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ORIGINAL PAPER

Mapping of near-surface formations by refraction seismic tomography: a case study from Al-Amerat, Sultanate of Oman

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Abstract

In this study, a seismic refraction survey is conducted to image the structure of the bedrock and overlying rocks in Wadi Al-Mayh from Al-Amerat, Northern Oman. The bedrock is a consolidated and impermeable metamorphic rock. The porous and unconsolidated rocks lying above the bedrock have played a key role in transporting and storing water from rainfall. Seismic data were collected from 8 seismic profiles acquired along the wadi. Tomographic inversion of the data has produced velocity models that have contributed to understand how the water accumulates, migrates, and charges the aquifer in the subsurface of the wadi. Data from the exposed rocks on surface and from a water-producing well in the area were used to calibrate the velocity models. The latter models were used to build 3-D depth map that not only helped to understand the distribution of porous and permeable zones but also has provided an interpretation for a water-producing well in the area that has run dry after decades of production.

Keywords Seismic refraction · Bedrock · Tomography · Structure · Groundwater

Introduction

Seismic refraction method is based on Snell's law, which governs the refraction of seismic waves propagating across the boundary between layers of different physical properties. These waves once are recorded on surface; they can be used to derive properties of the rocks along which they have traveled. Such properties include rock velocities, depths, topography, and thicknesses among much more physical and elastic properties. For seismic refraction to work, the velocity of sound wave must increase with depth. When this condition is met, the refracted wave arrives at the Earth's surface where it can be detected by geophones, which will convert ground motions to registrable electrical signals.

The simplicity of the refraction method and its applicability in different environments have played key roles in its popularity. In literature, an increasing number of published papers have demonstrated the success of the method in characterizing near-surface formations. In fact, recent advances in seismic equipment, software packages, and interpretation techniques have led seismic refraction method to be an effective and economical tool for numerous hydrology applications, engineering operations, in addition to mineral and petroleum exploration, see, for example, Saribudaka and Hauwert (2017), Pilecki et al. (2017), Farfour and Ademola (2018), and Farfour et al. (2019) among many others.

The area of this study is located along wadi Al Mayh between Tunis and Al-Mahyul villages in Al-Amerat city, Muscat, Oman. Seismic refraction method has been proposed to image near-surface geological formations responsible for water accumulation, migration, and storage. It is worth noting that there has not been prior seismic work done in the survey area; however, the seismic refraction method had been applied to many similar cases in Oman and in other areas around the globe. For example, Farfour and Adeteunji (2018) invoked seismic refraction tomography along with multichannel analysis of surface wave (MASW) to map the structure of near-surface formations in Qurayat Northern Oman for cavity detection. In Austin, Texas, Saribudaka and Hauwert (2017) have integrated refraction tomography with other geophysical methods to map the submerged conduits (caves, voids) carrying flow to water springs in the area. Avalos et al. (2016) have successfully implemented refraction tomography to map a buried bedrock topography and

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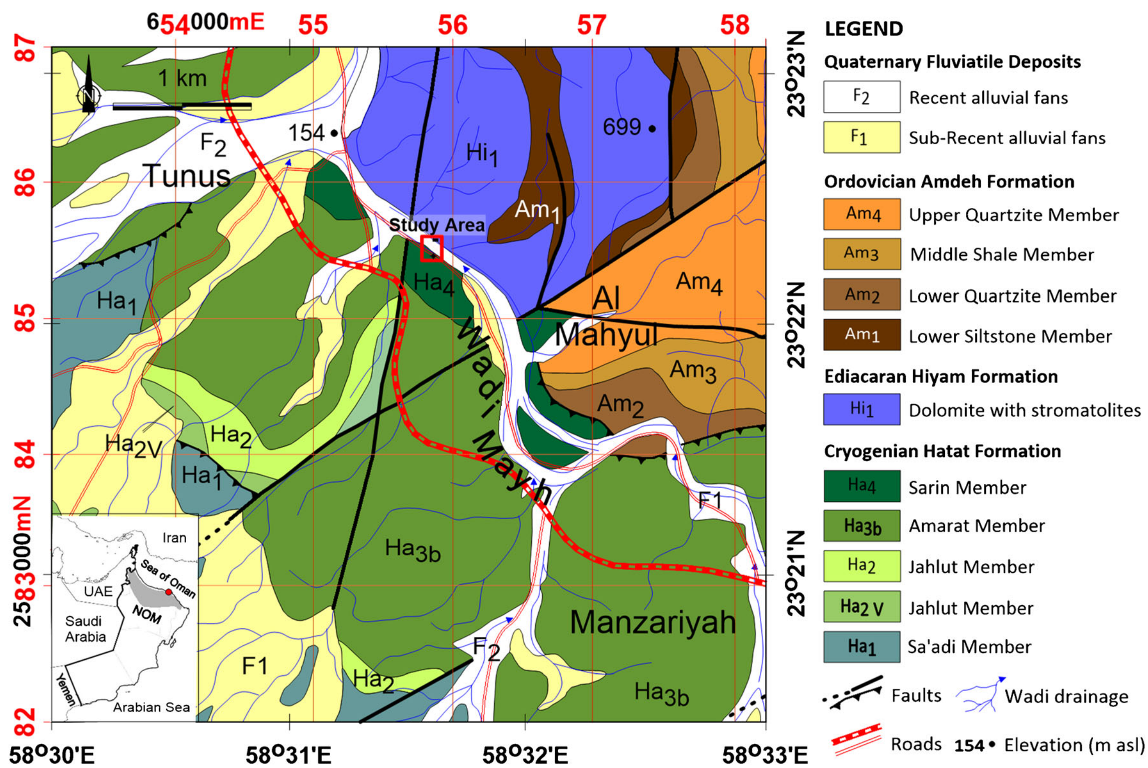

