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Chapter 3. GEOLOGICAL SETTING OF SANA'A BASIN

EXECUTIVE SUMMARY

The aim of this chapter is to describe the geology based on previous work and new fieldwork. The fieldwork covered the entire Sana'a Basin in general and the areas of Nihm, Bani Hushaish and Hamdan in particular, especially where the Cretaceous Tawilah sandstone outcrops at the ground surface. The fieldwork concentrated on delination of the geological formations and the incidence of geological structures.

The nature of the basin boundaries, especially in the northern (Al-Kharid area), eastern (Nihm and Bani Hushaish) and western sides of the basin (Wadis Al-Ahjur and the upper catchment of Wadi Surdud) have also been investigated.

3.1. Historical background

Geological exploration in Yemen dates from the 18th century with the travels of Niebuhr in 1763 (Geukens, 1966), who succeeded in crossing the area between Al- Hudeidah, Sana'a, Taiz and Al-Mukha. The first geological studies resulted from the exploration of Botez (1912) and Glaser (1913), which provided the foundation for future exploration. Lamare (1923) crossed the south-western and central parts of Yemen. He gathered considerable geographic and geologic data and established a preliminary stratigraphic column. Some years later, Rathjeins and Wissmann (1929) obtained permission to conduct scientific studies in the Al-Hudeidah-Sana'a-Taiz region. They made four trips in 1927-28, and completed the studies started by Lamare. More recently, several authors (Geukens, 1960, 1966; Grolier and Overstreet, 1978; Roland, 1979; Kruck, 1980, 1983, 1984; Overstreet et al. 1985, Robertson 1990 and Kruck et al, 1991) have established a geological column for the western part of Yemen (Including Sana'a Basin) and various scale geological maps. The first comprehensive work on the onshore stratigraphy of the western part of Yemen was carried out by Geukens (1960, 1966), who identified the Proterozoic basement which is unconformably overlain by the Wajid sandstone formation (Permian or older), Kohlan Group (early Jurassic), Amran Group (middle to late Jurassic), and the Tawilah Group (Cretaceous – early Tertiary). These sedimentary units are overlain by alkaline and sub-alkaline basalts, and per-alkaline silicic rocks of the Yemen Volcanic Group that erupted during the Tertiary. Finally, during the Quaternary period, alkaline volcanic rock and wadi deposits formed.

3.2. General outlines

The evolution of Sana'a Basin started in the early Cambrian, which follows the old tectonic trend of north-south and east-west directions. These two trends were probably reactivated by Hijaz and Najid progenies, which represent the oldest and dominant tectonic trends to affect Yemen and the Arabian Peninsula. During the Cambrian-Ordovician time, the initial main trend of the Sana'a Basin was formed and continental clastic sediments were deposited, such as the Kohlan sandstone group. During the Jurassic era, the subsidence increased, giving rise to a deep depression of a northwest-southeast trend. During this time, the Amran limestone group was deposited to give considerable thickness (more than 1600 m thick), as has been revealed in Arhab and Al-Hitarish wells (DS1 and DS2 Exploratory Deep Wells). During the Cretaceous era, Sana'a Basin was subjected to uplifting and received a lot of clastic rocks of the Al-Tawilah sandstone group. In the late Cretaceous, both Amran and Tawilah groups were affected by east-west tectonic movement resulted in the formation of extensional faults such as Wadi Dhahr, Wadi As-Sirr and Al-Sabaeen faults in Sana'a Basin. The basin stratigraphic sequence was intruded by Yemen volcanic rocks covering all the old sedimentary units. In the final stage of volcanic eruption, the Sana'a Basin was subjected to compressional deformation in which the Sana'a anticline was formed with fold axis of a north-south trend and plunging towards the south in a steep dip. The location of the fold axis in most areas of the Sana'a Basin is eroded away and now represents the Sana'a plain. The anticline fold is of asymmetrical type with low angle of two limps. In the north, the fold axis becomes horizontal, such as in the Thoma and the Arhab areas. In addition to this big fold, there are small folds associated with extensional faults resulting in tilting blocks and local compression (Al-Qutbah, 2002).

Two major factors have contributed to the complexity of the surface as well as the sub-surface geology and structures across Sana'a Basin. These two factors represent the effect of two young rift systems bounding the region from the south (Gulf of Aden Rift) and from the west (Red Sea Rift) and their superimposition on the much older regional Najid fault system (WEC, 2003). Two other active boundaries, such as the Zagrous thrust to the east and the Dead sea strike slip fault in the north, also contribute to the complexity of the geological conditions of the Basin (Al-Kotbah, 2002). This has resulted in the accumulation of old Paleozoic to Mesozoic sedimentary formations over the crystalline basement (Al-Qutbah, 2002).

Another stage of extensional faulting has resulted in the shaping of the basin, which was contemporaneous with the opening of the Gulf of Aden and the Red Sea rifts. Hadda, Assier and wadi Quthi faults represent some of these extensional faults. All these extensional faults strike E-W. The vertical displacement of Hadda fault reaches to more than 300 m. After a quiescence of volcanic activity and the presence of a large number of faults and fractures, late volcanic activity has occurred where a lot of dykes and plugs of different trends (the dominant trend north-south, northwest-southeast and east-west) intruded all the stratigraphic sequence from Precambrian to Tertiary rocks. Within Sana'a Basin and along north-south fractures, the rocks are eroded away, forming the intermountain plain of Sana'a Basin. The post tectonic movement that occurred during the Quaternary time was accompanied by volcanic activity that intruded the old rocks. This stage of volcanic activity has a very distinct morphology characterized by its distribution as scatter cones, cinders, dykes and plugs and, sometimes, spread as lava flow in the low land, Al-Kotbah, 2002.

3.3. Geological Fieldwork in Sana'a Basin

Based on the inception report, and after collecting and processing the previous data, as well as identification of the main information gaps related to geology, structures and surface distribution of the aquifers in Sana'a Basin, intensive geological fieldwork has been carried out within a period of about six months (December 2006 to June 2007) in order to bridge these gaps. The fieldwork covers the entire Sana'a Basin in general and the areas of Nihm, Bani Hushaish and Hamdan in particular, especially where the Cretaceous Tawilah sandstone outcrops at ground surface. The nature of the basin boundaries, especially in the northern (Al-Kharid area), eastern (Nihm and Bani Hushaish) and western sides of the basin (Wadis Al-Ahjur and the upper catchment of Wadi Surdud) have also been investigated. According to the inception report, the geological field survey focused mainly on several issues related to the Cretaceous Tawilah sandstone and the Quaternary Alluvial aquifers. Several problems related to these two main aquifers in the basin have been addressed. The most important issues studied are as below:

- Surface Geology (Delineation of surface distribution of aquifers),
- Stratigraphic Sequence of Sana'a Basin,
- Geological Structures of Sana'a Basin,
- Lateral and vertical lithological variation of the Tawilah group,
- Collection of fresh rock sample representing the different members in the Tawilah sandstone for effective porosity determination, and
- Nature of the lateral boundaries of The Cretaceous Tawilah aquifer.

This chapter has been devoted to throwing light on the findings of the geological field survey performed by Hydrosult consultants in order to address the main information gaps identified after reviewing the previous studies. Following is a brief description of the different issues mentioned earlier.

3.3.1 Surface Geology (Delineation of surface distribution of aquifers)

The recommendations of the inception report had indicated that the consultants would conduct field geological surveys in Sana'a Basin, giving particular attention to Hamdan, Bani Husheish and Nihm areas where the sandstone can be observed in outcrops with its stratigraphy reflecting intensive tectonic activities. Accordingly, the field team work began a geologic field survey in Sana'a Basin during the period between December 2006 and the end of June 2007. The total ground truth stations (GPS points) used to delineate surface distribution of the different lithostratigraphic units are 855 points, comprising 181 points in the Nihm area, 82 points at Bani Hushaish, 592 points at Hamdan and the rest of the basin. These GPS points have been plotted on the topographical, geological and satellite image maps for the purpose of comparison and validation of the data in order to ensure reliable results.

3.3.2 Geological field survey carried out in the Nihm area

The Nihm area is located in the northeastern part of Sana'a Basin between 1719957 and 1745510 N and longitudes 426779 and 456429 E. It covers an area of 545.655 km^2 and includes a survey of Yemen. The important villages in the area are Al-Madid, Khulaqah, Al-Haiathem Arisha, Al-Mahager Ghulat Assim, Mahali, Al-Maddi, Meswara, Bani Naji, Bani Faraj, Selaha, Al-Wagashah etc. A network of unmetered roads connects these villages with each other. The main Sana'a-Marib asphalt road passes through the area from west to east. The most important catchment areas are Khulakah, Arisha, Wadi Bani Tawaf (Shaiban), and Wadi Al-Qatab.

Geological fieldwork has been started in the remote parts of the Nihm area, which had not been studied geologically on the field so far. Obstacles usually facing previous studies in the Nihm area were mainly represented by unsafe, rigid topography and difficult access to remote and mountainous areas. During the fieldwork we required the help of influencial key persons, tribal Sheikhs, local council members and government officials in order to assist us in performing our geological fieldwork. The field team began an intensive geologic field survey in the Nihm area during the period of December 9-17, 2006 to develop the above-mentioned recommendations. A brief description of this fieldwork is given in Table 3-1. A detailed description of the geological field survey of the Nihm area is given in geological field survey note 1. The GPS points have been plotted on the Hydrogeological map (Figure 3-1).

Table 3-1 Summary of the geological field survey activities in Nihm area

S.N	Day	Date	Name of visited areas	No. of GPS points	No. of wells surveyed	Measured Physical Properties
1	Saturday	9/12	Khulaqah, Bani Zetr, Bani Mesar, Selahah, Wadi Bani Tawaf and Shaiban, Wadi Thajer, Wadi Al-Gail	33	3	--
2	Sunday	10/12	Meswarah, Eial Mohamed, Al madarej, Thabowa'h Road.	19	12	--
3	Tuesday	12/12	Khulaqah, AlSadrah and Bani Eraman	9	6	--
4	Wednes-day	13/12	Thumah, Al Mahajir, Wadi Sheraa, Markn and Bani Eraman	41	8	EC & pH
5	Thursday	14/12	Asir, Ghulat Assim, Shaban, Al - Wagashah	14	3	EC & pH
6	Saturday	16/12	Khulaqah, Bani Naji, Wadi Gailamah and Bani Saa	29	--	EC & pH
7	Sunday	17/12	Wadi Mahali, Wadi Al Qatab, Wadi Madfon	36	7	EC & pH
Total				181	39	

The geological survey in the Nihm area covered the delineation of surface distribution, geological structures and geological boundaries between the different lithostratigraphical units (Figure 3-3). It was found that the Cretaceous Tawilah sandstone, which is located along the eastern boundary of the basin (Al-Madarej and Al-Madfon areas), has been subjected to intensive tectonism. This can be attributed to two main factors. The first is represented by the major normal fault located close to the eastern boundary (Water Divide) between Sana'a and Al-Jawf Basins. This fault is northwest-southeast in direction, with approximate vertical displacement of about 300 m. Along this fault, the Jurassic Amran limestone was uplifted to the surface (about 300 m above ground level), forming a huge mountain range extending northwest-southeast for a considerable distance towards the old Jabali mine. The major fault can be traced easily on the satellite image (Figure 3-2). The second factor is represented by a series of volcanic plugs that intruded the Cretaceous Tawilah sandstone Group at several locations along the northeast boundary of the basin. The most important volcanic plugs recorded in this area are Jabal Al-Salda plug, Jabal Al-Harim and Jabal Al-Qatab (Photo 3-1). These volcanic plugs are aligned along a straight line located in proximity to the major fault. The geological survey indicated the extension of the Cretaceous Tawilah sandstone Group beyond the basin boundary, particularly at Al-Madarej, Wadi Al-Madfon, Jabal Al-Qatab and Wadi Al-Mahjar. Moreover, the collected lithological and structural data helped to verify and correct the previously compiled geological map of Sana'a Basin prepared by GAF, 2005 and construction of subsurface geological cross-sections of this area. On the other hand, the new data collected (well log lithology, water level, electrical conductivity and pH) helped in refining the aquifer geometry, potentiometric and depletion maps.

It is clear from the geological map of the Nihm area (Figure 3-2) that the different lithostratigraphic units outcropped at ground surface are the Jurassic Amran, Limestone, the Cretaceous Tawilah sandstone, and the Tertiary volcanic group. The areal distribution of these units is given in Table 3-2.

Table 3-2 Calculated surface area of lithostratigraphic units exposed in the Nihm area

Lithostratigraphic Units	Hydrosult (2007)	
	Area (km^2)	% of Area
Tertiary Volcanics	92.358	16.92608
Cretaceous Tawilah sandstone	187.634	34.38687
Jurassic Amran limestone	265.664	48.6871
Total Area of the Nihm Area	545.655	100%

It is clear from Figure 3-2 and Table 3-2 that the Jurassic Amran limestone is exposed mainly at ground surface in the north-western part of Nihm, covering an area of 265.664 km^2 (48.6871% of the Nihm area). The Cretaceous Tawilah sandstone is mainly exposed in the eastern, southern and western part of Nihm with an areal distribution of 187.634 km^2 (34.38687% of the Nihm area). The Tertiary volcanics group is mainly present as isolated outcrops in the eastern and southern parts of Niham with an areal distribution of 92.358 km^2 (16.92608% of the Nihm area).


Volcanic Intrusions
Tawilah sandstone

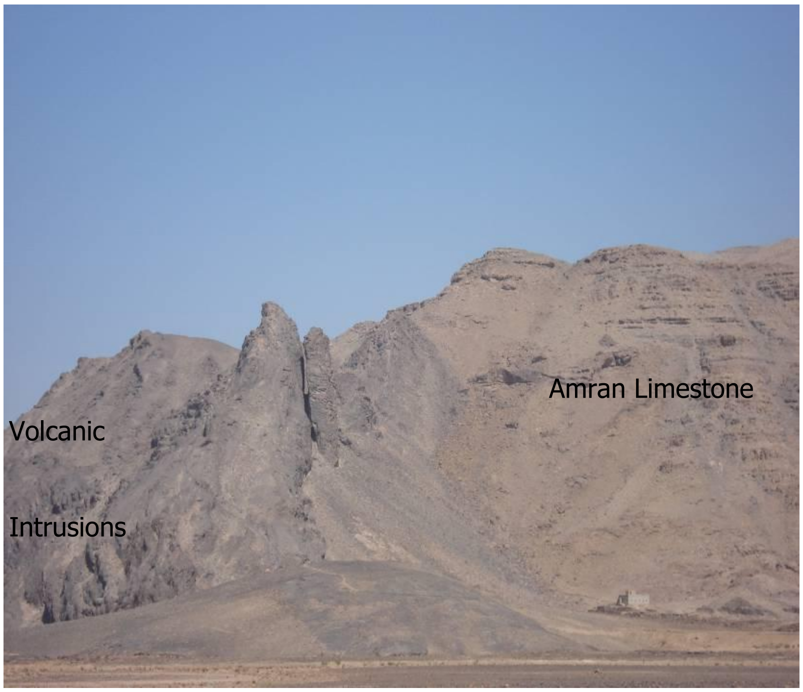

Amran Limestone
Volcanic
Intrusions

Photo 3-1 A & B Volcanic Intrusions along the north-eastern boundary of the basin (Nihm area)

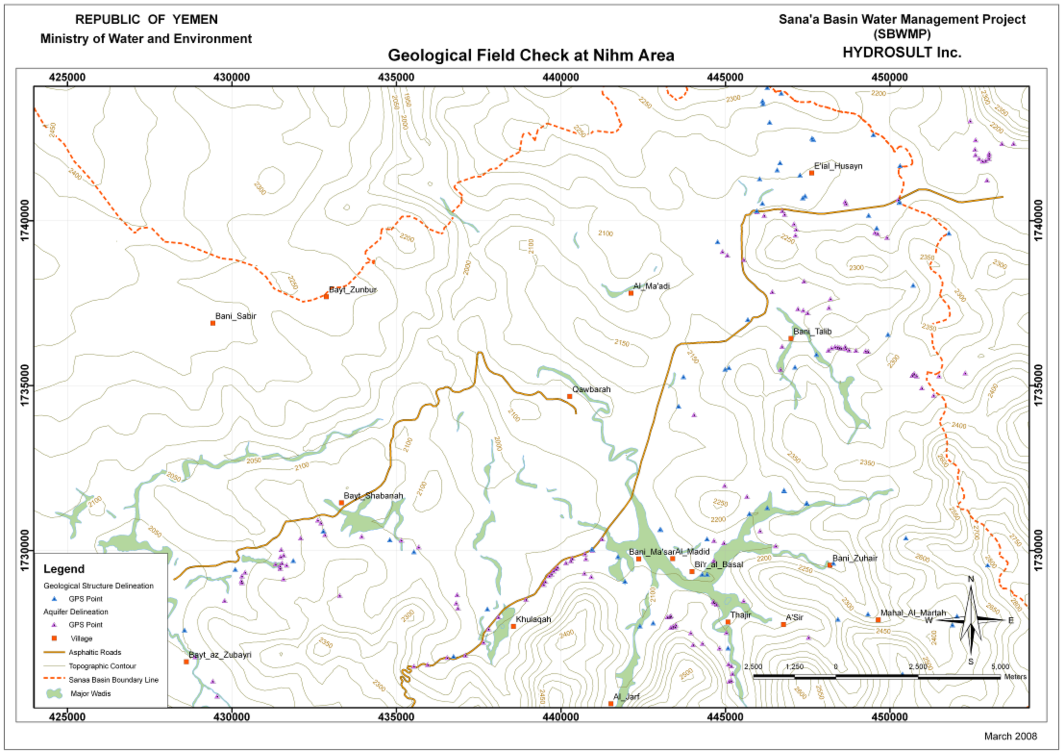


Figure 3-1 Layout of the fieldwork results carried out in the Nihm area, NE of Sana'a Basin (GPS locations)

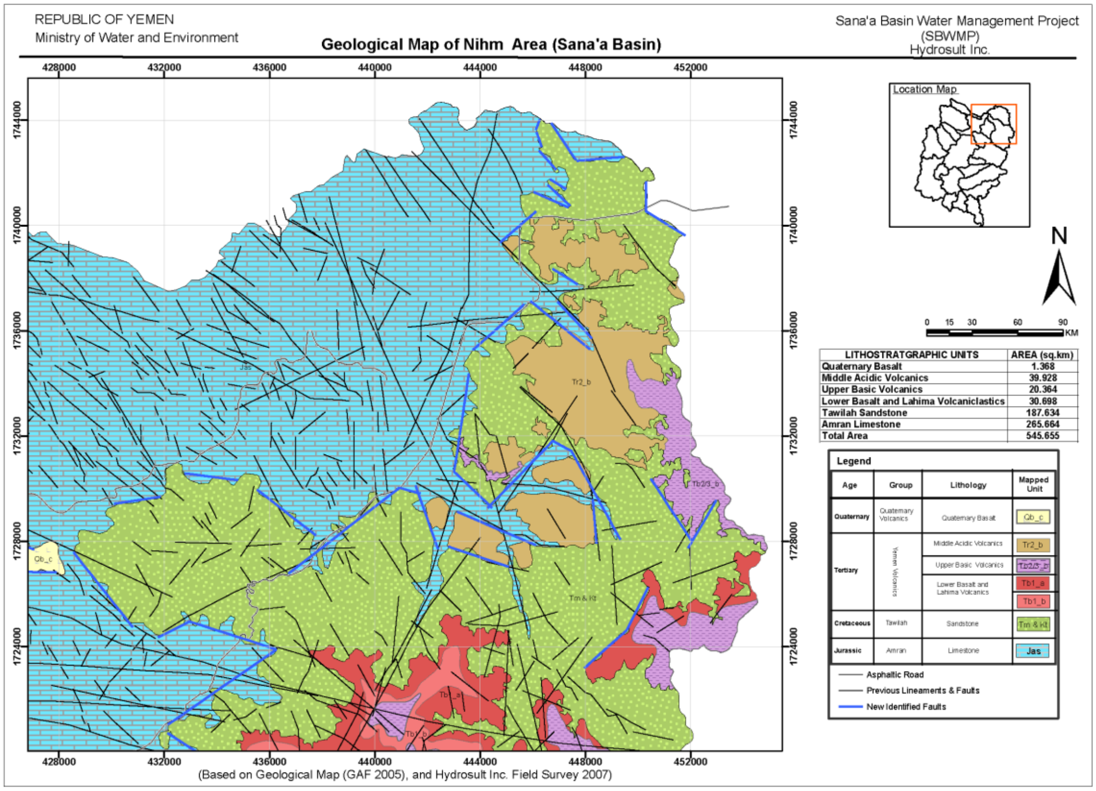


Figure 3-2 Geological map of Nihm area (Sana'a Basin)

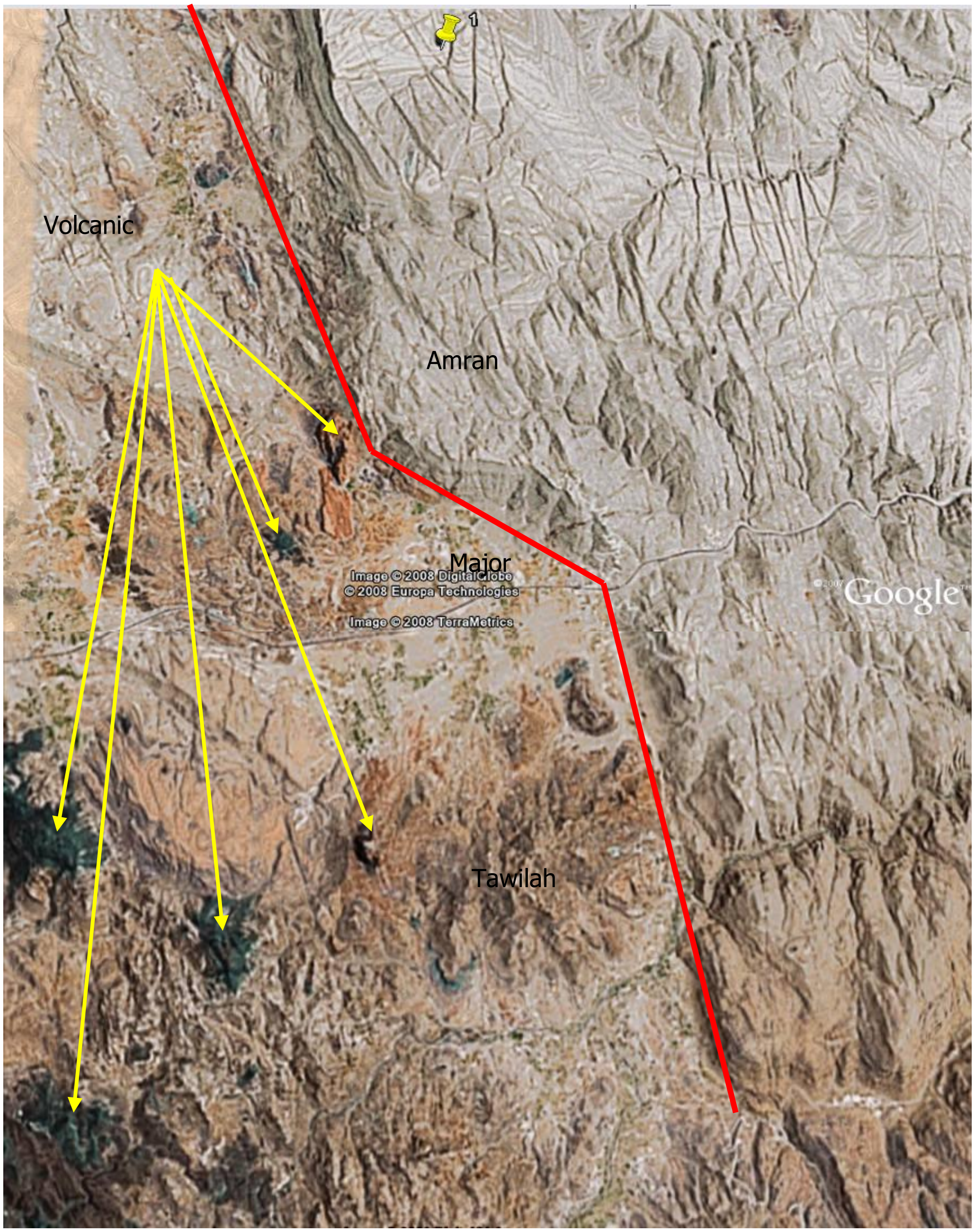


Figure 3-3 Satellite image showing the NE-SW major fault located NE of the basin boundary

3.3.3 Geological field survey carried out in the Bani Hushaish area

The Bani Hushaish area is located in the eastern part of Sana'a Basin between 1692000 and 1728000 N and longitudes 423100 and 448000 E. It covers an area of 433.934 km^2. The important villages in the area are Bait Alsayed, Al-Sharia, Bait Al-Nokhaif, Al-Abna, Bait Al-Jamrah, Bani Dawood, Wadi Mal Al-Dawlah, Ghadran, Al-Ghiras, Zijan etc. A network of unmetalled roads connects these villages with each other. The main Bani Hushaish-Sana'a asphalt road passes parallel to the main course of Wadi As-Sir. The most important catchment areas are Wadi Al-Sirr, Wadi Sawan, Wadi Al-Malika, Wadi Ghadran, etc.

