# Multichannel analysis of surface waves to map bedrock

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In many geologic settings, topographic variations and discontinuities in the surface of bedrock can influence the transport and eventual fate of contaminants introduced at or near the ground surface. Determining the nature and location of anomalous bedrock can be an essential component of hydrologic characterization. Preliminary analysis of the hydrologic characteristics of a site in Olathe, Kansas, U.S., based primarily on borehole data alone, suggested that a cluster of fractures and/or an unmapped buried stream channel may influence fluid movement along the drill-defined bedrock surface. Accurate mapping of the bedrock surface at depths ranging from 6 ft to 23 ft and identification of potential fracture zones within bedrock were achieved at this site by integration of the shear-wave velocity field, calculated using the multichannel analysis of surface waves (MASW) method, with a surgical drilling program.

Surface waves appearing on multichannel seismic data designed to image environmental, engineering, and groundwater targets have traditionally been viewed as noise. A recent development incorporating concepts from spectral analysis of surface waves (SASW) developed for civil engineering applications with multitrace seismic reflection methods shows great potential for detecting and in some cases delineating anomalous subsurface materials. Extending the common use of surface-wave analysis techniques from estimating 1-D shear-wave velocities to detection and/or imaging required a laterally continuous approach to data acquisition and processing. Integrating the MASW method with CMP-style data acquisition permits generation of a laterally continuous 2-D cross-section of the shear-wave velocity field. The MASW method, as used here, requires minimal processing and is relatively insensitive to cultural interference. Mating MASW with the redundant sampling approach used in CMP data acquisition provides a noninvasive method of detecting horizontal and/or vertical variations in near-surface material properties.

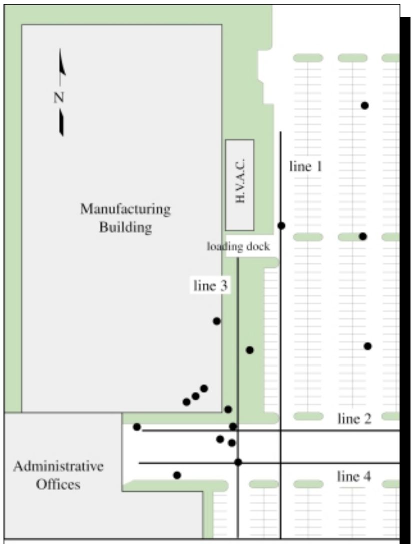

**Figure 1. Site map, Olathe, Kansas, U.S.**

Continuous acquisition of multichannel surface-wave data along linear transects has recently shown great promise in detecting shallow voids and tunnels, mapping the bedrock surface, locating remnants of underground mines, and delineating fracture systems. Cross-sections generated in this manner contain information about the horizontal and vertical continuity of materials as shallow as a few inches down to depths of more than 300 ft in some settings.

Subsidence-prone areas are likely targets for this type of imaging. Decreases in the shear-wave velocity related to decreases in compaction or localized increases in shear-wave velocity likely associated with the tension dome surrounding subsurface cavities appear to be key indicators of either active subsidence or areas susceptible to roof collapse. In situations where subsidence is active, a dramatic drop in shear-wave velocity seems characteristic of areas where earth materials have begun subsiding into voids. This low-velocity zone produces a unique signature in the shear-wave velocity field. Since the shear-wave velocity of earth materials can change when the strain on those materials becomes "large," it is reasonable to suggest that load-bearing roof rock above mines or dissolution voids may

