

Structural Study of the Amran Basin in NW of Yemen and Their Impact on the Recharge of Groundwater

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Abstract
Geological study covers the investigation of the structural elements and some of the hydrogeological conditions of the Amran Basin NW of Yemen. Generally, the water-supply situation in Amran basin is precarious due to more abstraction than recharge is taking place; consequently, groundwater levels continue to fall and the groundwater resource is increasingly being exhausted. The aim of this study is to identify the depth of ground water in Amran basin depending on several techniques such as: field data, remote-sensing images and geographic information system (GIS). The findings revealed that a wide range of depths of the water table, mostly relate to the structural features occur within the area. As a result, the presented study concluded that the maximum depths from the surface to the lowest contact between Kahlan Sandstone and Akbra Shale Formations ranges from 500 to 700m, this represents the lower contact of Amran Aquifer.
Keywords: Amran Basin; Structural elements; Groundwater; Recharge

1. Introduction

1.1 Aims and Objectives of the Investigation

Despite the fact that Western Yemen does receive a significant annual rainfall, the western part of the country is very mountainous and hence the runoff is both high and rapid, and for this reason the groundwater recharge is limited. No permanent surface water resources are available for exploitation and so the Amran aquifer is an important water resource for the area. Due to the increase in population density and living standards, the exploitation of sub-surface water resources has led to increased desertification and a decline in available groundwater supplies. This study aims at establishing a quantitative relationship between the availability of and the demand for water resources in Amran Basin area. Due to the above factors, notably the lowering of the groundwater table in the Amran Basin has resulted in severe water shortages during the last few years. Although many remedial actions have been implemented over this period, the water availability problem remains acute. The forecasted water budget deficit for the area was analyzed, and a number of control measures were developed with the view to restoring the water table and establishing a sustainable water resource system into the basin.

During the investigation, the tectonic deformation of the Amran Formation has been studied in considerable detail, and special emphasis has been placed on the folding, fracturing, jointing and faulting in the basin. In addition, the lithologies of the different rock-types in the basin have been studied, and particular attention was devoted to the dike systems.

1.2 Study Area

The study area covers the Amran Valley, which is located to the north of the provincial capital Amran, and is entirely confined to the Amran province, which is located about 50 km north west of Sana'a the capital of Yemen. The study area extends over an area of about 1580 sq km and measures approximately 98 by 16 km and includes the Amran Plain which covers about 900 sq km. The Amran valley is an inter-mountain plain which is located in the central-western high inter-mountain region of Yemen between latitudes 15° 30' and 15° 55' north and longitudes 43° 45' and 44° 15' east. It is one of the major agricultural plains in the western inter-mountain regions of Yemen and extends north east to south west for about 45 km with a west to east width that ranges between 6 and 10 km. The northeasterly boundary of the plain is bordered by the Dhi Bin district; the south westerly boundary is defined by the limestone escarpment in the Thula district, and the southern boundary is located northeast of the town of Raydah where the plain has been narrowed as a consequence of recent basalt flows (Figure 1). In Figure 1, the location map of the Amran Basin and the main valleys in the study area is portrayed.

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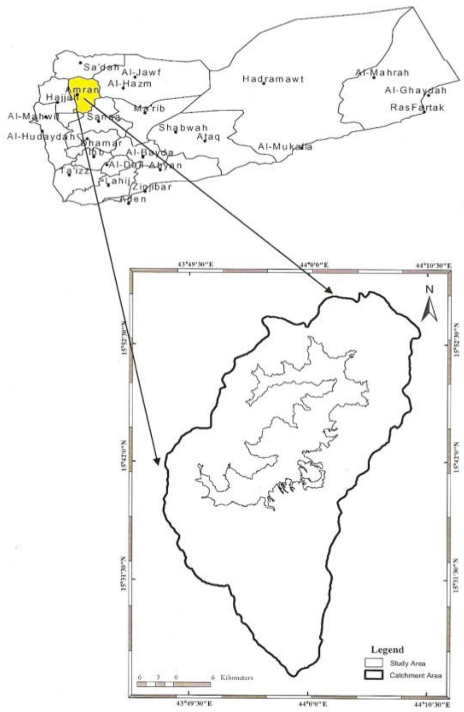


Fig. 1 Location Map of Amran Basin

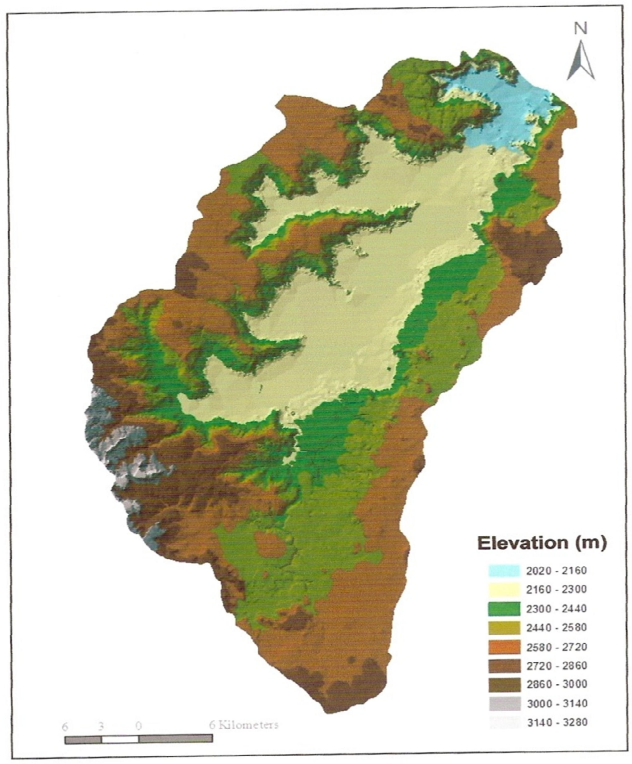


Fig. 2 The elevation of Amran Basin (Al-Ashwal 2008)

The Amran Plain is surrounded by mountains, and some of these are marked by steep limestone escarpments. These mountains are composed of limestone along the northern and western sides of the plain and mainly by basalt along the eastern and southern boundaries. The valley floor is relatively flat with a gentle slope and lies between 2180 to 2300 m above sea level (Fig 2). The Amran valley forms part of the catchment of Wadi Alkharid (north of the study area), which is one of the major tributaries that flows into the internal drainage basin of Wadi Al-Jawf in the east.

1.3 Study Methodology

The collection data was by direct field measurements, the data reduction and plotting of the data on topographic maps, and the capturing of the detailed descriptions and notes on a structural contour map for the area. During this investigation, the structures that had resulted from the tectonic deformation of the area were analyzed using satellite images, aerial photographs, and geological and topographic maps of the area, and the data thus extracted were captured and coded in a Geographical Information System (GIS). More than 1600 fracture planes that occur in the different rock-types in the area were measured in the field by recording the attitudes of the fracture planes. The geometries of the measured fractures were plotted on a stereographic projection and subsequently analyzed within a geological and tectonic context.

