Seismic Refraction Tomography for Karst Imaging

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Summary

Over the past fifteen years, we have applied various geophysical methods for karst detection and imaging on the Oak Ridge Reservation (ORR), Tennessee and other U.S. government sites. The ORR has an abundance of karst features, including sinkholes, voids, and epikarstal features and has served as a test area for many of these methods. In addition to non-seismic investigations, several seismic surveys, primarily seismic reflection and refraction, were conducted on the ORR between 1992 and 2005. Conventional layered model processing of these data proved inadequate. In this paper, we summarize the results of these surveys as well as the modeling that we conducted to understand these results, and present our observations on the strengths and limitations of seismic refraction tomography for karst investigations.

Introduction

In recent years, new software tools have been released for applying tomographic inversion to seismic refraction data sets. These offer an alternative to conventional data analysis tools for seismic refraction data, such as the delay-time method or generalized reciprocal method. They permit the seismic velocities to vary laterally and vertically, whereas the conventional approaches assume constant velocity layers which can vary in thickness within the profile. The tomographic methods require more shotpoints within the profile than the conventional approaches.

Soon after the new software tools were released, we began an assessment and comparison of their performance, using synthetic and field data sets. Initial assessment was focused on fundamental models such as layered models, dipping layers, and buried lateral transitions with three commercial software products (Sheehan et al., 2005). The assessment was conducted with support from the software providers and led them to make adjustments and improvements in the codes. The assessment next focused on the performance of the codes for investigations of karst areas. These areas are known to have complicated structures, including sinkholes, bedrock remnants, mud-, water- and air-filled voids, and other features. Bedrock varies from nearly unaltered high-velocity limestones and dolomites to in situ weathered soils, including clay-rich "saprolites". Such features were shown to be problematic for conventional refraction methods (Doll et al, 1999).

Seismic refraction tomography (SRT) can provide a more realistic alternative to conventional methods for karst areas. The assessment of seismic refraction tomography for karst applications is based on synthetic data and field data acquired on the ORR.

Oak Ridge Reservation Karst

The ORR has an abundance of karst features, including sinkholes, voids, and epikarstal features (Figure 1). These features are of concern because they can critically impact the offsite migration of contaminants. As an example, groundwater monitoring well GW-734 intercepted a mud-filled void in 1992, and a number of geophysical surveys were subsequently conducted to assess the karst feature at this site (Doll et al., 1999; Carpenter et al., 1998). In addition to several non-seismic investigations, many seismic surveys, primarily seismic reflection and refraction, were conducted on the ORR between 1991 and 2005). Seismic refraction surveys were conducted for depth to bedrock measurements (e.g. at the proposed Advanced Neutron Source ANS site, Nyquist et al., 1996), and characterization of karst sites. Seismic reflection surveys were conducted primarily for mapping structures that control contaminant transport in the vicinity of high-level waste sites (e.g. Doll et al., 1998; Doll, 1998; Carr et al., 1997; Liu and Doll, 1997). The results were used for selection of groundwater monitoring well locations. Although some of the reflection lines were disrupted by karst, there were no cases where the seismic reflection data could be used to image or characterize karst features (Doll et al., 2005).

Conventional seismic refraction methods have been used on the ORR and elsewhere to determine depth to bedrock, and other structures related to karst terrains. It is appropriate for mapping soil-filled sinkholes, where these occur as a shallow low velocity soil or soil/rock unit subtended by a higher velocity consolidated layer (presumably carbonates). As carbonates tend to have high velocities, these contacts are good refraction candidates, even when moderately weathered. Deeper karst, however, is more problematic for conventional delay-time or

