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ORIGINAL ARTICLE

# The Effects of Structural Elements on Groundwater of Wadi Yalamlam, Saudi Arabia Using Integration of Remote Sensing and Airborne Magnetic Survey

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## Abstract

The present study aimed to develop an integrated approach that utilized field geology, remote sensing and airborne magnetic data to identify the Quaternary aquifers impounded by dykes and explain the dykes/lineaments relationship and their effects on the storage and flow of the groundwater of Sadiyah sub-basin, lower part of Wadi Yalamlam basin, Western Arabian Shield, Saudi Arabia. Field visits supported by Landsat ETM + ratio images (5/7, 5/4 and 5/1) revealed the presence of three main dyke types that can be chronologically arranged from older to younger as: Sheared mafic and acidic dykes (D1); Damm dyke complex (D2); and Ghumayqah dykes (D3). Two dykes referred to the first type (D1) were traced with depth using airborne magnetic survey crosscutting the main course of Wadi Yalamlam around Sadiyah village at high angle. According to water table elevation measurements, the aquifer of lower Wadi Yalamlam area is divided into three parts namely I, II and III. The water table elevations decreased from 158 m in the first part (I) to reach 66 m in the third part (III) of the aquifer. This drop is attributed to the effect of dykes which act as natural barriers. The study area was affected by three major fault systems as confirmed by field study and total magnetic map. Two of these systems have NE–SW to ENE–WSW and N–S to NNW–SSE directions, whereas the third one represents the Najd fault system trends in NW–SE direction. The present study identifies two locations valid for agricultural expansion lie just to the north of Sheikh Said and Abu Helal Farms.

**Keywords** Remote sensing · Airborne magnetic survey · Dykes · Fractures · Groundwater · Wadi Yalamlam · Western Saudi Arabia

## 1 Introduction

The Arabian Shield represents the eastern part of the Arabian-Nubian Shield and covers the western part of Saudi Arabia. It extends from Ethiopia (south) to Jordan (north) and from Egypt (west) to Oman (east) covering an area of more than $2.7 \times 10^6$ km$^2$ (Johnson 2014). It consists of highly fractured granitoids, metavolcanics and metasedimentary rocks subjected to poly phases of subduction, amalgamation, and post-amalgamation tectonic events (Stoeser

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and Camp 1985). From the hydro-geological point of view, these rocks are characterized by insignificant primary porosity and permeability, so they are considered as secondary aquifers. In the past, they are neglected as a possible source of groundwater due to their low permeability and porosity. But in the last 30 years, several studies indicated that they can be considered as important source for fresh water. For example, Wadi Yalamlam, western Arabian Shield was selected by Subyani and Bayumi (2001), as a potential fresh water source for Makkah district. Bayumi (2008) indicated the possibility of drilling 14 wells in the downstream part of Wadi Yalamlam, Makkah province, Saudi Arabia, for generating a renewable amount of 7500 $m^3$/day to supply Makkah region in addition to $9 \times 106$ $m^3$ as a reserve in Wadi Yalamlam basin. The groundwater potential zones at Wadi Yalamlam basin are recognized by Madani and Niyazi (2015a, b) using integration of remote sensing, GIS and field measurements. They defined the lower parts of the wadi as the most promising areas for groundwater occurrences (high and moderate potential zones).

Several authors utilized the remote sensing techniques for distinguish the linear features and dykes (Madani 2011; Madani and Emam 2011; Emam et al. 2018). Madani and Niyazi (2015a, b) investigated the relationship between the lineament trends, drainage network and the groundwater occurrences at Bulghah gold mine area, Saudi Arabia. The subject of dykes impounded aquifers is dealt with by many authors (Takasaki and Mink 1985; Babiker and Gudmundsson 2004; Gupta et al. 2012; Sabale and Meshram 2012; Guihéneuf et al. 2014). Takasaki and Mink (1985) evaluated the major dyke impounded groundwater reservoirs, island of Oahu. Babiker and Gudmundsson(2004) studied the effects of faults and dykes on the groundwater flow along the Red Sea Hills, Sudan. Gupta et al. (2012) studied the temporal geoelectric behavior of dyke aquifers in northern Deccan Volcanic Province, India. Sabale and Meshram (2012) studied the effect of Bhokani dyke structure on groundwater between Sangamner and Sinnar areas, India. Guihéneuf et al. (2014) presented a detailed study of fracture properties and their relation to groundwater flow at local and watershed scales, Southern India. Comte et al. (2017) studied the effect of volcanic dykes on coastal groundwater flow and saltwater intrusion, Northern Ireland. In the basement terrain of the Saudi Arabia, none of the previous researchers executed a detailed study that revealed the effect of dykes and fractures on groundwater flow and storage. In the present study, the lower part of Wadi Yalamlam, Western Saudi Arabia was chosen to investigate a new approach tried to reveal the effects of dykes and faults on groundwater storage. This approach involved integration of field study, remote sensing, and aeromagnetic survey data.

Wadi Yalamlam is located about 125 km southeast of Jeddah city and is bounded by latitudes 20°26′ and 21°8′N and longitudes 39° 45′ and 40° 29′E (Fig. 1). The elevations of Wadi Yalamlam basin are varying highly within the range between 2850 m (a.s.l.) in the mountainous part in the east and 25 m (a.s.l.) in the downstream part of the basin. The main course of the wadi crosscuts the highly fractured granitoid rocks in the east till reach the coastal plain of the Red Sea. The main course of Wadi Yalamlam has ENE-WSW direction whereas; the lower part of the wadi has NNE-SSW to N–S directions and is covered by highly altered, fractured granitic gneiss and metabasalts.

The principal aquifer to be recharged beneath the Wadi Yalamlam basin is the Quaternary wadi deposits. Depths to the groundwater table in the lower part of the Wadi Yalamlam vary from 8 to 18 m around Sadiyah village (Bayumi 2008). The general groundwater flow in the Quaternary aquifer is assumed to be toward west in the upstream part and toward southwest in the lower part of the basin. Three field visits to Wadi Yalamlam area were performed through Jeddah-Shamysi-Al Lith road. A branch from this road crosscuts the study area passing through Sadiyah village. Around Sadiyah village two small farms are visited; Sheikh Said to the north and Abu Helal to the south. The study area is affected by many types of faults varying in dimensions, displacements and lengths crosscutting the various rock units distributed along the Wadi Yalamlam basin. They are considered as good pathways for groundwater movement. A shear zone represents a zone of strong deformation; recorded to the south of Sadiyah village is considered as a good situation for groundwater storage in the study area. Several dykes have N–S, E–W and NW–SE directions are recorded in the study area. The present study integrated field geology, remote sensing and airborne magnetic studies to clarify the influence of dykes, fractures and shear zones on groundwater storage and flow of Quaternary aquifer recorded at the lower part of Wadi Yalamlam, Western Arabian Shield, Saudi Arabia.