Fig. 1 Geological map showing the study area. The study area is highlighted by red box. The well locations is denoted inside the box

delineate tow paleo-channels at Hallsands beach, UK. Hirsch et al. (2008) mapped the bedrock surface beneath terrace deposits along the Bow River near Calgary, Canada. They found that refraction tomography provided excellent resolution of the bedrock boundary where the resistivity and GPR methods have failed.

Geology of the study area

The study area is underlain by pre-Permian rocks that comprise three principal stratigraphic units, from old to young: Cryogenian Hatat Formation, Ediacaran Hiyam Formation, and Ordovician Amdeh Formation (Fig. 1). The Hatat Formation is the oldest stratigraphic unit exposed in the Saih Hatat dome and is made up mainly of micaceous quartz–feldspar schist with a metabasalt interval. It is subdivided into the Saadi (metasedimentary schist), Jahlut (mafic schist, metabasalt, metagreywacke, and chert), Amarat (Banded metagreywacke and schist), and Sarin (metagreywacke, diamictite, and carbonate) members, all of which are exposed in the area. The Hiyam Formation is made up mainly of recrystallized carbonate that was deposited in an intertidal to supratidal environment. It is subdivided into white and yellow dolomite with stromatolites (Hi_1) and gray limestone (Hi_2). The lower part (Hi_1) is only exposed in the study area. The Amdeh Formation is a thick sequence of a metamorphosed clastic sequence mainly of quartzite and shale. It is subdivided into five members, from bottom to top, Lower Siltstone member, Lower Quartzite member, Middle Shale member, Upper Quartzite member, and the Upper Siltstone member (Le

