomy of a bioclastic grainstone megashoal (Middle Silurian, southern Ontario) revealed by ground penetrating radar" by Pratt and Miall (*Geology*, 1993); and "Use of ground penetrating radar for 3-D sedimentological characterization of clastic reservoir analogs" by McMechan et al. (GEOPHYSICS, 1997). An excellent introduction to geostatistics can be found in the book by Isaaks and Srivastava, titled *An Introduction to Applied Geostatistics* (Oxford University Press, 1989). Geostatistical analysis of the GPR data was completed using software provided in *GSLIB Geostatistical Software Library and User's Guide* by Deutsch and Journel (Oxford University Press, 1992). Details of the methodology used to analyze the GPR data are given in "Geostatistical analysis of ground penetrating radar data: a means of describing spatial variation in the subsurface" by Rea and Knight (*Water Resources Research*, accepted for publication 1997). LE

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APPENDIX. The experimental semivariogram is described by the following equation:

$$\gamma(\mathbf{h}) = \frac{1}{2N(\mathbf{h})} \sum_{i=1}^{N(\mathbf{h})} \left[z(x_i) - z(x_i + h) \right]^2$$

where h is the lag, or separation vector, between two data points, z(x) and z(x+h), and N is the number of data pairs used in each summation.