## 2 Geologic Setting and Field Description of Dykes

The exposed lithologies in the study area are mainly Proterozoic rocks comprising; metavolcanics of Baish group, Sadiyah formation (equivalent to the lower part of Baish group), Lith suite (plutonic equivalent of Baish group) and intrusions of Hurqufah suite (granite gneiss batholiths with less common granitic plutons) (Fig. 2). The above mentioned rock units are dissected by basic to acidic dyke warms trending in ENE–WSW, N–S and NW–SE directions. Figure 3 shows stratigraphic and chronologic relationships between these dykes and different Proterozoic rock units exposed at the study area. Three different types of dykes having different directions and mineralogical composition are recorded

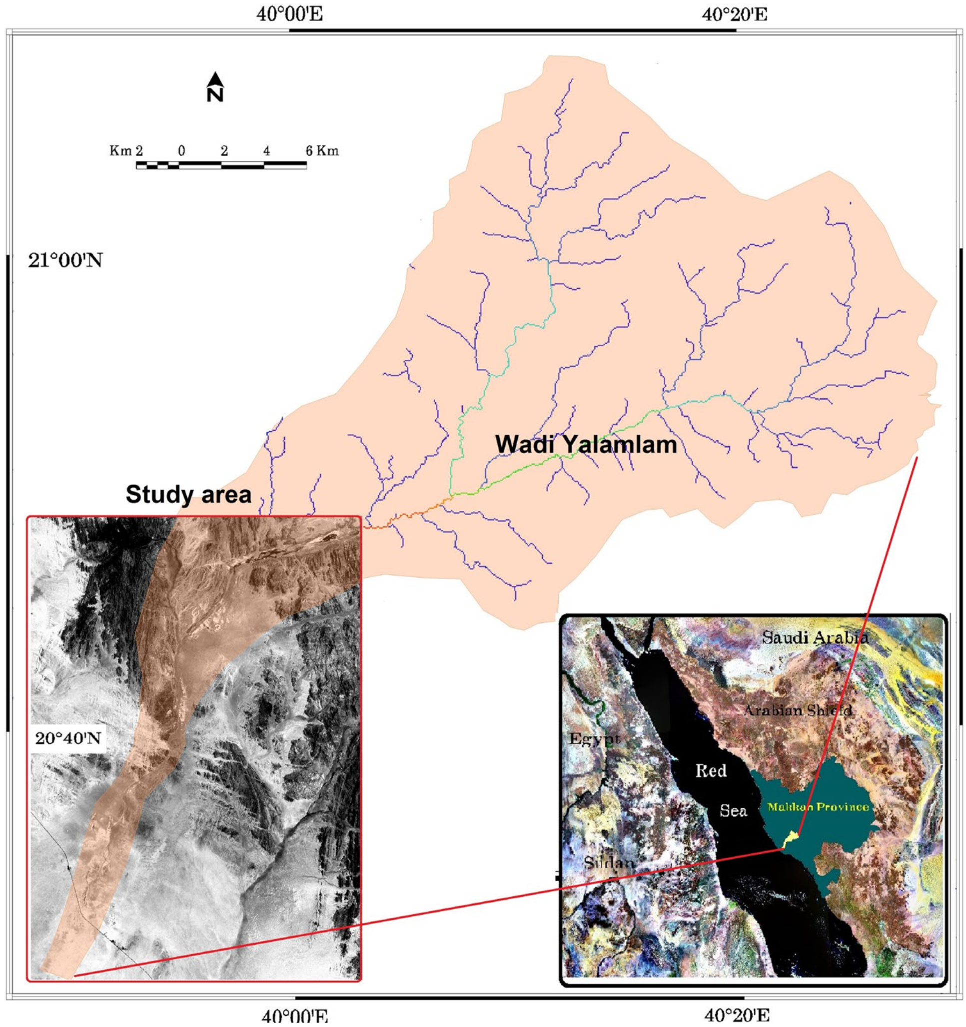



**Fig. 1** Location map of the study area

at the study area. These dykes are arranged from older to younger as follow: (1) Sheared mafic and acidic dykes (D1), recorded to the south of Abu Helal Farm as well as west of Jabal Hurqufah. (2) Damm dyke complex (D2), recorded around Sadiyah village. (3) Ghumayqah complex (D3), recorded crosscut Jabal Hurqufah. The following paragraphs describe the field relationships of these dykes.

Sheared mafic and acidic dykes (D1) represent the oldest type recorded to the south of Sadiyah village. They crosscut Baish group, Sadiyah formation and granitic gneiss of Hurqufah suite. They are observed in a wide shear zone trending in N70ºW direction, extend for several kilometers and they are highly deformed and weathered. As for the sheared mafic dykes, they are highly foliated, highly sheared, metamorphosed and range in thickness from 1 to 5 m. In general, they are fine- to coarse-grained rocks having dark grey to greenish grey color. They are highly jointed and contain basic xenoliths from Baish group. The sheared acidic dykes are recorded in two areas; the first lies to the south of Sadiyah village in association with sheared basic dyke whereas the second area lies to the west of Jabal Hurqufah crossing the main course of Wadi Yalamlam. In the first area the acidic dyke is light grey, medium- to coarse-grained rock, highly deformed with strong gneissosity. In the second area the older acidic dyke is represented by pegmatite and is recorded crossing the main course of Wadi Yalamlam to the other bank in E-W direction. It acts as a natural barrier affects the groundwater storage and movement. It is highly fractured by at least three sets of joints having NNW-SSE, NE-SW and WNW-ESE directions, some with an opening of about 15 cm.

Damm dykes (D2) are fresh younger dykes, range in age from 18 to 50 Ma. The term “Damm dyke complex” were named by Pallister (1982) describing two dense swarms of subparallel to parallel dykes trending in N–S trend at Jabal Ghamidiyah. Damm dyke complex consists of two main bimodal Alkaline and subalkaline series. Field visits revealed that the Damm dykes are recorded at two main sites crossing Wadi Yalamlam in N–S direction. The first site is located to the southwest of Abu Helal Farm near