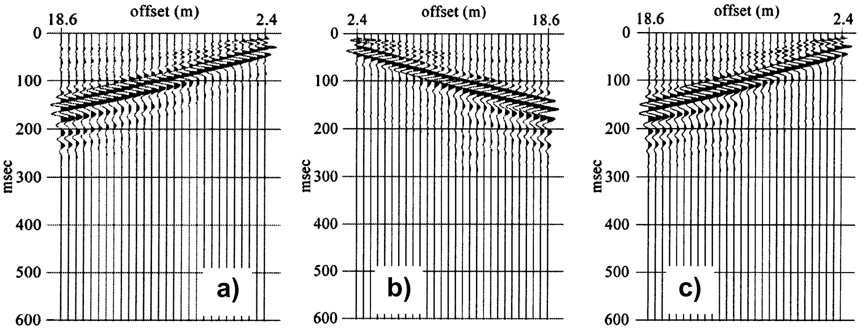

**Figure 2. Shot gathers of geophones with spikes (a), baseplates (b), or baseplates with weights (c).**

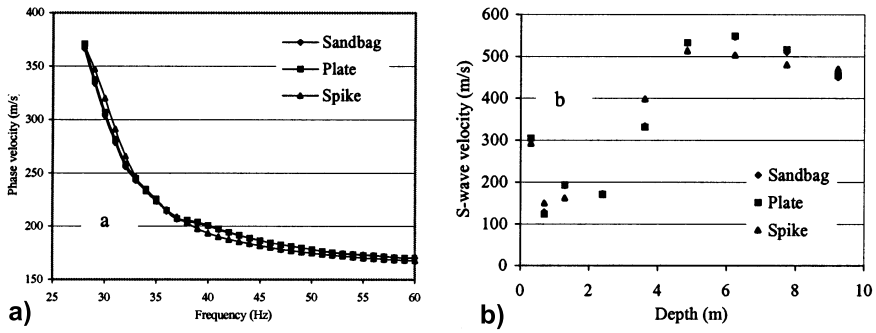

**Figure 3. Dispersion curves (a) extracted from Figure 2 and inverted *S*-wave velocities (b) based on the dispersion curves.**

experience elevated shear-wave velocities due to loading between pillars, or, in the case of voids, loading between supporting sidewalls. The key to exploiting surface waves as a site characterization tool resides in their sensitivity to shear-wave velocity, compressional-wave velocity, density, and layering of the half-space.

Several key characteristics of surface waves and surface-wave imaging make application of this technique possible in areas and at sites where other geophysical tools have failed or provided inadequate or questionable results. First and probably foremost is the ease with which surface waves can be generated. The relative high-amplitude nature of surface waves (in comparison to body waves) makes their application in areas with elevated levels of mechanical/acoustic noise possible. A half-space is all that is necessary to propagate surface waves. Surface-wave propagation does not require the velocity to increase with depth and/or a contrast at a boundary (i.e., velocity, density, or combination [acoustic impedance]). Conductivity of soils, electrical noise, conductive structures, and buried utilities all represent significant challenges to electrical or EM methods. These have little or no impact on the generation or propagation and generally no influence on the processing or interpretation of surface-wave data. This flexibility in acquisition and insensitivity to environmental noise allow successful use of shear-wave velocity profiling in areas where other geophysical methods are limited.

The Olathe case study discussed here was designed to target an area near the southeast corner of a building used to manufacture electronic components (Figure 1). Industrial fluids essential to the manufacturing process were routinely used and stored in and around this building. If these fluids were to leak from containment vessels or plumbing, a detailed transport and fate model would be imperative to rapid isolation and extraction of these hazardous fluids. This is a scenario not unlike thousands currently under investigation around the country. For the study described here, two sets of parallel intersecting profile lines were located as near the building as practical and in close proximity to existing borings. Existing borings and monitor wells were drilled and completed to define bedrock and/or to monitor groundwater. Acquisition parameters and geometry for MASW were selected to optimize the imaging of near-surface unconsolidated materials above bedrock, the bedrock surface, and several feet into bedrock. Depths of interest ranged from about 2 ft to 35 ft below the ground surface. Improving the bedrock surface map and delineating any potential contaminant pathways on or into bedrock were the primary objective of this survey.