1.4 Previous Investigations

A number of geological, hydro-geological, ground water, and geomorphological studies have been carried out across the study area by a number of researchers, including among other things DHV (1993), Jones (1996), SAWAS (1996), Modaqish (2003), and Al-Ashwal (2008), but no structural study has to date been undertaken. In addition, a number of investigations have also been carried out on the other basins in this area, notably the Sana'a Basin, and includes the study of Botez (1912) who studied the geology of the Sana'a area. Ital consulted (1973) who conducted a stratigraphics and structural analysis to identify groundwater source, Aboul Ela (1983) who studied the stratigraphy and structure of Wadi Zahar in the Sana'a Basin, Al-Enbaaway (1985) who ascribed the formation of the Sana'a Basin to Mesozoic tectonics, Exxon (1987) who used seismic studies to explore the subsurface structures and stratigraphics features, and Al-Kadasi (1994) who studied the Tertiary to Quaternary volcanism.

1.5 Geological and Hydro-geological Overview of the Setting of the Amran Basin

The dominant tectonic feature that currently affects the geology in Western Yemen is the rift zone along the Red Sea and the Gulf of Aden. According to the previous studies, the uplift in western Yemen started during the late Cretaceous and was caused by under-plating of the oceanic crust (Al Kotba and Al-Ubaidi 2001). This uplift was caused among other things the uplift of the crust in this area and the eastward tilted of a number of basins, including the Amran Basin. A consequence of the under-plating is also the extensive basalt volcanism as well as the emplacement of some Tertiary granitic intrusion along the escarpment which separates the uplifted Mesozoic sediments and Tertiary lavas from the subsiding Tihama plain in the east (Fig.3).

The distribution of the volcanic rocks represents the main tectonic feature that affects the hydro-geology of the area, because they form a number of rift features that give rise to several mountain's ridges and surrounding flatland basins. The thickness of the volcanic rock succession attains about 2000 m and it outcrops as mountainous ridges and the flat lying areas covered by younger soils. The groundwater in the Amran Basin occurs within several major aquifer systems. The Al-Twilah sandstone and the Amran limestone comprise an area of 850.8 square km within the Amran Basin and probably constitute the bulk of the groundwater storage capacity of the basin.

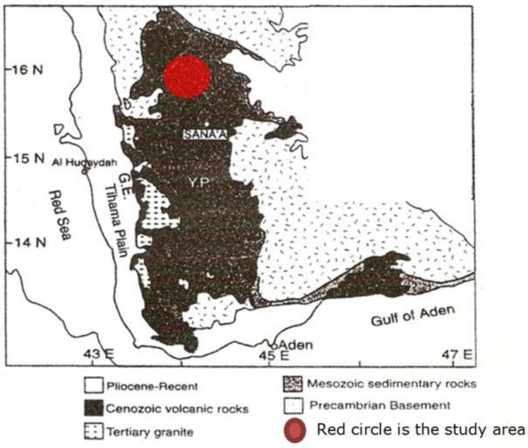


Fig. 3 Geological map of the western part of Yemen

The depth to the groundwater in these systems, as observed in existing deep water wells, varies from about 120 m on the eastern side, to more than 450 m on the western side of the basin. The groundwater of the Quaternary alluvium of the plain is assumed to be recharged from the surrounding Amran limestone, the Quaternary volcanic, the Tawilah sandstone in the south, and the wadi-fills that drain into the valley. The water table gradients in the Amran valley indicate that the groundwater flows to the northeast in the valley and then eastward into Wadi Attaf. The depth of the water table ranges from 30 m in Wadi Affar to 500 m around Amran city suggesting that besides excessive pumping other factors are also causing the extreme drop in the water table. The latter factors may be due to the complex structure of the area, and the low hydraulic capacities of the rocks.

The main aquifers are present in the hard rock in the area and consist essentially of fractured and faulted zones in the limestone, basalts and sandstones that extend deep into the sub-surface. The average depth of wells over the whole region was 183 m. The total annual average extraction was 70 million cubic meters. Aquifer depletion, based on the comparison between the 1991, 1996 and 2009 surveys is shown in Table (1).

Table. 1 The comparison between the previous studies (Wagner and Nash 1978) and present study

Year	2008	1991	1977
No. of well	2670	850	490
Depth of water ground level	120 – 550 m	29 – 250 m	10 – 70 m
Amount of discharge		38 million meter cubic	10 million meter cubic
Amount of shortage per year	18	5 – 10	0.2 – 2 meter / year

According to above results the Amran Basin is showing a sharp decline in the water table amounting to about 18 meters per annum and a corresponding increase in the number of wells. Increasing numbers of wells have been drilled in the Amran Basin in 2008, and the well density have now reached 12 well / km square.

2. Geological setting of the study area

The general geology of the Amran Basin was described by Al-Subbary (1995) and is shown on the 1: 200 000 Geological Map of the western part of Yemen (YGSMRB). This map shows that most of the area is underlain by Cenozoic volcanic rocks and a succession of Mesozoic sedimentary sequences. Since the above rock-types display a range of competencies and stress fields a range of tectonic structures, including faults, fractures, folds, etc. that have fomed in the area either before or after the development of Amran graben (Fig.4). This graben is an extensional structure which is located between some NW-SE trending parallel normal faults that are also parallel to the rift axis of Red Sea. The flanks of the basin consist of fault blocks that are tilted at 5 to 35 degrees away from the rift axis. These are bounded, by large normal faults that constitute the margins of the main graben. The initial fractures appear to have developed perpendicular to the bedding and were rotated during subsequent block tilting, when normal dip-slip movements took place.

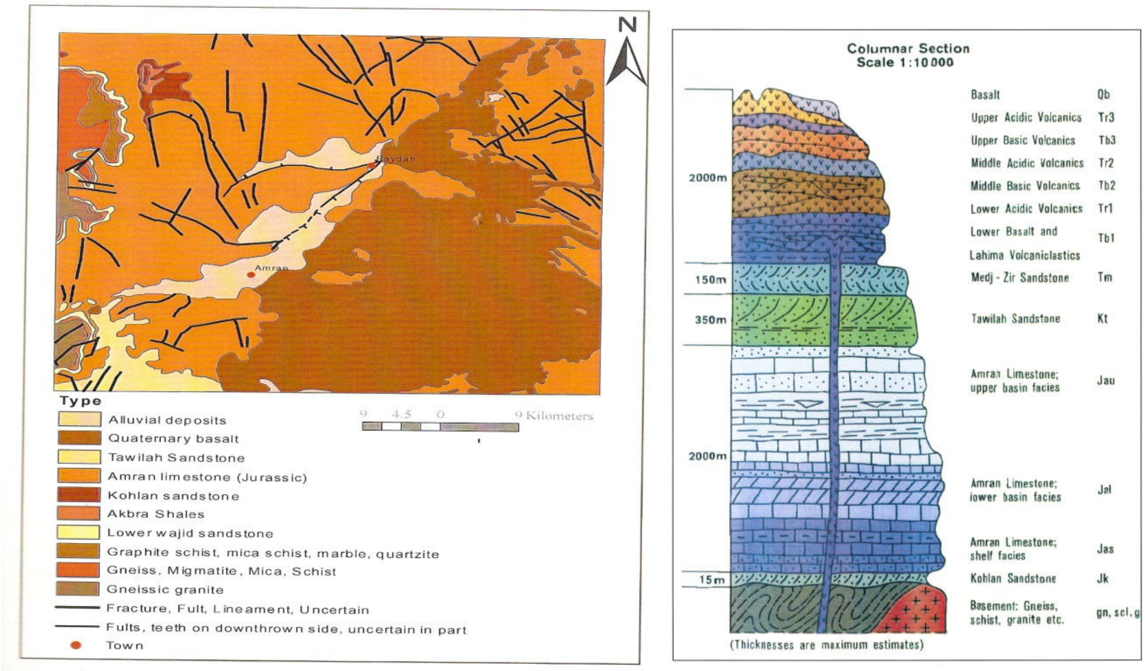


Fig. 4 Geological Map and vertical sequences of Amran area

2.1 Stratigraphy

According to published Geological Map, Formations ranging in age from the Jurassic to the Quaternary with a few windows of Precambrian basement are exposed in the study area. The geological succession consists of: Quaternary volcanic and sedimentary deposits

