Thamar University Journal of Natural & Applied Sciences ISSN: 2073-0764
2011 A(**4**) 49-65

Stratigraphic Sequence and Structural Evolution of the Sana'a Basin

Abdulkarim Al-Subbary[1], Ahmed Al-Kotbah[1], Naif Abu-Lohom[1] and Abeer Al-Asadi[2]

1Department of Earth and Environmental Sciences, Faculty of Science, Sana'a University, Yemen.Email: aalsubbari@hotmail.com
2Sana'a Water and Sanitation Local Corporation (SWSLC), Sana'a, Yemen

ABSTRACT

The stratigraphic sequence of the Sana'a basin ranges in age from Precambrian to Recent with some periods missing. Lithological outcrops of the Sana'a basin ranging in age from Jurassic to Quaternary, while the subsurface data reveals the occurrences of the Precambrian rocks.

Current research discusses the sedimentary and structural evolution of the Sana'a basin and indicates that significant tectonic phases occurred during the Jurassic, Cretaceous, Tertiary and Quaternary periods. Structural effects of these tectonic phases include uplift and subsidence for several times. However, the Sana'a basin formed during the Jurassic time under an inherited and reactivated structural control from the old N-S trend. Field studies indicate that the Sana'a basin was subjected to compression stage during the Paleocene time which resulted in the formation of an anticline with N-S axis, and then at the end of the Paleocene the area is affected by extensional faults to form half grabens such as Wadi Dhahr, and Haddah half grabens.

During the Tertiary Sana'a area has been affected by huge of volcanic activities especially in the southern part of the Sana' a basin to form the Yemen Plateau, then the major tectonic trends were reactivated by extensional stage which coincided with the NS - NW and ENE - WSW trend. However, most of these faults and fractures are filled by volcanic dykes of different composition. In Quaternary time another volcanic activity has occurred to form a lot of plugs and cones intruded into the old rock units.

Keywords: Structural Evolution, Extensional Faults, Tawilah Sandstone, Sana'a Basin, Yemen.

INTRODUCTION

The Sana'a basin is about 3200 km^2 in area with flat alluvium deposits covering an area of about 500km^2. (Fig.1). It is intermountain plain within the Yemen plateau and is surrounded by irregular topographic features. The

elevation of the Sana'a area ranges from 2150m in the plain to 3760 m in highest peaks in the Arabian Peninsula as in "Jabal Al-Nabi Shuaib" to the west of Sana'a city**.**

The Sana'a plain slopes gradually from 2350m in the southern part to about 2150m in the northern part. The bedding of the sedimentary and stratified volcanic rocks dips gradually from zero in the north, as in the Thomah area, to about 15^0 in the south, as in Al-Quthi area. (Italconsult, 1973). The major tectonic elements of Yemen are controlled by the main trends of the Gulf of Aden, the Red Sea, and the Najid fault systems (Fig.2).

The Sana' a basin is not studied structurally in detail and there is only limited studies from seismic and drilling information's. The basin area consists of crystalline basement rocks overlain by sediments of the Jurassic to Recent (Fig.3). Here, the basement rocks are considered only so far as they may influence the development of younger structures. The structural style of extensional basins depends not only on the orientation of the controlling stress regime relations to the zone of crystal extension and the amount of extensional stress, but also on the availability of pre-existing basement heterogeneities and on the lithological heterogeneities within the sedimentary basin fill which can be reactivated by tension. However, during the evolution of the Sana'a basin, the stress regime governing its development can change with time where the orthogonal extension may give way to trans-tensional faulting and or trans-compression deformation. The Sana'a basin is located close to very active and more complicated structural trends where oceanic floor spreading is going on now in the Red Sea, to the west, and the Gulf of Aden to the south. Two other active boundaries: the Zagrous Thrust, to the east, and the Dead Sea strike slip fault to the north (Khanbari, and Huchon, 2010) (Fig.2). These boundaries represent the major tectonic trends and the most important structural elements, which have controlled the formation of any reactivation structures, occurred in nearby areas. As mentioned before, the structural trends which controlled the formation of the Sana'a basin are inherited from the Proterozoic trends which have been rejuvenated during the early Jurassic time where a deep depression was formed with a NW-SE trend. The Sana' a basin is subjected to different tectonic trends of compression and extensional regimes. The extensional regime is the most dominant structures in the area and obscured all old structures (Al-Ubaidi and Al-Kotbah, 2003 and Khanbari, 2004). Several field trips of the Sana'a area are carried out and field measurements of faults and fractures are made. Investigation of rock units, faults and fractures in the study area were delineate all over the area, and detail recognize of faults and fractures show the main structures of normal faults with extensive fractures of three trends such as, E-W, NW-SE and N-S to NNW-SSE. More detail will be described below.

Structures

The Sana'a basin shows evidences of rejuvenated old structures, particularly those with NW-SE trend. The faults and fractures of the ancient Najd fault system have resulted in the formation of deep basin where the basement surface has subsided to more than 1800m, as in the Arhab and Al-Hatarish wells of the northern part of the Sana'a basin. In general, the Sana'a basin has been subjected to at least four trends of tectonic faults. Field observation shows that the Gulf of Aden trend had dissected the Sana'a basin into half grabens such as the Haddah, Wadi Dhahr and Wadi Al-Quthi faults. The Wadi Dhahr faults (Plate 1.B) belong to the Cretaceous time which affected in the cretaceous sedimentary rocks and not continues in the tertiary volcanic, while the Haddah and Wadi Al-Quthi faults are Tertiary faults. The maximum vertical displacement of extensional faults is recorded around Sana'a city such as in Haddah fault and reaches to more than 300m. This study is coinciding with

several studies of (Al-Kotbah, and Al-Ubaidi, 2001, Al-Ubaidi and Al-kotbah, 2003, Al-Subbary et al, 1998, Khanbari, 2004 & 2010). The main trends of faults and fractures measured in current study as shown in Dhudan area (plate 2.A) are coincided and control by the major tectonic elements of Yemen and the rejuvenation of the old regional structures of the Arabian Peninsula.

The structures in the study area are dominant by normal faults (plate 2.C) and fractures of extensional regime with accommodation structures associated with normal fault (plate 2.E & F), such as the tilting blocks of hanging wall, rollover anticline and sometimes drag folds. These accommodation structures are result of the internal compression stress due to the movement of fault blocks. However, the old tectonic trends play the main role in formation of tertiary faults and fractures which reveal clear effect in the old rock units outside the study area.

