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ORIGINAL PAPER

Magnetic and seismic refraction survey for site investigation of an urban expansion site in Abha District, Southwest Saudi Arabia

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Abstract Ground magnetic and seismic refraction survey is carried out on an urban extension site in the southwest of Ahud Rufeidah town, southwest Saudi Arabia. The purpose of the survey was to map the surface topography of the bedrock and thickness of the alluvium overburden. The ground magnetic survey based on an assumption that the alluvial sediments is less or non-magnetic relative to the underlying gneiss basement rock. In this context, a total of 3,750 survey stations were measured along 40 east–west survey profiles, striking roughly perpendicular to the extension of the expected structures. In addition, 13 seismic refraction spreads were conducted along four seismic survey profiles across the expected pathways of buried alluvial channels in order to provide additional details about the depth and boundaries of the buried channels. The ground magnetic survey results show the presence of a basin combining two sub-basins filled with alluvium sediments that occupy the middle area of the investigated site. This basin is a closed basin that has no outlet, and there are four small and narrow channels that convey water and sediments from the eastern and southern hills into sub-basins. These channels are represented by narrow and elongated low magnetic anomalies extending towards the basinal area. The thickness of the alluvial sediments is verified using seismic refraction survey that indicates a greater thickness, exceeds 20 m, of low velocity sedimentary overburden inside the interpreted sub-basins and surrounding buried alluvial channels. These soft alluvial sediments can be deceptive and dangerous for urban foundations.

Keywords Ground magnetic · Seismic refraction · Site investigation · Urban expansion

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Introduction

The site investigation is a necessary prerequisite step that should proceed any developmental project. Geophysical surveys have commonly effective tools in site investigation. These tools aid rapid and economic choice between a number of alternative sites for a proposed project and make a detailed site assessment at a chosen location. Furthermore, geophysical methods are used to determine the depth of bedrock and assess the variation in the thickness and nature of the overburden soil within the zone of the proposed project. Such information needs to be established for settlement analyses and assessment of subsidence risk. In all cases, geophysical tools are intended to supplement the direct methods, such as drilling and trenching; they are not substituting these methods. The number of borings that are required for adequate definition of subsurface conditions can be greatly reduced if the proper geophysical method is chosen to supplement the direct investigation program. In addition, the direct investigation is often limited by access, cost, and ground damage consideration, and if the spacing between the boreholes is too large, anomalous ground conditions may be missed (Dumbleton and West 1974). In this case, the surface geophysical tools enable such anomalous features to be mapped in detail at a relatively low cost (McDowell 1981) and consequently supplement the site investigation.

Recently, the Saudi Government has put a national strategy to develop new urban and industrial areas in order to solve the problem of population growth. New urban expansion projects are in the way to be executed in the investigated site. Therefore, this site should be studied thoroughly, and the subsurface geologic information must be available in the hands of the developmental planners before staring any urban activity.

Location

The survey was carried out on a site to the southeast of Ahud Rufeidah at the southern border of the city of Abha. The area locates between latitudes 18° 10′ 55″ N and 18° 11′ 41″ N and longitudes 42° 51′ 45″ E and 42° 52′ 20″ E, as shown in (Fig. 1). This site is chosen for geophysical investigation because it represents an urban expansion for the town of Ahud Rufeidah.

Geological setting

The study area lies on the southwest of the Asir Mountains, where surface dips gently northeastward away from the Red Sea escarpment. The basement rocks exposed in the study area represent the deepest erosional level of the Arabian Shield. These basement rocks are divided into two distinct units: Khamis Mushayt Gneiss and pegmatites. Khamis Mushayt Gneiss represents the main basement unit in the area and is composed of banded orthogneiss, migmatite with minor amphibolite, and paragniess. This unit is invaded by numerous pegmatite and aplite dikes and because its resistance to erosion has produced an erosional surface characteristic of the basement. The pegmatite unit is composed of quartz, orthoclase, plagioclase, and biotite. These two basement units are covered in some localities with heterogeneous and spatially variable alluvial sediments that are composed of pebbles, gravels, sands, and clays.

Geomorphologically, the studied site is located within Wadi Al-Rubah downstream plain area that is delimited on the southern and western sides by uplands that rise above the level of the valley to varying heights (Fig. 2). As many cases in the desert drainage systems, Wadi Al-Rubah has no external outlet and forms a gently sloping plain in its downstream area. The alluvium sediments have been transported to this downstream plain area by running water from the upstream and surrounding weathered gneiss uphills through incised network of narrow and active channels (Fig. 2). The presence of such small and narrow channels could be referred to the underlying weathered and easily eroded gneiss basement rocks and

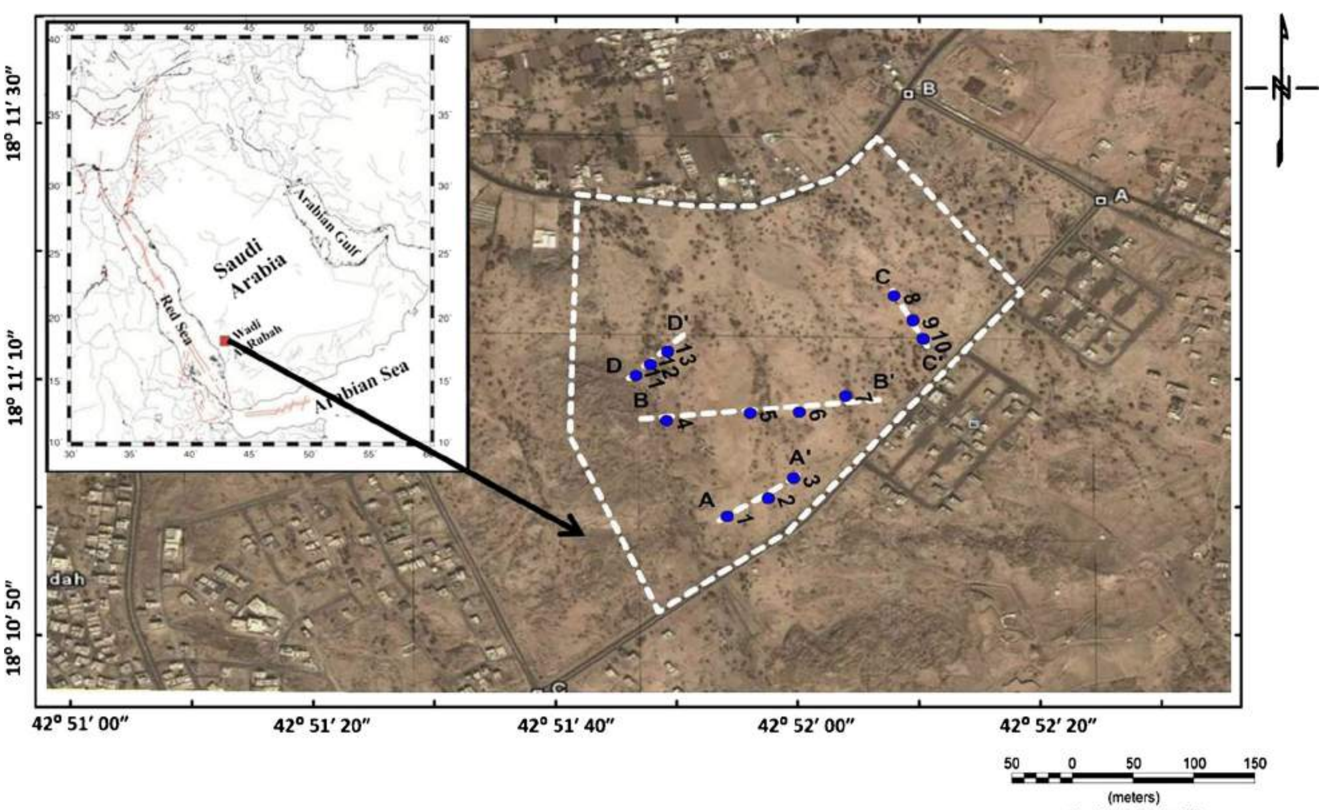

Fig. 1 Location map of the investigated site. *Blue dots* show the location of seismic spreads and the *white-dashed lines* represent the extension of seismic profiles