- Tertiary volcanic rocks.
- The Medj-Zir Series of the Tawilah Group (continental sediments).
- The Sabatayn Group.
- The Amran Group (limestone)
- The Kohlan Group (sandstone)
- Akbra Formation (shale)
- Precambrian basement

The thickness of the main rock unit formations occurs for the groundwater in the Amran Basin is shows in the following Table (2).

Table. 2 Thickness of the rock unit formations in the Amran Basin

Formation	Thickness in meters
Amran limestone	420 – 798 m
Kohlan sandstone	56 – 70 m
Akbra shale	112 – 126 m

3. Field and office methodologies employed during the investigation

A detailed investigation of the exposed faults involved the measurement of about 100 majors and about 500 minor faults and the lineation on the fault planes. About 2334 measurements of bedding planes, dikes, faults and vein's attitude was made at 175 stations (Tables 3 and 4). The data were plotted on equal area projections for each station (Fig 5 and 6). The field investigation indicates that the Amran limestone and Tawilah sandstone contains five main sets of fractures, which display a systematic variation both with regard to lithology and location. Most of the fractures in the Cretaceous sandstone and Jurassic limestone are open and filled with weathered basaltic dikes.

Table. 3 Number and main directions of the dikes in Amran Basin

N – S	N 30 E	N 70 E	N 30 W	E – W
21	12	15	28	10

Table. 4 The total measurements of structural elements and types in the field work

Bedding planes	497	21 %
Joints	1650	70 %
Faults	72	03 %
Dikes	57	02 %
Veins	43	02 %
Fissures	50	02 %
Total	2334	100 %

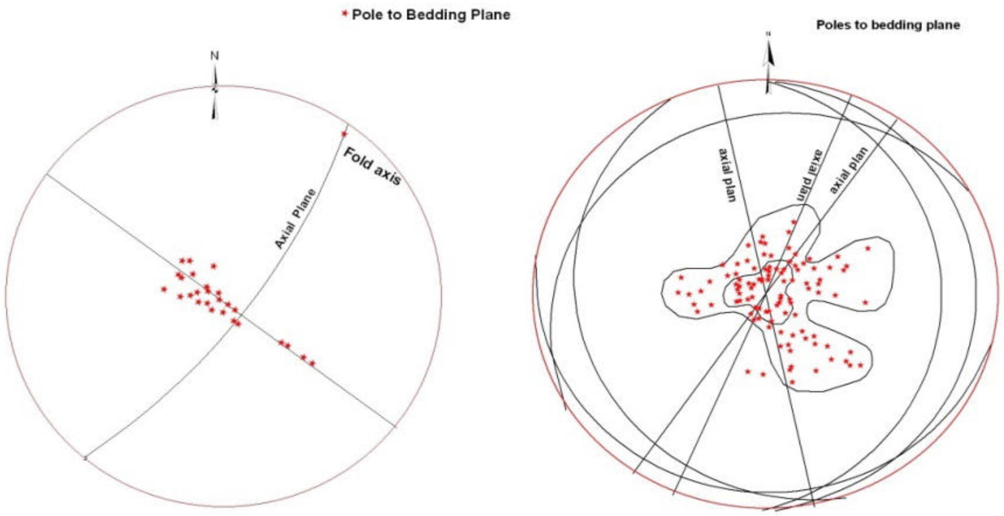


Fig. 5 Stereographic projection of folds and bedding planes shows different directions of the major and minor folds in Amran Basin

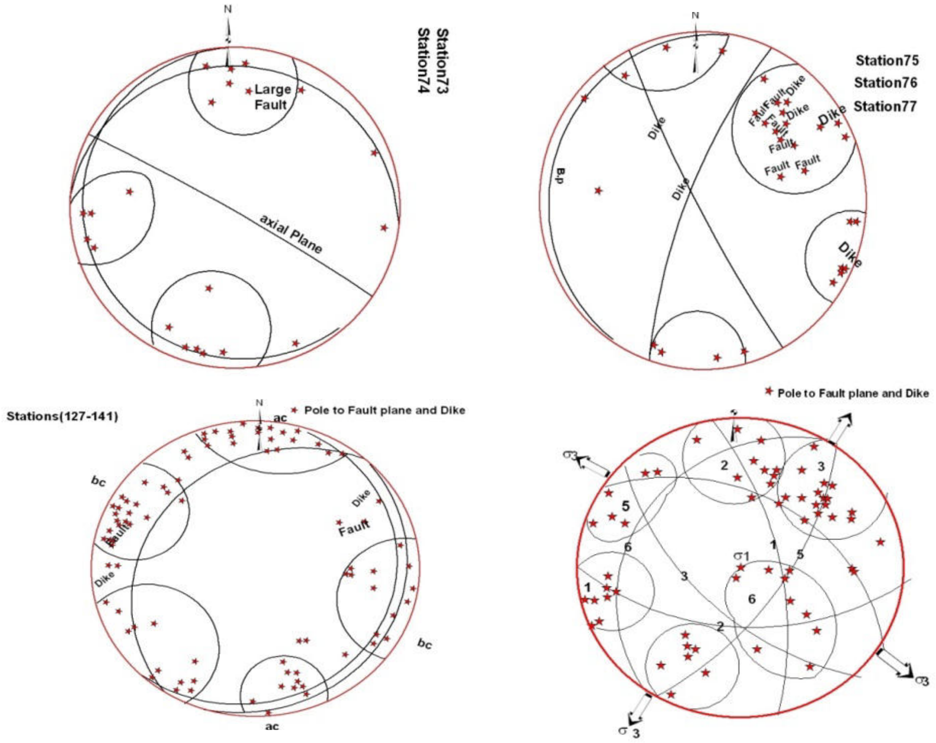


Fig. 6 Stereographic projection of fracture, fault, and dike planes in Amran Basin

Tectonic map (Fig. 7A) is showing all structural data that have been collected from the field, as well as a contour map was drawn to the depths of the wells (Fig. 7B). The contour lines appeared semi-circular or oval forms. These reflected the distribution and the amount of complexity in the structural geometric shapes of subsurface rock layers.