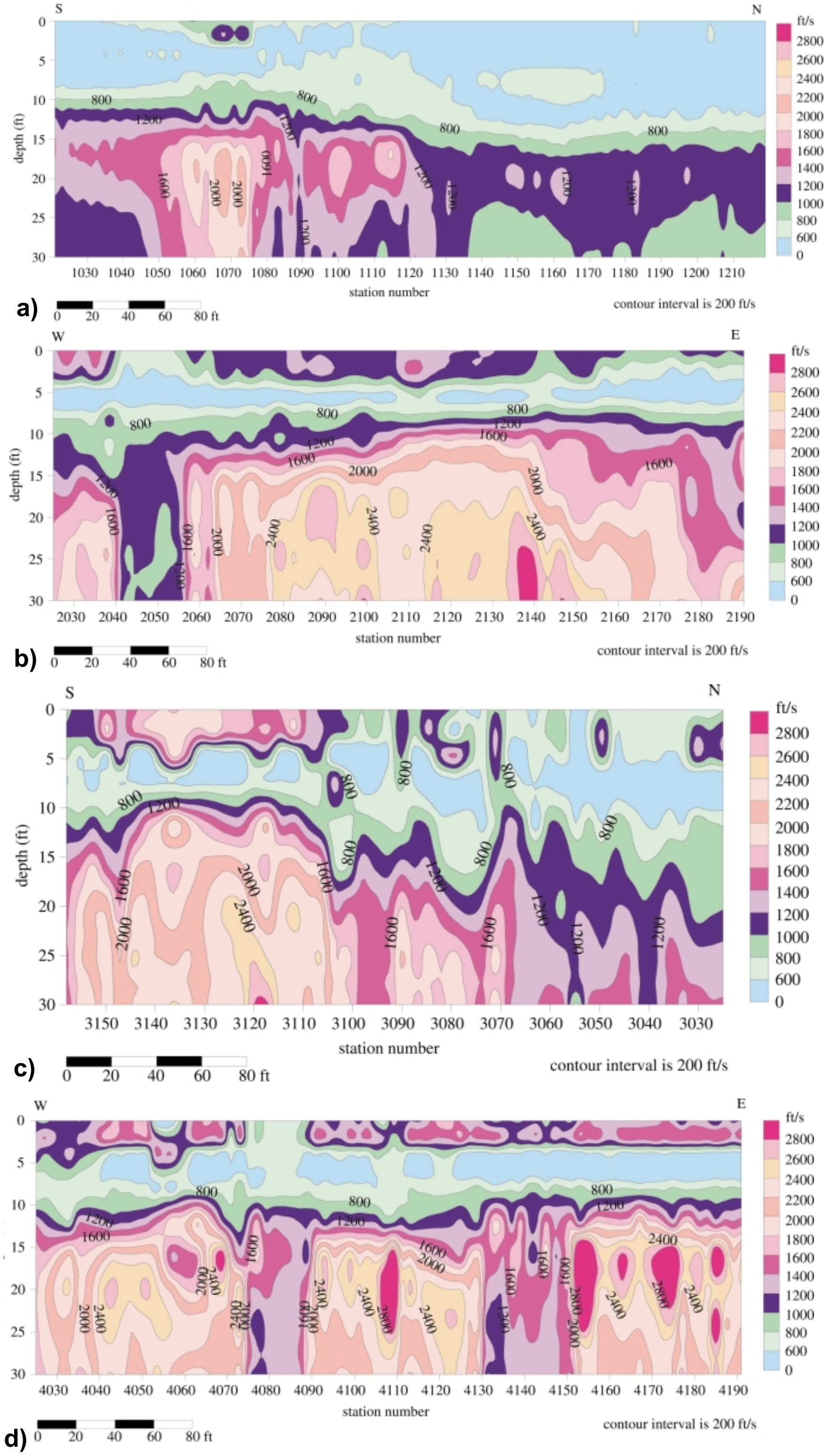

**Figure 4.** ***S*-wave velocity contours at the Olathe, Kansas, site, along line (a) 1, (b) 2, (c) 3, and (d) 4.**

**Data acquisition.** Data were acquired along two pairs of intersecting orthogonal lines (Figure 1). Standard CMP roll-along techniques were used to record nominal 48-channel shot records every 4 ft along the entire