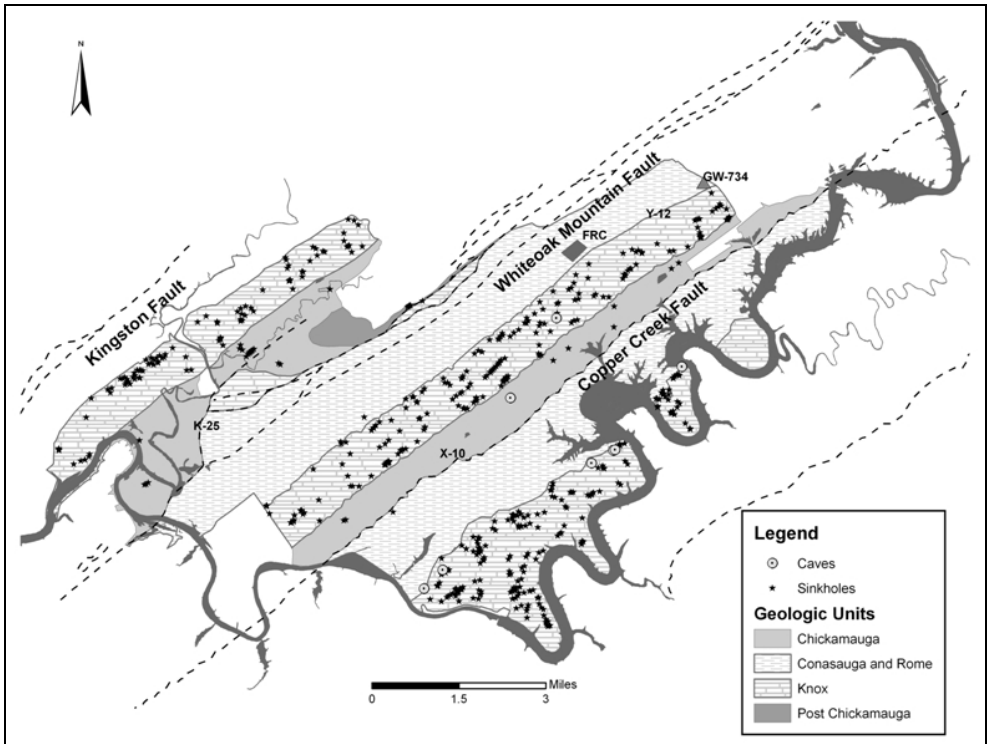

Figure 1. Karst and structural features of the ORR.

generalized reciprocal methods for refraction analysis. Air-, mud- or water-filled voids are manifested as low-velocity zones, and these methods assume constant velocity, or constant gradient layers. As a result, conventional seismic refraction methods often yield indicators of karst such as an apparent thickening of layers above karst voids. Seismic refraction analysis methods that allow basement velocity to vary beneath a constant velocity upper layer (such as the refraction statics routines in seismic reflection software packages) can also yield artificially low basement velocities beneath the void. These results show that conventional analysis can respond to voids, but these methods or data sets have inherent weaknesses that preclude proper imaging.

Synthetic Karst Modeling

Synthetic models were used to test various properties, limitations and capabilities of SRT for cavity detection. Traveltime curves were generated from 2-D models using the refraction tomography code GeoCT-II (version 2.3; GeoTomo, LLC). The synthetic models allow us to have a "reference" model with which to compare the results generated by SRT using another refraction tomography code Rayfract™ (version 2.51; Intelligent Resources Inc).

No synthetic model will ever be a completely accurate depiction of the real subsurface because it is comprised of discrete units, which are further broken down into small constant velocity grids. This means that however carefully constructed and applied, numerical analysis is based upon simplified and digitized representations of physical laws and models. In addition, most commercially available numerical modeling packages are based on 2-D models.

A sample of the models that we developed and the inversion results are shown in Figure 2. The most basic requirement for detecting a cavity is to have adequate ray coverage in the area surrounding it. Both survey geometry and the velocity structure affect the ray coverage. As the effect of geometry is well understood, we will focus on the effect of the velocity structure.

In order to be able to image a cavity successfully, there must be rays that penetrate deeper than the cavity and can be refracted back to the surface. One factor that can limit the depth of penetration is the presence of sharp high-contrast velocity boundaries. Rays will return to the surface if there is a change in velocity under the cavity or if the formation that contains the cavity has even a small vertical velocity gradient. Normally velocities will increase

