Arab J Geosci (2010) 3:221–248
DOI 10.1007/s12517-009-0046-0

ORIGINAL PAPER

Stratigraphy, deposition, and structural framework of the cretaceous (review) and 3D geological model of the lower cretaceous reservoirs, Masila oil field, Yemen

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Received: 4 December 2008 / Accepted: 14 April 2009 / Published online: 8 May 2009

Abstract The Masila area is located in the Hadhramaut region in east central Yemen. Oil was first discovered in the area in late 1990 with commerciality being declared in late 1991. Oil production began in July 1993. By the end of December 1999, the daily production rate was set at 210,000 stock tank barrels/day (STB/D) of very low gas–oil ratio (GOR) oil under partial to full water drive. About 90% of the reserves are found in the Lower Qishn Clastics Member of the Qishn Formation. This paper focuses on the detailed 3D geological modeling of the Lower Cretaceous Sequence conducted through an integrated study. There are three critical areas in the process of modeling reservoirs that involve geological and geophysical modeling, reservoir characterization, and reservoir flow modeling. This paper presents methodologies found useful during the modeling of these reservoirs including field case histories for the Lower Cretaceous reservoir in the Masila oilfield.

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Keywords Static 3D modeling · Porosity · Facies modeling · Fluid model · Reservoir characterization

General introduction

Extensive oil exploration drilling backed by regional and/or detailed geophysical surveys (increasingly based on seismic surveys) from the late 1970s have gradually unraveled a complex Mesozoic tectonic history responsible for the formation of a number of NW–SE and E–W trending rift basins and depressions. These were initiated mainly in the Late Jurassic and Early Cretaceous, principally by rejuvenation of ancient basement-controlled fractures during further Gondwanan breakup which led to the separation of India (with Eastern Gondwana) from Afro-Arabia. These basins exhibit considerably thick and rapidly varying stratigraphic sequences which reflect successive phases of rifting, subsidence and depositional settings in time, with the type and provenance of basin-fill helping to detail the developing paleogeography for each stage. The precise relationships of these varied intra- and interbasin facies are not yet properly understood.

The discovery of commercial oil and gas in several of these Mesozoic rift basins accelerated competitive exploration activity by a host of operating companies leading to the proliferation of informal locally applicable in-house subsurface lithostratigraphic nomenclature schemes. These, in the extreme cases, either ignore published surface nomenclature or else utilize existing surface-defined formation names which then become overloaded with undifferentiated coeval but depositionally and environmentally different units without due regard to internationally accepted rules. This confusion is further compounded by academic research from within and outside Yemen, with little or no access to subsurface data, and by service companies utilizing limited client-supplied data which is then extrapolated on a province-wide or a regional basis.

Mesozoic rift basins of Yemen

Tectonic setting of basins

The Mesozoic basins of Yemen vary spatially and temporally from the west to the east of the country. The interior rifts of the western and central areas (Wadi Shiham ad Dhali Basin, Sab'atayn Basin, and Balhaf Basin) are oriented NW–SE, following the Najd trend of the Precambrian basement of the Arab-Jan peninsula (Beydoun 1991, 1997). The earliest syn-rift strata within the Sab'atayn Basin (or Marib AI Jawf or Shabwa Basin) are lower to middle Kimmeridgian age (Holden and Kerr 1997) with maximum subsidence occurring in the Kimmeridgian and Tithonian (Redfern and Jones 1995). To the east of the Sayun-al Masila Basin (Beydoun 1971) and Jiza'-Qamar (Brannan et al 1997) basins are oriented progressively more east–west (Bosence 1995)

When the Socotran Platform is restored to its location prior to the Gulf or Aden spreading, the major structural elements have an east–west orientation while other lineaments parallel the ENE–WSW orientation of the Masila Basin (Birse et al. 1997). These basins are relatively younger than the NW–SE-oriented basins, with deposits of syn-rift strata ranging in age from the Hauterivian to the late Tertiary. The eastern portion of the Jeza-Omran Basin (Brannan et al 1997) and the Socotran platform were both involved with Oligocene to recent ocean margin rifting and subsidence of the Gulf of Aden and the earlier Mesozoic formation of the Northern Somalia Basin of the Indian Ocean (Birse et al. 1997).

The change in stress orientation with time has been suggested by Redfern and Jones (1995) and Birse et al. (1997) to relate the inherited NW–SE Najd trend in Central Yemen later to an external stress induced by the northward movement of India in the Cretaceous and Tertiary and involvement with the rifting and spreading of the Gulf of Aden (Bosence 1995).