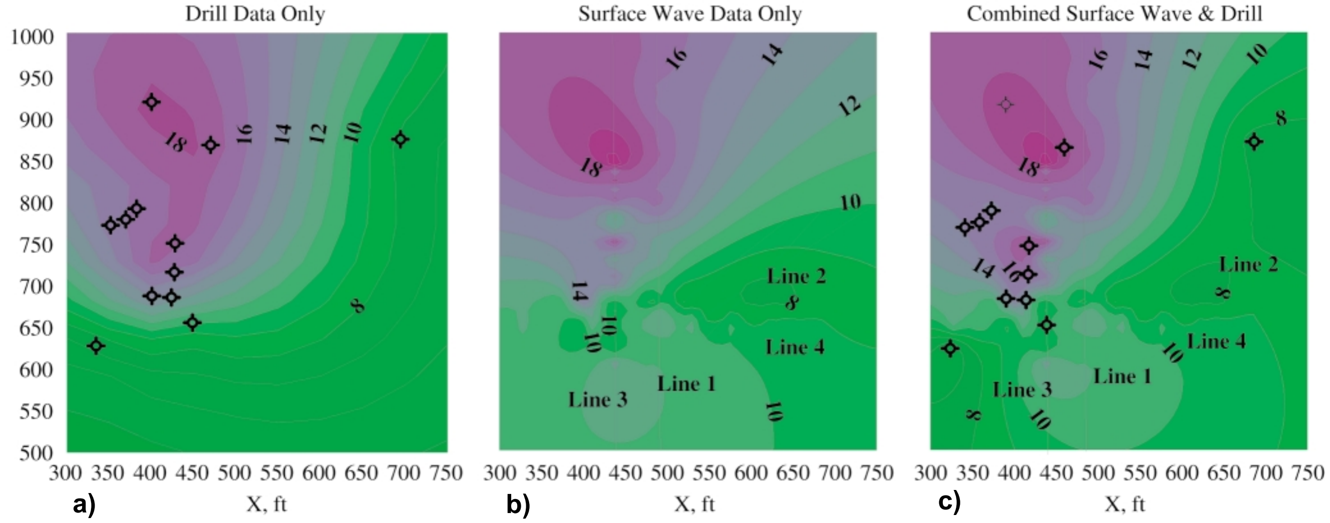

**Figure 5. Depth-to-bedrock contour map based on (a) drilling alone, (b) seismic data alone, and (c) a combination of both drilling and seismic data.**

expanse of each line. The asphalt surface covering most of the site necessitated the outfitting of the geophones with metal baseplates. About half of line 3 was in a grassy area where traditional spikes were used to couple the geophones. A 60-channel Geometrics StrataView seismograph recorded and vertically stacked four impacts of a 12-lb hammer on a 1 ft$^2$ plate at each shot station. Single 4.5-Hz Geospace GS11D geophones spaced 2 ft apart along the profile lines responded to frequencies from 8 Hz to 60 Hz (well within the requirements of this survey). Source-to-nearest-receiver offsets were nominally 8 ft, making source-to-farthest-receiver offset around 100 ft. This recording geometry and frequency range provided the optimum spread and data characteristics for examining earth materials at this site between about 3 ft and 50 ft of depth.

Recording acoustic data on asphalt or cement surfaces generally comes with coupling problems, limited amounts of vertically propagating body waves, and complex high-frequency trapped and guided waves. Many studies have shown that receiver-ground coupling is critical for high-resolution body-wave surveys. Maximizing frequency response and recorded body waves normally requires longer spikes, well seated into competent earth. Coupling experiments at this site suggest that receivers require only simple ground contact to record broad-spectrum surface-wave energy. Little or no improvement is evident in response (frequency versus amplitude) when geophones are "planted" by using spikes, placed on the ground using plates, or held to the ground with sandbags (Figure 2). This observation continues to fuel research into the use of land streamers, continuous recording techniques, and real-time data processing.