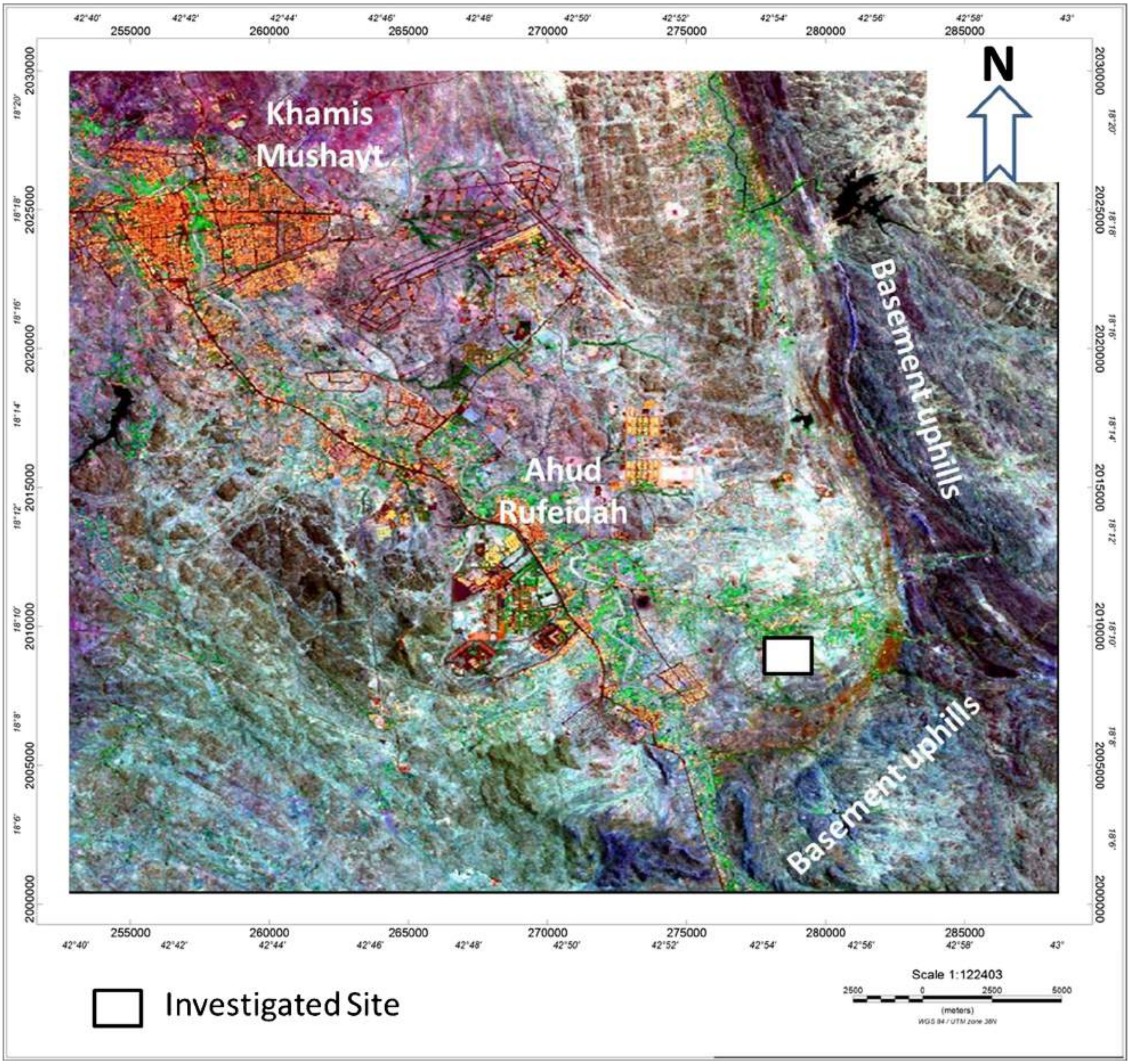

Fig. 2 Satellite image of Ahud Rufeidah area with the location of the investigated site and surrounding physiographic features

consequently increase in the channel depth and velocity. Structurally, left-lateral strike-slip fault, right-lateral strike-slip fault, joints, asymmetric anticline folds, similar folds, dikes, veins, and venlets structurally characterize the area. Tertiary normal faulting related to the development of the Red Sea depression is the latest structural events recorded (Coleman and Brown 1971).

Methods of study

Geophysical methods have been widely used in environmental and geotechnical studies for decades, and they are used with increasing frequency in many parts of the world as rapid, non-invasive survey techniques. The use of geophysical methods for investigating a site has the possibility to give an image of the subsurface to the geologists and geotechnical engineers (Benson et al. 1984; Goldstein 1994; Reynolds 1997; Benson and Yuhr 2002). In this respect, ground magnetic imaging has also been used in many studies in site investigation for civil engineering, particularly when used in conjunction with other geophysical tool such as seismic refraction technique. These tools are applied in investigating the shallow subsurface conditions in sites such as roads, tunnels, dams, quarries, hydroelectric power plants,

subways, nuclear power plants, bridges, and many other purposes (Sjogren and Sandberg 1979; Dutta 1984; Kilty et al. 1986; Hatherly and Neville 1986). In order to achieve the purpose of the present study, ground magnetic and shallow seismic refraction surveys have been conducted.

Magnetic method

Magnetic method is based on the measurement of local variations in the Earth's magnetic field. Such variations are associated with differences in magnetic susceptibility (the degree to which a body is magnetized) of rocks and soils. This method is a branch of geophysics that studies how the properties of the Earth's magnetic field change in different places on the Earth (Blakely 1995) and use these variations to predict structures, e.g., near-surface faults and contacts and delineate lateral distribution of the basement bedrock (i.e., Al-Garni 2004, 2005; Al-Garni et al. 2005; Reynolds 1997), and consequently the thickness range of sedimentary overburden.

