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ORIGINAL PAPER

Optimal aquifers and reservoirs for CCS and EOR in the Kingdom of Saudi Arabia: an overview

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Abstract An overview on the tectono-stratigraphic framework of the Arabian plate indicates obvious differences between two distinct areas: the hydrocarbon-prolific sector and non-hydrocarbon-prolific sector. These differences resulted from the interplay of a variety of factors; some of which are related to the paleo-geographic configuration (eustatic sea level fluctuations, climatic conditions, and salt Basins), others to differential subsidence (burial) and structural inversions. During the Paleozoic, the regional compression was caused by far field effects of the Hercynian orogeny. This led to major folded structures in central and eastern Saudi Arabia (e.g. Ghawar anticline). During the Mesozoic, the most important tectonic factor was the stretching of the crust (extension), accompanied with the increase in temperature, resulting in an increase of the accommodation space, and thicker sedimentary successions. Regional unconformities are mostly found where folded structures are dominant, and they acted as a carrier systems for the accumulation of hydrocarbon and groundwater. A good understanding of the stratigraphy and tectonic evolution is, thus, required to develop carbon capture and storage (CCS) and to design efficiently enhanced oil recovery (EOR) in both sectors. Oil and gas reservoirs offer geologic storage potential as well as the economic opportunity of better production through CO_2-EOR. The world greatest hydrocarbon reservoirs mainly consist of Jurassic carbonate rocks, and are located around the Arabian Basin (including the eastern KSA and the Arabian Gulf). The Cretaceous reservoirs, which mainly consist of calcarenite and dolomite, are located around the Gotnia salt Basin (northeast of KSA). Depleted oil and gas fields, which generally have proven as geologic traps, reservoirs and seals, are ideal sites for storage of injected CO_2. Each potential site for CO_2-EOR or CCS should be evaluated for its potential storage with respect to the containment properties, and to ensure that conditions for safe and effective long term storage are present. The secured deep underground storage of CO_2 implies appropriate geologic rock formations with suitable reservoir rocks, traps, and impermeable caprocks. Proposed targets for CCS, in the non-hydrocarbon-prolific sector, are Kharij super-aquifer (Triassic), Az-Zulfi aquifer (Middle Jurassic), Layla aquifer (Late Jurassic), and Wasia aquifer (Middle Cretaceous). Proposed targets for EOR are Safaniya oil field (Middle Cretaceous) (Safaniya, Wara and Khafji reservoirs), Manifa oil field (Las, Safaniya and Khafji reservoirs) (Late Jurassic), and Khuff reservoir (Late Permian-Early Triassic) in central to eastern KSA.

Keywords Tectono-stratigraphy · Hydrocarbon/non-hydrocarbon-prolific sectors · Paleoclimate · EOR & CCS · Arabian plate · KSA

Introduction

The Arabian plate extends from the eastern Mediterranean region to the western Zagros thrust zone, and comprises the whole Arabian Peninsula. It is enclosed by latitude 13° and 38° N and longitudinal 35° and 60° E. The

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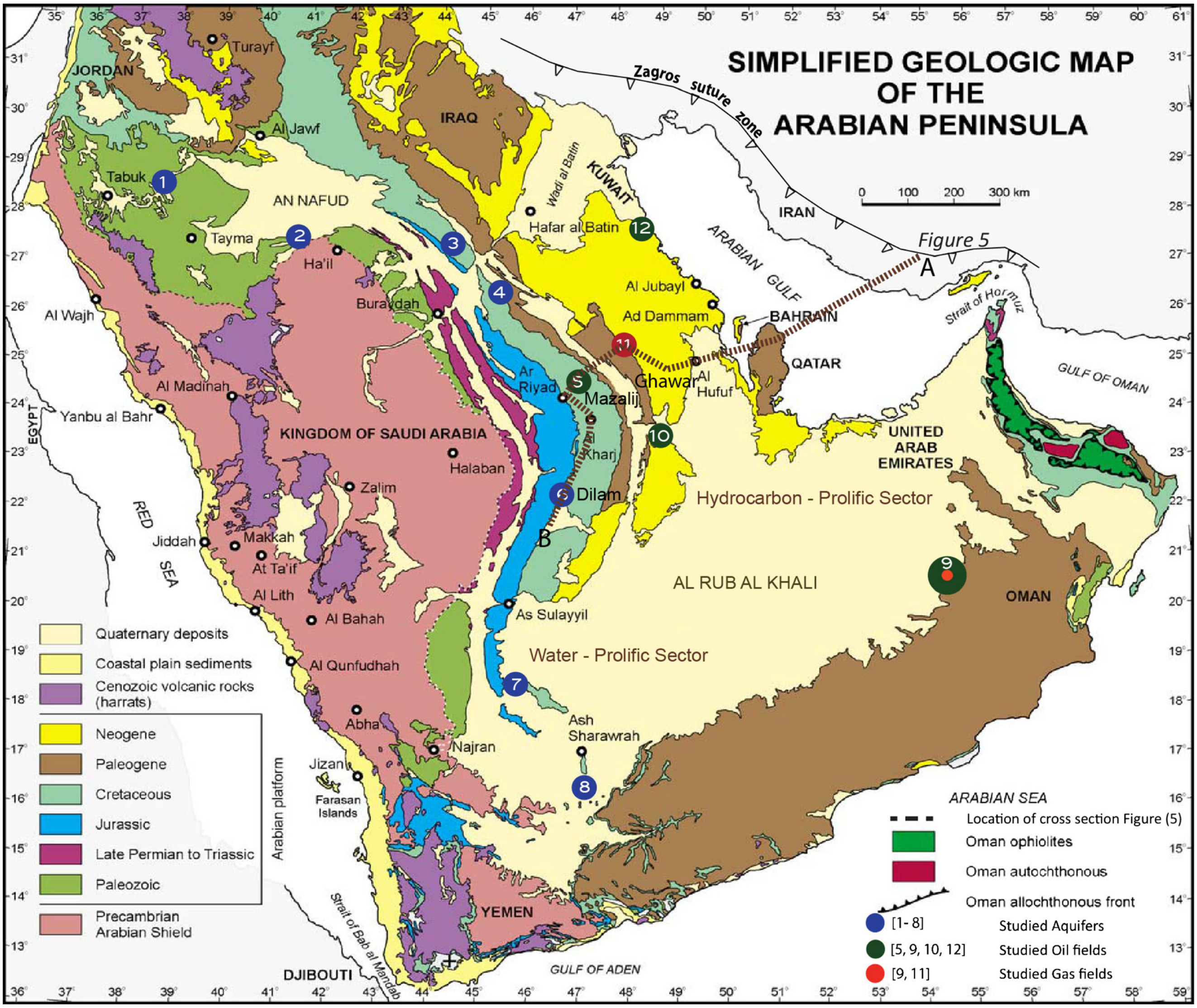