The field team work began an intensive geologic field survey in the accessible parts of ***Bani Husheish area*** during the period of December 19-27, 2006 to determine the mentioned recommendations. A brief description of the results of this fieldwork is given below (Table 3-3).

Table 3-3 Summary of the geological field survey activities in Bani Husheish area

S.N	Day	Date	No. of GPS points	No. of pumping tests	No. of wells surveyed	Measured physical properties
1	Tue.	19/12	15	--	3 wells	
2	Wed.	20/12	13	--	3 wells	
3	Sat.	23/12	9	1	6 wells	
4	Sun.	24/12	2	1		EC & pH
5	Tue.	26/12	14	2		EC & pH
6	Wed.	27/12	29	2		EC & pH
Total			82	6		

82 GPS ground truth points have been performed in the Bani Hushaish area for aquifer and geological structure delineation (Figure 3-4) (Table 3-3). The geological field survey indicated that both the stratigraphy and geologic boundaries of the different lithostratigraphical units in the Bani Hushaish area reflect simple tectonic activities by comparison to the Nihm area (Figure 3-5). The geological survey provides a better understanding of the nature of the structural geology and the areal extension of both the Cretaceous Tawilah sandstone and the Quaternary alluvial aquifers in this area. Moreover, the lithologic and geologic recent data obtained from the intensive field survey helped in verifying the previous geological map of Sana'a Basin, that compiled by GAF, (2005) and construction of subsurface geological cross sections of this area. In addition, the borehole data collected (well log lithology, water level, electrical conductivity and pH) helped in refining aquifer geometry, potentiometric and depletion maps (Table 3-3). On the other hand, the raw data of the six pumping tests carried out in the Bani Hushaish area provided a new approach to the local hydraulic connection between the two present

aquifers (The Cretaceous Tawilah and the Quaternary alluvial) in certain localities of the Bani Hushaish area. Detailed information is given in Chapter 5.

It is clear from the geological map of the Bani Hushaish area (Figure 3-5) that the different lithostratigraphic units outcropped at ground surface are the Cretaceous Tawilah sandstone, the Tertiary volcanic group and the Quaternary alluvial deposits. Using GIS techniques, the areal distribution of these units has been calculated and is given in Table 3-4.

Table 3-4 Calculated surface area of lithostratigraphic units exposed in the Bani Hushaish area

Lithostratigraphic Units	Hydrosult (2007)	
	Area (km^2)	% of Area
Quaternary Alluvial	141.075	32.5107
Tertiary Volcanics	199.436	45.95998
Cretaceous Tawilah sandstone	55.613	12.81600
Jurassic Amran limestone	37.809	8.7131
Total Area of the Bani Hushaish area	433.934	100%

It is clear from Figure 3-5 and Table 3-4 that the Jurassic Amran limestone is exposed mainly at ground surface in the northern part of the Bani Hushaish region, covering an area of 37.809 km^2 (8.7131% of the Bani Hushaish area). The Cretaceous Tawilah sandstone is exposed mainly in the central and northern parts of Bani Hushaish with an areal distribution of 55.613 km^2 (12.81600% of the Bani Hushaish area). The Tertiary volcanics group is mainly outcrops in southern and eastern parts of the Bani Hushaish area with an areal distribution of 199.436 **km**^{2} (45.95998% of the Bani Hushaish area). The Quaternary Alluvial outcrops in the central and western parts of the Bani Hushaish covering an area of 141.075 km^2 (32.5107% of the Bani Hushaish area).

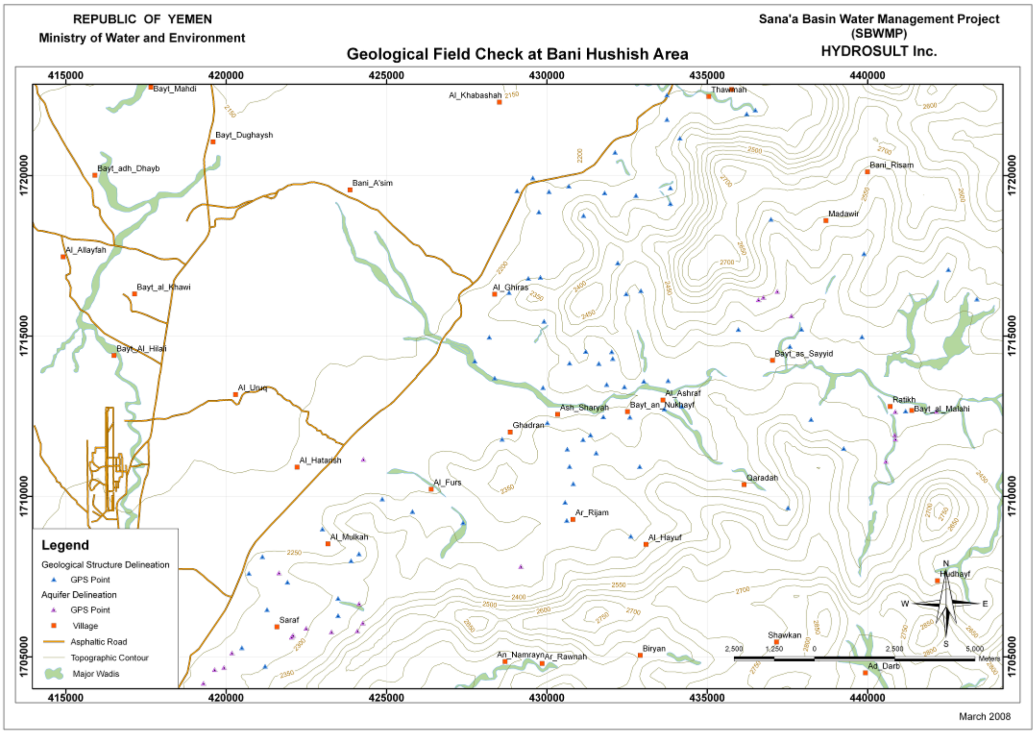


Figure 3-4 Location map of GPS points delineating structures and aquifer boundaries in the Bani Hushaish area

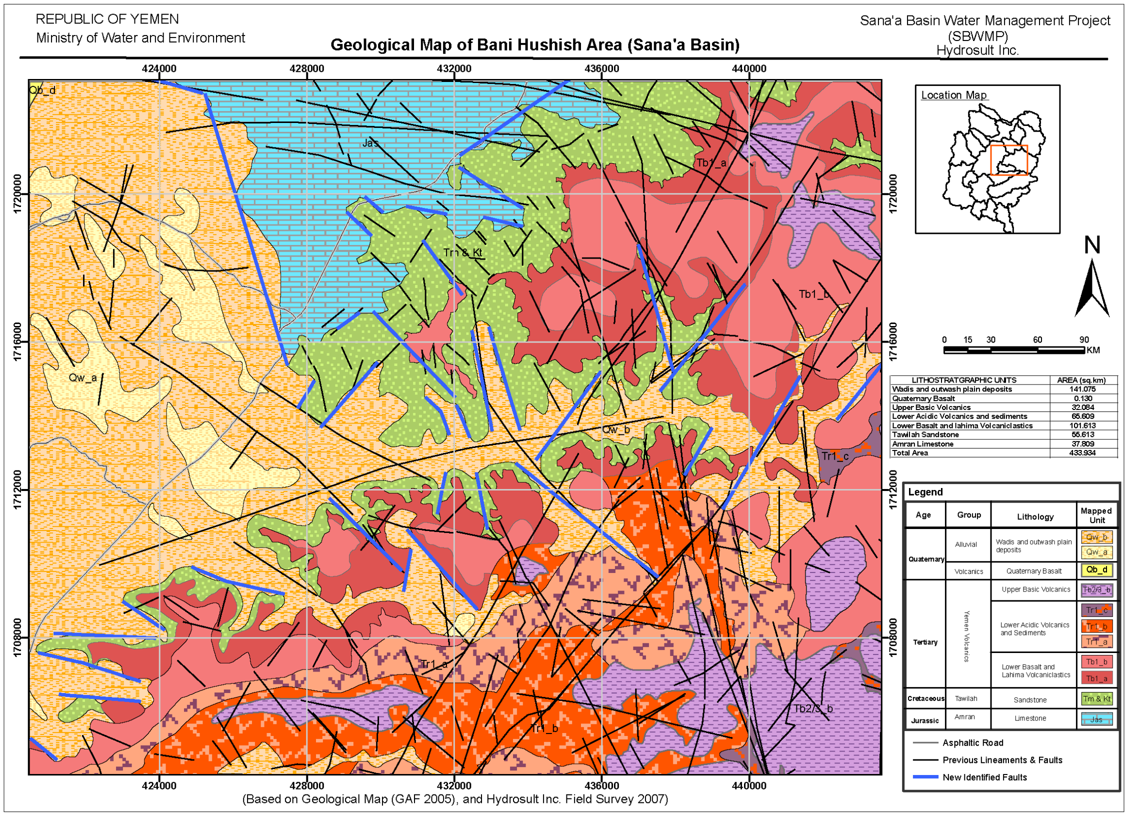


Figure 3-5 Geological map of the Bani Hushaish area (Sana'a Basin)

3.3.4 Geological field survey performed in the Hamadan area

The Hamdan area is located in the western part of Sana'a Basin between 1697687 and 1715474 N and longitudes 395383 and 417445 E. The important villages in the area are Al-ghurzah, Al Sedrah, Wadi Zahr, Taibah, Eram Tozan, south of Tozan, North, East of Tozan, Al-Mahjer, Wadi Al-Eqbal, Jabal Al-Naks, Wadi Zahr, Shamlan, Madam, Al-Jowah, Al-Mahjar Al-Hanajer, Bait Al-Hamzah, Bait Naam, Wadi Eram, 60th Street (Sana'a City), East of Ka'a Al-Monakkab, Shea'ab Tozan, Jader, Jabl Al-Humah, Jabl Shmsan, Kariat, Al-Qabil, Alman. A network of unmetalled roads connects most of these villages with each other.

The geological survey in the Hamadan area was carried out during the period between April 17 and June 23, 2007. A brief description of these field activities is given below (Table 3-5). The total GPS ground truth points that have been used to delineate the surface distribution as well as the structural features in the Hamdan area are 421 points (Table 3-5). These GPS points have been plotted on topographical, geological and satellite image maps for the purpose of comparison and validation of the data in order to ensure reliable results (Figure 3-6, 3-7 and 3-8).

Table 3-5 Summary of geologic field survey activities in Hamdan area

S.N	Day	Date	Name of visited areas	Directorate	No. of GPS points
1	Tuesday	17/04	Al-ghurzah, Wadi Aram, Al-Hanajer, Eram south of Tozan	Hamdan	61
2	Thursday	19/04	Al Sedrah, Wadi Zahr, Taibah, Eram south of Tozan, Al-Mahjer, Tozan	Hamdan	31
3	Sunday	22/04	Madam, Tozan, Al jowah –Madam, East of Tozan, Al mahjar East of Tozan, Tozan	Hamdan	52
4	Wednesday	25/04	Jader, Jabl Al-Humah, Jabl Shmsan, Jabl Eram, kariat Al qabil, Al man	Hamdan & Bani Al-Harith	82
5	Thursday	26/04	Shamlan, Al Hasabah	Hamdan & Al-Amanah	34
6	Wednesday	02/05	Bait Al Hamzah, Bait Naam, Al-ghurzah, East of Ka'a Al monakkab, Shea'ab Tozan	Hamdan	44
7	Thursday	03/05	North Tozan, Wadi Al-Eqbal, Jabal al Naks, Wadi Zahr, Shamlan	Hamdan	18
8	Wednesday	09/05	Wadi Eram, Wadi Zahr, Shamlan, 60Street,	Hamdan & Al-Amanah	57
9	Saturday	23/06	Hamdan(Shamlan, Dula'a, Al Dehara and Barish) , Bani Matar(Qa Al msebe, Qa Sahman, Matna ,Bit Qahin, mend and Al Subaha)	Hamdan & Bani Mattar	42
Total				-	421

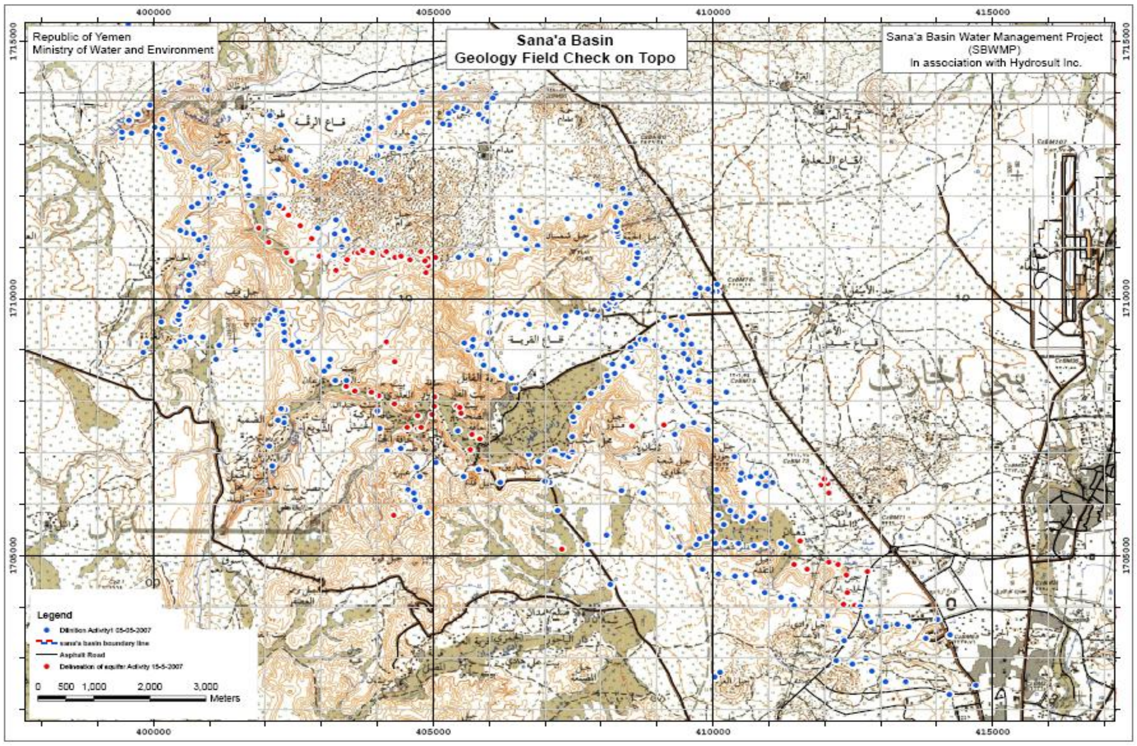


Figure 3-6 Location map of the GPS points surveyed to delineate the different aquifer boundaries in the geographic map of NW Sana'a Basin

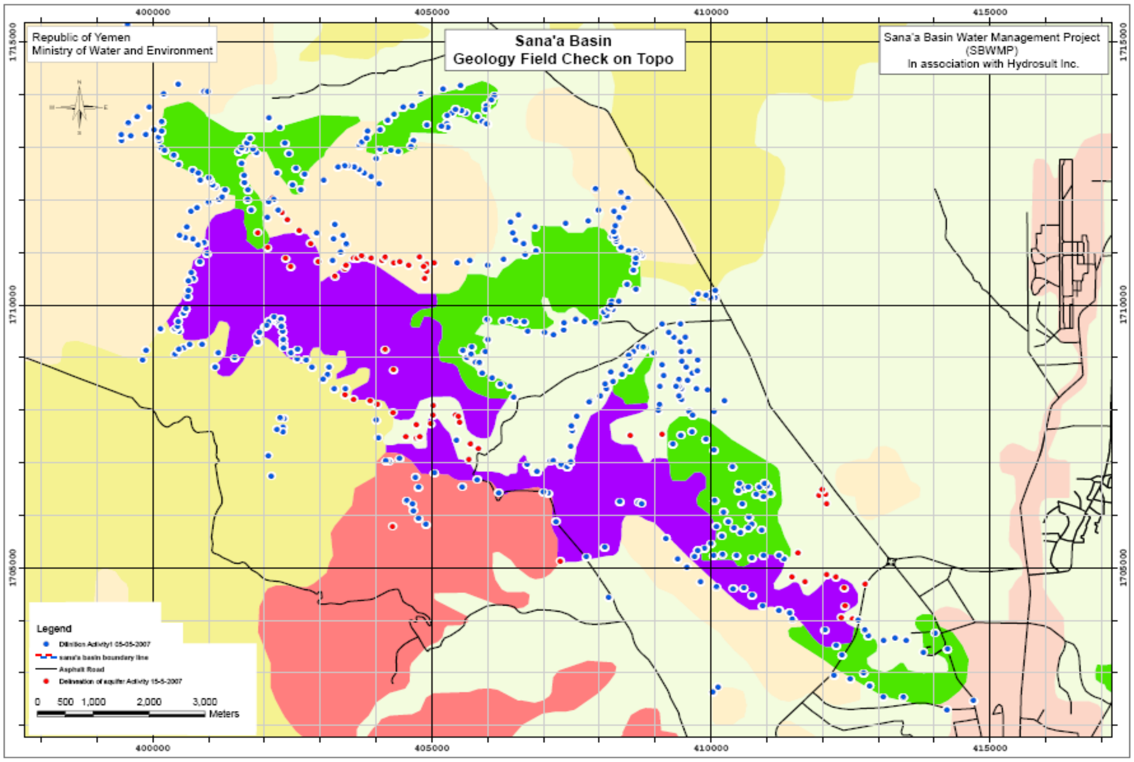


Figure 3-7 GPS points surveyed to delineate the different aquifer boundaries in the geologic map of NW Sana'a Basin

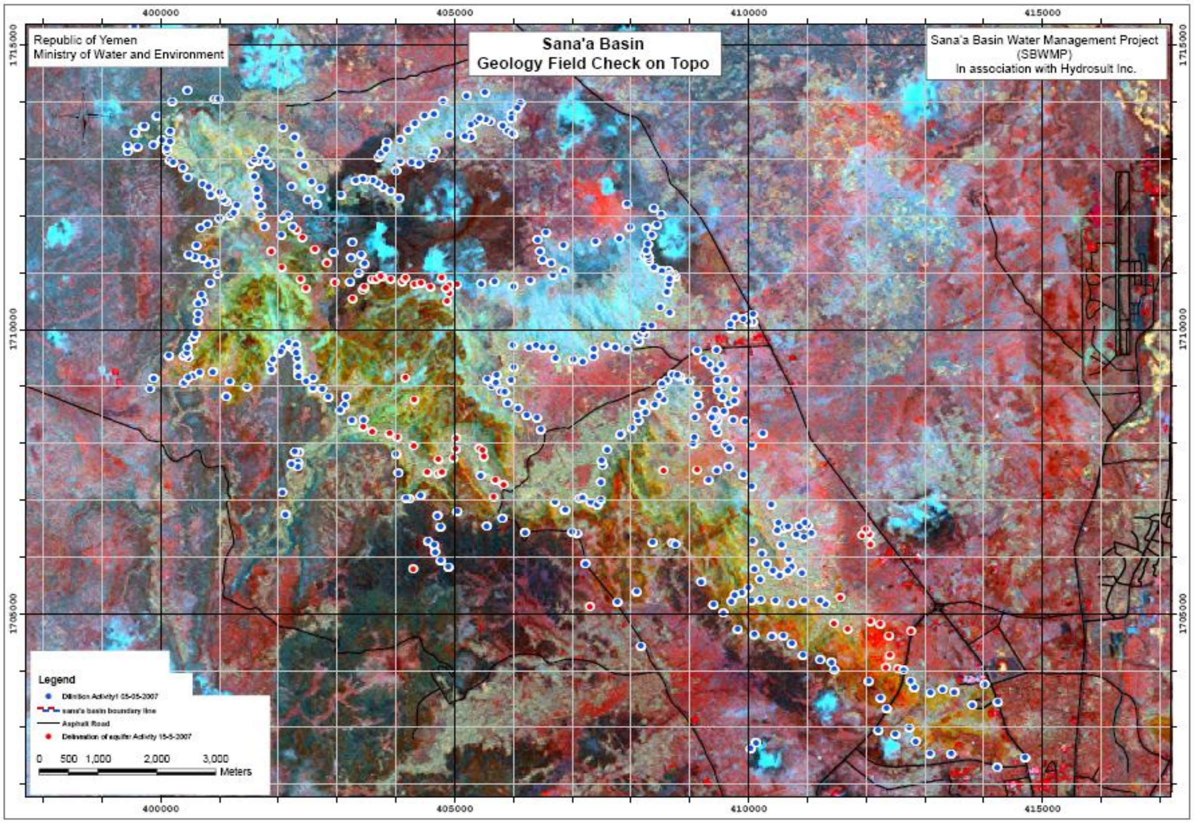


Figure 3-8 GPS points surveyed to delineate the different aquifer boundaries in the satellite image of the NW Sana'a Basin

It is clear from the geological map of Hamdan area (Figure 3-9) that the different lithostratigraphic units outcropped at ground surface are Cretaceous Tawilah sandstone, Tertiary volcanic group, Quaternary volcanics and Quaternary alluvial deposits. The areal distribution of these units is given in Table 3-6.

It has been confirmed by the intensive geological verification survey and the plotting of the GPS ground truth points that the Cretaceous Tawilah sandstone group has more areal distribution than was mapped by GAF, 2005, particularly in the south-western and the northern parts of Hamdan areas.

Table 3-6 Calculated surface area of lithostratigraphic units exposed in Hamdan area

Lithostratigraphic Units	Hydrosult (2007)	
	Area (km^2)	% of Area

Lithostratigraphic Units	Hydrosult (2007)	
	Area (km^2)	% of Area
Quaternary Alluvial	114.850	29.31
Quaternary Volcanics	74.000	18.87
Tertiary Volcanics	163.500	41.73
Cretaceous Tawilah sandstone	39.440	10.1
Total Area of Sana’a Basin	391.79	100%

It is clear from Figure 3-9 and Table 3-6 that the Cretaceous Tawilah sandstone is exposed mainly in the central and northern parts of the Hamdan area, with an areal distribution of 39.440 km^2 (10.1% of the Bani Hushaish area). The Tertiary volcanics group outcrops mainly in southern parts of the Hamdan area, with an areal distribution of 163.500 km^2 (41.73% of the Hamdan area). The Quaternary volcanics outcrop in the northern part of the Hamdan area, with an areal distribution of 74.0 km2 (18.87% of Hamdan area). The Quaternary Alluvial outcrops in the south and eastern parts of the Hamdan area, with an areal distribution of 114.850 km^2 (29.31% of the Hamdan area).

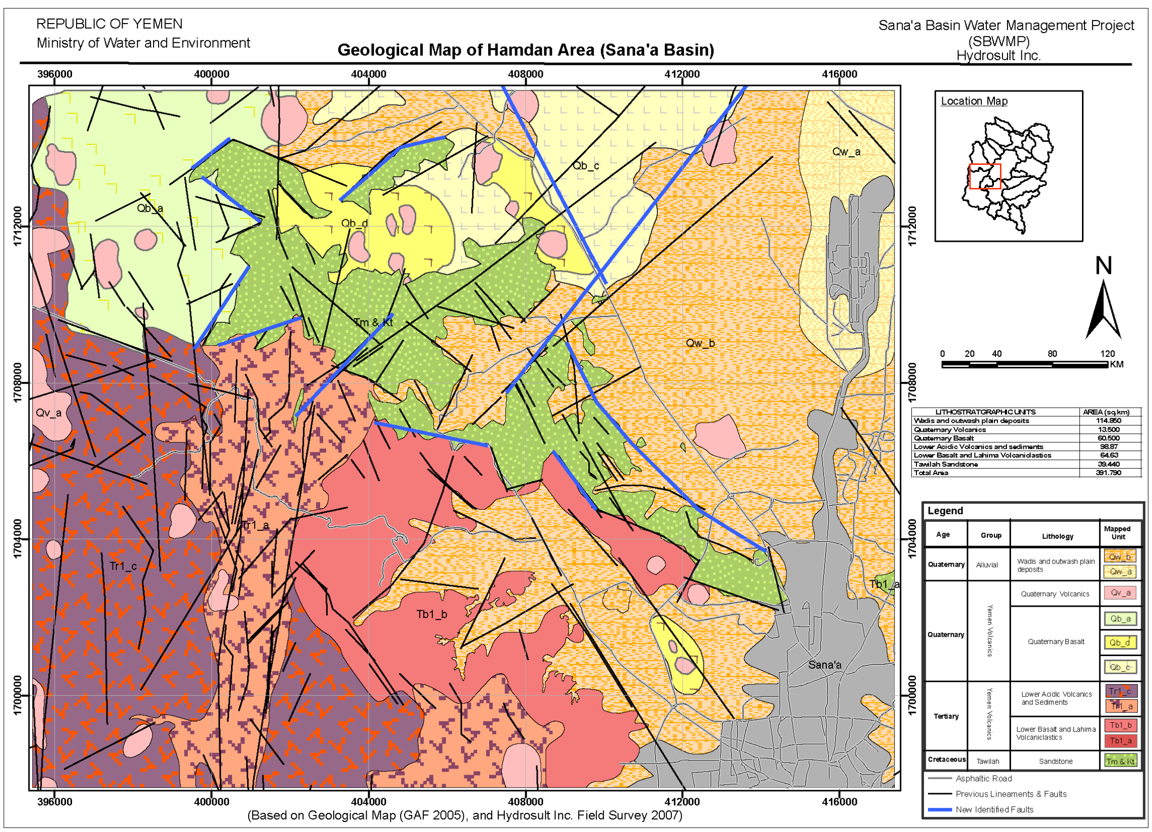


Figure 3-9 Geological map of Hamdan area (Sana’a Basin)

3.3.5 Geological field survey carried out in the Arhab area

The the Arhab area is located in the northern part of Sana'a Basin between 1722669 and 1735819 N and 412453 and 428643 E. It covers an area of 212.01 km^2. The important villages in the area are Bawsan, Bait Maran, Al-Semnah, Sheraa, Bait Al-Ethari. A network of metalled and unmetalled roads connects most of these villages with each other. The most important catchment area is the upper Wadi Al-Kharid.