Historical and stratigraphic review

Beydoun (1971) provides an overview of the history of stratigraphic studies and of petroleum exploration in Yemen prior to the initial results of the Yemen Stratigraphic Commission engaged with the difficult problem of producing a standard stratigraphic scheme for the country. A multitude of different names, different spellings, different usages, and different lithostratigraphic concepts has resulted in a plethora of lithostratigraphic names in Yemen. This confusion has resulted primarily from a combination of research and surveys independently established from two countries that became unified in 1990, the project of rapidly expanding exploration by a number of different companies working in different basins and also by the problem of correlating the large outcropping sections of the country with lithologically different subsurface data in the <10 km deep basins Bosence (1997).

The initial results of the commission are illustrated here in a series of detailed tables, and the final results are to be published in the near future as a new edition of the International Lexicon of the Stratigraphy of Yemen. Holden and Kerr 1997) proposed a revision of the early cretaceous stratigraphy of Yemen based on the earlier (Robertson Research, formerly Simon Petroleum Technology) petroleum geology study of Yemen that reviewed of the geology of some 58 wells, 7,500 km of seismic, and aeromagnetic and gravity data. They recognize a subsurface unconformity bound unit of up to 860 m of mudstones and limestones best developed in the Al Furt-l well is distinct from the overlying Qishn Formation and proposed the name Furt Formation. The Qishn is here subdivided into four members. Beydoun (1997), however, considered these units to be all part of the Qishn Formation and designated the lower mudstones and limestones (previously referred to informally as the “pre-Qishn B”) as the Sa’ar member. A series of detailed paleogeographic maps covering the Hauterivian to Albian have been produced by Bosence (1995)).

Some field data come from the remote and rarely visited island of Socotra and adjacent islets (Samuel et al. 1997). The Socotra Platform lies near the Somali coast today but prior to Gulf of Aden rifting was positioned adjacent to the Dhofar coast of Oman. Both areas are recognized as having a similar geological evolution with five main unconformity bound sequences. A lower to middle Triassic sequence is locally developed over the Precambrian basement as a sequence of fluvio-deltaic sandstones and conglomerates and shallow marine and sandstones and limestones. This sequence does not have an equivalent on mainland Yemen but is lithologically similar to the early Jurassic Kohlan and Shuqra formations.

Lying unconformably on the Triassic in Southeast Socotra are lower to middle Jurassic deltaic and shallow marine sandstones, followed by shallow marine limestones that have been correlated to thicker Jurassic sections observed in offshore seismic data. A widespread lower cretaceous (Barremian–Aptian) sequence comprises basal siliciclastics followed by platform carbonates containing rudist-rich packstone to grainstone shoals. A thin transgressive Campanian to Maastrichtian sequence is dominated by outer shelf, foraminifer-rich limestones. The final pre-Gulf of Aden rift sequence consists of marine sandstones of

Paleocene age that pass up into Paleocene to Eocene inner shelf foraminifer-rich packstones and wackestones. The first syn-rift deposits dated in the Gulf of Aden rift are reported as late Oligocene in age (Bosence 1995).

The post-Palaeozoic structure of the Socotra Platform is discussed by Birse et al. (1997) from a seismic grid tied into an exploration well. After restoration for Gulf of Aden rifting the main lineaments in the area are extensional faults trending 145°. Two main Mesozoic basins are described form the extensive southern part of the Socotran Platform and northern North Somali Basin of the Indian Ocean. The extensional Basin Phoenix extends 140° and is a possible extension to the western al Masila Basin of Yemen. It is a large asymmetric graben with strata dipping and thickening to the southwest with an estimated 3 km of upper Jurassic–lower Cretaceous syn-rift strata showing phases of footwall fan progradation. The newly discovered Rukh Basin trends at 45° and comprises some 2.5 km of syn-rift, upper Jurassic–lower Cretaceous strata. Faults have the same orientation as those on the northern margin of the North Somalia Basin and are considered to relate to breakup and southward movement of eastern Gondwanaland (Bosence 1995).

A final pre-Gulf of Aden, late Cretaceous to early Paleocene 80° translational phase is characterized by steep normal, vertical and steep reverse faults, inversion axes, and dextral strike-slip faults. The origin of this tectonism is not clear and cannot be related to translational movement on the Owen Fracture Zone or the Masirah transform fault systems.

In mainland Yemen the Jiza-Qamar Basin is the easternmost, deepest (>10 km) and youngest Mesozoic to Tertiary rift and has a complex three-stage history (Brannan et al. 1997). The rift initially developed in the late Jurassic to early Cretaceous (Socotra above) as part of the breakup of Gondwanaland. The rift was locally reactivated in the mid-Cretaceous and subsequently to this, thick fluvio-deltaic clastics infilled a rapidly subsiding basin. These are followed by late Cretaceous deep marine carbonates and clastics. Following an early Paleocene unconformity, shallow marine carbonates accumulated throughout the basin and also over much of the southern Arabian Plate.