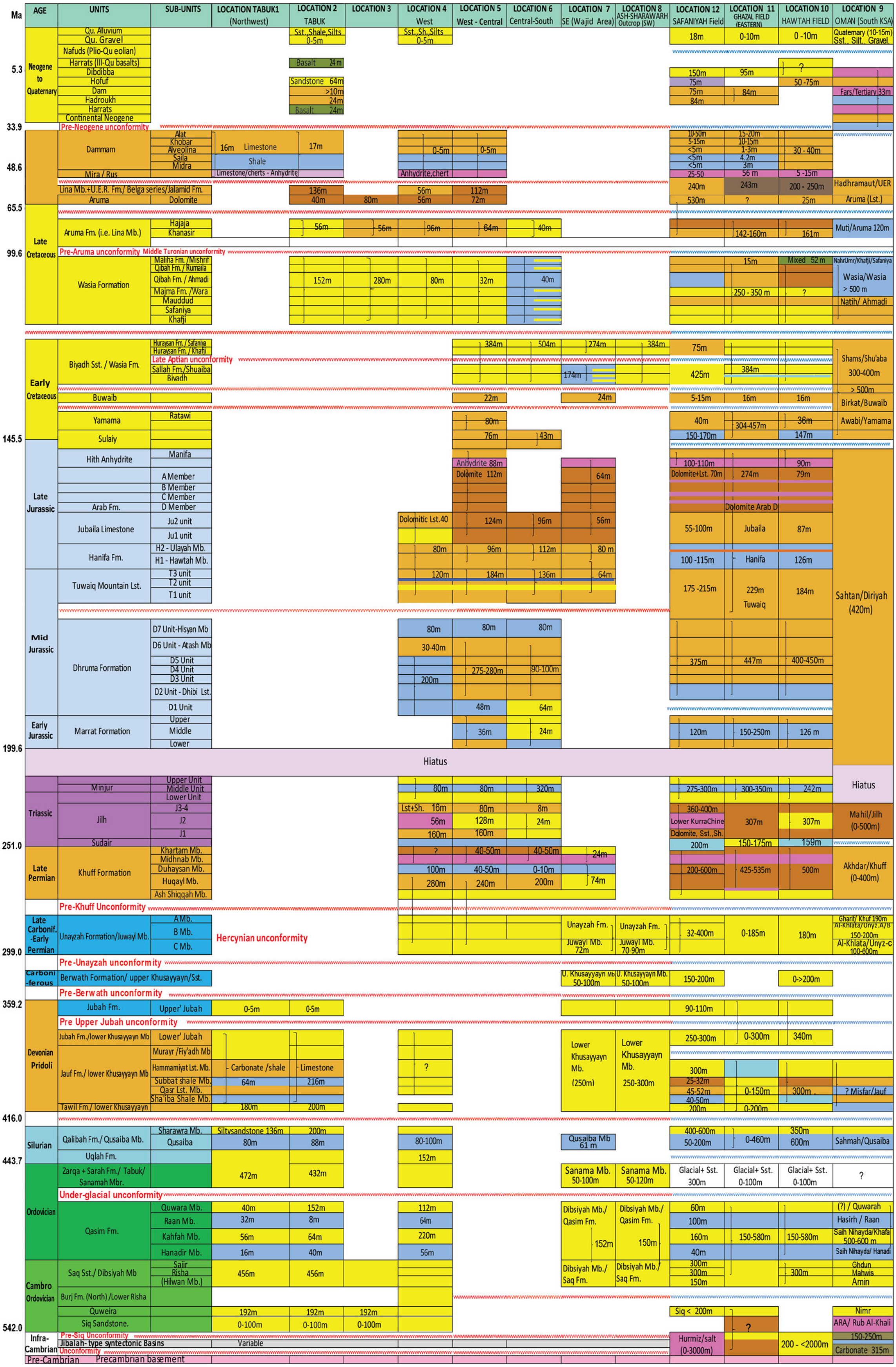
Fig. 1 Simplified geological map of the Arabian Peninsula, showing the studied hydrocarbon wells, aquifers and the regional cross section A-B of Fig. 5 location. (After Le-Nindre et al. (2003))

Arabian plate is subdivided in distinct geologic domains, i.e. the Arabian Shield in the west, the Arabian platform into the Center and the Arabian Gulf in the east. The study area covers the Kingdom of Saudi Arabia (KSA), which constitutes most of the Arabian plate (Fig. 1).

A comprehensive literature review of previous work and the general geology of the KSA were first conducted. It covered issues related on the geodynamics, tectonics, stratigraphy, paleoclimate, sea-level variations, hydrogeology, hydrostratigraphy, petroleum systems, and petro-physical properties of the rock formations, [i.e., Powers et al., 1966; Beydoun, 1991; Cole et al., 1994; Stump and Van Der Eem, 1995; Al-Sharhan and Narin, 1997; Al-Aswad and Al-Bassam, 1997; Al-Bassam et al., 2000; Sharland et al., 2001; Zeigler, 2001; Le-Nindre et al., 2003; Pollastro, 2003; Haq and Al-Qahtani, 2005; Bell and Spaak, 2007; and Rahman and Khondaker, 2012].

In order to summarize and analyze the vast wealth of available information, 12 synthetic lithostratigraphic columns were compiled representing the main oil productive and non-oil productive sectors (Fig. 2). Eight sites are located between the Tabuk area in the northwest and Ash-Sharawarh in the southwest across Wajid area (Figs. 1 and 2). The four other

Fig. 2 Twelve synthetic lithostratigraphic columns, representative of the main hydrocarbon productive and non-hydrocarbon productive sectors in the Arabian plate. The main unconformities in both sectors are illustrated. (Data compiled from [Morton, 1959; Powers et al., 1966; McClure, 1978; Murris, 1980; Wilson, 1981; Bazanti, 1988; Cole et al., 1994; Stump and Van Der Eem, 1995; Al-Sharhan and Narin, 1995, 1997; Cagatay, et al., 1996; Oterdoom et al., 1999; Jones and Stump, 1999; Al-Shayea, 2000; Pollastro, 2003 and Al-Ramadan et al., 2004]) ▶