The geological survey in the Arhab area was performed mainly with the objective to delineate the different lithostratigraphic units and the geological structures. The geological survey and the geological maps indicated that the lithostratigraphic units outcropped in the Arhab area are Jurassic Amran limestone, Quaternary volcanics and Quaternary alluvial deposits (Figure 3-10).

Table 3-7 Calculated surface area of lithostratigraphic units exposed in the Arhab area

Lithostratigraphic Units	Hydrosult (2007)	
	Area (km^2)	% of Area
Quaternary Alluvial	3.200	1.5094
Quaternary Volcanics	107.65	50.776
Jurassic Amran limestone	101.16	47.714
Total Area of Sana'a Basin	212.01	100%

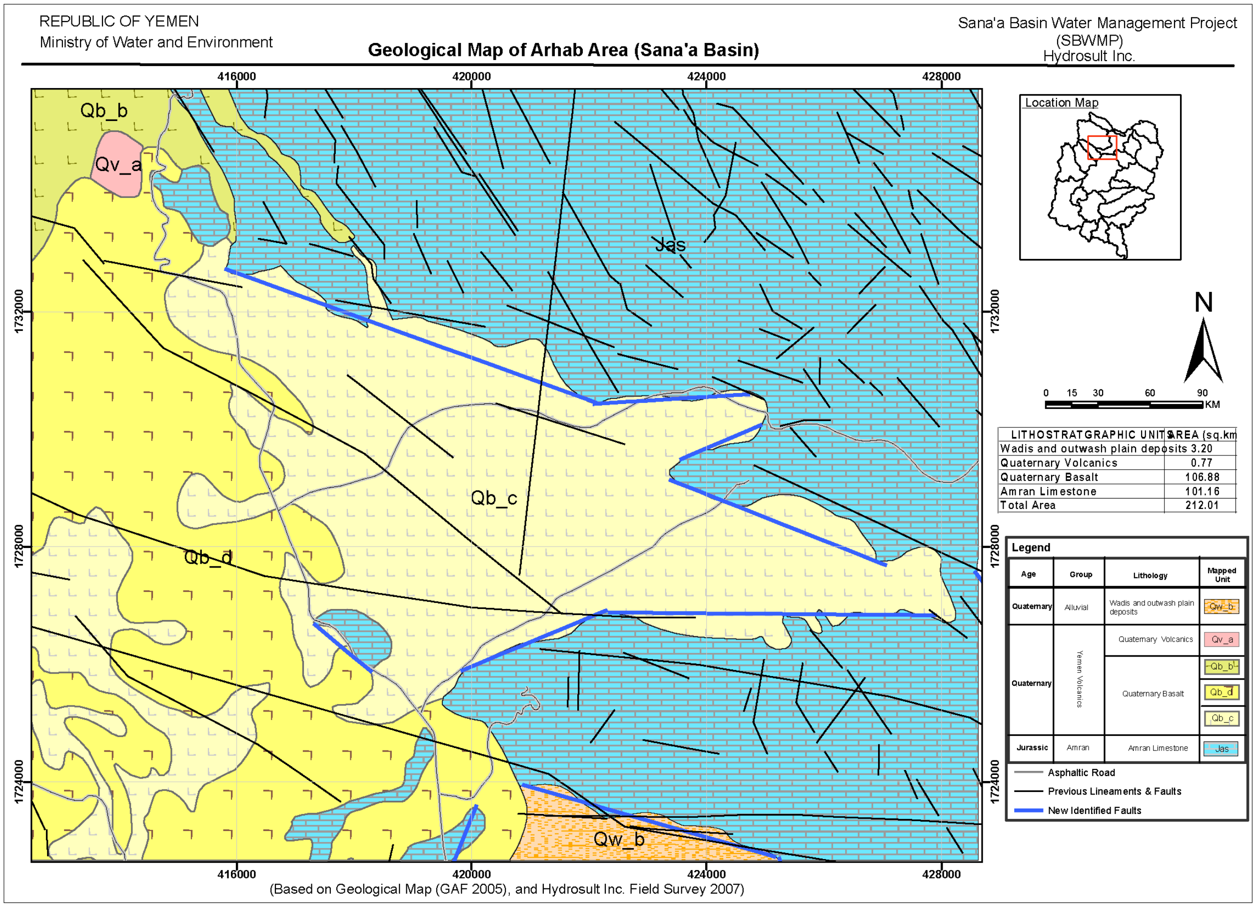


Figure 3-10 Geological map of the Arhab area (Sana'a Basin)

3.3.6 Geological field survey carried out in the rest of the Sana'a Basin

The geological survey in Sana'a Basin was mainly carried out with the objective to delineate the different lithostratigraphic units and geological structures. As indicated from the previous studies, the Jurassic Amran limestone, Tertiary and Quaternary volcanics do not represent potential aquifers in the basin.

The surface distribution of the lithostratigraphical units and the geological structures have been checked in several locations in the field such as Bani Al-Harith, Sanhan, Bani Bahlol, Khawlan, Bani Mattar, etc, where the distinction between the different lithological units was impossible and uncertain. The total number of ground truth GPS points is 205 points. A brief description of the fieldwork activities is summarized in Table 3-8.

Table 3-8 Summary of geological field survey activities in Sana'a Basin

S.N	Day	Date	Name of areas visited	Directorate	No. of GPS points
1	Thursday	26/04	Shamlan, Al Hasabah	Al-Amanah	34
2	Tuesday	01/05	Hejal, Al Hajeb, Al Kasa'ah, Al man, Jader, Thakban, Yanowr, Bait Al-shdady, Mahjar Al Talh, Al sheab	Bani Al-Harith	106
3	Saturday	12/05	Al Sufairah, 60 Streat	Al-Amanah	08
4	Saturday	16/06	Sanhan (Ghaymman, Sakhali, Qouraynah and Hisn Bait Weter). Khawlan (Jihana, Al Mayanah And Wahas). Bani Bahlol (Tana'am, Al Aenac, Dar Aiash, Wadi Jebi, Khayran And Hadath)	Senhan, Khawlan & Bani Bahloul	34
5	Tuesday	19/06	Sanhan (Dar Salm, Qaria Aldarm and Bit Al Ahmar). Khawlan (Bit Hader, Marbak and Shahik)	Senhan & Khawlan	23
Total				-	205

A clear picture of the distribution, area, type of contact of the different lithostratigraphic units in Sana'a Basin has been obtained and then reflected in the geological map (Figure 4.3). Static water level and physical water quality parameters have been measured during the fieldwork survey and then used for the construction of the potentiometric and water quality maps of the different aquifers. Well lithological data have also been collected from the field especially in the area where deep drilling was going on during the time of the fieldwork survey. These data have also been used to construct the aquifer geometry maps and the regional and local sub-surface geological cross-section.

3.4. Stratigraphic Sequence of Sana'a Basin

The stratigraphic sequence of Sana'a Basin ranges from Precambrian to Recent with some periods missing. The Phenarozoic rocks of the Sana'a Basin mainly consist of sedimentary and volcanic rocks. Figure 4.3 shows the different geological units outcropping inside the basin (Hydrosult, 2007). The stratigraphy of the Sana'a Basin is summarized in Table 3-9. During the geological field survey, areal distribution, lateral boundaries, geological structures, volcanic intrusions and nature of contact between the different lithostratigraphical units have been delineated and studied. A brief description of these lithostratigraphical units in Sana'a Basin from older to younger is given below:

3.4.1 Precambrian basement rocks

The present, as well as the previous geological field surveys, confirmed that the Precambrian basement rock did not outcrop at ground surface in Sana'a Basin. The lithological well data reveals the presence of Precambrian basement rocks in the subsurface, as has been recorded in Arhab and Al-Hatarish wells to the north of Sana'a City (DS1 in Arhab and DS2 in Al Hatarish areas), which represent the deepest wells drilled in Sana'a Basin (Kruseman and Vasak, 1996). These rocks outcrop mainly to the north and southeast beyond the boundary of the basin. They consist of granitic massifs intruded by several basaltic dykes (Beydoun, 1964; Geukens.1966). Archaean ages have been suggested for some basement exposures in the Abass area, Al'Baydhah district (Al- Kutbah, 1992).

3.4.2 Mesozoic sediments

Mesozoic sediments are widely distributed in Sana'a Basin. They are characterized by both clastic and carbonate deposits. The clastics were dominant during the late Triassic–early Jurassic and are represented by the Kohlan sandstone Group. The Kohlan Group grades up into a predominantly carbonate (Amran Group). Towards the east and along the Sana'a-Marib road, the evaporitic "Sabatayn Formation" of Beydoun (1964), or the "Sabatayn Group" of Al-Thour (1992), is sandwiched between the Jurassic Amran limestone and the Cretaceous Tawilah groups. The Tawilah group of continental conditions continued to dominate in the late Cretaceous with locally marine clastics (Medi-zir Formation) during the Paleocene, and they become interspersed with volcanic extrusions in the early Tertiary (Al-Subbary, 1995).

3.4.2.1 Kohlan sandstone Group

The term "Kohlan sandstone group" was first applied by Lamare et al. (1930) to the sedimentary succession exposed in the Kohlan area northwest of Sana'a, unconformably overlying Pre-Cambrian basement rocks (Table 3-9). It is the oldest sedimentary unit in Sana'a Basin, light-grey, white or pink in color. It consists of green shale with sandstone and conglomerate bands in the lower parts and sandstone and conglomerates in the upper parts (Naaman, 2004). It fines upwards through sands to pass conformably by an arkosic, cross-bedded and sometimes channeled fluviatile sandstone with some beds of conglomerate in the lower part. Compared to the Wajid sandstone, it has a higher proportion of mudstone and the quartz sand is more finely grained. Additionally, there are interbedded thin siltstone and conglomerate beds containing plant remains of the Liassic age (Lamare and Carpentier, 1932) while macrofossils and palynoglacial evidence suggest Triassic to Lower-Middle Jurassic age (Beydoun, 1982; Diggens et al., 1988). El-Nakhal (1984) interpreted the age of the Kohlan group as early Permian to Liassic.

The geological field check indicated that this geological unit did not outcrop at ground surface of the basin. Beyond the eastern boundary of the basin, the Kohlan group is exposed at Jabal Salab in the Nihm area and recorded in the Sana'a Basin from subsurface data only, such as in Arhab and Al-Hatarish deep wells (DS-1 and DS-2). It has a maximum thickness of about 45-50 m (Kruseman and Vasak, 1996).

3.4.2.2 The Jurassic Amran limestone Group

The term "Amran Series" was first applied by Lamare et al., (1930), to the sedimentary succession exposed near the town of Amran, 40 km to the northwest of Sana'a City, which contains the largest outcrops of the Amran limestone. It is also outcropped and extents in the north and northeastern parts of the Sana'a Basin with outcropped thickness of about 320 m (WEC, 2001) (Figure 4.3).

Based on the present geological survey, Amran Group covers about 16.581% of the Sana'a Basin area. The surface contact between Amran group and the different lithostratigraphical units outcrops at ground surface have been traced in several locations such as Jabal As-Sama, Bani Jermouz, Bait Dahra, Bait Al-Anz, Shera'a, Arisha, Al-Hayathem, Bani Zeter, Nobat Shekwan, Mahali, Meswarah areas (Photos 3-2 and 3-3). The surface contact has also been traced in the northwestern part of the basin (Hamdan area) with Tertiary and Quaternary Volcanics.

In the rest of the basin, the thickness of the Amran group is almost obscured, since the majority of the wells in Sana'a Basin do not penetrate the full thickness of the limestone group. The only available information about its subsurface thickness was obtained from two boreholes, DS-1 and DS-2, some 10 and 30 km respectively northeast of Sana'a City. Thickness of limestone in DS-1 is 1280 m and in DS-2 1260 m (Kruseman and Vasak, 1996). It occurs at depth beneath the Sana'a plain: at the airport, the top of the Amran is approximately 350 m deep overlain unconformably by Quaternary alluvial deposits; at Al-Rawdha 500 m and, further south near Sana'a City, 900 m or more (Naaman, 2004). The Jurassic Amran group is overlain by a sequence of lagoonal shales, marls and fine-grained sandstone interbedded with lignite, probably of Upper Jurassic or Lower Cretaceous age, which outcrops in narrow band in the north-eastern part of the basin (Naaman, 2004). It conformably overlies the Kohlan sandstone Group (Table 3-9).

Table 3-9 Stratigraphic sequence of Sana'a Basin (Adopted from BGR 1991)

Epoch / Age	Stratigraphy		Lithological Units Adopted from BGR (1991)	Thickness (m)
Holocene	Quarternary Alluvial		Wadi and outwash plain deposits	5-350
Pliocene	Quaternary Volcanics		Quaternary Volcanics	
			Quaternary Basalt	
Oligocene – Miocene	Tertiary Volcanic Group		Middle Acidic Volcanics	700-900
			Upper Basic Volcanics	
			Middle Basic volcanics	
Eocene - Oligocene			Lower Acidic Volcanics and sediments	
			Lower Basalt and Lahima volcanic clastics	
Hauterive – Eocene	Tawilah Group	Medj-zir Formation	Tawilah sandstone	350
		Al-Ghiras Formation		
Bathonian – kimmeridgian	Amran Group		Amran limestone	900
Lias	Kohlan Group		Kohlan sandstone	45-50

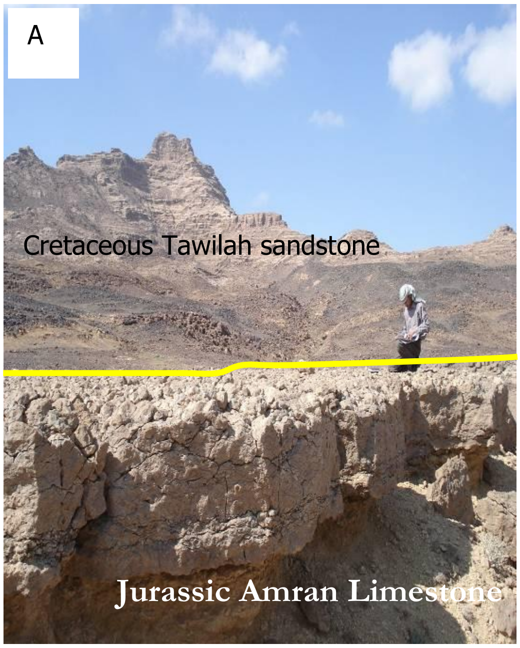
During the field survey, it was found that contact between the Jurassic Amran limestone and the overlying Cretaceous Tawilah sandstone is of two types, i.e. sharp and gradational contacts. The sharp contact was found in the eastern part of the Nihm and the Arhab areas (Photo 3-2), whereas the gradational contact is found in Bani-Hushaish, Bani Al-Harith and the western part of the Nihm areas (Photo 3-3). In the areas of gradational contacts, the un-named formation (shale and/or the Sabatayn formation) is present as a sandwich between the two above-mentioned groups.

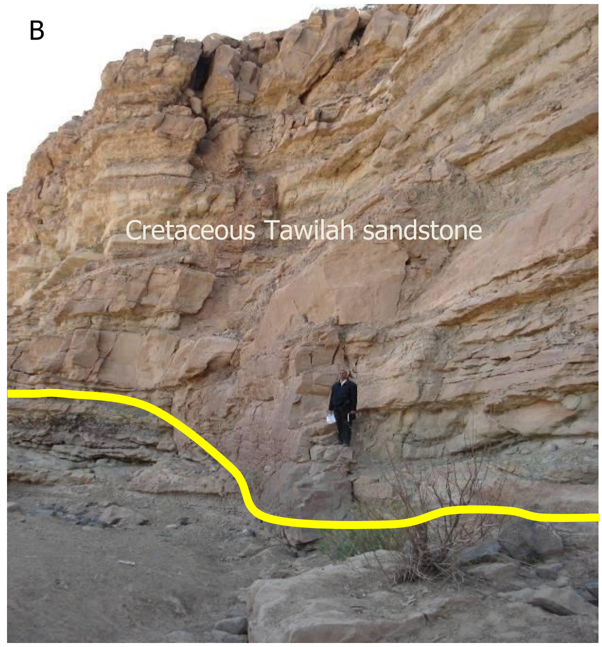
The Amran group consists mainly of tan to grey limestone, argillaceous limestone, calcareous shale, gypsum, and marls with intercalation of shales in some interval horizons such as in the Wadi Al-Ahjur formation (Italconsult, 1970).

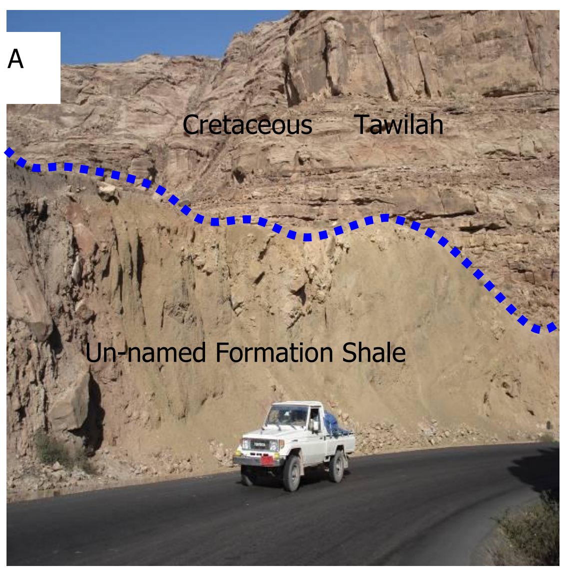
Al Thour (1992) divided the Amran group into three formations. The thickest, measured but incomplete sections, are 520 m thick with a composite total thickness of 900 m. The lowest Al Khothally formation comprises transgressive bioclastic limestones over the siliciclastic marine sands of the Kohlan group. The overlying Raydah formation has similar, shallowing-upward cycles, which are locally rich in corals and stromatoporoids or zooids. The uppermost Wadi Al- Ahjur formation (El- Anbaawy 1985) is regressive and shallows up through algal (Permocalculus)-rich limestone to quartz-rich limestones which are cut by a karstic surface developed on top of the Amran.

The Amran group is interpreted to represent a marine depositional environment (Lamare, 1930), and has been dated as Callovian to Kimmeridgian (El-Anbaawy, 1984), and Bathonian to Kimmeridgian (Al-Thour, 1992).

Photo 3-2 A & B Sharp contact between the Jurassic Amran limestone and the Cretaceous Tawilah sandstone


A
Cretaceous Tawilah sandstone
Jurassic Amran Limestone


B
Cretaceous Tawilah sandstone


A
Cretaceous Tawilah
Un-named Formation Shale


B
Cretaceous Tawilah sandstone
Sabatayn Group (Gypsum)

Photo 3-3 A-B Gradational contact between the Jurassic Amran limestone and the Cretaceous Tawilah sandstone

3.4.2.3 Sabatayn Group

This group is described from the salt domes of Shabwa area (lat. 15 22', long. 47 02) west Hadhramout as the "Sabatayn Series" by Wetzel and Morton (1948) and has been amended to Sabatayn Formation by Beydoun (1964). Al-Thour (1992) raised the rank to a Group and introduced a new formation to include the four members of Beydoun (1964) in this formation named the Safer Formation. According to Beydoun and Greenwood (1968), the maximum thickness exposed is 300 meters and the formation is made up of several members from base to top as follows: (1) the Shabwa Member which consists mainly of salts, (2) the Leyadim Member which is shale, (3) the Ayad Member which consists of gypsum and (4) the Mqah Member of classic sediments. The age is upper Jurassic according to Beydoun and Greenwood (1968), and it is conformably overlain by the Cretaceous Tawilah sandstone Group and underlain by the Jurassic Amran limestone Group.

During the field survey, this group has been delineated along the Sana'a-Marib main road at Zigan village (Bani Hushaish) (Photo 3-4), Bait AL-Rabouey, Al-Jayef village and Bait Dahrah (Bani Al-Harith) and at Thoma and Khulaga (Nihm area). It is exposed at ground surface at the boundary between the Jurassic Amran limestone and the Cretaceous Tawilah sandstone. It was difficult to measure the thickness of this group as most of the thickness is below ground level. The gypsum represents one of the main sources of income of the local peoples in the above mentioned areas, in which they used to excavate the gypsum and sell it on the market.

Photo 3-4 Sabatayn group exposed along the Sana'a-Marib road at Zigan village (Bani Hushaish)

3.4.2.4 The Cretaceous Tawilah sandstone Group

The term "Tawilah Series", first introduced by Lamare et al. (1930) was used to describe the Cretaceous sandstone succession that conformably overlies the Amran group. The type locality of this group is Al-Tawilah Village which is situated about 40 km northwest of Sana'a. The stratigraphy and age of the Tawilah group was documented by Lamare, et al. (1930), and subsequently by Geukens (1960,1966), Abou – Khadra (1982), Abou Khadra et al., (1983), Aboul Ela (1983), Kruck (1984), El-Nakhal (1988), Al-Subbary (1990) and Al-Subbary et al. (1993).

The geological field survey which involved the delineation of the Cretaceous Tawilah sandstone indicated that this group outcrops over about 8.371% of the basin, covering a large area around Sana'a City, especially in the north-western part, as in Wadi Dhahr and in the northern part of the basin, such as in the Al-Hatarish area and underneath the alluvial deposits in most of Sana'a Basin. It is also exposed in Bani Hushaish and the Nihm areas towards eastern and north-eastern parts of the basin respectively (Figure 3-1). Towards the south, this group presents under considerable thickness of volcanic and alluvial deposits. Regionally, the group extends to the central and southern Yemen highlands. It also outcrops over sizeable areas to the north and north-west of Sana'a Basin and along the eastern escarpment of the highlands (Naaman, 2004).

Jurassic Amran limestone – Cretaceous Tawilah sandstone Contact

During field visits, the lower boundary of the Tawilah sandstone Group was delineated in several locations. The field survey indicated the presence of three types of contacts between the Jurassic Amran and Cretaceous Sandstone Groups. The first is a sharp contact as has been traced at Wadi Thajir, Arisha (Nihm area) Photo 3-2. The second type is a gradational contact, in which a shale unit of un-named formation is present as a sandwich between these two groups as has been recorded in Naqil Bin Ghailan and Bani Zetar (Photo 3-3). The third type is also a gradational contact in which the Sabateen group is present as a sandwich between the two groups as recorded in Zigan village (Bani Hushaish) along Sana'a-Marib Road (Photo 3-4). The age of this group is determined by Al-Subbary in 1993, ranging from Late Cretaceous to Eocene.

Cretaceous Tawilah sandstone – Tertiary Volcanic Group Contact

The field visit traced the Cretaceous-Tertiary contact in several locations such as at Wadi Thajir, Nihm area, in which a sharp contact between the Cretaceous Tawilah sandstone and Tertiary volcanics groups was delineated (Photo 3-5).

The base of the Yemen Volcanic group is defined by the lowermost volcaniclastic unit (the Jihana Member) or volcanic rock (Al-Kadasi, 1994). A transition zone of volcaniclastic rocks and lacustrine sediments (Lahima member) rests disconformably on the uppermost lateritic paleosols of the Tawilah group. The sediments are situated below the first major basalt or ignimbrite that constitutes the base of the Yemen Volcanic group. A transition zone some twenty to forty meters thick was widely spread in the western part of Yemen (Menzies et al., 1994). The upper part of the Lahima Member consists of siltstones interbedded with thin, altered basaltic flows and contains detrital volcaniclastic feldspar fragments which testify to the presence of volcanics (Al- Kadasi 1994). Northeast of Sana'a at Jabal Kura', the transition zone comprises lapilli tuff, Volcaniclastic sediments and chert, with some siliceous sediments and contains abundant lacustrine gastropods and bivalves. Kruck et al. (1991) refer to this transition zone as the Lahima Volcaniclastics and noted that Eocene fossils had been recovered from this zone.