**Data processing.** Each 48-trace shot gather was recorded so all live receivers were within the optimum offset window for sampling the subsurface materials between 2 ft and 50 ft below ground surface with surface waves. Multichannel records were analyzed with SurfSeis (a proprietary software package of the Kansas Geological Survey), which facilitates use of MASW with continuous profiling techniques. Each shot gather generated one dispersion curve (Figure 3). Care was taken to ensure the spectral properties of the $t$-$x$ data (shot gathers) were consistent with the maximum and minimum $f$-$v_c$ values ($v_c$ is phase velocities of surface waves) contained in the dispersion curve. Each dispersion curve was individually inverted into an $x$-$v_s$ trace. Gathering all $x$-$v_s$ traces into shot station sequential order results in a 2-D grid of the shear-wave velocity field. The shear-wave velocity field generated in this fashion does "smear" to a limited extent velocity anomalies and requires an understanding of the overall resolution to interpret accurately.

**Interpretation.** Two-dimensional cross-sections derived as part of this study have several striking characteristics likely influencing the hydrologic characteristics of this site. Drill data acquired prior to the seismic survey helped optimize recording parameters and geometries and provided baseline ground truth for identifying of bedrock on the shear-wave profiles. The bedrock surface is characterized by its high velocity gradient, correlation to boreholes, and velocity range.

Data quality and characteristics across line 1 were consistent. Dispersive ground roll possessed an optimum bandwidth for investigating depths from about 4 ft and 30 ft below ground surface across the entire profile.

Bedrock on this line was confirmed between 10 ft and 15 ft below ground surface by drilling. From contoured shear-wave velocities the surface of bedrock appears relatively smooth with a pronounced localized velocity high in bedrock around station 1065 (Figure 4a). Based on the elevated shear-wave velocities in this zone, this anomaly likely signifies an increased shear modulus, correlating to harder or less fractured rock. Local outcrop studies routinely encountered shale overlaying fractured limestone units composed of competent blocks that range from a few feet to hundreds of feet in horizontal extent separated by fracture systems. This higher-velocity zone is likely to be a large block of limestone bounded by fracture-separated smaller blocks. Identification of individual limestone blocks is precluded by smearing that is due to the size of the receiver spread. When we contrast the southern and northern halves of this profile, bedrock material on the south appears to have the higher average shear-wave velocity. This could be related to either changes in material or fracturing of subbedrock materials. The more than 40% drop in shear-wave velocity of bedrock materials across this line represents a significant change in average "stiffness." It is possible that the limestone unit drill-confirmed to be present beneath the shale bedrock on the south end may be missing on the north end, leaving only shale for the first 20 ft or so below the surface of bedrock on the north end.

There are two features on line 2 with the potential to affect fluid movement along the surface of bedrock (Figure 4b). An extreme drop in shear-wave velocity beneath station 2050 is either a paleochannel infilled with weathered bedrock material or a fracture/fault zone. On the western flank of this abrupt low-velocity zone is a very localized velocity low beneath station 2040. This feature is pronounced and topographically the lowest point along this line on the bedrock surface. Immediately beneath station 2050 a drop in the shear-wave velocity is evident from the ground surface to about 5 ft or so. This shallow low-velocity zone correlates with the known location of a sewer line buried along the eastern side of the building. The second noteworthy feature on this line is the broad channel feature on the east end of the line, defined by the gradual drop in shear-wave velocity beyond station 2140. This bedrock channel could be the result of cut-and-fill, with the infill material having distinctly different properties than the low-velocity unconsolidated sediments above bedrock.