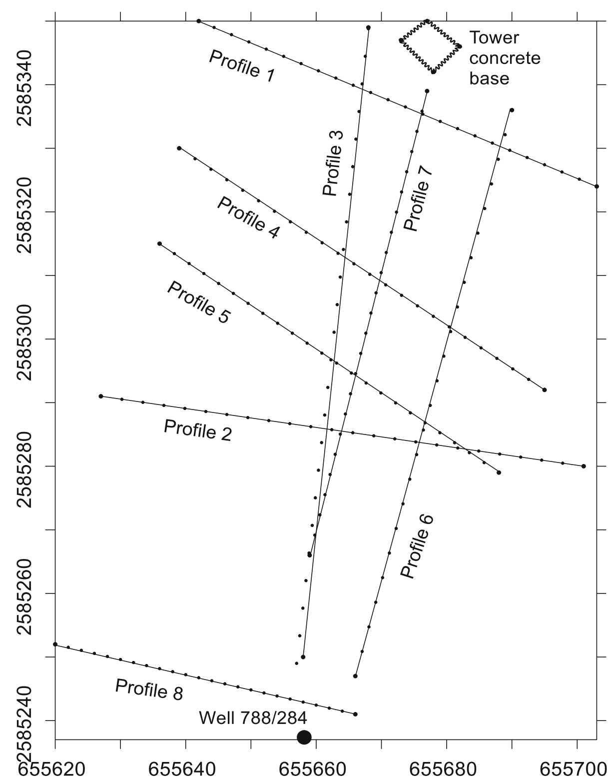

Fig. 2 A survey map showing the profiles location and orientations

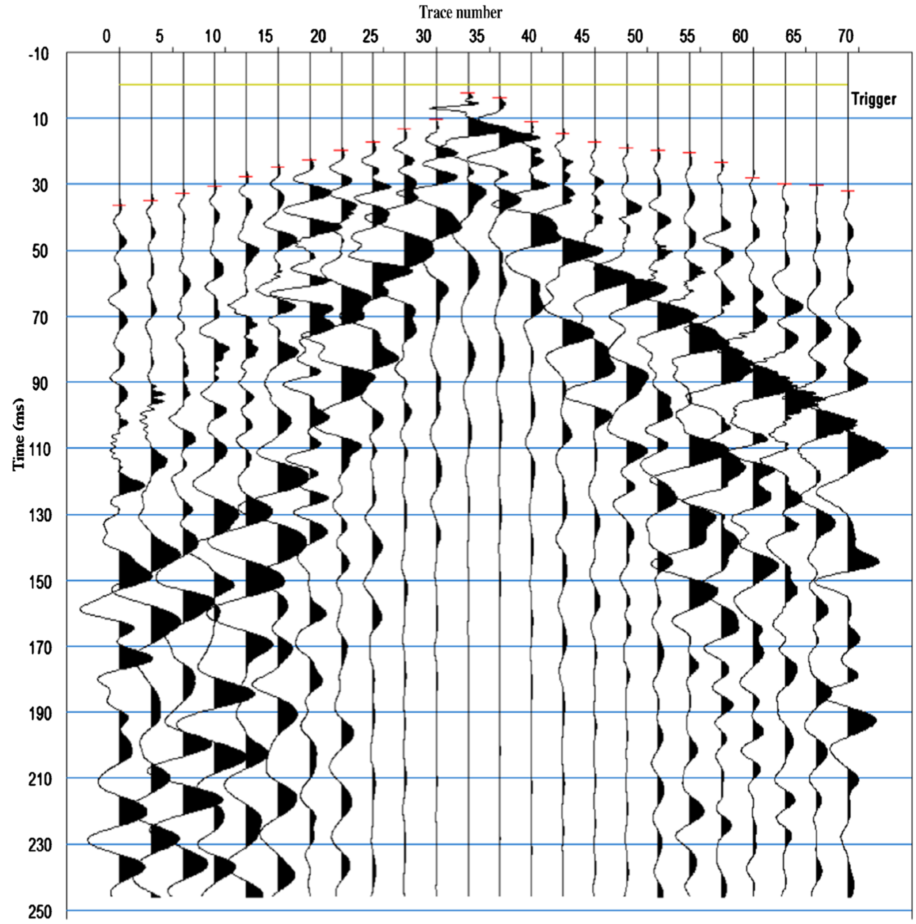

Fig. 3 Shot recorded in the middle of Profile 4 with first breaks (picks in red)

Métour et al. 1986). The first four members are represented in the study area. In the area, where the mountains are relatively low, Recent and sub-Recent alluvial fans and wadi alluvium of Late Tertiary-Quaternary age are exposed.

Methodology

The survey was designed to image near-surface formations that may have control on the ground-water flow (Farfour and Al-Hosni 2018). The survey consists of 8 lines with twenty four 4.5 Hz geophones at 2.5 to 3 m spacing. With 70 to 80 m spread length, the refraction method can be a reliable imaging tool for up to 20 m depth, which is sufficient in our case. The energy source was a 5-kg (11 lb) hammer against metallic plate with accelerometer trigger. The latter source is considered adequate because the depth to basement around the area is shallow and hardly exceeds 30 m.

The geophones were planted and checked for optimum physical contact with the ground. The lines were distributed over the area to ensure a good coverage around the well. It was ensured that best results were obtained, by stacking the recorded signal 5 times on the seismograph. This would also help to reduce the problem of artifacts that often occur in seismic inversion. Figure 2 displays the coordinate and orientation of the profiles. Profiles 1, 2, 4, 5, and 8 were run along the wadi, while the Profiles 3, 6, and 7 were crossing the wadi. For calibration purposes, some lines were intentionally crossing the bedrock, which was exposed on surface; this in addition to line 8, which was shot so close to a well in the site such that data from seismic can be calibrated directly with formation exhibited in the well. The well location is depicted in Fig. 2. For each line, seven shots have been recorded, two offset shots and five shots along the spreads. The data were then loaded to a software and prepared for the inversion by assigning the geometry and manually picking the first arrivals for all the shots.

First breaks were manually picked, and velocity models were created with Zond2D seismic refraction interpretation software. The data were of reasonably good quality that did not require any prior filtering. Figure 3 shows a selected shot with first break picked.

For the inversion, we have used focused inversion introduced by Portniaguine and Zhdanov 1999. The inversion method is based on specially selected stabilizing functionals, called minimum gradient support (MGS) functionals, which minimize the area where strong model parameter variations