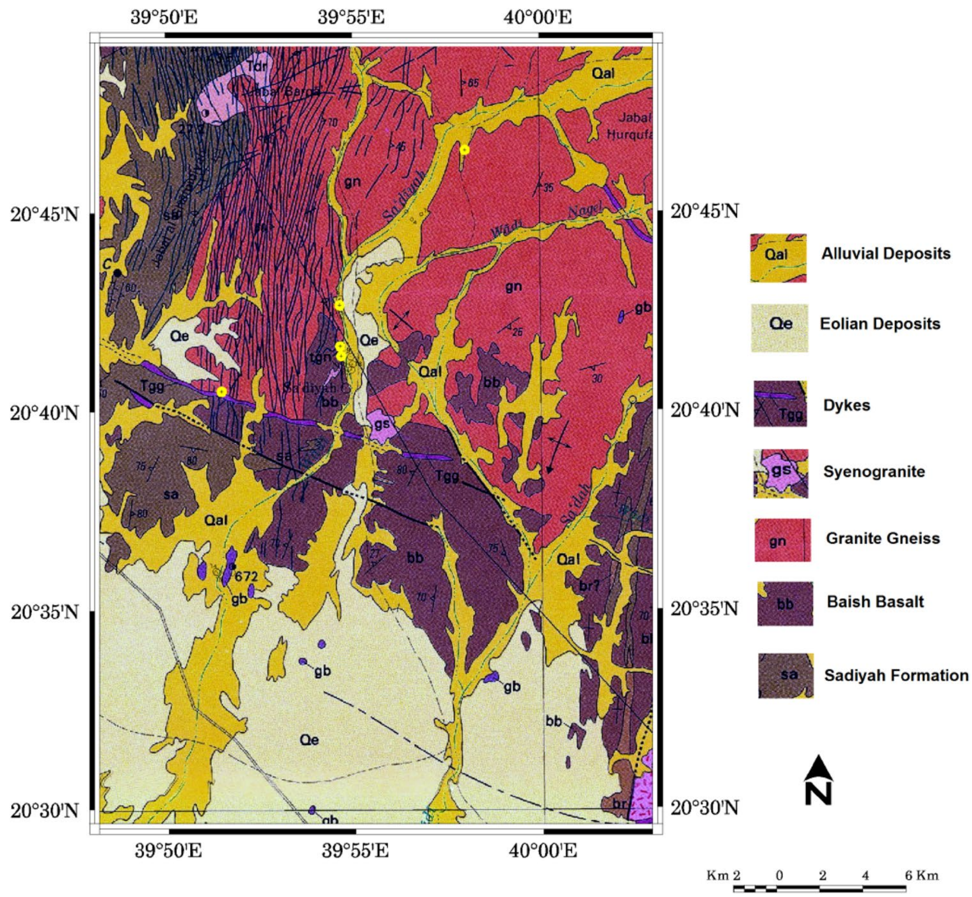



**Fig. 2** Geologic map of the lower part of Wadi Yalamlam area, after Pallister (1986)

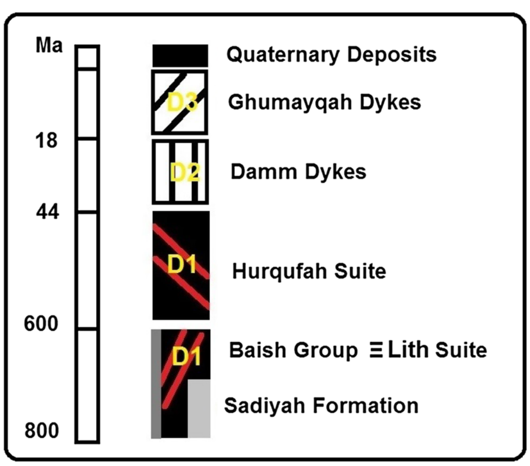



**Fig. 3** Stratigraphic and chronologic relationships of dykes, with Proterozoic rock units at the lower part of Wadi Yalamlam area

to the asphaltic road in the western sector of the mapped area. They are thin and their thickness range from 1 to 3 m. Two types of Damm dykes (basic and acidic) are observed crosscutting the older sheared dykes (Fig. 4a). They are massive, dark grey to olive grey, pale brown in color, fine- to medium- grained, non-metamorphosed rocks, represented by basalts and dacite having N–S to NNE–SSW direction. The second site is located to the north of Sadiyah village in which the N26ºW acidic dyke swarms are observed crosscutting the highly altered granitic gneiss (Fig. 4b) and having two main sets of joints with the following measurements (333°/70ºW and 084°/72ºN).

The term Ghumayqah dyke complex (D3) or "continental dyke" was termed first by Coleman et al. (1979) to describe thick, widely spaced gabbro intrude the Proterozoic rocks in NW direction. Coleman et al. (1979) observed Ghumayqah dykes crosscutting the Damm dyke complex east–southeast of Harret Tafil. Field visits carried throughout the present study reveal that Ghumayqah dykes are recorded crosscutting Wadi Yalamlam and intruding the granitoid rocks of JabalHurqufah (Fig. 4c). They trend mainly in N–S direction with a thickness range from 20 to 50 m, extend up to 20 km and are dissected by many E-W faults. They are typically basic (mainly dolerite) and exhibit what is called "railroad track" which occurred due to differential weathering between central coarse-grained and peripheral fine-grained.

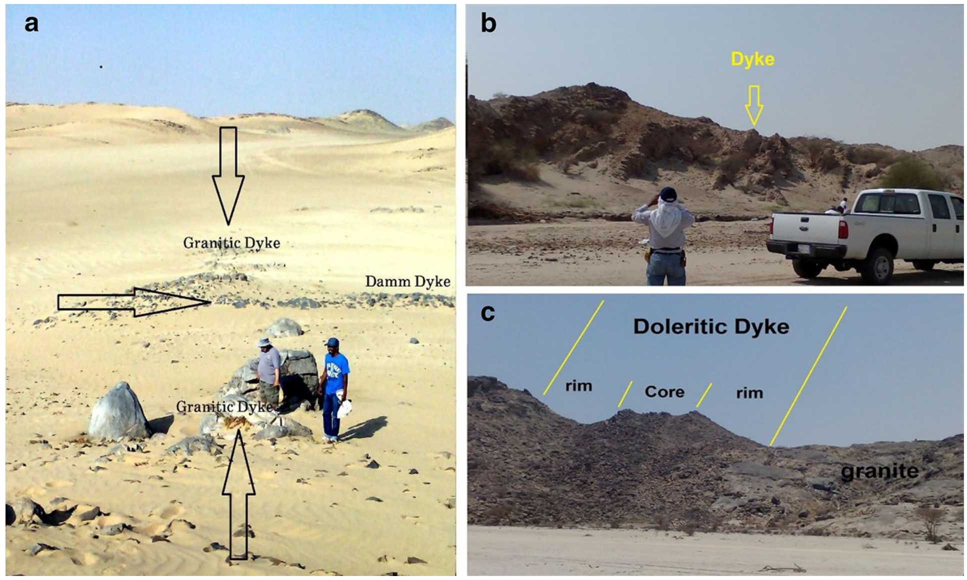



**Fig. 4** Field photos show: **a** Sheared older dyke of granitic composition (D1) cutting by N–S Damm dyke (D2), looking west. **b** Acidic dyke swarm follow Damm complex direction crossing Wadi Yalamlam and intruding rocks of highly altered granitic gneiss, looking SW. **c** Ghumayqah dyke (D3) cross-cutting the Hurqufah granitic rocks, looking North

## 3 Materials and Methods

The flow chart (Fig. 5) shows the various steps carried throughout the present study. It includes: (1) multispectral Landsat ETM+, which is used to distinguish the different types of dykes distributed in the study area; (2) depth to water table measurements which are collected from the uncovered wells around the dykes; (3) aeromagnetic maps covered the study area are digitized and utilized to locate dykes wit depth in the study area; (4) finally data integration and allocation of the most promising areas for dykes impound aquifers in the study area.