Dykes in the Cretaceous Tawilah sandstone Group (Photo 3-6)

Abundant mafic and felsic dykes cut all stratigraphic sections of the western Yemen (form the Precambrian basement through Cretaceous Tawilah sandstone to the Yemen Volcanic Group). During the geological field survey these dykes and plugs have been delineated at several locations. It has been found that the majority of dykes in Sana'a Basin are oriented broadly N-S to NW-SE and E-W to NE-SW which is compatible with the extensional fault orientation. Two types of dykes have been identified. The first is of felsic composition and characterized by its low resistance to erosion by comparison with the country rocks. It also shows fracturing and jointing which make favorable locations for groundwater movement (Photo 3-6 A,B,C). The second type consists of mafic composition and show high resistance to erosion in comparison to the country rocks. Its vulnerability for fracturing and jointing is very low, making it act as a barrier for groundwater movement (Photo 3-6 D). Regional NE-E oriented extension was occurring during the dyke injection, which broadly coincides with the direction of Arabian Plate motion defined by continental reconstructions and transform fault orientations (Sultan et al., 1992).

Photo 3-5 Sharp contact between Cretaceous Tawilah sandstone and Tertiary Volcanic group

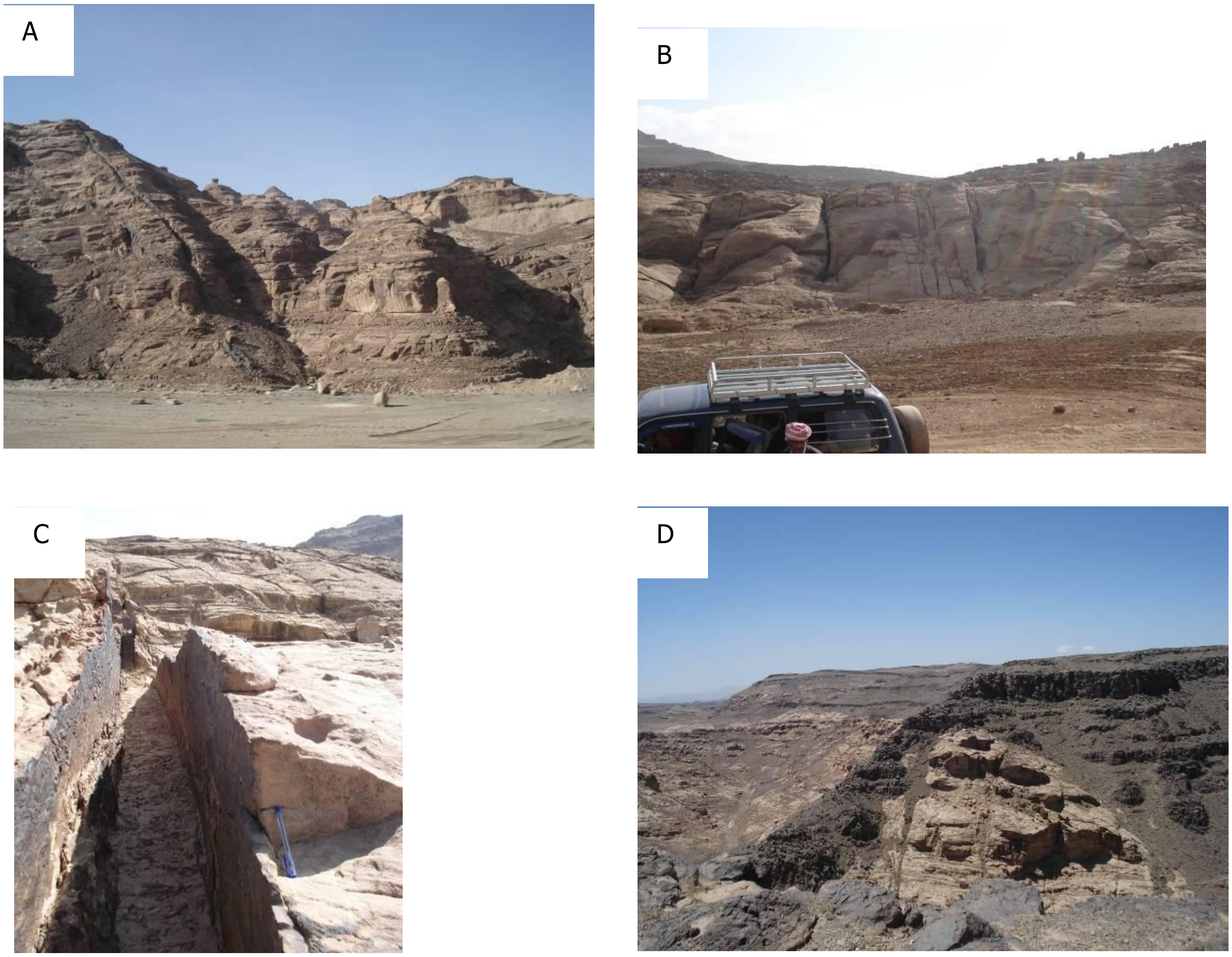


Photo 3-6 A-D Tertiary volcanic dykes cutting through the Tawilah sandstone group

3.4.2.5 The Tertiary Volcanic Group

At the end of the Mesozoic era, tectonic uplift, with associated erosion, removed most of the Jurassic and Cretaceous sediments from central Yemen. These movements were accompanied by intense volcanic and intrusive activity that extended throughout most of the Cenozoic. The term Yemen volcanic group replaces the former name, Trap Series, as recommended by Geukens, (1966). The Yemen volcanic group of Grolier and Qverstreet (1978) are widespread in the high plateau to the west and covers about 50.000 km^2 of the country (Geukens, 1960, 1966, Grolier and Overstreet, 1978). This volcanic group is made up mainly of alternating lava flows, (basalts, andesites, or trachyte porphyries), and different types of tuffs (Grolier and Overstreet, 1978; Menzies et al., 1991, 1992).

The geological field survey which involved delineation of the Tertiary Volcanic Group indcated that this group is the dominant lithological unit outcropping over about 1867.779% of the basin

(57.70%), especially in the southern, western and eastern parts. They form high plateaus to the south, west and east of the Sana'a plain and underlie the Quaternary Alluvial deposits in the south of the basin. Basic intrusive rocks of Tertiary age are present throughout the basin in the form of volcanic plugs, dykes and sills (Photo 3-7). The alignment of the volcanic necks is oriented NNW-SSE. Dykes are well-fractured and oriented NNW-SSE and NNE-SSW. The total thickness is variable, reaching an estimated maximum of 700 to 900 m (WEC, 2001).

The surface contact between this unit and other rocks has been studied in several locations in Hamadan, Arhab, Nihm, Bani Hushaish, Bani Matar, Bani Bahloul and Khawlan areas. The thickness of this group increases towards the south, as has been confirmed from well log data and the previous geophysical studies.

According to GAF, 2007, the Tertiary volcanics group in Sana'a Basin has been subdivided into five units from older to younger as below:

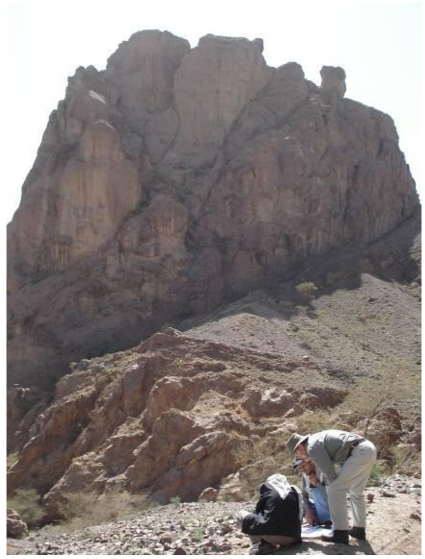
- Lower Basalt and Lahima Volcaniclastics,
- Lower Acidic Volcanics and Sediments,
- Middle Basic Volcanics,
- Upper Basic Volcanics, and
- Middle Acidic Volcanics.

Ingrid U.P., Joel Baker et al, 2005 performed a detailed volcanic stratigraphic study in the Sana'a area and the escarpment to the west. A series of eight stratigraphic sections, which range in thickness from ~50 m to >1 km, were logged and sampled. These sections from east to west are: Jabal Kura'a, in Bani Hushaish, Wadi Dhar, in Hamdan Shibam Kawkaban, Jabal Shahirah, Bayt Baws, south of Sana'a City, Haddah, southwest of Sana'a City, Bayt Mawjan, and Escarpment.

Two sections rest on Cretaceous-Paleogene pre-volcanic sandstones, and thus provide constraints on the timing of the local initiation of flood volcanism. The sections provided a large and stratigraphically well-constrained sample suite covering all major volcanic units (silicic ash flow and air fall deposits, and silicic and basaltic lavas).

Columnar Joints of volcacic intrusion, Wadi Sawan (Baryan)

Volcanic Plugs in Wadi Shahek, Khawlan Area



Volcanic Intrusion, Wadi Dhar

Photo 3-7 Tertiary Volcanic dykes at Sawan, Shahek and Hamdan

The new stratigraphic data (Ingrid U.P. Joel A. Baker, et al, 2005) allow the volcanic evolution of the Sana'a area of the northern Yemen plateau to be divided into three phases (from oldest to youngest):

1. Main flood basalt phase (~30.3 to 29.7 Ma),
2. Main silicic pyroclastic phase (29.7 to 29.5 Ma), and
3. Upper bimodal volcanic phase (29.5 to 27.7 Ma).

1. Main flood basalt phase (~30.3 to 29.7 Ma)

This phase is the volumetrically dominant component of volcanism, representing 60 to 70% of the total erupted volume (Baker et al, 1996). In the Sana'a area, sections range from ~50m of mafic volcaniclastic deposits (including both epiclastic sediments and basaltic pyroclastic deposits of tuff containing accretionary lapilli: Ross et al. 2005) in the Jabal Kura'a section, to a >250 m thick sequence of ponded lava flows at Wadi Dhar, where some lava flow units have individual thicknesses up to 50 m. Some basaltic lava flows can be geochemically correlated between sections in the Sana'a area (Jabal Shahirah, Shibam Kawkaban, Wadi Dhahr). The increase in number and thickness of basaltic lava flows from east to west suggests that the vent sites for initial basaltic volcanism were located towards the Red Sea proto-rift. In the Sana'a area the end of the initial phase of mafic volcanism is marked by the Kura'a Basalt, a distinctive highly plagioclase-phyric lava flow that can be correlated over >30 km. Following this, evidence for a hiatus in volcanic activity or periods of nondeposition or erosion is represented by several epiclastic deposits (~15 m of fluvial sediments, some containing silicified logs up to 1 m long) in the Jabal Shahirah section.

2. Main silicic pyroclastic phase (29.7 to 29.5 Ma)

The second phase of volcanism, the main silicic pyroclastic phase, initiated with the emplacement of the Jabal Kura'a Ignimbrite (the first regional ignimbrite found on the northern Yemen plateau) and ended with the emplacement of the Iftar Alkalb mega-breccia. This period of silicic volcanism includes six large-volume pyroclastic flows erupted rapidly over a period of 0.25±0.23Ma. The silicic units are rhyolitic, rhyodacitic and trachytic in composition. Locally, the silicic units constitute up to 50% of the volcanic stratigraphy of the Yemen plateau. The main silicic pyroclastic phase is further identified by a brief transition to reversed polarity recorded by the Sana'a Ignimbrite, and a return to normal paleomagnetic polarity for the Iftar Alkalb mega-breccia. The erosive nature of the Iftar Alkalb basal contact and this unit's relationship to laterally adjacent basaltic lava flows in the Sana'a area, the Haddah section, and a basaltic mega-breccia found in the Escarpment section add stratigraphic complexity to the interpretation of this phase of volcanic activity, as discussed below.

3. Upper bimodal phase (29.5 to ~ 27.7 Ma)

The final phase of flood volcanic activity, the upper bimodal phase, is defined as the succession of units that are younger than the Iftar Alkalb mega-breccia (29.48 Ma). It is a laterally heterogeneous and lithologically highly variable sequence of thin silicic lavas, tuffs and ignimbrites (generally <10 m), intermediate and basaltic lavas and volcaniclastic units, with sedimentary sequences and erosional surfaces present. The thickness of this sequence varies from 30 to >60 m, and it is capped by the thick (30 to 60 m), eutaxitic Bayt Mawjan Ignimbrite (27.67±0.12 Ma) that is exposed throughout the northern Yemen plateau at the highest stratigraphic level. Most of the silicic units in the upper bimodal phase have phenocryst assemblages of anorthoclase, ilmenite, magnetite, ± quartz, and, for the first time in the eruptive sequence, hydrous phases of amphibole are observed in the silicic units. This final sequence of units is stratigraphically complex and not well constrained because many units occur in only one section. The sequence represents the waning phase of flood volcanic activity and is characterized by small eruptions of hydrous magma from localized volcanic depocenters, as evidenced by the highly variable stratigraphy and compositions. Of the six minor silicic units in the Bayt Mawjam section, three (all ignimbrites) belong to the 'high 208Pb/206Pb' group and three (two airfall tuffs and a lava flow) belong to the 'low 208Pb/206Pb' group. This suggests that these units represent intercalated eruptions from multiple eruptive sites. Younger volcanic units have only been located in the north-east Sana'a region. Baker et al. (1996) investigated a sequence of ~30 mafic lavas that overlie the Bayt Mawjan Ignimbrite at Jabal Ragbaan, ~5 km east of the Jabal Kura'a section.

Different studies have been done to determine the age of Yemen volcanics such as Al-Kadasi, 1994 and Al-Gulani, 1995. These studies gave a wide range of Oligo-Miocene age. All studies reveal that the Yemen volcanics are occurred as a series of eruptions during stages of volcanic activity.

3.4.2.6 The Quaternary Volcanics

Volcanic activity continued into the Quaternary time forming a plateau of extensive basalt cones in the northwest of the basin interlayered with tuffs and alluvial sediments. They originated from a great number of volcanic cones in the basin which extends from Arhab to Hamdan in the north and northwest and from there they extent SSW along the western border and also in the innermost part of the basin, near the western edge of the Sana'a Plain. An isolated Quaternary volcano with basalt flows also occurs in the southern part of the basin (Italconsult, 1972). In general, the Quaternary volcanics overlies, the

Jurassic Amran limestone, Cretaceous Tawilah sandstone and / or Tertiary volcanics. The Quaternary volcanic rocks are dominated by alkali basalt.

The Quaternary volcanics represent the smallest units in the Sana'a Basin. It mainly outcrops at the northwestern part of the basin. Several scattered volcanic cones have been reported in Hamdan, Bani Matter, Hizyaz etc. It has been found from the present geological survey and delineation activities that this unit covers an area of about 56.54583 km^2 (1.747%) of Sana'a Basin area.

The fieldwork survey indicated the presence of two types of eruptions. The first eruption involves the cinder cones eruption, which is explosive type volcanics. This type is found mainly in the northwestern part of the basin (Hamdan area) and along the main Sana'a-Amran asphaltic road (Photo 3-8).

The second eruption is the lava sheet rocks which occurred In Arhab and Hamdan areas occupying the low land area and main stream channels (Photo 3-9).

As has been reported by Ambraseys *et al.*, 1994, the Quaternary volcanics can be divided into four phases on the basis of relative age and morphological relationships: (1) the sub-horizontal, plateau-forming basalt flows; (2) at least two large stratovolcanoes which erupted the most evolved compositions in the entire volcanic field; (3) some 60 scoria cones, constructed by a combination of Strombolian- to Hawaiian-type eruptions; and (4) a number of aa-type lava flows, that were fed from parasitic vents around the base of the ash and spatter cones.

Photo 3-8 Quaternary Volcanic cones in the north western part of the basin (Dhawdan, Hamdan)

Photo 3-9 Volcanic Lava sheets of Quaternary time in northwestern part of the basin (Hamdan)

3.4.2.7 Quaternary Alluvial Deposits

The geological fieldwork and the geological map (Figure 4.3, Hydrosult, 2007) indicated that the unconsolidated deposits of the Quaternary time cover about 15.599% of the Sana'a Basin area. It has been found that the Quaternary deposits are confined to Wadi beds and low areas that form the Sana'a plain. The alluvial aquifer is widely spread in the Sana'a plain, where Wadis debouch into it. It consists of alternating of coarse grained horizons (mainly silty sand and gravel) and very fine-grained horizons (mainly silty sand and silt) (Photo 3-10). The thickness of these fine horizons varies from 5 to 30 m and the thickness of the coarse sediments horizons from 5-20 to 60-70 m. The thickness of the Quaternary loose deposits varies considerably, reaching 400 m and more in the central part of the plain where it overlies the Jurassic Amran limestone as has been confirmed during the present study through the subsurface cross-sections and the three dimentional fence diagram. To the south, it has thicknesses of 50-100 m and overlies the Tertiary volcanic group.

Depositional environment appears to have been of fluvio-lacustrine nature, which led to the accumulation of clay and silt of 100 m to 300 m deep (Naaman, 2004). Coarse-grained colluvium and alluvial occurs in the Wadi beds at the foot of hills. Lithologically, the Sana'a alluvials are primarily argillaceous with sand and gravel interbeds which often contain a large proportion of clay (Howard Humphrey 1983).

The alluvial thickness map prepared by Hydrosult, 2007 shows small basins in the vicinity of and in the plain, 8 km south of Sana'a City, where these deposits overlie Tertiary volcanic. Two of these basins have thicknesses of about 100 m. The deepest basin is situated north of Sana'a City, where these deposits overlie the Jurassic Amran limestone with a maximum thickness of 400 m (near the airport), separating the eastern and western outcrops of the cretaceous sandstone in Bani Hushaish and Hamdan areas respectively. A fourth basin exists in the north east of Sana'a and has a different orientation than the other three, whose orientation is mainly NNW – SSE.

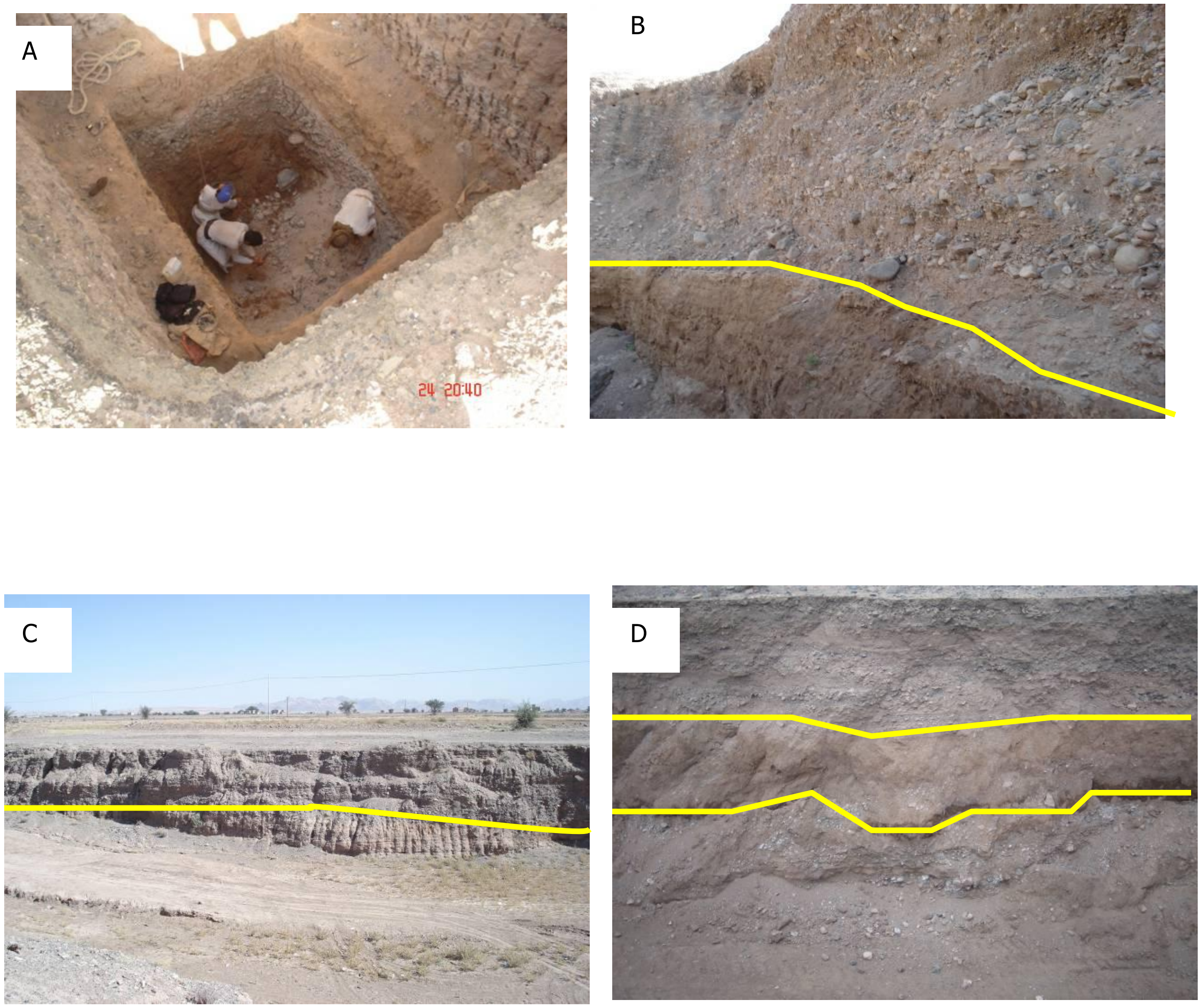


Photo 3-10 A-D Alternation of fine and course sand in Sana’a Central alluvial plain

3.5. Geological Structures of Sana’a Basin

The delineation of the main geological structures in Sana’a Basin in general and the areas of Nihm, Bani-Hushaish and Hamdan in particular have been carried out through the following steps:

- Reviewing the previous geological and structural maps,
- Studying the available satellite image maps, and

- Geological field survey.

It is important to mention that the delineation field activities of the geological structures were mainly carried out in the areas where the Tawilah sandstone outcropped at the ground surface. In addition some geological structures have been traced in Arhab, Sanhan, Khawlan and the rest of the basin.

3.5.1 Surface geological structures

The main structural elements in Sana'a Basin are represented by Joints, folds, unconformities and faults.

3.5.1.1 Joints

The Tawilah sandstone is highly jointed, with almost conformable patterns with the fault trends, Italconsult, 1973. The most major fractures are shown in Figure 3-11. They are distributed in a non-uniform manner and their density indicates zones of greater weakness and tensions. One of the most fractured zones is that where the Cretaceous sandstones outcrops in northwest from Dhaban to Wadi Dhar and also further north. This is of the greatest consequence as regards the possibility of favourable geohydrological conditions in this zone and therefore this area was subjected to detailed fracture analysis (Italconsult, 1973) The Tertiary volcanics has been subjected to fracturing and jointing also (Photo 3-11).

3.5.1.2 Folds

Small scale fold have been traced during the fieldwork of the present study. In Tozan village (Hamdan area) a small scale symmetrical fold has been delineated in the Quaternary volcanic rocks (Photo 3-12a). In Wadi Thajir (Nihm area) asymmetric fold have been traced in the Tawilah sandstone group (Photo 3-12b). In Wadi Al-Kharid area an anticline and syncline small fold have been delineated adjacent to each other in the Jurassic Amran limestone group (Photo 3-12c). Only one large open anticline fold plunging to the south is recorded and confirmed from the geological cross-section and the field survey. The axis runs parallel to N-S direction of Sana'a Basin. It is asymmetrical where the western limb is (about 20º SW) while the other limb is about 10ºSE (Italconsult, 1973).

3.5.1.3 Unconformities

The main unconformities are recorded mainly between the upper part of the Jurassic Amran limestone and the lower part of the Cretaceous Tawilah sandstone (Thula Member). Transitional beds (either shale and/or gypsum) especially in the margins of the area (Al-Ghiras, Bait Al-Raboay, Thuma and Khulaqa) indicated by angular relations between the two groups.

3.5.1.4 Faults

The delineation of the structural faults is one of the main study objectives. It has been found that all the traced structural faults are of normal gravity type that formed as a result to the extensional activities. The important regional structural faults delineated in the present study are plotted in the lineament map with distinctive color (Figure 3-11). It has been found that, the dominant surface structures are at least of four main trends (including the previous and recent identified fault systems):

- **Northwesterly faults group**: includes NW and NNW faults trending almost parallel to the Red Sea and sometimes oblique to the Red Sea trend.