Ma
AGE
UNITS
SUB-UNITS
LOCATION TABUK1 (Northwest)
LOCATION 2 TABUK
LOCATION 3
LOCATION 4 West
LOCATION 5 West - Central
LOCATION 6 Central-South
LOCATION 7 SE (Wajid Area)
LOCATION 8 ASH-SHARAWARH Outcrop (SW)
LOCATION 12 SAFANIYAH Field
LOCATION 11 GHAZAL FIELD (EASTERN)
LOCATION 10 HAWTAH FIELD
LOCATION 9 OMAN (South KSA)
5.3
33.9
48.6
65.5
99.6
145.5
199.6
251.0
299.0
359.2
416.0
443.7
542.0
Neogene to Quaternary
Late Cretaceous
Early Cretaceous
Late Jurassic
Mid Jurassic
Early Jurassic
Triassic
Late Permian
Late Carbonif.-Early Permian
Carboniferous
Devonian Pridoli
Silurian
Ordovician
Cambro Ordovician
Infra-Cambrian
Pre-Cambrian
Qu. Alluvium
Qu. Gravel
Nafuds (Plio-Qu eolian)
Harrats (III-Qu basalts)
Dibdibba
Hofuf
Dam
Hadroukh
Harrats
Continental Neogene
Pre-Neogene unconformity
Dammam
Alat
Khobar
Alveolina
Saila
Midra
Mira / Rus
Lina Mb.+U.E.R. Fm./ Belga series/Jalamid Fm.
Aruma
Dolomite
Aruma Fm. (i.e. Lina Mb.)
Hajaja
Khanasir
Pre-Aruma unconformity Middle Turonian unconformity
Wasia Formation
Maliha Fm. /Mishrif
Qibah Fm. / Rumaila
Qibah Fm. / Ahmadi
Majma Fm. /Wara
Mauddud
Safaniya
Khafji
Biyadh Sst. / Wasia Fm.
Hurayan Fm. / Safaniya
Hurayan Fm. / Khafji
Late Aptian unconformity
Sallah Fm./Shuaiba
Biyadh
Buwaib
Yamama
Ratawi
Sulaiy
Hith Anhydrite
Manifa
Arab Fm.
A Member
B Member
C Member
D Member
Jubaila Limestone
Ju2 unit
Ju1 unit
Hanifa Fm.
H2 - Ulayah Mb.
H1 - Hawtah Mb.
Tuwaiq Mountain Lst.
T3 unit
T2 unit
T1 unit
Dhruma Formation
D7 Unit-Hisyan Mb
D6 Unit - Atash Mb
D5 Unit
D4 Unit
D3 Unit
D2 Unit - Dhibi Lst.
D1 Unit
Marrat Formation
Upper
Middle
Lower
Hiatus
Minjur
Upper Unit
Middle Unit
Lower Unit
Jilh
J3-4
J2
J1
Sudair
Khuff Formation
Khartam Mb.
Midhnab Mb.
Duhaysan Mb.
Huqayl Mb.
Ash Shiqqah Mb.
Pre-Khuff Unconformity
Unayzah Formation/Juwayl Mb.
A Mb.
B Mb.
C Mb.
Hercynian unconformity
Pre-Unayzah unconformity
Berwath Formation/ upper Khusayyayn/Sst.
Pre-Berwath unconformity
Jubah Fm.
Upper' Jubah
Pre Upper Jubah unconformity
Jubah Fm./lower Khusayyayn Mb
Lower' Jubah
Jauf Fm./ lower Khusayyayn Mb
Murayr /Fiy'adh Mb
Hammamiyat Lst. Mb.
Subbat shale Mb.
Qasr Lst. Mb.
Sha'iba Shale Mb.
Tawil Fm./ lower Khusayyayn
Qalibah Fm./ Qusaiba Mb.
Sharawra Mb.
Qusaiba
Uqlah Fm.
Zarqa + Sarah Fm./ Tabuk/ Sanamah Mbr.
Under-glacial unconformity
Qasim Fm.
Quwara Mb.
Raan Mb.
Kahfah Mb.
Hanadir Mb.
Saq Sst./ Dibsiyah Mb
Sajir
Risha
(Hilwan Mb.)
Burj Fm. (North) /Lower Risha
Quweira
Siq Sandstone.
Pre-Siq Unconformity
Jibalah- type syntectonic Basins
Unconformity
Precambrian basement
Variable
Sst.,Shale,Silts 0-5m
Basalt 24m
Sandstone 64m
Limestone
Shale
Limestone/cherts - Anhydrite
Anhydrite,chert
Carbonate /shale
Limestone
Siltysandstone 136m
Unayzah Fm.
Juwayl Mb.
U. Khusayyayn Mb
Lower Khusayyayn Mb.
Qusaiba Mb 61 m
Sanama Mb.
Dibsiyah Mb./ Qasim Fm.
Dibsiyah Mb./ Saq Fm.
Glacial+ Sst.
Hurmiz/salt (0-3000m)
Quaternary (10-15m) Sst., Silt, Gravel
Fars/Tertiary 33m
Hadhramaut/UER
Aruma (Lst.)
Muti/Aruma 120m
Nahr Umr/Khafji/Safaniya
Wasia/Wasia > 500 m
Natih/ Ahmadi
Shams/Shu'aiba 300-400m
> 500m
Birkat/Buwaib
Awabi/Yamama
Sahtan/Diriyah (420m)
Mahil/Jilh (0-500m)
Akhdar/Khuff (0-400m)
Gharif/ Khuf 190m
Al-Khlata/Unyz-A/B 150-200m
Al-Khlata/Unyz-C 100-600m
? Misfar/Jauf
Sahmah/Qusaiba
(?) / Quwarah
Hasirh / Raan
Saih Nihayda/Khafaj 500-600 m
Saih Nihayda/ Hanadi
Ghdun
Mahwis
Amin
Nimr
ARA/ Rub Al-Khali
Carbonate 315m
Dolomite Arab D
Lower KurraChine Dolomite, Sst.,Sh.
Tuwaiq
Hanifa
Jubaila

sites are located between Safaniyah in the northeast and Oman in the southeast, and include the Ghawar area (Figs. 1 and 2).

Geo-sequestration of CO_2 is burdened with systematic risks, which relates to the geological characteristics of the site, nature and efficiency of reservoirs, underlying and overlying impervious formations, and the prevailing fluid-flow regimes [Kaldi, 2008; Barkto et al., 2009; and Taglia, 2010]. Understanding the links between tectonics and stratigraphy, throughout a large, geological time-scale, is believed to help in defining such major factors (listed above) that affects the success of CO_2 underground storage and eventually, associated EOR.

First, a stratigraphical model is proposed including most of aquifers and reservoirs in the study area (i.e., the KSA). Then, we identify, in this contribution, the potential rock units suitable for long term application of CO_2 sequestration and reservoirs which could be used for enhanced oil recovery (EOR), in order to reduce anthropogenic greenhouse gases, and their effects on global climate change.

Geological setting

Based on generalized plate-scale chronostratigraphy charts, unconformities, sea level variation, climate and the paleogeographic location of the plate across geological times, the impacts of paleoclimate and tectonic activity on depositional environments and hydrocarbon evolution can be highlighted. The Paleozoic rock series have been characterized, accordingly, through two distinct cycles.

During an early Paleozoic cycle (Cambrian–Ordovician–Silurian), the Arabian plate was first located near the equatorial line in the Cambrian time, resulting in a relatively warmer climate, and an increase in the accommodation space due to induced sea level variation. This coincided with rifting, extension, at the northern Gondwana margin [Konert et al., 2001] (Fig. 3). In the Ordovician, the Arabian plate drifted toward the south latitudes and that coincided with several tectonic pulses. Consequently, collision tectonics led to major uplifts (e.g., Oman), and affected considerably sedimentary and facies patterns [Oterdoom et al., 1999; Al-Jallal and Al-Sharhan, 2005] (Fig. 4). The Arabian plate continuously moved toward the South Pole until it reached the latitude of 55° [Konert et al., 2001]. Here, the paleoclimate witnessed an expansion of major continental ice sheets in Ashgillian time, and the effects of late Ordovician glaciations [El-Ghali, 2005], which reached eastward, from Jordan through western Saudi Arabia [McClure, 1978]. This remained until the Silurian, when the whole plate returned to the equatorial line. It was accompanied with the increase in temperature, resulting in deglaciation and sea level rise, consequently source rock (hot shale) deposited in anoxic conditions [McClure, 1978].

The late Paleozoic cycle (Carboniferous–Permian–Early Triassic), started with a remarkable event of erosion and non-deposition driven by the propagation of far field compressional stresses through the area, the “Hercynian event.” The Arabian plate moved again toward the South Pole and the paleoclimate started to control the plate-scale depositional processes. Glaciations spanned the Late Carboniferous and ended with return to the equatorial line associated with increased temperatures in the late Permian-early Triassic, coincident with slab pull in the south-facing subduction zone [Konert et al., 2001] (Fig. 3).

Throughout the Mesozoic, the stratigraphic architectures and geometries confined within the Arab Basin, resulted from the sea level fluctuations, due to the effects of eustatic changes or relative uplift and subsidence in the vicinity of the Arabian Arch. Besides, the petroleum systems within this Basin (and the hydrocarbon-prolific sector) are pretty much influenced by such stratigraphic configuration. During the middle Jurassic to early Cretaceous times, the axial zone of the Arabian plate underwent subsidence in both prolific and non-prolific sectors, leading to sea level rise and marine sedimentation covering large areas of the Arabian plate (Fig. 4).

From early to middle Cretaceous, continuous subsidence in the Arabian arch occurred in the hydrocarbon-prolific sector, whereas the Arabian Arch was reactivated and uplifted toward the west in the non-prolific sector. This led to a local sea level fall and deposition of siliciclastic (marine and non-marine series) (Figs. 2 and 4).

Accordingly, there are obvious differences in the tectonic evolution between prolific and non-prolific areas, which could be illustrated through the presence of distinct structural features. In the prolific area (eastern margin of the Arabian Gulf), there are wide spreading of faults due to extension and subsidence, whereas in the western part, uplift structure are dominant and that can be observed by the difference in topography between these two areas. In addition, the thicknesses of the sediments may reflect the related tectonic events, which increase toward the eastern part of Saudi Arabia, and that could be due to the continuing subsidence and deposition, mostly without breaks and evidenced by a decrease of the number of unconformities, whereas in the western part, most of the geological rock formations are thinner, with relatively high amount of unconformities (Figs. 2 and 5).

