JOURNAL OF SEISMIC EXPLORATION **18**, 329-000 (2009)

SEISMIC INVESTIGATION OF TWO COASTAL SABKHAS, EASTERN SAUDI ARABIA

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(Received March 24, 2009; revised version accepted June 17, 2009)

ABSTRACT

Al-Shuhail, A.A. and Al-Shaibani, A.M., 2009. Seismic investigation of two coastal sabkhas, eastern Saudi Arabia. *Journal of Seismic Exploration*, 18: 329-345.

Sabkhas are common topographic features in eastern Saudi Arabia. Characterization of sabkha stratigraphy and structure is of both geological and economic significance due to their importance for oil exploration, as well as their influence on urban development. In this study, we use seismic refraction methods to determine velocities and thicknesses of the uppermost layers in two coastal sabkhas in eastern Saudi Arabia, namely the Al-Aziziyah and Ar-Riyas sabkhas.

Our data were acquired using a standard reversed-refraction profile with five shots distributed across the profile and 24 vertical 14-Hz receivers spaced at 5 m. Data processing included amplitude gain, band-pass filtering, and manual picking of first arrivals. Interpretation of the data from Al-Aziziyah sabkha shows three main layers: a dry sandy layer having an average velocity of 300 m/s with a variable thickness between 0.1 and 1.0 m, a wet sandy layer having an average velocity of 1775 m/s with a relatively uniform thickness of 60 m, and bedrock with an average velocity of 2850 m/s. Data from Ar-Riyas sabkha also shows three main layers: a dry sand-mud layer having an average velocity of 300 m/s with a variable thickness between 0.2 and 0.9 m, a wet sand-mud layer having an average velocity of 2150 m/s with a relatively uniform thickness of 60 m, and bedrock with an average velocity of 3550 m/s.

Although the two studied sabkhas are about 80 km apart and are of different ages, they have relatively similar stratigraphic columns, seismic velocities, and thicknesses, suggesting a similar geological origin and history. Knowledge of this stratigraphic similarity is helpful in planning seismic surveys in sabkhas, but more study is needed before results from this study should be generalized and applied to other sabkhas elsewhere in the world.

KEYWORDS: coastal sabkhas, seismic refraction, eastern Saudi Arabia, Al-Aziziyah sabkha, Ar-Riyas sabkha.

0963-0651/09/$5.00

INTRODUCTION

Sabkha is an Arabic word for salt flat, an equilibrium geomorphic surface whose level is dictated by the local water table. Coastal sabkhas are common topographic features of eastern Saudi Arabia and cover about 30% of both developed and undeveloped lands; they also cover extensive areas along the Red Sea. Inland sabkhas are also important, occupying about 30% of the surface area. Sabkhas were first documented in the Arabian Gulf by Curtis et al. (1963) and were subsequently described along the coast of Baja California, Mexico (Phleger, 1969; Shearman, 1970), the coast of Sinai (Gavish, 1974) and many other areas of the world. Fig. 1 is a map showing the distribution of sabkhas in the Arabian Peninsula.

Several hypotheses have been published on the origin and evolution of solutes in sabkhas (Yechieli and Wood, 2003; Warren, 2006). The latest of these hypotheses is the "ascending-brine model" proposed by Wood et al. (2002) which contrasts significantly with both the "seawater flooding" model (Kinsman, 1969; Butler, 1969; Butler et al., 1973; Patterson and Kinsman, 1977, 1981) and "evaporative pumping model" (Hsü and Siegenthaler, 1969; Hsü and Schneider, 1973; McKenzie et al., 1980) previously proposed to explain the source of the solutes in the coastal plains of Abu Dhabi, United Arab Emirates. More on the ascending brine model can be found in a series of publications that have significantly changed the views on the role of groundwater and sea water in the sabkha environment (Wood and Sanford, 2002; Wood et al., 2002; Yechieli and Wood, 2002; Wood et al., 2005; Eckardt et al., 2005; Tyler et al., 2006; Wood and Sanford, 2007). The main methodology behind the latest model is the calculation of water and solute fluxes that depend on isotopic, hydraulic, and chemical analyses. Estimation of water table below the ground surface and depth to the bedrock (which defines the bottom of the sabkha) play a major role in the calculation of solute and water fluxes.

Sabkha brines can be of economic potential due to their high concentrations of magnesium, potassium and other elements (Sabtan et al., 1997; Sanford and Wood, 2001; Wood et al., 2002; Wood et al., 2005). Any study that tries to characterize sabkhas and their mineral content will first need to determine the location of the water table and the depth to bedrock. Determination of both the water table and bedrock beneath the sabkha is also of major significance to land-use management, and understanding the hydrodynamics and stratigraphy of sabkhas. Geophysical methods are commonly used to characterize the shallow subsurface of sabkhas (e.g., Abbas et al., 2004; Van Dam et al., 2008). In this study, we use the seismic refraction method to delineate the water table and bedrock depths in two coastal sabkhas located in the eastern province of Saudi Arabia.