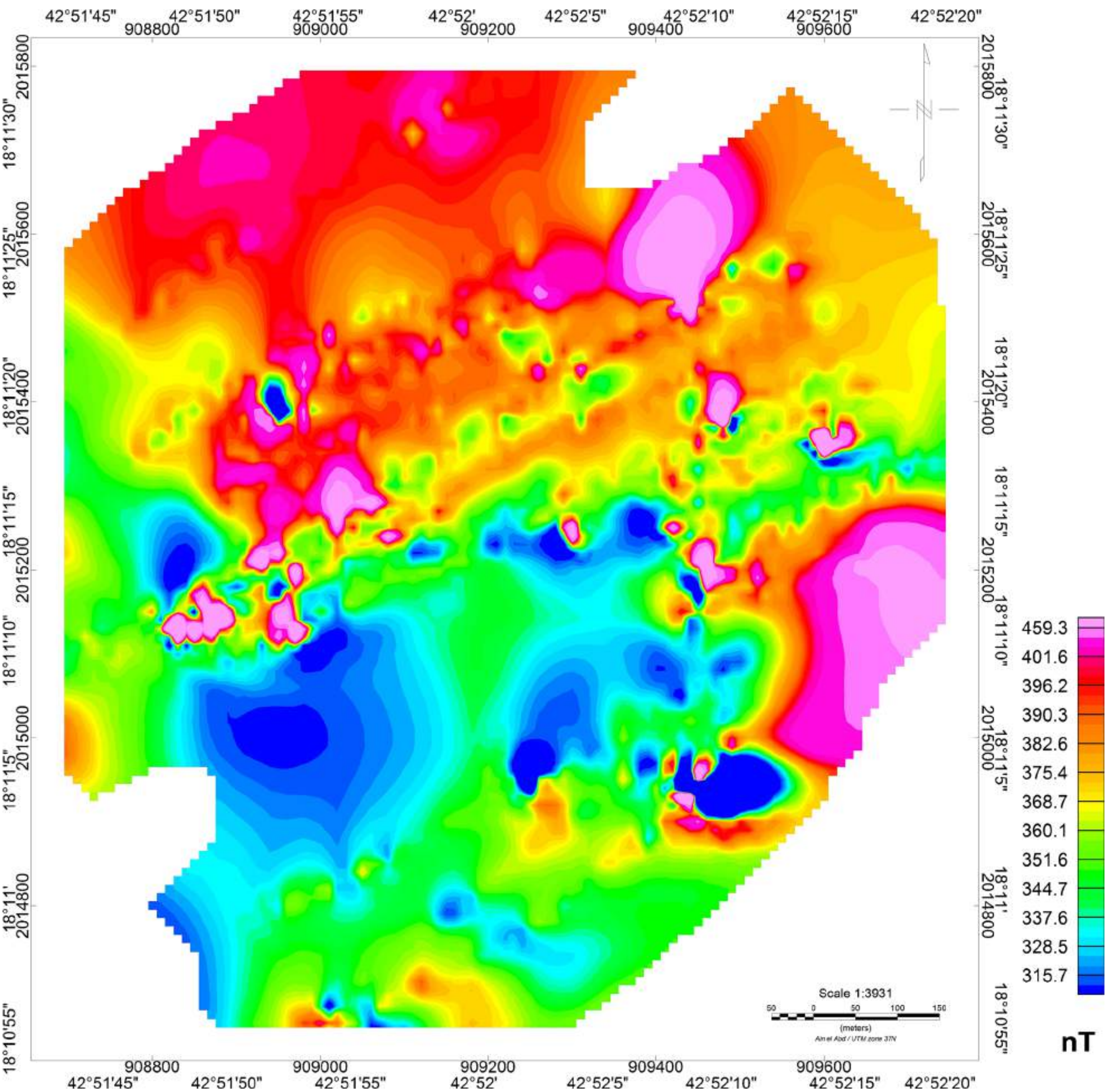

Fig. 3 Reduced to the Pole (RTP) magnetic anomaly map

The present investigated site consists of a thick cover of alluvial sediments that overlie the gneiss basement rocks. The assumption is that the overburden alluvial sediment is more or less non-magnetic whereas the host gneiss rock carries some magnetization. This is because the magnetic susceptibility of the alluvial sediments can safely be assumed very low, and gneiss commonly carries small amounts of magnetite and dark minerals. Therefore, the gneiss basement rocks are more magnetic than the overlying alluvial sediments. This contrast in the magnetization between the gneiss basement rocks and overlying sedimentary cover increases the expectation of the success of magnetic survey in the study area.

Seismic refraction method

The seismic refraction technique utilizes acoustic waves generated by an impact or small explosive source to measure depths of bedrock or overburden layers of sedimentary rock and to infer bedrock faults or fracture zones. The rays are refracted across layer boundaries where there is a difference in elastics and density properties. Detectors layout at regular intervals measure the first arrival of the energy and its time. Field layout of refraction survey should be designed according to the site situation and required depth and resolution of

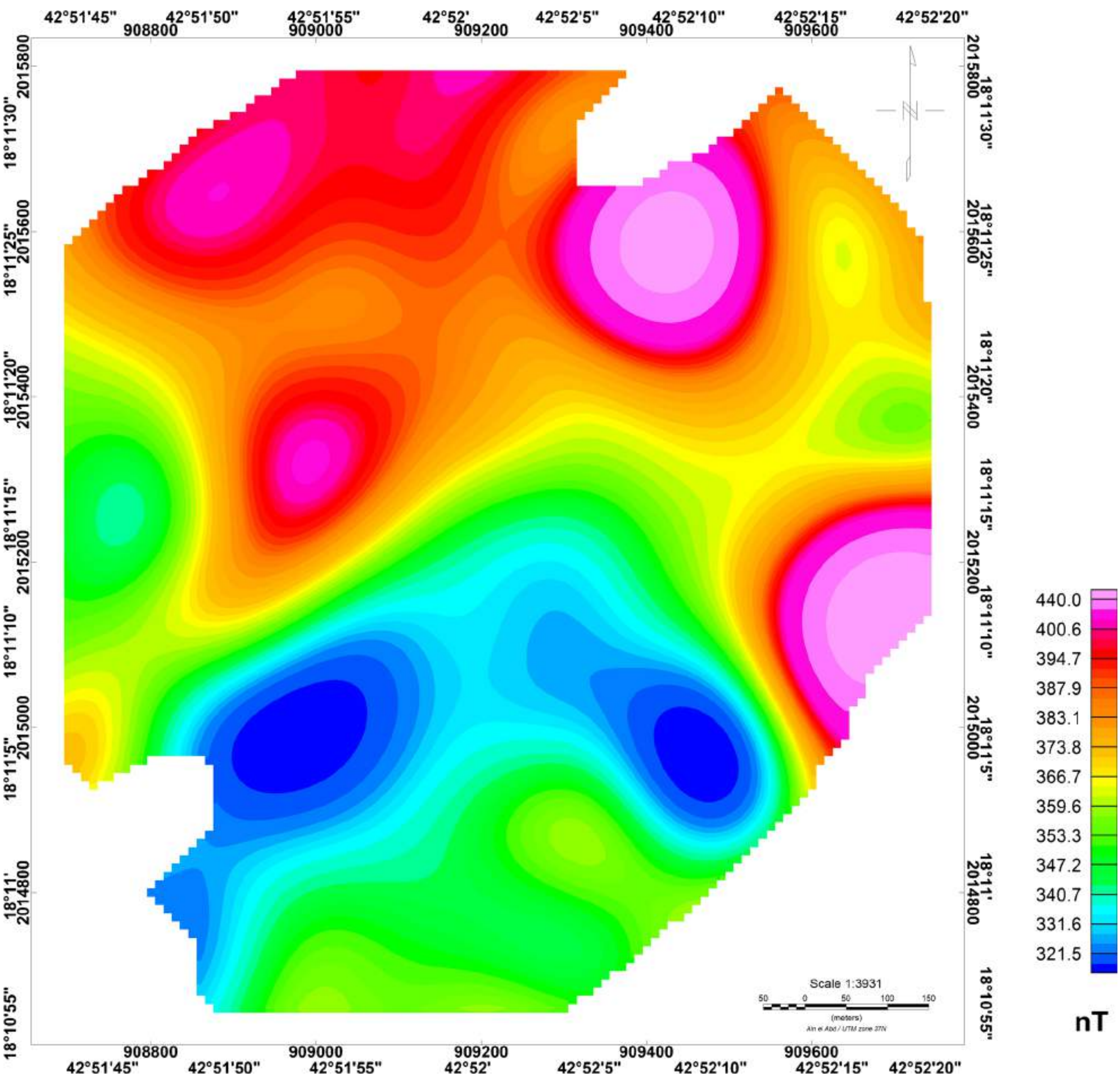

Fig. 4 Regional magnetic anomaly map

subsurface investigation. The data are plotted in time–distance graphs to identify individual layers and to compute layer thicknesses and seismic velocities. Specific geologic conditions, such as bedrock fractures or valleys, may be interpreted directly from these time–distance plots or by using several seismic modeling techniques. Foreknowledge of site conditions and understanding of its geological situation always assist in data interpretation. This technique has been used in geotechnical investigations, for example, in foundation studies, site investigation, fault investigations, dam safety analyses, and tunnel alignment studies.

Data acquisition

Brief accounts of the conducted data acquisition during the field survey using the employed survey methods are discussed as follows.