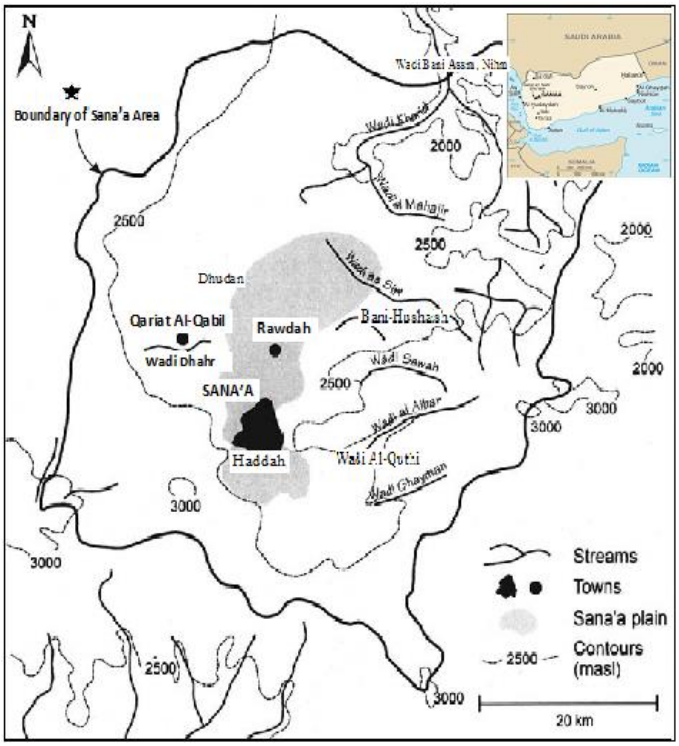
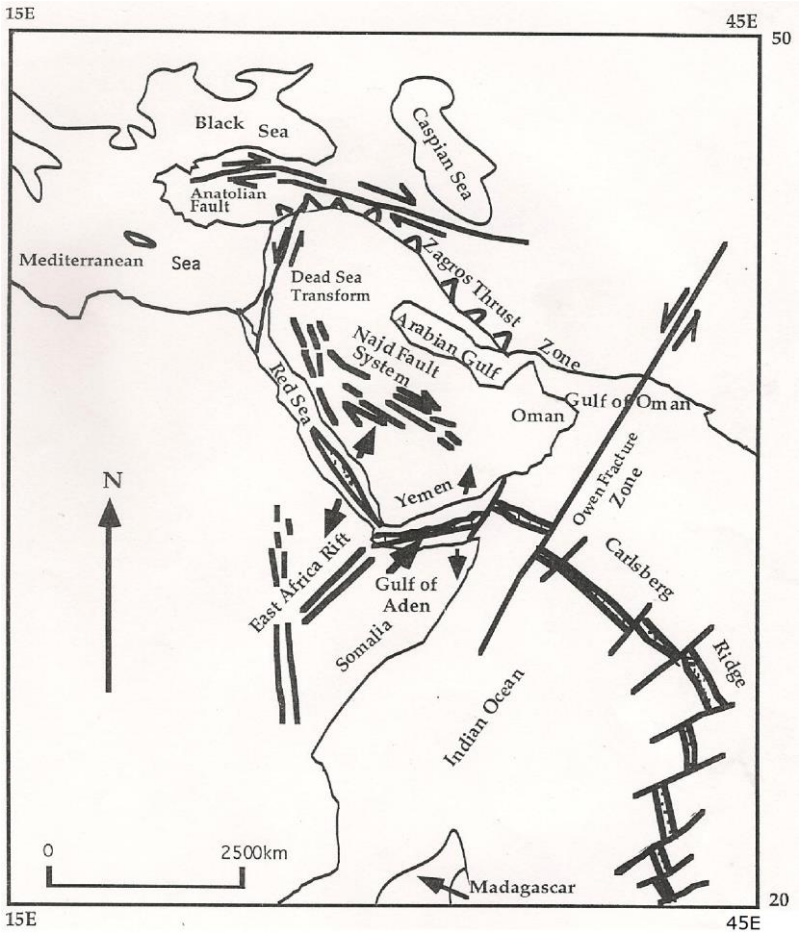


Figure (1): Location map of the study Area (Modified After Richard Helmer and Ivanildo Hespanhol, 1997 & WEC, 2001)

Strike Slip Faults

It is not easy to recognize the strike slip faults in the Sana'a area because of the intensive extensional faults dissecting the Tertiary volcanic rocks and the similarities of the rock units. Also there is no contrast in lithologic rock units or marker beds to recognize the horizontal displacement. However, from several field trips and detail survey, horizontal striations are observed and recorded in several locations within the Sana'a basin; these

horizontal striations are recorded in the Tertiary outcrops in the Sana'a zoo and in Khawlan area while vertical slickensides are recorded in the Cretaceous Tawilah sandstones in Wadi Dhahr area (Plate 2.B). These slickensides are strong support to our view that, Sana'a anticline is just an accommodation structure with strike slip faults. The horizontal movement has an E-W direction and the Sana'a anticline is formed an oblique to the major strike slip fault. Further evidence for horizontal movement probably support by the occurrence of the folds formed in different locations in volcanic rocks such as the recognition of thrust faults which recorded in Naqil Yasleh area. All these evidences indicate that the area is subjected to compressional tectonic which reflected in present of strike slip fault.



Figure(2): Regional Tectonic Map of the Arabian Plate, (After Al-Kotbah 1996).

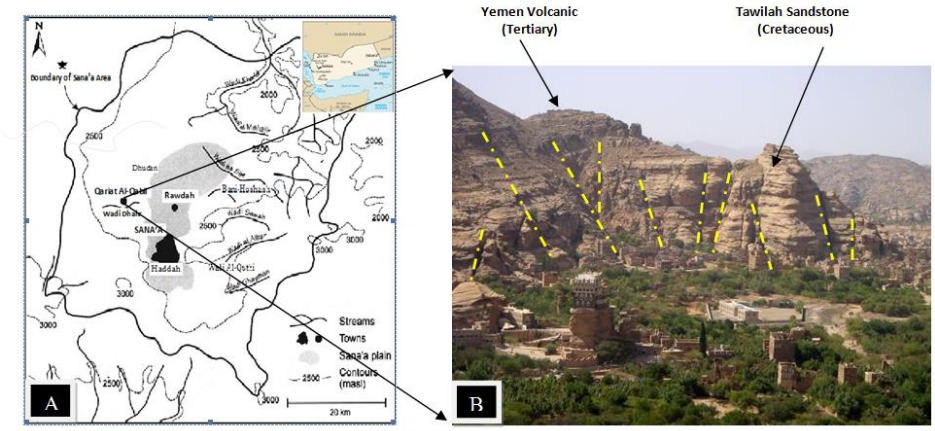


Plate 1.

A. Map showing the major features of the Sana'a basin, (After Richard Helmer and Ivanildo Hespanhol, 1997)
B. Panoramatic view of the Tawilah Group, at Wadi Dhahr Indicate the main fractures along the succession.