Water dominant sector (non-hydrocarbon prolific area)

In the eastern part of Saudi Arabia, where hydrocarbon accumulations are rather lacking, aquifers are mainly Paleogene in age [Bakiewicz et al., 1982], i.e., the Umm Er Radhuma and

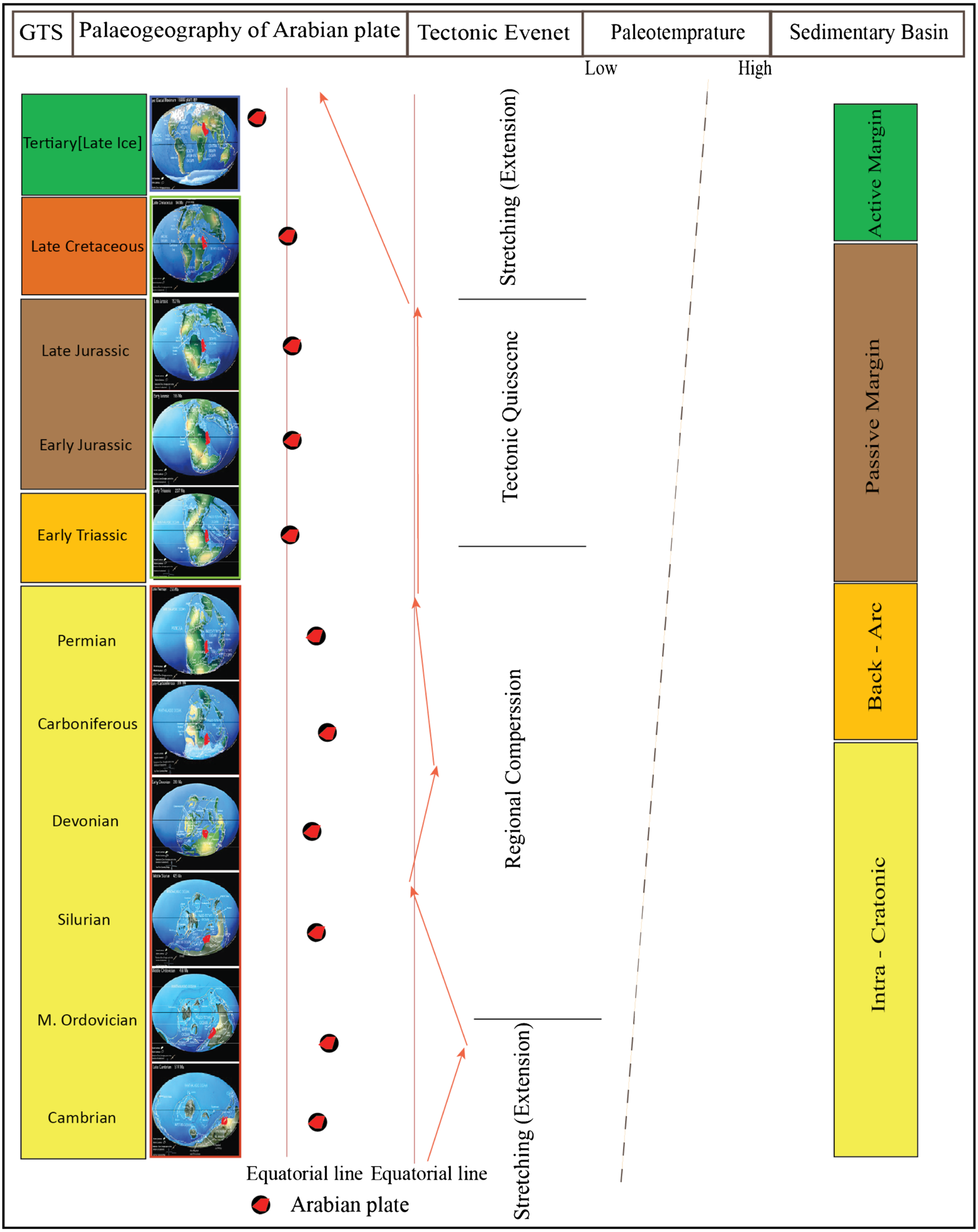


Fig. 3 Conceptual composite figure showing the tectonic drifting of the Arabian plate and Paleoclimate. (Modified from [Brown, 1972 and Scotese, 1998])

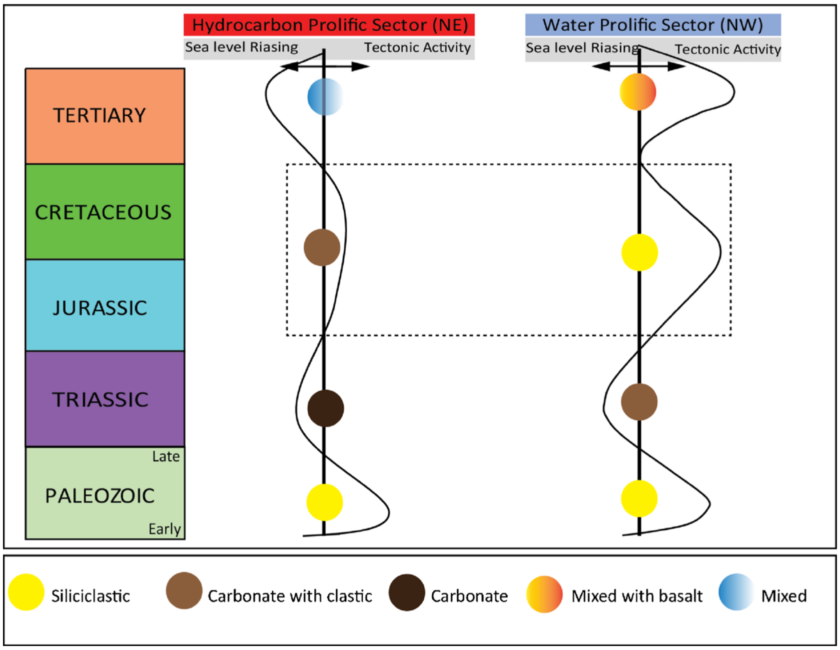


Fig. 4 Conceptual figure shows the impact of the tectonic activity and the eustatic sea level variations on the Arabian plate evolution across geological times

Dammam formations. The Rub'Al-Khali embayment province hosts also such aquifers [Edgell, 1987a]. In northwestern Saudi Arabia, the major aquifer-hosting, tectono-sedimentary Basins are the Tabuk Basin, the Wadi as Sirhan Basin, the Widyan Basin margin and the northeastern interior homocline [Edgell, 1987a, b] (cf. Figure 1).

Al-Aswad and Al-Bassam [1997] have divided the deeper Paleozoic rock series into eight basic aquifer units separated from each other by aquitards. The hydrostratigraphical units of the Mesozoic-Cenozoic in Saudi Arabia overly the Sudair mega-aquitard [Al-Bassam et al., 2000], and the classification proposed by the latter authors was based on the inherent properties of the sedimentary rocks, namely the porosity, permeability, presence of aquitard, thickness and areal extent. Accordingly, based on the combination of large amounts of hydrogeological data from previous published articles and unpublished work, we present a summarized hydrostratigraphical chart of the Arabian plate (Fig. 6).