Prior to Gulf of Aden rifting, there was a break in sediment accumulation from the late Eocene to the Oligocene represented by a syn-rift unconformity. Whilst onshore areas were uplifted by over 1 km, the eastern areas continued to subside and became a carbonate province with active rifting giving rise to deep water and slope carbonates in the lows and shallow carbonate platforms on the footwall highs. From the late Miocene, these platforms have been gradually drowned by subsidence and westerly derived clastics.

Landsat images and a digital elevation model, covering the central and southern portions of the Masila Basin in the Republic of Yemen, have been used to enhance the mapping of poorly imaged structural features. An absence of recent post-rift sediments within the study area permitted Mesozoic and Cenozoic extensional surface features to be mapped from satellite data and then extrapolated to analogous subsurface structures identified on a 2D seismic grid.

The structure of the outcropping Umm Er Radhuma Formation was interpreted by picking control points on the base of the widespread Eocene Jeza Formation. The control points were then back-interpolated onto a "digital elevation model" constructed from Russian topographic maps. Contouring of the gridded control points generated a structure map of the Umm Er Radhuma Formation. The interpreted structure maps and faults were combined with well and seismic data to develop 2D structural cross-sections and 3D models of the study area. Sixteen leads were identified on the surface maps, and three were corroborated by the seismic data. An exact correlation of the surface structure to the top of the zone of interest (Qishn Carbonate Member) proved impossible due to static problems. The deepest coherent reflector was the Dha Sohis Member of the Harshiyat Formation, which lies approximately 360 ms above the Qishn Carbonate Member.

Hydrocarbon occurrence

The Arabian Plate contains some 66% of the world's proven oil reserves and about 33% of its gas (Beydoun 1991). The major fields are located towards the northeastern margin of the plate where Mesozoic epeiric seas provided exceptionally extensive source, seal, and reservoir rocks. Yemeni hydrocarbon occurrences contrast markedly with those of the northeast in that they are localized in a number of Mesozoic rift basins (Fig. 1). Some of these have little surface expression, and it was not until geophysical surveys in the early 1980s that their extent and economic importance was realized (Maycock 1986). The location and fill of these basins has had an important control on the hydrocarbon prospectivity in the region. The older interior basins were at times isolated from the Gondwanaland continental margins by active rifting in the Kimmeridgian, permitting deep basinal conditions (Bosence 1995).

These favored accumulation of the organic rich muds of the Madbi Formation of the Sab'atayn and the Say'un Basins that provide source rocks for the Alif, Ayadh, and Masila oilfields (Fig. 1; Al Taheri et al. 1992; Redfern and Jones 1995). Subsequent isolation of the Sab'atayn Basin in a low latitude climate led to evaporation and precipitation of the salts of the Sab'atayn Formation that assist in the trapping of oil and gas in the Alif fields. Those basins,