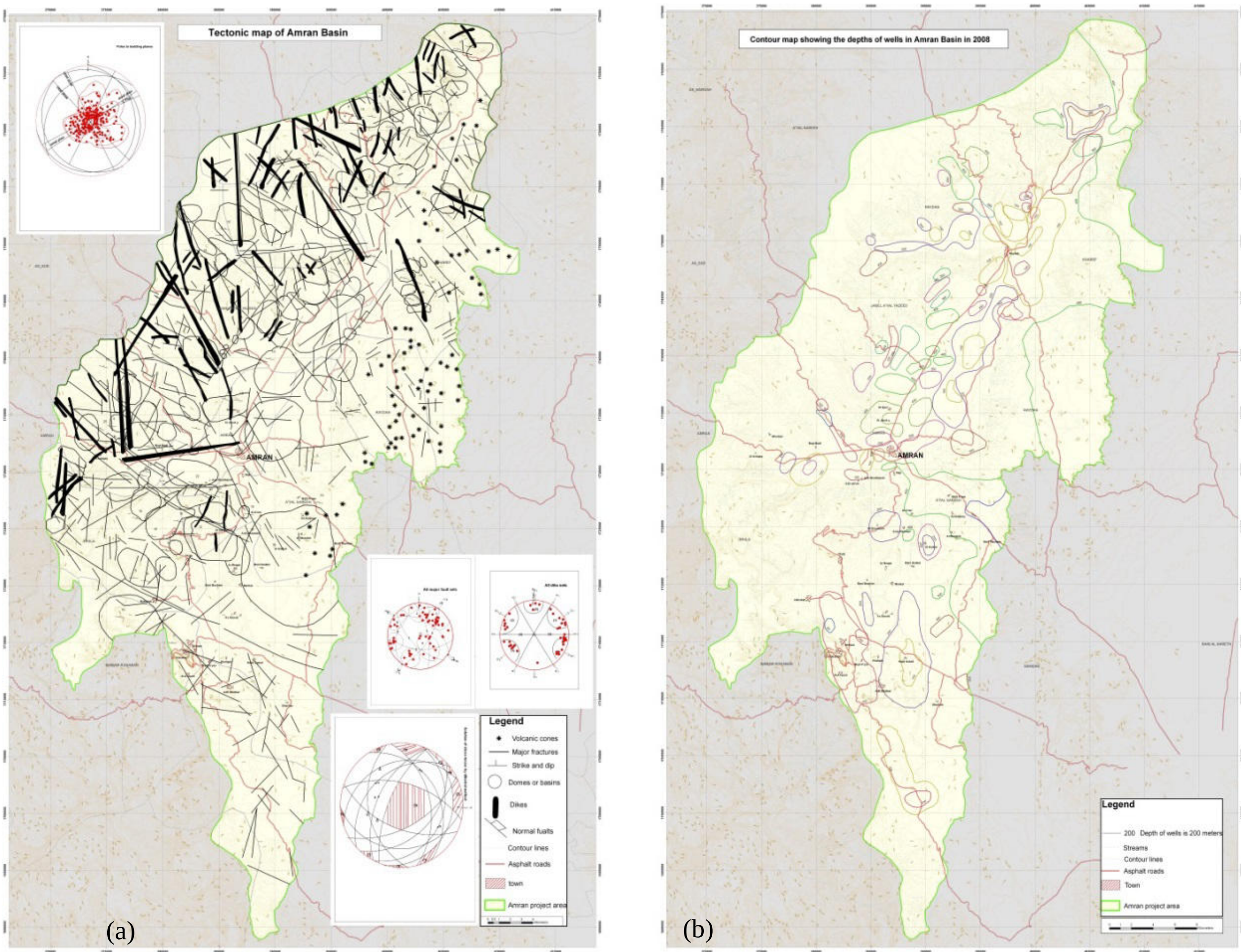
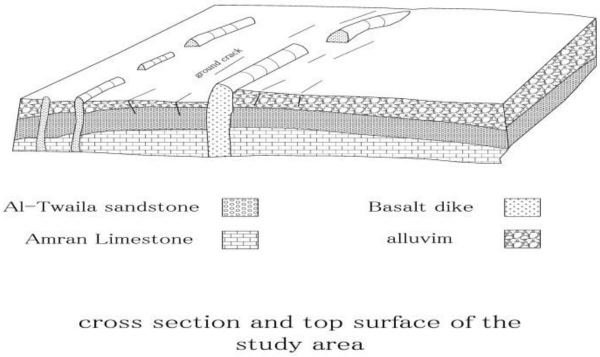


Fig. 7 (a) Tectonic map and (b) Contour well depths map in Amran Basin in 2008

3.1 Structure and tectonics of the Amran Basin

The main structural features in the Amran Basin consist of Dikes, Folds, Faults and Joints. The Tertiary and Quaternary dikes cut through a thick overburden of Mesozoic sedimentary rocks. These dikes have a northwest-southeast orientation that is parallel to the volcanic cones which may have caused up-doming and extension faulting. More than 87 Tertiary basaltic dikes are present in the basin, and the width of the dikes varies from 3 to 15m. Collectively, they account for a total expansion of about 500 m. Most of the dikes in the basin are steeply inclined (Fig 8).

(a)



(b)

Fig. 8 (a) Dikes in Amran Basin (b) Most of these dikes are parallel to faults and affected to uplifted area and change the dipping of beds

According to the field observations, three main sets of dikes are present with the oldest orientated in a NE-SW direction, the youngest in a NW-SE direction and the third is E-W direction. Most domes and fold axes observed in the study area are parallel to the dikes, and the orientation of most of the major faults is also parallel. Most of these folds in the study area appear as domes and basins (Fig 7A) and contributed to the total deformation in the Amran Basin. According to observed data (about 500 readings of bedding planes) the folds in the area are dome and basin-shaped, and the strata dip away from or to the center of the domes or basins. Folds within the area are divided according to their wavelengths into major folds and minor folds. About 100 major folds and more than 150 minor folds, most of them domes, were observed. The major folds have wavelengths varying between 2 and 4 km and amplitudes in the order of hundred meters. These folds occur in the thick units of limestone. The shape of the hinge anticlines is broad and rounded. Most of these folds in the Amran limestone are associated with dikes and faults. According to the stereographic projections of bedding planes (see Figs 5 and 6), the inter-limb angles of these folds range between 170° in the upper beds to 100° degrees in the lower beds. The folds are generally open folds. The observed field data were used to construct a phi-diagram (Fig 5). This shows that two major domes and anticlines can be classified geometrically as equal folds (Tremlett, 1987) that plunge 5 degrees to the SSE and 25 degrees to the SW.

The inter-limb angles of the minor folds vary from 90 to 130 degrees, and the fold axes vary in orientation across the area. The stereographic projections for different areas and folds show that the trends of axes are NE-SW, N-S and NW-SE. These variations occur laterally and vertically. The folds are mostly upright plunging folds with plunge angles who also vary across the area. The plunge is 20 degrees in the north. Most of the folds are separated by faults, and the major folds contain about 20 to 30 minor folds. The wavelength of the these folds varies between 300 and 500 m. These folds occur above and below the Amran limestone in the marl and shale beds, but show that there is no correlation between the inclination of the axial planes of these folds and the axial plane of the large Amran anticline. The shapes of the hinge anticlines are variable from nearly angular in the inner arc beds and are broader and rounded in the outer arc beds. These are disharmonic folds.