Magnetic data acquisition

The survey was carried out with two proton magnetometers, one of which was used as a diurnal base station magnetometer where the surveyor for the field survey held the other. The survey was carried out in an approximate regular grid with

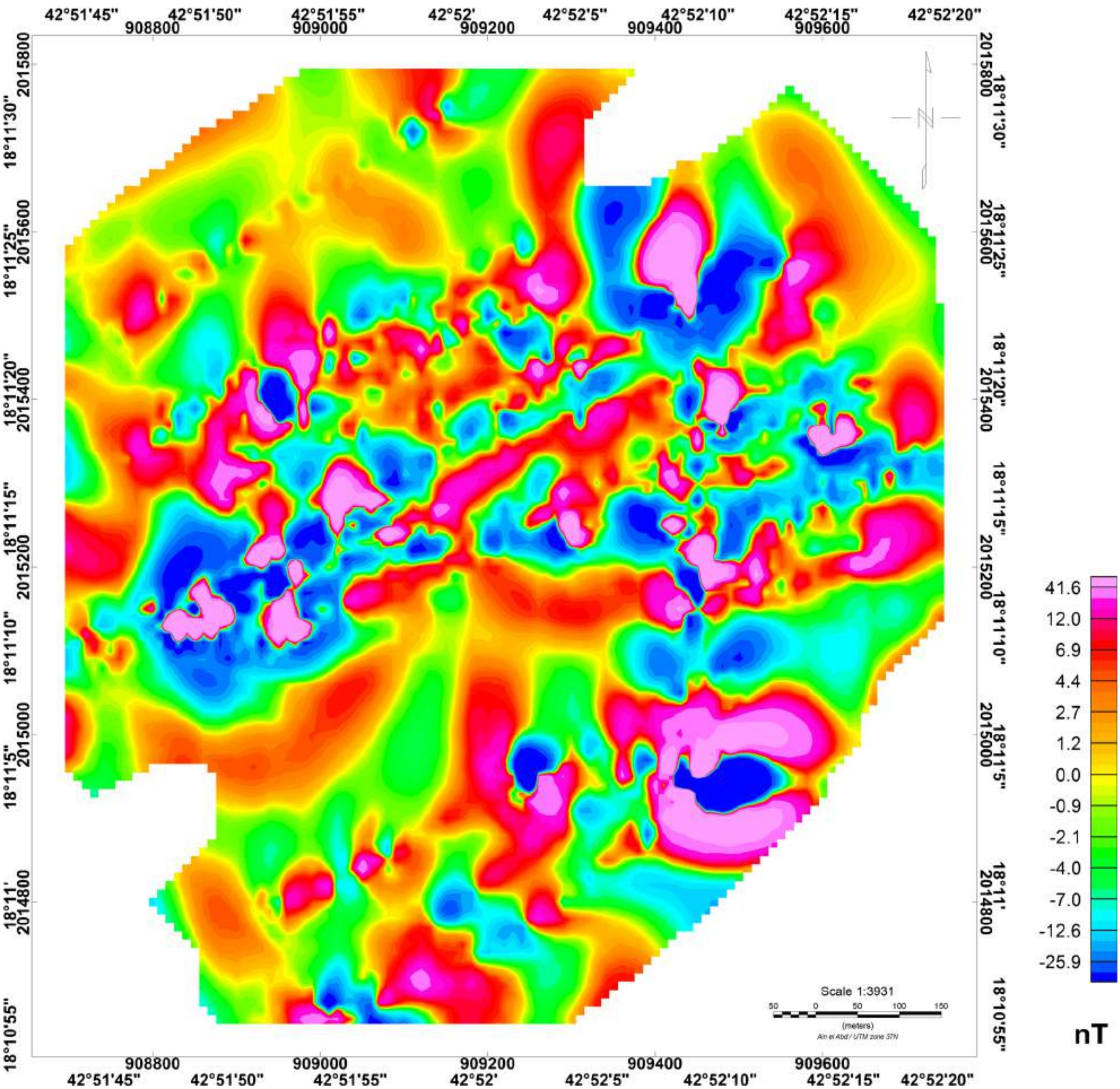

Fig. 5 Residual magnetic anomaly map

20-m nominal line spacing and 5-m nominal station spacing, and the coordinates of the survey points along the grid was taken using the handheld GPS. All magnetic anomalies are relative to the base station. These measurements were carried out during the period of 15 June to 15 July 2013. A total of 3,750 survey stations were measured along 40 east–west survey profiles, striking roughly perpendicular to the extension of the expected structures.

Seismic data acquisition

Thirteen seismic spreads of 115 m length using 24 channels seismograph, with 5-m spacing and near- and far-offset distance of 0 m have been conducted along four survey profiles (Fig. 1). The total length of the survey profiles ranges from 113 m for profile D-D′ to about 485 m for profile B-B′. The seismic spreads were oriented in the NNW-SSE direction parallel to the expected alluvial channels and perpendicular to the direction of the survey profiles. Geophones of natural frequency around 40 Hz were used to provide adequate signals with usable frequency content. Using 10-kg hammer dropping, two shots (forward and reverse) were fired for every seismic spread. The first shot is a normal shot at a distance of 0 m before first geophone; the second is a reverse shot, which was next to geophone 24. The elevations along the acquired seismic lines were taken using handheld global positioning systems (GPS) data. There is no remarkable change in elevation across the surveyed site, and the seismic spreads nearly follow horizontal or near-horizontal ground surfaces.

Data processing

Magnetic data processing

The present magnetic data were gridded, mapped, and contoured on a daily basis in the field to insure high-quality

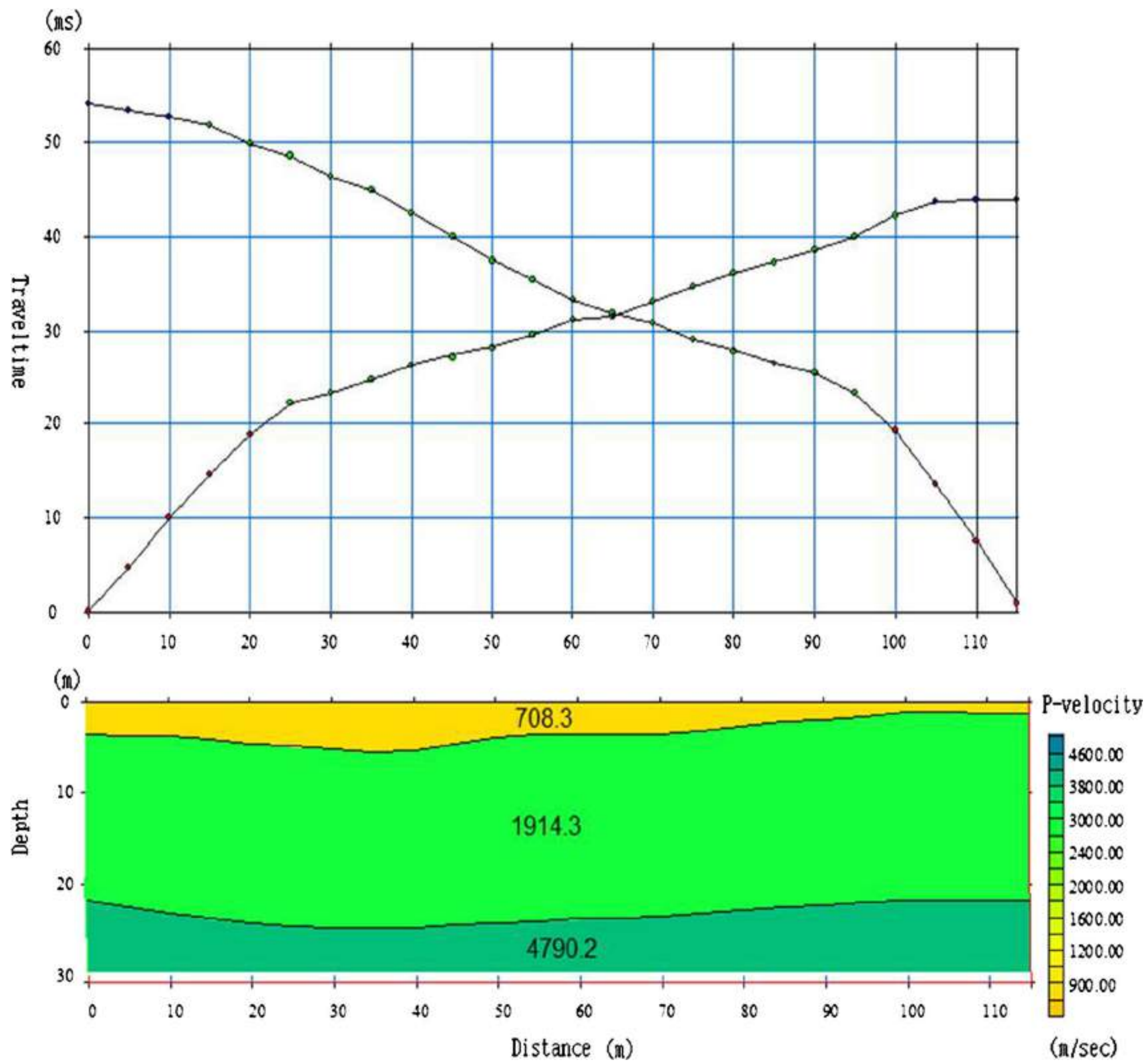

Fig. 6 Representative example of travel–time curve underlain by its interpretation

