Pressure and Thermal Regimes and Systems in the Sedimentary Sequence of Central and Eastern Saudi Arabia

Mohamed Al Mahmoud

Abstract

Reservoir pressure data in central and eastern Saudi Arabia reveals the presence of two normally-pressured (NPR 1 and NPR 2) and two overpressured (OPR 1 and OPR 2) regimes. The NPR 1 comprises the sequence from the Saq through the lower Jilh Formations, from outcrops to 15,000 ft below ground. The NPR 2 comprises the sequence from the upper Jilh through the Dammam Formations and extends from outcrops to 14,000 ft. The OPR 1 comprises the sequence from the Saq through the Khuff Formations at depths from 12,000 to 19,000 ft. Overpressures in the OPR1 are a result of reduced porosity and permeability, and gas generation from the Qusaiba shale. The OPR 2 comprises the lower Jilh Formation at depths between 10,000 and 13,000 ft. Compaction and/or hydrocarbon charging from the Qusaiba shale could be the reason for overpressures in the OPR 2. The NPR 1, NPR 2, and OPR 1 are divided into pressure systems by stratigraphic seals, but these are locally breached by unconformities or faults forming local anomalies. Geothermal gradients illustrate shallow and deep thermal regimes (STR and DTR) separated by a high thermal conductivity zone (HTCZ). The STR extends from land surface to 8000 ft, with low and high gradients in the up-dip and down-dip areas, respectively. The DTR extends from 10,000 to 19,000 ft, with no differences in gradients between the up-dip and down-dip areas. The HTGZ lies between 8000 and 10,000 ft, with low gradients.

Keywords

Pressure regimes • Arabian Basin • Saudi Arabia

Introduction

The subsurface fluid environments are characterized by measurable physical and chemical properties such as fluid pressures, temperatures, and chemical composition. Characterization of these properties can provide useful concepts in the exploration and development of oil, gas, and water resources. For example, characterization of fluid pressures or compositions in a sedimentary sequence leads to identifying communication and/or compartmentalization of reservoirs and aquifers which is important information for decisions related to drilling of exploration and development wells.

Oil and gas exploration, along with water well drilling in central and eastern Saudi Arabia (Fig. 1) since the 1930s, has resulted in a wealth of data on the subsurface rock and fluid properties. Fluid pressure, temperature, water salinity, hydrocarbon source rocks, reservoirs, and seals are some of the important data collected from the deep and shallow well drilling. Oil and gas wells provided data on reservoir pressures, temperatures and water salinity in both shallow and deep reservoirs. However, such data is conventionally used to characterize reservoirs at depths greater than 6000 ft and only at an oilfield scale. Data from water wells are normally used to study

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M. Al Mahmoud (✉)
Dhahran Geological Consulting, Dhahran, Saudi Arabia
e-mail: al_mahmoudmj@yahoo.com

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Fig. 1 Regional geological map of central and eastern Saudi Arabia

aquifers at regional scales. Studies of Saudi Arabian aquifers provided regional hydraulic head, salinity and water temperature maps for most of the major aquifers from ground surface to depths of about 6000 ft (MAW 1984).

The present study utilizes all available fluid and geologic data from shallow and deep wells to define and characterize the thermal and pressure regimes and systems in central and eastern Saudi Arabia for the first time. It also provides an original insight to the factors that controlled the evolution of the subsurface pressures and temperatures in central and eastern Saudi Arabia.

The subsurface fluid pressures can be characterized in terms of their distribution on the stratigraphic sequence in which they exist. The patterns of pressure distribution are commonly referred to as pressure regimes, systems, or compartments. These terms have been used inconsistently in the literature (e.g. Law and Spencer 1998; Swarbrick and Osborne 1998). In this paper, they are used as defined below:

A *pressure regime* includes a stratigraphic sequence that constitutes one fluid environment of either normal pressure or overpressure and which is **completely** separated from other regimes by a competent stratigraphic seal at the basin scale.

A *pressure system* is a subclass of the pressure regime; it includes a reservoir or group of reservoirs contained between two stratigraphic seals within a pressure regime, but these seals are locally breached and the pressure systems are locally in hydraulic communication with each other. The pressure system should have a pressure range that can be segregated in pressure/depth plots from pressure ranges for other systems in the same pressure regime.

A *pressure compartment* is a block of a single-reservoir pressure system which is characterized by one pressure/depth gradient and is separated from other blocks by a permeability barrier such as a fault or lateral change in lithofacies.

This classification of subsurface pressures is totally based on observations of the present-day pressure patterns which, likely, could have not been persistent throughout geologic time. Therefore, the classification presented here represents only the present-day status of the cumulative evolution of subsurface pressures.

The rate of increase in temperature with depth below land surface is referred to as the geothermal gradient. The global model for geothermal gradients excludes the shallow zone from land surface to an approximate depth of 100 ft where geothermal gradient is highly affected by the diurnal and seasonal changes in air temperature. Below this zone, the geothermal gradient averages 1 °C (1.8 °F) for every 100 ft (Walton 1970; Ward, 1975; Freeze and Cherry 1979; Todd 1980). This geothermal gradient could change from one area to another due to variations in subsurface heat transfer. On a global scale, the geothermal gradients evolve as a result of the flow of heat from the deep layers of the earth towards its surface. Heat is transferred from deeper layers of the earth by conduction through the rock material and by convection through the fluids contained in the rocks with the conduction being the dominant mechanism (Freeze and Cherry 1979).

The heat capacity of water is more than four times that of the average matrix component of sedimentary rocks (Deming 1994). Therefore, regional heat transfer in sedimentary basins is profoundly affected by the groundwater flow in aquifers (Majorowicz 1987). Field studies (e.g. Majorowicz and Jessop 1981; Chapman et al. 1981) and theoretical studies (e.g. Hitchon 1984; Luheshi and Jackson 1986; Person and Garven 1989) have revealed that moving fluids are capable of transferring a large amount of heat over long distances which can cause significant disturbance in the thermal regimes of sedimentary basins. The general pattern of heat distribution in sedimentary basins constituting regional aquifers is that the heat dissipates in the up streams of aquifers by the flow of relatively cold groundwater from recharge areas, and increases in the down streams of aquifers towards discharge areas (Diao et al. 2004). This pattern could be locally disturbed by cross-flow between deep and shallow aquifers. Therefore, heat may increase above normal in relatively shallow aquifers due to up-ward flow of hotter water from deep aquifers or vice versa. From this perspective, the coupling between groundwater flow and heat transfer emphasizes the significance of utilizing groundwater flow indicators such as water pressure and salinity data in defining and characterizing thermal regimes in sedimentary basins and explaining anomalies in such regimes.

Stratigraphic Setting

Lithostratigraphic Sequences

The Phanerozoic sedimentary sequence of Saudi Arabia consists of more than 25,000 ft of sandstone and carbonate rock units with subordinate shale and anhydrite ranging in age from Cambrian to Recent (Powers et al. 1966). The Paleozoic formations generally consist of siliciclastic units, whereas the Mesozoic and Cenozoic formations consist mainly of carbonate and anhydrite, with minor shale and sandstone units in the Middle Cretaceous (Fig. 2). The lithological characteristics of the Phanerozoic sequence are relatively consistent throughout central and eastern Saudi Arabia. The outcrops of the Phanerozoic rock units make curved belts flanking the eastern margin of the Arabian Shield (Fig. 1). In the subsurface, all Phanerozoic formations generally dip at 1°–2° towards the northeast, east and southeast following the Arabian Shield basement rocks' configuration.

The Paleozoic rocks consist mainly of a massive sequence of continental to shallow marine siliciclastics transgressing to carbonates (Khuff Formation) towards the Mid-Late Permian (Fig. 2). The total thickness of this sequence ranges from approximately 8000 ft in the basinal areas to about 2000 ft on the uplifted areas where significant erosion occurred (Pollastro 2003). The sandstone units have relatively high porosity and permeability on the western areas near the outcrops forming prolific regional aquifers. Towards deeper areas in the east, the porosity and permeability decrease due to compaction and further deteriorate due to quartz cement and diagenetic illite formation (Carney et al. 2002; Franks and Zwingmann 2010; Arouri et al. 2010). The Paleozoic sandstone units are the primary targets for oil in central Arabia and sweet gas in eastern and northwestern Saudi Arabia. The Paleozoic shale units generally act as regional seals for the underlying sandstone aquifers and hydrocarbon reservoirs (Fig. 2).

The Mesozoic sequence consists in its lower part of the Sudair shale and the Jilh and Minjur carbonates and sandstone. In the middle part, it consists of carbonate units with subordinate shale and anhydrite represented by the sequence from the Marrat through Buwaib Formations. In the upper part, it consists of the sandstone of the Biyadh and Wasia Formations which are capped by the carbonate of the Aruma Formation (Fig. 2). Oil and water wells drilled through the Mesozoic formations show that the carbonate and sandstone units act as regional and sub-regional aquifers and oil reservoirs, whereas the shale and anhydrite units act as regional seals.

The Cenozoic sequence consists mainly of carbonate units with subordinate marl, shale and anhydrite units (Fig. 2). The carbonate units are extremely porous and permeable forming regional prolific aquifers in eastern Saudi Arabia. They also constitute secondary oil reservoirs offshore in the Arabian Gulf. The subordinate marl, shale and anhydrite units act as regional top seals to the underlying carbonate units.