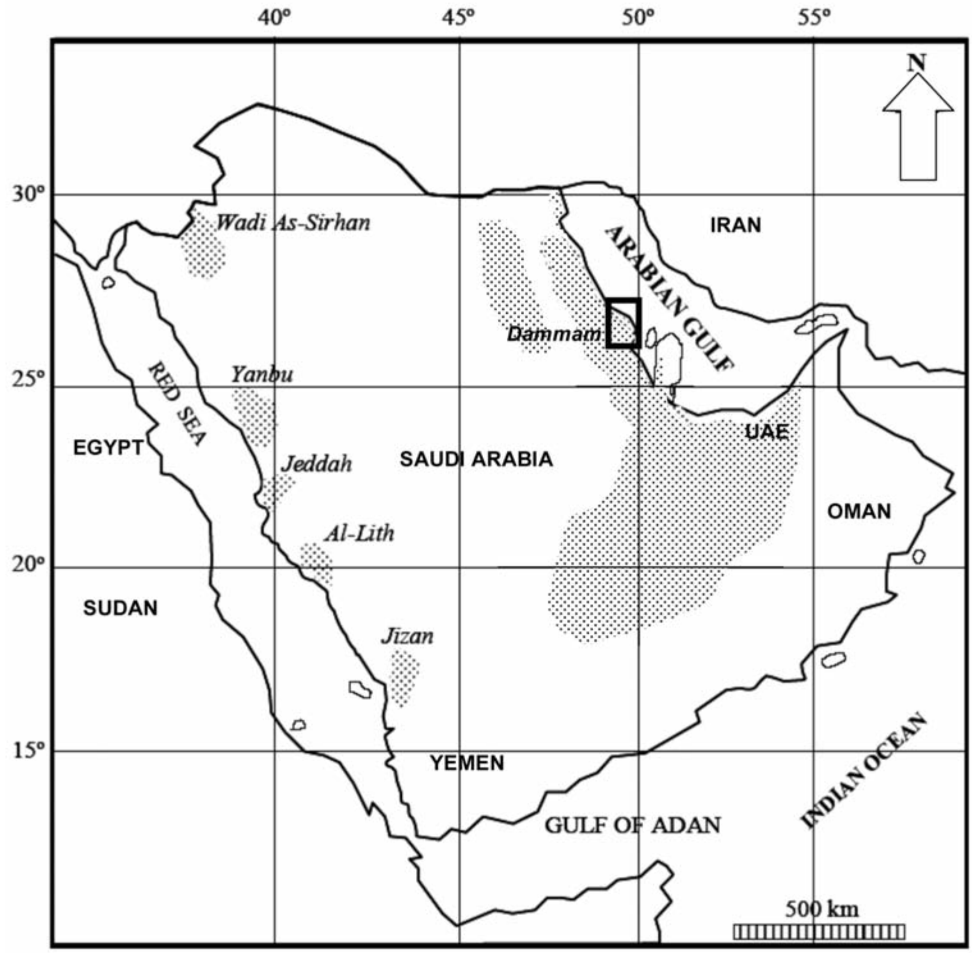

Fig. 1. Occurrence of Sabkhas in the Arabian Peninsula (modified from Al-Amoudi et al., 1992). The rectangle on the shoreline of the Arabian Gulf indicates the study area.

DATA ACQUISITION, PROCESSING AND INTERPRETATION

The profiles in this study consisted of 24 vertical 14-Hz receivers spaced at 5 m intervals. Five points were shot along each profile: a forward long shot (FL) at a distance of 5 m from the first receiver, a forward short shot (FS) at the first receiver (offset 0.5 m perpendicular to the profile), a center shot (C) at profile center, a backward short shot (BS) at the last receiver (offset 0.5 m perpendicular to the profile), and a backward long shot (BL) 5 m beyond the last receiver (Fig. 2). The receivers were buried just below the ground surface

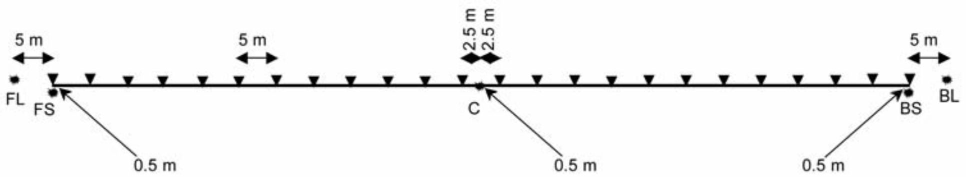

Fig. 2. Schematic image of the geometry of seismic profiles used in this study.

to minimize wind and cultural noise. The source was a 10-kg hammer striking a 10×10×2.5 cm steel plate. Each shot record is a stack of 6 hammer hits to increase the S/N ratio of the data. The record length was 0.5 s with a sampling interval of 0.5 milliseconds (ms). In addition, boreholes were dug at the ends of each profile to compare the depth to water table calculated by seismic refraction analysis with the true depth to water table in these boreholes.

Data processing included the following steps:

1. Automatic gain control (AGC) with a window length of 0.1 s was used to enhance amplitudes in the deeper parts of the section.

2. A 30-40-275-300 Hz band-pass filter was used to filter out undesired very-low and very-high noise.

3. Direct and head-wave arrival times were manually picked at each receiver location. These picks were used to calculate layer velocities and thicknesses. It should be noted here that it was not possible to pick these arrivals at every receiver location of every profile. In cases where it was not possible to pick arrivals, we resorted to linear interpolation and/or extrapolation of missing picks. Fig. 3 shows (A) a raw shot record; (B) the shot record after AGC; and (C) the shot record after AGC and filtering.

In the two study sites, the ground surface was flat across the profiles such that no topographic correction was required.