data were being collected. All magnetic anomalies are corrected for daily variations using base station data. IGRF correction was calculated (field strength=39,099 nT, Inc.= 23.96 and Dec. 2.02) and removed. Grids were constructed from the original magnetic survey data with a cell size of 5 m using a minimum curvature algorithm. The total magnetic intensity was reduced to the pole (RTP, Fig. 3) to overcome the bipolarity phenomena of the magnetic data. The RTP data were separated into regional (Fig. 4) and residual (Fig. 5) components through an application of the Butterworth filter technique using a central wavenumber of 0.09 and degree 8. All these processing steps were executed using commercial software package Geosoft Oasis montaj (Geosoft Inc 2008).

Seismic data processing

The recorded seismic data has been processed using SeisImager/2D™ software package (Geometrics Inc 2009) as follows: (1) identifying and picking of the first breaks at each geophone, then these data used to construct the travel time–distance curves (Fig. 6); (2) the

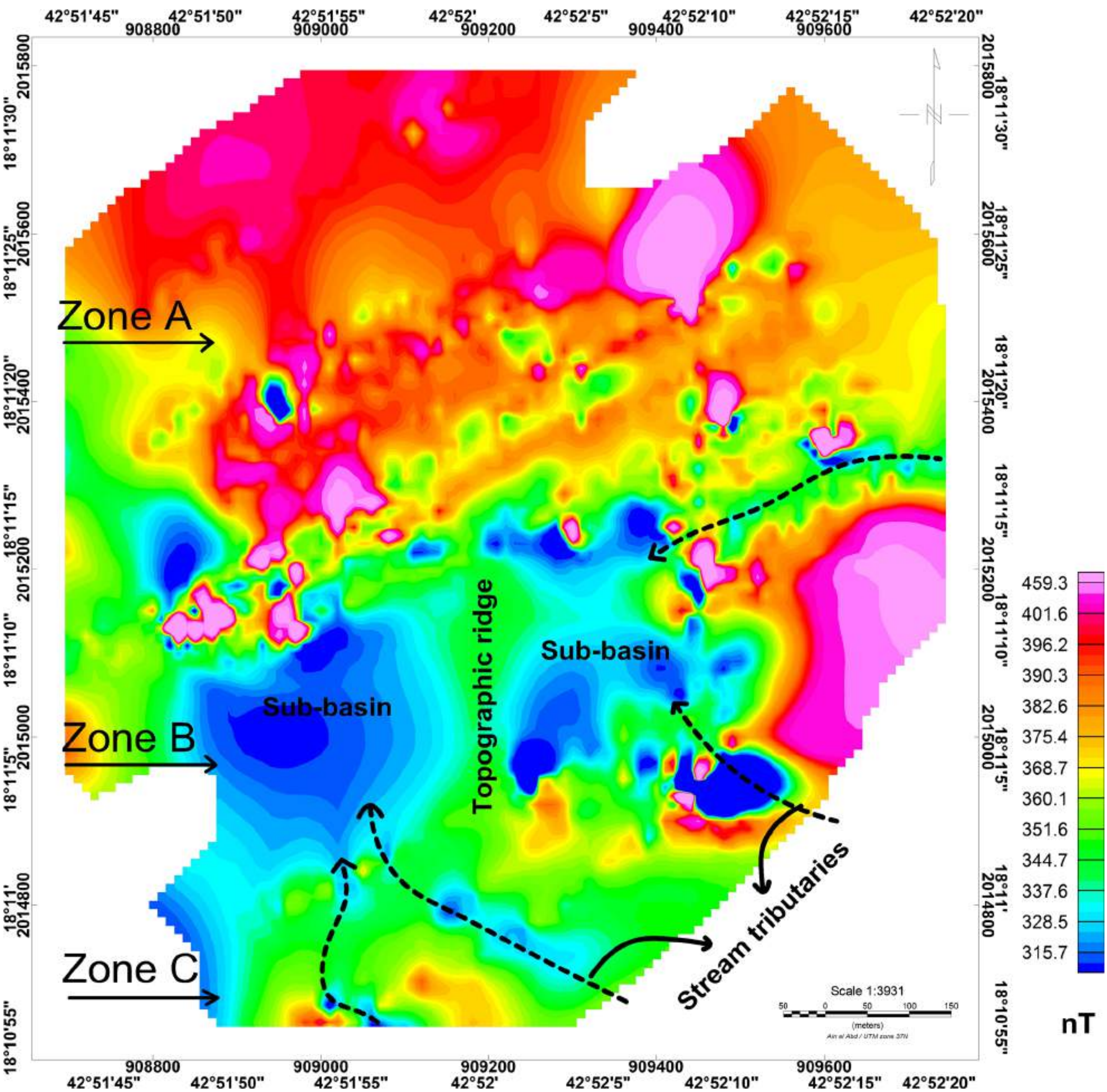

Fig. 7 RTP map with geological interpretation

Fig. 8 The photograph shows the gneiss outcrops and a thin sedimentary cover in the northern zone of the site

