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Tectonostratigraphy of Yemen And Geological Evolution: A New Prospective

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Abstract— **The accretion and breakup of supercontinent would form the dominant control on the geographic position and timing of all tectonically intercede activity, and would there by profoundly influenced the tectonostratigraphic record of an area. This paper is summarized and discussed in detail the tectonostratigraphic events that correspond to the stratigraphic evolution in Yemen. In light of previous literatures papers, and proposed models of the formation of earth attempted has been made to re-arrange and re-ordered in a manner that be affected by or controlled by tectonics events and re-shaped formation in favor of these events. The objective of this paper is to elucidated the tectonostratigraphic of Yemen started from the Neoproterozoic time, when west Gondwana and east Gondwana collide ahead to the separation of India from afro-Arabia, ultimately to the last event represented by the opening of Gulf of Aden and Red sea and subsequent basins formed in or related to these events. All these events are effected the gross sedimentary accumulation, depositional environment and thickness of stratigraphy of Yemen.**

Index Terms—**Tectonostratigraphy, Geological evolution, Tectonic environment, Yemen.**

I. INTRODUCTION

The stratigraphic manners in which The Sedimentological characters of sedimentary rocks i.e environment, sediment transport agencies and the nature of the syn to post depositional tectonic activities modify the stratigraphic order of deposition are significant in terms of their depositional environment, the thickness of the formations and primary structures. Since the tectonics related to stratigraphy are manifested in the distribution of sediments in Yemen. We try to trace these effects to better understanding and generalized the geological evolution of Yemen.

II. THE PAN-AFRICAN OROGENY EVENT

The pan-African orogeny was a series of prominent Neoproterozoic orogenic belts , which related to the formation of supercontinents, caused mechanisms are not well understood till now.This Orogeny is developed due to collision of East Gondwana and West Gondwana in Neoproterozoic time. Then developed as suture zone between East Gondwana and West Gondwana, the northern part of this orogeny is represent the Arabian Nubian Shield, whereas the southern part represent Pan-African Orogeny .This orogeny is participated to some extent to the geology of Yemen as following. The basement rocks of Yemen is considered a part of the Arabian shield which can be divided into five terranes. Asir terrane, Abbas terrane, Al Bayda terrane, Al Mahfid terrane and Al Mukalla terrane.They arrange in manner that reflect the magnitude of tectonic process in time and space. Two of them represent island arcs which are abducted to continental crust, the Al Bayda terrane, and Al Mukalla terrane. The remaining three others form Archean to Proterozoic gneissic terranes, the Abbas terrane, Asir terrane and the Al Mahfid terrane. During Ordovician the sediments were transported from southwest to northeast as deduced from the abundant cross bedding structure, in both facies of Wajid Sandstone in Saudi Arabia, dated to be of Ordovician age, towards what is know the center of the Arabian shield.

The Wajid sandstones is present only in the northern Yemen, particularly north Sa'dah governorate and east, north Al Jawf governorate. Presumably, the paleoslope of the region was towards the northern-east as indicated from two lines of evidence, i.e. increase in thickness of Wajid sandstone toward north-east, second is the absence of this formation in southern Yemen.Due to tectonic uplift event in mid Carboniferous that related to merging of Laurasia and Gondwanaland to compose Pangea, ice sheet developed on uplift places and sediments of glacial origin were accumulated in Yemen represent by Akbarah formation. This formation is completely absent from east Yemen, but exists in northern Yemen.Overlying Akbarah Formation is the Kuhlan Formation which represents fluvial to nearshore depositional environment. It is widespread with small scale outcrops through Yemen. The well knownstrata type section of this formation is in Hajjah(Kuhlan village). The thickness varies considerably in peneplained floor at the time of deposition. The Kuhlan Formation is overlain by dolomite/limestone of Shuqra Formation which was part of a wider Tethys ocean shelf on the passive margin of Arabian shield.

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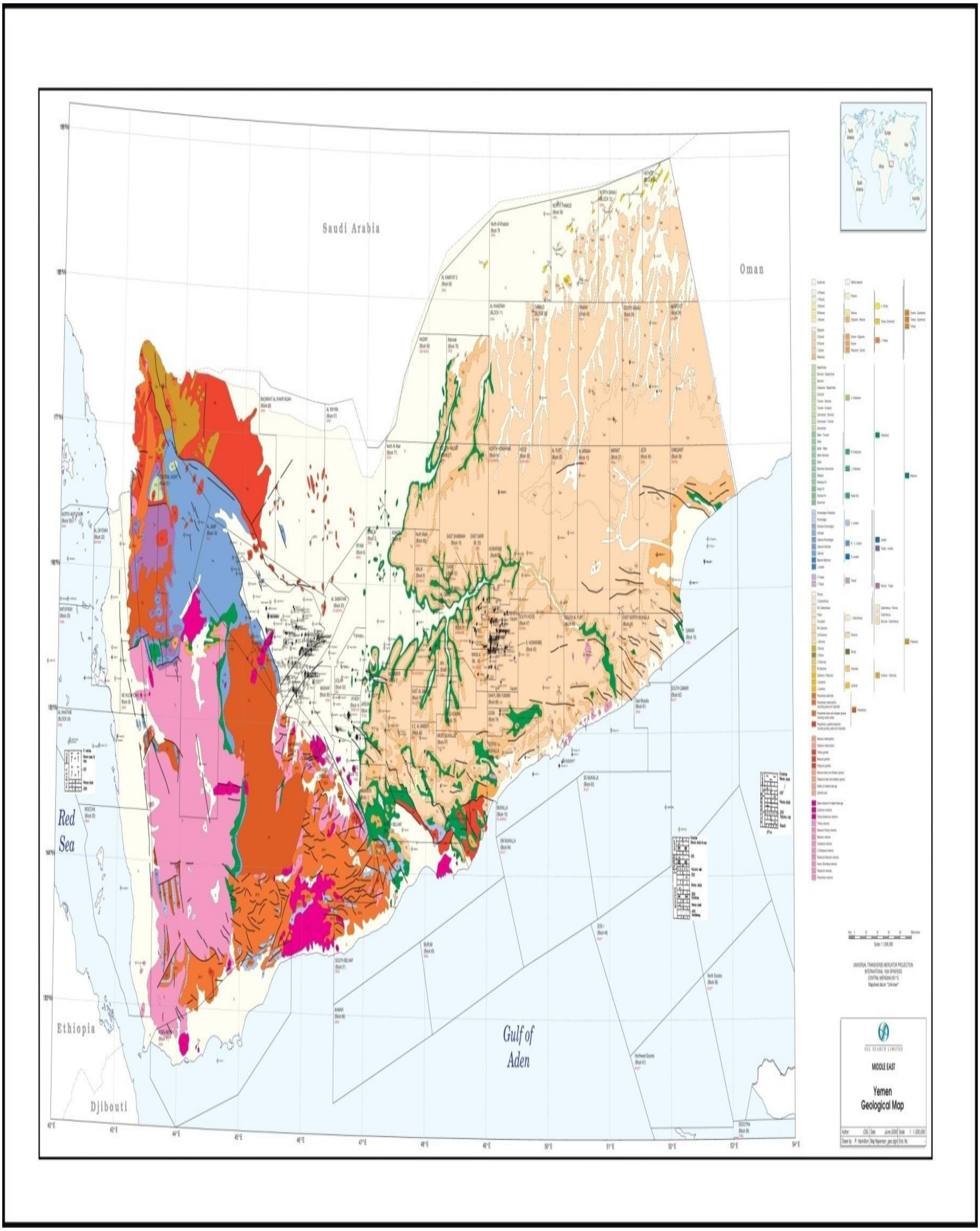