We used the delay-time seismic refraction method to interpret our data (Sheriff and Geldart, 1995; Milsom, 2003). This method uses the bedrock-refraction traveltimes picked at every receiver location from all sources along the profile. It also uses the reciprocal time (i.e., total traveltime from source to source), which can be extrapolated from the traveltime at one source to the furthest receiver. The refraction profiles were analyzed to calculate the following parameters at each receiver location:

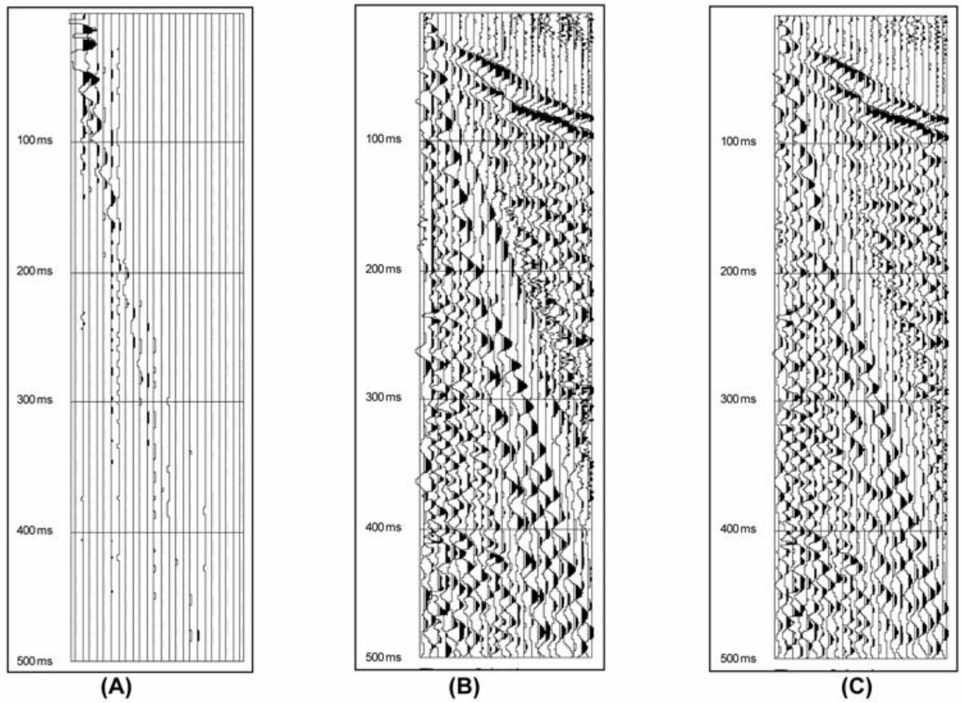

Fig. 3. (A) Raw shot record; (B) record after AGC (C) record after AGC and filtering.

A. Velocity (V_1) and thickness (H_1) of the uppermost layer.

B. Velocity (V_2) and thickness (H_2) of the second layer.

C. Velocity (V_3) and depth ($Z_3 = H_1 + H_2$) of the bedrock.

RESULTS

Fig. 4 shows a simplified map of Saudi Arabia with the study sites indicated. Two sites were selected: one in the siliciclastic Al-Aziziyah coastal sabkha and the other in the carbonate-dominated Ar-Riyas coastal sabkha. The objective of this selection is to compare the subsurface structure of these seemingly very different costal sabkhas.