- **Northeasterly faults group**: includes NE and ENE faults which possibly follow the trend of the Gulf of Aden.
- **East-West faults group**: The majority of the wadis in the Sana'a basin are faulted valleys such as wadi Dhahr and wadi As-Sir and.
- **North-south faults group**: Very limited number of faults having north-south direction have been delineated.

3.5.1.5 Lineaments

The occurrence and movement of groundwater in any terrain is mainly controlled by many factors such as geology, geomorphology, structure, soil and land use pattern. However, the subsurface features, such as shear zones, faults and geologic contacts greatly influence the groundwater system. These subsurface features usually have surface manifestations that should be determined in any groundwater exploration program. The surface expression of these subsurface features is usually linear or curvilinear topographic features, either negative or positive. They could be determined by tracing almost the tonal-textural discontinuity (photo lineament). The careful analysis of these photo lineament may reveal considerable information about the groundwater availability in any investigated area. So, photo lineaments are considered as important groundwater indicators for mapping groundwater prospective zones.

In 2001, the satellite Analysis of Cropping and Irrigation Water Use study of Sana'a Basin has been conducted by Water and Environment Centre" (University of Sana'a, Yemen) and the International Institute of Aerospace Survey and Earth Sciences (ITC-Enschede, The Netherlands). The study has indicated that the influence of the lineament and structures in the value of permeability or transmissivity is in decreasing order: fault zones, fracture zones and undisturbed rocks, Foppen (1996).

A comprehensive lineament study was carried out by Italconsult, 1973 as a part of the hydrogeological study (Water Resources for Sana'a and Hodeidah). They developed a lineament map for the entire Sana'a Basin (Figure 3-11) and were previously discussed in Chapter 2.

In general, the western, eastern and southern parts of the basin are occupied with volcanic rocks. Several faults have been identified, traced towards the western parts of Sana'a City such as that located at Haddah area (Photo 3-13). Bani Mattar area is located in the western part of Sana'a basin. The Tawilah sandstone group does not outcrop in this area. It is reported from the well log data of the new drilled wells to the west of the Sana'a City. (Hydrosult, 2007) that the Tawilah sandstone is present in sub-surface at about 600-700 m depth, overlying with quite thick volcanic rocks.

Photo 3-11 Fracturing, Jointing of the Tertiary Volcanics rocks (Haddah)

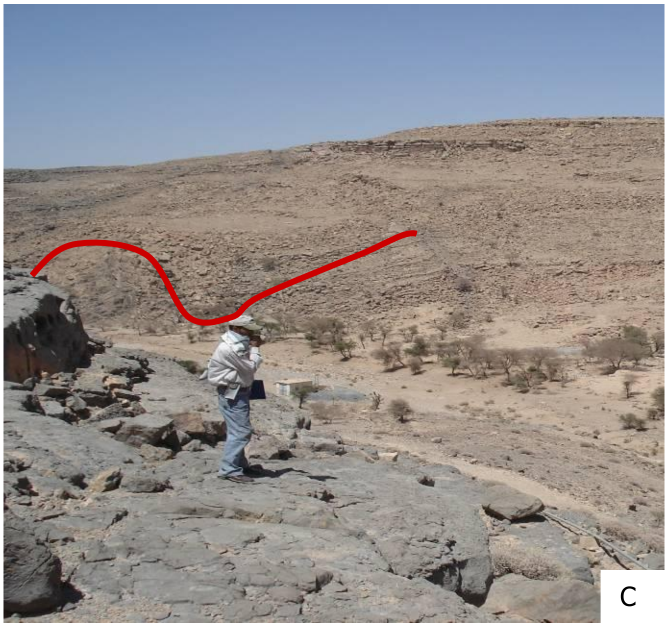


Photo 3-12 A-C Small-scale fold delineated in the volcanic, sandstone and limestone terrains

Photo 3-13 A panorama view showing the faulting within the Tertiary volcanic in the western side of Sana’a City (Ingrid U.P., Joel Baker et al, 2005)

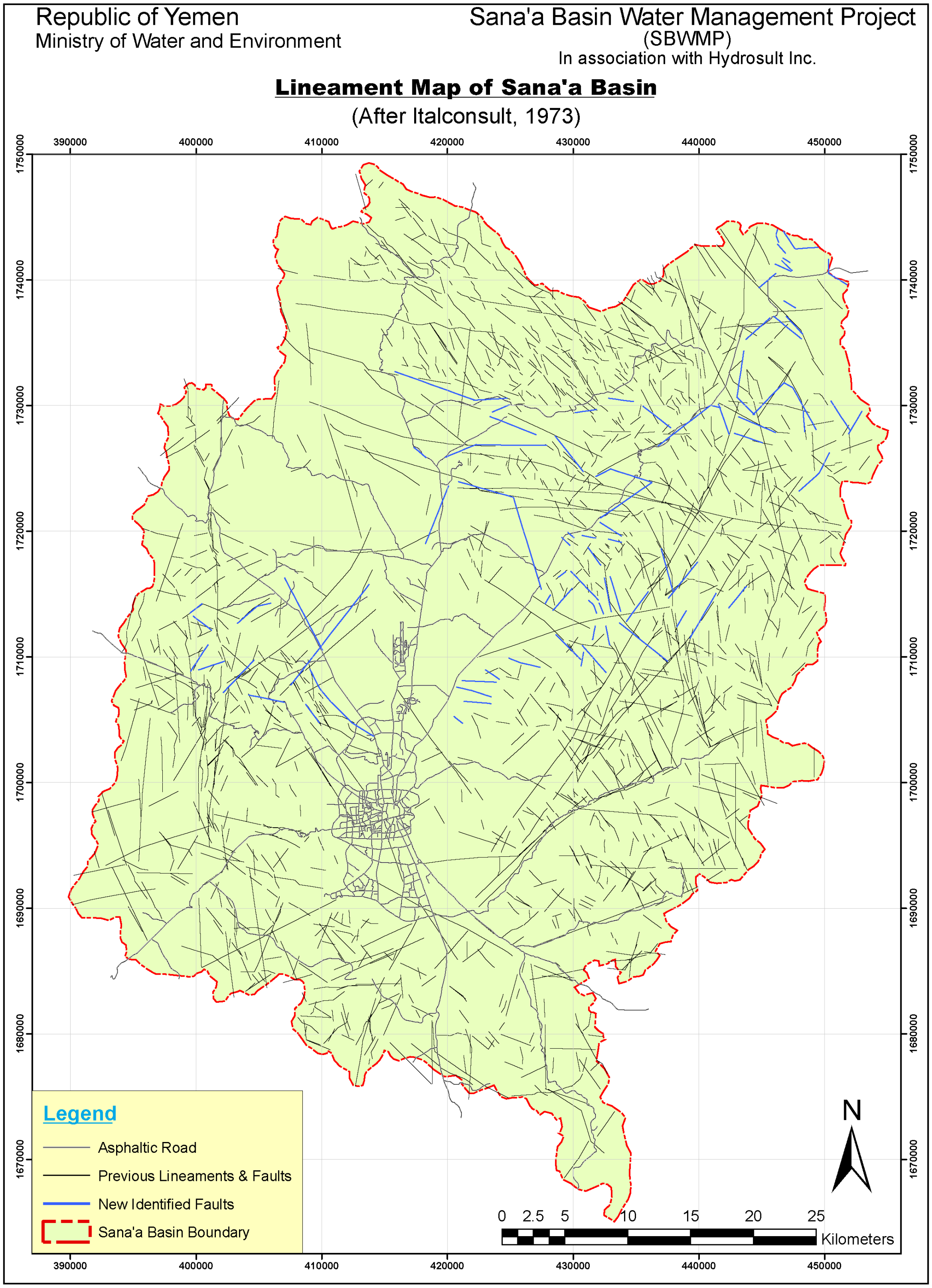

Republic of Yemen
Ministry of Water and Environment
Sana'a Basin Water Management Project
(SBWMP)
In association with Hydrosult Inc.
Lineament Map of Sana'a Basin
(After Italconsult, 1973)
390000
400000
410000
420000
430000
440000
450000
1750000
1740000
1730000
1720000
1710000
1700000
1690000
1680000
1670000
Legend
Asphaltic Road
Previous Lineaments & Faults
New Identified Faults
Sana'a Basin Boundary
N
0 2.5 5 10 15 20 25
Kilometers

Figure 3-11 Lineament map of Sana’a Basin (modified after Italconsult, 1973)

3.5.1.6 Geological structures in the Nihm area

As has been mentioned earlier, the Nihm area is located in the northeastern part of Sana’a basin along an active structural boundary between the mountainous area and Al-Jawf graben. Along the eastern side of this boundary several horst and graben structures are present. The most important one is the great graben of Al-Jawf basin which developed as a result to a series of step faults dipping towards east.

In contrary, along the western side of this boundary (Al-Madarj area) the lithostratigraphical units were subjected to intensive tectonics and volcanic intrusions due to its proximity to Al-Jawf graben. In this particular area several structural faults, horst and graben structures have been delineated. The Mesozoic sediments in the area has been intruded by volcanic plugs and dykes. These plugs are arranged in a certain direction of northwest - north-south directions (Photo 3-14).

The Tawilah sandstone group in this area was subjected to intensive tectonics. As a result, the Tawilah group is scattered as isolated blocks overall the area and separated from each other with Jurassic Amran limestone forming alternating horst and graben structures. The volcanic intrusion may behave locally as barriers to groundwater flow.

A detail delineation of the geological structures in the Nihm area was carried out during the geological field survey in the period between 9-17 December, 2006.

During the field survey fourty eight normal structural faults were delineated and checked in the fields. Out of these, 31 faults are having northwest-southeast trend and 17 faults of northeast-southwest trend (Figure 3-3). Detail description of these geological structures in given in Table 3-10.

It has been found that, the majority of these faults are of NW-SE approximately parallel to the Red Sea rift system. Major wadis in the Nihm areas have been developed along these faults such as Wadi Assarah, Wadi Ghailamah, Wadi Mahali, Wadi Al-Jerjour, Wadi Madfoun, Wadi Al-Gail and Wadi Assir, wadi Khulaqah, Wadi Arisha, .etc.

The Cretaceous Tawilah sandstone was affected by numerous dykes which intruded this group during the opening of the Red Sea on the Tertiary period. The main trends of these dykes are NW-SE. They consist mainly of mafic lava but felsic dykes are also present.

Table 3-10 Type, coordinates and directions of the geological structure in the Nihm area

No	Type of structure	Coordinates				Direction
		Start point		End point		
		X	Y	X	Y	
1	Fault	449332	1728073	447472	1731431	NW-SE
2	Fault	447472	1731431	447468	1731437	NW-SE
3	Fault	447634	1742500	446706	1743892	NW-SE
4	Fault	448250	1735709	446948	1737104	NW-SE
5	Fault	447424	1740750	446575	1741538	NW-SE

No	Type of structure	Coordinates				Direction
		Start point		End point		
		X	Y	X	Y	
6	Fault	448175	1735300	445920	1737129	NW-SE
7	Fault	437764	1728229	435536	1729964	NW-SE
8	Fault	433331	1719949	432127	1720724	NW-SE
9	Fault	447267	1741381	446660	1741757	NW-SE
10	Fault	451794	1739619	450282	1740553	NW-SE
11	Fault	447701	1737772	446753	1738355	NW-SE
12	Fault	447478	1731428	447472	1731431	NW-SE
13	Fault	447472	1731431	446790	1731810	NW-SE
14	Fault	447352	1740689	446042	1741272	NW-SE
15	Fault	446115	1727860	443129	1729123	NW-SE
16	Fault	445081	1727041	442804	1727805	NW-SE
17	Fault	436273	1723898	432969	1724957	NW-SE
18	Fault	432969	1724957	432959	1724960	NW-SE
19	Fault	441736	1729816	441652	1729839	NW-SE
20	Fault	441652	1729839	440952	1730034	NW-SE
21	Fault	434801	1730325	432780	1730586	NW-SE
22	Fault	427918	1726834	426805	1726844	NW-SE
23	Fault	448286	1729613	448422	1727914	NW-SE
24	Fault	441550	1730128	441652	1729839	NW-SE
25	Fault	441652	1729839	442402	1727711	NW-SE
26	Fault	446146	1743547	446346	1742983	NW-SE
27	Fault	450487	1730380	452042	1728012	NW-SE
28	Fault	428559	1727585	430809	1724741	NW-SE
29	Fault	446241	1742850	446892	1742125	NW-SE
30	Fault	443039	1730637	444369	1729353	NW-SE
31	Fault	444369	1729353	444448	1729277	NW-SE
32	Fault	446274	1744039	446128	1743629	NE-SW
33	Fault	450384	1726255	449576	1724639	NE-SW
34	Fault	452974	1729561	451902	1727742	NE-SW
35	Fault	450308	1741669	450299	1740553	NE-SW
36	Fault	443578	1734371	443015	1730634	NE-SW
37	Fault	446780	1731829	444369	1729353	NE-SW
38	Fault	444369	1729353	444295	1729277	NE-SW
39	Fault	449576	1724629	447960	1723192	NE-SW
40	Fault	445679	1737000	443727	1735267	NE-SW
41	Fault	446127	1740527	444764	1739358	NE-SW
42	Fault	440937	1730034	436737	1726790	NE-SW
43	Fault	436263	1723891	432148	1721045	NE-SW
44	Fault	432992	1724969	432969	1724957	NE-SW
45	Fault	432969	1724957	431773	1724352	NE-SW
46	Fault	426805	1727786	427064	1727684	NE-SW

No	Type of structure	Coordinates				Direction
		Start point		End point		
		X	Y	X	Y	
47	Fault	431866	1729693	430104	1729431	NE-SW
48	Fault	449496	1742607	447675	1742460	NE-SW

Photo 3-14 Tertiary dykes intruded the Mesozoic sediments in the Nihm area

3.5.1.7 Geological structures in the Bani Hushaish area

The Bani Hushaish area is located in the northeastern part of Sana'a Basin. In this area, along the southern cliffs of Wadi As-Sirr as well as the cliffs forming the Rawdah plain, the Ghiras formation is represented by the rock of the Kawkaban member only. The lower two members (Thula and Shibam members) are not cropping out in these particular locations. This is possibly due to the effect of the major Wadi As-Sirr (E-W) fault with downthrow southward. Along this fault, Wadi As-Sir has been developed and ditches into the alluvial plain of Sana'a Basin.

A detail delineation of the geological structures in the Bani Hushaish area was carried out during the geological field survey in the period between 19-27 Dec. 2007. During the field survey 38 structural normal faults were delineated and checked in the fields (Figure 3-6). Out of these, twenty eight faults are having northwest-southeast trend and ten faults of northeast-southwest trend. Detail description of these geological structures in given in Table 3-11.

It has been found that, the majority of these faults are having NW-SE trend approximately parallel to the Red Sea rift system. And major wadis in the Bani Hushaish area have been developed along these faults such as Wadi Ghadran, Wadi Al-Malikah, Wadi Sawan, etc. All these wadis ditch into the alluvial plain of the basin.

The Cretaceous Tawilah sandstone was affected by numerous dykes which intruded this group during the opening of the Red Sea on the Tertiary period. The main trends of these dykes are NW-SE. They consist mainly of mafic lava but felsic dykes are also present.

Table 3-11 Type, coordinates and directions of the geological structure in the Bani Hushaish area

No	Type of structure	Coordinates				Direction
		Start point		End point		
		X	Y	X	Y	
1	Fault	433025	1713585	432475	1716310	NW-SE
2	Fault	431866	1713484	431620	1714136	NW-SE
3	Fault	432417	1713412	432055	1714295	NW-SE
4	Fault	432620	1708760	430707	1710934	NW-SE
5	Fault	431620	1714136	431214	1714513	NW-SE
6	Fault	430068	1719497	429564	1719926	NW-SE
7	Fault	421216	1704703	420492	1705283	NW-SE
8	Fault	424143	1708210	423000	1708983	NW-SE
9	Fault	433851	1719613	432127	1720724	NW-SE
10	Fault	425809	1709528	424868	1709920	NW-SE
11	Fault	423491	1706819	421912	1707326	NW-SE
12	Fault	433854	1719126	432778	1719378	NW-SE
13	Fault	421912	1707326	420709	1707601	NW-SE
14	Fault	427389	1709181	425809	1709528	NW-SE

No	Type of structure	Coordinates				Direction
		Start point		End point		
		X	Y	X	Y	
15	Fault	431803	1719458	430684	1719669	NW-SE
16	Fault	423491	1706283	421274	1706471	NW-SE
17	Fault	423897	1707992	421129	1708123	NW-SE
18	Fault	430823	1710398	430620	1709253	NW-SE
19	Fault	432593	1712470	432897	1710931	NW-SE
20	Fault	436988	1718635	437937	1715207	NW-SE
21	Fault	432931	1716409	433781	1713607	NW-SE
22	Fault	425233	1722720	427470	1715367	NW-SE
23	Fault	431145	1718752	432211	1717276	NW-SE
24	Fault	429797	1716824	432022	1714506	NW-SE
25	Fault	428607	1711780	430570	1709817	NW-SE
26	Fault	429072	1719522	429753	1718866	NW-SE
27	Fault	433666	1712718	437519	1709645	NW-SE
28	Fault	424068	1723040	425178	1722725	NW-SE
29	Fault	431763	1712477	431536	1711352	NE-SW
30	Fault	438991	1713687	438241	1712397	NE-SW
31	Fault	441379	1715081	439280	1711483	NE-SW
32	Fault	428206	1714960	427752	1714212	NE-SW
33	Fault	435971	1715200	434207	1712806	NE-SW
34	Fault	439889	1717563	437576	1714670	NE-SW
35	Fault	443595	1715395	442374	1713896	NE-SW
36	Fault	429910	1715455	428374	1713687	NE-SW

No	Type of structure	Coordinates				Direction
		Start point		End point		
		X	Y	X	Y	
37	Fault	429421	1716792	428821	1716353	NE-SW
38	Fault	435034	1723040	432148	1721045	NE-SW

3.5.1.8 Geological Structures in Hamdan area

Hamdan area is located in the northwestern part of Sana'a Basin. The Tawilah sandstone group in this area was subjected to intensive tectonics. As a result, the Tawilah group is scattered as isolated blocks all over the area.

A detailed delineation of the geological structures in Hamdan area was performed during the geological field survey during the period between April 17 and June 23, 2007. During the field survey, 17 major faults were delineated and checked in the field. Of these, 9 faults have a northeast-southwest trend and 8 faults of northwest-southeast trend (Figure 3-10). A detailed description of these geological structures in given in Table 3-12.

It has been found that the major wadis in Hamdan areas have been developed along these faults, such as Wadi Dahban, Wadi Bayt Nam, Wadi Dhahr, etc.

The Cretaceous Tawilah sandstone was affected by numerous dykes which intruded this group during the opening of the Red Sea in the Tertiary period. The main trends of these dykes are NW-SE. They consist mainly of mafic lava (Photo 3-15), but felsic dykes are also present (Photo 3-16).

Table 3-12 Type, coordinates and directions of the geological structure in Hamdan area

No	Type of structure	Coordinates				Direction
		Start point		End point		
		X	Y	X	Y	
1	Fault	410054	1710539	409907	1710820	NW-SE
2	Fault	409907	1710820	407468	1715480	NW-SE
3	Fault	401231	1712127	399750	1713259	NW-SE
4	Fault	407025	1706391	404150	1706980	NW-SE
5	Fault	409046	1709031	409819	1707494	NW-SE
6	Fault	408698	1706249	409802	1704751	NW-SE
7	Fault	409819	1707494	410697	1706453	NW-SE
8	Fault	412416	1704744	414125	1703684	NW-SE
9	Fault	407518	1707748	409907	1710820	NE-SW
10	Fault	409907	1710820	413530	1715480	NE-SW
11	Fault	400167	1708960	402276	1709667	NE-SW
12	Fault	404816	1714025	405943	1714283	NE-SW

No	Type of structure	Coordinates				Direction
		Start point		End point		
		X	Y	X	Y	
13	Fault	400957	1710981	399556	1708868	NE-SW
14	Fault	404614	1709765	402145	1707150	NE-SW
15	Fault	410697	1706453	412416	1704744	NW-SE
16	Fault	404803	1714012	403265	1712666	NE-SW
17	Fault	400469	1714250	399494	1713485	NE-SW

Photo 3-15 Tertiary mafic dyke intruding the Cretaceous Tawilah sandstone in the Hamdan area

Photo 3-16 Tertiary felsic dyke intruded the Cretaceous Tawilah and volcanic rocks in the Hamdan area

3.5.1.9 Geological Structures in the Arhab area

The Arhab area is located in the northern part of Sana'a Basin. It consists mainly of Jurassic Amran limestone. The Jabal As-Sama (Jabal means mountain) of limestone rocks was uplifted to the surface, blocking the outlet of the Sana'a plain as has been confirmed from the sub-surface structural map of Exxon, 1987 (Figure 3-13) which indicated that Jabal As-Sama was uplifted and formed a horst structure. It was uplifted to the ground surface as a result of faulting (two normal faults). The southern side of this mountain is controlled by a major fault of approximately east-west direction between the older Jurassic Amran limestone and the younger Quaternary alluvial deposits (Photo 3-17). The northern part of this mountain is also controlled by a major fault of approximately east-west direction between the older Jurassic Amran limestone and the younger Quaternary volcanics.

A detailed delineation of the geological structures in the Arhab area was performed during the geological field survey. During the field survey, ten faults were delineated and checked in the fields. Of these, six faults show a northwest-southeast trend and four a northeast-southwest trend (Figure 3-10). Detailed descriptions of these geological structures are given in Table 3-13.

In addition, at Arisha, Al-Mahajir Bait AL-Anz, several faults have been delineated. They are normal faults with NW-SE direction. They act as potential areas for groundwater occurrence. Along these faults, the Tawilah sandstone has been moved down and the Amran limestone uplifted.

Table 3-13 Type, coordinates and directions of the geological structure in the Arhab area

No	Type of structure	Coordinates				Direction
		Start point		End point		
		X	Y	X	Y	
1	Fault	419707	1722665	420086	1723612	NE-SW
2	Fault	423541	1729477	424941	1730078	NE-SW
3	Fault	422309	1726924	419820	1725890	NE-SW
4	Fault	424744	1730595	422064	1730426	NE-SW
5	Fault	428626	1727501	428559	1727585	NW-SE
6	Fault	418301	1725869	417309	1726692	NW-SE
7	Fault	422128	1730447	415798	1732726	NW-SE
8	Fault	425178	1722725	420863	1723953	NW-SE
9	Fault	427918	1726834	422330	1726882	NW-SE
10	Fault	423365	1729142	427064	1727684	NW-SE

It has been found that, in the area north of the village of Samnah, the Tertiary volcanic overlies the Jurassic Amran limestone (Photo 3-12). This indicates that the Cretaceous Tawilah sandstone was completely eroded before the deposit of the Tertiary volcanics.

A strike slip fault within the Jurassic Amran limestone has been recorded. Along this fault, the natural springs of Samnah have emerged (Photo 3-18).

Several factures and joints trends were delineated through the Jurassic Amran limestone. The most dominant joint trends more or less follow the trend of the major fault planes (Photo 3-19).