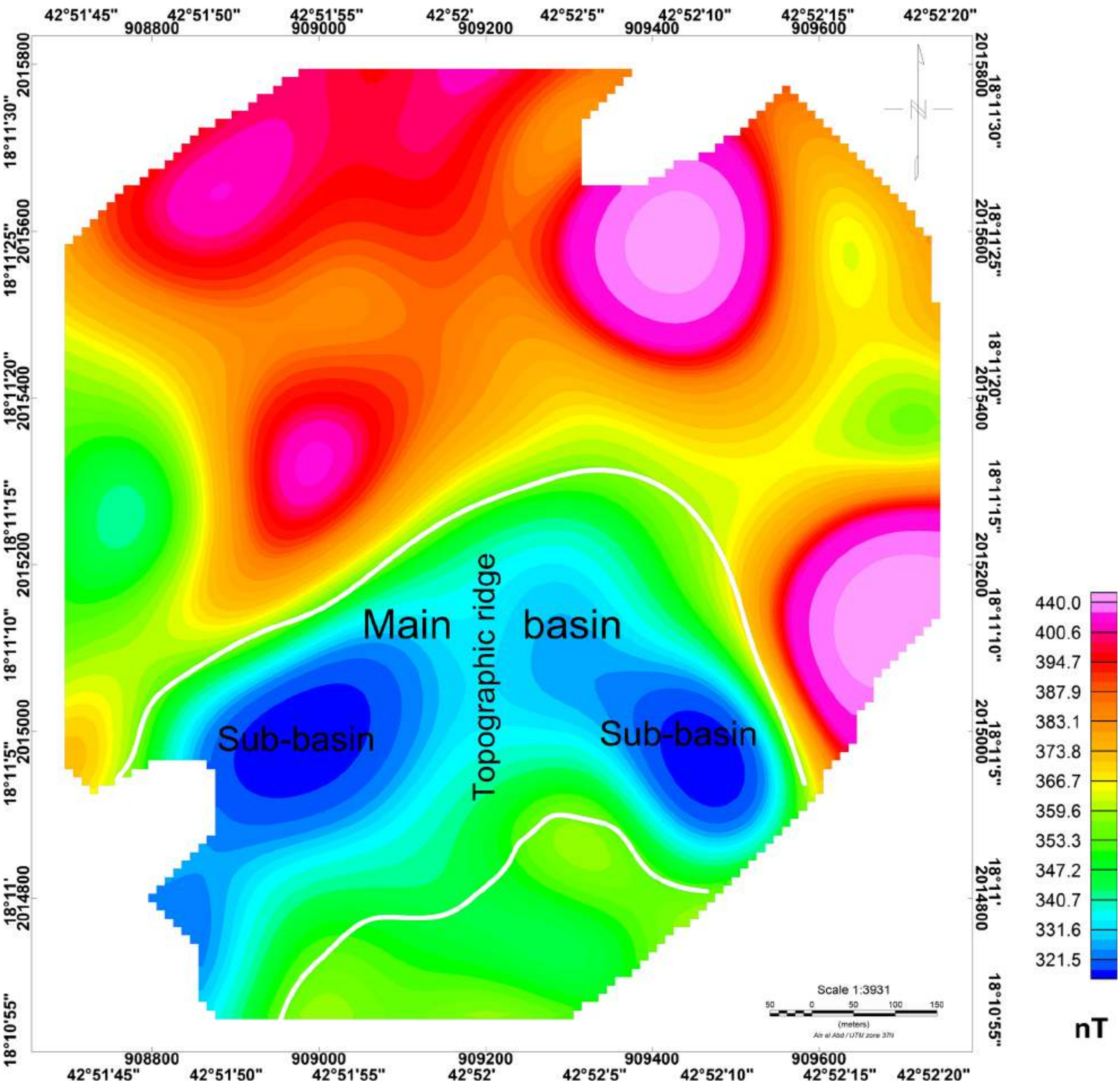

Fig. 9 Regional magnetic anomaly map overlain by geologic interpretation

velocity model has been generated using the time–term inversion technique; (3) and finally, the depths to the top of the underlying layers were calculated and plotted (Fig. 6). The time–term technique employs a combination of linear least squares and delay time analysis to invert the first arrivals for a velocity section. The time–term method is a simple travel–time inversion developed by Scheidegger and Willmore (1957) and was widely used for seismic refraction in the 1960–1970s (Willmore and Bancroft 1960; Berry and West 1966; Meru 1966; Smith et al. 1966; Yoshii and Asano 1972; Iwasaki 2002).

Results and discussion

Ground magnetic results

The assumption was that the overburden alluvial sediments are more or less non-magnetic whereas the host gneiss rock carries some magnetization; therefore, a magnetic susceptibility contrast between gneiss bedrock and overlying alluvial sediments is expected. Depending on this assumption, the studied site can be classified into three zones with different patterns, shapes, and magnitudes of magnetic anomalies (Fig. 7). The exact boundaries between these zones are difficult to outline, and hence, the areas are marked with letters A, B, and C.

The northern zone (A) is dominated by relatively high magnetic anomalies that referred to the area where the gneiss basement rocks are very shallow, and in some locations within this zone, the gneiss basement rocks outcropped on the surface forming the strong, sharp, and local magnetic anomalies (Figs. 7 and 8). The central zone (B) shows two broad and extended low magnetic anomalies that is separated by a moderate magnetic anomaly. These anomalies indicate the presence of two sub-basins separated by a topographic ridge or valley floor divide, i.e., low drainage divide that runs across the main basin, and separates the two adjacent sub-basins (Fig. 7). These two sub-basins combined into larger drainage basin with a total area of about 17,745 m^2 (Fig. 9). These broad and low magnetic anomalies are interrupted by isolated, local, and strong magnetic anomalies that reach amplitude that exceeds 500 nT (Fig. 7). These local magnetic anomalies are correlated with local and isolated outcropped and near-surface gneiss basement blocks as shown in Fig. 10. The southern zone (C) is characterized by the presence of elongated and narrow negative magnetic anomalies intervening relatively moderate to high anomalies and extend generally from the southeast to northwest direction. These narrow and elongated negative anomalies indicate the presence of small and narrow channels that filled with alluvial sediments having low magnetic susceptibility relative to basement gneiss rocks (Fig. 7).

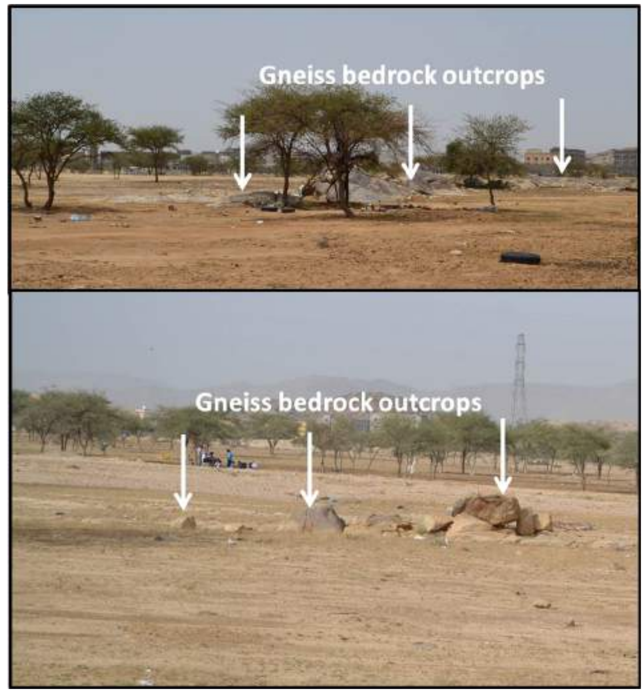

Fig. 10 Local and small gneiss outcrops in the central part of the site

In order to identify magnetic lineaments that could be responsible for the configuration of the interpreted sub-basins and surrounding alluvial channels, the tilt derivative (TDR) of the magnetic field was created (Verduzco et al. 2004). In the TDR anomaly map, it is possible to identify several distinct edges of the faulted blocks that are very difficult to detect in the map of the total magnetic anomaly field. In this map, the zero crossing of the TDR is close to the edge of the structure, so the “zero contour” coincides with the magnetic interpreted faults. Bodies with positive susceptibility contrast are shown in red and the blue color indicates significantly decreased magnetization. The results indicate that there is a clear dominance of NW-SE and NE-SW trending faults that crosscut each other (Fig. 11). The second most prominent orientation is NNW oriented faults (Fig. 11).

Seismic refraction results

Shallow seismic refraction method gives information about the subsurface in terms of seismic velocities. These velocities are directly related to the quality, hardness, compaction, and water content of the medium. However, as qualitative classification, the calculated seismic velocities are classified into three velocity ranges that

are used for identifying the subsurface rock layers in the studied site (Table 1). The initial velocity model has been generated by quick time–term inversion of the data. Then, this model was used as input parameter for the tomographic inversion that aims to find the minimum travel time between source and receiver for each source–receiver pair. This can be achieved by solving for *l* (raypath)

Table 1 Identification of subsurface layers

Subsurface strata	Seismic velocity range
Unconsolidated alluvial sediments	300–700
Compacted alluvial sediments	1,307–2,094
Hard and massive gneiss rocks	3,032–5,388