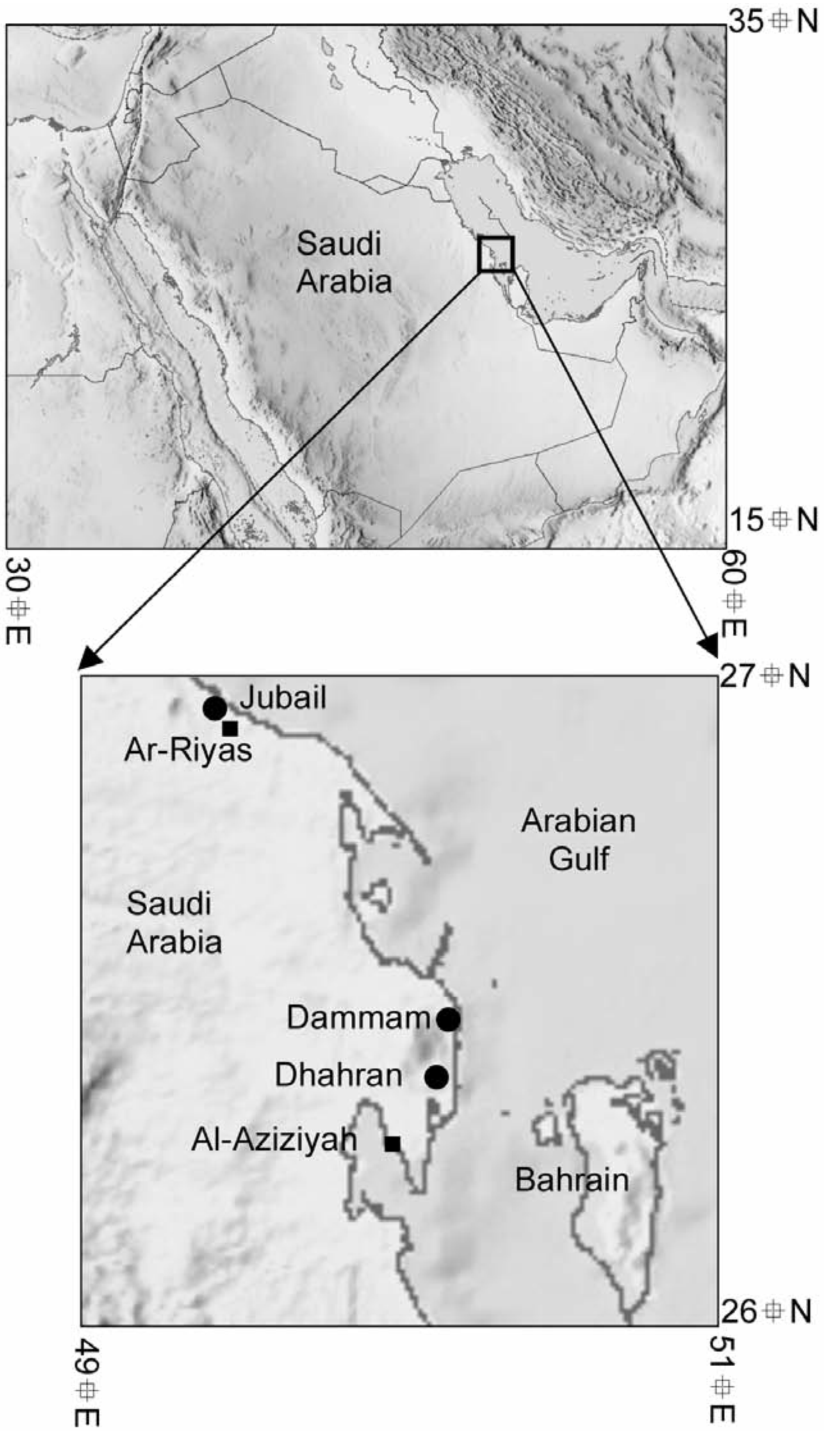

Fig. 4: Map of Saudi Arabia with inset showing study sites.

Al-Aziziyah sabkha

This study site is located in the Half-Moon Bay area of Al-Aziziyah coastal sabkha in eastern Saudi Arabia. The sabkha surface is flat and featureless and dominantly covered by unconsolidated quartzose sand, although in some places it is encrusted by a thin veneer (up to 2 cm thick) of halite. Other evaporitic and diagenetic minerals present include calcite, aragonite, dolomite, gypsum, and anhydrite. Only a few kilometers south of the study site, thick halite deposits (up to 3 meters thick) locally occur in coastal sabkhas. Sabkhas of this area to the south of Dammam are characterized by a siliciclastic matrix, while sabkhas of the Jubail area are much more carbonate-dominated.

The seismic profile was laid along a line that was almost perpendicular to the shoreline with the profile center at a distance of about 300 m from the shoreline. Fig. 5 shows the vertical profile of the soil at this site, which consisted of a homogeneous dry sandy soil underlain by a water-saturated sandy

Fig. 5. Photo showing the soil vertical profile at the FS shot location of Al-Aziziyah site.

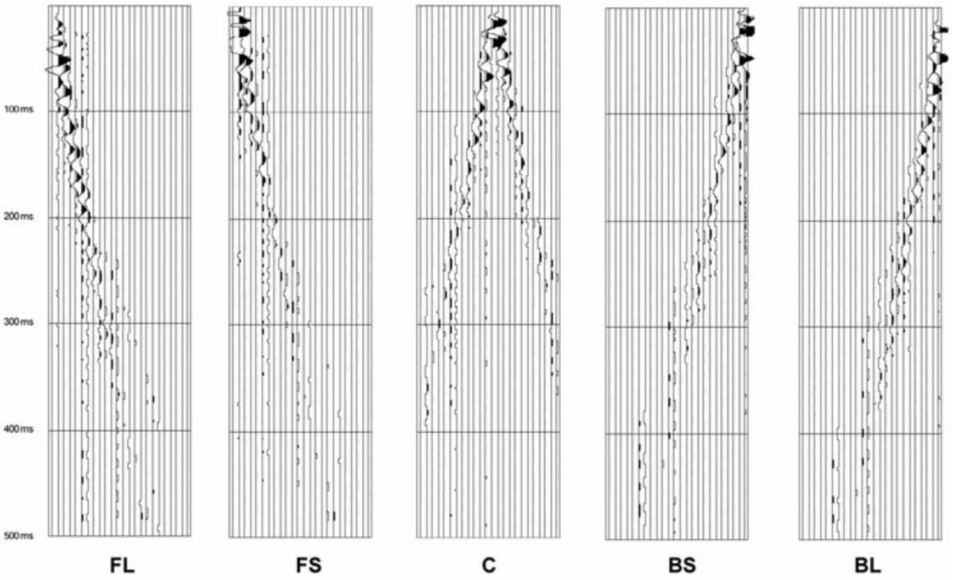

Fig. 6(A). Raw shot records in the Al-Aziziyah site.