Unconformities

The sedimentary sequence of Saudi Arabia constitutes several regional unconformities of which the most significant and aerially extensive are the Pre-Unayzah, pre-Marrat, pre-Aruma, and pre-Neogene unconformities (Fig. 2). Except for the pre-Marrat unconformity, which was caused by the global marine regression of the Early Jurassic (Haq and Al-Qahtani 2005), all these major unconformities are a result of uplift and erosion during tectonic events. This uplifting had caused differential erosion of the underlying

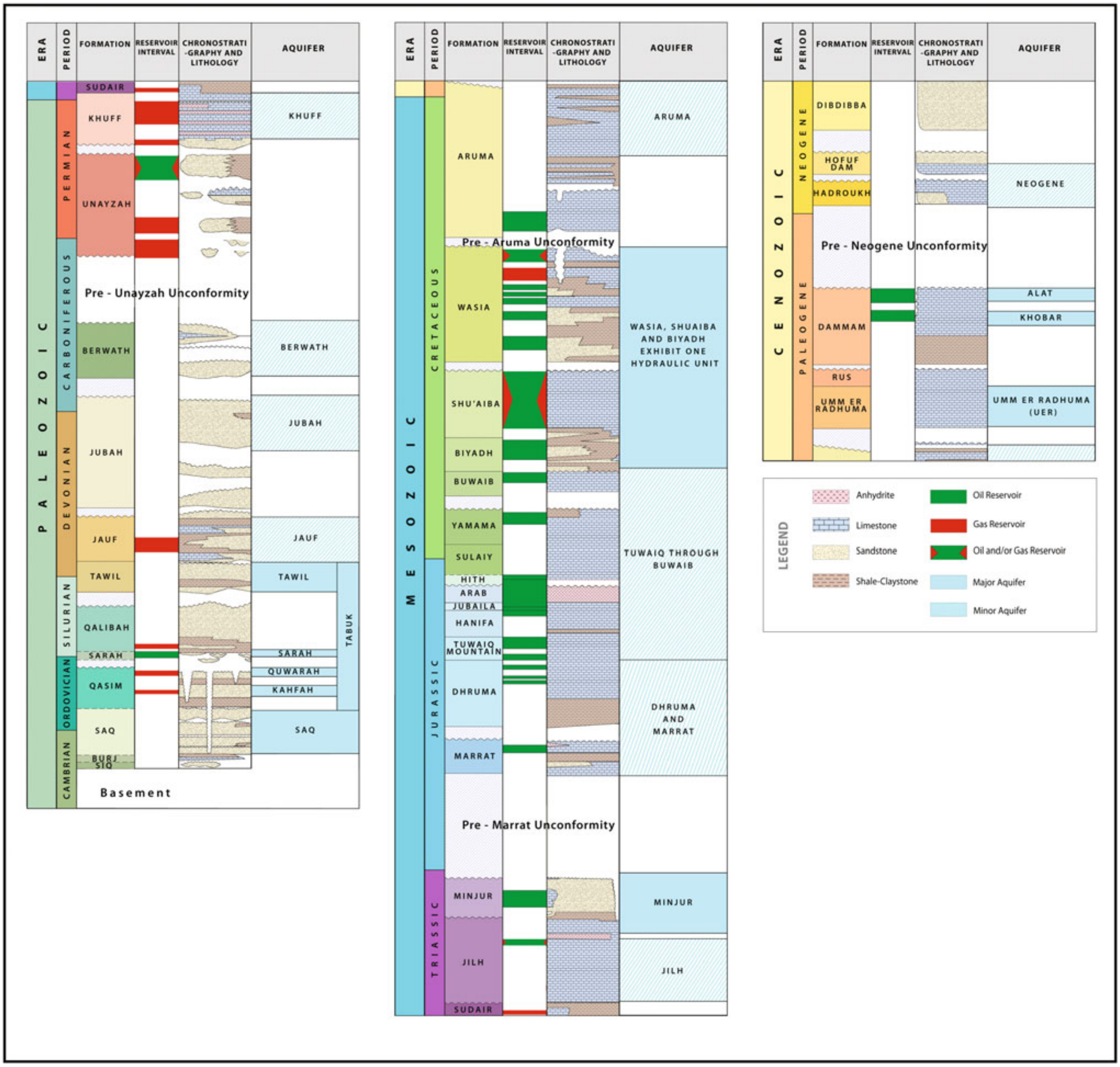

Fig. 2 Stratigraphic column of central and eastern Saudi Arabia showing the oil and gas reservoirs, and major and minor aquifers

rock units with the maximum erosion over major anticlines such as the Ghawar Anticline (e.g. Al-Laboun 1988; McGillivray and Husseini 1992).

The unconformities play important roles in the development of the hydrocarbon and aquifer systems of eastern Saudi Arabia. For example, they form hydrocarbon traps flanks of anticlines such the Jauf gas play on the flanks of the Ghawar anticline (Wender et al. 1998). They also cause cross-formational flow of groundwater in aquifers (BRGM 1977).

Stratigraphic Seals

Geologic data from oil and gas fields and from aquifers provided valuable information on stratigraphic units acting as top seals for hydrocarbon traps and aquifer systems. These seals are mainly shales in the Paleozoic and Cretaceous siliciclastic sequences, anhydrite within the Mesozoic carbonate sequence, and anhydrite, marl, and shale units in the Cenozoic sequence (Fig. 2).

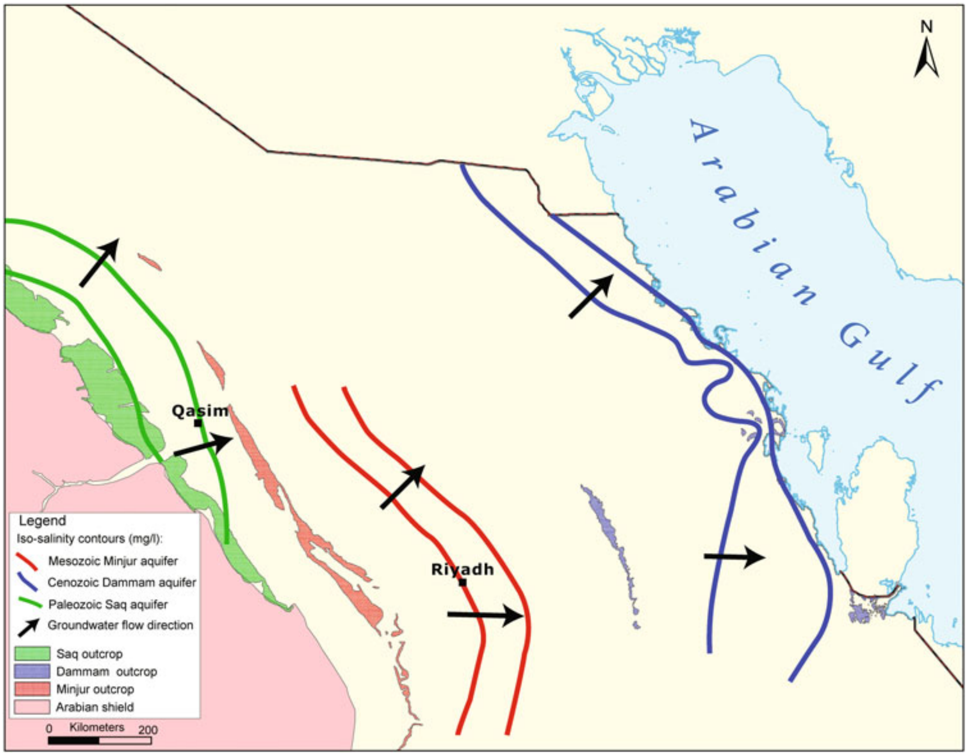

Fig. 3 Regional water salinity and groundwater flow in central and eastern Saudi Arabia (modified after MAW 1984)

In the Paleozoic section, seals include the Ordovician Hanadir and Ra'an shale members of the Qasim Formation, the Silurian Qusaiba shale member of the Qalibah Formation, the Devonian D3B shale unit of the Jauf Formation, and the impermeable lower carbonate unit of the Permian Khuff Formation. These units are known to act as effective top seals for different aquifers near the outcrops (MAW 1984 as well as for the oil and gas reservoirs in central and eastern Saudi Arabia (Konert et al. 2001).

In the Mesozoic section, seals include the Lower Triassic Sudair shale, the Middle Triassic Jilh Dolomite, the anhydrite units of the Arab-D, Arab-C, and Arab-B members of the Jurassic Arab Formation, the Hith Anhydrite, and the Late Cretaceous Lower Aruma Shale. Beside these, other shale and argillaceous carbonate units are known to act as local seals in some oil fields (e.g. Alsharhan and Kendall 1986; MAW 1984).

The regional stratigraphic seals in the Cenozoic sequence are known form hydrogeologic studies of the Tertiary aquifers (e.g. ITALCONSULT 1969; BRGM 1976; BRGM 1977). These seals include the Middle to Upper Paleocene argillaceous carbonate in the lower part of the Umm er Radhuma Formation, the Lower Eocene anhydrite and marls of the Rus Formation, and the Middle Eocene Midra and Saila shale Members of the Dammam Formation as well as the marl units in the Khobar and Alat Members of the Dammam Formation.