Folds

In general, Sana'a Basin as a part of the whole Yemen plateau is subjected to compression uplift during the late Tertiary time and the Sana'a anticline is formed as accommodation structure associated with strike slip fault. The Sana'a anticline is most likely related to horizontal movement and is just an accommodation structure associated with major tectonic movement. The Sana'a anticline is of N-S axis and plunging to the south with steep dip. The locations of fold axis in most areas of the Sana'a basin are eroded away and represent the Sana'a plain now. The anticline of Sana'a area is of symmetrical type with low angle of two limbs. In the north, the fold axis becomes horizontal such as in Thomah and Arhab areas. In addition to this big fold, there are small folds associated with extensional faults as resulting of tilting blocks and local compression (Al-Subbary, et al., 1999).

GEOMETRICAL ANALYSIS OF FAULTS AND FRACTURES

Detailed analyses of faults and fractures have been carried out to deduce their geometrical structures and trend of extension. The strike and dip of fault and fracture planes were measured using the Brunton compass. More than sixty fault and fracture planes are measured in addition to the major faults mapped. The plotting of fault and fracture planes are plotted as poles on the lower hemisphere equal area net (Fig. 5), by using the computer program, the Fabric, version 1.8 (Strakcy, 1977). The plotting shows four trends of faults and fractures detected in the area. The dominant Trends of faults are NW-SE and ENE-WSW and these trends are most probably synchronous with the rifting of the Red Sea and the Gulf of Aden. The other two trends are rejuvenated from old tectonic movements such as the N-S and the NE-SW direction. All these faults and fractures show very steep to moderate dips which may indicate these faults and fractures extend to a great depth. Some faults and fractures are passages of igneous dykes of different compositions. The slip

movement of these faults is very steep. The principal stress axis is nearly vertical with occasional slight oblique component.

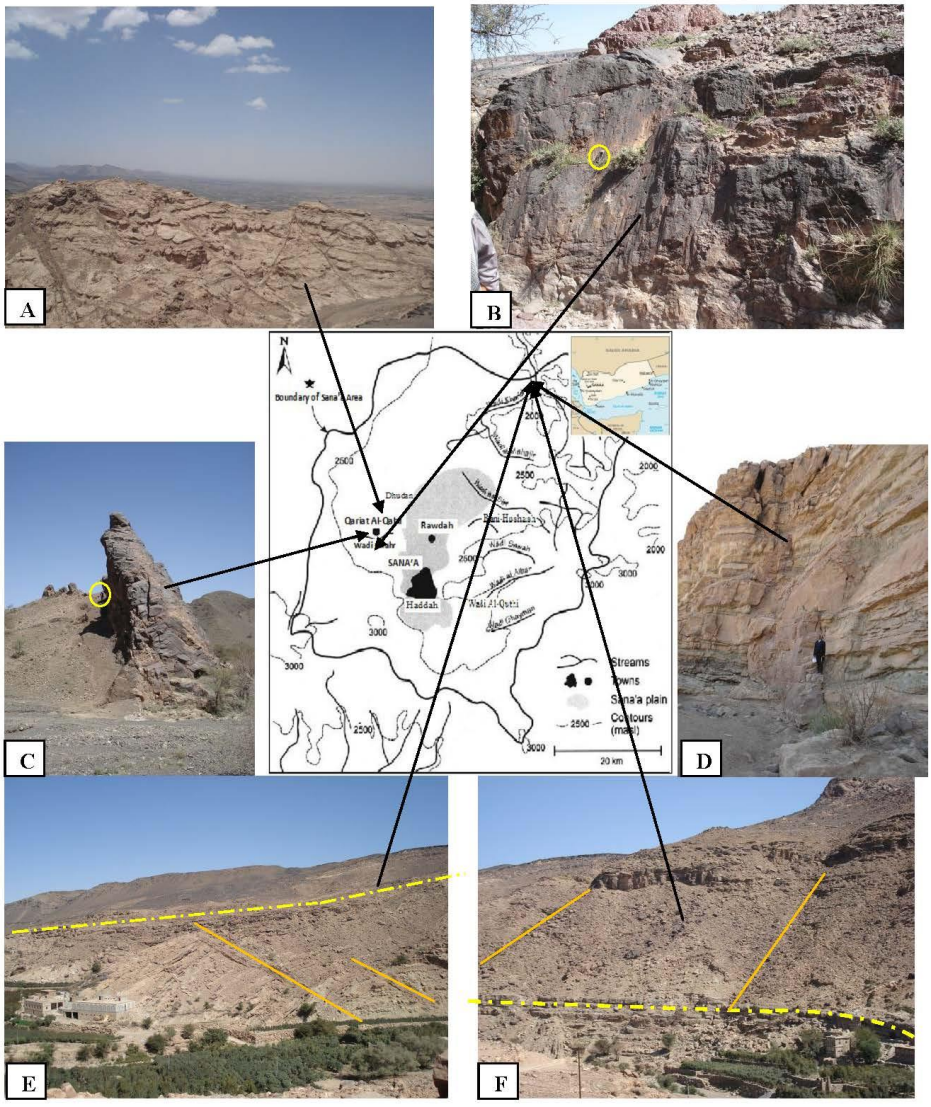


Plate 2.

A) Deferent trends of fractures in Dhudan Area, Hamdan. **B)** Vertical slickenside's, Tawilah Group in Wadi Dhahr. **C)** Basaltic dyke intruded the Tertiary volcanic in Wadi Dhahr, Hamdan. **D)** Escarpment of normal fault resulted in the uplift of Amran Group in Wadi Bani Assim. **E)** The contact between the Amran group and Tertiary volcanic rocks reveal normal faults affected in Amran Group in Wadi Shaiban, Nihm. **F)** Escarpment due to normal fault resulted in the exposed of Tawilah Group and Amran Group in Wadi Bani Assim, Nihm.
Yellow circle shows the scale