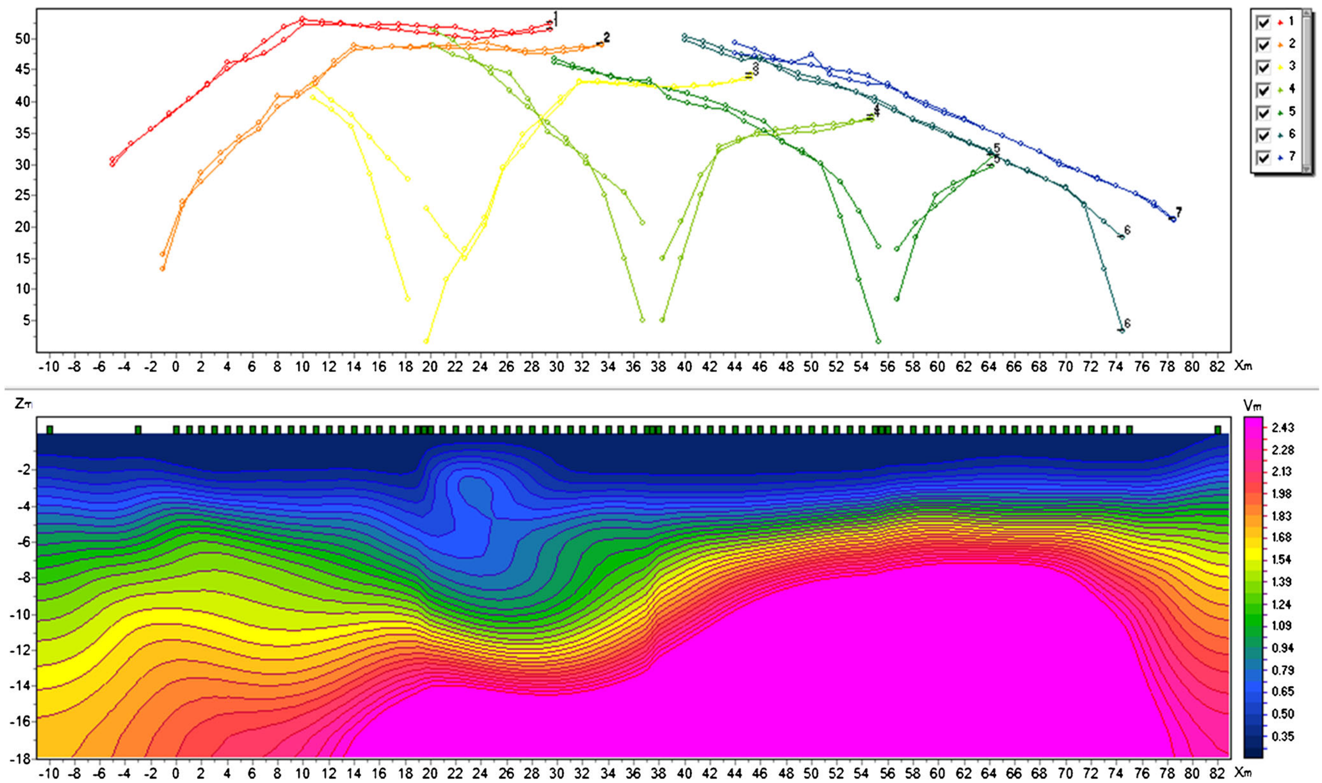

Fig. 4 The travel-time and the inverted velocity model from Profile 01. Velocity in the color bar is in kilometer per second, and depth is in meter

and discontinuity occur. In their paper, Portniaguine and Zhdanov (1999) provide a detailed description of the method and its application in geophysical imaging. They demonstrate how this inversion algorithm maintains accuracy despite complexity of geology compared with other methods. Tomography would allow lateral velocity variations and vertical gradients to be imaged as opposed to most conventional refraction interpretation methods, which produce constant velocity layers.

Two profiles were used for velocity calibration. Profile 6 was crossing the exposed bedrock from the North. Profile 8 was shot close to the well to be used also as a calibration point. Initial comparison of velocity data in profile 6 with exposed bedrock suggested a bedrock velocity ranging from of 1900 m/s and above.

Results and discussion

First arrival times for the recorded profiles have been used to build an initial model for the tomographic inversion. In tomographic inversion, the final model depends heavily on the characteristics of the initial velocity model. The observation of inverted sections inferred that velocities vary with depth. These velocities typically express the speed of seismic waves, which is directly related to the rock elastic properties. The velocities vary also from point to another along the same profile, which indicates variation in geomorphology of the layers. This infers that there are several strata within the overburden, which overlies the hard basement rock. Calibration with rocks exposed on surface suggested a range of velocities for the bedrock between 1900 and 2500 m/s. The overlying alluvium layers exhibit much lower velocities. The variation in velocity can be associated also with the degree of consolidation of these sediments, and their porosity and permeability (Osazuwa and Chinedu 2008, Avalos et al. 2016, Adelineta et al. (2018)).

The line 1 in Fig. 4, for example, shows a very clear depression in a form of low-velocity trend. The same features appear in other lines that have been shot in the same direction such as lines 2, 3, 5, and 6 (Figs. 5, 6, 7, and 8). The images from the profiles indicate that the subsurface slopes gradationally from north and south of the profile towards the center. The low-velocity features could be attributed to the presence of loose and unconsolidated material deposited in a channel-like structure that would possibly allow the water to flow in subsurface to its destination. In the lines crossing the wadi, variable topography was observed, which suggests the sinuosity of the channel. Figure 9 displays a good example from Profile 7. At later stage, the 2-D velocity models derived from tomographic inversion were used to produce a 3-D map of the bedrock underlying the channel's sediments. The bedrock was picked in all the tomographic sections.