Fig. 1: Geological Map of Yemen

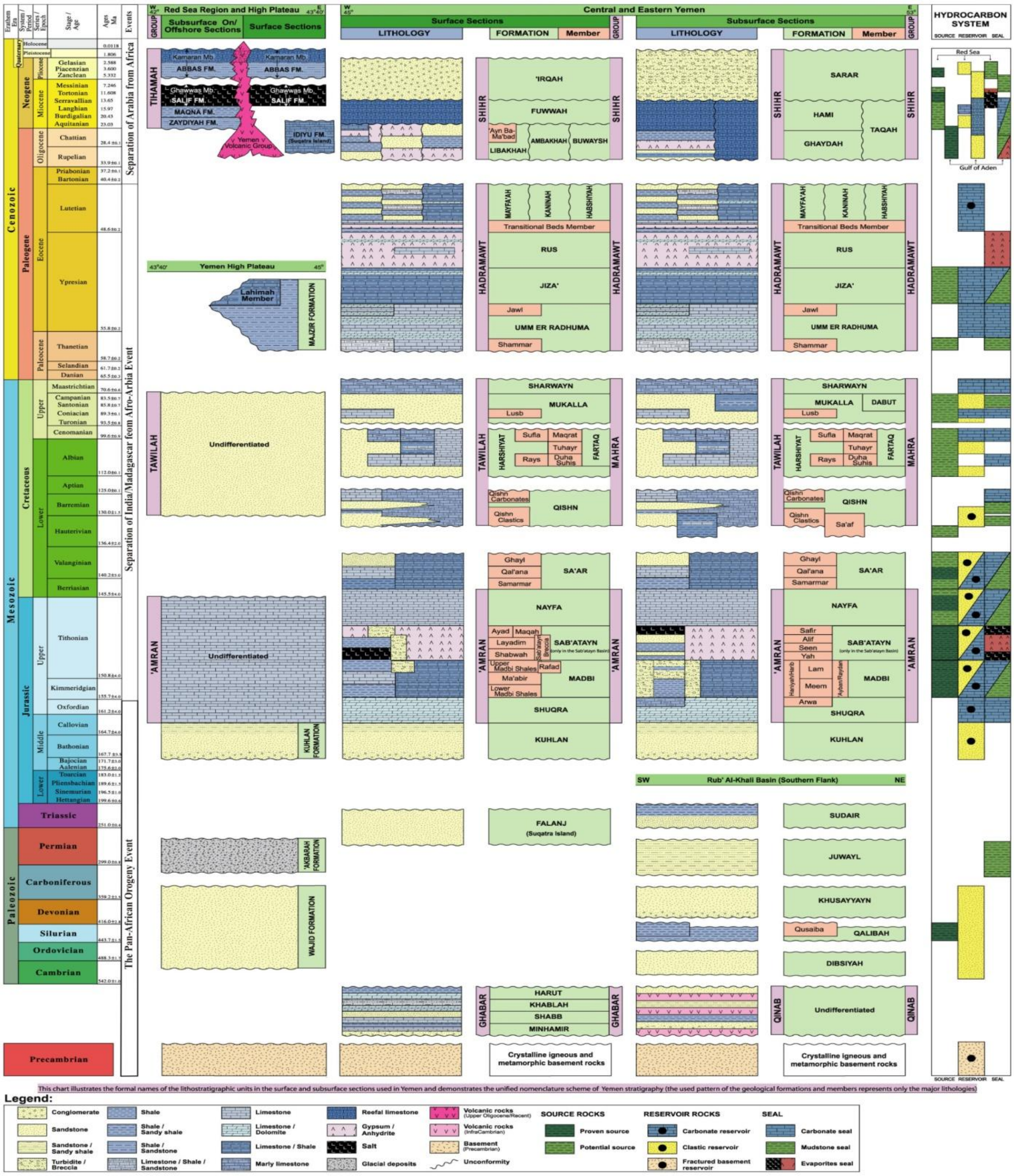

Fig. 2: Lithostratigraphic chart and hydrocarbon system of Yemen modified after As-SAruri, (2003/2004)

The Precambrian basement of Yemen covers a key location in the Pan-African orogeny of Gondwana. The history of the tectonostratigraphic evolution of the basement rocks of Yemen will be traced in the following statement. The suturing event of eastern Gondwana and western Gondwana that spanned the interval from ≈ 750 to 530 Ma (Meert, 2003) resulted from a great collision zone called the East African Orogen, of which the Arabian-Nubian shield is the northern half zone (Fig. 1).

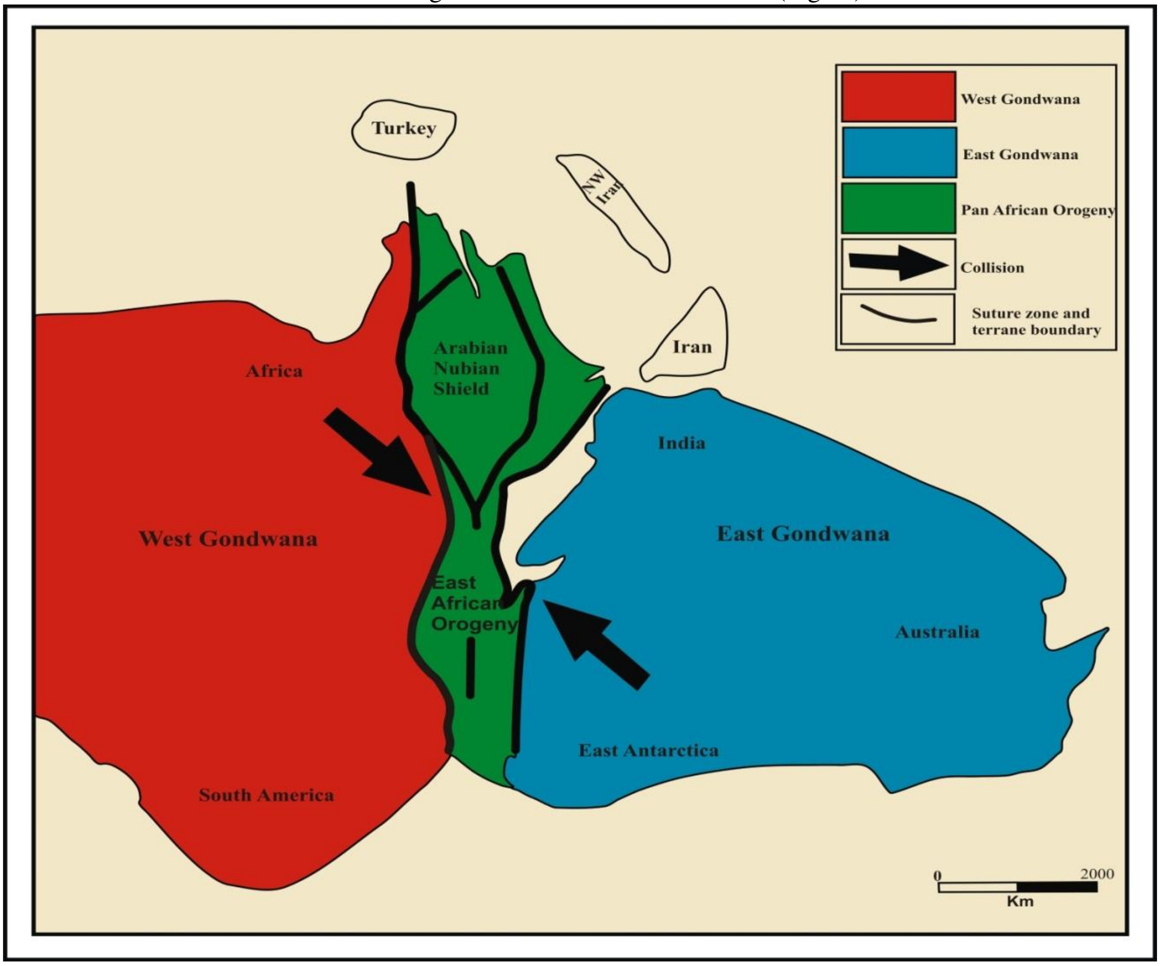

Fig. 3: Reconstitution of collision of East Gondwana and West Gondwana and Development of Pan-African Orogeny. (Modified after Jacobs and Thomas, 2004)

The mechanisms and driving force responsible for this suturing is still not well understood. Eastern Gondwana makes up much of the continents of Australia, and India, while the western Gondwana composed of South America and Africa. The Arabian-Nubian Shield (ANS) consists of Precambrian rocks on the flanks of the Red Sea in Western Arabia and northeastern Africa (Johnson and Woldehaimanot, 2003). It represents one of the largest Neoproterozoic crustal growth events on Earth and was exposed after uplift and erosion during Oligocene and younger times. The ANS is dominantly juvenile continental crust, i.e. crust formed from mantle-derived melts(Stern & Abdelsalam, 1998). Much of the ANS formed in the Neoproterozoic that span nearly from 1000 to 541Ma years ago and thrusted to Arabia by processes indistinguishable from those of modern plate tectonics. It is a collage of well identified intra-oceanic tectonostratigraphic arc terranes which are separated by recognizable sutures commonly marked by ophiolites (Hargrove et al., 2006). The main geologic evolution of the Arabian Nubian shield is limited to the period ranging from 900 to 530Ma that led to the formation, amalgamation, and accretion of theses terranes in Arabian countries (Genna, Nehlig, Le Goff, Guerrot, & Shanti, 2002). As in many other ancient continental areas, the tectonostratigraphic units that comprise the Arabian Shield are mostly fault-bounded, and the geologic histories of neighboring units commonly have contrasting elements. These fault-bounded 'tectonostratigraphic terranes' are allochthonous and were brought together by processes of accretion(Nehlig, Genna, & Asfirane, 2002).