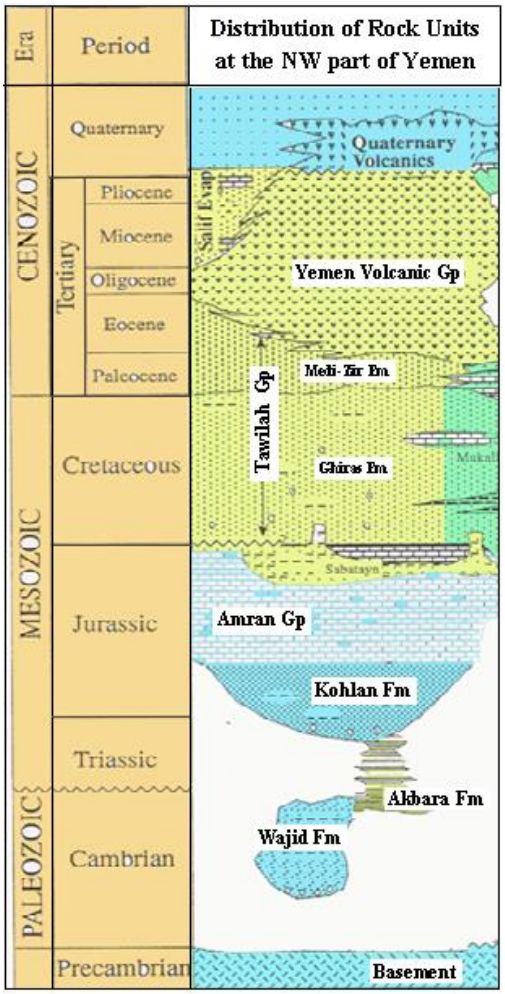


Figure (3): Simplified Stratigraphic Sequence of NW Yemen (After Al-Subbary 1995)

The stratigraphic sequence of the Sana'a basin is obtained from previous field studies and data. The stratigraphic sequence ranges in age from Precambrian to Recent with some periods missing. The Phanerozoic rocks of the Sana'a basin mainly consists of sedimentary and volcanic rocks. The sedimentary rocks in the Sana'a basin are exposed as outcrops ranging in age from Jurassic to Quaternary, while the subsurface data reveals the occurrences of the Precambrian rocks as in the Arhab well. The stratigraphic column (Fig.3) summarized the different rock units of the NW Yemen. The Kohlan Formation is a siliciclastic unit and is exposed in the Jabal Salab (Al-Wosabi, 2001 and Al-Wosabi, & Wasel, 2010) in Nehim area, and recorded in Sana'a basin from subsurface data of Arhab and Al-Hatarish wells (Fig.6 & 7). The maximum thickness is about *45-50m* thick (Sawas, 1996), and ranges in age from lower to middle Jurassic (Bydoun, 1982, Diggens, et al., 1988). The Kohlan Formation consists of course to medium grained sandstones together

with, conglomerates in the lower pan with interbedded shales and siltstones with plant remains. It is light grey to white or pinkish in color and it fines upward and passes conformably into carbonates of the Amran Group (Geukens, 1966)

The Middle Jurassic-Early Cretaceous rocks, represented by the Amran Group exposed in the northern part of the Sana'a basin as in Thomah area and Naqil bin Ghaylan. This group consists mainly of limestones and gypsum with intercalated shales in some horizons as in Wadi Al-Ahjur Formation. Throughout Sana'a area the Amran Group is recorded from subsurface only and at different depths depending on the vertical displacement of faults (Fig.7). The thickness of the Amran Group ranges from 320m in the northern part of Sana'a basin to 100m thick in the southern part as recorded in well DS1 & DS2 (Fig.6). Most recent aquifer delineation study of Sana'a Basin carried out by Hydrosult, 2010, indicated that the thickness of Amran Group decreases as we move toward south. This can be probably confirmed the southern edge of the Basin. This thickness decrease of Amran Group indicates the edge of the basin.

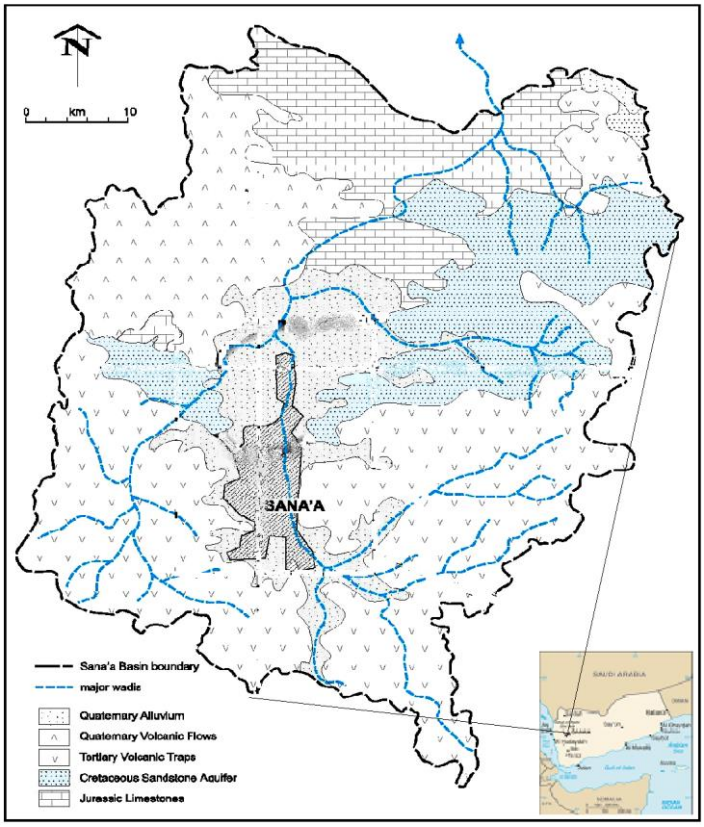


Figure (4): Regional Geology of the Sana'a Basin (after Stephen Foster et al 2003).