Structural Setting

All formations in central and eastern Arabia dip towards the east and northeast at an angle ranging between 1° and 3° (Powers et al. 1966). This gentle dip is dissected by several major anticlines such as the Ghawar and Khurais which typically extend in a more or less north-south direction. Seismic data show that basement rock faults exist underneath these anticlines. Seismic data show that the vertical displacement on these faults is mainly in the Paleozoic sequence. However, wireline and image logs for some horizontal wells show faults with relatively small vertical displacements (<50 ft) in the Jurassic and Cretaceous formations.

The present day structural elements of central and eastern Saudi Arabia are a result of several tectonic phases through which the central and eastern Saudi Arabia went during the Phanerozoic time (Powers et al. 1966; McGillivray and Husseini 1992; Wender et al. 1998; Al-Husseini 2000). The onset of the basement faults took place in the Late Precambrian when the Arabian Plate was subjected to east-west

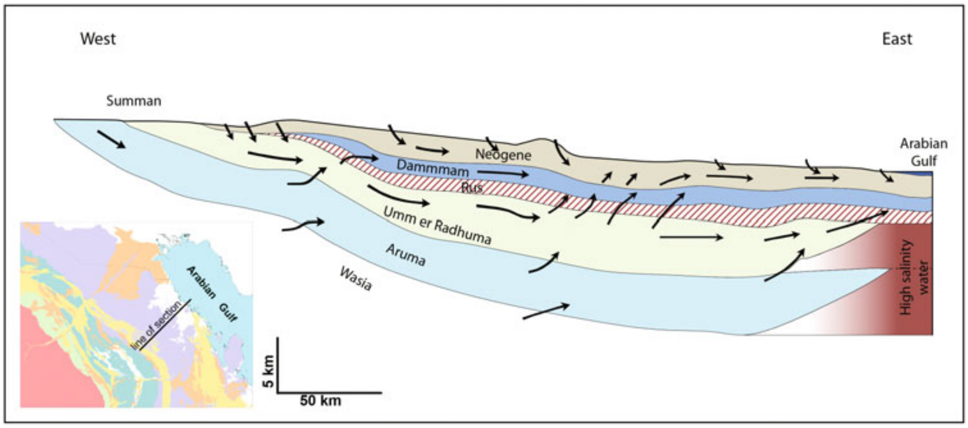

Fig. 4 Regional hydrogeologic cross-section through the Upper Cretaceous and Tertiary aquifers of eastern Saudi Arabia showing the down-dip and cross-formation flow (modified after Bakwiecz et al. 1982)

compressive stresses (Al-Husseini 2000). Reactivations of these faults during the alternating tectonic phases of the Phanerozoic resulted in the evolution of anticlines, unconformity surfaces associated with uplifting, and faulting of the overlying sedimentary formations.

Hydrogeologic Setting

The Phanerozoic stratigraphic column of central and eastern Saudi Arabia constitutes 7 major and more than 10 minor aquifers (Fig. 2). Numerous hydrogeologic studies (e.g. Naimi 1965; ITALCONSULT 1969; B.R.G.M. 1976; 1977) covered the Paleozoic aquifers only in central Arabia and the Mesozoic and Cenozoic aquifers in eastern Saudi Arabia. The Paleozoic aquifers are very deep in eastern Saudi Arabia, therefore, they were not targeted by the hydrogeologic studies which focused only on water resources. Aquifer maps from the hydrogeologic studies have shown a general decrease in hydraulic head and an increase in water salinity from the outcrop belt in the west to the deeper areas in the east, following the regional structural dip. This relationship between the regional dip and the hydraulic head and salinity trends indicate that the aquifers are dominated by gravity flow. Figure 3 shows regional trends of groundwater salinity in selected aquifers illustrating the regional flow directions from the outcrops in the west towards the deeper areas in the east. The hydrogeologic studies have also shown that the seals separating the aquifers are generally leaky and the regional groundwater flow is towards the Arabian Gulf (Fig. 4).

Aquifer studies by the Ministry of Agriculture and Water indicate that the meteoric water recharge during the Pleistocene-Holocene at the outcrops has differentially flushed the aquifers (Edgell 1996). It is likely that the differential flushing is due to the spatial variation in aquifer permeability. The flushing with Pleistocene-Holocene meteoric water has reached to as deep as 7000 ft in the vicinity of the Ghawar field (Stenger et al. 2003). The salinity data from two aquifers

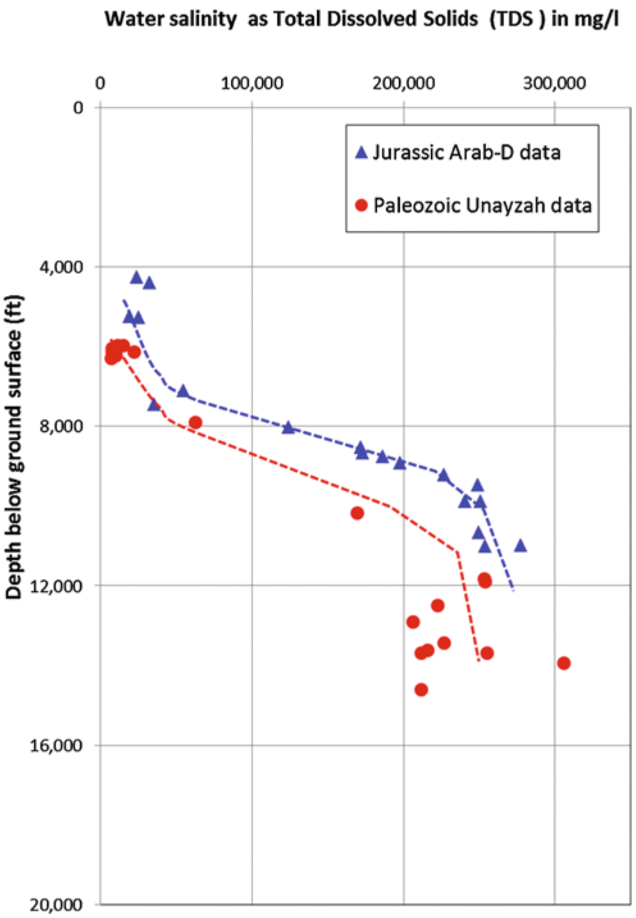

Fig. 5 Groundwater salinity variation with depth in the Arab-D and Unayzah reservoirs of central and eastern Saudi Arabia

(the Jurassic Arab-D and Paleozoic Unayzah) show that the relatively low salinity water has reached to depths around 8000 ft which suggests that the meteoric water flushing could have reached to that depth (Fig. 5). Below 8000 ft, the water salinity starts to increase sharply to as high as 250,000 mg/l at 10,000 ft. Below 10,000 ft, the salinity does not significantly increase with depth likely because that the formations contain connate water which is super-saturated with salts and not flushed with the meteoric water.

Hydrocarbon Systems

The hydrocarbon province of central and eastern Saudi Arabia constitutes two major petroleum systems; the Paleozoic and Jurassic petroleum systems (Pollastro 2003). Each system includes regionally extensive source rock facies and multi reservoirs and seals pairs. A relatively minor hydrocarbon system exists in the Triassic lower Jilh Formation (Jenden et al. 2004).

Geochemical studies by Abu-Ali et al. (1991) concluded that that the Paleozoic System was sourced primarily from the "hot" shale in the basal Qusaiba Member of the Silurian Qaliba Formation. Basin modeling indicates that the Qusaiba "hot" shale has been generating hydrocarbons since the mid-Cretaceous time (Abu-Ali and Littke 2005). Gas generation from the Qusaiba "hot" shale, which started in the Cretaceous, dominates in eastern Saudi Arabia whereas oil generation is in relatively small areas in central Saudi Arabia (Abu-Ali and Littke 2005). Main reservoirs in the Paleozoic system exist in the sequence above the source rock, specifically in the Khuff, Unayzah, and Jauf Formations (Fig. 2). The regional seal of the Paleozoic system is the Triassic Sudair shale, which completely separates it from the overlying Mesozoic systems (Konert et al. 2001). The Silurian Qusaiba "hot" shale forms the main source and ultimate seal