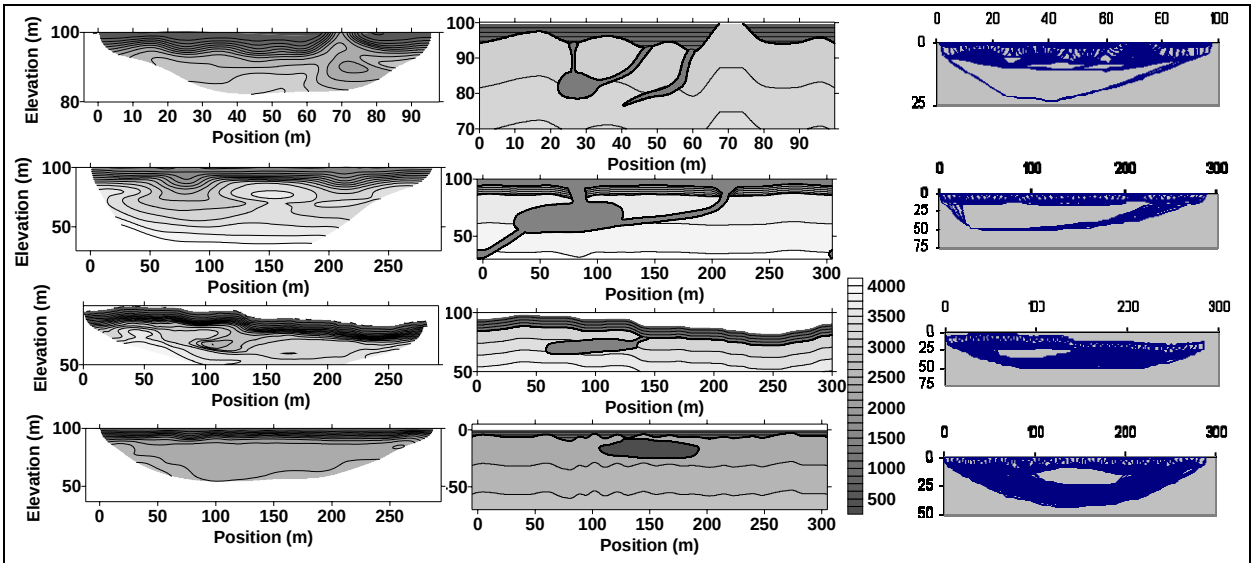

Figure 3. Inversion results (left), synthetic models (center) and ray paths (right).

slightly with depth in sedimentary rocks, so in a karst investigation this requisite can be easily met.

Ray coverage alone is not enough to insure that the cavity can be detected. Models that are otherwise identical can be created with and without voids to evaluate travel time changes due to the void. We have found cases where the ray coverage around the cavity is extensive, but the first arrival traveltimes generated from the model do not reflect the presence of the cavity, making it impossible for the inversion algorithm to detect the cavity. Usually, even when a cavity has a significant effect on the travel times the inversion may result in a feature with velocities only a little lower than that of the surrounding volume. This muted response is unlikely to give the user confidence that a cavity has actually been detected.

SRT can create false positives as well as false negatives (e.g. top row, Figure 2). These artifacts have even been observed when inverting synthetic data, which does not include the detrimental noise and picking errors. These errors are likely to increase the occurrence of false negatives and false positives.

Sharp boundaries tend to shield underlying areas from ray coverage. The synthetic models examined in this study were all created by adding layers and objects with distinct seismic velocities and velocity gradients. Care was given to avoid unrealistically sharp transitions to the extent possible with available codes.

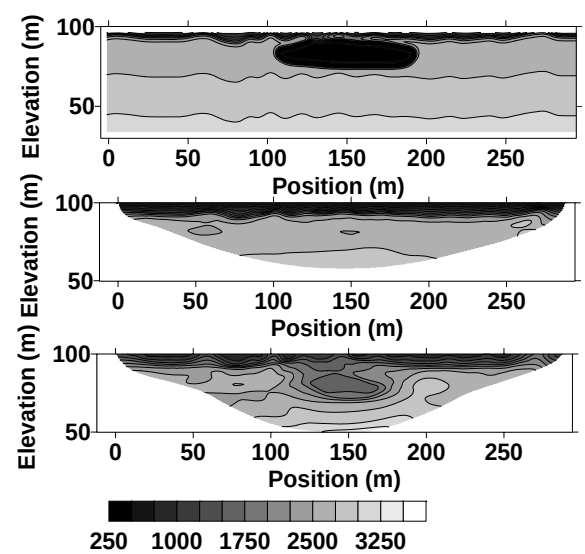

Figure 2. Top: smoothed synthetic velocity (m/s) model. Middle: Inversion results with no velocity smoothing. Bottom: Inversion result with velocity matrix smoothing

Matrix smoothing of models before generating the travel time curves can be used to reduce boundary sharpness. Analysis of these smoothed models suggests this could partially explain why the field data are more effective than the synthetic. In one model where the unsmoothed cavity could not be detected, the smoothing allows the cavity to be detected, and to exhibit the same level of velocity contrast as the model (Figure 3). However, applying the same smoothing to other models was unsuccessful. Therefore one of two things must be true: 1) Our models represent situations where SRT would fail or 2) Our models are still inaccurate in some way that is not resolved by the smoothing that we have applied.