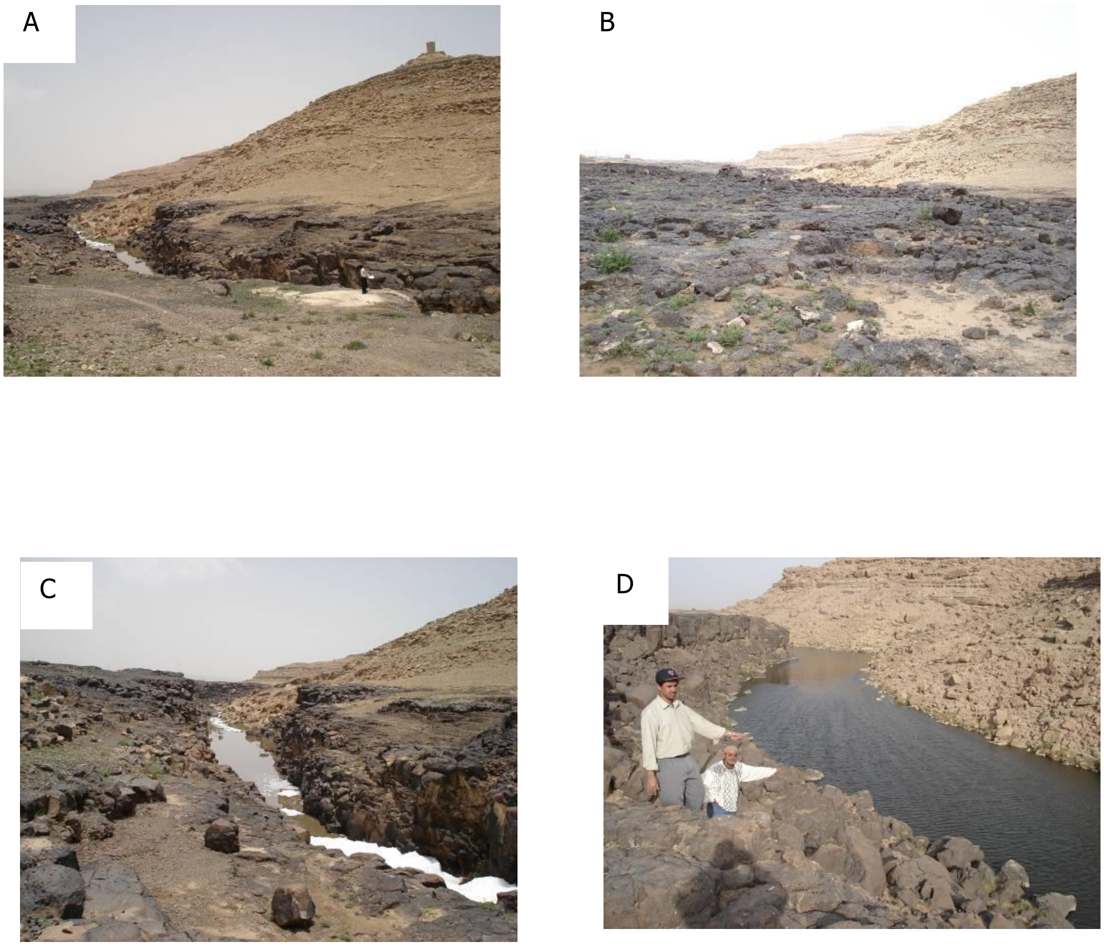


Photo 3-17 A-D **Sewage water flows along the extent of a major fault plain between Jurassic limestone and Quaternary Volcanics**

Photo 3-18 Strike slip fault controlling emergence of Samnah Natural Springs through Amran limestone (Arhab Area)

Photo 3-19 Fractures and joints in the Jurassic Amran limestone

3.5.1.9.1 Sub-Surface geological structures

The subsurface geological structures affecting the old deeper lithostratigraphic units have been traced with the help of the previous geophysical studies. Some of the surface structures in Sana'a Basin are the manifestation of the deeper old faults. They affect the present geological condition as they have reactivated from time to time. In addition, they influence the nature of the sedimentary aquifer geometry and hence the occurrence, availability and movement of the groundwater.

The previous geophysical studies (JICA, 1992 and SAWAS, 1993) carried out their geophysical investigation in the southern part of the basin in order to delineate the subsurface structures and to predict the depth and thickness of the Tawilah sandstone aquifer in order to be an alternative source of water for Sana'a City. The geophysical survey carried out by SAWAS, (1993) gives details of the subsurface structures on Sana'a south along with a predicted elevation of the top of the Tawilah sandstone aquifer (Figure 3-12). It is clear from this figure that Al-Sabaeen faults, with their down throw in the Hizyz area, form a great full graben. This full graben is very valuable for seeking groundwater (SAWAS, 1993). In the northern part, another full graben is interpreted from subsurface data.

The geophysical seismic survey carried out by Exxon, 1987 indicated the presence of deep geological structures (Figure 3-13). Different types of structures can be traced in this figure as follows:

- Horst structures,
- Graben structures,
- Normal faults,
- Step faults.

Several half-grabens are present to the east and south of the Sana'a area and shown in the structural contour map of the depth to basement (Exxon, 1987). It is clear from this figure that the majority of the sub-surface faults take NWW-SEE directions. In the northern part, a horst and graben structure can be traced easily, forming the Jabal As-Sama horst. Towards the south, several half-grabens are present. These faults have influenced the depositional condition of the Mesozoic time and controlled the configuration of the different lithostratigraphical units.

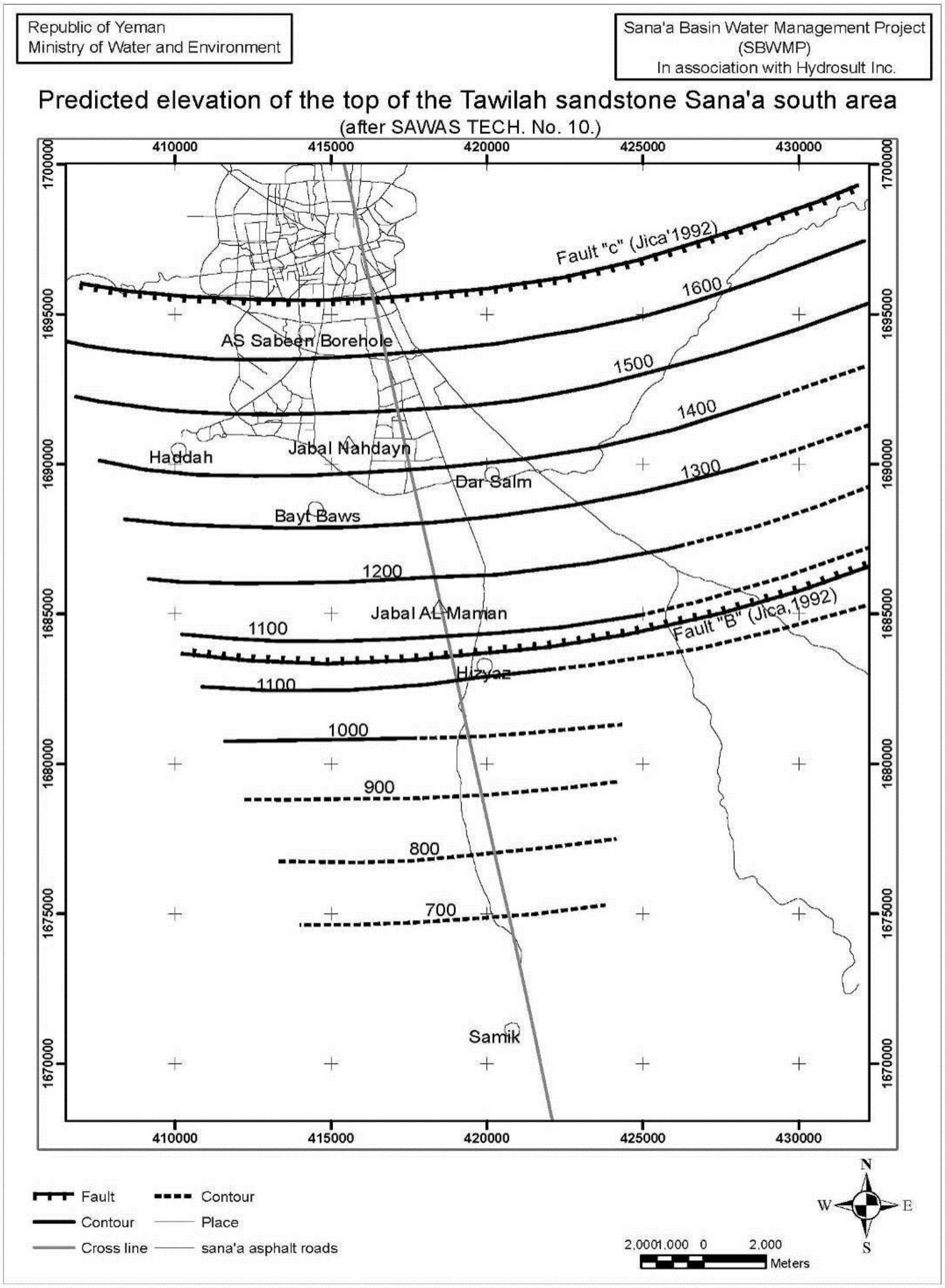

Republic of Yemen
Ministry of Water and Environment
Sana'a Basin Water Management Project
(SBWMP)
In association with Hydrosult Inc.
Predicted elevation of the top of the Tawilah sandstone Sana'a south area
(after SAWAS TECH. No. 10.)
410000
415000
420000
425000
430000
1700000
1695000
1690000
1685000
1680000
1675000
1670000
Fault "c" (Jica'1992)
Fault "B" (Jica,1992)
1600
1500
1400
1300
1200
1100
1100
1000
900
800
700
AS Sabeen Borehole
Haddah
Jabal Nahdayn
Dar Salm
Bayt Baws
Jabal AL Maman
Hizyaz
Samik
Fault
Contour
Cross line
Contour
Place
sana'a asphalt roads
2,0001,000 0 2,000
Meters
N
S
W
E

Figure 3-12 Predicted elevation of the top of Tawilah sandstone Aquifer Sana'a South area (After SAWAS, 1993)

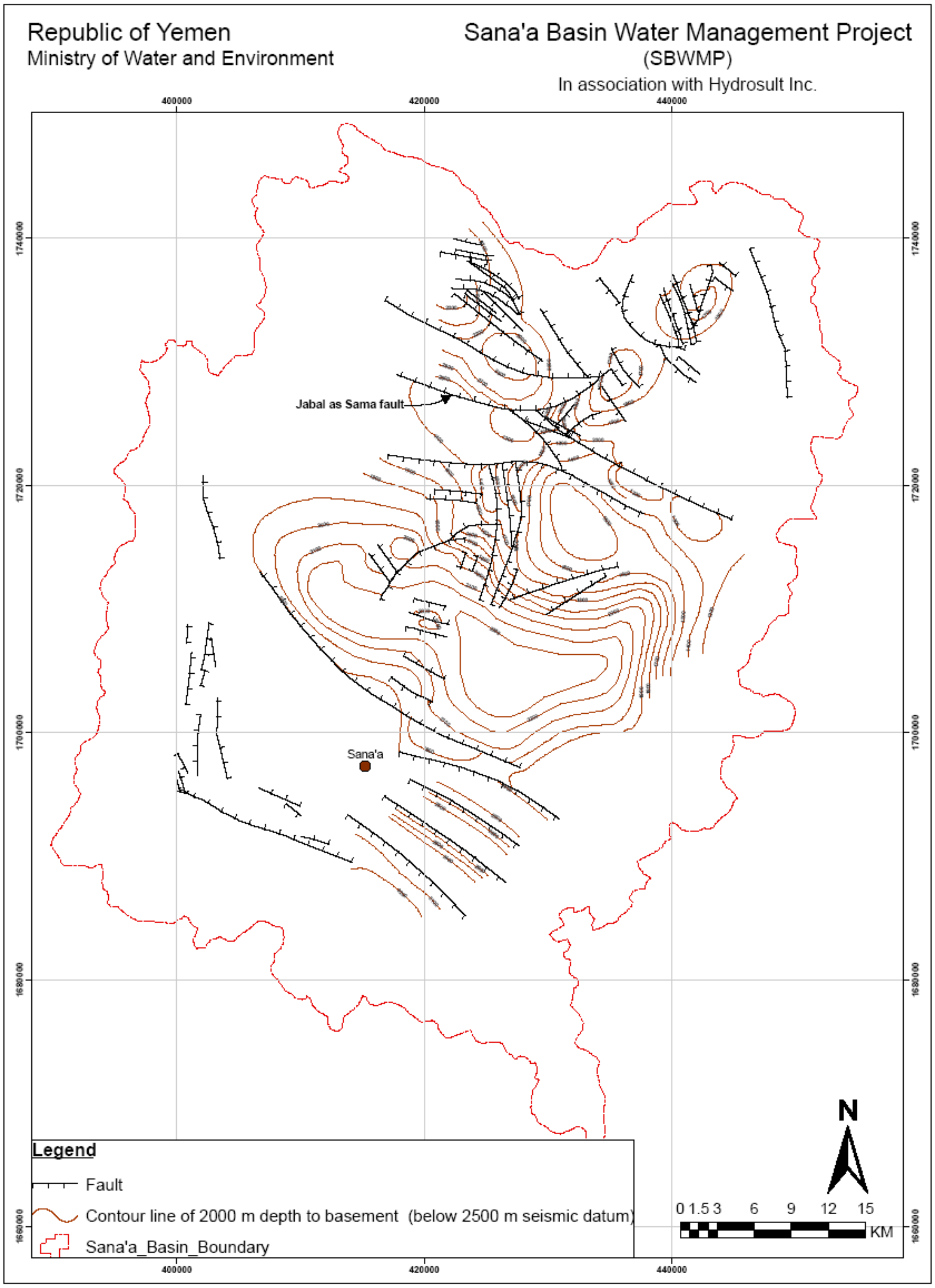

Republic of Yemen
Ministry of Water and Environment
Sana'a Basin Water Management Project
(SBWMP)
In association with Hydrosult Inc.
400000
420000
440000
1740000
1720000
1700000
1680000
1660000
Jabal as Sama fault
Sana'a
Legend
Fault
Contour line of 2000 m depth to basement (below 2500 m seismic datum)
Sana'a_Basin_Boundary
N
0 1.5 3 6 9 12 15
KM

Figure 3-13 Structures and Depth to Basement contour map (Modified after Exxon, 1987)

3.6. The lateral and vertical lithological variation in of the Tawilah sandstone group

The Tawilah group is a build-up of white, yellow or reddish fine to coarse-grained, sometimes gravelly, well-stratified friable sandstone, frequently cross-bedded, with layers of red to violet claystone, siltstone and ironstone, the latter being up to 2-3 m thick at a maximum. They are generally mature quartz arenites. Conglomerates of well-rounded quartz and quartzite clastics are common. The average total thickness of the Tawilah group, according to previous seismic study (Exxon, 1986), drilling records and outcrop data, is about 350 m in Sana'a Basin.

Lateral lithological variations

Italconsult, 1970, studied in detail the Tawilah sandstone group in very good outcrops in Sana'a Basin, where a stratigraphic section has been measured at Jabel Al-Jadir for a total thickness of 186.5 m. The base of this measured section is about the middle of the total sandstone section according to nearby well data from the Italconsult wells (ST-4, S E-7). From study of this reference section, it seems that no major variations occur in the full measured thickness and formation (Italconsult, 1970). A characteristic particular to the group is fracturing. The density of fracturing is variable. Some major fractures are occupied by basaltic dikes, frequently decomposed (Italconsult, 1970).

In 1983, Abou-Khadrah et al studied the stratigraphy and structures of the Cretaceous Tawilah group in the area of Sana'a Basin. In this study, the lithostratigraphy of the Tawilah sandstone is interpreted from five measured sections. These sections are, from west to east: Jabal At-Tawilah, Kawkaban-Al-Ahjur, Thula, Wadi Dhahr and Al-Ghiras – Jabal Marmar.

In 1995, Al-Subbary carried out a detailed lithostratigraphical and facies analysis study of the Tawilah sandstone group in the western part of Yemen in general and Sana'a Basin in particular. He studied the Tawilah outcrops in the western part of Yemen in the form of five main Traverses (areas). Traverse 1 passes through Sana'a Basin from west to east. Along this traverse, five lithostratigraphic measured sections have been studied and described in detail. These sections, from west to east, are: Jabal Iram in Hamdan, Jabal Maramar in Bani Hushaish, Jabal Kura'a in Wadi As-Sir, Jabal Thoma and Jabal Ghulat Assem in the Nihm district. The maximum thickness of these measured sections is 391 m, which was measured at Jabal Ghulat Assem (Figure 3-14). The latitude, longitude and altitude information on these measured sections are provided in Table 3-15.

Table 3-14 Coordinates and Altitudes of the selected sections studied (Source of the Data, Al-Subbary, 1995)

Sec. No.	Section's Name	Location			Thickness in m
		Latitude (N)	Longitude (E)	Altitude m asl	
1	Jabal Iram	15º 30' 44"	44º 03' 23"	2010	242.00
2	Jabal Marmar	15º 35' 28"	44º 24' 44"	2260	387.00

Sec. No.	Section's Name	Location			Thickness in m
		Latitude (N)	Longitude (E)	Altitude m asl	
3	Jabal Thumma	15º 34' 30"	44º 32' 31"	2258	160.00
4	Jabal Kura'a	15º 29' 20"	44º 25' 08"	2373	63.00
5	Jabal Gulat Asim	15º 36' 18"	44º 32' 22"	2160	391.00

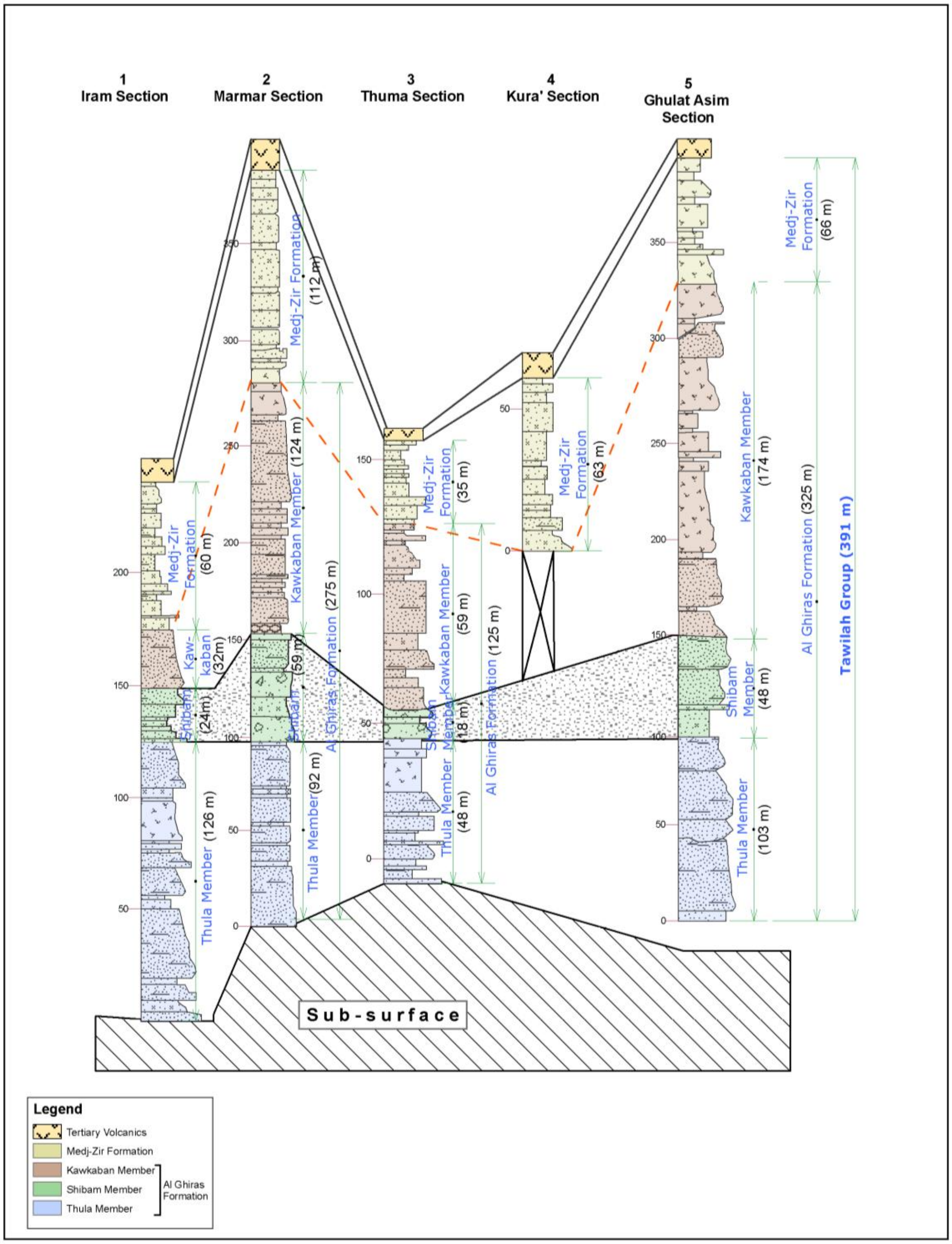

1
Iram Section
2
Marmar Section
3
Thuma Section
4
Kura' Section
5
Ghulat Asim Section
Medj-Zir Formation (60 m)
Kaw-kaban (32m)
Shibam (24m)
Thula Member (126 m)
Medj-Zir Formation (112 m)
Kawkaban Member (124 m)
Shibam (59 m)
Al Ghiras Formation (275 m)
Thula Member (92 m)
Medj-Zir Formation (35 m)
Kawkaban Member (59 m)
Shibam Member (18 m)
Thula Member (48 m)
Al Ghiras Formation (125 m)
Medj-Zir Formation (63 m)
Medj-Zir Formation (66 m)
Kawkaban Member (174 m)
Shibam Member (48 m)
Thula Member (103 m)
Al Ghiras Formation (325 m)
Tawilah Group (391 m)
Sub-surface
Legend
Tertiary Volcanics
Medj-Zir Formation
Kawkaban Member
Shibam Member
Thula Member
Al Ghiras Formation

Figure 3-14 Correlation between the five measured sections of Tawilah sandstone that outcropped in Sana'a Basin (modified after Al-Subbary, 1995). Vertical lithological variations

Al-Subbary, 1995 subdivided Tawilah sandstone group into two mappable units: Al-Ghiras and Medj-zir Formations. Each formation has been further subdivided into several members (Table 3-15 and Photo 3-20).

During the present study, an intensive field survey performed on previous outcropped sections, especially at Jabal Gulat Assem in the Nihm area, in order to study the vertical variation in lithology. Based on the Al-Subbary study, 1995 and the recent field verification, a brief description of these formations and members is given below:

Ghiras Formation (Photos 3-20 A & B)

It is mainly fluvial facies and contains three members from base to top as below:

The Thula member (Photo 3-21 A)

It consists of cross-bedded sandstone, graded bedded and coarse to fine grains and the upper part is pebbly and conglomerate 60 m thick. The type section of this member is represented by the lower 107 m of the Ghiras formation under the Castle of Thula. Further description is provided in Table 3-15.

The Shibam member (Photo 3-21 B)

It consists of reddish sandstone (marker bed) and has coarse to fine grains, cross-bedded with a layer of red to violet claystone, siltstone and ferruginous 40 m thick in the north-western part of the Sana'a Basin. The type section of this member lies at Shibam town. Further description is provided in Table 3-15.

The Kawkaban member (Photo 3-20 C)

It consists of pebbly, fine-grained yellow sandstone, with conglomerate containing thin lamina of iron and manganese oxide. It is very compacted and measures 90 m in thickness (Al-Subbary 1995). The type section of this member is recorded below the Kawkaban village with a thickness of 122 m. Further description is provided in Table 3-15.

Mejd-zir Formation (Photos 3-20 A & B)

The Ghiras formation of the uniform sandstones is overlain without break by Paleocene arenaceous-argillaceous beds. The Cretaceous/Paleocene boundary is not well marked, there being continuity of facies. Indeed, the Medj-zir formation towards the base is composed of sandstones very like those of the Ghiras, although the grain size is smaller and the beds are better cemented. Towards the top, among the many reddish sandstone layers of apparently continental origin, more frequent interbeddings of siltstone, claystone and clay ranging from grey to dark red in colour are encountered (Italconsult, 1970). Due to the greater amount of clayey material present, the hydraulic characteristics of this formation are much less favourable (Italconsult, 1970). It is shallow marine to lacustrine facies. This formation is classified by Al-Subbary, (1995) into three members from the base to the top as below:

The Zijan member (Photo 3-21 D)

It is brown in color with medium to fine-grained sandstone in the lower part and interbedded with greenish-gray to brown carbonaceous rich with siltstone of 25-30 m in thickness. This member is found in Wadi As 'Sir to the northeast of the Sana'a City. Further description is provided in Table 3-15.

The Kura'a member (Photo 3-21 E)

It represents the middle part of Medj-zir formation with variable color, very fine grained sandstone and siltstone with lenticular claystone (20-30 m thick) and the type locality is Wadi Kura'a. Further description is provided in Table 3-15.

The Lahima member (Photo 3-21 F)

It is the top of the Tawilah group in contact with the Tawilah and the Tertiary Volcanic (Al-Subbary, 1995). Further description is provided in Table 3-15.