The Arabian Nubian shield (Fig. 2) is considered one of the youngest of the earth's lithospheric plates having exposure when rifting occur to form the Gulf of Aden, Red sea and split off from Africa continent.

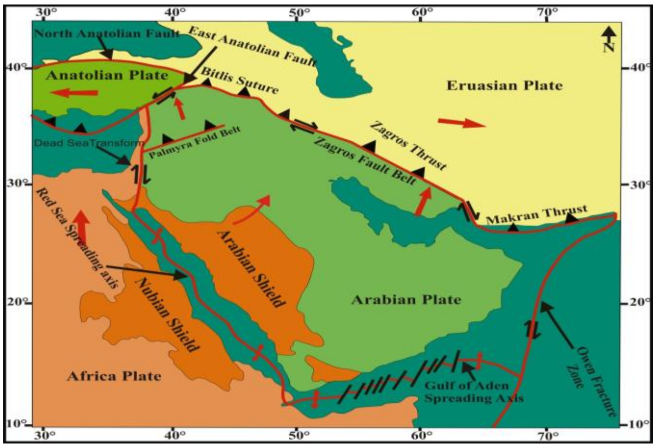

Fig. 4: Re-Construction of Development of Arabian-Nubian Shield Related to Pan-African Orogeny.(Modified afterRobert J. Stern, 2010)

Its crust comprises Precambrian crystalline basement, well exposed in west. Arabian–Nubian Shield had been developed during the Upper Archean (?) to Neo-Proterozoic age and well-formed accreting micro-plate gneiss terrains and volcanic island arcs(Abu El-Ata, EI-Khafeef, Ghoneimi, Abd Alnabi, & Al-Badani, 2013). Several tectonic-stratigraphic terranes within the Arabian Nubian shield have been identified by various authors as(Stern & Johnson, 2010). These terranes are generally bounded by tectonic zones, which regarded as suture zones partly containing ophiolite complexes or fragments of former oceanic crust(M. a. As-Saruri & Wiefel, 2012). Basement rocks in Yemen presumed of Precambrian age, apart of Arabian-Nubian shield, Particularly the southern part of shield. Exposures of upper continental crust dominate the geology of western Arabia as a result of Oligo-Miocene rift-flank uplift during formation of the

Red Sea Basement is also exposed in scattered outcrops in eastern Arabia adjacent to the Gulf of Aden and the Indian Ocean (Stern & Johnson, 2010). Basement rocks in Yemen cover around (105.000km2) area and exposed in the northwestern and southeastern parts of the country(Heikal, Al-Khirbash, Hassan, Al-Kotbah, & Al-Selwi, 2013). Comprehensive studies on the basement rocks of Yemen have been done by some writers (Heikal et al., 2013); (Whitehouse et al., 2001); (Whitehouse, Windley, Ba-Bttat, Fanning, & Rex, 1998); (M. a. As-Saruri & Wiefel, 2012), (Stoeser et al. 1991), (Whitehouse et al., 1998), (Whitehouse et al., 2001), and (Whitehouse et al., 1998) Whitehouse et al. 1993, 1996, 1998, 2001), and (Windley et al. 1996) identified five terranes within Yemen (Fig. 3), three are continental in origin (Asir, Abbas, and Al-Mahfid) and two representing island arc terranes (Al-Bayda and Al-Mukalla).

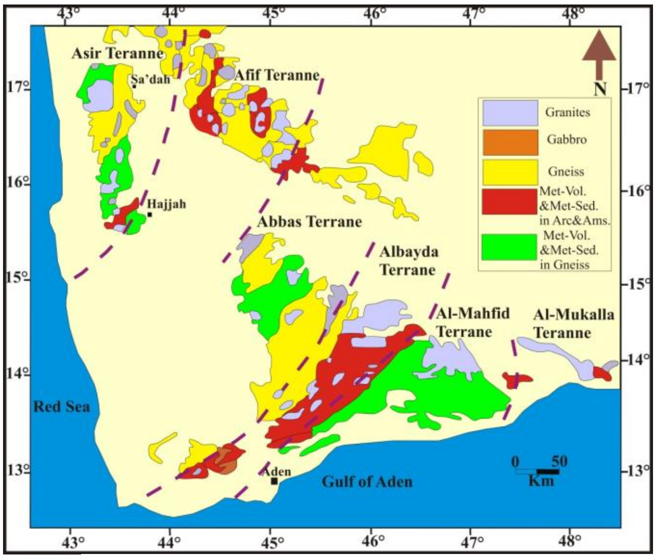

Fig. 5: Distribution of the basement rocks and its divisions into terranes.(Modified after Stoeser et al. 1991; Whitehouse et al. 2001; Windley et al. 1996)

These terranes include Archean to Proterozoic gneissic terranes, a Pan-African island arc terrane and suture zones that correlate with those on the eastern margin of the Arabian shield and in northern Somalia (Kröner and Sassi 1996). (Bosworth, Huchon, & McClay 2005) divided Precambrian basement of Yemen into six terranes that alternate between early Precambrian gneiss and Neoproterozoic island arcs accreted together during the Pan-African orogeny alternate between early Precambrian gneiss (comprise Najran, Abbas, and Al-Mahfid terranes) and Neoproterozoic island arcs (including An Nimas, Al-Bayda and Al-Mukalla terranes) accreted together during the Pan-African orogeny. (Johnson and Stewart 1996) questioned the extension of the Afif terrane to Yemen.

Table 1: Showing Characteristics of Basement rocks terranes of Yemen (Sources: Johnson, 2000; Windley et al., 1996)

Terrane Name	Dominant Lithology
Asir	Greenschist, Gneiss, metavolcanics and sedimentary rocks
Abbas	Gneiss, metamorphosed, supracrustal rocks, greenschist
Al Bayda	Greenschist-grade rhyolite, andesite, basalt, tuff
Al Mahfid	Megamtizedorthogneiss, amphibolite, granite, tourmaline-aplite, pegmatite
Al Mukalla	Tuffs, feldspar prorphyry lava, volcanic breccias, rhyolites, basalt, quartz-porphyry dykes

In the following statement I will briefly discuss these terranes, The Precambrian terranes include: (1) the Asir terrane consisting of basement gneiss and arc-type volcanics. The Asir terrane is composed of Amphibolite-facies gneisses alternating with greenschist-grade supracrustal belts. The isotopic data is not available for Asir terrane in Yemeni side, but it has been assigned 840-740 Ma age in Saudi Arabia(Whitehouse et al., 2001).

(2) the Abbas terrane represents Precambrian continental crust of southeast Arabian shield. The Abbas terrane composed of amphibolite facies orthogneisses containing belts of supracrustal rocks (rhyolites and schists)(Whitehouse et al., 1998). (Yeshanew, 2014) defined two age groups for Abbas terrane i.e. 790-730 Ma, and 630-590 Ma, the letter belonging to the post-collisional stage. Whereas (M. A. As-Saruri, Sorkhabi, & Baraba, 2013) assigned age probably 2.7-1.3 Ga for Abbas terrane.

A major belt of metamorphosed supracrustal rocks known as the Rada Group occurs within the Abbas gneiss terrane, containing rhyolite, biotite schist, chlorite schist, amphibolite, metatuff, meta-arkose and marble. These supracrustal rocks are intruded by numerous discordant intermediate to basic dykes(Whitehouse et al., 1998).

Both the Abbas and Al-Mahfid terranes record a major 760 Ma event which generated orthogneisses in the Abbas terrane and granitic sheets in the Al-Mahfid terrane, together with the major Pb loss recorded in the late Archean zircons.(Whitehouse et al., 1998).