Subsets from Landsat-7 ETM+ image (Path 171, Row 043), acquired in 2010, covering the study area (Fig. 6) are prepared and digitally processed using band ratio technique to reveal the image signatures of dykes. ETM+ scene has eight broad spectral bands. Six of these bands detect visible,

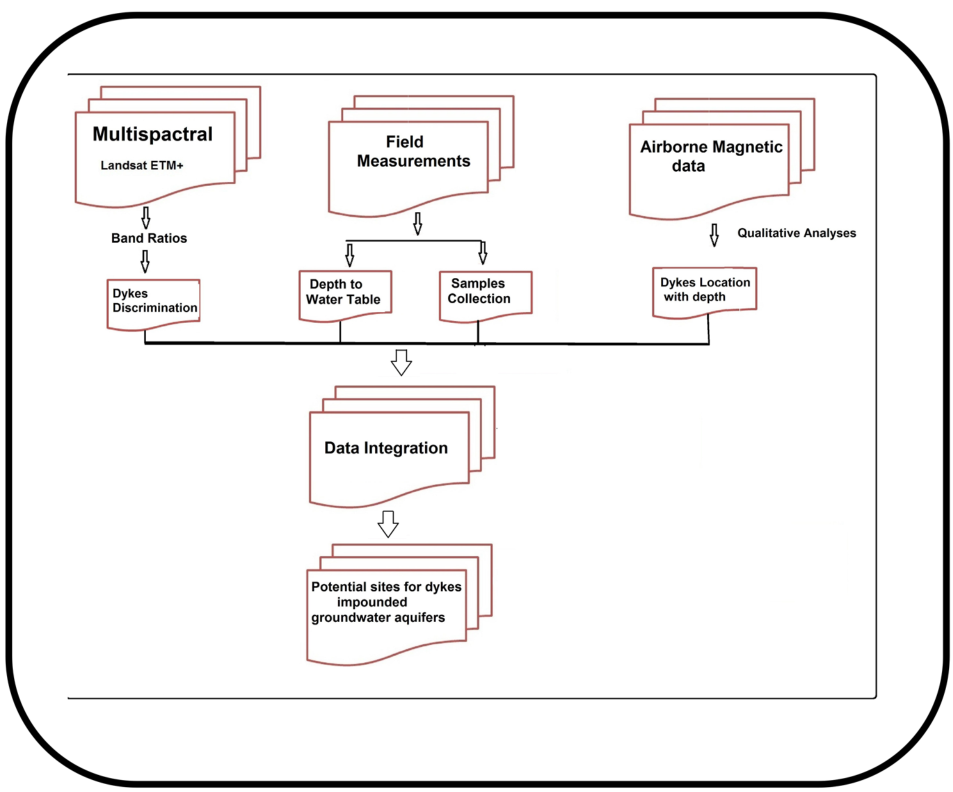



**Fig. 5** Flow chart demonstrates the various steps used in the present study

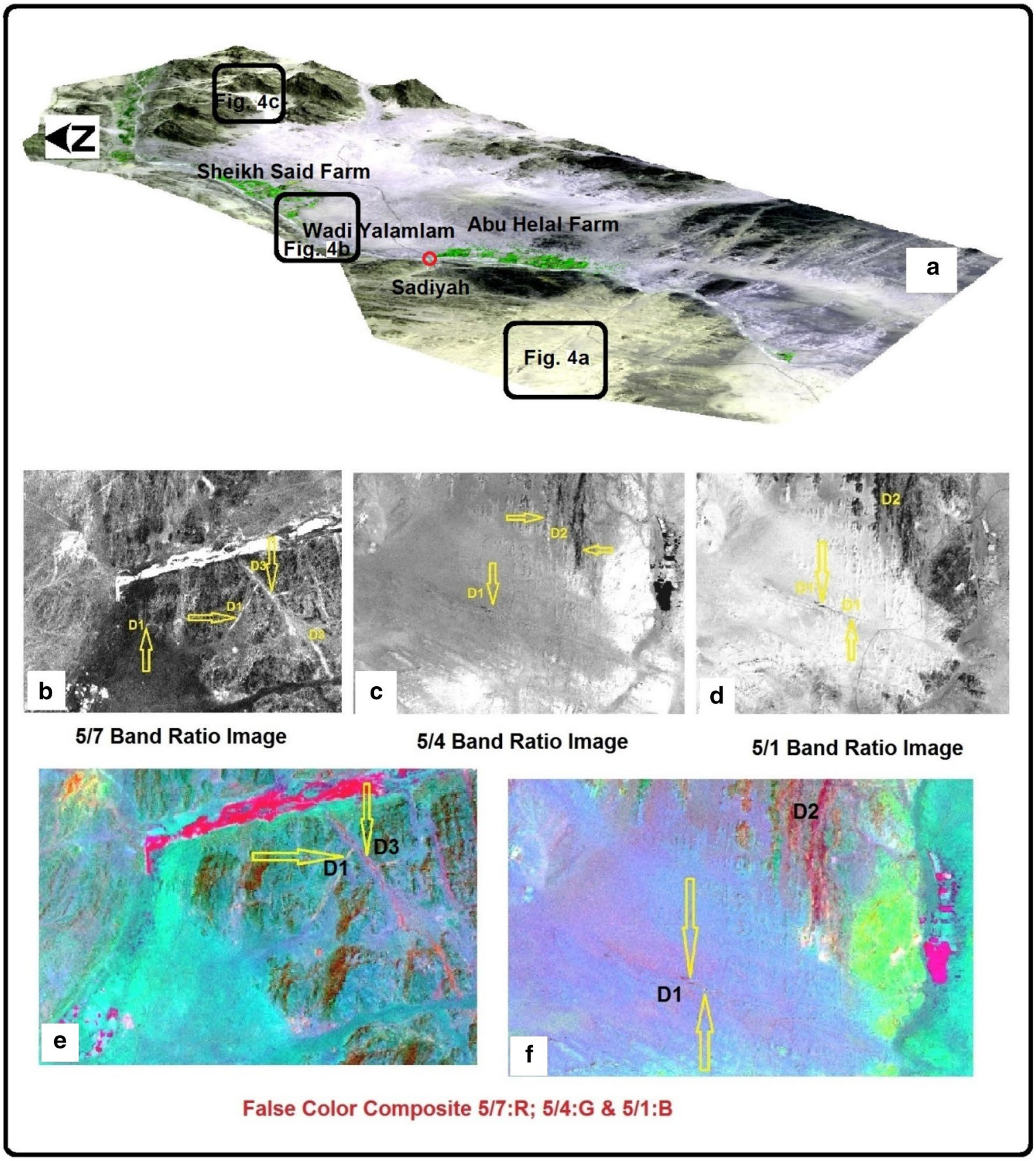



**Fig. 6** **a** 3D perspective view of enhanced FCC RapidEye imagery (3, 5 and 4 in RGB) draped over ASTER GDEM digital elevation model, lower part of Wadi Yalamlam basin. Note, large and small boxes defined field photos (Fig. 4a–c) and the locations of ratios image subsets (**b**–**f**), respectively. **b** 5/7 band ratio image. **c** 5/4 band ratio image. **d** 5/1 band ratio image. **e**, **f** False color composite band ratios (5/7, 5/4 and 5/1 in RGB) image subsets