Figure (5): Stereonet plot of Fault trends of Sana'a Basin

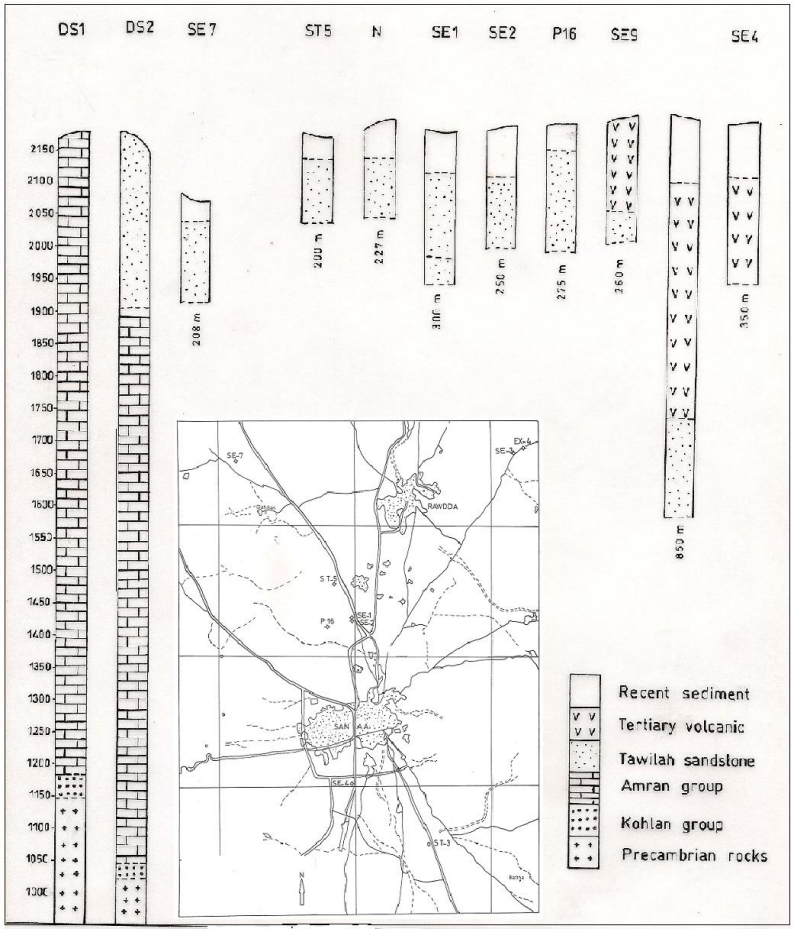


Figure (6): Subsurface lithologic logs of boreholes in Sana'a Basin along with location map. (Based on Kruscman, 1996).

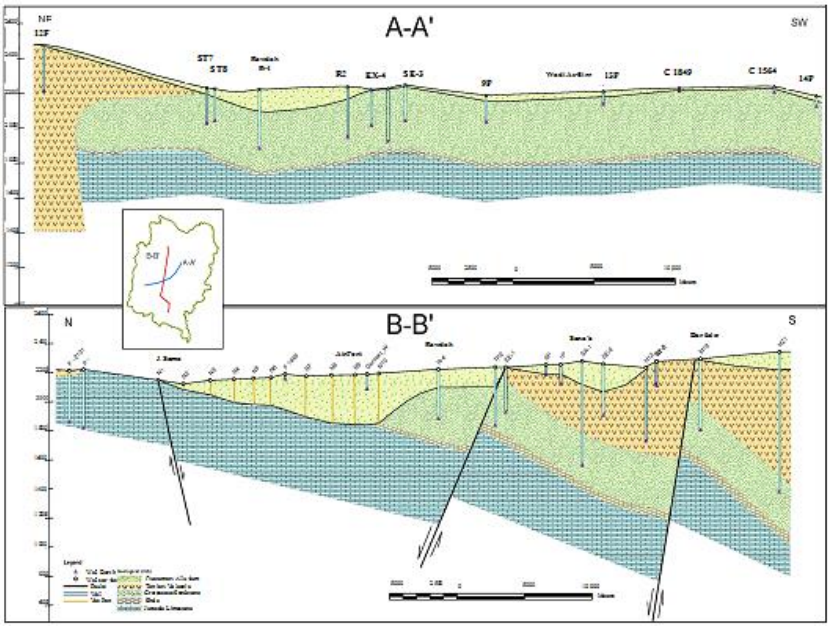


Figure (7):Hydro-geological Cross-Section across the Sana'a Basin, (After Hydrosult, 2010)

Stratigraphic Sequence in the Sana'a Basin

The age of the Amran Group is middle Jurassic-Early Cretaceous (Geukens, 1966 and El-Anbaawy (1985). The principal lithofacies is well cemented, limestone and dolomite intercalated with marls and shale containing macro and micro fossil. These fossils include skeletal marine mollusks, echinoderms, coral reefs, stromatoperids and foraminifer (Lamare, et al., 1930). El-Anbaawy, 1985 described very distinctive interval algae-rich in the Amran Group and named it Wadi Al-Ahjur Formation which represents the beginning of sea regression.

The queries in the Amran Group are particularly evaporating dominant in the Sabatain Formation (Bydoun, 1964, El-Anbaawy, 1985, which is raised to group by Al-Thour 1992). It consists of salts and lenses of gypsum with interbedded with marls and shale (Fig.3).

The Tawilah Group is a clastic dominated sequence exposed in a large area around Sana'a region, especially the northwestern part as in Wadi Dhahr and in the northeasterner part of the basin such as in Bani-Hushaish area (Fig.4). The age of this group ranges from Late Cretaceous to Eocene (Al-Subbary, et al., 1993). The thickness of the Tawilah Group reaches to more than 400m thick in the Al-Ghiras area and thins westward to 150m which may point toward the source area (Al-Subbary, 1995). Beds with a nodular texture and distinct multicolored horizons indicate that pedogenic processes were responsible for important hematite concentration in the uppermost paleosol accumulations of the Tawilah Group (Al-Subbary, et al, 1998).

The Tertiary volcanic is called as Yemen Volcanic Group which consists of alternating lava flows of basalt, andesitic or trachyitic porphyries. These Tertiary volcanic rocks formed today the Yemen plateau which reaches to more than 3660m above sea level such

as Jabal Al-Nabi Shuaib to the west of the Sana'a. All studies reveal that the Yemen volcanic are occurred as series of eruptions during stages of volcanic activity, and thickness is excess to 2000m thick, while some different studies determine the age of Yemen Volcanic and give wide range of Oligo-Miocene age, (Menzies et al., 1991, Baker, et al., 1993 and Al-Kadasi, 1994). The Quaternary volcanic rocks are dominated by alkali basalt. It occurs widely in the study area and particularly to north and northeastern part, and the age determination is about 5ma (Al-Kadasi, M., 1994). The Quaternary volcanic can be recognized two types of eruptions; the first eruption involves the cinder cones eruption which is explosive type volcanic, and are found in the north and northern part of the Sana' a basin (Fig.4). The second eruption is the lava sheet rocks and occurs along the Sana'a-Amran road to the northwest part of the Sana'a basin. The Quaternary deposits are mainly alluvial sediments and conglomerates which reach in thickness to more than 30m thick in the middle of the Sana'a basin such as in the Sana'a university campuses

Historical Evolution of the Sana'a Basin

Historical evolution of the Sana'a basin started in early Cambrian following the old tectonic trend in the N-S and NW direction. These two trends were probably reactivated from Hijaz and Najid orogenies representing the oldest and dominant tectonic trends affected Yemen and the Arabian Peninsula (Al-Kotbah, 1992). During the Cambrian-Ordovician, the initial main trend of the Sana' a basin has formed and the continental clastic sediments were deposited the Kohlan Formation. During the Jurassic time subsidence increased and formed deep depression of NW-SE trend. During this time the Amran group was deposited given rise to a thickness of more than 1600m as measured in Arhab and Al-Hatarish wells (Fig.6). The main trend of the Sana' a basin parallels to the Al-Jawf-Marib basin which was probably belonged to the same age and both were formed by the same tectonic movement rejuvenated from the Najid trend (Fig.2), and this may require more detail studies. During the Cretaceous time the Sana' a basin was subjected to uplifting and received a lot of clastic rocks of Tawilah Group. Current study indicated that, both Amran and Tawilah Groups were affected by tectonic movement of E-W trend resulted in the formation of extensional faults such as the Wadi Dhaher and Al-Sabbeen faults (Al-Kharpy, 1996). This movement is recorded for the first time in the Sana'a basin based on field observations and subsurface data (Fig.7). The extensional faults, which strike E-W, are more likely a proof that the Gulf of Aden is an old trend and was formed before its opening.