(3) Al Bayda terrane produced in arc environment, is composed mainly of meta-volcanics and schist. The Al Bayda terrane composed of greenschist-grade island arc-type rhyolites, andesite, basalts and tuff and granitic plutons (Whitehouse et al., 1998). Ophiolites occur at both its eastern and western margins, and it is intruded by post-tectonic granitic plutons. The Al Bayda arc is also intruded by undeformed rhyolite dikes along its eastern margins(Yeshanew, 2014). (M. A. As-Saruri et al., 2013) assigned age of this Al Bayda terrane probably 2.5-1.2 Ga. (Whitehouse et al., 2001) Collected various samples from different localities in Al Bayda island arc terrane and calculated the age using Pb-isotopic data, ranged 2.87-1.02 Ga.

(4) Al-Mahfid terrane mainly comprises granite-gneiss. The Al-Mahfid Terrane consists of belts of high-grade gneiss, amphibolites, gneissic granites, as well as low-grade ophilitic fragments comprising gabbros, basalts, marbles, and the thin conglomerate. The gneisses gave depleted mantel model age ranges of 2.73–3.03 Ga and are interpreted as remnants of late Archean continental crust; Pan-African reworking of the high grade rocks added juvenile components, resulting in mixed model ages(K. a. Al-Wosabi, Alaug, & Khudeir, 2014). The Al-Mahfid gneiss terrane exhibits a protracted and complicated history (Heikal et al., 2014).

(5) Al-Mukalla terrane comprises greenschist-grad island arc type tuffs, rhyolites, basalts, lava breccia. The Mukalla Proterozoic basement is located in the south-east edge of the Mukalla horst, in the linking zone between the Marib Shabwah-Hajar basin and the Mukalla-Sayut basin(Le Garzic et al., 2011).

(Lenoir et al. 1994; Sacchi and Zanferrari 1987) and (As-Saruri and Wiefel1998) identified four provinces within the Yemen basement based on their litholgic and structural features and structural development. These provinces are bounded by major faults or sutures. (Whitehouse et al. 2001) attempted to correlate the Yemen terranes with the Saudi Arabian and Somalia on the basis of geological description, geometric constrains and isotopic and geochronological data. They identified that the boundary between the terranes form major crustal lineament, which change from approximately north-south orientation in Saudi Arabia to northeast to southwest orientation in southwest Yemen and Somalia. (Le Bas et al.2004) studied the carbonatite-marble dykes of Abyan province and indicate the mixing of mantle and crustal carbonate materials revealed by isotope and trace element analysis.

On such excellent exposures, Hajjah, Al Bayda, Mukairas, Haifan, Mudiyah–Mukalla, and Eastern Aden areas (Shabwa and SW Hadramawt), that reflect a clean picture to deduce in good agreement for integrating classification and Lithostratigraphy of the basement rocks in Yemen.

Most recent work by (M. a. As-Saruri & Wiefel, 2012) studied and subdivided the intrusive rocks in the Mudiyah–Mukalla area into four tectonic stages: the anatectic stage (Ahwar Supergroup), the syntectonic stage (Gharish Supergroup), the post-tectonic stage (Tha'lab Group), and the late orogenic stage (Ghabar Group). In addition, by age determinations (K/Ar) of several samples from Mudiyah–Al Mukalla basement rocks, (Windley et al. 1996) recorded an age of 3.03–2.73 and 2.5–1.2 Ga for Ahwar and Gharish Supergroups, respectively, that are distributed in Al Mahfid and Al Bayda terranes. (Sassi et al. 1993) recorded an age of 700–640Ma for the island arc metavolcanics (Tha'lab Group) in Al Mukalla area.

WAJID FORMATION

The Wajid Sandstone, of probable Early Paleozoic age, rests nonconformably on crystalline rocks of the southern part of the Arabian shield and considered the oldest formation in the region. The Wajid Sandstone is extensively described from southern Saudi Arabia, because it is widely exposed there.

The term ‘ Wajid Sandstone’ was first used in an unpublished Aramco report for these strata in Saudi Arabia. (Powers et al, 1966) and (Powers, 1968) formally proposed the term and described a type section in Southwestern Arabia.

The southern part of the formation, near the Yemen border, consists of fluvial sandstones with minor siltstones and silty shales. The depositional environment is considered fluvial, as demonstrated by the presence of fining-upward cycles, channels, trough cross bedding, and absence of all organic trace(Dabbagh & Rogers, 1983).

The age of Wajid Sandstone, of probable Cambrian/Ordovician rests disconformably on crystalline rocks of the southern part of the Arabian shield(El-aal & Kharashy, 2014). The precise age of Wajid Sandstone is a controversial matter due to lack of fossils but from stratigraphic position it considered older than Permian. Abundant cross bedding in both facies of the Wajid Sandstone indicates a northward transport direction, towards what is now the center of the Arabian shield(Dabbagh & Rogers, 1983). Wajid sandstone deposits from Saudi Arabia into northern Yemen cover a wide area north of Sa’dah and east and north of Al-Jawf area. The southern boundary east of Al-Jawf province is a fault while some remnant hills exist in small isolated grabens west of the Sa’dah depression.

No specific reference section was selected but in Jabal Dal’an, north of Sa’dah, the formation exceeds 200m in thickness.

AKBARAH FORMATION

El-Nakhal (1987) pointed out that the name Akbarah Shales had already been applied informally in the explanation of units on the geological map of Yemen. Akbarah formation (Late Carboniferous-Permian): tillite (pebbles & boulders of basement rocks), shales, mudstones, sandstones and siltstones. At the Kuhlan Village section, the Akbarah Formation is in two parts. The lower part is composed of thick sandstone beds fining upwards to siltstone and thick fissile shale. These units are interbedded with massive and stratified diamictite beds. Dropstones are embedded within the sandstone and the shale beds, and their size decreases upward illustrating increasingly distal conditions. This part is interpreted broadly as of glacial origin. The upper part is composed of several cycles beginning with beds of thin, fine-grained sandstone fining upwards to thick fissile shale beds, interpreted to be of marine origin(Stephenson & Kader Al-Mashaikie, 2011). The depositional environment of the Akbarah Shale is thought to be lacustrine or fluvio-glacial. The largest thickness is measured by Yemen stratigraphic commission in Wadi Jannat/Al Ashmour around 109m. Regionally the Akbarah Shale is correlated with other glacial deposits in Ethiopia, Saudi Arabia and Oman(Ph.D. Thesis of F. Al-Huzaim, 2005). The Akbarah Shale is absent in the western part of Yemen(Ph.D. Thesis of F. Al-Huzaim, 2005). The mechanisms of deposition can be deciphered in the following statement. Due to the tectonic event (uplift) in mid-Carboniferous related to merger of Laurussia and Gondwanaland to compose Pangea, sheet cover is developed in South Africa and sediment of glacial origin are deposited in the region. These sediments represent in Yemen by Akbarah Formation. The stratotype section for the Akbarah Formation, is in the Kohlan area of northwest Yemen, approximately 65 kilometers northwest of Sana'a in outcrops close to the village of Beit Al-Kooli.A maximum thickness of 130m, with an average thickness between 40m and 80m. Lithostratigraphic similarities suggest possible correlation with the Haushi Group in Oman. The Akbarah Formation (Sharas Member and Khalaqah shale) assigned to the Late Carboniferous-Early Permian(El-Nakhal, 2002)(Stephenson & Kader Al-Mashaikie, 2011) confirms that the lower Kuhlan Formation and the Akbarah Formation, are likely to be late Carboniferous in age and equivalent to the lower parts of the Al Khlata Formation of Oman. The age of this formation is assigned as late Paleozoic glacial deposits. The absence of the Akbarah Formation from south and east south due to extensive weathering processes.

KUHLAN FORMATION

The siliciclastic beds outcropping around the village of Kuhlan, northwest Yemen, were originally designated the Kuhlan Series by Lamar & Carpenter (1932). Later the sandstone part of the sequence was renamed the Kuhlan Formation by the Yemeni Stratigraphic Commission (Beydoun et al., 1998). Kuhlan village, where the type section and several typical outcrops of the Kuhlan Formation are situated, is located about 70 km northwest of Sana'a city. There the formation has a thickness of about 200m but also crops out in a narrow belt in the mountains of the high plateau of northwest Yemen (Stephenson & Al-Mashaikie, 2010). The Kuhlan Formation is a variable clastic unit dominated by sandstones, siltstones and conglomerates. The sediments are immature, poorly-sorted with metamorphic rock fragments and an argillaceous matrix. Minor amounts of mudstone and anhydrite also occur(Brannan, Sahota, Gerdes, & Berry, 1999).