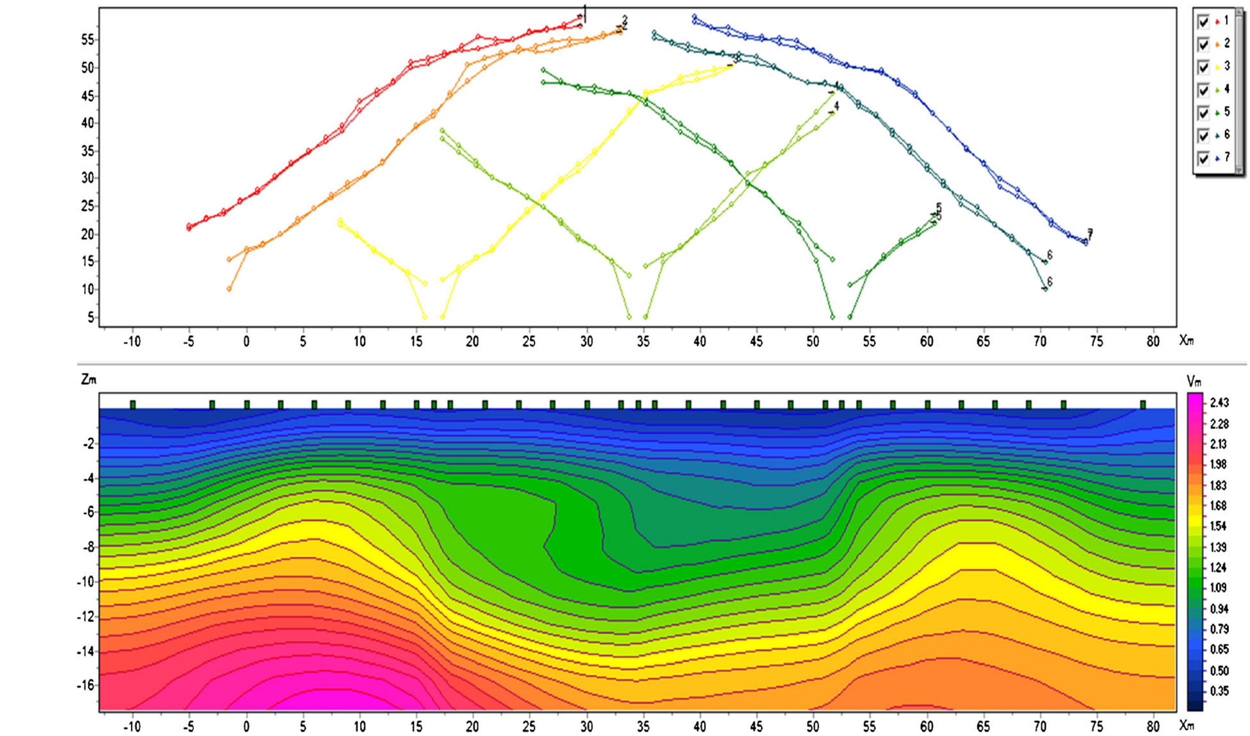

Fig. 5 The travel-time and the inverted velocity model from Profile 02. Note the channel like structure appearing in the middle of the section. Velocity in the color bar is in kilometer per second, and depth is in meter

The picks were then gridded and converted to a map. The resulting map is displayed in Fig. 10. The map has provided more complete image of the target. For more confident interpretation, the models have been calibrated with the exposed rocks in the survey area and inside the well. Note that the well has become dry after decades of production. The map revealed that the well receives its water from depressed zones. These zones were filled with

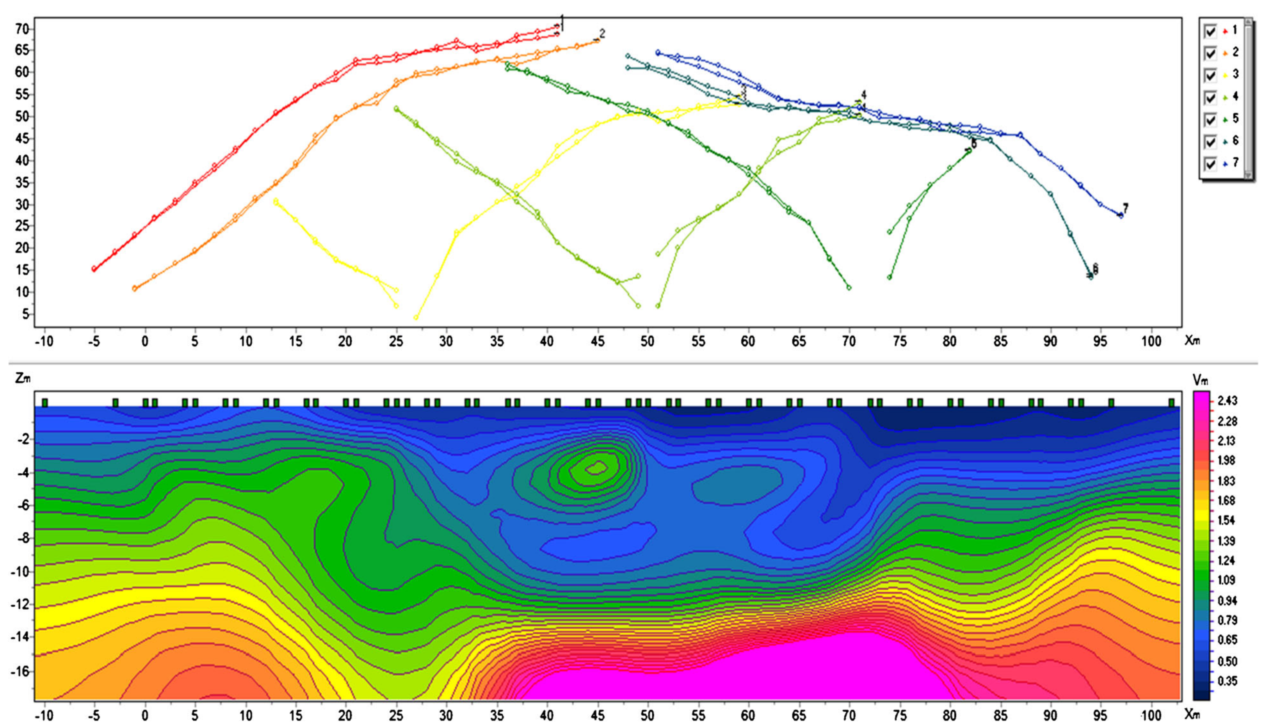

Fig. 6 Profile 4 (following the same direction of profile 1) also showing the channel-like structure. Velocity in the color bar is in kilometer per second, and depth is in meter