Near Infrared (NIR) and Short Wave Infrared (SWIR) radiations (0.45–2.35 µm) with 30 m spatial resolution. Several authors dealt with the lithological discrimination using band ratio technique (Sultan et al. 1987; Davis and Berlin 1987; Madani 2000, 2014; Madani et al. 2003). Band ratio technique can be prepared simply by dividing the DN values of each pixel in one band by the DN values of another band (Drury 1993). The ratio values must be rescaled to 0–255 range to display. The aeromagnetic survey is a powerful tool in delineating the regional geology and structure of buried basement terrain, dykes crossing wadi sediments and calculating depth to the basement and basement topography (Dobrin 1960, 1976; Nabighian 1972, 1974; Parasnis 1975; Blakely 1995; Hsn et al. 1996). It defines the size, shape, and location of bodies by mathematical treatment of the observed magnetic field values (Reford and Sumner

1964). In this study two aeromagnetic contour maps (No. 591 and 574), covering the study area, scale 1: 50,000 produced by Aero service corporation (1967) were analyzed. The aeromagnetic contour maps were converted into digits values and the magnetic derivative maps were produced by processing of the digits total intensity magnetic data. They were subjected to several processes which made them easier to analyze the data qualitatively and quantitatively and also to speed up the process of individual anomaly interpretation. The reduction to the pole (RTP) filter is applied to total intensity magnetic map TMI map (Fig. 7) to remove the dipolar phenomena as appear in RTP map (Fig. 8). Qualitative analysis is an attempt to get a preliminary idea about the characteristics of the causative bodies, depending on form, shape, trend, differences in amplitude, change or discontinuity of direction and extension of anomalies (Nettleton 1976).

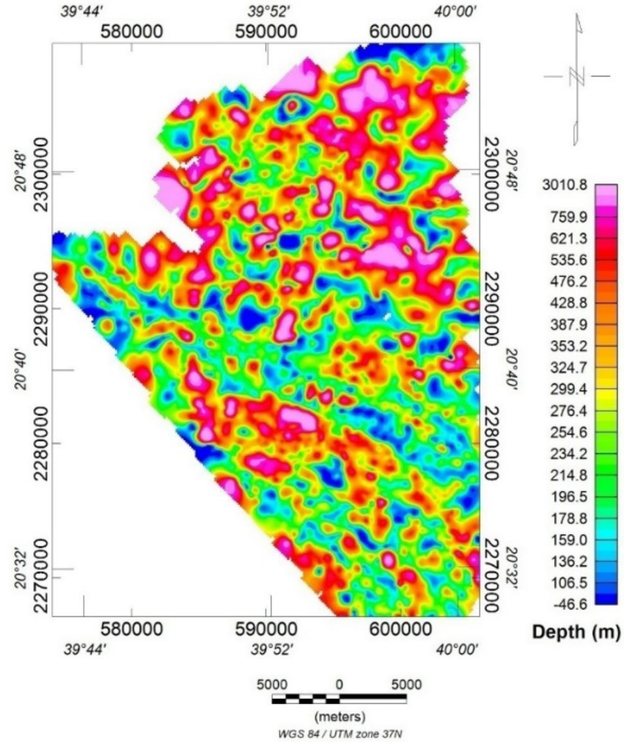



**Fig. 8** Filled-color contour map of the calculated depths using source parameter imaging (SPI) technique, the lower part of Wadi Yalamlam

## 4 Results and Discussion

### 4.1 Utilization of Band Ratio Technique for Dykes Discrimination

Visual inspection of all generated band ratio images revealed that the most informative band ratios for dykes discrimination are 5/7, 5/4 and 5/1 band ratio images. Figure 6a is the 3D perspective view of enhanced False color composite RapidEye imagery (3, 5 and 4 in RGB) draped over ASTER GDEM digital elevation model using 3D surface view module of ENVI package. RapidEye data were purchased, whereas ASTER GDEM data were downloaded from NASA open source site.

It shows the lower part of Wadi Yalamlam, Sadiyah village, Sheikh Said and Abu Helal farms. On 5/7 band ratio image pegmatite dyke (D1) and basic Ghumayaqah dykes (D3) have white image signature (Fig. 6b). Petrographic study of these dykes reveals that the main alteration products are serpentine minerals, carbonates, chlorite, sericite and Fe-oxides. The main absorption features of serpentine and calcite is observed around band-7 wavelength region which leads to lower the dominator and increase ratio value and hence the image signature appears white. Basic Damm dyke has black image signature on 5/4 band ratio image (Fig. 6c), whereas acidic dyke has light grey image signature. Figure 6d shows 5/1 band ratio image which distinguishes the sheared basic and acidic dyke types (D1) by their black and grey image signatures, respectively. The information contained in the above three band ratio images (5/7:R; 5/4:G and 5/1:B) was integrated into one false color composite image subsets (Fig. 6e, f). They are clearly discriminating pegmatite dyke from Ghumayqah dykes by their white and red image signatures, respectively (Fig. 6e) and basic

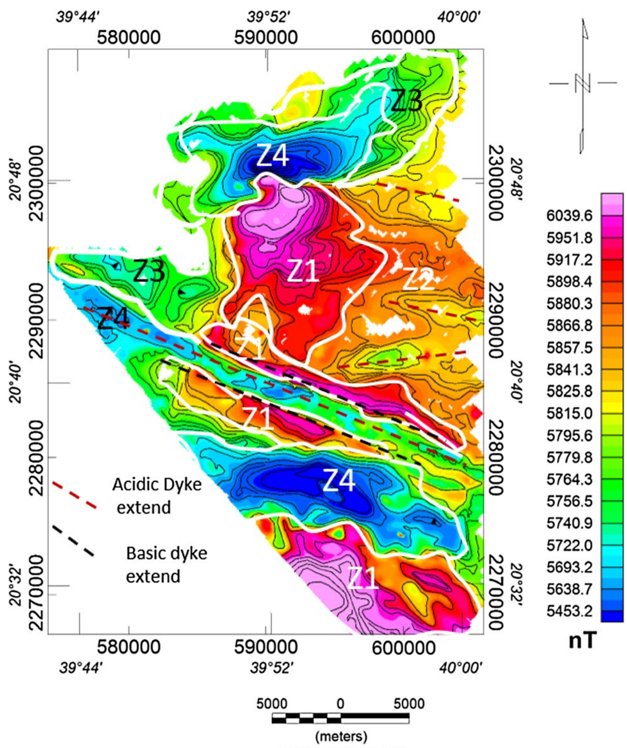



**Fig. 7** Interpreted zonation of total magnetic contour map, the lower part of Wadi Yalamlam area

Damm dykes from acidic dykes by their brownish red and pale green image signatures, respectively (Fig. 6f).