GW-734 Karst Site

Data were acquired above a known karst feature at well GW-734 on the ORR. The mud-filled void at this site was encountered during installation of a monitoring well with the top of the void at 18m and at least 12m of vertical extent. More details on the site are available in Carpenter et al., 1998 and Doll et al., 1999.

Conventional delay-time analysis of a seismic refraction line at the site yields the result shown in Figure 4. This result provides no indication that a karst feature might occur at this site.

A more suitable approach was provided within the FOCUS (DISCO) seismic reflection software in a static correction module that corrects for near-surface time delays. Tomographic seismic refraction statics routines in the FOCUS software package allow bedrock velocity to vary while assuming that the surface layer velocity remains constant. In practice, of course, the soil layer velocity will not be constant, but the allowance for a varying bedrock velocity is an improvement over constant velocity assumptions. When applied to the data from GW-734, we observe two effects (Figure 5). A profile of the depth to bedrock (Fig. 5a) shows a depressed bedrock surface at the location of the void. The calculated bedrock velocity (Fig. 5b) is lower in the area of the void than in adjacent areas. Both effects are reasonable artifacts for a void in these data.

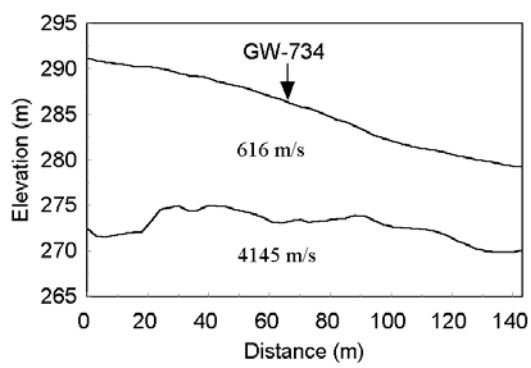

Figure 4. Delay-time result for first arrival analysis at well GW-734.

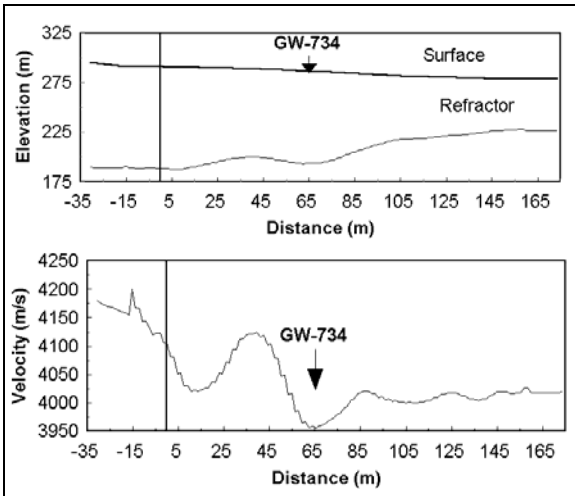

Figure 5. Bedrock surface and velocity, as determined with FOCUS refraction statics

The FOCUS refraction statics results require more shots across the geophone spread than does the conventional delay-time result. On the other hand, they provide strong indicators of the presence of karst that cannot be derived from the delay-time analysis. Both methods rely only on the travel times of first-arrivals. Most importantly, the FOCUS results demonstrate that analysis of seismic first arrivals is sensitive to the presence of karst, even though the inherent assumptions of delay-time and FOCUS statics are too restrictive for karst terrains.

Finally, SRT was applied to the data from GW-734. The result is shown in Figure 6. The SRT image indicates a low velocity zone beginning at 18m, at the known depth of the void. Previous two-and-a-half dimensional gravity modeling (Doll et al., 1999) suggests that the void may be wedge-shaped. This gravity model is superimposed on the tomographic image in Figure 6 as a dashed line. We note that a low velocity spur from the primary low velocity zone on the SRT image coincides with the southern end of the gravity wedge, but the SRT image does not extend to sufficient depth to provide adequate comparison with the gravity model.