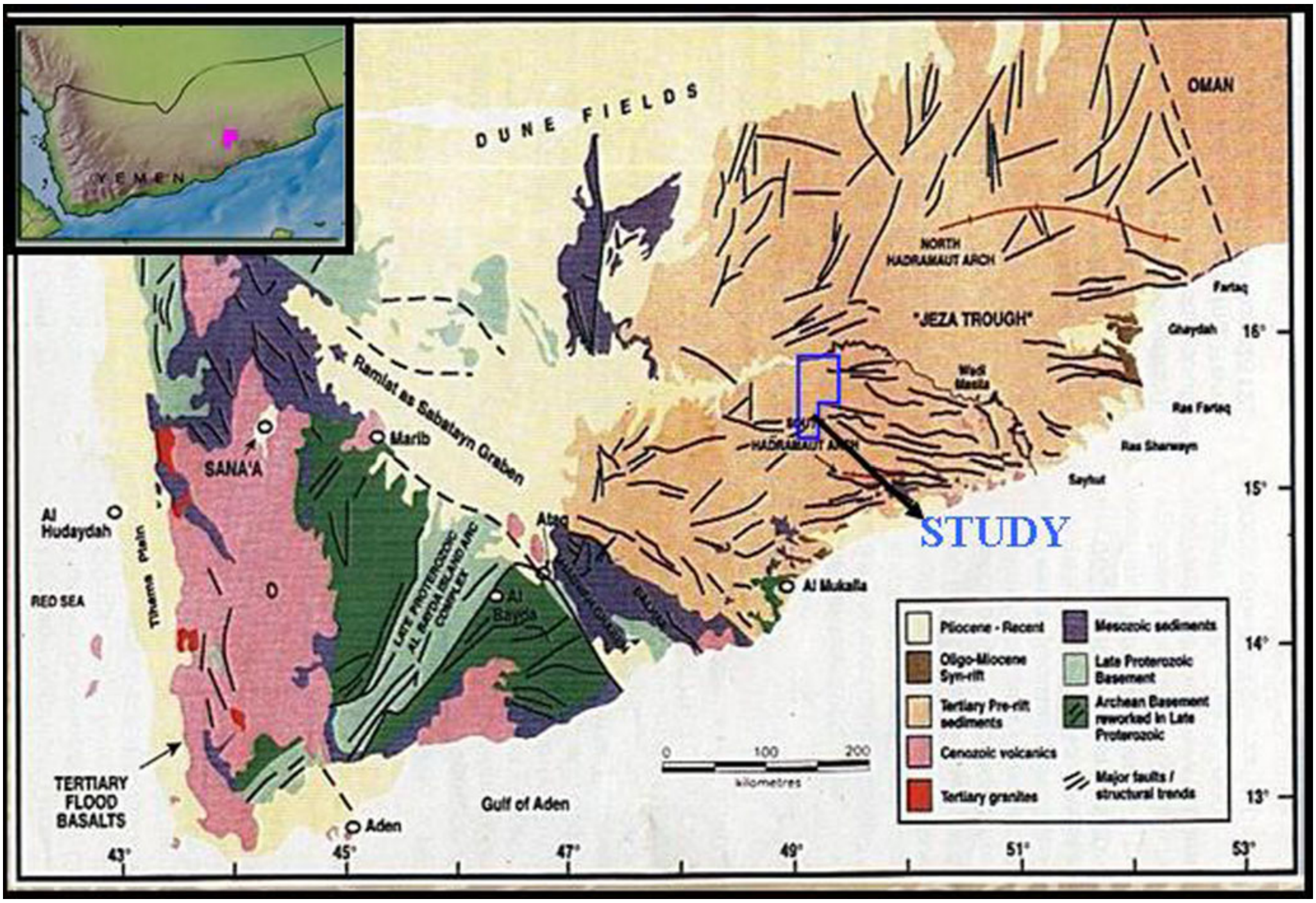


Fig. 1 A simplified geological map of Yemen, showing the location of study area

located nearer the Gondwanaland margin, remained more open marine in character and did not experience evaporative conditions and salt accumulation (Bosence 1995).

In the fields of the Masila block, the early Cretaceous marine Qishn Formation provides both the reservoir sandstone and an overlying sealing tight limestone unit (Mills 1992; Redfern and Jones 1995).

Masila basin (Masila block fields)

The structural morphology of this basin appears complex, poorly known, and published interpretations all differ. Most agree that the basin has a western area oriented NW–SE and parallel with the adjacent Sab'atayn Basin. A possible additional northern extension is the Sir Basin, which is variously interpreted to have a NW–SE orientation (Redfern and Jones 1995) or a NNE–SSW orientation (Ellis et al. 1996), or it is separated as a possible subcircular structure (Beydoun 1997). To the east the Sayun-al Masila basin is oriented more east–west and is a broadly symmetric graben with a large intrabasin high known as the Masila Terrace (Mills 1992; Redfern and Jones 1995).

The Madbi Shales of (Sab'atayn Basin) source the Masila block fields which are located over horsts that comprise the Masila Terrace (Mills 1992). Downfaulting of the Madbi source allows upward migration into older (early Jurassic) Kohlan Formation sandstone reservoirs that are sealed by limestones of the Shuqra Formation. The largest hydrocarbon volumes are reservoired in sands of the Qishn Formation sands of Barremian–Aptian age that have produced at rates of up to 12,670 b/d of 29–33 API gravity oil with little dissolved gas (Mills 1992; Beydoun et al 1993) and are sealed by tight limestones of the Qishn Formation. The absence of the Sab'atayn salt from this basin provides a direct migration pathway from the Late Jurassic Madbi source to the early Cretaceous sands. The production facilities for these fields are designed for 120,000 bopd and the estimated recoverable reserves are 235 million bbls (Mills 1992).

The Qishn Formation comprises shallow shelf to fluvio-deltaic sandstones in Central and Western Yemen and is likely to be equivalent to the lower fluviatile sandstones of the Tawilah Group of Western Yemen (Beydoun et al. 1993). To the east, it becomes more carbonate rich and passes into the purer carbonate facies of the Mahra Group (Beydoun 1997).