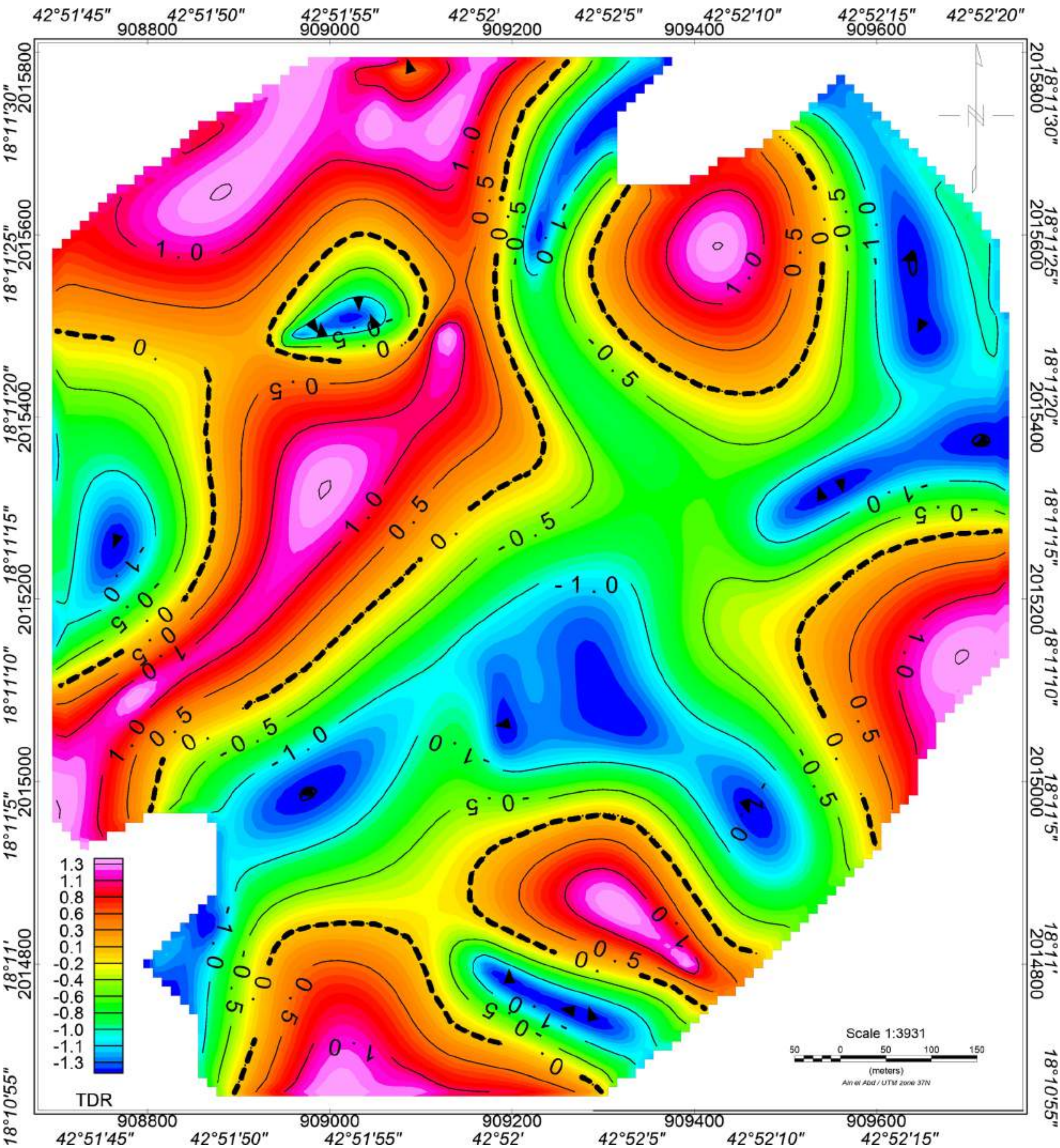

Fig. 11 Tilt derivative map (TDR) of the site

Table 2 Velocities and thicknesses of the interpreted seismic layers

Spread no.	Coordinates		Layer 1		Layer 2		Layer 3	
	x	*y*	V_1	H_1	V_2	H_2	V_3	H_3
1	909,110.4	2,014,719	300	2	1,586.7	5	5,065.3	–
2	909,214.1	2,014,777	541.8	2	1,441.1	10	4,979.4	–
3	909,278.0	2,014,839	300	1	2,093.6	3	5,189.6	–
4	908,948.7	2,015,008	708.3	2	1,914.3	20	5,000	–
5	909,162.2	2,015,036	612.5	5	1,547.1	12	5,050.2	–
6	909,287.9	2,015,042	490.2	1.5	2,009.4	13	5,387.6	–
7	909,405.7	2,015,094	433.5	3	1,360.4	15	5,112.9	–
8	909,523.4	2,015,402	482.4	2	1,306.7	8	4,920.3	–
9	909,573.3	2,015,328	617.2	4	1,801.4	11	5,231	–
10	909,601.2	2,015,272	361.7	3	1,365.8	8	5,277.5	–
11	908,867.5	2,015,145	324.7	2	–	–	4,962.8	–
12	908,903.9	2,015,180	521.3	7	–	–	3,032.3	–
13	908,947.0	2,015,220	527	3	–	–	5,271.3	–

V_1, V_2, and V_3 are the velocities of the first, second, and third layers; H_1, H_2, and H_3 are the thicknesses of the first, second, and third layers

and *s* (inverse velocity or slowness) according to the following algorithm;

$$t_i = \sum_{j=1}^{N} S_{j \quad ij}$$

Finally, two refractors were detected for the seismic sections in the investigated site indicating the presence of three distinct velocity layers, starting from the topmost low velocity layer to the high velocity layer of the hard gneiss bedrock. The calculated thickness and velocities of the interpreted seismic layers are listed in (Table 2) and plotted in 2-D cross-sections showing the distribution of the subsurface layers (Fig. 12). The locations and orientation of the acquired seismic refraction spreads and survey profiles are selected based on the interpretation the ground magnetic data.

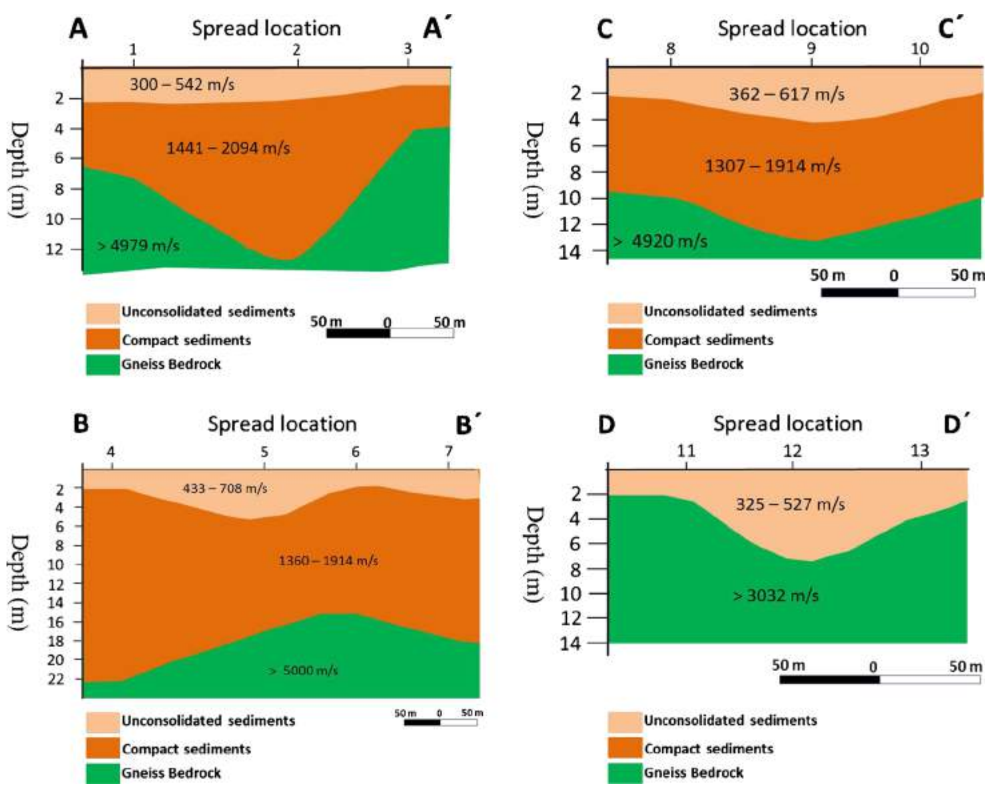

Fig. 12 2-D seismic cross-sections along the surveyed seismic profiles

In the following, the data of the seismic sections gathered during the present survey along four seismic profiles are discussed.