The Kuhlan Formation overlies the dominantly argillaceous Akbarah Formation. The depositional environment is fluviatile to nearshore environment that passes upward into littoral to shallow marine facies and represent the phase of sedimentation associated with the Jurassic transgression.

Lithologically, the Kuhlan Formation consists of yellowish brown, pinkish and red, massive, cross-bedded, medium to fine-grained sandstone, which is interbedded with thick, fissile and stratified siltstone/shale beds of grey to red color. The Kuhlan Formation can be correlated with equivalent rock units in neighboring countries such as Afar region, Saudi Arabia, Somalia, and Sultanate of Oman.(M. Al-Wosabi & Wasel, 2011). The age is considered Middle Jurassic to early jurassic.

SHUQRA FORMATION

This formation was considered as representing a part from the Jurassic outcrops and had been referenced to as "Amran Series" by (Little1925) and Lamare 1930). It was also described as Shuqra Limestone by (Hudson 1954). Latterly, Beydoun (1964) described it as Shuqra Formation. The recorded type section of this formation was measured by (Wetzel and Morton 1950) in unpublished report) at Jabal Urays and lies at a distance 15 km N17°E of Shuqra City which is located on the Coast of Aden Gulf. They measured 98m of dark gray well-bedded limestone; however, they did not assign the top part of the measured section. . It is Lithologically composed of carbonate marl/shale, and depositional environment is shallow marine of the platform and of pre-rift areas. Formation is exposed in wide geographic areas in the northern, western, and southern parts of Yemen with variable thickness due to erosion.

ASSOCIATED BASINS

The Sedimentary basins that are formed during the first event are (1) the Rub' Al-Khali basin (southern flanks), bounded to the south by the Hadramawt arch (oriented approximately W–E) towards which the Paleozoic and Mesozoic sediments pinch out; (2) the Sana'a basin, encompassing Paleozoic through Upper Jurassic sediments; and (3) the southern offshore Suqatra (island) basin filled with Permo-Triassic sediments correlatable with that of the Karoo rift in Africa. (M. A. As-Saruri, Sorkhabi, & Baraba, 2013).

II. SEPARATION OF INDIA/MADAGASCAR FROM AFRO-ARABIA EVENT.

The India/Madagascar and Africa separation worked out in late Jurassic caused extensional tectonic in Yemen. It is remarkable to notice that there is no volcanic activity related to this event. But remarkable feature is generation of graben/horst structures that shaped new topographies for sediments accumulation especially in east and southeast of Yemen. Seismic images, well data, and field observations from the Mesozoic basins of Yemen indicate that the rifting started during early Kimmeridgian in the western part, during middle Kimmeridgian–Lower Tithonian in thecentral part, and shortly later in the eastern parts of Yemen. Subsequent northeastward separation of the Indian plate is reflected in the easterly and southerly propagation of basin subsidence and sediment fills in Yemen during Tithonian-Valanginian times (Beydoun et al. 1996; Bott et al. 1992).

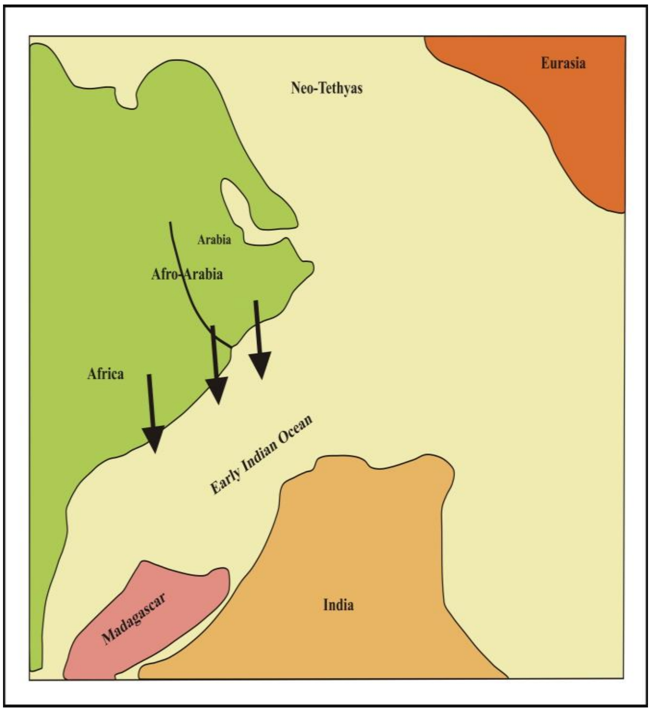

Fig. 6: Re-construction of Separation of India/Madagascar from Afro-Arabia in late Jurassic Early Cretaceous.(Modified after Adrian Immenhauser1999).

MADBI FORMATION

This formation was described as a part of Jurassic outcrops as "Amran Series" by (Little 1925) and as transitional beds by (Lamare 1930). It was described as Madbi Formation by (Beydoun 1964) with thickness 240m. The type section measured at Jabal Madbi, Shabwah Province, was found to be conformably underlain by Shuqra Formation and overlain by either the Tawilah Group in some places or Nayfa Formation in the others. The age of Madbi Formation can be regarded as early Kimmeridgian to Middle Tithonian. The depositional environment is pelagic, with phases of anoxia and periodic margin within the rift basins.

into intra-and post-salt reservoirs is restricted by the evaporates(Seaborne, 1996). This formation is deposited during latest Jurassic (Tithonian) late rift phase sedimentation. The Sab'atayn Formation (Beydoun 1964) is made up of sandstones and evaporites with some clay interbeds. In the Marib-Shabwah Basin, this formation is only exposed as diapiric salt domes and is widely found in the subsurface (average total thickness of 545m),(Beydoun et al. 1998). The Sab'atayn Formation is divided into four conformably overlying members including the Yah, Seen, Alif and Safer members (Beydoun et al. 1998). The Alif Member is made up of sandstone with some shales and with evaporites intercalations at the upper part of the member. This member is only found in the subsurface and it was deposited in fluvial to deltaic environments. The Alif sandstone Member of the Sab'atayn Formation together with the other minor reservoir sandstones within the Yah, Seen, and Safer members of the Sab'atayn Formation are regarded as the main hydrocarbon reservoir in the Marib-Shabwah Basin. The salt and shale beds of the Sab'atayn Formation are serving as seal rocks for most of the Marib-Shabwah Basin reservoirs. These halite strata act as barriers against the vertical migration of petroleum and thus, are effective seal rocks(Al-aug, Mahmoud, Deaf, & AL-Ameri, 2014).

NAYFA FORMATION

Nayfa Formation consists Predominately of Limestone slightly dolomitic, slightly argillaceous interbedded with minor Dolomite and Shale. Beydoun (1964) encounters carbonate, calcareous shales, shales and claystone interbeds in the type locality of Hajar Trough. In subsurface exploration drilling boreholes, the Nayfa Formation was encountered in all the main Yemeni rifted basins (Al-Areeq & Alaug, 2014). The Deposition of the Nayfa Formation took place during a new phase of transgression probably associated with the erosion of the marginal barriers that were present during Madbi times that resulted in partial re-introduction of open-marine sedimentation into Sab'atayn and Say'un-Masila Basins

(Redfem&lones, 1995). The age of the Nayfa Formation is between Late Tithonian to the Berriasian (Lowermost Cretaceous) (Beydoun et al., 1998). The Nayfa Formation is of similar facies throughout, in both coastal and inland-sections, and represents the northward spread of open-sea conditions, At other salt domes the Nayfa Formation has been removed by erosion (Powers, Ramirez, Redmond, & Elberg, 1966). The Nayfa Formation can be considered as a potential source interval for post rift reservoir(Almatary, 2006).

SA'AR FORMATION

This deposit conformably overlies the Nayfa Formation and is composed mainly of limestone, dolomitic limestone with some mudstone, and sandstone. Oil companies classified this formation into lower Saar carbonate and upper Sa'ar clastic(Hakimi, Abdullah, & Shalaby, 2012).

Early Cretaceous syn rift carbonates and clastics of the Sa'ar Formation were deposited within the rift in eastern Yemen particularly in Qamar basin whilst thin carbonates were deposited outside the basin.(Brannan, Gerdes, & Newth, 1997).