The shear-wave velocity profile of line 3 is characterized by several geologically significant changes in material properties (Figure 4c). These data correlate quite well with the four boreholes in close proximity. This profile provides insight into the gross texture and irregular nature of the bedrock surface. The velocity high at about station 3130 may act as a hydrologic barrier, separating fluid introduced south of station 3140 from any north of station 3120. The deepest bedrock observed on any of the surface-wave profiles (estimated to be around 25 ft) is present at the northern end of line 3 near the loading-dock area of the manufacturing building. Pinnacle-looking bedrock structures are prominent on the north end of line 3. Delineating the short-wavelength undulations (pinnacle features) in the bedrock surface along the southern end of this line would not have been economical with borehole data alone. We can infer that these localized highs and lows in the bedrock surface would greatly increase the hydrologic complexity of fluids moving along the bedrock surface. Suggesting that these severe pinnacle-type features are representative of the true bedrock surface brings up questions of resolution and accuracy in subsurface sample point placement. In highly variable areas, smearing will be more evident and significant to the accuracy of geologic models. Some distortion will be present in all cases when using this method to delineate anomalies or to study changes in material properties.

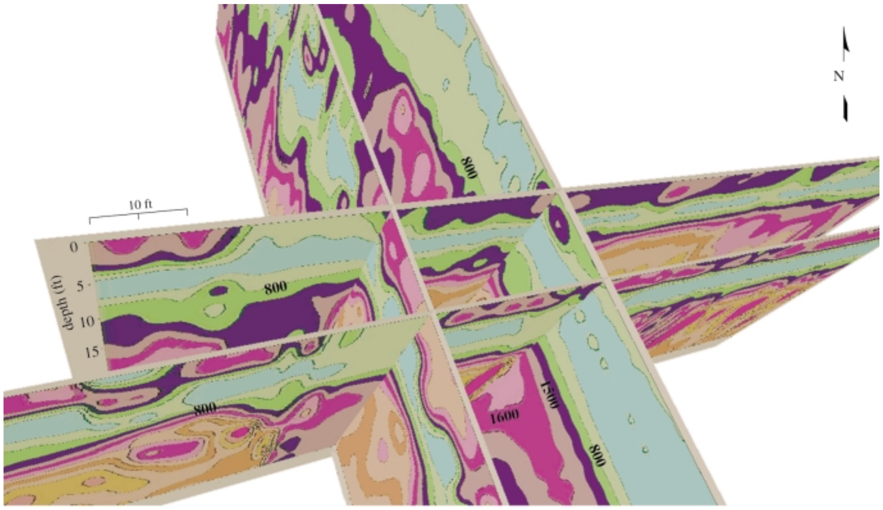

**Figure 6. This 2.5-D bench representation of lines 1, 2, 3, and 4 allows delineation of bedrock features across this site. Bedrock has been drill-confirmed to be consistent with the 800 ft/sec contour across this entire site.**

Two striking features on line 4 are candidates for breeches in the confining properties of bedrock (Figure 4d). The most interesting feature on this line is located beneath station 4080 and seems to be directly associated with a similar feature beneath station 2050 on line 2. Velocity contrasts associated with this channel-fault/fracture, its physical dimensions, and relative location are consistent between the two profiles. A low-velocity zone extending from very near the surface down to about 5 ft is the footprint of the sewer trench seen on line 2 that runs along the eastern side of the manufacturing building. Correlation of the sewer trench with the extreme velocity low in the bedrock cannot be assumed a simple coincidence. Therefore, a borehole was drilled to confirm that the lower-velocity channel in bedrock between stations 4075 and 4088 was real and not an artifact of the sewer trench and methodology. This deep channel is probably the most hydrologically significant feature related to transport and fate in proximity to the southeast corner of the building. Consistency in physical shape and velocity of this feature with the one interpreted on line 2 is testament to the consistency in the measurement characteristics for unique subsurface features. This bedrock low-velocity zone will influence how fluid moves along and within shallow bedrock; it could act either as a barrier or a conduit.

Bedrock seems to get shallower toward the eastern end of line 4. This observation is also consistent with interpretations of line 2. The anomalous feature located beneath station 4140 on line 4 is difficult to correlate directly to line 2. If this fracture/fault-channel feature rapidly widens to the northeast, it would correlate with the much wider channel-looking feature on the northeast end of line 2. This feature may not exist beneath line 2. Considering the variability commonly observed in outcrop, abrupt termination or changes in fractures of this magnitude would not be considered unrealistic. Line 4 possesses several features that will affect transport and fate models for this site.