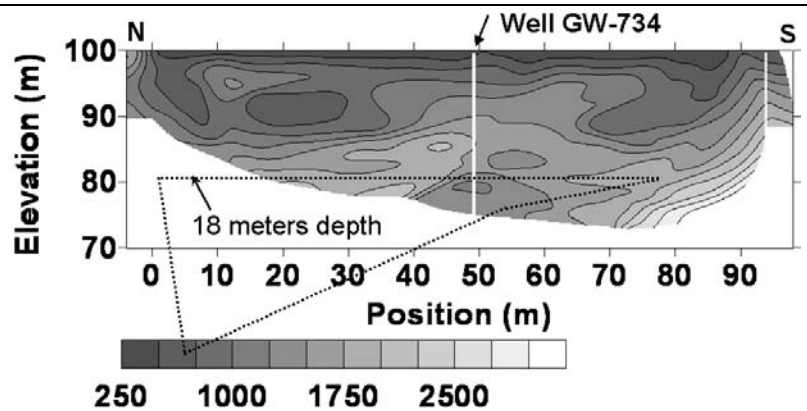

Figure 6. SRT solution for the karst feature at GW-734. Gravity model from Doll et al., 1999 is overlain as a dashed line.

Field Research Center

Five refraction tomography profiles were collected in support of the Natural and Accelerated Bioremediation Research (NABIR) Field Research Center (FRC). NABIR is a DOE sponsored research program to develop and evaluate bioremediation tools for contaminated sites. Liquid wastes containing nitrate, uranium, technetium, tetrachloroethylene, and other contaminants were disposed of in sludge ponds until the mid-1980s, at which time the ponds were remediated and capped with a parking lot. A large contamination plume within the underlying unconsolidated saprolite and inter-bedded shale and carbonate bedrock is now spreading away from the site of the old ponds.

A set of four new SRT profiles (designated by Line A, C, D and E, Figure 7) were acquired in support of research at the NABIR FRC site. Lines A and C are oriented parallel to an earlier line (Doll et al., 2002), designated Line B for this paper.

Lines A, D, and E used one-meter receiver spacing and two-meter shot spacing. Line B consisted of three collinear lines which were combined for analysis. Line C was collected using 2 meter receiver spacing and 4 meter shot spacing. All data were collected using a 48 channel Geometrics Strataview seismograph. Ten Hz geophones were used for Lines A, C, D and E and 40 Hz receivers were used for line B.

Lines A, B and C each show a well-defined (~10m wide) low velocity feature (Figure 8). These low velocity features are all similar in size, at the same approximate depth, and fall on a line that is parallel to geologic strike at the field site (Figure 7). There is no such feature in lines D

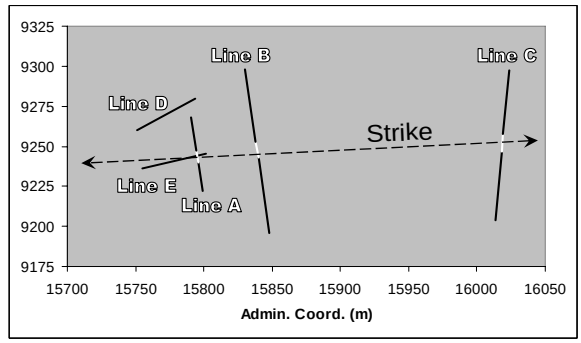

Figure 7: Map view of seismic lines at the FRC site

or E, which run roughly parallel to strike and perpendicular to the other three lines.

The ray coverage for Lines A and C are shown in Figure 9. In both cases the area of the low velocity feature has very low ray coverage, as in the example discussed earlier. Because of this and the correlation to geologic strike it is reasonable to assume that these low velocity features are not artifacts, but rather indicate a continuous structural feature, possibly a conduit. This feature yields seismic velocities of approximately 1500-2000 m/s in a matrix of 3000-4000 m/s. Geologic units in the shallow subsurface at this site include both shale and carbonate units. Therefore, the low velocity feature could be a void associated with carbonate dissolution, or highly fractured zone or void associated with a structural flexure in shale. In either case, it is quite possible that it could serve as a contaminant pathway. If it is a dissolution feature, we note that it is below the water table so it could not be air-filled, and its velocity is so low that it would have to be water- or mud-filled.