Most probably the rift of Aden was formed during the Cretaceous time and had been an exposed continent receiving no sediments. The Wadi Dhahr faults were confirmed as having formed during late Cretaceous where they crossed cut the Tawilah Group prior to the development of the Tertiary Volcanics (Plate 1.B).

In general, Yemen was subjected to a major volcanic activity during the Tertiary time to a state-wide series of volcanic eruptions. This volcanic activity resulted in the formation of Yemen plateau which stands today to more than 3660m above sea level. However, the Sana'a stratigraphic sequence was intruded by these volcanic rocks and covered all old sedimentary rocks of the Sana'a area. At the final stage of volcanic eruption, the Sana'a area was subjected to a compression stage where the Sana'a anticline was formed whose axis trends N-S. This axis dies out in the north with steep plunge in the south, then another stage of extensional faulting resulted which shaped up the present area, and represents an extensional tectonic regime contemporaneous with the opening of Gulf of Aden and the Red Sea (Khanbari and Huchon 2010). This stage produced the most dominant structures

where it obscured all old structures. The extensional faults include the Haddah, Aser and Wadi Al-Quthi faults. The vertical displacement of Haddah fault reaches more than 300m. All these faults are striking E-W. However, a horizontal movement has affected the Tertiary volcanic in an E-W direction and was created by reactivated faults in this direction. After the volcanic quiescence these major faults and fractures were subjected to a late volcanic activity occurred where a lot of dykes and plugs (Plate 2.C) of different trends (the dominant trends are N-S, NW-SE and E-W) and composition have intruded all the stratigraphic sequence from Precambrian to the Tertiary rocks, along N-S fractures of the present area of the Sana'a city, the rocks were eroded away forming the intermountain plain of Sana'a Basin.

The quaternary post tectonic movement is accompanied by a volcanic activity intruded older rocks with a very distinctive morphology characterized by a distribution of scatter cones, cinders, dykes and plugs and occasionally spread as lava flow in the low lands.

Subsurface Geological Cross-Section

a. Northeast - Southwest Cross Section (A-A')

This cross-section has NE-SW direction and constructed based on data of well logs (12P, ST-7, ST-8, R-4, R2, EX-4, SE-3, EX-3, 9P, 13P, C1849, C1564 and 14p) (Fig.7 A-A'). It extends from Al-Maleka Village (Bani-Hushaish) located northeast of the basin to Wadi Hamadan located southwest of the basin. It shows the lithostratigraphical sequence of the geological units from the Jurassic Amran limestone at its base followed by Cretaceous Tawilah Sandstone Group and Quaternary Alluvial Deposits at its top. Tertiary Volcanic Flows exist at the northeast part of this cross-section.

The cross-section did not show any structural elements disturbing the different stratigraphical units. It shows the following aquifer system:

- Aquifer 1: Quaternary Alluvium
- Aquifer 2: Quaternary and Tertiary Volcanic
- Aquifer 3: Tawilah Cretaceous Sandstone and
- Aquifer 4: Jurassic Amran limestone

This sub-surface cross-section confirmed that:

- The alluvial aquifer has attained its maximum thickness at the area between airport and Al-Rawdaa and
- The geological sequence has been intruded by volcanic rocks at the south-western part of this cross-section.
- No structural element were detected along this cross-section as all the faults are of E-W direction

b. North –South cross section (B-B')

It is the most important cross-section. It has N-S direction and constructed based on data of well logs (F-2131, P, F1445, German well, R-4, TP2, SE-1, 6P, 1P, SE-1, SE-4, H12, ST-3, SE-5, M-18, HZ1) and geoelectrical data (Vertical Electrical Sounding VES, N_1 to N_{10}) (Fig.7 B-B'). It extends from Jabal Al-Sama (Arhab) on the North to Dar Salm on the South. It shows the stratigraphical sequence of the geological units from the Jurassic Amran limestone at its base followed by Cretaceous Tawilah Sandstone Group and Quaternary Alluvial Deposits at its top. The Tertiary Volcanic flows and Amran Limestone Group are exposed at the most northern part of this cross-section (i.e. beyond the limit of this cross-section).

A set of normal faults of approximately E-W directions have been detected along this cross-section. The first structural fault has been detected at the southern part of this section (Dar Salm Fault, south of Sana'a city). It is showing a down throw side toward north of about 350 to 400m. The second structural fault has been detected at the central part of the cross-section (Al-Jeraf Fault, North of Sana'a city**)**. The third structural fault has been detected at the most northern part of the cross-section (Jabal Al-Sama Fault). This fault is located at the contact between the recent alluvial deposits and the Jurassic Amran limestone.

It is indicated from the cross-section that these normal faults represent a full graben structure. This graben structure accommodates an appreciable thickness of the alluvial deposits especially at the area between Al-Rawda and Jabal Al-Sama.

As mentioned earlier, Sana'a basin was subjected to compression uplift during the late Tertiary time to form the Sana'a anticline. The Sana'a anticline is of n-s axis and plunging to the south with steep dip. The location of fold axis in most areas of the Sana'a basin is eroded away and represents the Sana'a plain recently.

This cross-section provides useful information and helped in resolving and confirming the following issues:

a. The use of the additional borehole logs and the geophysical resistivity (vertical electrical sounding ves) data confirm that the tawilah sandstone aquifer has been completely eroded at the area located between the airport and al-rawdaa.
b. The sana'a basin has been subjected to tectonic activities which play a major role on the hydro geological regime.
c. The cross-section indicated that the sub-surface as well as surface faults are having the trend.

SUMMARY AND CONCLUSION

This paper discussed and investigated a basis for prediction of subsurface structures within the Sana'a basin which is suitable for the containment of the main source for drinking water of the Sana' a city. However, the understanding of the tectonic setting within the Sana'a basin is of high importance, since such a study has proved beneficial and received much attention in the last few years. This study is considered the first attempt to establish a detailed structural study. Stratigraphically, the Sana' a basin has a geological column ranging in age from Precambrian to Recent. These stratigrathic units from top to bottom as follow:

Quaternary (volcanic rocks and wadi deposits)
Tertiary volcanic (sheeted volcanic and basal basalt)
Tawilah Group (clastic rocks)
Amran Group (carbonate rocks)
Kohlan Formation (clastic rocks)
Precambrian rocks (Basement rocks).