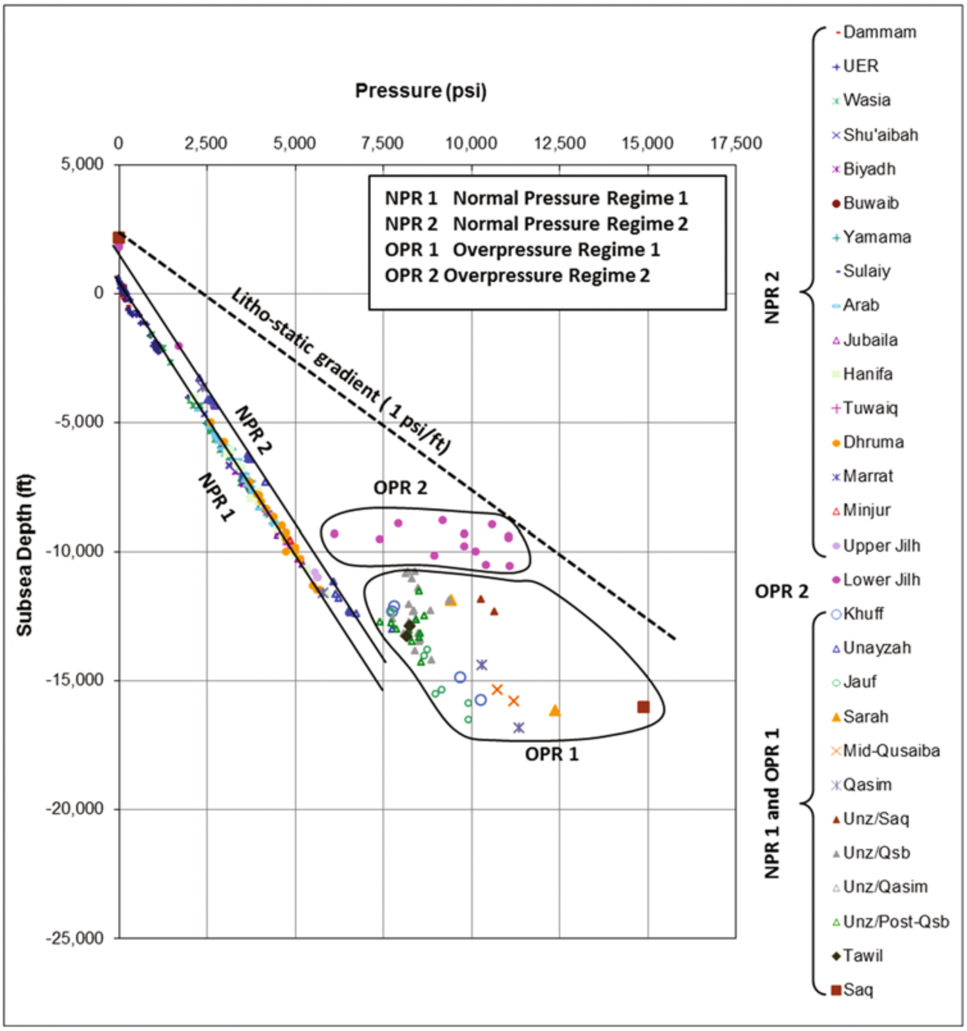

Fig. 6 Pressure/depth plot for all reservoirs in central and eastern Saudi Arabia

to the secondary sub-Qusaiba reservoirs in the Silurian Sarah Formation (Al-Husseini 1991).

The prolific Jurassic oil system of Saudi Arabia constitutes two organic-rich intervals of carbonate mudstones in the Tuwaiq and Hanifa Formations as source rocks (Ayres et al. 1982). Porous carbonate facies forming reservoir units along with anhydrites or argillaceous carbonates forming sealing units exist in the Dhruma, Tuwaiq, Hanifa, Arab, and Hith Formations. The Jurassic reservoirs constitute the main oil producing units in Saudi Arabia. Oil reservoirs also exist in the Cretaceous and Tertiary Formations (Fig. 2), and they are charged mainly from the Jurassic source rocks (Alsharhan and Nairn 1994).

Pressure and Thermal Regimes and Systems

Pressure Regimes and Systems

Pressure and static water level data from more than 220 oil, gas or water wells were used to study the pressure patterns in the sedimentary sequence of central and eastern Saudi Arabia. The static water level data represents pre-production aquifer water levels and are considered as pressures with value of zero at the depth they were measured. The reservoir extrapolated pressure data were obtained from drill-stem test reports. The whole data set covers 25 reservoirs ranging in age from Cambrian to Eocene.

The subsurface fluid pressures in central and eastern Saudi Arabia can be characterized based on the relative magnitudes of pressures and their relationship with their stratigraphic position. The fluid pressures can be classified into pressure regimes, systems, and compartments as defined earlier. Pressure regimes and systems in a basin can be identified and characterized using pressure/depth plots whereas pressure compartments can be identified using either pressure/depth plots or pressure maps.

A regional pressure-depth plot (Fig. 6) allows for classification of 4 pressure regimes named as Normal Pressure Regime 1 (NPR1), Normal Pressure Regime 2 (NPR 2), Overpressure Regime 1 (OPR 1), and Overpressure Regime 2 (OPR 2).

The NPR 1 comprises the sequence from the Cambro-Ordovician Saq Formation through the Lower part of the Triassic Jilh Formation (below the Jilh Dolomite). All reservoirs in this regime are characterized by normal pressures from the outcrops in central Arabia at an average elevation of 2000 ft above sea level to as deep as 13,000 ft below sea level (15,000 ft below ground surface). Within the NPR2, there are slight differences in pressures suggesting the presence of leaky seals between these reservoirs. Al-Aswad and Al-Bassam (1997) reported that the sandstone aquifers within the Paleozoic (NPR 2) are separated from each other by aquitards (leaky shale units). Similar to NPR 1, the identification of the pressure systems within NPR 2 requires an integrated hydrogeologic mapping of the aquifers.

The NPR 2 comprises the stratigraphic sequence from the Triassic Upper Jilh (above the Jilh Dolomite) through the

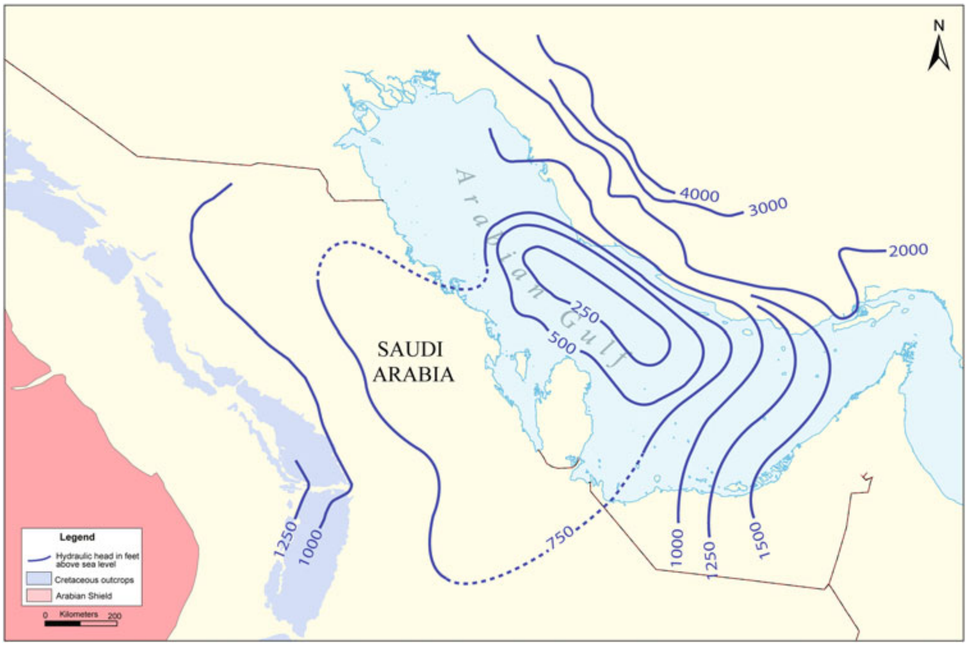

Fig. 7 Regional hydraulic head map of the Cretaceous aquifers (compiled and modified from Pelissier et al. (1980) and Naimi (1965))