Data resolution is an issue that must be addressed when using this technique. It is appropriate to question the unlikelihood that bedrock surface on line 3 possesses the extreme pinnacle topography suggested by this section. The general trend of these data is accurate, as verified by drilling. Outcrop studies have noted bedrock blocks scattered beneath weathered material consistent with the highs observed on this 4:1 vertically exaggerated section. It must be kept in mind that surface-wave imaging techniques involve the inversion of a wave that has sampled an area nearly as wide as deep. As well, the sampling depth is generally considered to be half the wavelength. Assuming the wave is limited to the 2-D plane, the velocity value assigned to a single sample point in the subsurface has been calculated using a wave that has sampled an area several times the square of the sample point depth. Therefore, structures observed on shear-wave cross-sections are likely smoothed, subdued, and/or a sculpted version of what really exists in the subsurface.

Resolution of the drill-defined bedrock surface map improves significantly after incorporation of shear-wave velocity data (Figure 5). Depth-to-bedrock contours based on drill data alone grossly defined the configuration of bedrock in proximity to the boreholes. However, due to the sporadic nature and nonuniformity in drill-hole spacing, drill data alone do not allow subtle and, in many cases, extremely significant bedrock features to be extended, or in some cases even detected. The bedrock contour map produced using only shear-wave data from this site lacks the necessary off-line control. Incorporating the drill data and shear-wave data greatly improved the detail and sitewide resolution of the depth-to-bedrock map as compared to either data set individually. Adding a few more seismic lines could noticeably improve the 3-D aspects of the bedrock contours.

Displaying the data in a 2.5-D fence diagram allows appraisal of the consistency in measured shear-wave velocity and helps to interpolate features between lines (Figure 6). Analysis of measurement uniqueness for a given surface location suggests that bedrock ties are quite good. However, correlation of shallow features (< 5 ft) from line to line lacks consistency at the tie points when spread orientation is changed. This observation is consistent with the fact that each shear-wave velocity trace is determined through simultaneous analysis of all arrivals within the spread. For this data set each shear-wave velocity value has been influenced by material along a 94-ft long spread. The more abrupt and larger the velocity contrast associated with a feature, the larger the gradient on the velocity contours. Subtle changes and small (one-fourth spread length) anomalies will be difficult to confidently delineate using the MASW and continuous profiling techniques. However, abrupt, large gradient changes in velocity, such as those associated with voids or collapse features, have been detected with lateral dimensions as small as a few feet.

**Summary.** High-velocity gradients within the shear-wave velocity field consistent with drill-confirmed bedrock are considered diagnostic of the bedrock surface and were used to map the top of bedrock on all four lines collected at this site. Localized lateral decreases in the shear-wave velocity below the bedrock surface were classified as fracture zones or erosional channels. Calculating the shear-wave velocity field from surface-wave arrivals was accomplished with a high degree of accuracy regardless of cultural noise. The insensitivity of MASW to cultural obstacles and noise was demonstrated at this site (e.g., approximately 220 000 square yards asphalt parking lot, electrical and mechanical noise from nearby industrial facilities, traffic noise from the adjacent highway, exploratory drilling on the asphalt parking lot, and aircraft noise). Depth-to-bedrock maps produced using shear-wave velocity and drill data possesses significantly higher resolution than maps produced using drilling or shear-wave velocity data individually. There is less than 1 ft of difference in the depth-to-bedrock interpreted from surface-wave data compared to the depths determined through drilling.

Improved resolution on the surface of the bedrock provides insight into the texture of bedrock and permits identification and appraisal of short-wavelength variations in the bedrock surface. The goals and objectives of this survey were met. Advantages of mapping the bedrock surface with the shear-wave velocity field calculated from surface waves include the insensitivity of MASW to velocity inversions, ease of generating and propagating surface-wave energy in comparison to body-wave energy, and sensitivity to lateral changes in velocity.