Table 3-15 Lithostratigraphic Classification of the Tawilah Group (After Al-Subbary, 1995)

<table>
<tr><td rowspan="2">TERTIARY</td><td colspan="3">ROCK UNIT</td><td>DESCRIPTION</td><td>DEPO. ENVIR.</td></tr>
<tr><td colspan="3">YEMEN VOLCANIC GROUP</td><td>Bimodal volcanics (alkali basalts, rhyolite and ignimbrites) associated with some Tertiary granite</td><td></td></tr>
<tr><td rowspan="8">PALEOCENE - EOCENE</td><td rowspan="8">TAWILAH GROUP</td><td rowspan="8">MEDJ-ZIR FORMATION</td><td rowspan="4">LAHIMA MEMBER</td><td>Silts, clays and cherts with dark-grey silts fossil-ferrous limestone horizon</td><td rowspan="8">ALTERNATING MARINE & NON-MARINE DEPOSITS</td></tr>
<tr><td>Iron-rich laminated siltstone and mudstone with few nodules of iron oxides and cherts</td></tr>
<tr><td>Silt / claystone with gastropods</td></tr>
<tr><td>Fine-grained cross-bedded sandstone with iron rich paleosols & few gastropods</td></tr>
<tr><td rowspan="3">KURA MEMBER</td><td>Ferruginous claystone and mudstone beds with iron concretion paleosols</td></tr>
<tr><td>Dark brown very fine sandstones and weathered</td></tr>
<tr><td>Yellowish-brown, patched, with vertical burrows</td></tr>
<tr><td>ZIJAN MEMBER</td><td>Dark-colored fine to medium grained sandstone, very compact, with silt/claystone interbeds with fossiliferous sandstone at the base</td></tr>
</table>

CRETACEOUS		GHIRAS FORMATION	KAWKABAN MEMBER	Yellowish-brown, medium, cross-bedded sandstone and channel conglomerate interbedded with siltstone, containing few wood fossils	BRAIDED, FLUVIAL-CHANNEL DEPOSITS
			SHIBAM MEMBER	Brownish-red ferruginous sandstone with conglomeratic and pebbly intervals	
			THULA MEMBER	Light coloured, medium to coarse, cross-bedded sandstone, intercalated with grey mudstones	
AMRAN GROUP				Highly fossiliferous limestone , dolomites and shale	

A

Photo 3-20 A-B Al-Ghiras and Medj-zir Formations of Tawilah Group at the Bani Hushaish area

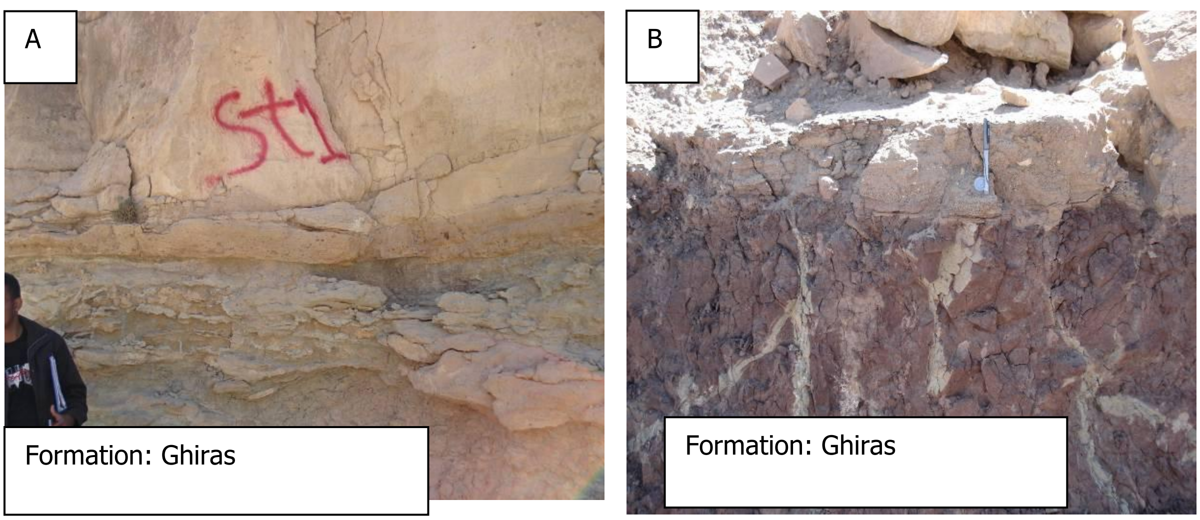


Photo 3-21 A-F Members of Al-Ghiras and Mejd-zir Formations (Cretaceous Tawilah Group)

The detailed field study of the lateral and vertical variations in the lithology of the Tawilah sandstone carried out by Al-Subbary, 1995 indicated that the entire sequence of the Tawilah group consists of twelve (12) distinctive sedimentary facies. These facies were distinguished and classified based on differences in certain sediment characteristics such as grain size, color, sedimentary structures and changes in the lithological composition. Each facies represents a particular type of depositional environment and/or process. The boundaries between these facies are generally transitional. The lateral and vertical distribution of facies and its correlation along the east-west traverse (measured outcrop sections studied nos. 1-5 in Sana'a Basin). The correlation between these cross-sections shows that the fluvial facies associations of the Ghiras Formation have been deposited through the traverse with no major variation in the lithology. On the other hand, the Shibam Member could be an important key bed (distinctive red colouration) and is very well exposed in all studied sections with very little variation in thickness. According to previous sedimentological and stratigraphical studies carried out by Italconsult, 1973, Abu Khadra, 1983 and al-Subbary, 1995, it is clear that there are no major vertical or lateral variations in the Tawilah sandstone lithology such as clay beds or impermeable layers which will affect the groundwater flow.

A detailed description of the lateral and vertical facies changes of Tawilah sandstone was elaborated in Chapter Two (Preparatory Activities).

3.7. Collection of fresh rock samples representing the different members in the Tawilah sandstone for effective porosity determination

Not all deliverables are equally important. Among the most important tangible output maps are the groundwater storage maps because they integrate all the information of the other maps, insofar as they shed light on aquifer storage. The main function of the other maps is to underpin this map category, so they should be designed accordingly. It is clear that determination of the effective porosity of the rock samples is essential for construction of these maps.

Unfortunately, the contract with the Lebanese drilling company (WARD) for the three exploratory boreholes located in the western part of the Sana'a Basin does not include taking core samples from the Tawilah sandstones. Therefore – contrary to what had been assumed earlier – only cuttings will be available. Consequently, as indicated in the inception report, it will not be possible to carry out "laboratory analysis on cores from exploratory boreholes" as was specified in the Terms of Reference for Subcomponent 3d (i). In order to meet the main objective of the envisaged coring – i.e. getting information on storage properties of the fresh aquifer rock – a different approach has to be chosen based on the inception report. The best alternative seems to be taking fresh representative rock samples for different horizons or stratigraphic members of the Tawilah sandstone outcrops studied during the geological field survey. Based on the inception report, about 10 samples have to be collected and sent to a qualified laboratory for analysis in order to determine total and effective porosity.

An intensive review of previous literature related to the Tawilah sandstone outcrops has been carried out. This review revealed that Al-Subbary, 1995 conducted a detailed sedimentological and stratigraphical study of the Tawilah sandstone Group, on the Western parts of Yemen. The following aspects have been studied in details for each formation and its members:

- Lithology,
- Thickness,
- Stratigraphical position,
- Fossil content,
- Depositional environment,
- Age, and
- Sedimentary structures, etc.

During the extensive fieldwork conducted by Hydrosult consultants and NWRA partners in the Nihm, Hamdan and Bani Hushaish areas, it was found that Jabal Ghulat Assem is the suitable section to be sampled for determination of the total and effective porosity due to the following reasons:

- It represents all formations and members of the Tawilah Group,
- Of the five sections described in Sana'a Basin, the Jabal Ghulat Assem has the maximum thickness (391 m) (Table 21)
- The underlying and overlying lithostratigraphical units (Jurassic Amran limestone and Tertiary Volcanic Group) can be easily delineated.
- Presence of a good truck road passing through the entire thickness of this outcrop section, facilitating the sampling procedures.

A combined field visit to Jabal Ghulat Assem was arranged with engineer Ghaleb Al-Sufiani from the General Directorate for Research, Laboratories and Standards, Ministry of Public Works and Highways on Sunday (11-2-2007) in order to define each member and identify the proper locations for the collection of these samples. Ten rock sample locations representing the different members of the Tawilah aquifer have been identified and demarcated on the outcrops using the GPS and other tools. Table 3-16 gives some information about the selected locations of the described samples.

Table 3-16 Description of the fresh rock samples collected from Jabal Ghulat Assem, Nihm area (Location, Altitude, members, Formation and Group)

No. of sample	Coordinates		Altitude (m asl)	Described Section	Group	Formation	Member
	N	E					
St.1	1727824	446363	2146	J. Assim, Nihm	Tawilah	Ghiras	Thula
St.2	1727423	446930	2230	J. Assim, Nihm	Tawilah	Ghiras	Thula
St.3	1727369	446986	2261	J. Assim, Nihm	Tawilah	Ghiras	Shibam
St.4	1726171	448692	2367	J. Assim, Nihm	Tawilah	Ghiras	Kawkaban
St.5	1725484	448491	2470	J. Assim, Nihm	Tawilah	Medj-zir	Zijan
St.6	1725422	448463	2481	J. Assim, Nihm	Tawilah	Medj-zir	Kura
St.7	1725420	448447	2491	J. Assim, Nihm	Tawilah	Medj-zir	Kura
St.8	1725336	448426	2499	J. Assim, Nihm	Tawilah	Medj-zir	Kura
St.9	1725346	448385	2509	J. Assim, Nihm	Tawilah	Medj-zir	Lahima
St.10	1725389	448381	2512	J. Assim, Nihm	Tawilah	Medj-zir	Lahima

In order to analyze the proposed undisturbed fresh rock samples of the Tawilah sandstone group, several visits were made to the authorities and laboratories concerned in connection to this topic, such as the Geological Survey and Mineral resources Board, Ministry of Oil and Minerals and the General Directorate for Research, Laboratories and Standards, Ministry of Public Works and Highways. Finally, it was found that these authorities do not have the facilities to determine effective porosity. Hence, it was important to arrange for other possible alternative outside Yemen in order to determine the effective porosity.

In order to obtain valid results from tests on brittle materials, careful and precise specimen preparation is required. During June 2007, condensed fieldwork was performed to collect the Cretaceous Tawilah sandstone core samples from the chosen locations mentioned (Table 3-16).

3.7.1 Collection of cores and preservation

Test material is normally collected from the field in the form of drilled cores. Field sampling procedures should be rational and systematic, and the material should be marked to indicate its original position and orientation relative to identifiable boundaries of the parent rock mass (photos 3-22 to 3-27). Ideally, samples should be moisture proofed immediately after collection either by waxing, spraying, or packing in polyethylene bags or sheet. Due to the difficulty of melting wax in the field (Jabal Ghaulat Assem), the team first packed every core from all sides in thin, clear polyethylene sheets. After returning to the office, the team began work to coat the wrapped cores with a lukewarm wax mixture to an approximate 6.4 mm thickness, as described in the diagnosis methodology (cited in Department of the army office, soil sampling 1972).

3.7.2 Constraints during preparation of cores for traveling abroad

It is often necessary to store samples for several days to complete a large testing program. The deformation and fracture properties of rock may be influenced by air, water, and other fluids in contact with their internal (crack and pores) surfaces. So the wax layer must be protected from being scratched in the packing process before shipping. On the other hand, although the hard, dense rock and low porosity like Cretaceous Tawilah sandstone rocks will not normally be affected by moisture, this type of material is normally allowed to air-dry prior to testing to bring all samples to an condition of equilibrium. It is recommended that the core not be exposed to excessive heat because this may cause an irreversible change in rock properties.

3.7.3 Procedure for effective porosity determination

The effective porosity determination on samples from the Cretaceous sandstone was performed in the Egyptian Petroleum Research Institute Corelab (EPRI CORELAB). Helium porosity under a confining pressure technique was used. In this procedure, each sample was weighed and then placed in a sealed sample chamber (matrix cup), using steel disks to minimize void space. The reference cell containing a known volume was pressurized with Helium to 100 psi. The Helium in the reference cell was then allowed to expand into the chamber containing the sample. So, grain volume of each sample was measured. To measure pore volume, each sample was loaded into a hydrostatic core holder. An effective overburden pressure of 1000 psi was applied to each sample. The Helium was then allowed into the sample under the above-mentioned confining pressure and the pore volume was measured. By knowing the summation of grain volume and pore volume, bulk volume was calculated. Then, dividing pore volume by bulk volume, porosity was calculated.

The results of the effective porosity determination are presented in chapter 8.

Photo 3-22 Preparation of rock sample from Al-Ghiras Formation - Thula member

Photo 3-23 Preparation of rock sample from Al-Ghiras Formation - Shibam member

Photo 3-24 Preparation of rock sample from Al-Ghiras Formation - Kawkaban member

Photo 3-25 Preparation of rock sample from Medj-zir Formation - Zijan member

PHOTO MISSING HERE

Photo 3-26 Preparation of rock sample from Medj-zir Formation - Kura'a member

Photo 3-27 Preparation of rock sample from Medj-zir Formation - Lahima member

3.8. Nature of Lateral Boundaries of the Cretaceous Tawilah sandstone

3.8.1 Impermeable lower boundary

The Jurassic Unnamed Formation and Amran limestone Group are assumed to be impermeable, since the data show that both two units have a very low production of water. This means that there is no flow across the boundary of the Cretaceous Sandstone and the Unnamed Formation. The model developed by Foppen, 1996, only takes into consideration flow in the Cretaceous, Tertiary and Quaternary lithostratigraphical units. There are two arguments to dispute the validity of this assumption:

- In the north of the Sana'a Basin, the Jurassic e Amran limestone Group must be part of the groundwater flow system to some extent, since there the Wadi Al Kharid springs are located.
- Chemical data from groundwater in the Kohlan sandstone below the Amran Group in the DS1 borehole indicate fresh water with an EC of around 1500 micro Siemens. This must be recharge entering the Kohlan sandstone through the Amran limestone, indicating vertical groundwater flow (SAWAS, 1996).

3.8.2 Western Boundary

The western boundary of the Sana'a Basin is partly the escarpment south-west of Shibam, where elevations drop from over 2600 m asl east of Shibam to around 2100 m asl south-west of Shibam. The area is part of the catchment of Wadi Surdud composed almost entirely of rocky outcrops of very irregular topography (Photos 3-28 A & B). Dufour (1989) has made a reconnaissance survey there. He stated that "along the eastern and northern slopes of the Wadi Al-Ahjur a great number of springs were found. They are found at a distinctive topographical level of 2300-3500 m asl, which corresponds with the lowest part of the Tawilah sandstone or the Amran limestone-Tawilah sandstone boundary.

The Ayoun Surdud is a group of four springs located at elevations varying between 1140 and 1220 m. They have been studied and described in some detail by Neumann-Redlin (1991). The total discharge of the four springs is, according to measurements between March 1989 and March 1990, from 700 to 800 l/s. The water is fresh with electrical conductivities varying between 430 and 730 micromhos/cm and a temperature of 28-31°C. Their chemical composition is that of a calcium bicarbonate water, although with sulphate contents that suggest dissolution from gypsum layers. The Ayoun Surdud constitutes the main discharge from a regional aquifer system composed of Mesozoic rocks (Jac Van der Gun, 1996).

Van der Gun (1986) estimated the total yield of the springs feeding Wadi Al-Ahjur to be around 1000 l/s. This comes from the western, northern and eastern slopes of the Wadi Al-Ahjur. Foppen (1996) stated that, in terms of modelling, this can serve as an indication of the outflow across the western boundary of the model area (Sana'a Basin). From Shibam further north, the area becomes Amran limestone. From the escarpment further south the area becomes Tertiary Volcanics. No significant springs or discharge zones are present. It is not known whether the Cretaceous Sandstone is present below the Tertiary Volcanics. In his cross-sections, Charalambous (1982) assumes that it is not present, although data fail to support this (Foppen, 1996).

During the course of this study, field visits were made to Wadi Al-Ahjur and Ayoun Surdud located at Wadi Kawfa (Coordinates 1697012 N and 367485 E and Altitude 1219 m asl) on the upper catchment of Wadi Surdud. The main goals of these visits were to understand the hydrogeological condition at and around the Wadi springs, study the structural elements controlling the emergence of these springs and understand the relation of the springs yield to the groundwater aquifers in Sana'a Basin.

Geologically, the Cretaceous Tawilah sandstone group is widespread and outcropped in the northern part of the area. They have been subjected to several block faults. The majority of these faults are NW-SE in direction and run parallel to the Red Sea rift. The hanging walls have been down thrown towards the west at variable distances (Photo 3-29, Figure 3-15). The Cretaceous Tawilah sandstone group consists mainly of sandstones and argillites. The Mesozoic sedimentary rocks are elsewhere in the area, mostly covered by rocks of the Tertiary Yemen Volcanics. Quaternary sediments occur mainly in and along wadi beds, in small pockets and narrow belts. The complexity of the geology is further increased by numerous faults and by Tertiary intrusions.

The origin of Ayoun Surdud can be related to the tectonic features that have offset the permeable and water-bearing rocks (Cretaceous Tawilah sandstone) against the impermeable basement rocks or other rocks of low permeability; hence, groundwater flowing in the Mesozoic rock units is forced to the surface (Photo 3-30). In the area of the Wadi Surdud springs (locally called "Wadi Kawfa"), the Tawilah sandstone group has been deposited unconformably over the Precambrian Rocks (Photo 3-31 A-D). The larger springs are located along the Wadi Kawfa, which is produced and controlled by a normal fault which strikes NW-SE, parallel to the Red Sea rift. The different lithological units outcropping along the two side of Wadi Kawfa are Precambrian Basement rocks and Cretaceous Tawilah sandstone. Along the structural fault, the eastern side of Wadi Kawfa has been moving downwards while the western side of the Wadi has been moving upwards. The productive springs are emerging from the unconformable sharp contact between the Precambrian basement rocks and the Cretaceous Tawilah sandstone at the Eastern side of Wadi Kawfa (Photo 3-32), while very little seepage of water can be traced along the western side of the Wadi (Photo 3-33). Huge Travertine deposits, stalactites and stalagmites of calcium carbonate have been deposited along the contact of the Cretaceous Tawilah sandstone group and the Pre-Cambrian basement rocks. The large amounts of water produced from this spring located on the eastern side of Wadi Kawfa can be attributed to the larger areal distribution of the Tawilah sandstone aquifer on the eastern side of the wadi, which extends from the western boundary of Sana'a basin to Wadi Kawfa.

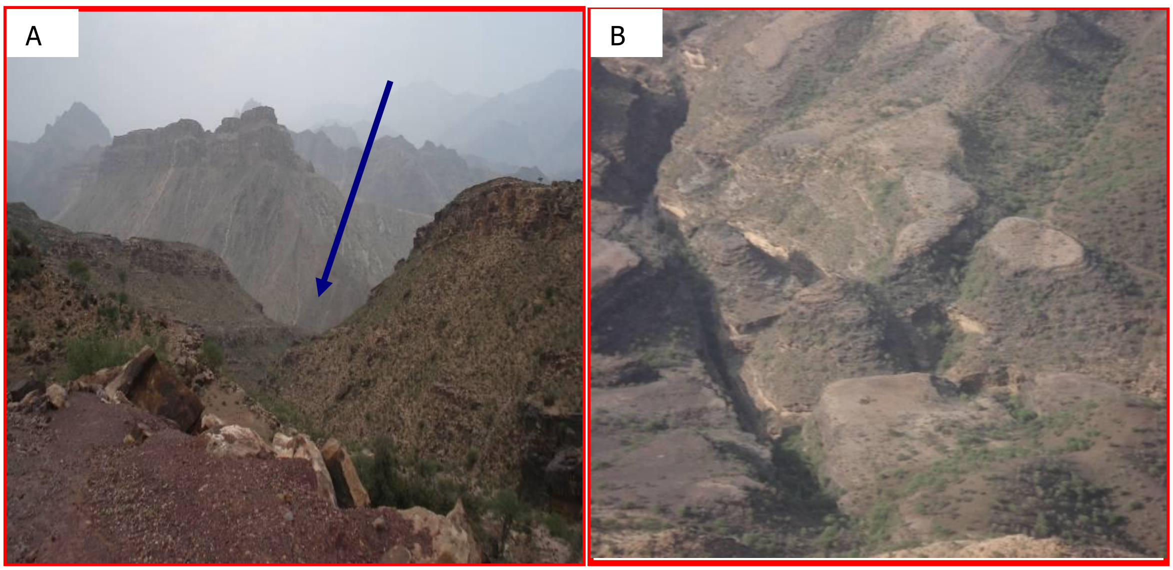


Photo 3-28 A-B Main Topographic Features of the Upper Wadi Surdud Catchment

Photo 3-29 NW-SE step faults running parallel to the Red Sea rift

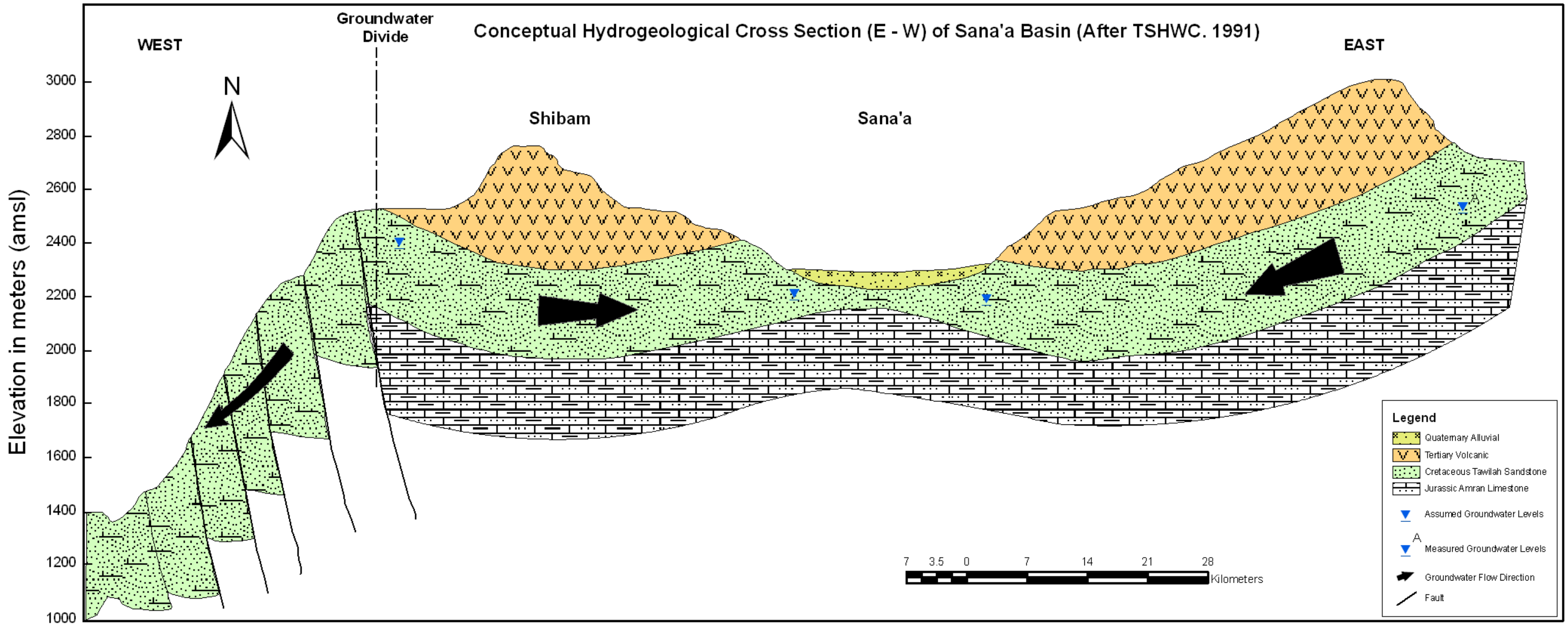


Figure 3-15 Conceptual hydrogeological cross-section (E-W) of Sana'a Basin (After, TSHWC, 1992)

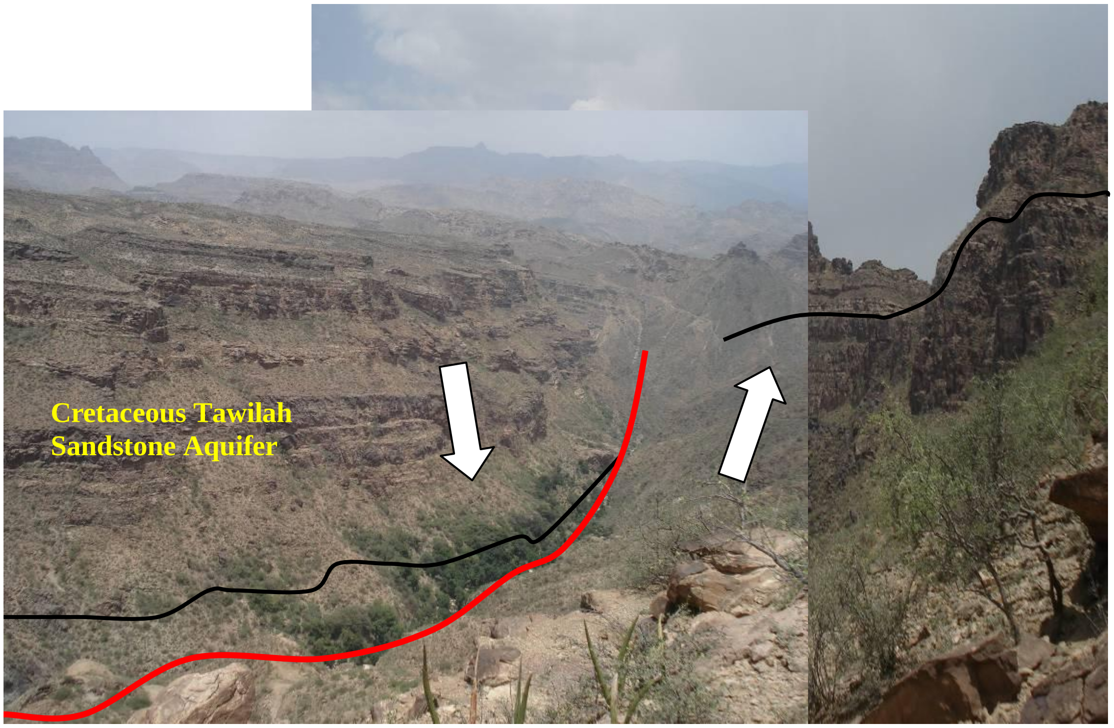


Photo 3-30 Panorama view showing the different lithological units and the structural faults along the Wadi Kawfa