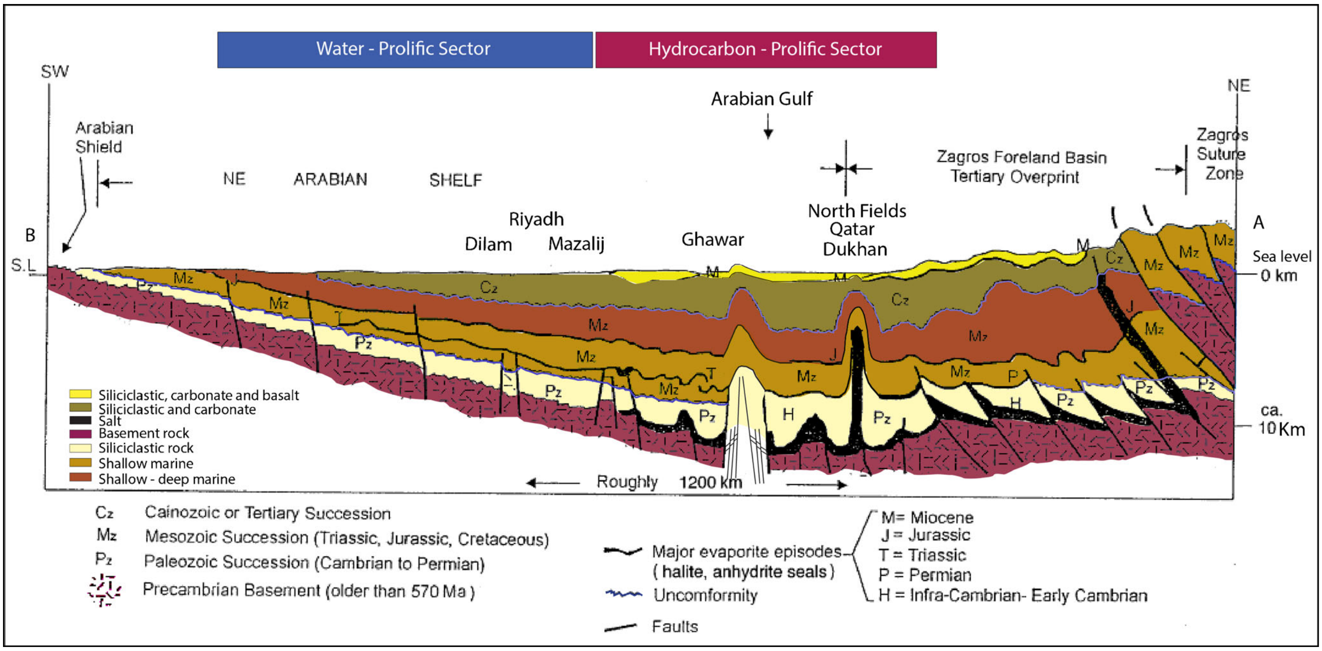


Fig. 5 Schematic section from Zagros suture zone—to Arabian Gulf—to Arabian shield. (Modified from [Beydoun, 1998 and Konert et al., 2001]). For location see Fig. 1

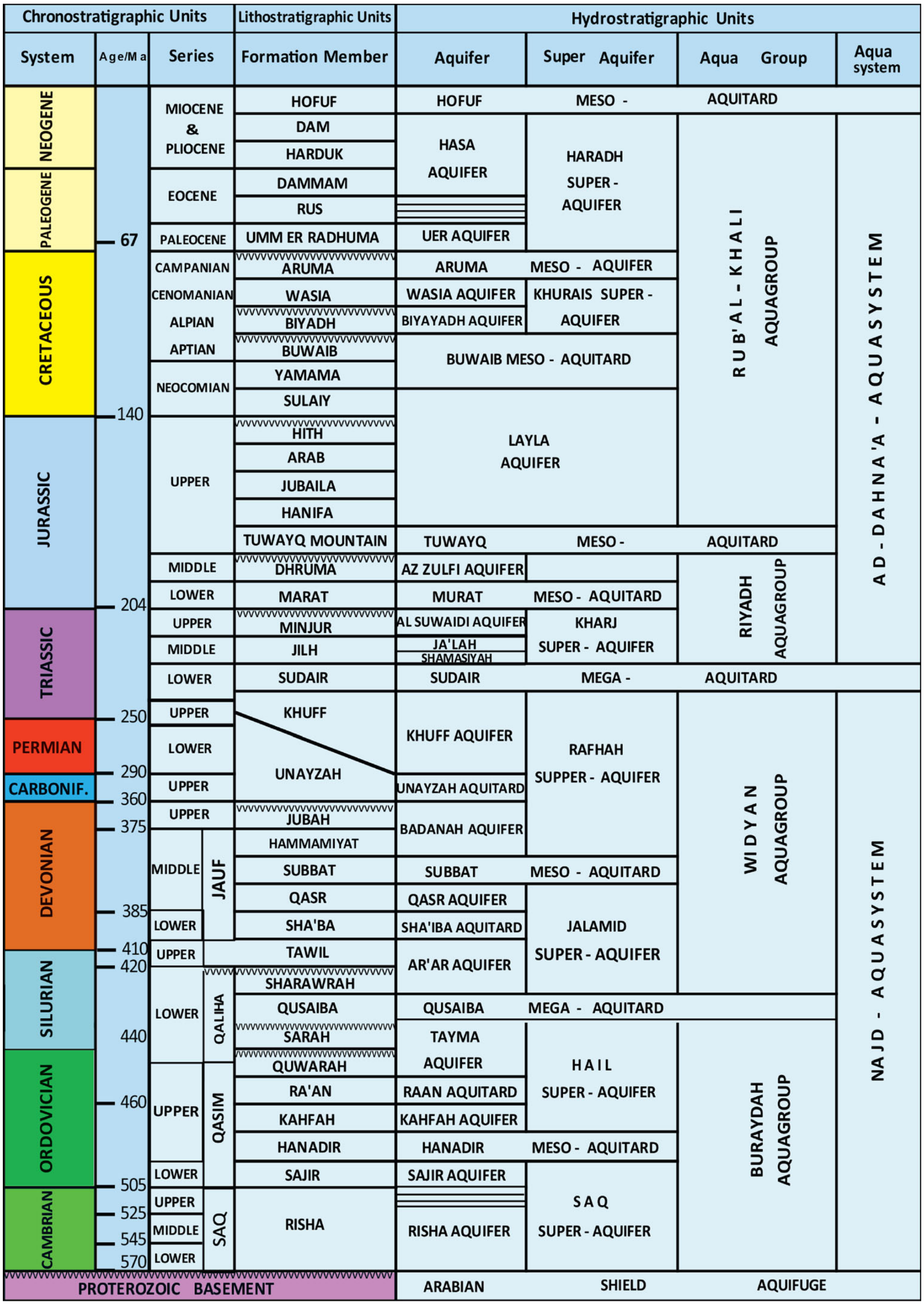


Fig. 6 The Hydrostratigraphical units of Paleozoic, Mesozoic, and Cenozoic of Saudi Arabia. (Modified from [Al-Ahmadi, 2009; Edgell 1987a, b, 1990; Al-Aswad and Al-Bassam, 1997; Al-Bassam et al., 2000; BRGM, personal communication and Ministry of Agriculture and Water, 1984])

Hydrocarbon dominant sector

The major Paleozoic reservoirs of central Arabia are sandstones of the Devonian Jauf and Permian Unayzah formations. Further to the east, in the Arabian Gulf region, the main Paleozoic reservoirs are made up of carbonates of the Upper Permian Khuff formation. Other reservoirs include clastics of pre-Qusaiba sequence that are fault-bounded and sourced laterally by down-faulted Qusaiba shale member. These reservoirs are characteristically affected by silica cementation, which decreases their flow properties [Jones and Stump, 1999].

Many of the Ordovician sandstone reservoirs are sealed by the overlying Lower Silurian Qusaiba shale. The Devonian Jauf sandstone reservoir is sealed by a very distinctive shaly unit called (D3B) in the Ghawar field [Pollastro, 2003]. The impermeable anhydrite, carbonate rocks and shale beds of the Khuff formation and/or equivalent unit, also constitute a major regional seal for the central Arabia, Qusaibah Paleozoic sequence. Basal Khuff strata form the top seal to the Permian Unayzah reservoir in Ghawar field.