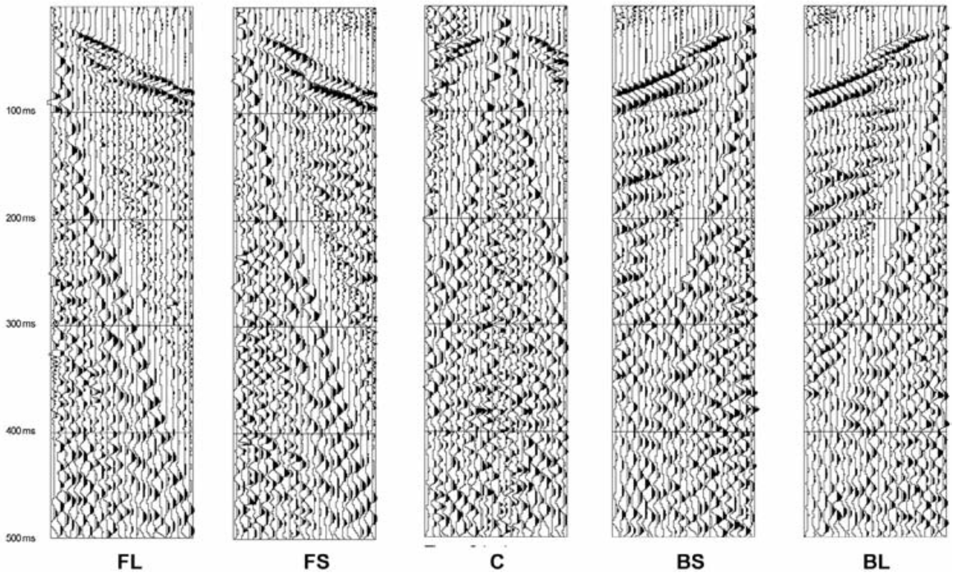

Fig. 6(B). Processed shot records in the Al-Aziziyah site.

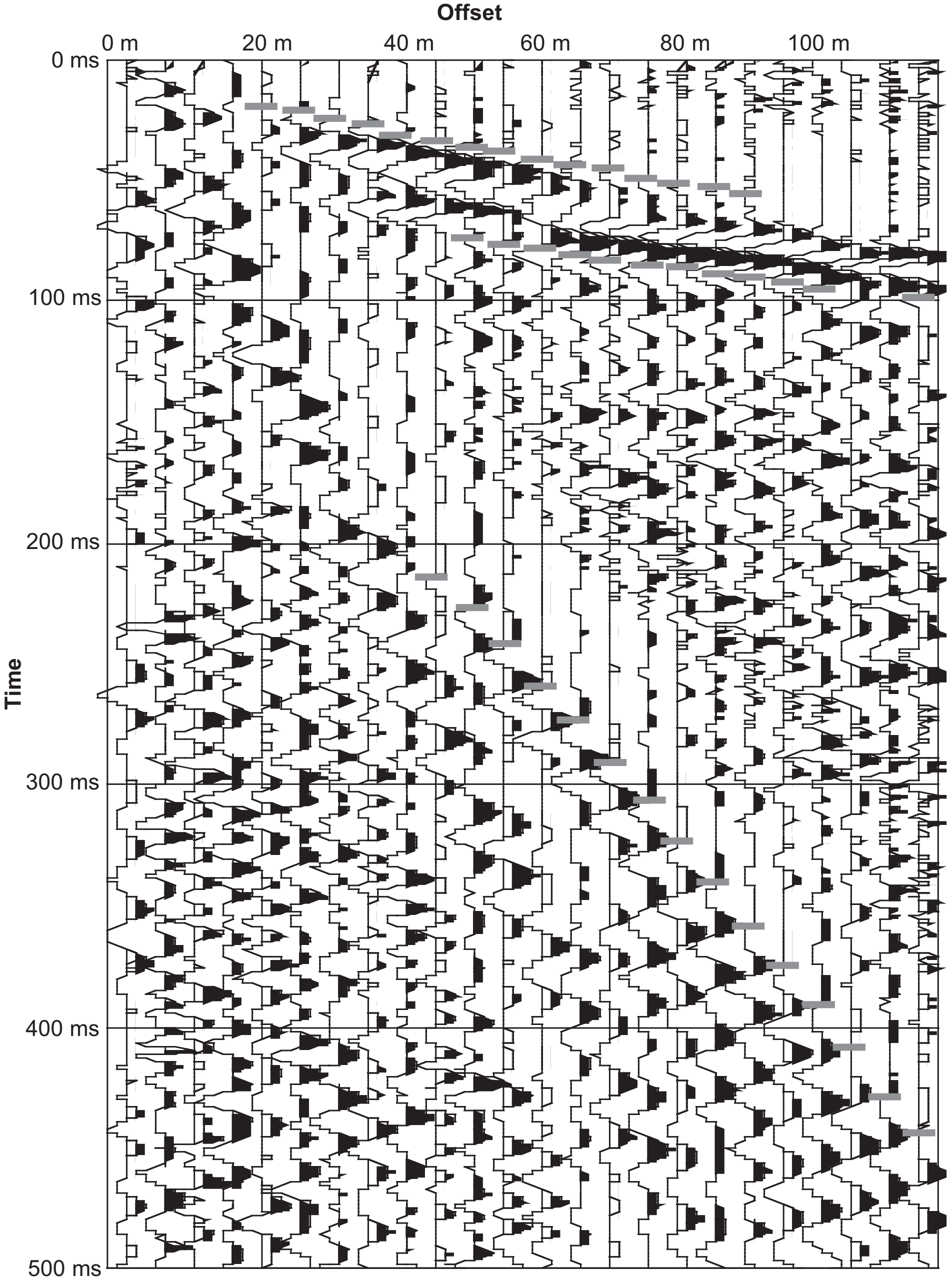

Fig. 6(C). Processed FS shot record in the Al-Aziziyah site showing picked direct (lowermost gray lines), first head-wave (uppermost gray lines), and second head-wave (middle gray lines) arrivals.

soil. The seismic signal (direct and head P-waves) in this data set had a dominant frequency of 75-90 Hz. Fig. 6 shows (A) the raw profiles, (B) the processed profiles, and (C) the FS profile with the picks posted. The picked events are interpreted as: the direct wave in the dry layer (lowermost gray lines), the head wave from the saturated layer (uppermost gray lines), and the head wave from the bedrock (middle gray lines). Using the delay-time method to analyze the time-distance (T-X) picks, we calculated the following velocities:

* $V_1 = 300$ m/s

* $V_2 = 1775$ m/s

* $V_3 = 2850$ m/s

Fig. 7 shows the estimated depth to the water table and the bedrock across this profile. To verify our depth estimate, we compare our estimated depth to the water table using the seismic data (66 cm) with that observed in the shallow borehole (71 cm) dug near the location of the first receiver (Fig. 5). The error in estimating the depth to the water table is approximately 8%. This agreement indicates the good accuracy of our interpretation. Although we do not have access to information on the bedrock depth in this area, we suggest that our estimate of the depth to bedrock would have a similar accuracy. The estimated direct-arrival velocity ($V_1 = 300$ m/s) falls within the range of typical P-wave

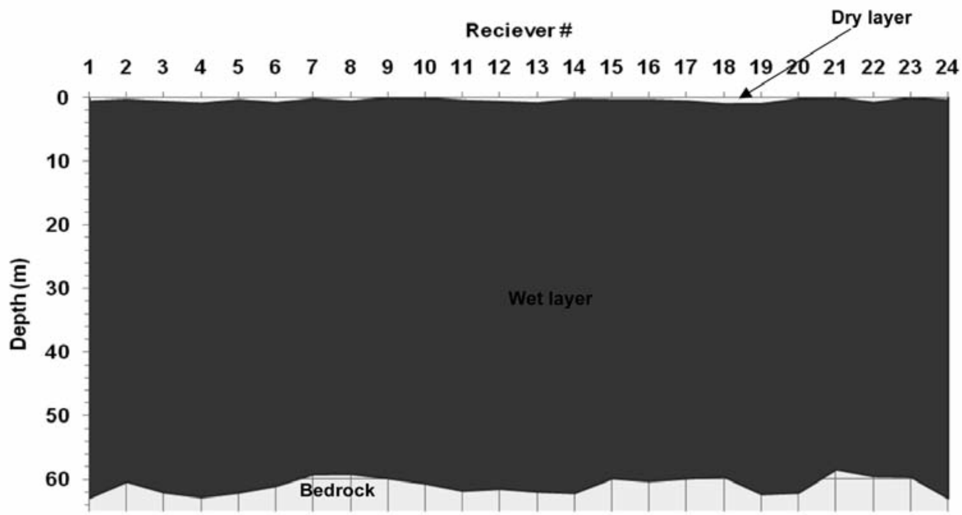

Fig. 7. Vertical profile of the Al-Aziziyah site showing the dry layer (very thin light gray layer at top of profile) and wet layer (thick dark gray layer).

velocities in unconsolidated dry layers, the estimated velocity of the first head wave (V_2 = 1750 m/s) falls in the range of typical P-wave velocities in unconsolidated water-saturated layers (Bachrach, 1998; Al-Shuhail, 2002; Liner, 2008), while the estimated velocity of the second head wave (V_3 = 2850 m/s) indicates a highly weathered sedimentary bedrock at this site.

Ar-Riyas sabkha

This study site is located in the Ar-Riyas coastal sabkha near the industrial city Jubail. The seismic profile location is about 10 km to the west of the shoreline. Sediments of the Ar-Riyas sabkha are distinctly layered, with a 3-cm surface crust of fine-grained sand lightly cemented with halite and gypsum; thick halite crusts of up to 10 cm thickness occur locally. Sylvite (KCl) and epsomite ($MgSO_4.7H_2O$) were also identified at one location in this sabkha. Below the crust are alternating 5 to 10 cm-thick layers of poorly sorted fine- to medium-grained sand and gray mud, with the mud containing considerable amounts of calcite and dolomite. Gypsum and anhydrite were found both above and below the water table. Organic material, thought to be algal in nature, was found in a number of locations. Bedrock is believed to be either Hadrukh or Dam Formations (both are limestones of Upper Miocene age) and was not encountered in excavations of about 10 meters depth. Fig. 8 shows the vertical profile in a borehole dug near the first receiver of our profile in this sabkha.

The seismic profile at this site consisted of 24 vertical 14-Hz receivers that were laid along a line. The seismic signal (direct and head waves) in this data set had a dominant frequency of 100-115 Hz. Fig. 9 shows (A) the raw profiles, (B) the processed profiles, and (C) the FS profile with the picks posted. The picked events are interpreted as: the direct wave in the dry layer (lowermost gray lines), the head wave from the saturated layer (uppermost gray lines), and the head wave from the bedrock (middle gray lines).

Using the delay-time method to analyze the T-X picks, we calculate the following velocities:

- V_1 = 300 m/s
- V_2 = 2150 m/s
- V_3 = 3550 m/s

Fig. 10 shows the estimated depth to the water table and the bedrock across this profile. To verify our depth estimate, we compared our estimated depth to the water table using the seismic method (55 cm) with that observed in the shallow borehole (60 cm) dug near the location of the first receiver (Fig. 8).

The error in estimating the depth to the water table is about 8%. This agreement indicates the good accuracy of our interpretation. Previous work in this sabkha (Al-Amoudi, 1992) showed no bedrock within 15 m depth. Given this information and the good accuracy between the true and estimated depths to the water table, we predict that our estimate of the depth to bedrock (55 cm) has a similar accuracy. The estimated direct-arrival velocity (V_1 = 300 m/s) falls in the range of P-wave velocities in unconsolidated dry layers, the estimated velocity of the first head wave (V_2 = 2150 m/s) falls in the range of P-wave velocities in unconsolidated water-saturated layers (Mavko et al., 1998), while the estimated velocity of the second head wave (V_3 = 3550 m/s) could be that of a mildly weathered limestone bedrock at this site.