Whereas in the central Yemen appears to have been an isolated basin in which lacustrine sediments of the Sa'ar Formation accumulated(Ziegler, 2001). Sa'ar Formation is shallow marine deposits environment due to marine transgression. TAWILAH GROUP/MAHRA GROUP

The Tawilah Group is predominantly clastic with lenses of marl and limestone thickening eastward,

whereas the Mahra Group is mainly a limestone-marl facies with sandstone intercalations(Brannan et al., 1997)(Powers et al., 1966). In the Northern part of Yemen, this group was described as Cretaceous Sandstone Series by Little (1925) and as Tawilah Series by Lamare (1930). Beydoun (1964) gave it a group rank. The original type section of Lamare (1930) was located in Jabal Al-Tawilah, about 50 km northwest of Sana'a City. On the other hand, in the southern Yemen, three reference sections were selected. The first section (492m) was measured at Jabal Al Rays (near Al-Mukalla City) where it was subdivided into three formations: Qishn, Harshiyat, and Mukalla. The second

section was measured (675m) at Jabal Billum and it was divided into Qishn Formation and Harshiyat–Mukalla sequence. The third reference section was measured (+700 m) at Jabal Suqayma and it was difficult to recognize any formation in this sequence. The group consists mainly of sandstone with some intercalations of siltstone, marl, shale, and red sandstone. The reddish color may be due to the occurrence of iron oxides. This is Hauterivian to Maastrichtian in age according to Beydoun et al. (1998).
The Tawilah Group comprises mainly sandstones with minor mudstones. The sandstones contain plant roots and exhibit cross-bedding and ripple marks. Some beds contain a marginal marine fauna but most of the unit was deposited in fluvial or Aeolian conditions(Brannan et al., 1999).

Table 2: Simplified Formations Age of Cretaceous Groups throughout Yemen Modified after (Powers et al., 1966)

<table>
<tr><th rowspan="2">Age</th><th colspan="4">Southern Yemen</th><th colspan="2">Northern Yemen</th></tr>
<tr><th colspan="2">Western Province</th><th colspan="2">Eastern Province</th><th rowspan="6">Tawilah Group</th><th rowspan="4">Majzir Formation</th></tr>
<tr><td rowspan="2">Senonian (probably Campanian Maastrichtian)</td><td rowspan="5">Tawilah Group</td><td rowspan="2">Mukalla Formation</td><td rowspan="5">Mahra Group</td><td>Sharwayn Formation</td></tr>
<tr><td>Dabut</td></tr>
<tr><td rowspan="2">Cenomanian to Albian (probably including some Turonian)</td><td rowspan="2">Harshiyat Formation</td><td>Mukalla Formation</td></tr>
<tr><td>Fartaq Formation</td><td rowspan="2">Ghiras Formation</td></tr>
<tr><td>Aptian-Barremian</td><td>Qishn Formation</td><td>Harshiyat Formation</td></tr>
</table>

The outcropping Cretaceous System in Yemen consists of continental and marine clastics and carbonates which are distributed in three main lithofacies: continental facies, transitional facies, and marine facies, (Fig. 5). These are included within the Tawilah Formation in the northern provinces, and the Mahra Group in the southern provinces

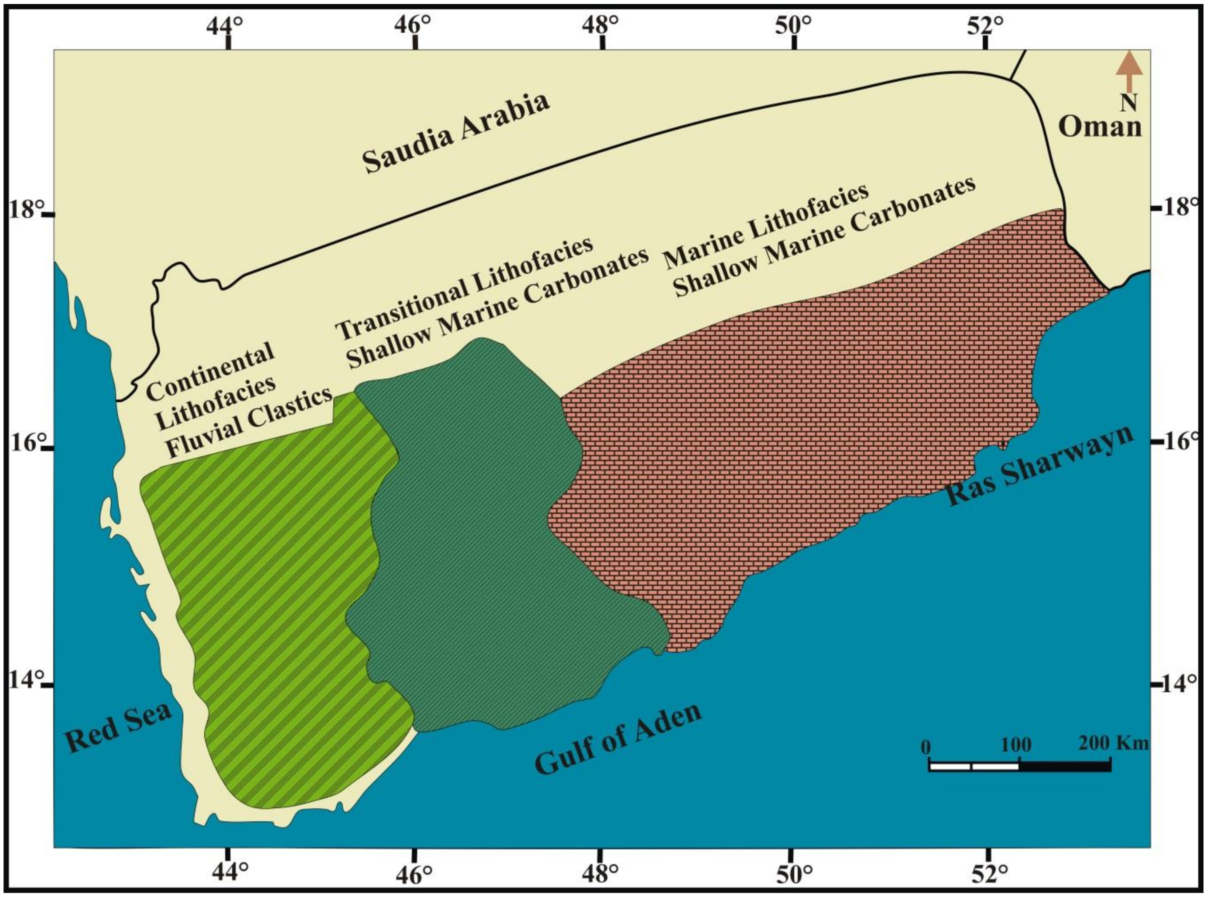

Fig. 7: Distribution of the Cretaceous rocks and its divisions into Depositional Model .(Modifiedafter El-Nakhal (2001).

The shallow marine conditions which existed over the whole of Yemen in the late Jurassic were terminated by a regression possibly early cretaceous in the western part of Yemen, whereas shallow marine conditions persisted in eastern Yemen (Beydoun, 1966). This regression was accompanied by an influx of medium and coarse clastic which accumulated in the northern Yemen to form Tawilah Group. Paleocurrent data and facies distributions in the Tawilah group deposits indicate that the sandstones which dominate the group in western Yemen were deposited by rivers flowing from east or northeast.

QISHN FORMATION

This is the lowest formation for the Mahra Group. The Qishn Formation was introduced by Wetzel and Morton in an unpublished report prepared in 1948 (cited in Beydoun, 1964, 1966, Beydoun and Greenwood, 1968). Its type section lies in the Mahra at Ras Sharwayn, near Qishn. A reference section for this formation in the western regions was designated at Jabal Rays near Al Mukalla, (Beydoun, 1964, 1966, Beydoun and Greenwood, 1968, Beydoun et al., 1993). At its type section, the Qishn Formation consists of 411m of fossiliferous limestone with marl interbeds. In the western regions, the reference section of the present formation attains a thickness of about 32m. The sequence includes a basal conglomeratic sandstone this is followed by marl and fossiliferous, sandy, shaly, massive to well bedded limestone. Its lower contact with the Precambrian basement or with the Upper Jurassic rocks is unconformable, whereas its upper contact with the Harshiyat Formation is conformable.