Traps are mostly structural and related to basement block faulting, tectonic salt movement and deformation (halokinesis) as well as wrench faulting [Pollastro, 2003] (Fig. 7). Generally, in Saudi Arabia and Iraq, the direction of hydrocarbon migration is toward the west [Cole et al., 1994] (Fig. 5).

The best and most prolific Mesozoic reservoirs occur in the Upper Jurassic Arab formation; especially Arab C and D members, where bulk rock porosity averages 25 % and permeability exceeds 100 md [Edgell, 1987a, b]. Seal units for the carbonate rock reservoirs of the major Arab formation are made up of anhydrite beds of the upper part of the Arab and Hith formations [Murris, 1980]. Other known reservoirs include the porous carbonate-rock units within the Hanifa and Tuwaiq Mountain formations [Koepnick et al., 1995]. During the middle Cretaceous, regressive sandstones, which are prolific hydrocarbon reservoirs (Wara, Safaniya, Khafji) of the Wasia group, were deposited. They are sealed by Rumailah member which consists of limestone, and Ahmadi member which consists of shale of the Wasia formation.

Long term CO_2 sequestration

The major factors that are believed to influence the sequestration of CO_2 as (CCS) in aquifers are: lithology, storage coefficient, transmissivity, porosity, permeability, thickness, depth, TDS, reservoir type, and hydrostratigraphical units (Table 1). Most of these factors were documented and compiled from previously published work during this study, allowing the characterization of the best candidate aquifers with respect to geological sequestration (discussed below).

With respect to prospective geological CO_2 sequestration for EOR within producing oil/gas fields in the prolific sector, many issues should be taken into account; such as the source of CO_2, chemistry of water, hydrocarbon miscible activity, original oil in place (% OOIP), depth, dip of the layer, initial pressure, saturation pressure, fracture pressure, and temperature. CO_2 displacement processes are highly sensitive to pressure, reservoir type, wetness, heterogeneity, and oil density (API) [i.e. Barkto et al., 2009].

Climatic implications and economic perspectives

Due to continuously rising global demand for energy, the consumption of fossil fuels is expected to rise through 2035, leading to greater CO_2 emissions [International Energy Agency, 2011], CCS technology offers the opportunity to reduce emissions while maintaining a role for fossil fuels in national energy portfolios. The CCS technology has the potential to reduce CO_2 emissions from a coal or natural gas-fuelled power plant by as much as 90 % [Finkenrath, 2011]; hence, it could provide efficient means for significant reductions of CO_2 emissions.

Besides, oil produced by CO_2-EOR projects can be considered to be relatively less carbon releasing than oil produced by standard techniques [Taglia, 2010]. Consequently, whether CO_2 sequestration is applied through CCS projects into aquifers or as CO_2-EOR procedures in old producing fields, the net results are a decrease in anthropogenic greenhouse gases and a globally more economic and cleaner energy production.

Discussion

The main objectives of this study are to highlight the significance of understanding the tectono-stratigraphic and paleoclimatic evolutions on selecting sites for carbon capture and storage (CCS), and to provide a first-hand inventory of potential targets for CCS and CO_2-EOR in the Kingdom of Saudi Arabia (KSA). The KSA possesses mature oil and gas fields, which have trapped hydrocarbon for millions of years. They may provide excellent choices for CO_2 underground sequestration. Besides, EOR can be achieved by pumping CO_2 in some depleting reservoirs, resulting in an economic approach for improving production and decreasing greenhouse gases emissions. Still, some of the deep lying aquifers with low quality groundwater can be also used for CCS, under vast, unpopulated regions (such as the Rub' Al-Khali region).

According to a generalized geological review of the KSA, an easternmost prolific sector and an adjacent westward non-prolific sector have been defined (see above). For instance, obvious changes in thicknesses and lithologies are observed in these two sectors as Saudi Arabia was affected by far-field effects of the Hercynian orogeny.

The non-hydrocarbon-prolific sector belongs to a zone which remained tectonically stable from early Cambrian till late Ordovician. It is characterized by deposition of clastics formations [Siq, Quweria, and Saq sandstones, as well as Qasim (transgressive-regressive cycles)].

During late Ordovician, two glaciations episodes affected the Arabia plate, represented by the Zarqa and Sarah formations [McClure, 1978; Bell and Spaak, 2007].

Then, a new period of increasing temperature due to the move of the Arabian plate toward the equatorial

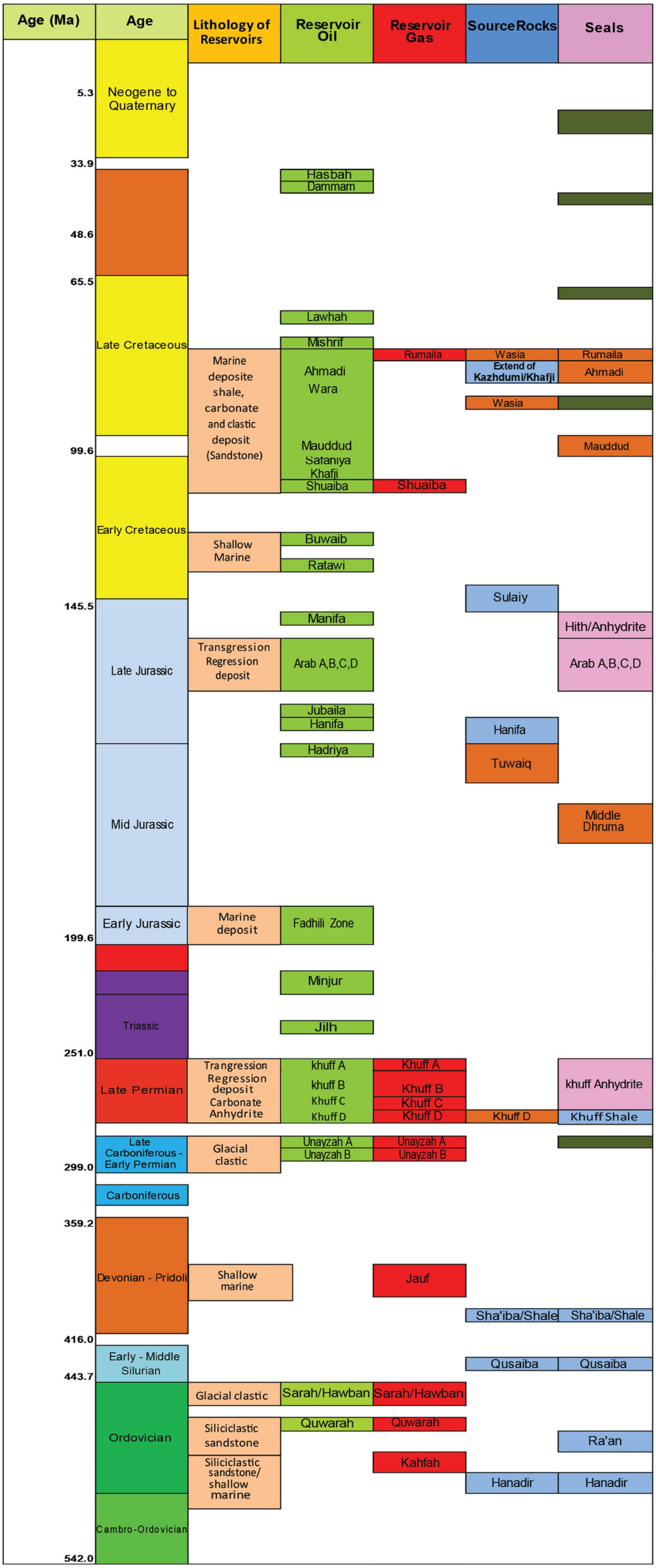


Fig. 7 Schematic representation of the major petroleum systems of the Arabian Plate. (Compiled From [Ayres et al., 1982; Benedyczak and Al-Towailib, 1984; Al-Marjeby and Nash, 1986; Al-Husseini, 1991; Abu-Ali et al., 1999; McGillivrary and Husseini, 1992; Fox and Ahlbrandt, 2002; Al-Ghamdi et al., 2008 and Arouri et al., 2009])

Table 1 Main hydrogeological units and their assessed factors (hydrostratigraphical properties) for CO_2 sequestration. (Data compiled from [*Different sources*; BRGM, personal communication; Sharaf and Hussein, 1996 and Saudi geological Survey, n.d.])