Most of the marl and marl-rich limestone beds are folded, and the wavelength of these depends on the lithologies. The folds are concentric folds where the layer thickness is uniform. In general, the bedding of Al-Tawilah sandstone and Amran limestone is inclined and constitutes open folds with amplitudes of up to hundreds of meters. The Amran Basin is an elongate and symmetrical anticline. Most of the upper beds of the Amran Group are less folded, and this may be related to presence of sub-surface dikes.

According to the aerial photographs and the LANSAT Images the Amran Basin and the surrounding area is located between two large domes that extends for about 70 to 100 km from Wadi Mor in the west to Bani-Hushiash in the East, and it is about 50 km wide. Field's work verified that Amran beds have produced many elongate domes and basins, which are more than 2 km in length and up to 500 m wide, and are orientated in a NW-SE direction. It is probable that the entire area is uplifted as a large dome.

Regional compression after the deposition of the Al-Tawilah Group resulted in folding that produced the anticlines and dissected faults. The main fold in this area has by the large inter-limb angle (between 110 and 130 degrees), a steeply dipping axial plane, and a low axial plunge (20 degrees towards N160). These folds are composed of limestone and marl beds with the incompetent beds have provided the glide zone for the disharmonic folding between the lower limestone bed and upper sandstone unit. As a result of the presence of dikes and the basin-ward tilt of the margin, the carbonate platform and the upper Cretaceous sequence slid on the shale layers and broke up into smaller blocks. This process caused the folding of the marl and marl-rich limestone. Analysis of the data suggests that the thin-skinned extension need for the raft tectonics was accommodated basin-ward by folding of the overburden up to a point where all the extension has been taken up, and the overburden left largely undisturbed. Dome and Basin Structures are shown in the structural map of Amran Basin. Faults are present between these folds. These structures with faults and fractures are important to the ground water levels and the flow directions.

The major faults within the study area on which the slickenside and the lineation have developed on the faulted planes were used to deduce the direction of movement and the mechanism of deformation. The Amran Basin is bounded by six sets of major normal fault which trend in a NW-SE direction and on the north-eastern and south-western borders of the Amran Basin, some shorter NE-SW to E-W trending faults are present. The faulted NW-SE trend of the basin boundaries is parallel to the major, normal faults and to the major discontinuity in the great escarpment. The tilted block geometry with NE dipping normal faults and associated SW-dipping crustal blocks can be recognized on the NE-SW cross sections (Fig 9).

Most of these structures are of Tertiary to Quaternary age and are parallel to the main Red Sea Rift. Extension is accounted for by the tilted, domino style, fault blocks. The eastern and western margins of the Amran Basin are bounded by faults, which cross the basin and exceed 3000 m in length. The set of NE trending faults represents the continental continuation of the oceanic transform faults that are present in the Red Sea. Most groups are perpendicular to the bedding plane and are mostly conjugate faults with N-S, NE-SW and E-W strike orientations. The normal faults are numerically the most important and represent the youngest group of faults in the area. The maximum principal stress is nearly vertical but the intermediate axes, which trend NW-SE, are nearly horizontal. The extensional axes are also nearly horizontal but trend in a NE-SW direction. This suggests that fracturing is thought to be caused by the expanding of the dikes.

Fig. 9 Vertical fault surface with differential movements and slickenside

In general, the Amran valley floor is defined by 2 major tectonic structures that roughly strike southeast to northwest. The Amran Graben crosses the southwest to the northeast Raydah Graben over distances of some 50 km at an average width of six km. The total displacement of down throw is several hundreds of meters (about 600m), and the horizontal displacement (heave) ranges from 500-700m. The grabens are bordered by numerous fault systems, which turn to the east in the north and follow the Wadi Attaf valley.

The dikes in the Amran Basin have produced large scale normal faulting in the overburden, with 9% extension recorded in the overburden. The surface uplift over the dike crests in the Amran Basin is estimated to be approximately 500m. Based on the field observations and the geophysical data, five cross-sections were constructed (Fig 10 and 11) which portrays the main structural features in the Amran Basin. The cross sections show that most of the faults in the basin are normal faults, which strike in a direction parallel to the Red Sea. This faulting is generally ascribed to tensile stress.

4. Discussion

During the Red Sea rifting process, a system of regional transforms and normal faults formed that extend inland over tens to hundreds of kilometers. Laughton et al. (1970) and Cochran (1981) suggested a continuity of sea floor spreading in the Red Sea and Gulf of Aden between 10 Ma and recent times. Several geological controls over the geometry of the faults which formed from the basement to the cover rocks have been proposed. Hunchon et al. (1991), Davison et al. (1994) and Al-Ubaidi and Al-Kotbah (2003) recognized that a N 40 E extension constitutes the major structural event that took place in Yemen. In western Yemen, this extension is characterized by tilted crustal blocks that are bounded by normal faults. Because the Oligocene lavas are deformed, the extension post-dates the main mantel plume activity (Davison et al. 1994). According to these studies, the intrusion of high viscosity Tertiary granitic plutons created a zone of uplift that is located about 70 to 80 km inland from the coastline. Inland from the parallel coastal faults is a zone of conjugate NE-SW and NW-SE striking faults that are associated with the 20 to 30 Ma volcanism that resulted in a diffuse E-W extension which was a precursor to the actual Red Sea rifting.

According to the previous studies (Justin et al. 1994, Huchone and Kanbari 2003, Al-Ubaidi 2003), the area was affected early by NE-SW compression, which produced the folding and the first sets and systems of fractures and resulted into the development of thrust faults and the later E-W extension that produced the major and minor normal fault systems.

Experimental work has shown that fractures only occur after significant tectonic extension (Mastin and Pollard 1988) and the work done here suggests that such fractures occur in the basins in Yemen. The field observations show that the bounding faults of these basins are of normal faults, which develop in response to be tensional stresses. Previous studies suggested that the Miocene dikes and associated volcanic activity in the Amran Basin form during the periods of crustal extension when the border faults in the basin formed. The border faults are parallel to the normal faults that bound the tilted blocks of crustal rocks and also to the topographic discontinuities along the escarpment. The tilted blocks of cover rocks are bounded by NE dipping normal faults and are themselves dipping to the SW.

The field data shows that a high density of dikes is exposed in the area, and most of these dikes have the same strike direction as the major faults (fig.12). It is proposed that the overburden overlying the dikes extended and caused the overburden to slide from the dome crests through listric faulting, whereas the sediments underlying the study areas were shared and shortened in a horizontal direction. The vertical dikes are unconformable overlain by the gently folded overburden consisting of variable lithologies, which are dissected by numerous faults. In the eastern part of the basin where the Quaternary volcanic cones outcrop, the dikes are parallel to the northwest–southeast orientation of the volcanic cones. The latter probably caused the up-doming of the overburden and the extensional faulting and fracturing.

According to the field observations and experimental work, it is believed that the fracturing in Amran Basin extended to the contact between Kohlan sandstone and Akbra Shale, which is believed to be the boundary of the Amran Aquifer. Figure (12) is summarized and shows the distribution of all structural elements in this basin.