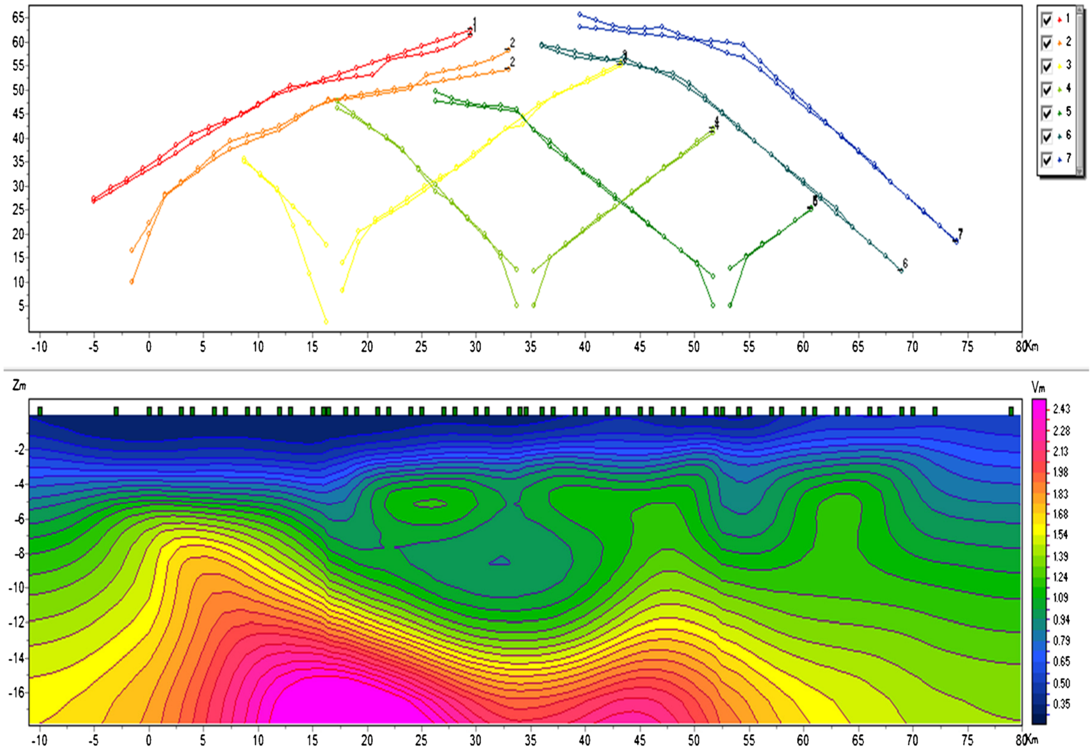

Fig. 7 Profile 5 (was shot parallel to 4) is also showing clear channel-like structure. Velocity in the color bar is in kilometer per second, and depth is in meter

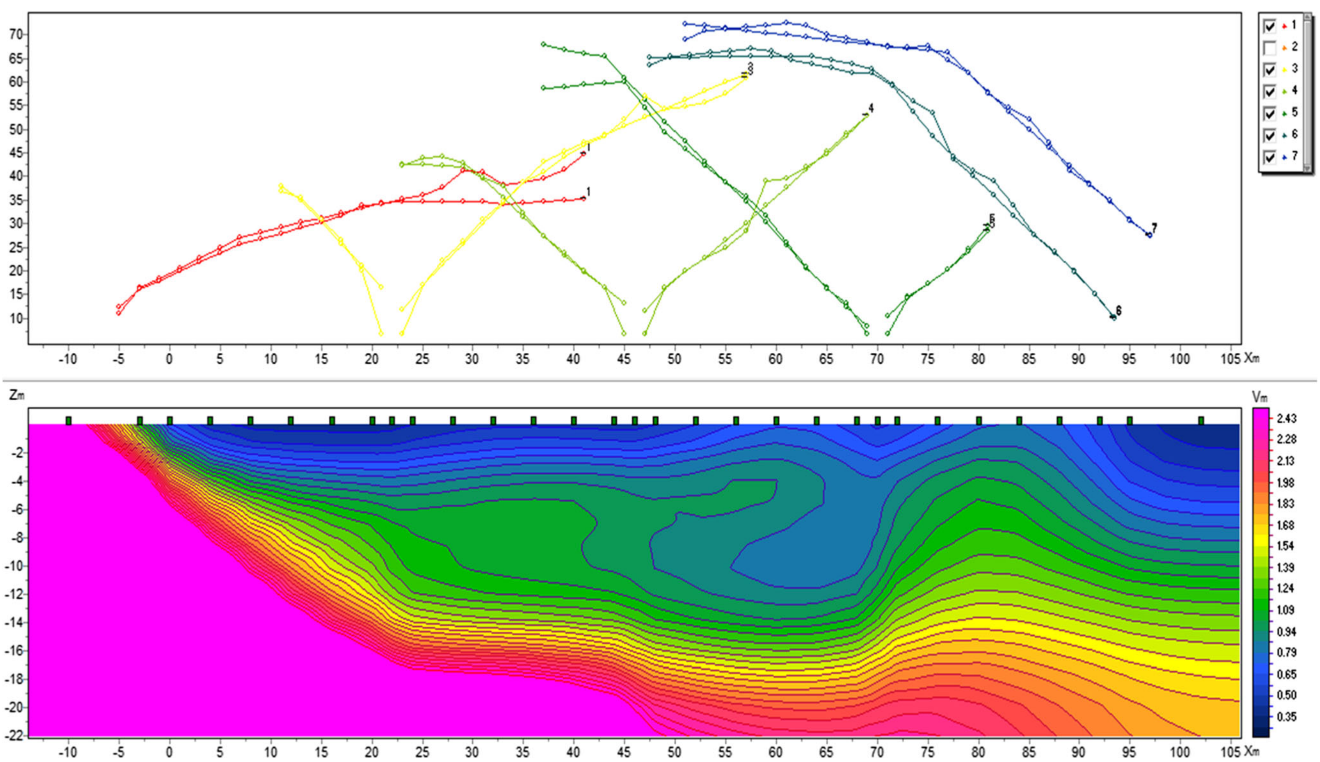

Fig. 8 Profile 6 showing that the bedrock is exposed on surface. This was used as a calibration point. Velocity in the color bar is in kilometer per second, and depth is in meter