Litho-stratigraphic units	Comment	Transmissivity m^2/s	Storage coefficient	TDS mg/l	Area expolated	Source	Water quality	Porosity%	Permeability m d m/s
Harrats aquifer Hofuf meso-aquitard		15×10^{-3} (NW) 40×10^{-3} (SE)	1×10^{-2} 3×10^{-2} 2×10^{-3}	2000	Varies	Edgell, 1990			
Hasa aquifer	Haradh Super-Aquifer	1×10^{-2} to 3×10^{-6}	1×10^{-2} to 2.6×10^{-5}	1000–35.000	Hasa, Coastal Belt and Wadi MiJah	AL-BASSAM et al., 2000	Fair to good quality water		
Rus aquitard		Rus aquitard							
Umm Er Radhuma aquifer		7×10^{-5}_0.62	10^{-5} to 5×10^{-3}	900–10.000 Av.2257	Hasa Haradh	Alyamani and Atkinson, 1993	Enriched in Na^+, Ca^+, Mg^{2+}, Cl^{-1} and So_4^{-2} Mineralization increases with depth (Cl^{-1}, Na)		4×10^{-5} 1.1×10^{-2}
Aruma meso-aquitard		Aruma meso-aquitard							
Wasia aquifer Biyadh aquifer	Khurais super-aquifer	1.5×10^{-2} to 3×10^{-4}	2×10^{-2} to 3×10^{-4}	400–1550	Khrais, Wadi Dawasir and kharj		Water quality is good near the outcrop (mainly calcium and sulfate) but decreases with depth as the NaCl content increases.	10–29 % in Wadi as Sirhan Basin	In Safaniya field 0.5–2700
Buwaib meso-aquitard		Buwaib meso-aquitard							
Layla aquifer		1.6×10^{-3} to 5×10^{-3}	1×10^{-4}	720–5000	Layla Wadi Hanif & Yam am a	AL-BASSAM et al., 2000		10–29 % In Central (Hanifa) Av. 17 % in Eastern 5–30 (Av.13.25 Arab Fm. in Eastern	1.1 1–1000
Tuwaig meso-aquitard		Tuwaig meso-aquitard							
Az-Zulfi aquifer		1×10^{-2} to 1.6×10^{-2}	1×10^{-3}	2400–4850	Az-Zulfi	AL-BASSAM et al., 2000	Poor quality water		
Marrat meso-aquitard		Marrat meso-aquitard							
Al-Suwaidi aquifer Ja'lah aquifer Shamaslyah aquifer Sudair mega-aquitard	Kharj Super-Aquifer	7.2×10^{-3} 1.7×10^{-3}	1.3×10^{-4}	1000–4100	Riyad, Karj, Sudair and Washem	AL-BASSAM et al., 2000	Mineralization (Cl and Na) increasing with depth. Lower sandstone generally of poorer quality. In Riyadh area good quality		1×10^{-5} to 13×10^{-5}
Khuff aquifer	RAFHAH super aquifer	53×10^{-3} AV.(0.6×10^{-3})	0.19 0.72×10^{-4}	5000	Varies areas	BRGM, personal communication	Poor quality water	3– 20 % in North Safaniyah	500–2000
Unayzah aquitard		Unayzah aquitard						9.7–20 %	13–2498
BAdanah aquifer		8×10^{-6} to 1.7×10^{-5}	1×10^{-2}	500–1500	Varies Widyan Basin margin	Wood-Mackenzie	Moderate to good quality	30 % at depth of 4260 m	8×10^{-6} to 1.7×10^{-5}
Subbat meso-aquitard		Subbat meso-aquitard							
Qasr aquifer	Jalamid super-aquifer	$< 1.0 \times 10^{-3}$ 2×10^{-2}	2×10^{-3}	300	JAUF	BRGM, personal communication	Good quality water	2–15 %	8.5×10^{-6}
sha'iba aquitard		Sha'iba aquitar				BRGM, personal communication			
Ar'ar aquifer		0.1×10^{-3} to 23.0×10^{4}	0.01×10^{-4} to 2×10^{-4}	1000 to 500	JAUF-SAKAKAH and North AL-QASIM		Moderate to good quality	Taw il Aquifer 10–20 % in Tabuk Basin	2×10^{-5} 13×10^{-5}

Table 1 (continued)

Litho-stratigraphic units	Comment	Transmissivity m^2/s	Storage coefficient	TDS mg/l	Area expolated	Source	Water quality	Porosity%	Permeability m d m/s
Qusaiba mega-aquitard Tayma aquifer	Hail super-aquifer	Qusaiba mega-aquitard 0.6×10^{-3} to 3.5×10^{-3}	1.4×10^{-4} to 6.8×10^{-4}	1500	Various area	BRGM, personal communication AL-WATBAN (1976)			
Ra'an aquitard Kahfah aquifer		Ra'an aquitard 0.07×10^{-3} to 2.1×10^{-3}	0.8×10^{-4} to 6.7×10^{-4}		Tabuk area	BRGM, personal communication ALWATBAN (1976)		8–20 % in Tabuk Basin	7×10^{-8} 1.6×10^{-5}
Hanadir meso-aquitard Sajir aquifer Risha aquifer	Saq super-aquifer	Hanadir meso-aquitard 27×10^{-3} to 18.7×10^{-3}	0.01–0.04 1×10^{-4} to 20×10^{-4}	420–630 (NW) (Tabuk area) 300–1000 various areas	Various areas	BRGM, personal communication	Fresh water and safe for irrigation chloride and sulfate are the dominant anions calcium and sodium are the dominant cations	10–25 %	13×10^{-5}(Saq vicinity) 6×10^{-4} to 9.0×10^{-6} (Al-Qasim An) 3.5×10^{-4} to 9.0×10^{-6} (Tabuk area)

position (Fig. 3). The deposition of the Tawil formation during early Devonian consists of continental clastic sandstone, and middle-late Devonian is recorded by the Jauf formation which consists of carbonate and shale. It was then followed by the late Devonian Jubah formation [Jones and Stump, 1999] (Fig. 2).

Paleozoic carbonate rocks are rare, and in general sandstone is the dominant lithology in the rock formations toward the south (Rub'Al-Khali region). The thicknesses of the Paleozoic formations are almost twice larger in the hydrocarbon-prolific sector (compared to those in the non-prolific sector), which matches with the general northeastward trend of thickening and tilting [Beydoun, 1991, 1998] (Fig. 5). During the Permian, the northern and eastern margins of the plate were affected by rifting (inducing a rise of the asthenosphere) as well as a general increase in surface temperature caused by warmer climatic conditions [Murris, 1980, and Konert et al., 2001]. By mid-Permian time, an eperic carbonate platform was established. Evaporites are present in the central part of the KSA and toward the northeast. Clastic material was mainly derived from the erosion of the western hinterland, with local supplies from the east in the high Zagros [Murris, 1980].