Four tectonic movements are recorded from field relationships and structural analysis of the faults and fractures in addition to correlation of units. These are summarized as follow:

1. The Jurassic tectonic movement resulted in the formation of the Sana'a basin. This tectonic movement is a reactivation of the old trend of the Najid fault system. The

formation of the Sana' a basin is contemporaneous with the formation of the Marib-Al-Jawf basin of NW-SE strike.

2. The second tectonic movement occurred during the Cretaceous time with an E-W trend. It is herein proved that this trend had existed prior to the opening of the Gulf of Aden.
3. The third tectonic movement affected the Sana'a basin, is the volcanic activity that had occurred during the Tertiary time and resulted in the formation of Yemen plateau.
4. The fourth tectonic movement accompanied by a volcanic activity took place during the Quaternary time where all older rocks were injected by dykes and plugs of different trends and is still active now.

The use of the additional borehole logs and the geophysical resistivity (vertical electrical sounding) data in the subsurface geological cross section confirm that the tawilah sandstone aquifer has been completely eroded at the area located between the airport and al-rawdah as clearly indicated in cross-section b-b'.

REFERENCE

[1] Al-Kadasi, M. (1994). Temporal and spatial evolution of the basal flows of the Yemen volcanic group. Unpublished Ph.D. Thesis, London University, 301p.

[2] Al-Kharpy. Kh. Z., (1996). Hydrogeological study of the wadi Al-Kharid spring, source of water supply. Phase 3 (SAW AS 3) TECH. NOTE NO. 27 NWSA/TNO, SANA'A lDelf.1.

[3] Al-Kotbah, A.M., (1992). Structural Studies on the basement rocks, Abas area, Al-Bayda District, Yemen Republic, Unpublished MSc thesis, University of Sana'a, 161p.

[4] Al-Kotbah, A.M., (1996). Structural Geology of South Hadhramout area, Yemen Republic, **V. 1**, PhD thesis, Glasgow University 246pp.

[5] Al-Kotbah, A. and Al-Ubaidi, M. (2001). Principle stress orientation of Yemen faults in the Mesozoic age, Faculty of Science Bulletin, **V. 14**, P 85-103.

[6] Al-Subbary, A. (1990). Stratigraphical and sedimentological studies on Al-Ghiras area, northeast of Sana'a, Yemen, unpublished M.Sc. thesis Sana'a Univ. 184p.

[7] Al-Subbary, A. (1995). The Sedimentology and Stratigraphy of the Cretaceous-Early Tertiary Tawilah Group, Western Yemen. PhD thesis (unpublished) Royal Holloway University of London, 184pp.

[8] Al-Subbary, A., Nichols, G., and Bosnce**,** D., (1993). "Cretaceous–Tertiary Pre-Rift Fluvial/Shallow Marine Sediments in Yemen", *Geological Society of Egypt***,** Cairo, *Special* Publication on tectonic and sedimentation of Red sea-Gulf of Aden region., no. **1**, p 383-407.

[9] Al-Subbary, A., Nichols, G., Bosnce**,** D., and M. Al-Kadasi, (1998). "Pre-rift Doming, Peneplanation or Subsidence in the Southern Red Sea, Evidence from the Medj-Zir Formation Tawilah Group of Western Yemen", in *Sedimentation and Tectonics of Rift Basins.* eds., B. Purser and D. Bosnce, London: Chapman and Hall, pp. 119-134.

[10] Al-Subbary, A., Hamimi, Z. and Al-Kotbah, A. (1999). Tectono-sedimentary framework of the Cretaceous-Early Tertiary Tawilah Group, Wadi Dhahr District, Republic of Yemen. Egypt. J. Geol., **43** (2), 219-235.

[11] Al-Thour, K., (1992). Stratigraphy, Sedimentology and Diagenesis of the Amran Group (Jurassic) of the region to the west and north –west of Sana'a Yemen Republic, (Ph. D. Thesis): Univ. of Birmingham, England, 293 pp.

[12] Al-Ubaidi, M., and Al-Kotbah, A., (2003). The Magnitudes of the Paleostresses of Yemen Faults in the Sedimentary cover, Faculty of Science Bulletin, Sana'a University, **V 16**, P 95-109.

[13] Al-Wosabi M. A. (2001) Stratigraphical and Sedimentological Studies on the Jurassic Amran Sequence East Sana'a District, Yemen Republic. Unpublished PhD Thesis, Sana'a University. 278pp.

[14] Al-Wosabi, M. & Wasel, S., 2010, Lithostratigraphic subdivision of the Kohlan Formation in Yemen. Arab. J. Geosci. DOI: 10.1007/s12517-010-0236-9.

[15] Baker, J., Thirwall, M., Al-Kadasi, M. and Menzies, M.(1993). Cenozoic Flood Volcanism in Yemen: Crustal Contamination of Plume and Asthenosphere Derived Magmas. EUG, Strasbourg (Abs.)

[16] Beydoun, Z. R. (1964). The Stratigraphy and Structure of Eastern Aden Protectorate. Overseas Geology. Min. Resources, Bull. Suppl. **V. 5**, 107 pp.

[17] Beydoun, Z. R. (1982). The Gulf of Aden and NW Arabian Sea. In: The Ocean Basins and Margins, V. 6. The Indian Ocean. Narin, A. E and Stehli, F. G. (Eds), Plenum. New York, p. 1407-1418.

[18] Bloemendaal, S., (1990). Sources for Sana'a Water Supply (SAWAS II). Well Inventory Sana'a South (Draft). NWAS-TNO Yemen-Netherlands.

[19] Bloemendaal, S., Heederik, J.P., and Van Kuijk, M.J., (1994). Well-field Investigations Sana'a-South. (Revised version based on 1991b) Technical Report No.3. Sources for Sana'a Water Supply Phase 2 (SAWAS-2) TNO Inst. Of Applied Geosciences, Delft/NWSA, Sana'a

[20] Diggens, J., Dixon, R., Downie, R., Harris, J., Jakubowski, M., Lucas, P., Matthews, S., Southwood, D. And Ventris, P., (1988). A geological model for the evolution of the Marib-Jawf Basin, Yemen Arab Republic, V. 1. Robertson Research International Limited, Report no. 6216/IIB, Project no. RRPC/878? IBB/40018 (Unpublished)

[21] El-Anbaawy, M.I. (1985). Geological evaluation of the Late Jurassic evaporites of AI-Ghiras district Yemen Arab Republic, Bull. Fac. Sc. Sana'a Univ. **Vol. 5**, P 40-58.

[22] Geukens, F. P. (1966). Geology of the Arabian peninsula (Yemen), U. S. Geol. Survey Prof. Paper, 560-8: P 1-23.