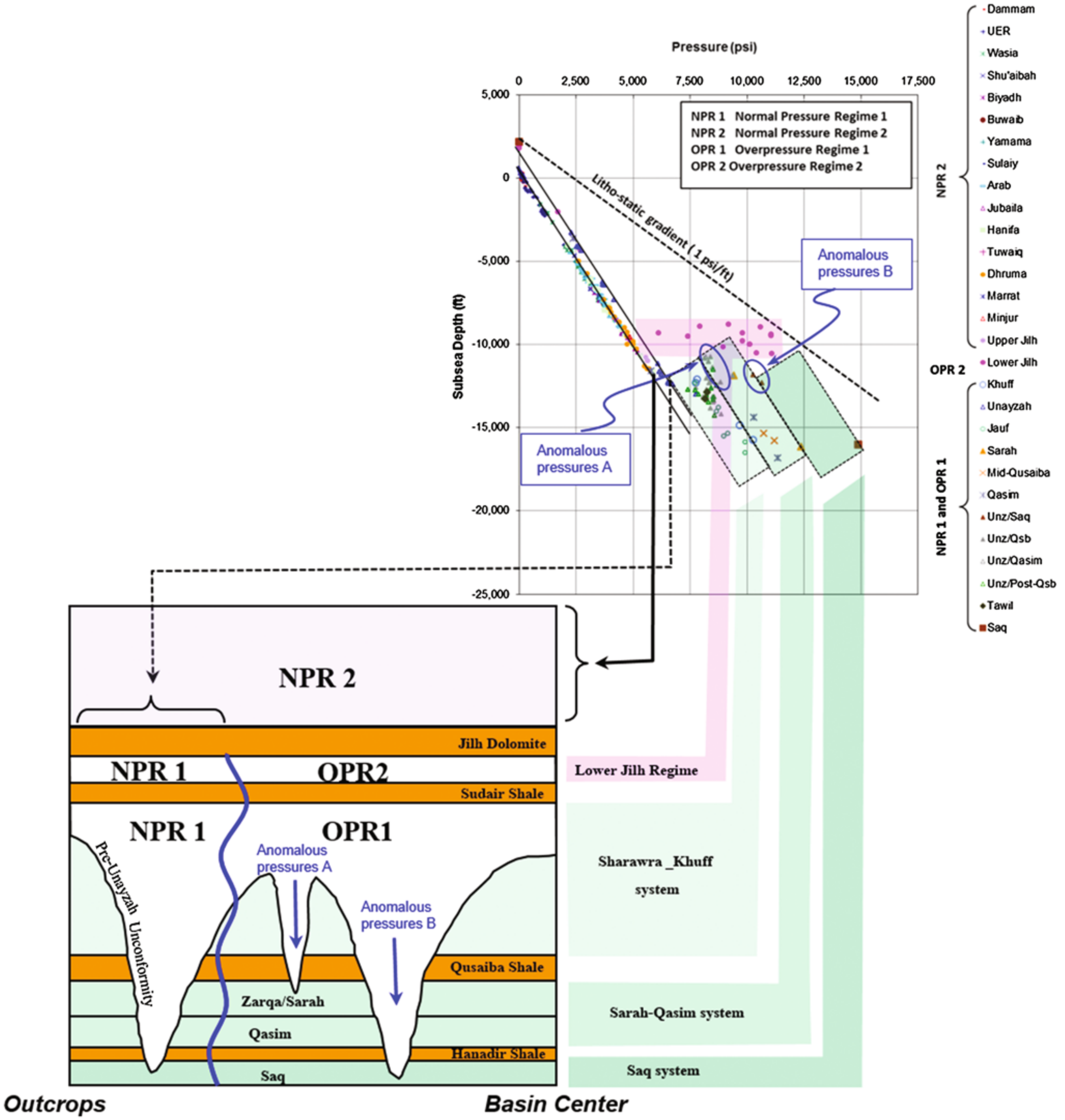

Fig. 8 Pressure/stratigraphy relationship in central and eastern Saudi Arabia

Tertiary Dammam Formation. The linear variation of pressure with depth indicates a normally-pressured sequence from the ground level at an elevation of 2000 ft above sea level to as deep as 12,000 ft below sea level (14,000 ft below ground surface). Geographically, this regime extends from the formation outcrops in central Arabia to the Arabian Gulf in the east. It is likely that this regime also extends into western Iran as suggested by the potentiometric surface map of the Cretaceous aquifers (Fig. 7). The average pressure gradient of NPR1 is calculated at approximately 0.48 psi/ft. Slight differences in pressure between reservoirs are noticeable in this regime. These differences are due to the presence of leaky seals between the reservoirs as confirmed by several hydrogeologic studies such as ITALCONSULT

(1969), and BRGM (1977). Therefore, the NPR 1 constitutes several pressure systems that can be identified only through an integrated hydrogeological mapping of aquifers in this regime.

NPR 1 and NPR 2 have similar pressure gradients (approximately 0.48 psi/ft), but they are totally separate from each other indicating the presence of a regional stratigraphic seal between the two regimes. From the pressure distribution on the stratigraphic units (Fig. 6), the seal between NPR1 and NPR2 exists in the middle of the Jilh Formation and is likely to be the dense Jilh Dolomite; possibly with some of the underlying shale in the lower Jilh. Both regimes are hydraulically connected to the outcrops and have been continuously recharged with meteoric water since the Pleistocene age (Edgell 1996).

The first overpressure regime (OPR 1) comprises the sequence from the Cambro-Ordovician Saq Formation through the Triassic lower Jilh Formation at depths ranging from approximately 10,000 ft to more than 17,000 ft below sea level (12,000 ft to more than 19,000 ft below land surface). The OPR 1 and NPR 2 overlap with each other in the depth range from 10,000 to 13,000 ft below sea level (12,000–15,000 ft below ground surface). This overlap is attributed to spatial variations in reservoir porosity and permeability in this interval as will be discussed later in this paper.

The substantial differences in pressures within the OPR1 have made it easy to classify it into 3 main pressure systems separated by locally breached seals. These systems are named here the Saq, Sarah-Qasim, and Sharawra-Khuff systems. The seals separating these pressures systems, from bottom up, are the Hanadir and Qusaiba shales. The upper system (Sharawra-Khuff) is separated from the overlying OPR 2 by the 700 ft thick Sudair shale. Seals exist within each pressure system, but due relatively small differences in pressures, they can only be recognized on oil field and well scales using well test data. The pressure increases from shallower to deeper systems with a pressure range of 1500–2000 psi for each system (Fig. 8). The pressures in all systems are well below the average litho-static gradient of 1 psi/ft (Fig. 6) suggesting that the leakage through the seals between these systems is not due to overpressure-related fracturing. However, this does not exclude the possibility of seal leaking through overpressure-related fracturing in the past if the paleo-pressures had exceeded the litho-static gradient at any geologic time. In areas where the seals are substantially or totally eroded by the Pre-Unayzah unconformity, the Unayzah reservoir of the Sharawra-Khuff system overlies either the Sarah-Qasim system or the Saq system. Pressures in the Unayzah reservoir at these areas become closer to the underlying pressure system (Anomalous Pressures A and B in Fig. 8). The Unayzah pressures in these areas are considered anomalies in the Sharawra-Khuff pressure system and are associated with anomalies in the reservoir temperatures as will be illustrated later. Due to the absence of local heat generation sources such as igneous intrusions or radioactive mineral concentrations in the Unayzah reservoir, the local high temperature anomalies are considered to be indicators for local fluid communication with deeper systems. Therefore, the Unayzah pressure anomalies, in the areas where the underlying seals are eroded, are a result of high pressure-high temperature water flow from the underlying systems; i.e. the Sarah-Qasim or Saq systems.

Figure 6 shows that the OPR 2 comprises only the lower part of the Triassic Jilh Formation at depths between 8000 ft and 11,000 below sea level (10,000 and 13,000 ft below ground surface). The data for this regime span a wider range of pressures than any other sequence. It is obvious from the pressure/depth relationship that this regime is isolated from both the overlying OPR1 and underlying NPR 2 by strong seals. The OPR 2 is isolated from the underlying OPR 1 by the regionally extending thick Sudair shale. The OPR2 is separated from the overlying NPR 2 by the non-porous extensive Jilh Dolomite, possibly, with some of the shale and anhydrite units at the upper part of the lower Jilh sequence.

Overpressure Generation Mechanisms

Several possible mechanisms have been proposed for the generation of reservoir over-pressures in the subsurface, e.g. the compaction of rapidly deposited sediments, gas generation, and generation of extra-water volumes by mineral transformation such as gypsum to anhydrite (Law and Spencer 1998; Swarbrick and Osborne 1998). In old basins, the dominant mechanism for generating overpressure is the fluid volume expansion resulting from gas generation (Law and Spencer 1998).

Basin modeling by Abu Ali and Littke (2005) indicates that the present-day gas generation window for the Qusaiba source rock in central and eastern Saudi Arabia starts at a depth of about 12,000 ft. It is also interesting that the porosity and permeability of the Paleozoic sandstones are significantly reduced at depths exceeding 12,000 ft due to cementation with quartz overgrowth and illite (Carney et al. 2002; Franks and Zwingmann 2010). This is the same depth at which the OPR 1 starts which indicates that the gas generation aided by the reduced porosity and permeability of the reservoirs are the likely factors involved in generating overpressures in the OPR 1. It is thought that the reduction of porosity and permeability in the Paleozoic reservoirs acted on retarding the upward gas migration which have resulted in the generation of overpressures at depths below 12,000 ft. NPR 2 is continuous from the ground surface to a depth of approximately 15,000 ft in some areas with an overlap with OPR 2 in the range 12,000–15,000 ft. This overlap is likely related to spatial variations in the reservoir porosity and permeability in the interval between 12,000 and 15,000 ft. In areas where relatively high porosity and permeability exist below 12,000 ft, the upward gas migration is less restricted which prevents the evolution of overpressures. Therefore, the overlap between the NPR 2 and OPR 1 in the interval 12,000–15,000 ft is attributed to lateral variations in reservoir porosity and permeability within this interval.

The OPR 2, in the lower Jilh Formation, shows an extremely wide range of overpressures (Fig. 6) over a small interval of depth which suggests a domination of isolated pockets of overpressured reservoirs. The mixed facies of carbonates, shales, and anhydrites and the quick lateral variations of these facies form a suitable geologic environment for the development of isolated compartments with wide range of overpressures. Compaction and/or hydrocarbon generation along with the quick facies changes in the lower Jilh Formation could be the main reason for the generation of the overpressures in the lower Jilh Formation.