During Early Triassic, hot arid conditions are prevailed over the whole Basin. A coeval increase in clastic influx from the western hinterland is evident. The climate became less arid and there was apparently a relative drop in sea level, caused either by eustatic lowering of the sea level or a rise of the Arabian Arch (Fig. 4). During the Jurassic, high sedimentation rates characterized the transgressive limestone deposits of the Marrat formation (Figs. 3 and 8). A gradual return to more humid climate occurred in the Early Cretaceous (Fig. 3). This led to the disappearance of evaporite from the sedimentary records. The regional sea level dropped, and ramp type deposition prevailed. Whereas the clastic influx was still limited, and restricted to the far southwestern part of Arabia. It was followed by a period of increasing clastic influx represented by the Biyadh formation, which occupied the area from the central-west to the southwestern parts of the Saudi Arabia [Powers et al., 1966]. Clastic influx restricted carbonate production. It was followed by the deposition of the Wasia formation (sandstone with shale), whereas toward the northeast (hydrocarbon-prolific sector) this formation consists mainly of transgressive carbonate and evaporite deposits (Fig. 8).

Differential sea level variations between two sectors are suggested resulting from the re-uplift of the axial zone of the Arabian Arch from early to middle Cretaceous. Hence, a local apparent sea level fall has affected this area (including most of the non-prolific

Stratigraphic Section of the (NW) Sector		
Formation	**Lithology**	**Thickness(m)**
Neogene-Quaternary	Mixed	0 -5 m
Dammam	Limestone	0 -5 m
Rus	Anhydrite	
UER	Limestone	136 m
Aruma	Limestone	40 m
Aruma	Mixed	55 m
Wasia/Sakaka	**Sandstone**	**80 m**
Jubaila	Lst.+Dolomite	40 m
Hanifa	Limestone	80 m
Tuwaiq	Limestone	120 m
Dhruma	Shale	330 m
Minijur	Sandstone	275-300 m
Jilh	Mixed	200-220 m
Sudair	Shale	176 m
Khuff	Shale	100 m
Unayzah	Limestone	120 m
Tawil	Sandstone	80 m
Qalibah Qusaibah	Shale	5-110 m
Zarqa	Tilite	152 m
Qasim	Shale + Sst.	420 m
Saq	Sandstone	550 m

Stratigraphic Section of the (NE) Sector		
Formation	**Lithology**	**Thickness (m)**
Neogene Quaternary	Mixed	200-300 m
Dammam	Limestone	50-75 m
Rus	Anhydrite	25-50 m
UER	Limestone	240 m
Aruma	Dolomite+Lst	530 m
Aruma	Lst. + Dolomite	
Wasia/ Sakaka	**Limestone**	**400-500 m**
Biyadh	Sandstone	425 m
Buwaib	Limestone	5-15 m
Yamama	Limestone	40 m
Sulaiy	Limestone	100 - 110m
Hith	Anhydrite	
Arab [A, B, C&D]	Mixed	60-70 m
Jubaila	Limestone	55-100 m
Hanifa	Shale	100 -115 m
Tuwaiq	Limestone	175-230 m
Dhruma	Limestone	375 m
Marrat	Limestone	120 m
Minijur	Sandstone	275-300 m
Jilh	Mixed	200-220 m
Sudair	Shale	Av. 200 m
Khuff	Dolomite Anhydrite	200-600 m
Unayzah	Sandstone	32-400 m
Berwath	Sandstone	150-200 m
Jubah	Sandstone	90-110 m
Tawil	Sandstone	200 m
Qalibah Qusaibah	Shale	0-600 m
Zarqa	Tilite	300 m
Qasim	Shale + Sst.	360 m
Saq	Sandstone	750 m

Fig. 8 Simplified stratigraphic sections and sea level variations representing the northwestern and northeastern sectors of the Arabian plate, respectively. (Modified from [Sharland et al., 2001; Haq and Al-Qahtani 2005])

sector) (Fig. 4). In the northeastern area, the subsidence of the Arch was continuous. It started in the middle Jurassic and spanned through middle Cretaceous times, leading to relative sea level rise. With the prevailing humid climatic conditions, different lithologies are observed for the same chronostratigraphic units in the Cretaceous, as we move from west to east across the Arabian Basin. For instance, the Wasia/Sakaka formation in the northwest are characterized by clastic sandstones deposited on a proximal shelf environment, whereas the same chronostratigraphic unit is made up of relatively deeper carbonate intrashelf facies in the northeast (Fig. 8). Furthermore, the overlying Aruma formation (Late Cretaceous) is mainly made up of sandstone in the Tabuk area (northwest of KSA), and grades laterally to carbonate rocks to the northeast, where it accumulates hydrocarbon instead of water as in the Tabuk area (Fig. 8).

The Paleozoic times are supposed to be of lower overall temperatures and higher humidity than the Mesozoic [Konert et al., 2001]. This seems to remain undifferentiated across Arabia. During the Mesozoic, slightly different paleo-climatic conditions appear to have been established in the eastern and western margins of Saudi Arabia; toward the west, temperatures seem to have been lower and a higher humidity prevailed, invoking considerable erosion and weathering.

The Paleozoic rock aquifers have relatively low TDS (mostly lower than 1500 mg/l) with lower porosity and permeability values compared to those of the Mesozoic units [Ahmed and Abderrahman, 2008; Saudi geological Survey, n.d.] (Table 1). Accordingly, the major proposed targets for CCS in the non-prolific regions are Kharij super- aquifer (Triassic), Az-Zulfi aquifer (Middle Jurassic), Layla aquifer (Late Jurassic), and lastly, the Wasia aquifer (Middle Cretaceous).

Extensive studies on the reservoirs properties in the KSA have been achieved for hydrocarbon exploration [e.g., Magara et al., 1992; Sail et al., 1998; Koepnick et al., 1995; Hussain et al., 2006; Sahin et al., 2007; Macrides, and Neves, 2008], compiled the results of these studies with the present geological assessments resulted into proposition of the best targets for EOR (i.e., Safaniya oil field (Middle Cretaceous) (Safaniya, Wara and Khafji reservoirs), Manifa oil field (Las, Safaniya and Khafji reservoirs) (Late Jurassic), and Khuff reservoir (Late Permian-Early Triassic)) in central to eastern the Kingdom of Saudi Arabia.

Unconformities across the Arabian plate constitute an important factor for CO_2 storage, because most of them act as a lateral carrier systems which allow higher circulations of fluid (water, gas, and oil). The present study has identified 12 major unconformities (Fig. 2).

Conclusions

- This study recognized hydrocarbon-prolific sector (mainly reservoirs area) in the northeastern, eastern and central parts of KSA and non-hydrocarbon-prolific sector (mainly aquifers areas) in the western parts of KSA.

- The Paleozoic rock sequences are affected by far field Hercynian orogeny. Relatively thinner rock units with clastics as dominant sediments, prevailed. The Mesozoic rock sequence is affected by extension. Relatively thicker, less unconformities, a smaller number of reservoirs, mainly carbonate sediment, and a relatively higher numbers of seals. It was a period of relative tectonic quiescence, mainly controlled by an increase of temperature and sea level rises.

- The main differences in lithology between the two sectors across the Arabian plate are driven by tectonic inversion operating in the axial part of the central Arabian Arch, which induced uplift and erosion in the western (non - hydrocarbon-prolific sector), and relative subsidence in the eastern (hydrocarbon-prolific sector). This is evidenced by the lithology variation of the Wasia formation in the two sectors.

- Proposed targets for CCS, in the non-prolific sector, are Kharij super-aquifer (Triassic), Az-Zulfi aquifer (Middle Jurassic), Layla aquifer (Late Jurassic), and Wasia aquifer (Middle Cretaceous).

- Proposed targets for EOR are Safaniya oil field (Middle Cretaceous) (Safaniya, Wara and Khafji reservoirs), Manifa oil field (Las, Safaniya and Khafji reservoirs) (Late Jurassic), and Khuff reservoir (Late Permian-Early Triassic) in central to eastern KSA.

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