Fig. 8. Borehole at the first receiver of the seismic profile acquired in the Ar-Riyas sabkha.

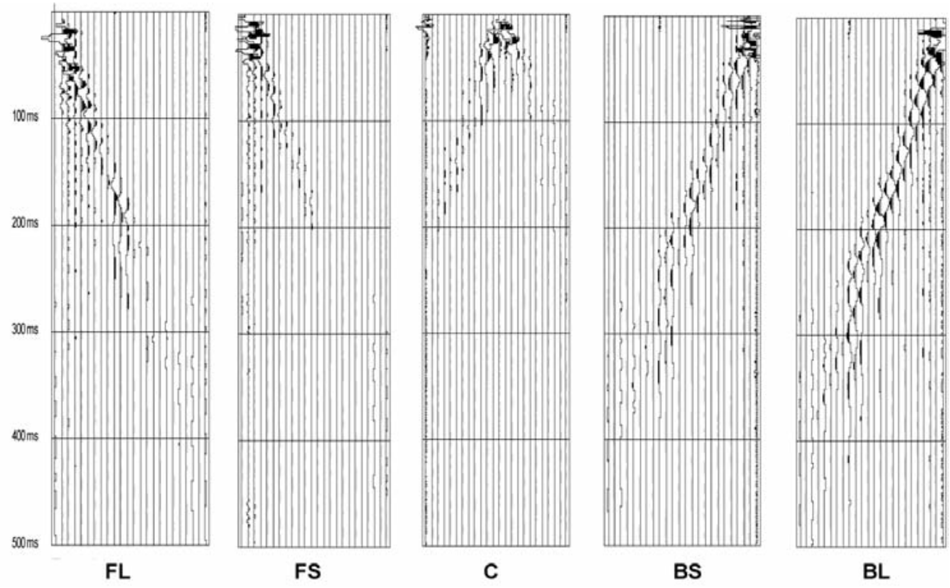

Fig. 9(A). Raw shot records in the Ar-Riyas sabkha.

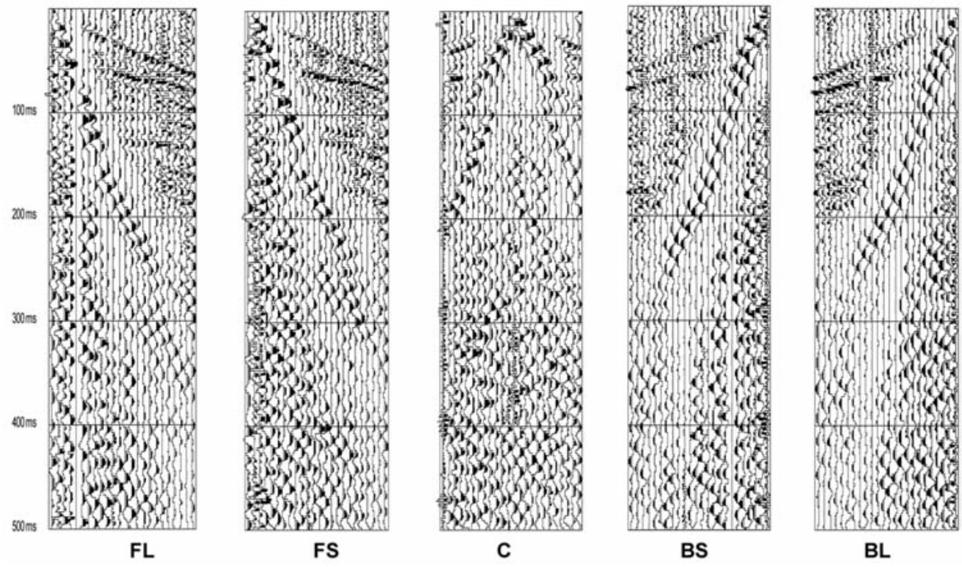

Fig. 9(B). Processed shot records in the Ar-Riyas sabkha.

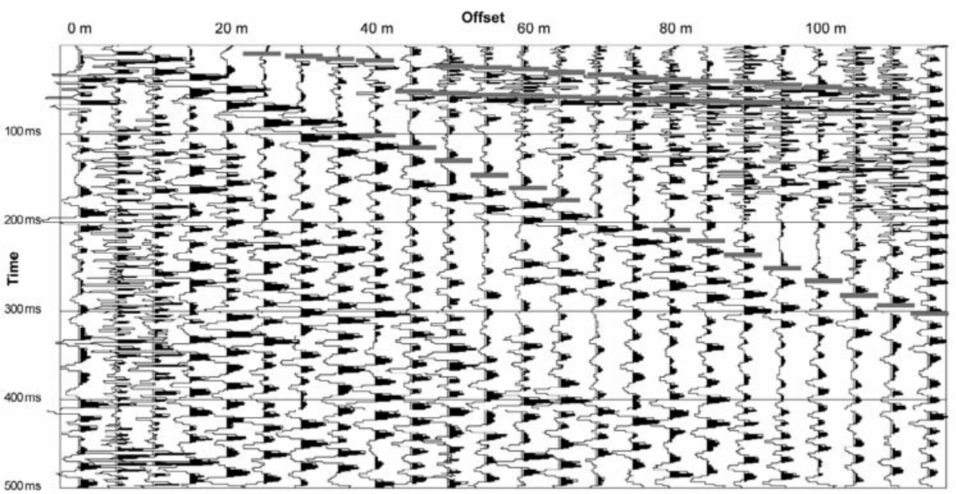

Fig. 9(C). Processed FS shot record in the Ar-Riyas sabkha showing picked direct (lowermost gray lines), first head-wave (uppermost gray lines), and second head-wave (middle gray lines) arrivals.