5. Conclusion

The presented paper showed that the recharge problem in the Amran Basin is due to the complexity of the geological structures as well as low annual rainfall, a high yearly potential evaporation rate and contributes to low recharge. Structurally, the Amran Basin is located between the Quaternary volcanic and Jurassic limestone rocks into which the dikes have intruded. The vertical dikes are unconformable overlain by gently folded overburden of variable lithologies, which are cut by numerous faults. The dikes cut through the thick overburden and form a part of NW-SE oriented, a trend of volcanic cones, which have caused the up to doming of the overburden and the active extensional faulting. The results show that these fractures are orientated in the same direction of the dikes, and that they cross the margin and base of Amran Basin.

Major and minor upright folds and vertical and sub-vertical fractures (faults, joints and vines) are conspicuous in outcrop and are widespread in the Amran Basin. Most of these fractures are parallel to the major valleys, cliffs, slopes, and the faults that form the escarpment. These fractures, their competency, and the permeability of the rocks in which they occur are the important structures that permit both surface and sub-surface water flow in the basin. The nature of the rock-types and the distribution of the dikes are the most important parameters that control the style of deformation and hence the distribution of the ground water aquifer.

A strong relationship between well depths and the structural elements in this area was observed, with the depth of wells in dome structures being deeper than in basin structures. It thus appears that besides excessive pumping, other factors such as faults, dikes and folds also impact of a drop in water levels. The structural study suggests that the ground water flow has not been constant in the same areas and that changes in flow direction influenced by faults, dikes, domes, basins, rock's types, fracture densities, and their dip directions of fractures.