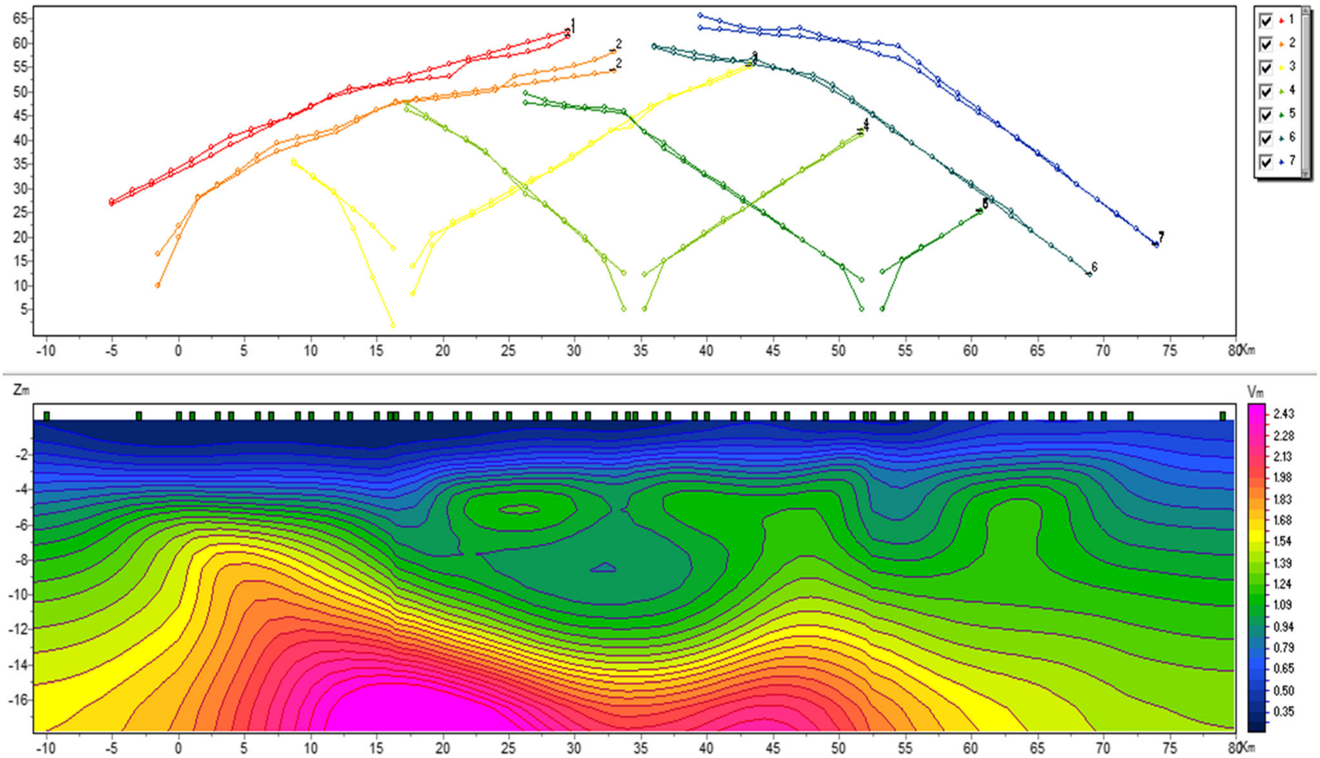

Fig. 9 Profile 07 showing different topographic features as it is crossing the wadi. Velocity in the color bar is in kilometer per second, and depth is in meter

concrete bases to establish a transmission tower in the area (Fig. 11). The concrete foundations occupied an area of 25 m^2 area and extend below the surface to a depth of 5 to 6 m. These foundations have contributed to fill the area with sediments transported with the wadi's flowing water. This has resulted in the loss of considerable space for water accumulation and storage that used to charge the well.

Note that after establishing the towers, although the wadi did not cease flowing in every raining season, the well's charge and production have drastically declined and eventually run dry. Figure 12 shows the rainfall statistics for the years following the towers construction and before.