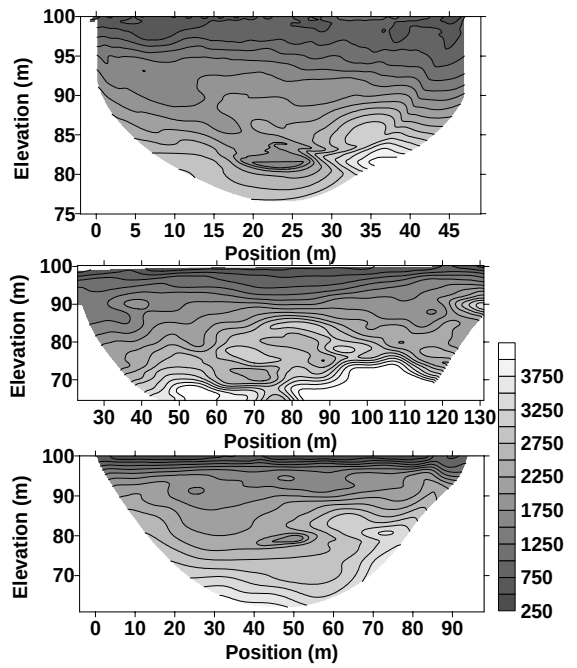

Figure 8. SRT results for Lines A, B, and C at the FRC site. Low velocity zones at about 80m elevation are indicated in all three profiles.

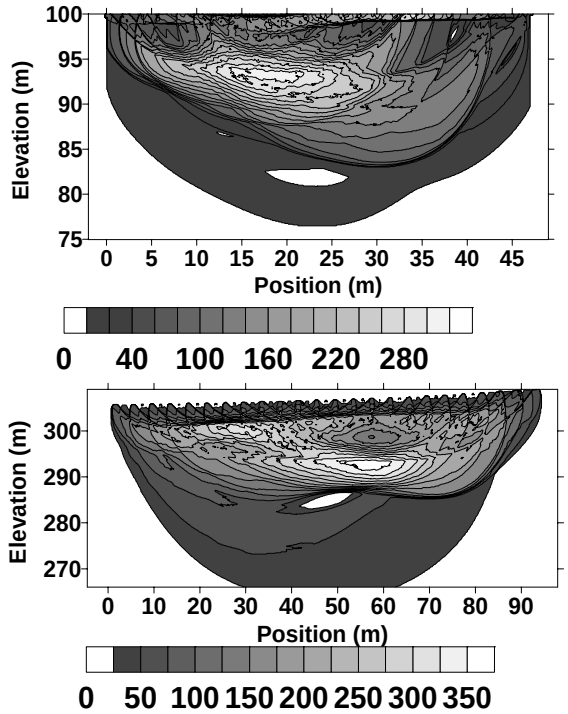

Figure 9. Ray coverage for Lines A and C, at the FRC site.

Discussion

The synthetic results demonstrate that under certain circumstances SRT can be more effective than conventional refraction analysis methods. Field results at the GW-734 known karst site are consistent with the measured attributes of a known void and with previous gravity models. At the FRC site, a low velocity zone that is consistent along three profile lines may be a karst conduit. Model results inferred that the feature should not be detectable. We hope to drill into this feature soon to better understand its nature and cause.

Dobecki and Upchurch (2006) have recently affirmed the effectiveness of SRT for karst investigations. They report particular success in using SRT with shear waves.

Further advances are needed in order to make SRT more effective for karst investigations. First, it is important to recognize the limitations of two-dimensional modeling where velocities vary significantly in three-dimensions. Development of three-dimensional SRT codes should be pursued to provide more accurate and reliable images of karst.

SRT solutions are nonunique and dependent on the starting model that is used. Several approaches are taken by current codes, some using layered solutions, Delta t-V and other models. Profiles derived from MASW solutions have been compared with SRT results (Sheehan et al., 2004) and have been suggested as the basis for starting models. Palmer (2006) indicates that amplitude information should also be used to reduce the nonuniqueness of SRT solutions. Ivanov (2005a,b) discusses an approach for characterizing nonuniqueness in seismic refraction data.

Conclusions

We have demonstrated that SRT is a promising tool for improved imaging of karst sites. Commercially-available software codes have become more reliable and consistent in the past few years. Further improvements in SRT analysis, including three-dimensional analysis, shear wave surveys, and use of amplitudes to reduce nonuniqueness are warranted.

Seismic Refraction Tomography for Karst Imaging

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