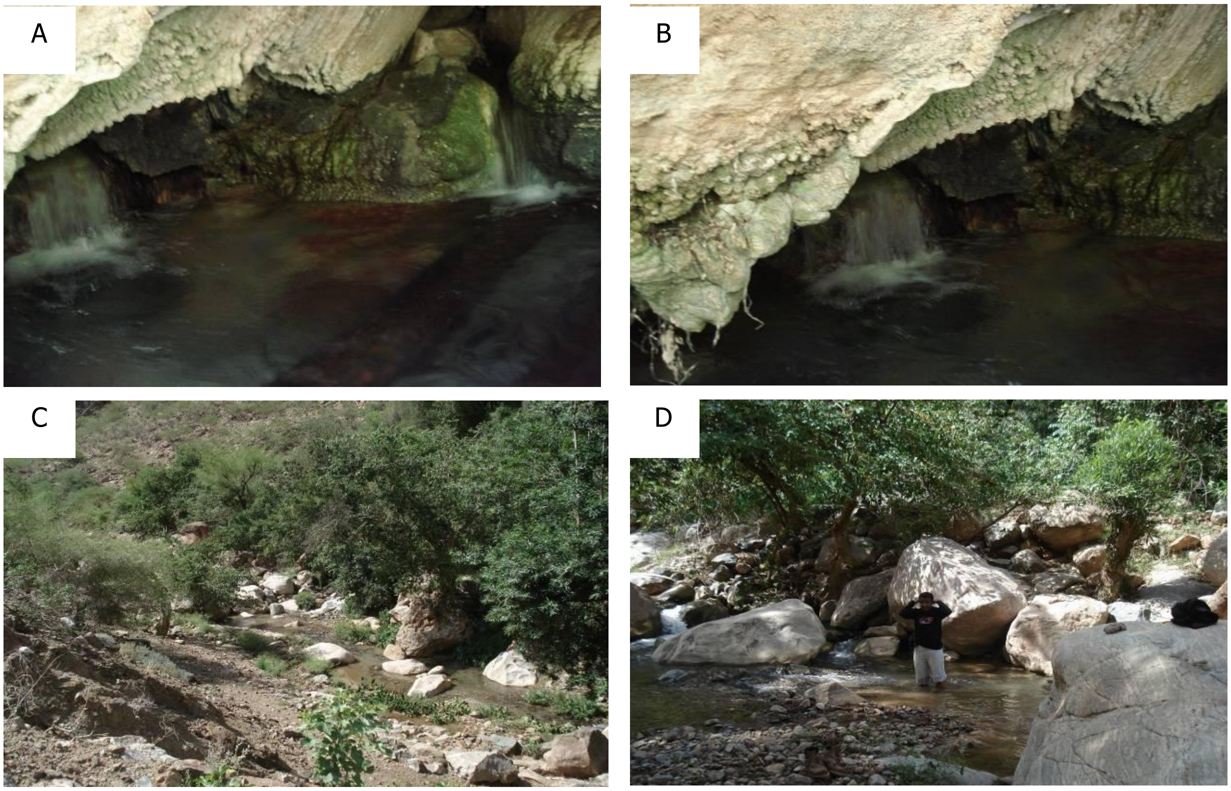


Photo 3-31 A-D Springs at the Eastern Escarpment of the Wadi Kawfa

Photo 3-32 Unconformable sharp contact between the Cretaceous Tawilah sandstone group and the Precambrian basement rocks

Photo 3-33 Seepage of water along the western side of Wadi Kawfa

The electrical conductivity, pH and temperature of the spring water were measured in the field during this field visit. The measured values show that the electric conductivity reaches 440 **µS/cm** and that the **pH** value is 7.6, while the spring water temperature reaches 26.5**˚C**. In summary**,** the recent measured spring water quality showed comparable values to those measured in March 1989 and March 1990, indicating that there are no noticeable changes in water quality. Interviews with local peoples indicated that there is now considerable reduction of the spring yield, indicating that the groundwater aquifers in the upstream are the main source of the spring water. The study of the geological maps and the fieldwork observation indicate large aerial distribution of the Tawilah sandstone aquifer over the area located between Sana'a Basin and Wadi Surdud Springs.

Previous studies indicated that the sources of spring water are in the Mesozoic complex aquifer which presents at higher altitude in and around Sana'a basin. Taking into consideration the travel time of groundwater from the upper stream area to Wadi Surdud spring, the electrical conductivity of groundwater in Sana'a basin and Wadi Surdud Springs shows comparable values. In order to confirm this finding, it is important to conduct a hydrogeochemical investigation of the spring water using the isotope technique to determine the source of this water and to carry out a detailed study using chemical tracer techniques to determine the groundwater flow direction.

3.8.3 Northern Boundary (Wadi Al-Kharid – Flow Boundary)

Wadi Al-Kharid is a mountain stream originating in the Sana'a area. It is one of the main tributaries of the Wadi Al Jawf system, which conveys excess flood waters from the eastern Yemen Mountain flanks to the sands of the Ramlat as Sabatayn. The Wadi Al-Kharid, has a modest and virtually perennial base flow fed by springs and seeps north of Jabel As Sama (SAWAS, 1995).

Under normal conditions, the Sana'a Plain absorbs all surface water draining towards it from the surrounding mountains. In principle, runoff may pass over the Sana'a Plain and finally through the gorge north of the plain to be funneled into Wadi Al-Kharid, but this probably occurs only very seldom, during rare periods of extremely high rainfall.

The floods of Wadi Al-Kharid are normally produced by rains in the hilly areas north of the Sana'a Plain only. This area is called the 'effective catchment' (SAWAS, 1995). Of the total area of Sana'a Basin (3200 km^2), only 1020 km^2 of this can be considered as 'effective catchment' from the point of view of direct runoff passing the area's outlet under normal conditions.

The piezometric maps of the Sana'a Plain (Italconsult, 1973) indicates that groundwater under the plain generally takes a northerly direction, and apparently passes through the limestone ridge (Limestone ridge of Jabal As-Sama) that blocks the Sana'a plain. Water from these springs has a temperature of 34-37°C, an electrical conductivity of 1200-1300 mg/l, and $SO4^{-2}$ as the dominant anion. The combined yield of the springs is said to be rather stable, around 200 l/s (Moskhiprovodkhoz, 1986).

In limestone country (northern boundary), it is known that karstic (solution) systems, as irregular tunnels and cavities, may have developed along lineaments, even though the limestones do not show much surface karst. Karst often develops over a long period of time as it is associated with -fossil- groundwater levels and flow systems. Therefore, it cannot be excluded that groundwater leaves the Sana'a basin through the sandstone and limestone in the north. This is conditional to the piezometric surface being lowered to the north. The latter seems to be the case. The springs at the head of Wadi Al-Kharid could bear witness to the outflow, provided the hydrochemistry of the spring waters is similar to that of the groundwater of the alluvial and Tawilah sandstone. The fact that the spring discharges have declined during the period of important groundwater abstraction in the northern Sana'a basin suggests a hydraulic connection (WEC-ITC, 2001).

Also along the north-eastern boundary, groundwater may escape from the basin through the sandstone and perhaps through the underlying limestone. However, it is not known whether -fossil-karst systems occur at greater depths. They could have been developed during the Jurassic-Upper Cretaceous hiatus and at places where thin sandstones overlying limestones occur.

During the course of this study, a field visit was made to this area. It was reported by local peoples that the spring yield has decreased tremendously in recent years and is no longer used for drinking purposes. Most of the spring water used to be collected into storage tanks and the farmers pumped it to nearby areas for agricultural purpose only (polluted water). These springs and the seepage zone in their surroundings are likely to constitute the main natural discharge mechanism for groundwater of the aquifers under the Sana'a Plain. This has been confirmed through the presence of a large bond of sewage water and dense vegetation in the area surrounding these springs. The slightly thermal springs occurring at an elevation of 2000 m on the limestone plateau near Samnah, only a few kilometres north of the plain, suggest that a structural fault (Strike slip fault) plays an important role in this respect (Photo 3-34).

Wadi Kharid had a permanent base flow during 1995, although rather low (averaging some 60 l/s). It is said that the wadi sometimes goes entirely dry, but no records exist to prove it or to indicate the frequency of occurrence (SAWAS, 1995). It has been found during the present visit that the base flow in wadi Al-Kharid become very small. It has been reported by local peoples in that area that the spring water is used only by animals and can not be used for drinking purposes. (Photo 3-35). Most of the base flow emerges through springs in the limestone aquifer. It has been found that these springs are controlled by normal structural faults (Photo 3-36).

Figure 3-16 shows a sub-surface geological cross-section across the Sana'a Basin, from the area of the Jabel As Samma to the Wadi Al-Kharid springs (Exxon, 1987). The lithostratigraphical units encountered along this cross-section are from older to younger, the Pre-Cambrian basement, Kohan sandstone, Amran limestone, Tawilah sandstone and the Quaternary alluvial deposits. It is clear from this cross-section that the area of Arhab that is dominated by the Jurassic Amran limestone has been subjected to intensive structural tectonic activities. Several approximately E-W normal faults have been detected along this cross-section. As a result, graben and horst structures have been developed. The Jabal As-Samma is a horst structure, whereas the area between Jabal As-Samma and the Wadi Al-Kharid springs is graben structure. It is clear also that the Spring of Wadi Al-Kharid has emerged as a result the structural control. Since groundwater in the Sana'a Basin flows from south to north and since the Sana'a Basin is closed to the north by the Jabel As Samma, it is very clear that groundwater must leave the area through the Amran limestone. Eventually part of the groundwater will be discharged into the Wadi Al-Kharid springs (Foppen, 1996).

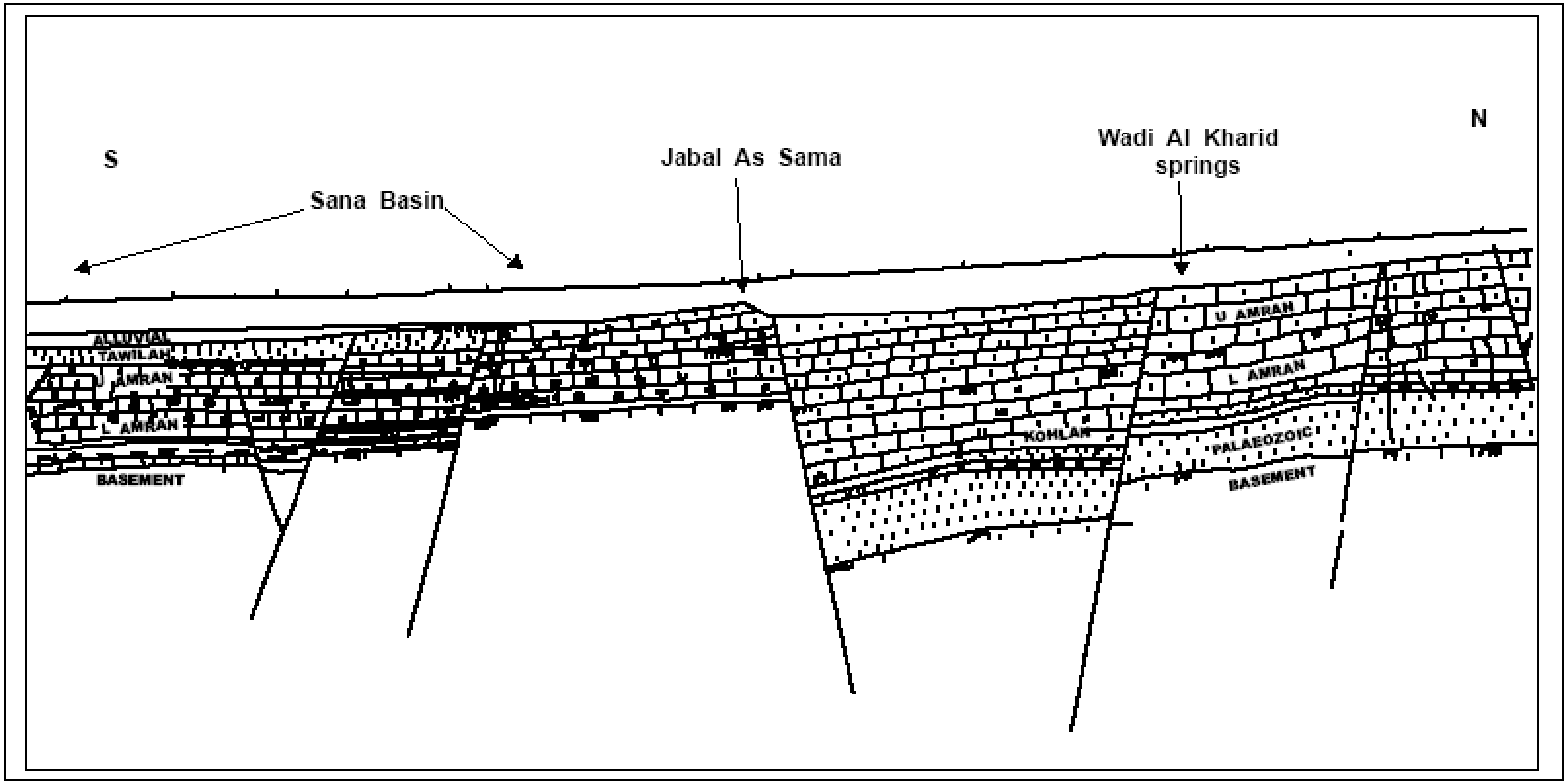


Figure 3-16 Sub-surface geological cross-section across Sana'a-Jabal As Sama-Wadi Al-Kharid Springs (From Foppen, 1996 based on Exxon, 1987)

Photo 3-34 Strike slip fault controlling emergence of Samnah Natural Springs through Amran limestone (Arhab Area)

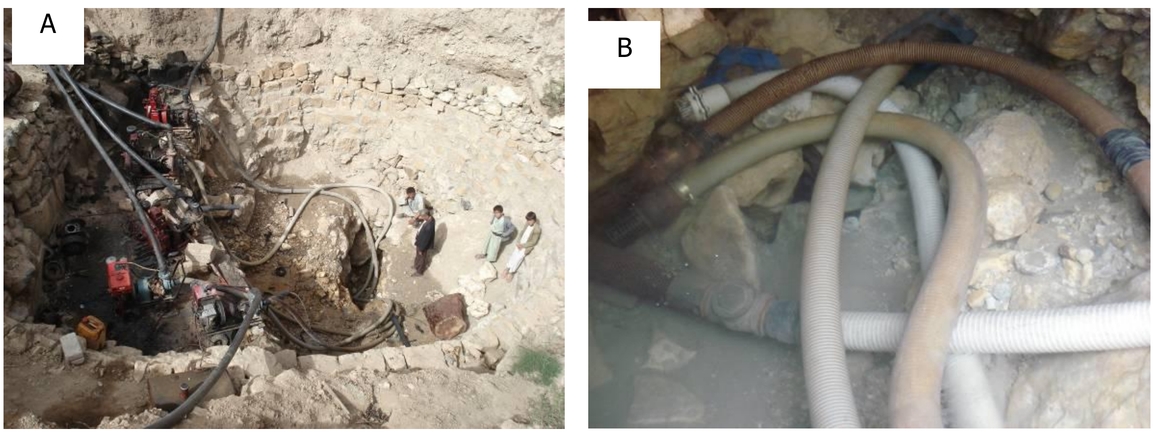


Photo 3-35 A-B Abstraction of spring water for agricultural purpose

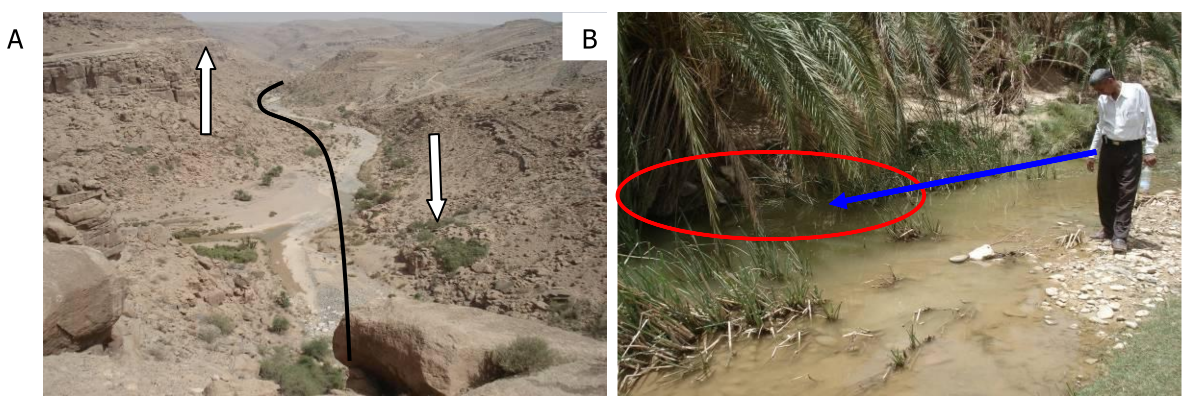


Photo 3-36 A-B Emergence of Al-Kharid Natural Springs through a major fault in the Jurassic Amran limestone (Arhab Area)

3.8.4 The Eastern Boundary

Fieldwork in the eastern part of the basin reveals that the Cretaceous Tawilah sandstone group extends laterally outside the basin boundary at several locations in the Nihm area such as, Al-Madareg, Al-Madfone, Al-Mahgar (Photo 3-37). In the Bani Hushaish area, along the basin boundary, the Tawilah sandstone group has been subjected to step fault towards the eastern part (Al-Jawf Basin). No volcanic dyke has been reported to act as a barrier to groundwater movement along the basin boundaries. Several volcanic intrusions have been reported in the Nihm areas outside the basin boundary such as Al-Salda, Al-Harim and Al-Katab. These volcanic intrusions have intruded the Tawilah sandstone outside the basin boundary.

Ezzat (1984; the Integrated Rural Development Project of the Khawlan Area) has provided information on groundwater flow in the Khawlan area. The map prepared shows the isohypses in the Yemen Volcanics east of the Sana'a Basin catchment area. It seems that groundwater flow is directed towards the east with groundwater levels from 2500 m asl in the west to 2000 m asl in the east. Going from the Yemen Volcanics to the east, first the Cretaceous Sandstone outcrops and then the Jurassic Amran limestone. If the Amran is assumed to be impermeable, then all groundwater would be collected in the Tawilah and flow either north, south or even west. This is not very likely, according to this map. The Amran limestone does not appear to be a no-flow boundary (Foppen, 1996).

Along the eastern and southern boundaries, groundwater may flow out of the basin because of topographic conditions. The flow through the upper saturated part will be mainly through fractures because the Tertiary volcanics have low intrinsic permeability. At larger depths, flow could occur through the sandstones that crop out beyond the eastern boundary. However, not many major fractures could be identified in that area and fracture flow is therefore supposed to be low (WEC-ITC,2001).

Figure 3-17 shows a water level map of the Tawilah sandstone aquifer that was constructed based on data of 715 deep bore wells (WEC, 2001). It is clear from this map that the direction of groundwater flow is towards inside and outside the basin, indicating flow boundary towards east.

Photo 3-37 Present of the Tawilah sandstone group outside the boundary of Sana'a Basin

2. Groundwater Elevation of the Tawilah Aquifer

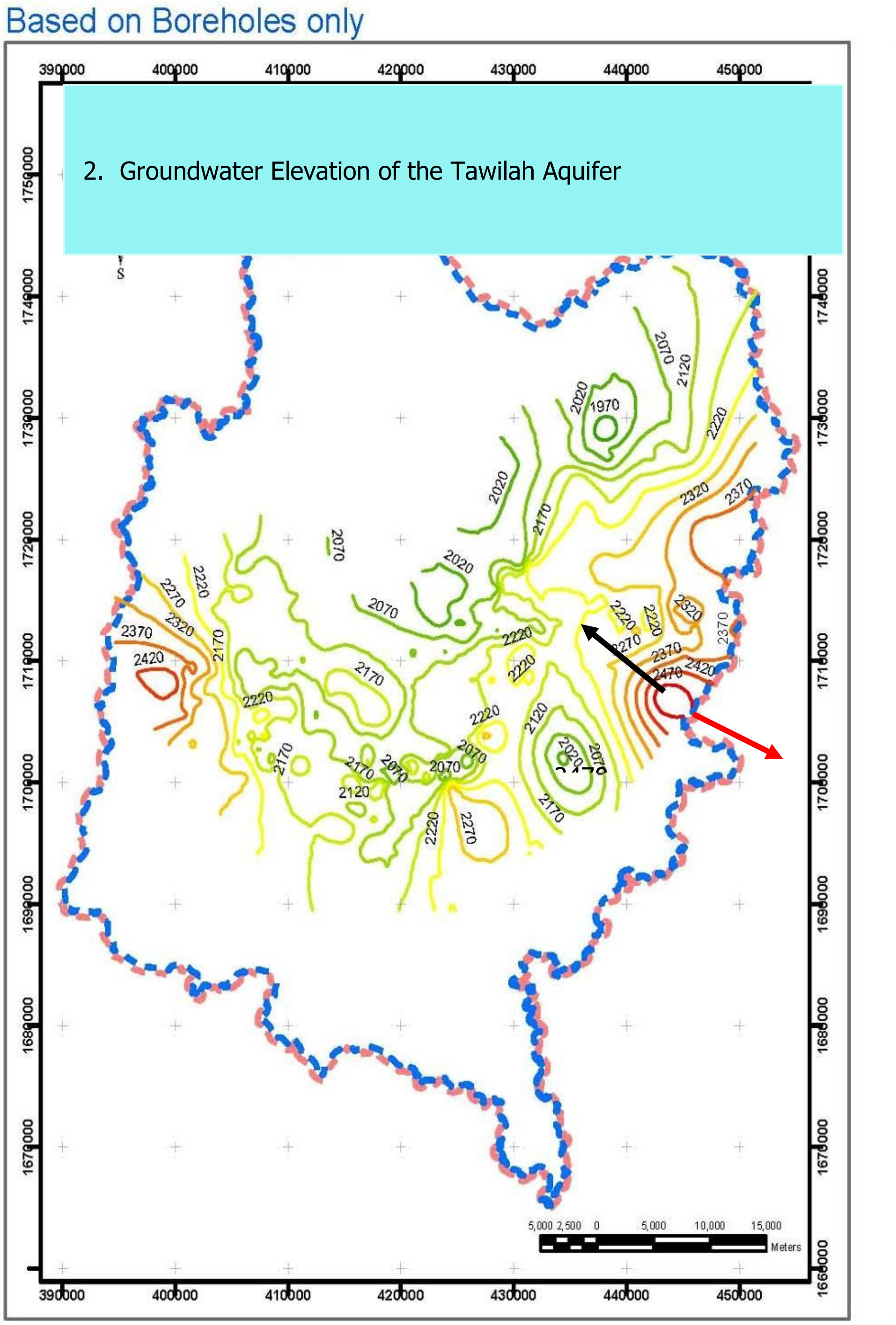


Figure 3-17 Groundwater level map of the Tawilah aquifer showing a flow towards the east

3.8.5 Southern Boundary

Volcanic rocks make up the area around the southern boundary. Some major fractures and a few normal faults occur in that part. The previous geological maps prepared by Robertson, 1990 and Kruck, 1991 agree on the existence of a fault just west of the road from Sana'a heading south, although the two maps do not agree on the pattern of the fault. Since not many large lineaments could be interpreted in that area, it is believed that only little groundwater leaves the basin along the southern margin through fractures (WEC-ITC, 2001).

Due to the lack and insufficience of sub-surface data, there is no information available about the southern boundary of the Sana'a Basin. It is not known if and how groundwater flows in this part of the Cretaceous Sandstone. With regard to the aquifer geometry, two cases can be assumed:

- The Sandstone forms a broad syncline towards Taiz where it outcrops at ground surface.
- Just north of the Sabaeen well, the Sandstone is faulted (van Dalfsen, 1996) and there is a possibility that the Sandstone blocks north and south of the fault line are not connected. South of the fault line, the Sandstone is present and forms a broad syncline towards Taiz.
- In both cases, it is clear that the presence of physical boundaries of the Sandstone (faults, complete erosion of the Sandstone) south of Sana'a is completely unknown.