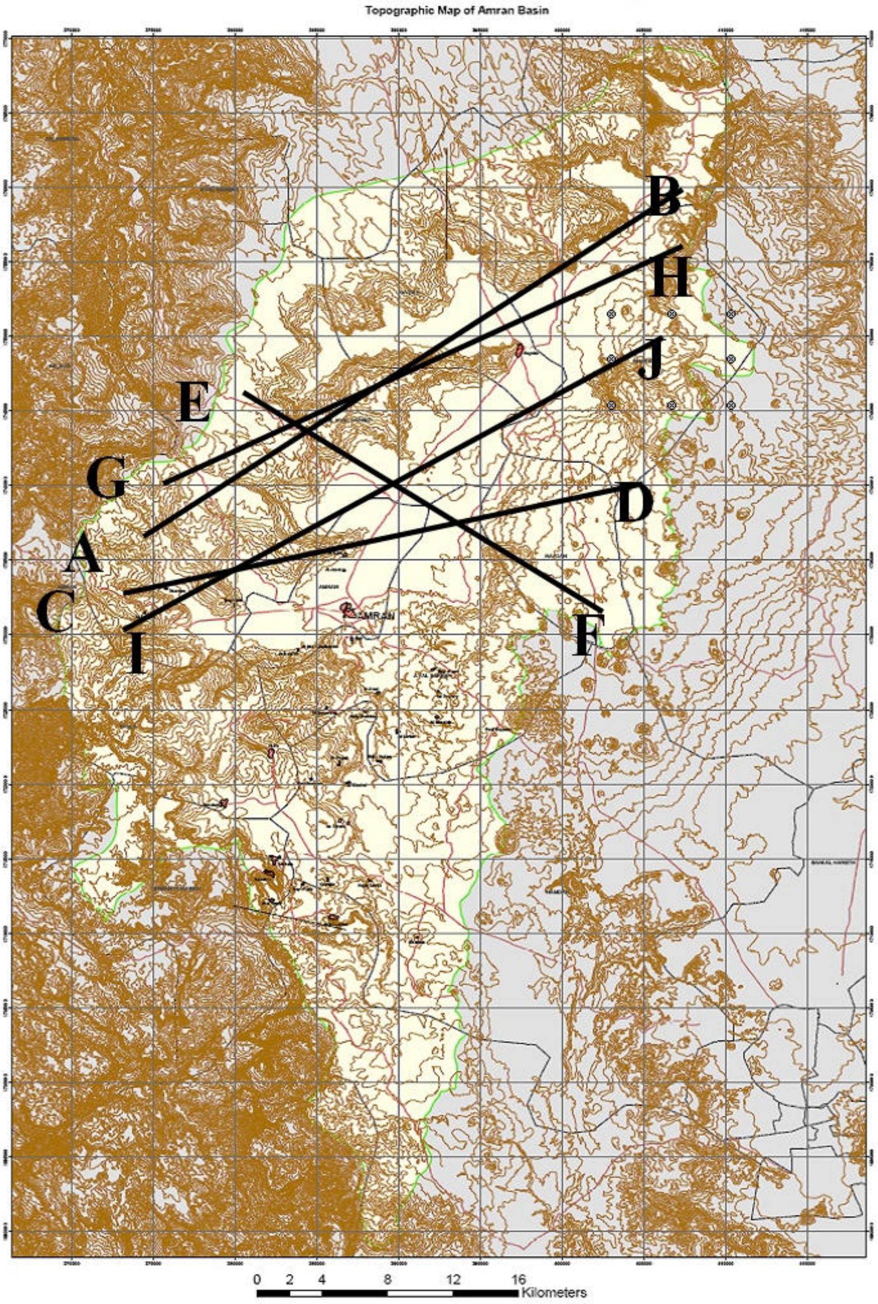


Fig. 10 Topographic map of Amran Basin and the locations of cross sections

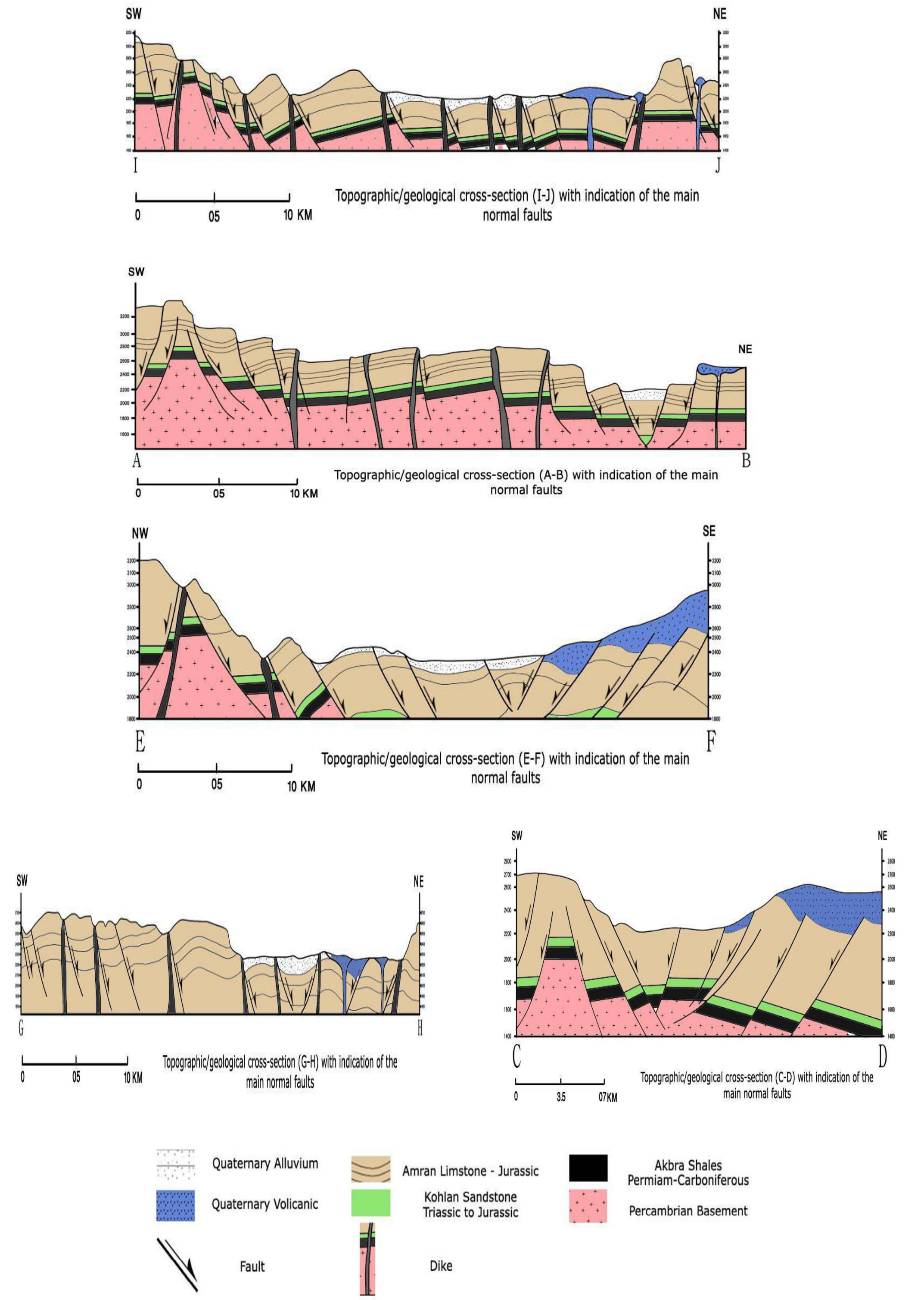


Fig. 11 Five cross sections in Amran Basin

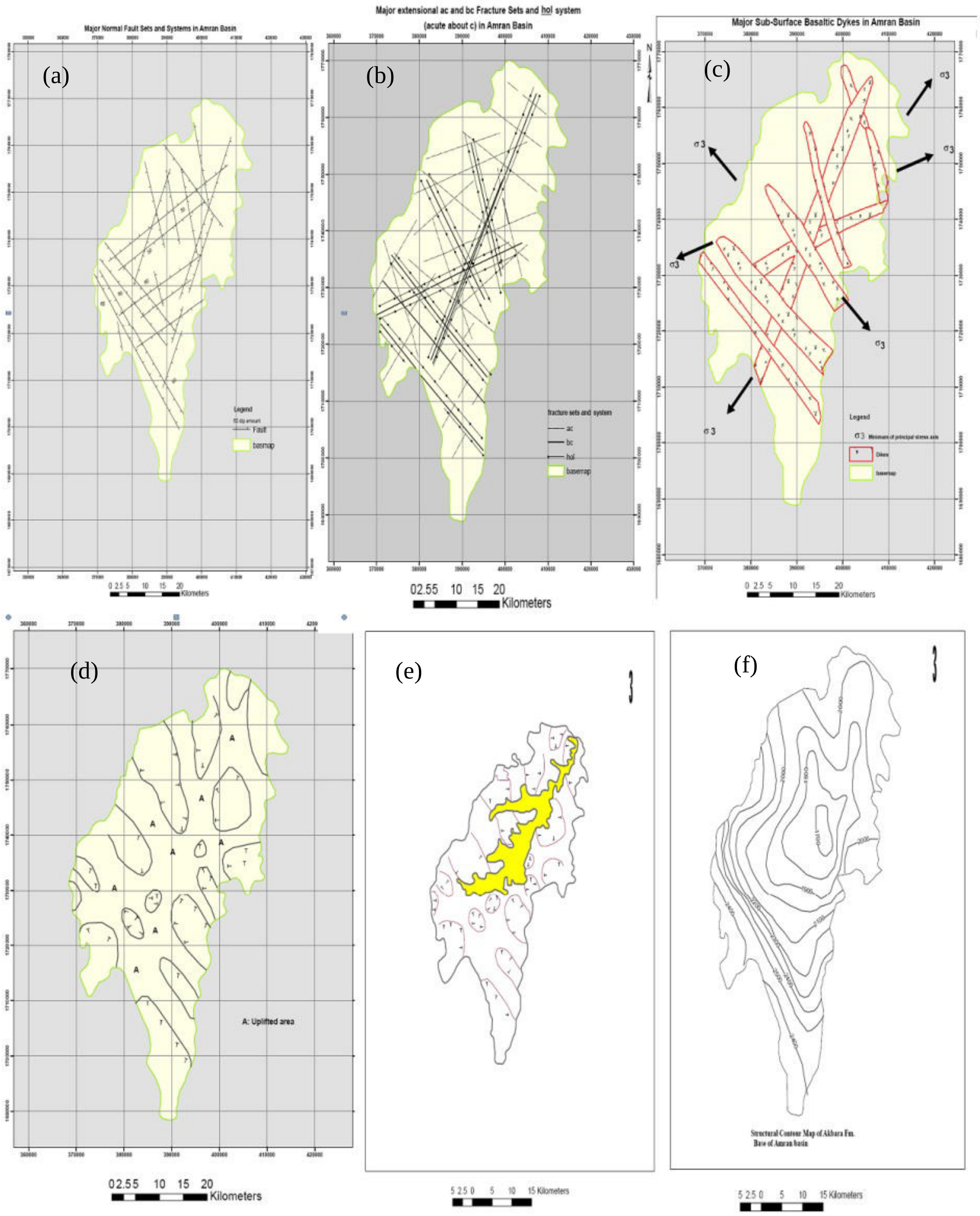


Fig. 12 (**a)** the Major normal fault sets and systems in Amran Basin (**b)** The major fracture sets and system in Amran Basin (**c)** The major trends of subsurface dikes in Amran Basin (**d)** the Basin structures and uplifted areas in Amran Basin (**e)** shows the location of the Amran plain and basin structures in Amran Basin (**f)** The model of Amran subsurface Basin (structural contour of Akbara Fn., which represents the base of Amran Basin).

The tectonic and structural contour maps (Fig 13) suggest that the best reservoirs for ground water aquifers in the Amran Basin are:

1- Subsurface basin structures (about 50 basins mostly within Amran Fn.),

2- Fault, dike, planes, and fracture beds.