Seismic profile A-A′

This profile lies to the south of the study area (Fig. 1) with a total length of 210 m. The results indicate that a subsurface structure consists of three seismic layers (Fig. 12a); the first layer is unconsolidated overburden with seismic velocity ranging from 300 to 542 m/s and thickness reaches 2 m. The second layer is a compacted alluvium with velocity ranging from 1,441 to 2,094 m/s and maximum thickness of about 10 m. The third layer is a massive gneiss bedrock with seismic velocity that exceeds 4,979 m/s. The interpreted subsurface model for this line shows deeper massive rock centered at station 2. This low-velocity depression zone confirmed the magnetic interpretation results of the existence of narrow channels cutting the massive gneiss bedrock filled with alluvium deposits.

Seismic profile B-B′

This profile consists of four seismic refraction spreads and locates along the central part of the investigated area (Fig. 1) with a total length of 485 m. The results indicate that the subsurface structure consists of three seismic layers (Fig. 12b); the first layer is unconsolidated overburden with seismic velocity ranging from 433 to 708 m/s and thickness varies from 1.5 to 5 m. The second layer is a compacted alluvium with velocity ranging from 1,360 to 2,009 m/s and maximum thickness of about 20 m. The third layer is massive gneiss bedrock with seismic velocity which exceeds 5,000 m/s. The interpreted seismic model along this profile indicates deeper basement along this profile with a greater thickness of alluvial overburden that exceeds 20 m. This result comes comfortable with the broad low magnetic anomaly (Figs. 3 and 4) that occupies the central zone of the investigated site.

Seismic profile C-C′

This profile is composed of three seismic refraction spreads numbered 8, 9, and 10 and located in the western side of the investigated site with a total length of 153 m (Fig. 1). The obtained subsurface structure consists of three layers (Fig. 12c); the first layer is interpreted as unconsolidated alluvial overburden with seismic velocity ranging from 361 to 617 m/s and thickness that reaches 4 m. The seismic velocity of the second layer ranges from 1,306 to 1,801 m/s, indicating compact sediments. Hard and massive gneiss bedrock is mapped below this layer with seismic velocities which exceeds 4,920 m/s. The interpreted subsurface model for this line shows deeper massive rock centered at distance of 91 from the center of spread 8, indicating a narrow valley depression filled with alluvium deposits.

Seismic profile D-D′

This profile is located to the east of the site (Fig. 1) and consists of three spreads numbered 11, 12, and 13 with total length of 113 m. The resulted 2-D ground model (Fig. 12d) indicates that the first layer is unconsolidated alluvium with seismic velocity ranging from 325 to 527 m/s and maximum thickness of about 7 m. Below this layer, the seismic velocities increase abruptly to reach 5,271 m/s indicating the presence of hard and massive gneiss bed rock.

Conclusions

Ground magnetic and seismic refraction surveys were conducted at an urban extension site to the southwest of Ahud Rufeidah town in order to investigate the shallow subsurface and determine the depth to the bedrock and thickness of the overlying alluvial sediments. The results of ground magnetic survey show that the investigated site is dominated in its middle part by a topographic basin, which is sub-divided into two sub-basins filled with alluvium sediments and separated by a topographic ridge. The results indicate that there are four small and narrow channels that convey water and sediments from the eastern and southern hills into the sub-basins that have no outlet as verified from the satellite image and field study. The thickness of the alluvial sediments inside the basins and across the alluvial channels is calculated using seismic refraction data. The results indicate a low-velocity sedimentary overburden with greater thicknesses (exceeds 20 m) inside the basin and across the interpreted buried alluvial channels. The fine-grained alluvial sediments that deposited within the site through the dominant hydro-geomorphologic processes can be a deceptive and dangerous for urban foundations.

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References

Al-Garni MA (2004) Application of magnetic and electrical geophysical methods in exploration of groundwater resources of Wadi Malakan, Saudi Arabia. Journal of King AbdulAziz Univeristy: Earth Sciences 16:67–93

Al-Garni MA (2005) Investigating the groundwater occurrence in Wadi Rahjan and its potential contribution to Ain Zubaida using magnetic and electric methods, KSA. Journal of King AbdulAziz University: Earth Sciences 18:23–47

Al-Garni MA, Hassanein HI, Gobashy M (2005) Ground-magnetic survey and Schlumberger sounding for identifying the subsurface factors controlling the groundwater flow along Wadi Lusab, Makkah Al-Mukarramah, Saudi Arabia. J Appl Geophys 4:59–74

Benson RC, Yuhr L (2002) Site characterization strategies: old and new. Second Annual Conference on the Application of Geophysical and NDT Methodologies to Transportation Facilities, Federal Highway Administration, April 15–19, Los Angeles, California

Benson RC, Glaccum R, Noel M (1984) Geophysical techniques for sensing buried wastes and waste migration. NTIS PB84-198449

Berry MJ, West GF (1966) An interpretation of the first arrival data of the Lake Superior experiment by the time-term method. Bull Seism Soc Am 56:141–171

Blakely RJ (1995) Potential theory in gravity and magnetic applications. University Press, Cambridge, 441 pp

Coleman RG, Brown GF (1971) Volcanism in the southwest of Saudi Arabia. Geol Soc American Abs with programs 3(7):529

Dumbleton MJ, West G (1974) Guidance on planning, directing and reporting site investigation. TRRI, Laboratory Report 625. Transport and Road Research Laboratory, Crowthorne

Dutta NP (1984) Seismic refraction method to study the foundation rock of a dam. Geophys Prospect 32:1103–1110

Geometrics Inc. (2009) SeisImager/2D^{TM}, version 3.3

Geosoft Inc. (2008) Geosoft Oasis Montaj, 2nd edition, version 7.0.1 (OL)

Goldstein NE (1994) Expedited site characterization geophysics: geophysical methods and tools for site characterization. Prepared for the US Department of Energy by Lawrence Berkeley Laboratory, Univ. of California. 124 p

Hatherly PJ, Neville MJ (1986) Experience with the generalized reciprocal method of seismic refraction interpretation for shallow seismic engineering site investigation. Geophysics 51:276–288

Iwasaki T (2002) Extended time-term method for identifying lateral structural variations from seismic refraction data. Earth Planets Space 54:663–677

Kilty KT, Noriss RA, McLamore WR, Hennon KP, Euge K (1986) Seismic refraction at Horse Dam. An application of the generalized reciprocal method. Geophysics 51:266–272

McDowell PW (1981) Recent developments in geophysical techniques for the rapid location of near-surface anomalous conditions by geophysical methods. Ground Eng 14:20–30

Meru RF (1966) An iterative method for solving the time-term equations, J. S. Steinhart and T. J. Smith, Ed., Geophys. Monogr. 10: 495–497

Reynolds JM (1997) An introduction to applied and environmental geophysics. Wiley, NY, 806 pp

Scheidegger A, Willmore PL (1957) The use of a least square method for the interpretation of data from seismic surveys. Geophysics 22:9–22

Sjogren BO, Sandberg J (1979) Seismic classification of rock mass qualities. Geophys Prospect 27:409–442

Smith TJ, Steinhart JS, Aldrich LJ (1966) Lake Superior crustal structure. J Geophys Res 71:1141–1172

Verduzco B, Fairhead JD, Green CM, MacKenzie C (2004) New insights into magnetic derivatives for structural mapping. Lead Edge 23:116–119

Willmore PL, Bancroft AM (1960) The time-term approach to refraction seismology. Geophys J R Astron Soc 3(3):419–432

Yoshii T, Asano S (1972) Time-term analysis of explosion seismic data. J Phys Earth 20:47–57