The Qishn Formation crops out in several localities along the coastal regions of the southern provinces. It was also detected in the subsurface of both the offshore and onshore areas of the southern provinces where it reflects the same characteristics of the formation in the outcrop (Beydoun et al., 1993). However, Beydoun et al. (1993) pointed out that in the subsurface of Wadi Hadhramaut area, the Qishn Formation sand development was much greater and thicker than anticipated in an interval previously thought most likely to be dominated by carbonates and shale.

HARSHIYAT FORMATION

The Harshiyat Formation is represented in both the eastern and western parts of the southern provinces of Yemen. It was suggested by Wetezel And Morton in 1948, in an unpublished report (Beydoun, 1964, 1966). Its type section lies in the western parts in Hadramawt, at Jabal Al Rays. A reference section for the Harshiyat Formation in the eastern parts was designated in Mahra and Masila, Tihayr area. In its type area the present rock unit consists of 293m of fine to coarse, ferruginous, calcareous, friable to hard, well bedded to massive, current-bedded sandstones with siltstone, shale, marl, dolomitic limestone, and recrystallized, fossiliferous limestone interbeds. This sequence of clastics contains two persistent limestone or dolomitic limestone interbeds, the lower of which constitutes the Rays Member, whereas the upper constitutes the Sufla Member. Both members pinch out westwards. The reference section of the Harshiyat Formation in the eastern parts in Wadi Masila, consists of 195m of green, purple, brown, fossiliferous shale, and varicolored, partly calcareous, fine- to medium-grained, current-bedded, fossiliferous sandstone with marl and shale interbeds. This formation extends conformably between the underlying Qishn Formation, and the overlying Mukalla Formation. In its upper parts, the present rock unit bears numerous fossils and on paleontological and stratigraphical grounds it was dated as Albian-Cenomanian.

FARTAQ FORMATION

The occurrence of the Fartaq Formation is restricted to the eastern regions of the southern provinces. It is a limestone-marl lateral equivalent of the upper horizons of the Harshiyat clastics of the western regions. This rock unit was introduced by Wetzel and Morton in an unpublished report prepared in 1948 (Beydoun, 1964, Beydoun and Greenwood, 1968). Its stratotype lies at Ras Fartaq, Mahra (lat. 15° 59' N, long. 52° 09' E), where it consists of 510m of fossiliferous limestone and marl with a basal shale bed. This formation is conformably underlain by the Qishn Formation, and overlain by the Mukalla Formation. The Fartaq Formation has yielded a rich assemblage of fossils which dates it as Albian to Cenomanian, to probable Turonian. In Wadi Masila, the Fartaq Formation attains a thickness of 206m which represents the upper part of the type section. In this locality, the formation is divisible into three distinct units which were treated as members. These are, in ascending order, the DhaSohis, Tihayr, and Maqrat Members.

MUKALLA FORMATION

The Mukalla Formation is recognized in both the western and eastern parts of the southern provinces. It is the only formation which persists in the two parts without significant changes in the lithic characteristics. The Mukalla Formation was introduced by Wetzel and Morton in an unpublished report prepared in 1948, to include the clastic sequence directly underlying the Tertiary rocks in Hadramawt. The stratotype lies in the western parts, in Mukalla, at Jabal Al-Rays (lat. 14° 35' N, long. 49° 08 E),. The stratotype consists of 165m of colored, fine- to coarse-pebbly, current-bedded, friable to hard sandstones with marl and siltstone interbeds. The current-bedded sandstones represent fluvio-deltaic sediments which are barren of marine fossils. In the AthThil'ah as Sufla, this formation includes a thin fossiliferous limestone bed underlain by a sequence of marls, and these form the Lusb Member. The Mukalla Formation thickens westwards. It conformably overlies the Harshiyat Formation and unconformaly underlies the Umm err Radhuma Formation. The middle part of this formation bears an assemblage of Campanian fossils. On stratigraphical and paleontological evidence it was considered to be of Senonian, probably Campanian to Maastrichtian age.

DABUT FORMATION

The DabutFormation encountered only in subsurface. This formation consists of a mixed package of' carbonates and clastics. The lower part is dominated by fine grained grey to white limestones with minor grey shales. The upper part comprises grey, medium to fine grained well sorted sandstones, grey shales and claystones, with minor siltstones and limestones. The age range of the formation is Early Campanian to Early Maastrichtian. The formation is entirely marine in the offshore wells but some paralic clastics occur at the top of the unit in onshore wells 16/U-1 and Wadi Jeza 1.(Brannan et al., 1997).

SHARWAYN FORMATION

The Sharwayn Formation is the top formation of the Mahra Group in the eastern parts of the southern provinces. The formation grades westwards from limestone, through marl and limestone, to marl, sequence. It was described in an unpublished report by Wetzel and Morton in 1948, and amended by Beydoun (1964). Its stratotype lies in Mahra, at Ras Sharwayn, where it consists of 66m of fossiliferous, yellow brown to olive green, soft marl, and shale with harder calcareous concretions, overlain by fossiliferous marly, crystalline, locally nodular, gray, hard limestone. It is conformably underlain by the Mukalla Formation, and overlain by the Umm ERR Radhuma Formation with probable disconformity. The formation has yielded numerous fossils which date it as Maastrichtian.

In the northwestern part of Yemen, the Tawilah group can be divided into two mappableunit, Ghiras Formation for the lower unit and Majzir Formation for the upper unit.

GHIRAS FORMATION

Ghiras Formation is coarse to medium-grained and contains matrix-supported intra-formational sandstone clasts, some mud and small quartz pebbles. Type locality of this formation is at Al-Tawilah Village, 50 km northwest of Sana'a at approximate (15° 30'N and 43° 42'E bearing). The thickness measured is around 413m. The contact with the underlying Jurassic Amran Group is either conformable or unconformable. The upper contact between Tawilah Group and the Tertiary volcanics is well exposed in this locality.

MAJZIR FORMATION

The Majzir Formation is mainly medium to fine-grained sandstone, interbedded with siltstones, some of which are brown with abundant iron concretions and other greenish-grey to brown carbonaceous rich siltstone with some iron concretions. The Majzir Formation consists of finer grained sandstones, darker brown color, more thinly beds of the lower Ghiras Formation. Burrow casts and siltstones are very common in this formation.

HADRAMAWT GROUP

At the end of Cretaceous sequence, a marine transgression flooded the most eastern Yemen (Hadramawt Group) establishing wide-spread shallow marine carbonate deposition. The Late Paleocene- Early Eocene units comprise homogeneous argillaceous, detritus carbonates and hard, compacted, massive and bedded dolomitized fossiliferous limestone (Umm Err Radhuma Formation) that changes to shallow marine carbonate rocks (Jeza Formation). Jeza deposits are widespread in the Middle Eocene followed by the deposition of anhydrite beds (Rus Formation) and carbonate rock (Habshiyah Formation), (Hakimi & Abdullah, 2014). Whereas the western Yemen highlands were dominated by volcanic activity (Beydoun and Greenwood, 1968).

This formation was described as "Eocene" by Little (1925) and as a part of Hadramawt Group by von Wissmann et al. (1942). Sander (1952) was the first author that described it as Umm Err Radhuma Formation in Wadi al Batin, Saudia Arabia. The reference section in Yemen is a cliff face east Say'un, Wadi Hadramawt (Beydoun et al. 1998). The main lithology of Umm Err Radhuma Formation in the reference section is gray to cream limestones, partly silicified in the upper part, while its lower part is chalky limestones with hard dolomitized limestones. Also, it is noted that no well-preserved fossils are observed in the outcrops, although drilled wells contain intervals of well-preserved microfossils that played a great role in correlation with the outcrops (Beydoun et al. 1998).

UMM ERR RADHUMA FORMATION

The lowermost Umm Err Radhuma Formation of Paleocene - Lower Eocene age comprises shallow marine limestones, shales, marls and evaporites (Beydoun and Greenwood, 1968) with thicknesses that vary from 200m to 700m (Agip, 1981). In eastern Yemen, it is shallow marine limestone comprising monotonous cliff forming foraminiferalgrainstones. The basal Umm Err Radhuma Formation contains reworked Maastrichtian fossils indicating a break in sedimentation between the Cretaceous and Tertiary in the east. Beydoun (1964) reported a disconformable contact.