**Suggestions for further reading.** "Seismic techniques to delineate dissolution features in the upper 1000 ft at a power plant site," and "Using MASW to map bedrock in Olathe, Kansas," both by Miller et al., SEG 1999 *Expanded Abstracts*. "Multichannel analysis of surface waves using Vibroseis (MASWV)" by Park et al., SEG 1996 *Expanded Abstracts*. "Multichannel analysis of surface waves," by Park et al., GEOPHYSICS, v. 64, n. 3. "Estimation of shear wave velocity in a compressible Gibson half-space by inverting Rayleigh wave phase velocity," by Xia et al., SEG 1997 *Expanded Abstracts*. "Estimation of near-surface shear-wave velocity by inversion of Rayleigh wave," by Xia et al., GEOPHYSICS, v. 64, n. 3. "Evaluation of the MASW technique in unconsolidated sediments," and "A pitfall in shallow shear-wave refraction surveying," both by Xia et al., SEG 1999 *Expanded Abstracts*. E

*Acknowledgments: We appreciate the support provided by Harding Lawson Associates for this applied research project. Technical assistance by David Laflen, Nathan Geier, as well as the document preparation work of Mary Brohammer and Amy Stillwell greatly contributed to this work.*

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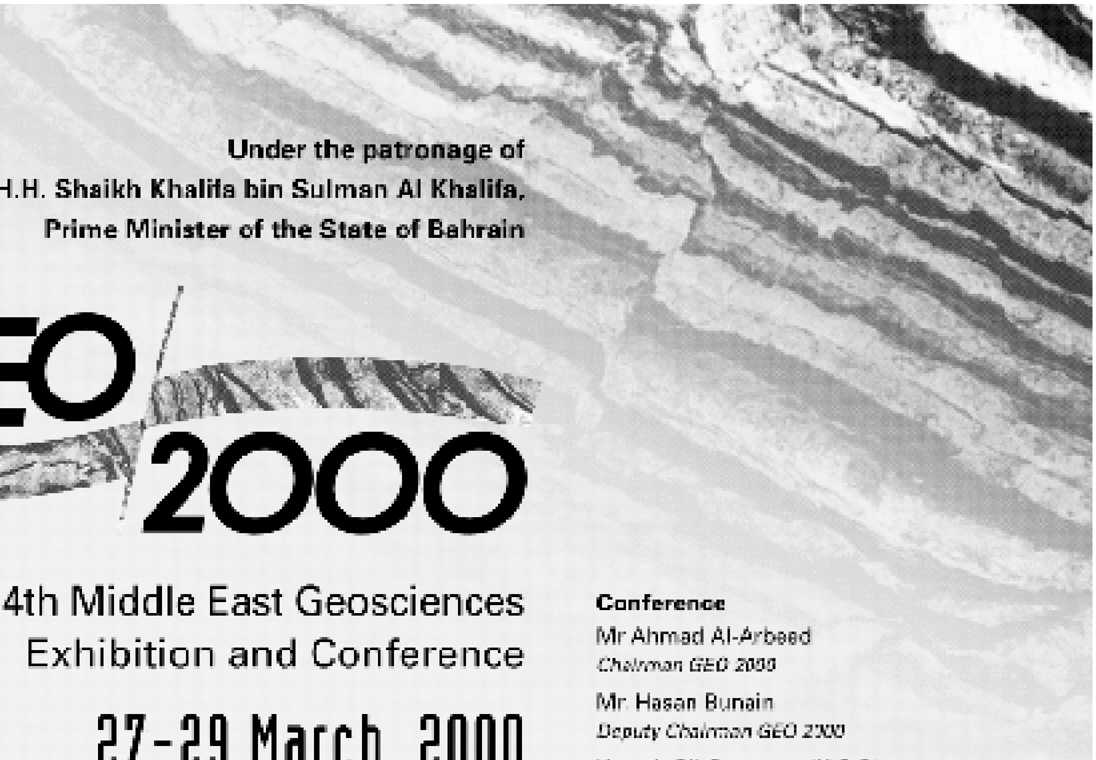

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