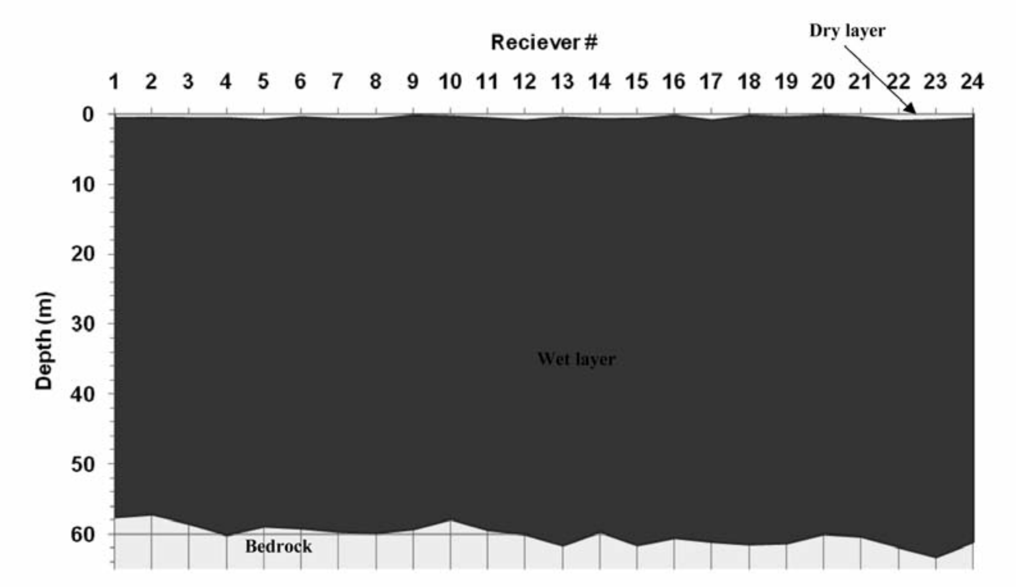

Fig. 10. Vertical profile of the Ar-Riyas site showing the dry layer (very thin light gray layer at top of profile) and wet layer (thick dark gray layer).

SUMMARY AND CONCLUSIONS

Characterization of sabkha stratigraphy and structures is of great significance for geological, engineering, and economical reasons. Of particular concern is the depth to the bedrock and to the water table - important in geological and geophysical studies. In this study, we use the seismic refraction method to estimate the velocities and thicknesses of the upper layers in the Al-Aziziyah and Ar-Riyas coastal sabkhas of eastern Saudi Arabia.

The seismic data in each sabkha consisted of a reversed-refraction profile with five shots distributed across the profile and 24 vertical 14-Hz geophones spaced at 5 m. The seismic energy source was a 10-kg sledgehammer hitting a steel plate, with each shot being the sum of 6 hits. The record length was 0.5s with a sampling interval of 0.5 ms. A shallow borehole that only penetrated the groundwater table was dug along each profile for verification of the seismic results. Data processing included: AGC with a window length of 0.1 s, a 30-40-275-300 Hz band-pass filter, and manual picking of the direct and head-wave arrivals at each receiver location. The delay time method was used to interpret the results.

The following three main layers were interpreted from the Al-Aziziyah sabkha data: a dry sandy layer having an average velocity of 300 m/s with thickness ranging between 0.1 and 1.0 m, a wet sandy layer having an average velocity of 1775 m/s with a relatively uniform thickness of 60 m, and bedrock with an average velocity of 2850 m/s. The Ar-Riyas sabkha also shows three main layers: a dry sand-mud layer having an average velocity of 300 m/s with thickness between 0.2 and 0.9 m, a wet sand-mud layer having an average velocity of 2150 m/s with a relatively uniform thickness of 60 m, and bedrock with an average velocity of 3550 m/s.

The thickness of the dry layer of each sabkha was compared to its thickness observed in boreholes. The agreement between the two was always within 8%. This good agreement increased the confidence in the wet-layer thickness estimates, although the boreholes did not penetrate to the bedrock. The fairly low velocity of 300 m/s in the dry layer agrees with modeled and observed velocities in dry sandy layers reported by Liner (2008) and others. The estimated velocities of the wet layers also agree with previous studies on similar layers (e.g., Bachrach, 1998). The bedrock velocities are typical of weathered sedimentary rocks.

Although the results of this study show good agreement with observed and reported results in similar environments, we recommend drilling of a borehole that penetrates the bedrock along each seismic profile. This will serve as a good benchmark for validating all of our results. We also recommend the use of at least two longer seismic profiles along perpendicular directions in order to better characterize the sabkhas.

ACKNOWLEDGEMENTS

We would like to thank King Fahd University of Petroleum and Minerals (KFUPM) for supporting this work. We also thank King Abdulaziz City for Science and Technology (KACST) for supporting this work under project number 26-83. We are thankful to Mohammad Aqel, Azizullah Khan, and Ademola Adetunji from KFUPM for their help during the acquisition and processing of the data.

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