JEZA FORMATION

The Jeza Formation overlies the Umm Err Radhuma Formation conformably with either a gradational or a sharp contact, e.g. east Yemen. It consists of calcareous paper shales and well-bedded fine-grained limestones. To the east the sequence gives way to wakestones and calcareous mudstones (Robertson Group, 1992; Agip, 1981). Thicknesses increase to the south from approximately 50m to the northeast to less than 150m north of the Wadi Hadramawt (Robertson Group, 1992).

RUS FORMATION

The Rus Formation has gradational and conformable contacts with the underlying Jeza Formation, and comprises bedded gypsum and anhydrite with bands of chert, marl, gypsiferous chalk, dolomitic limestone and siliceous diatoms. Thicknesses are around 50m reaching 200m north of Wadi Saqhawat and less than 400m in the west Mukalla area.

HABSHIYAH FORMATION

The Habshiyah Formation, which is about 175m in thickness and overlies the Rus Formation, consists of paper shales and chalky limestone (Beydoun and Greenwood, 1968).

ASSOCIATED BASINS

Several sedimentary basins are formed due to extensional tension that related to this event. Multi-oriented basins trends formed from western Yemen to eastern Yemen. These basins are in western Yemen, Siham AD Dali' and central Yemen, the Marib-Shabwa (or Sabatayn) and Balhaf basins are oriented NW–SE (Bott et al., 1992; Brannan et al., 1997), reactivating Najd trend faults. To the east, the Sayut-al Masila, Qishn, and Jiza-Qamar basins are oriented more E–W (Redfern and Jones, 1995; Beydoun et al., 1996; Bosence, 1997).

III. SEPARATION OF ARABIA FROM AFRICA AND OPENING OF GULF OF ADEN AND RED SEA EVENT.

SHIHR GROUP

The Shihr Group is a transgressive series laid down in coastal embayments and tectonic depressions after emergence of the land surface at the end of the Eocene Epoch. The group consists of limestone, marl, shale, and gypsum, and rests on a variety of older formations. The group is not represented in the west and west north of Yemen due to high topography in this part or maybe deposited as thin beds and then eroded. The observation of Shihr Group comes from locality near Shihr costal area of Mukalla city.

The thickness of this group is variable but not less than 60m and not more than 450m. Due to uplift some small restricted basins are formed and this is reflected in varying thickness and depositional environments and this formation is considered the youngest rocks beds in eastern Yemen. The depositional environment of Shihr Group includes estuarine, continental and marine.The Shihr Group is considered early to middle Oligocene in age.

YEMEN CENOZOIC CONTINENTAL FLOOD BASALTS

The Tertiary continental Magmatism of Yemen was associated to the early opening phases of the Red Sea and the Gulf of Aden, and was part of the Afro-Arabian rift system (AARS), which included the Ethiopian Rift and the Afar Triangle during Late Eocene to recent, the geological evolution of North Africa was dominated by the development of the Red Sea-Gulf of Aden-East Africa Rift System that resulted in the separation of the Arabian plate. The opening of narrow, elongated oceanic domains along the Gulf of Aden and the Red Sea from Miocene times resulted in the separation and northwards drift of the Arabian plate, allowed by sinistral movement along the Levant-Dead Sea fault zone. Rifting initiated in the Early Oligocene in several small, en echelon E-W to ESE-WNW trending basins in the Gulf of Aden province. By the Oligocene-Miocene transition, rifting had spread to Afar and throughout the Red Sea system. The onset of continental rifting began ~22 Ma ago, and encompassed the whole length of the present-day Red Sea basin and Gulf of Aden(Bosworth et al., 2005). Strong magmatic activity predated and accompanied rift tectonics, favoring extension by weakening the lithosphere. Oceanic spreading followed advanced continental rifting about 5 Ma ago with volcanic (mainly basaltic) activity(Bosworth et al., 2005). In the late Oligocene-early Miocene to the present time, large volumes of flood basalts emplaced at discrete eruptive centers along the western margin of the Arabian plate from the Gulf of Aden to the Mediterranean. These plateau basalts are concentrated on the Arabian side of the Red Sea without matching counterparts on the Nubian plate, and represent one of the largest areas of predominantly alkali-olivine basalts in the world. In Yemen, Oligo-Miocene to Recent (pre-/syn-rift) volcanic complexes were emplaced in the western and southwestern parts. The area of this volcanism, which included Continental Flood Basalts, occupied approximately one-tenth of the total area of the country(Mattash et al., 2013), and approximately 28% of the total area of the Arabian Plate volcanic rocks(Mattash et al., 2013). The Yemen flood volcanics are characterized by: 1) large volumes of magmatic activity; 2) large-scale crustal extension; 3) mildly alkaline basalts and 4) bimodal distribution of basic and acid magma products. Volcanic products from Yemen are akin to coeval volcanic rocks from Djibouti, Ethiopia, and some parts of the Kenyan rift. This work presents a review of petrological data for the rift-related volcanic rocks of Yemen(Mattash et al., 2013)

YEMEN VOLCANIC GROUP

The Yemen volcanic group consists of two rock units, Yemen trap series (YTS) and Yemen volcanic series (YVS). The YTS forming the lower part of the Yemen volcanic group and developed through the period from the Late Oligocene to Early Miocene (31–26 Ma) related to the Afar plume that impacted the Arabia–Africa area during the Oligocene and also to the opening of the Red Sea and the Gulf of Aden. The YTS occurs in the form of lava flows and intrusions and covers an area of about 45,000 km2 of the country with maximum thickness of more than 2,500m in the western part and gradually decreases eastward to a few tens of meters thick near the contact with the basement (J.M., Khanbari Fournier and Huchon 2010).

TIHAMA GROUP

The Tihama Group consists of sediment of lower Miocene and older, overlain by upper Miocene evaporate succession with subordinate shale, limestone and sandstone in the edge. And overlain by Pliocene clastic succession topped by reef carbonates.

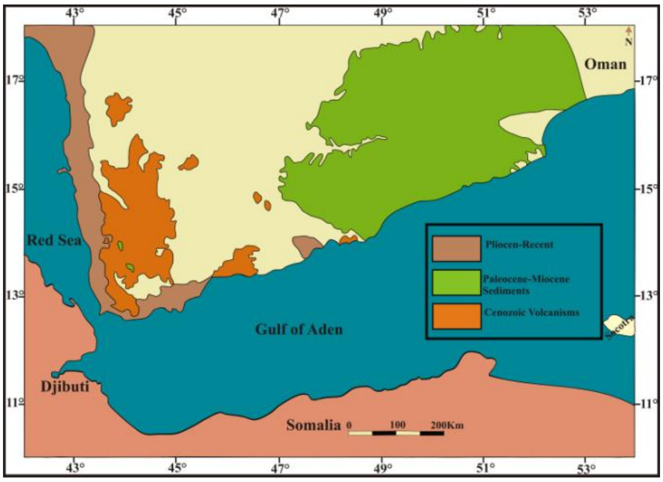

Fig. 8:Simplified geological map of outcrops of Formations Related to Opening Gulf of Aden and Red Sea.(Modified after Philippe Huchon2003).

ASSOCIATED BASINS

The Cenozoic rift basins are related to the third event, separation of Arabia from Africa by the opening of the Red Sea to the west and the Gulf of Aden to the south of Yemen during the Oligocene-Recent. These basins are filled with up to 3,000m of sediments showing both lateral and vertical facies changes. The Cenozoic rift basins along the Gulf of Aden include the Mukalla–Sayhut, the Hawrah–Ahwar and the Aden–Abyan basins (all trending ENE–WSW), and have both offshore and onshore sectors as extensional faulting and regional subsidence affected the southern margin of Yemen episodically. The Tihamah basin along the NNW–SSE trending Red Sea commenced in Late Oligocene, with oceanic crust formation in the earliest Pliocene. The Late Miocene stratigraphy of the Red Sea offshore Yemen is dominated by salt deformation.

CONCLUSION

The geology of Yemen has influenced by a complex tectonic history in the first event. It is evident from the various terranes with various origin(continental and island arc). During the second event of tectonostratigraph renewed tectonostratigraphic activity without related volcanisms activity produced various depositional environments. Transgression and regression have been the significant controlling factor for sedimentary and patterns. The huge gap hatus which is evident from the absence of some systems stratigraphy such as Triassic to upper Jurassic need extensive study to elaborated the major causes.

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