## 4.2 The Role of Airborne Magnetic Survey for Identifying the Buried Dykes and Structural Elements

The aeromagnetic survey is a powerful tool in delineating the regional geology and structure of buried basement terrain, dykes crossing wadi sediments and calculating depth to the basement and basement topography (Dobrin 1960, 1976; Nabighian 1972, 1974; Parasnis 1975; Blakely 1995; Hsn et al. 1996). It defines the size, shape, and location of bodies by mathematical treatment of the observed magnetic field values (Reford and Sumner 1964). In this study two aeromagnetic contour maps (No. 591 and 574), covering the study area, scale 1: 50,000 produced by Aero service corporation (1967) were prepared and analyzed. The aeromagnetic contour maps were converted into digits values and the magnetic derivative maps were produced by processing of the digits total intensity magnetic data. They were subjected to several processes which made them easier to analyze the data qualitatively and quantitatively and also to speed up the process of individual anomaly interpretation. The reduction to the pole (RTP) filter is applied to total intensity magnetic map TMI map (Fig. 7) to remove the dipolar phenomena as appear in RTP map (Fig. 9). Qualitative analysis is an attempt to get a preliminary idea about the characteristics of the causative bodies, depending on form, shape, trend, differences in amplitude, change or discontinuity of direction and extension of anomalies (Nettleton 1976).

The interpreted magnetic zonation map for the total intensity magnetic map is clearly defined the basic and acidic dykes extension location and the main interpreted zonations in the study area. Four magnetic zones were identified and mapped in total intensity magnetic map (Fig. 7) according to the magnetic characters, frequency and amplitude. The first zone (Z1) is characterized by very high magnetic anomalies reach up to more than 5898 nT and is associated with granite gneiss which a crossed by set of swarms of Damm dyke complex. (basaltic dykes and veins) in the north part, these magnetic characters are also appear in the southern part reflecting the Biash basalt, the elongated features which take NW–SE direction are belonging to this zone and reflecting basic dyke intrusions. This zone (Z1) shows high magnetic characters, very high frequency and very high amplitude. The second zone (Z2), represents the relatively high magnetic values characterized by magnetic anomalies ranging from 5825 and reach 5898 nT and is associated with granitic gneiss which situated in the mid of the eastern part of the study area. They have a vast areal extent. The anomalies of this zone are mainly aligned nearly in the NW–SE directions.

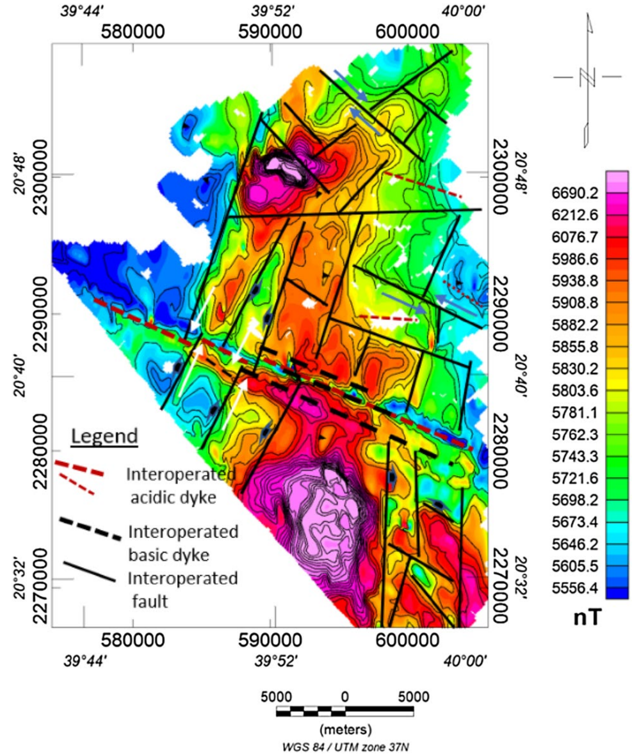



**Fig. 9** Interpreted faults and lineament features of RTP magnetic contour map, the lower part of Wadi Yalamlam area

This zone (Z2) shows high magnetic characters, high to moderate frequency and high to moderate amplitude. The third zone (Z3) represents the anomaly trending mainly to NE–SW. The magnetic values characterized by magnetic ranging from 5722 to 5825 nT and restricted in the north and northwest of the study area and reflecting the magnetic characteristics of Sadiyah formation and granite gneiss (Figs. 2 and 7) which show low magnetic values.

The fourth zone (Z4) is characterized by low magnetic values ranging between 5722 and 5825 nT and is associated with syenogranite in the north and south of the area. These rocks appear in the surface or extended under the Sadiyah formation. The elongated magnetic feature may reflect acidic dyke invaded between the two basic dykes in NW–SE direction in the mid of the map (Fig. 7). This location represented a major shear zone trending in NW–SE direction and injected by basaltic and acidic dykes. These dykes are very important to the storage of the groundwater in the Quaternary aquifer of Sadiyah sub-basin in which they crosscut the main course of Wadi Yalamlam at high angle and act as natural barriers. The two dykes may make good barrier to the ground water in the front of these dykes in the opposite direction of drainage of ground water flow except the locations of cut faults to these dykes which may allow to some of ground water to flow.

#### 4.2.1 Source Parameter Imaging (SPI) Technique

Oasis montaj software was employed to compute the SPI image and depth. The depth to magnetic source was determined through several mathematical processing from RTP grids. SPI image map revealed that the depth estimate of the upper basement depth (i.e., top of the sediment/basement interface) ranges between 46 and 3010 m (Fig. 8).The colour scale in this figure represents the depth estimates to magnetic source rock/body within the study area. The light blue to deep blue colours correspond to areas of thin sediment or shallower magnetic character. The upper colours (purple and orange) correspond to areas bodies of thick sediments or deepest magnetic bodies. SPI technique is used in estimating magnetic depths, which also known as a local wave number (Thurston and Smith 1997). The SPI analysis indicates that the depth to the top of the sediment/basement interface, at the northern part of Wadi Yalamlam, is mainly deeper than the southern part. The elongated trend over the shear zone trending NW–SE with its dykes reflects shallower depth or may appear at the surface.