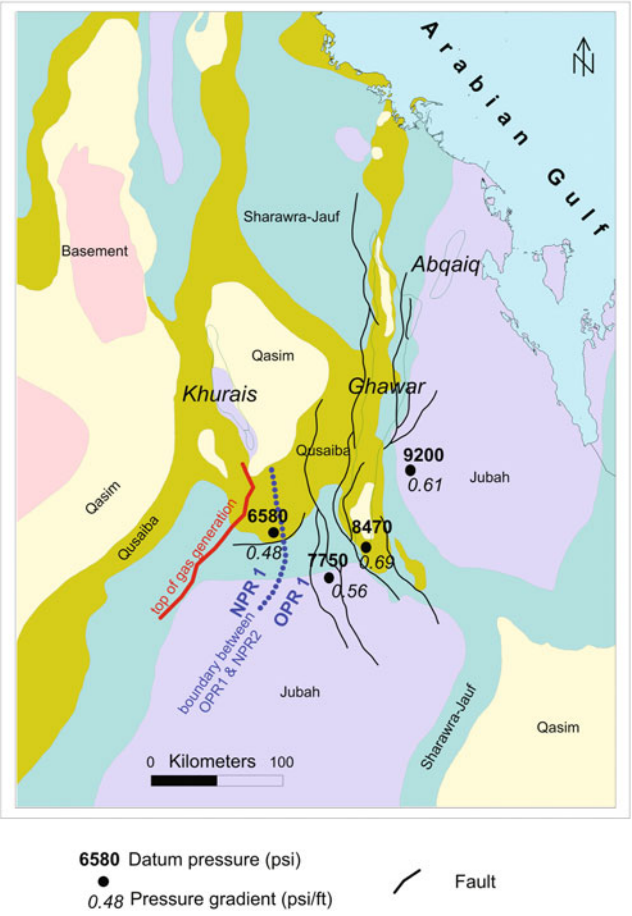

Fig. 9 Unyazah reservoir datum pressures and pressure gradients showing compartmentalization by faults

Spatial Distribution of Overpressures

The wide overlap zone (12,000–15,000 ft) between the NPR 1 and OPR 1 indicates that accurate mapping of the overpressures in the subsurface requires the availability of data with sufficient geographic distribution for all reservoirs in the OPR 1. The limitations of data with the variability in overpressure ranges in the OPR 1 make it difficult to generate pressure distribution maps for the OPR 1. Most of the data available to this study is for the Unayzah reservoir; therefore, it was possible to map the overpressure distribution only for the Unayzah reservoir (Fig. 9).

The Unayzah reservoir pressure generally increases towards the east following the regional dip of the Arabian platform (Fig. 9). Moreover, the pressure gradients vary across faults indicating reservoir compartmentalization by the faults…

As highlighted before, that the presence of relatively high porosity and permeability in the Unayzah Formation within the depth interval 12,000–15,000 ft would make the upward gas migration less restricted which results in preventing the evolution of overpressures in this interval. Therefore, the boundary between OPR 1and NPR 2 is located down-dip from the top of the gas generation at 12,000 ft (Fig. 9).

Thermal Regimes

Figure 10 shows a plot of Bottom Hole Temperature (BHT) data from wire line logs versus True Vertical Depth at which the temperature was measured. Some data scattering is seen in the temperature/depth plot. Never the less, the data available to this study in its present format is relatively good enough to investigate the general trends in geothermal gradients.

Figure 10 shows that there are two main thermal regimes: a shallow thermal regime (STR) and a deep thermal regime (DTR) in central and eastern Saudi Arabia. STR and DTR are separated from each other by a high thermal conductivity zone (HTCZ) with low geothermal gradient in the depth range between 8000 and 10,000 ft below ground surface. Based on the relative magnitude of temperature in the wells, both thermal regimes are classified into low-temperature wells and high-temperature wells with an overlap zone. The low-temperature wells are located westward and up-dip of

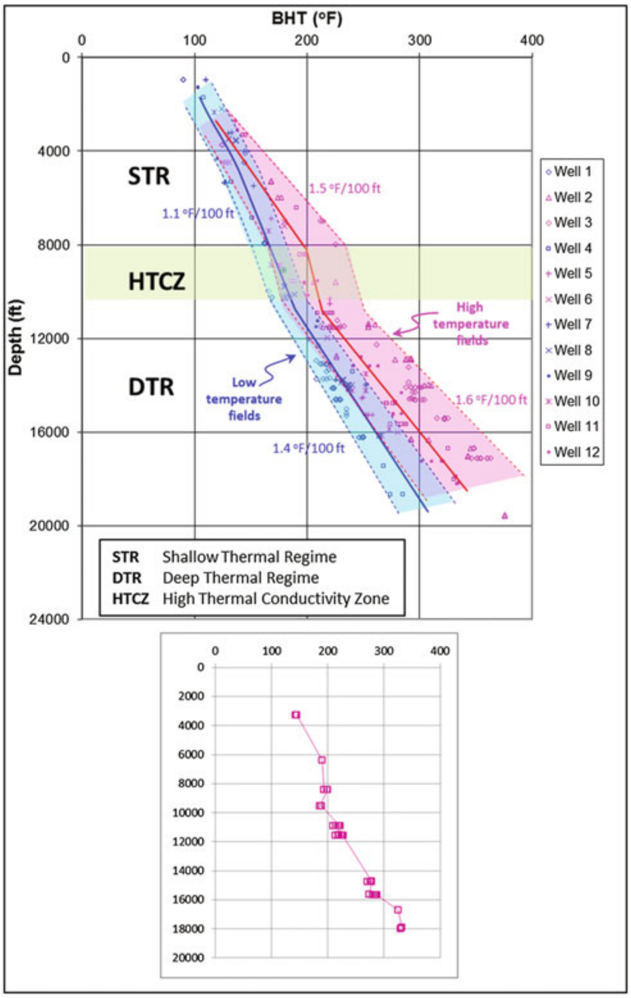

Fig. 10 Temperature/depth plot for selected wells in central and eastern Saudi Arabia with an extracted plot for well 11 showing the details of temperature changes with depth

the high-temperature wells with an overlap zone between the two (Figs. 10 and 11).

The STR extends from the ground surface to about 8000 ft below ground surface (about 6000 ft below sea level). The temperature in this regime increases from about 90 °F at 1000 ft below ground surface to about 220 °F at 8000 ft below ground surface. The average geothermal gradients for the low-temperature and high-temperature wells in this regime are 1.1 and 1.5 °F/100, respectively.

The DTR extends from approximately 10,000 ft to more than 19,000 ft below ground surface (about 8000–16,000 ft below sea level). The temperature of this regime increases from as low as 180 °F at 10,000 ft below ground surface to more than 370 °F at 19,000 ft below ground surface. The average geothermal gradients for the low-temperature and high-temperature wells in this regime are 1.4 and 1.6 °F/100 ft, respectively. The DTR has a relatively wider range of lateral variations in temperatures than in the STR.

The HTCZ lies 8000 and 10,000 ft below ground surface (about 6000 and 8000 ft below sea level). Geothermal gradients across the HTCZ are very low indicating a relatively high heat conductivity zone. The HTCZ is less obvious in the low-temperature wells suggesting that there is a cooling effect from the STR in these wells. The cooling may be attributed to the aquifer flushing by the cold meteoric water through the outcrops.

The depths of the boundaries between the thermal regimes (Fig. 10) are comparable to the depths at which the water salinity gradients change (Fig. 5). This suggests that the pattern of geothermal gradients in these thermal regimes is very much related to the fluid environment rather than to the rock matrix. Also, the geothermal gradient in the low-temperature wells changes from 1.1 °F/100 ft in the STR to 1.5 °F/100 ft in the DTR indicating a cooling effect in the up-dip areas of the aquifers close to the recharge areas. On the other hand, high-temperature wells show a smaller difference between the geothermal gradients for the STR and DTR (1.4 °F/100 in the STR to 1.6 °F/100 in the DTR) which indicates a much less effect of cooling in these wells. This pattern of variations in geothermal gradients is in line with the general pattern of heat transfer observed in gravity-dominated groundwater flow basins. At the edges of these basins, the geothermal gradient and surface heat flow are depressed by the downward moving water (Deming 1994; Diao et al. 2004). In the deeper parts of the basin where the groundwater can only move upward, higher geothermal gradients and higher heat transfer to surface exist. Mid-way between the highest and lowest elevations of the basin, groundwater flow is largely horizontal and the effect on temperature is minimal.

Anomalies in the Pressure and Thermal Systems

Anomalies in reservoir pressures and temperatures have been observed in the NPR2 and OPR1 at several locations. For example, BRGM (1977) showed anomalously high temperature, hydraulic head, and salinity in the Neogene, and Dammam aquifers in the middle of the Ghawar anticline. BRGM 1977 interpreted these anomalies to be caused by the upward flow of hotter and higher pressure water from the Early Tertiary Umm er Radhuma aquifer into the Late Tertiary Dammam and Neogene aquifers through the area where the Middle Tertiary sealing Rus Formation is eroded by the pre-Neogene unconformity (Fig. 12).