In 2007 a super cyclonic storm has hit the country and caused heavy rainfall and flooding in the area. However, the

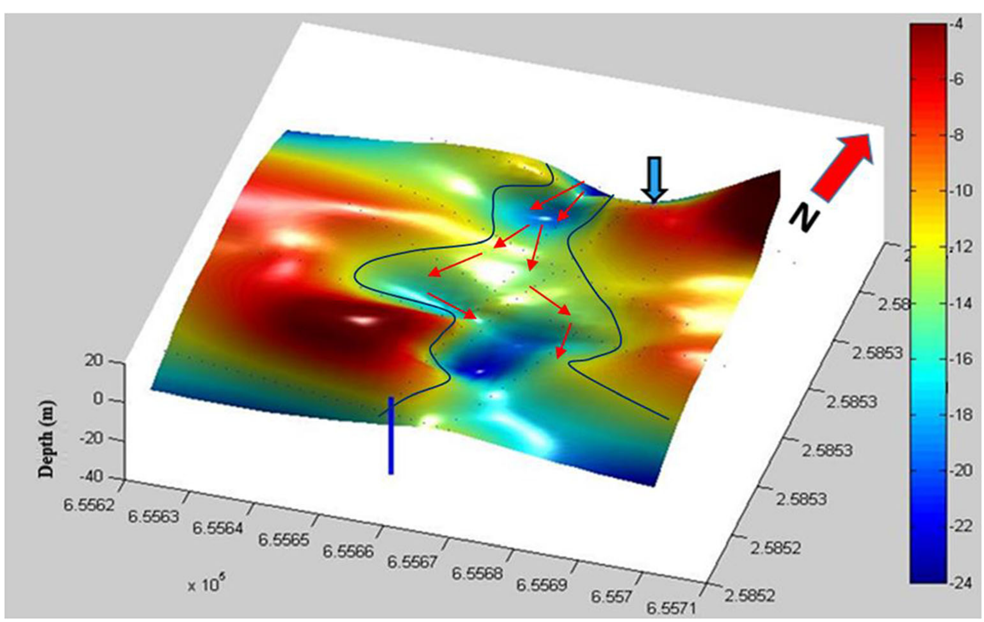

Fig. 10 3-D map view of the targeted bedrock topography. The arrow show the porous and permeable zone. The blue line shows the well location

Fig. 11 Photo showing the wadi flow after heavy rainfall (left). The photo on the right is a satellite image (taken on December 20, 2013) showing the location of the well and the concrete foundations. The concrete basis has contributed to fill the depressed area, where water accumulates and stay for long time, with sediments transported with the flowing water

well remained dry except from the water that accumulated during the storm. This has confirmed that the system of ground-water storage and flow charging the well imaged in this study has deteriorated.

Conclusion

Seismic refraction tomography has been applied to map the topography of consolidated rock and overlying rocks in Al-Amerat, Sultanate of Oman. These rocks have formed a geological setting that was responsible for accumulation, migration, and storage of ground water in the area. The velocity models from tomography inversion revealed that consolidated rock was characterized by high velocity and variation in topography. The overlying formations have shown low-velocity trend that was observed in different lines and interpreted to be porous like-channel structure that might be responsible for the water passage to its destination. The 3-D map obtained from the velocity sections calibrated with the exposed formations has provided more support for our interpretation. The latter map has given explanation for a water-producing well in the area that has run dry.

The study demonstrates the usefulness of seismic refraction tomography, supported with information from hydrology and geology in solving problems related to near-surface formations controlling ground-water storage and production.

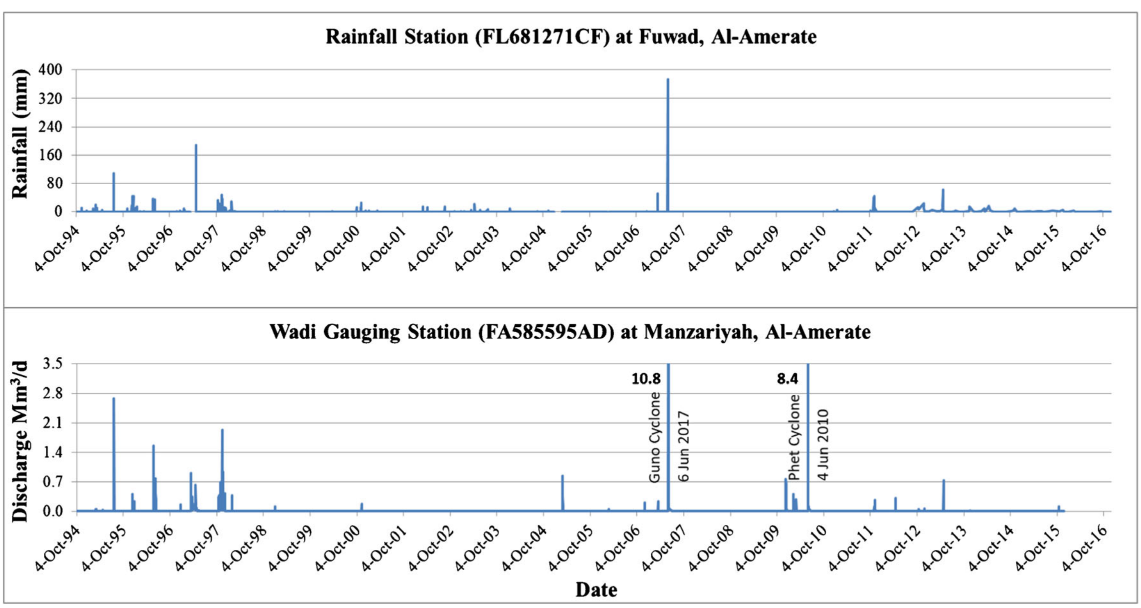

Fig. 12 Rain fall information recorded by gauging stations located along Wadi Al-Mayh to the east of the study area

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