The interpreted total magnetic map (Fig. 7) and RTP magnetic map (Fig. 9) supported by field observations, measurements and petro-fabric study revealed the presence of three main fault sets and shear zones affected the study area. These fault groups are: (1) NE-SW to ENE–WSW group, (2) NW–SE to WNW–ESE group (Najd fault system), and (3) N–S to NNW–SSE group, which are described in the following paragraphs in details.

### 4.3 The Effects of Dykes on Groundwater Storage and Flow

The principal aquifer to be recharged beneath Wadi Yalamlam basin is the Quaternary wadi deposits aquifer. Unfortunately, there is no information about the groundwater status along the upstream and middle parts of the wadi. Only few wells scattered in the lower part of Wadi Yalamlam basin were observed and measured during the present study. Based on field measurements, depth to the water table in the lower part of the Wadi Yalamlam varies from 7 to 18.6 m. The general direction of groundwater flow in this Quaternary aquifer is assumed to be towards the southwest in the study area. Rainfall occurs in the mountainous part of the study area as thunderstorms of high intensity followed by usual dry periods. The average annual rainfall over the study area ranges from 140 mm at the mountainous part and 60 mm at the Red Sea coastal plain (Madani and Niyazi 2015a, b). Sporadic precipitation occurs over mountainous part and is channeled throughout extensive wadies, drains toward west as surface runoff to reach the flat coastal plain in its way to the Red Sea. Part of the running surface water is infiltrated through the highly fractured basement rocks as subsurface flow running in alluvial aquifers flooring the wadies. Additionally, there is a big portion of rainwater penetrates fractured rocks in the upstream parts to reach the alluvial aquifers. Throughout the field visits to the study area, data from 12 wells distributed around the main dykes crosscutting the lower part of Wadi Yalamlam are gathered and recorded. Parameters which are measured in each well are coordinates, elevation, well diameter and depth to the groundwater which is achieved using water meter (010/Triangle Frame) instrument. Field observation for water table level measurements was planned to identify water wells near each dyke identified in Sadiyah sub-basin. Usually, looking for water wells just before and behind the dyke to examine if there is a difference in water table variation due to the existence of dykes. This is usually done by surveying the area in two ways. The first way is by looking at the satellite images to identify farming area around dykes, which indicate possible locations for water wells. The second way is by visual observation through the area around dykes during sites visits. As mentioned before in Sect. 2, the present study recorded two main dykes (northern and southern) crossing Wadi Yalamlam area. Around the northern dyke water level measurements are collected from five wells, two of which (SA04, SA05) are located to the north of the dyke while the three others (SA01, SA02 and SA03) are within Shaikh Said farm. As for the southern dyke the water level measurements are collected from three wells (MC01, MC02 and MC03 (to be compared to water level depths measured in four wells (SB01, SB02, SB03 and SB04) within Abu Helal farm.

According to the water table elevations and field observations of Sadiyah sub-basin, the aquifer is divided into three parts namely I, II and III (Fig. 10). The first part locates to the north of Sheikh Said farm in the lower part of the main channel (north of 20°47′ latitude) with water table elevation above 158 ms. The second part of the aquifer is the area includes Sheikh Said and Abu Helal Farms between the two major dykes. The measurements of the water table elevations at Sadiyah village and just the north of Sheikh Said farm (north of 20°44′–south of 20°47′) reach 124 m. Whereas they attain 108 m in the area of Abu Helal farm (north of 20°39′ south of 20°44′). The third part of the aquifer represents the rest of downstream part (south of 20°39′) with water table elevation below 66 m. These subdivisions were categorized according to th e field observations which clarify the effects of dykes distributed in the lower part of Wadi Yalamlam (Sadiyah sub-basin). The northern dyke is clearly serve as a subsurface dam that prevents an easy flow for the groundwater from the upstream part of the aquifer northern to Shaikh Said farm where the water table is more than 158 meter and goes down to 135.5 m just behind the dyke in Shaikh Said farm and surroundings (Fig. 11). Two wells were observed and their water levels were measured in the area northern to the dyke in whom they attained