The present study reveals anomalously high temperatures and pressures in the Unayzah reservoir in southern Ghawar (Fig. 13). In this case the water flows upward from the

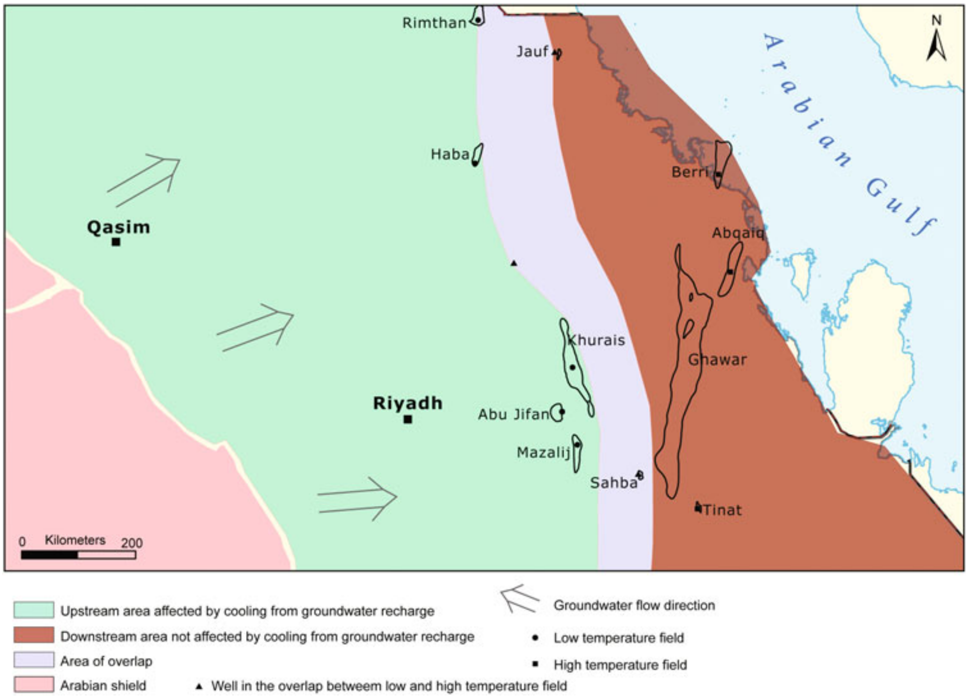

Fig. 11 Low and high temperature areas of central and eastern Saudi Arabia

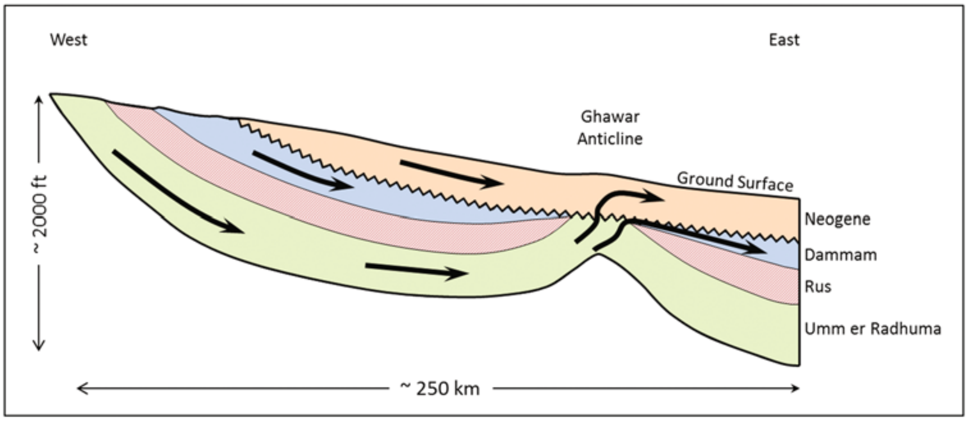

Fig. 12 Regional schematic cross-section through eastern Saudi Arabia showing the groundwater cross-formation flow in the Ghawar anticline (drawn from the concept by BRGM 1977)

Qasim Formation into the Unayzah reservoir in the area where the Qusaiba sealing shale is eroded and the Ordovician Saq-Qasim section is subcropping underneath the Unayzah.

Another anomalously high temperature is also obvious in the Unayzah reservoir at the Muradhaf, Mihwaz, and Dilam areas (Fig. 14). Here, the Qusaiba shale is not eroded, and the anomalous temperatures are associated with faults (Fig. 14). It is believed that in these areas, the water flows upward from the Qasim Formation to the Unayzah reservoir through the fractured damage zones surrounding the fault core zones. Fault damage zones typically act as conduits for vertical fluid flow whereas fault core zones act as barriers to fluid flow (Caine et al. 1996).

From the above examples of anomalous pressure and temperature areas, it is apparent that cross-seal water flow

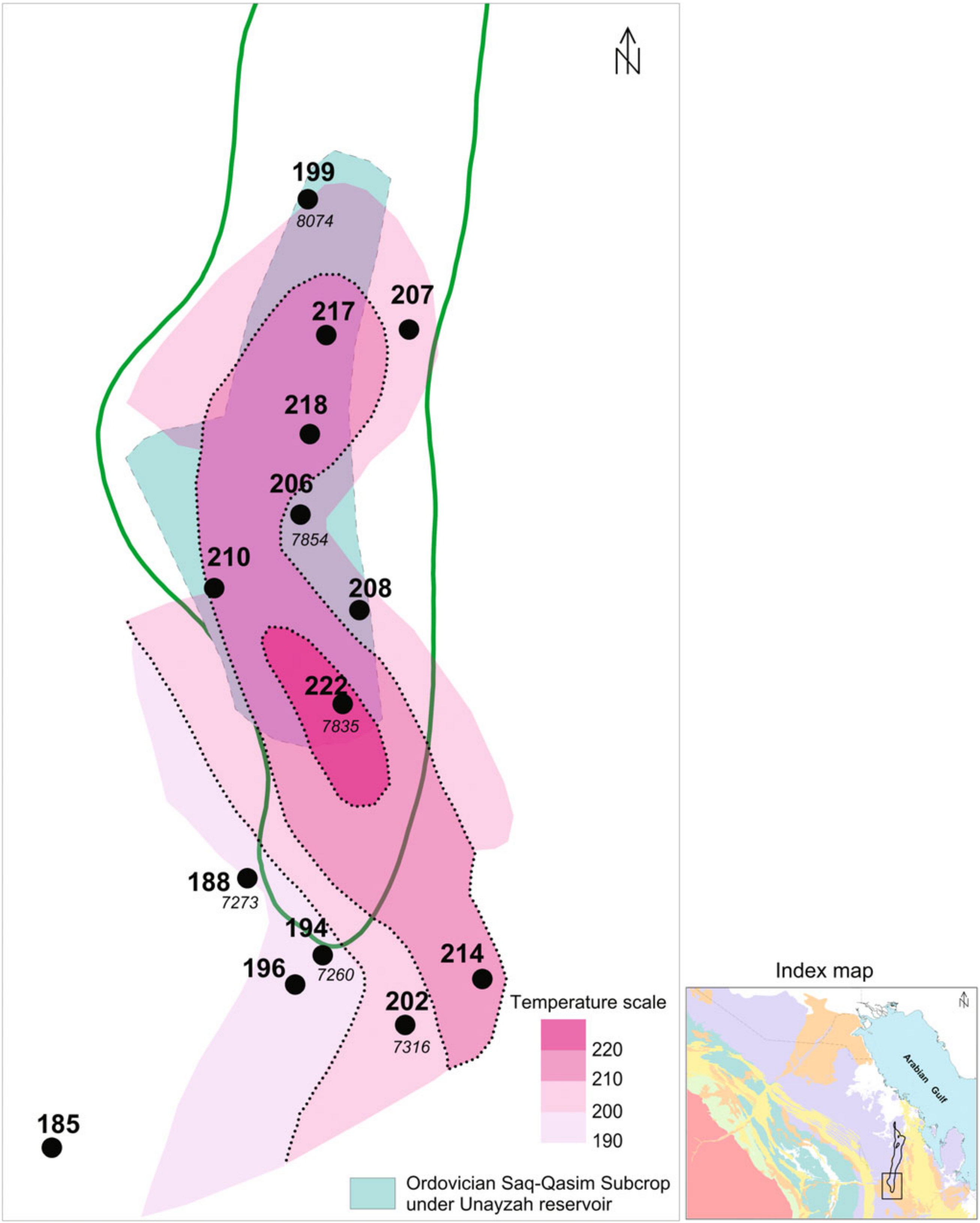

Fig. 13 Map of the Unayzah reservoir in South Ghawar showing an increase of temperature and pressure towards the Saq-Qasim subcrop area

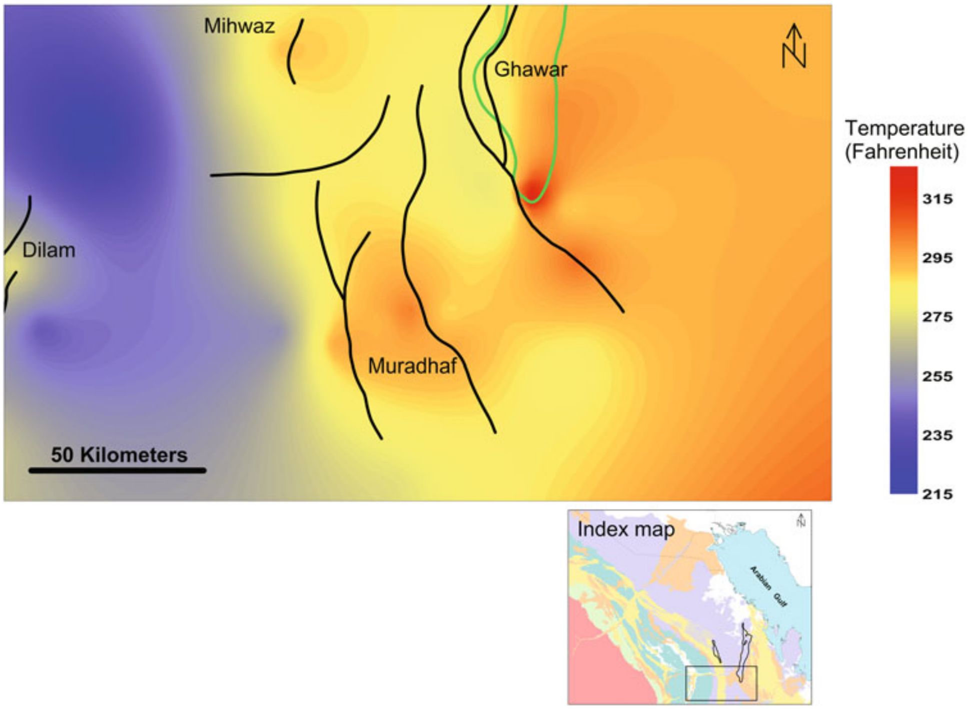

Fig. 14 Temperature map for the Unayzah reservoir in central and eastern Saudi Arabia showing the anomalously high temperatures associated with faults near Muraddaf, Mihwaz, and Dilam

could take place in two geologic settings: in areas where the sealing formations are eroded, and in areas where the fault damage zones act as conduits for the cross-seal flow. It is also possible that the two geologic settings coexist in one area.