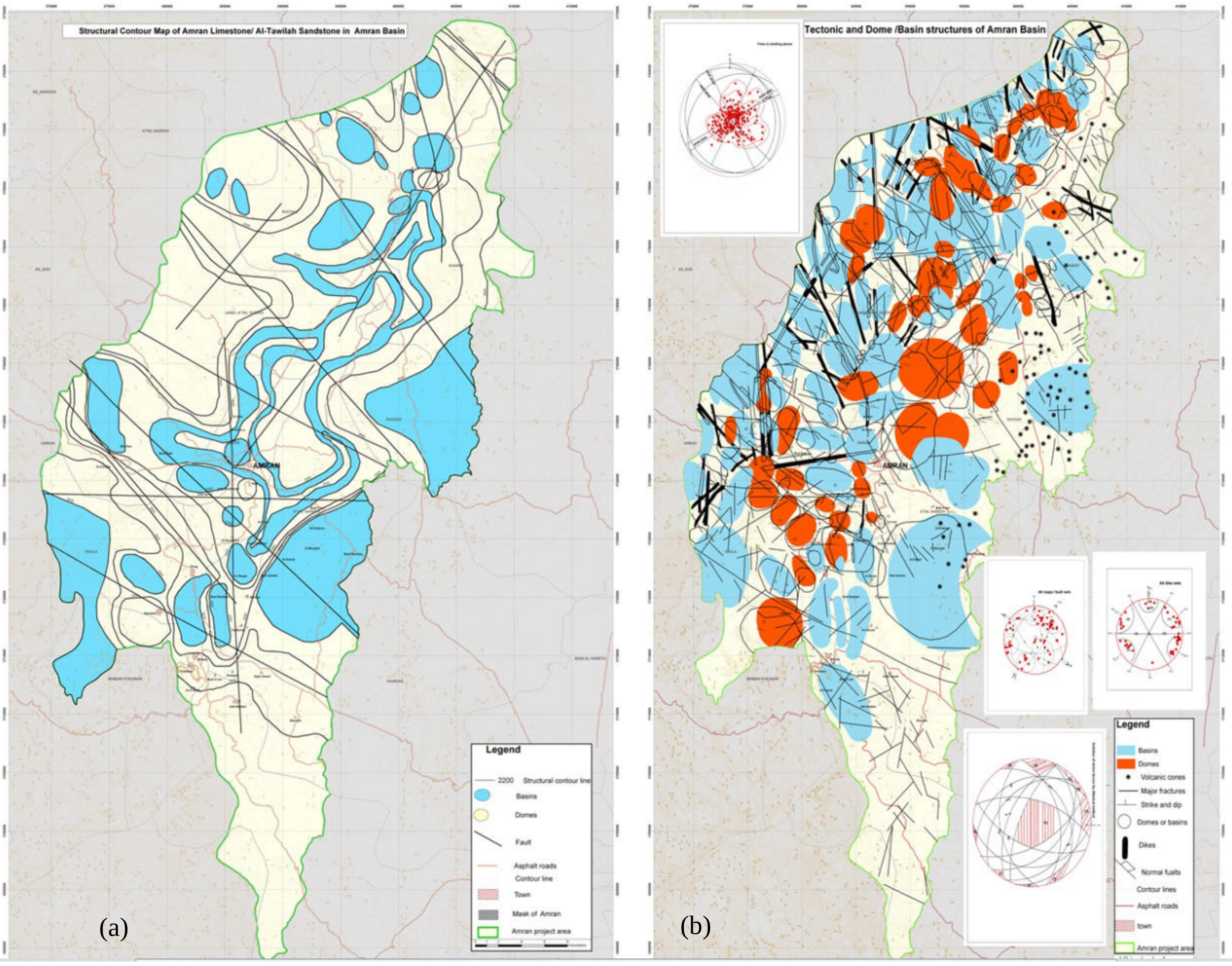


Fig. 13 (a) Structural contour map of Amran Basin (**b)** The relationship between tectonic and domes and basins in Amran Basin

On the other hand, the lowest groundwater storage capacities are present in the marl and clay beds, and in the subsurface dome structures. The Amran Basin does not appear to be a single tectonic unit, but appears to be segmented into compartments each with its own structure and subsidence history. It appears that the Tertiary subsidence in the eastern Rydah Graben is larger than in Amran Basin and also receives the major part of the sediment load. The Tertiary subsidence in the Qa`a Shames Basin is also less than in the Qa`a Al-Hamidah Basin and it also receives less of the river discharge.

Depending on field and geophysical data, the greatest depths of Amran and Raydah aquifers are about 500 to 700 m below the surface at Qa`Al Boun, which represents the contact between Kohlan Sandstone and Akbra Shale Formations. Most fracture planes (faults, joints, veins and fissures) are dipping to the center of the grabens, and the best aquifer is located east of the Qa`a Al-Hamedah plain and east of Raydah town which corresponds to the greatest depth of the basin. According to the field data and the structural contour map, the average depths of the ground water table ranges from 200 to 250 m. It is estimated that about 2/3 of the volume of the water resources in the Amran Basin still remains in situ and about 1/3 water until the storage volume has been exhausted.

The tectonic model of Amran Graben is concluded as:

During the opening of the Red Sea and the northeasterly movement of the Arabian plate strike-slip and normal faults developed as a consequence of the rifting and the period of volcanic activity. This resulted in a "domino type" deformation with major NW trending sub-vertical planar and listric extensional faulting along the margin of the basin. The second major set of structures that formed during this time is the NE-SW striking to tear faults, which are presumably related to the dip-slip faults. During the third stage Tertiary and Quaternary dikes intruded, which caused up doming of the crustal rocks and the development of active extensional faults. According to this model, the faulting and fracturing was caused by the intrusion of sub-surface dikes. In summary, the Amran graben was formed as a consequence of Mesozoic extension and Tertiary subsidence (Fig 14).

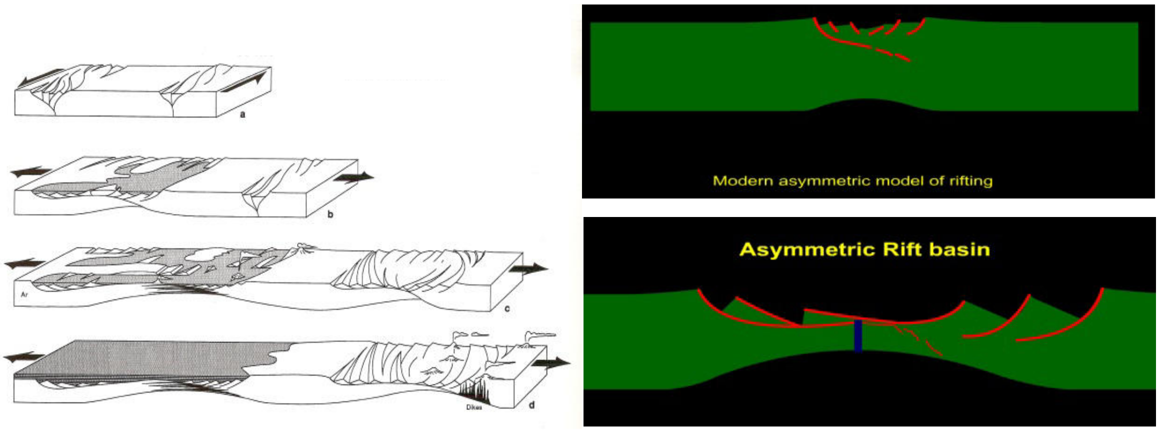


Fig. 14 Tectonic model of area shows the interpretation of relationships between crustal stretching, block tilting and the evolution and tectonic of Amran Basin

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