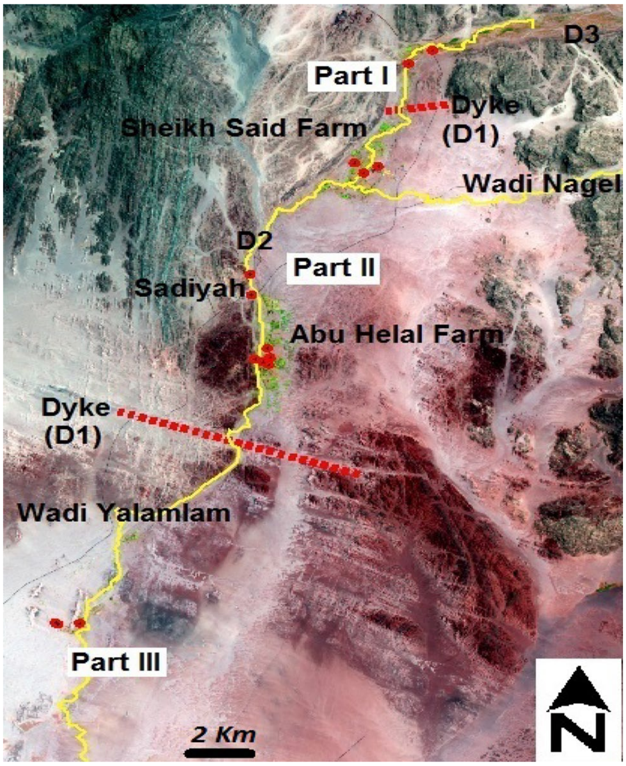


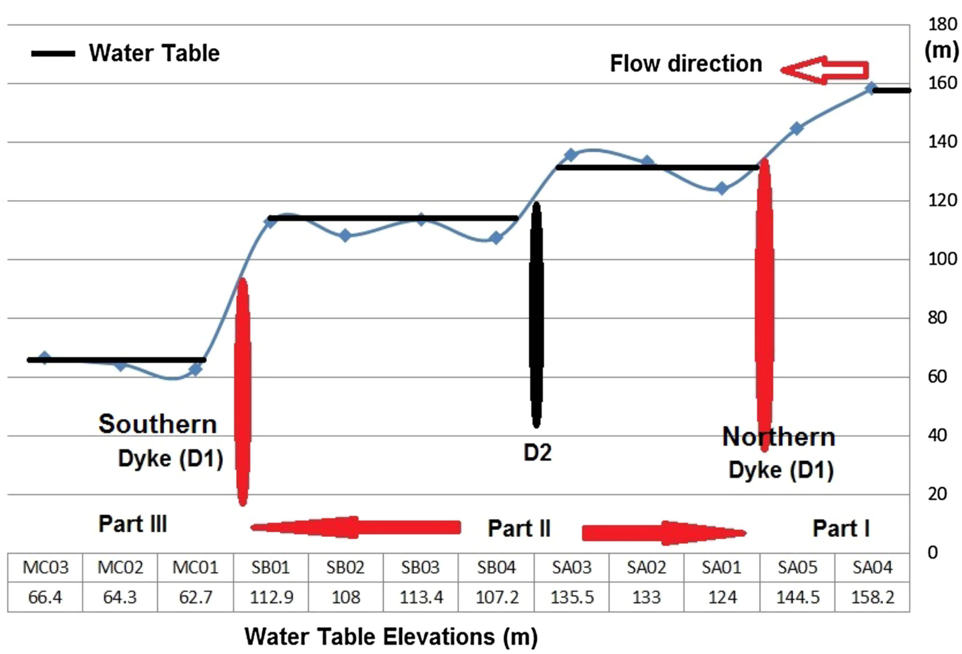

**Fig. 10** False color composite Landsat imagery shows subdivisions of the aquifer of Sadiyah sub-basin, lower Wadi Yalamlam area

158.2 m (well SA04) and 144.5 m (well SA05). The reason for this dramatic difference between water levels in those two wells, even they are very close to each other, is that the pump in well SA05 had been running for few hours when measurement was taken. Well SA04 is just an observation well dug by the National Water Company and has no pumps. It is noticed that this northern dyke has a major effect on groundwater level and production in the aquifer even there is a small sub-basin (wadi Nagel) drains into the area just east and south to Shaikh Said farm in a flat area providing more recharge to the ground water. The drop of water table is more than 20 m between the north and south of the dyke areas.

Part II of Sadiyah aquifer represents the area lies between the two main dykes (Figs. 10, 11). Collecting observations during the field visits to the wells help in understanding the aquifer behavior in part II. The dyke swarms obey D2 type are crossing the aquifer between Sadiyah village and Shaikh Said farm diagonally from north to south causing a drop in water table from 135 m around Shaikh Said farm to 108 m at Sadiyah village. D2 dyke is not one single dyke, but a series of parallel dykes that may serve as water barriers. These dyke swarms are also affect the water table in the aquifer since the drop is about 16 m. These dyke swarms may prevent any recharge from the fractured rocks in the west side of Sadiyah village. The water table level continues in the same level until Abu Helal farm and further as observed in water level measurements in wells in that area. Water table looks unchanging between Sadiyah village and Abu Helal farm even there is a heavy pumping occurs around Abu Helal farm.

The southern major dyke is crossing the aquifer at high angle separating the lowest part of Sadiyah aquifer from the rest of the basin (Figs. 10, 11). This dyke exists in a flat area of the basin where less running water reach there and spread over a wide flat sandy land. These conditions cause more water to infiltrate into the soil and more evaporation

**Fig. 11** Water table elevations (meters) in relation to dykes exposed at Sadiyah sub-basin, lower part of Wadi Yalamlam area



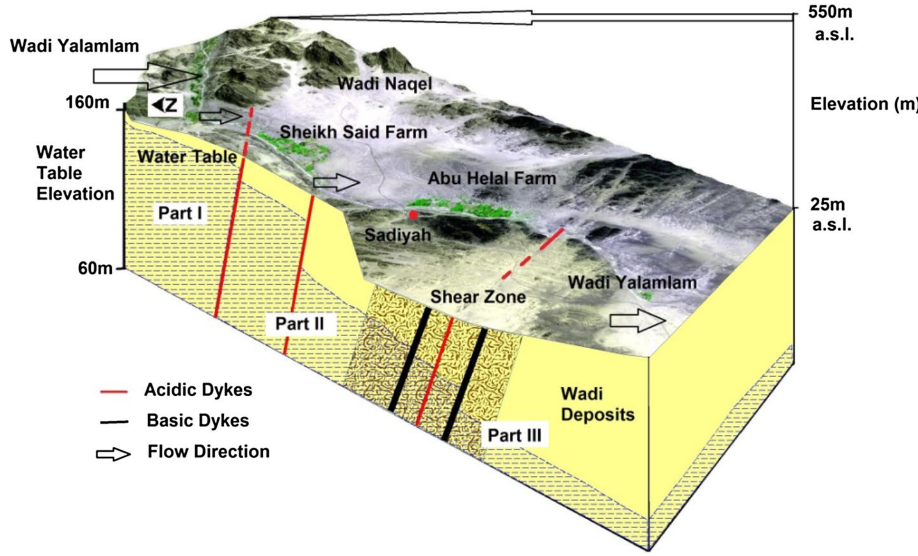



**Fig. 12** 3D perspective view of enhanced FCC Rapid Eye imagery (3, 5 and 4 in RGB) draped over ASTER GDEM digital elevation model, Wadi Yalamlam basin shows the effect of dykes (red) on the Sadiyah sub-basin

to occur. When water infiltrate in a larger area, it stays close to the soil surface and got evaporated easily. Additionally, more evaporation occurs when larger area of the soil is wet. Because of those conditions in the area at southern dyke and southwestern part of the basin, an extreme drop in water level is expected. This is what was observed when water level measurements in the area southern to the D1 dyke dropped more than 44 m.

Figure 12 shows the 3D perspective view of FCC RapidEye image (bands 3, 5 and 4; RGB) draped over digital elevation model of ASTER data. It shows the effects of dykes on the storage and flow of the Quaternary aquifer of Sadiyah sub-basin, lower Wadi Yalamlam. The cross-section view is drawn based on elevation data, depth to groundwater measurements and field observations collected throughout the present study. Water table elevations are calculated from depth to water table collected throughout the present study.

## 5 Conclusions

According to collected data and obtained results of present study, the following points are concluded:

- Field visits to the study area supported by the processed FCC Landsat band ratio images revealed the presence of three main different types of dykes.
- The older sheared basic and acidic dykes are very important to the storage of the groundwater in the Quaternary aquifer of Sadiyah sub-basin in which they crosscut the main course of Wadi Yalamlam at high angle and act as natural barriers. These older dykes are recorded within the N70 W shear zone observed to the south of Sadiyah village.
- The Quaternary aquifer of Sadiyah sub-basin is divided into three parts, each has distinctive characteristics. The water table elevations decreased from 158 m in the first part (I) to reach 66 m in the third part (III) of the aquifer.
- Field measurements aided by the interpreted total magnetic map and supported by the petro-fabric study reveal the presence of three main fault systems affect the basement rocks covering the study area. These faults are trending in NE–SW to ENE–WSW, NW–SE to WNW–ESE (Najd Fault System) and finally N–S to NNW–SSE directions.
- The present study presents two new extensions favorable for agricultural activities.

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