An Integrated Thermo-Pressure Model

The main characteristics of pressure and thermal patterns in the sedimentary sequence of central and eastern Saudi Arabia are summarized in the 2-D model shown in Fig. 15. The model illustrates, schematically, the distribution of the pressure and thermal regimes and systems along with groundwater flow directions and salinity distribution. It also shows the anomalies in the geothermal gradients associated with breaching of seals within individual regimes.

The sedimentary sequence of central and eastern Saudi Arabia constitutes primarily aquifers that are separated from each other by stratigraphic seals; mainly shales in the Paleozoic sequence and anhydrites or shales in the Mesozoic and Cenozoic sequences. With the exception of the Sudair shale and Jilh Dolomite, these seals are known to be locally breached causing cross-aquifer flow to exist throughout central and eastern Saudi Arabia. The Sudair shale acts as a strong seal that separates the Paleozoic aquifers and petroleum system from the Mesozoic aquifers and petroleum system. The regionally dense Jilh Dolomite formed an upper seal for the overpressure regime in the lower Jilh Formation.

The whole sedimentary sequence of central and eastern Saudi Arabia has been recharged with meteoric water since the Pleistocene. Regionally, the meteoric water formed relatively fresh water zone in the shallow areas (<8000 ft). Also, it has resulted in lower geothermal gradients in the upstream areas. The gas generation from the Silurian Qusaiba Shale which started in the Late Cretaceous has resulted in the generation of an overpressured system in the Paleozoic sequence at the deep areas of central and eastern Saudi Arabia.

Unconformities and faults are obviously important geologic factors in characterizing pressure systems. Unconformities and faults cutting through seals create opportunities for hydraulic communication between pressure systems allowing for the generation of local pressure and temperature anomalies. Faults could play double action role; their damage zones act as vertical conduits for cross–seal flow between pressure systems, and their core zones could act as seals forming different pressure compartments within individual pressure systems.

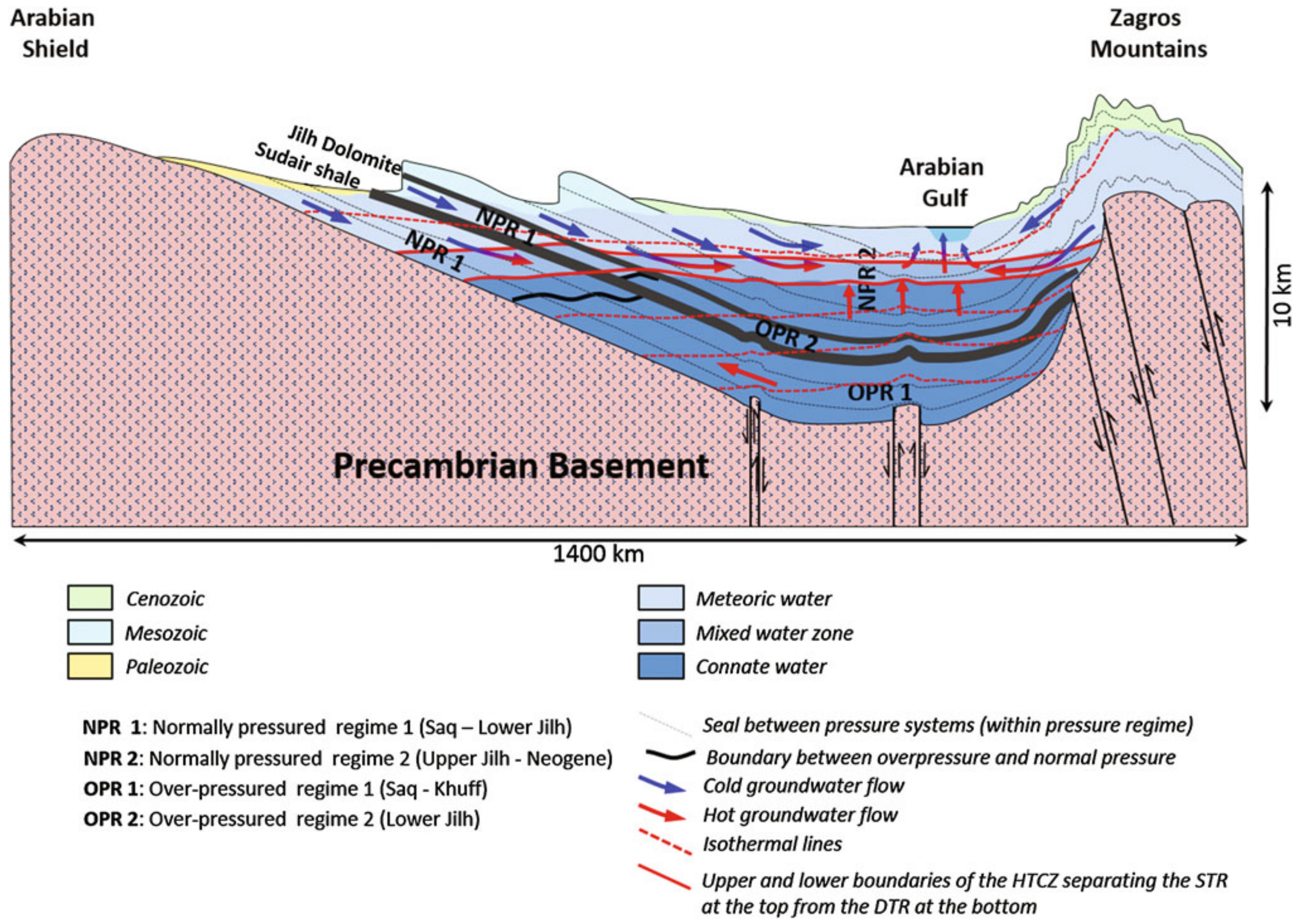

Fig. 15 Regional 2-D model illustrating the pressure regimes and systems, thermal gradients, groundwater flow and salinity in central and eastern Saudi Arabia

Conclusions

Pressure and thermal regimes and systems in the sedimentary sequence of central and eastern Saudi Arabia have been defined for the first time. The pressure regimes which are totally separated from each other by stratigraphic seals include:

(1) Normally pressured regime (NPR2) in the sequence from the Cambro-Ordovician Saq Formation through the Lower part of the Triassic Jilh Formation (below the Jilh Dolomite). This regime extends from the formation outcrops at ground surface to as deep as 15,000 ft.
(2) Normally pressured regime (NPR2) in the sequence from the Triassic Upper Jilh (above the Jilh Dolomite) through the Tertiary Dammam Formations. This regime extends from the formation outcrops at ground surface to as deep as 14,000 ft.
(3) Overpressured regime (OPR1) in the sequence from the Cambro-Ordovician Saq Formation through the Triassic Khuff Formation at depths ranging from approximately 12,000 to more than 19,000 ft. This regime constitutes 3 main pressure systems; named here as the Saq, Sarah-Qasim, and Sharawra-Khuff systems. These systems are separated from each other by seals that are breached locally by unconformities or faults resulting in local hydraulic communication.
(4) Overpressured regime (OPR2) in the lower part of the Triassic Jilh Formation at depths between 10,000 and 13,000 ft.

The thermal regimes include:

(1) Shallow thermal regime (STR) that extends from the ground surface to depths around 8000 ft. This regime exhibits low geothermal gradient in the up-dip areas and normal geothermal gradient in the down-dip areas.
(2) Deep thermal regime (DTR) that extends from approximately 10,000 ft to more than 19,000 ft. This regime exhibits normal geothermal gradients in both the up-dip and down-dip areas.

(3) High thermal conductivity zone (HTCZ) in the depth range between 8000 and 10,000 ft.

Several factors are thought to have controlled the evolution of the pressure and thermal regimes and systems in the sedimentary sequence of central and eastern Saudi Arabia. The most important of these factors are the reservoir flushing with meteoric water during the Pleistocene-Holocene, gas generation in the Paleozoic sequence since the Cretaceous, porosity and permeability reduction with depth, and the regional stratigraphic and structural settings of the area.

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