[23] Hydrosult, Water and Environment Centre (WEC), TNO-NITG (2010), Hydrogeological and Water Resources Monitoring and Instigations (unpublished Report)

[24] Hydrosult Inc. (2010); Assessment of Water Resources Potential of Sana'a Basin, Ministry of Water and Environment, Sana'a Basin Water Management Project. Volume 1 (Activity 1, Part 1).

[25] Italconsult (1973). Sana'a basin groundwater studies. Water supply for Sana'a and Hodayda. Prepared for the ministry of public works. Y.A.R. and the world health organization as executing agency in UN development programme 507, VI AND II

[26] Khanbari K., 2004: Using Remote Sensing, GIS and Field data for fracture analysis of Wadi Dhahr area, Republic of Yemen, Faculty of Science Bulletin, **17**, p 91-102.

[27] Khanbari K., and Huchon, P., 2010: Paleostress analysis of the volcanic margins of Yemen. Arab J Geosci **3**:529–538

[28] Kruscman, G. P. (1996). Deep sandstone drilling programme. Drilling report 05-2 Tech. Note no. 21 source for Sana'a water supply phase3. 9SAWAS-3) Sana'a! Delft.

[29] Lamare, P., Basse, E Mauric, L., Al-Ferd and Teihard De Chardin, P. (1930). Studies geologoue, en Ethiopia, Sommalie, et Arabie meridional, soc. Geol. France Mem. Now ser, **V. 6**, p. 1-83

[30] Lamare. P. (1932). Note Prelimaire sur la structure de la région dy Yemen. Soc. Geo. Frana, sammairc des Seances, Complcs rendus. ser, **4**, 23p.

[31] Menzies, M., Bosence, D., El-Nakhal, H., Al-Khirbash, S., Al-Kadasi, M. and Al-Subbary, A. (1991). Lithosphiric extension and the opening of the Red Sea; Sediment-Basalt relationship in Yemen. Terra Nova, No. **2**, p. 340-350.

[32] Menzies, M.; Barker, J.; Bosence, D.; Dart, C; Davison, I.; Hurford, A; Al-Kadasi, M.; McClay, K.; Nicholas, G.; Al-Subbary, A. and Yelland, A. (1992). The timing of magmatism, uplift and crustal extension: preliminary observations from Yemen. Jour. Geol. Soc. "special publication", **v. 68**, pp. 293-304.

[33] NWSA. Sana'a TNO, Delft (1994). Well field investigation Sana'a south, Tech, Report no. 03, source for Sana' a water supply, phase 2, (SAW AS 2).

[34] Richard Helmer and Ivanildo Hespanhol, 1997: Water Pollution Control - A Guide to the Use of Water Quality Management Principles, Published on behalf of the United Nations Environment Programme, the Water Supply & Sanitation Collaborative Council and the World Health Organization by E. & F. Spon, WHO/UNEP / ISBN 0 419 22910 8

[35] SAWAS (1996). Sources for Sana'a Water Supply. SAWAS Final technical Report and executive Summary National Water and Sanitation Authority Sana'a, Republic of Yemen. Netherlands Institute of Applied Geosciences TNO, Delft, The Netherlands

[36] Stephen Foster, Peter Koenig & Satoru Ueda (2003). Yemen: Rationalizing Groundwater Resource Utilization in the Sana'a Basin, Ministry of Planning & Development (MOPD) and Sana'a Basin Water Management Program (SBWMP) Profile Collection Number 3 Report.

[37] Strakcy (1977). The contorting of orientation data represented in spherical projection. Can. J. Earth Sci. **14**, 177-168.

[38] WEC (2001); Basin Characterisation and Selection of Pilot Study Areas. Volume II Water Resource Availability and Use. Sana'a Basin Water Resources Management Study (SBWRM - PPT). Final Report.

التتايع الطباقي والتطور التكتوني في حوض صنعاء

عبد الكريم أحمد الصباري[1]، أحمد محمد القطبة[1]، نايف أبو لحوم[1] وعبير آلأسدي[2]

1قسم علوم الأرض والبيئة، كلية العلوم، جامعة صنعاء، اليمن
البريد الإلكتروني : aalsubbari@hotmail.com
2مؤسسة المياه والصرف الصحي المحلية (SWSLC)، صنعاء ، اليمن

ملخص

التتابع الطباقي للصخور في حوض صنعاء تتراوح أعمارها من عصر ما قبل الكمبري إلى العصر الحديث، مع غياب بعض الفترات . ونجد بأن المكاشف الصخرية في حوض صنعاء تتراوح أعمارها بين الجوراسي إلى الرباعي، في حين أن البيانات تحت السطح يكشف عن وجود صخور هي من عصر ما قبل الكمبري.

هذا البحث يناقش التطور الترسيبي والركيبي في حوض صنعاء والذي يشير إلى أن المراحل التكتونية المهمة وقعت خلال العصر الجوارسي ، الطباشيري ، الثلاثي وكذا العصر الرباعي، حيث الآثار التركيبية لهذه المراحل التكتونية تتضمن مراحل حركة الرفع والإنخفاض مرات عديدة، ومع ذلك فقد تكون حوض صنعاء خلال العصر الجوراسي تحت سيطرة البنيات الموروثة من العصور القديمة ومن ثم أعيد نشاط التحكم البنائي من الاتجاه الشمالي – الجنوبي القديم.

لقد أكدت الدراسات الميدانية بأن حوض صنعاء قد تعرض لمرحلة ضغط خلال عصر الباليوسين والتي أسفرت عن ظهور طية محدبة محورها يأخذ إتجاه شمال – جنوب. وفي نهاية عصر الباليوسين تأثرت المنطقة بالصدوع والشروخ الإمتدادية ليظهر إنخساف نصفي مثل الإنخساف النصفي لوادي ظهر ، والإنخساف النصفي لمنطقة حده، أما خلال العصر الثلاثي فقد تأثرت منطقة صنعاء بنشاطات بركانية ضخمة لا سيما في الجزء الجنوبي من حوض صنعاء لتشكل هضبة اليمن ، ومن ثم تعرضت المنطقة مرة أخرى لنشا ط تكتوني متأثرا بالمرحلة الإمتدادية التي تزامنت مع الإتجاه السائد شمال جنوب – شمال غرب وكذا مع الإتجاه شرق شمال شرق—غرب جنوب غرب. لذلك فإن معظم هذه الصدوع والشروخ قد إمتلاءت بالسدود البركانية بمختلف التركيب المعدني. وفي فترة العصر الرباعي حدث نشاط بركاني آخر نتج عنه تشكيل الكثير من الرقاب البركانية والمخاريط التي اقتحمت وحدات الصخور القديمة.