Stratigraphic nomenclature of the cretaceous units of Yemen

The stratigraphic nomenclature schemes utilized for the sedimentary column of Yemen were, until the middle of the 1980s, based entirely on formal to semiformal lithostratigraphic units described from measured surface sections exposed mainly in the dissected and faulted shoulders of the Gulf of Aden and Red Sea rifts and in the high plateau of the western part of Yemen for the Cretaceous successions (Beydoun 1997). But the common nomenclature and the distribution of the units from west to east is illustrated in Table 1

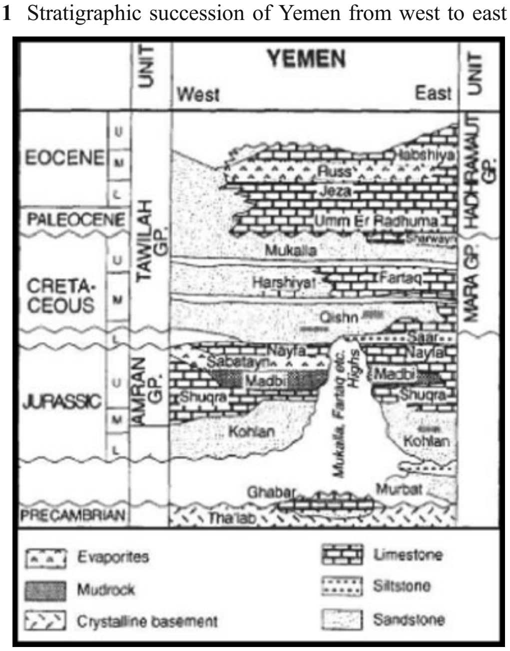
That work incorporated and partly modified the semiformally described but well established names for former North Yemen by Lamare (1930) and Geukens (1960, 1966) covering the Jurassic system (Kohlan and Amran Series modified to Kohlan Formation and Amran Group) and the Cretaceous system (Taoulah Series modified to Tawilah Group). A number of attempts were subsequently made in the 1980s to formalize the Lamare and Geukens nomenclature used in former North Yemen by renaming or redefining or revising or abandoning various units in accordance with international rules, (EI-Nakhal 1987, 1988, 1990).

Subsurface hydrocarbon exploration initially commenced with drilling in the early 1960s in the Red Seacoastal area of former North Yemen and somewhat later (middle 1960s) in the northern interior part of former South Yemen along and north of the Hadhramawt Arch. The exploration effort developed sporadically during the 1970s but was increasingly backed by both regional and new detailed geophysical surveys. Intensive exploration activity from the 1980s and especially during the early 1990s after unification has gradually unraveled a complex Mesozoic tectonic history and basin evolution the distribution and outlines of which had hitherto been masked under the overlying tabular Tertiary blanket of sediments and/or extrusive flood basalts (Beydoun 1997).

This tectonic evolution was principally linked to the late Jurassic–early Cretaceous breakup of Gondwana and was initiated along ancient lines of crustal weakness related to a basement grain developed during the final stages of cratonization of the Arabian Shield. Rejuvenation of these NW–SE and E–W oriented fracture systems during Mesozoic breakup of Gondwana was mainly in the form of polyphase extensional tectonics. Individual basin inception has been time-staggered with the NW–SE fracture system rejuvenation along the ancient Najd fault trend commencing in "Kimmeridgian times in the Ad-Dhali" and Sab'atayn basins (Marib-Shabwa-Hajar sectors; Schlumberger 1992; Beydoun et al. 1996; Ellis et al. 1996) and propagating into the Balhaf Basin during the Cretaceous (Beydoun et al. 1993, 1996). By contrast, the Say'un-Al Masila basin appears to have evolved principally during the late Jurassic to early Cretaceous with the Jiza-Qamar Basin subsiding rapidly during the Cretaceous and continuing into the Tertiary in its eastern sector (Bott et al. 1992; Beydoun et al. 1993, 1996; Redfern and Jones 1995; Ellis et al. 1996; see also Jungwirth and As-Saruri 1990). Episodic subsidence movements, punctuated by sporadic, and localized short pulses of inversion and erosion appear to have affected some basins or sectors of basins, but there is as yet insufficient regional control to enable more precision because of the Tertiary tectonic overprinting (Beydoun 1997).

This history of Mesozoic extension, subsidence, and partial inversion in basin development has given rise to considerable variations in the details of sedimentation at the local level, but nevertheless, it does not obscure overall broad patterns of sedimentation. These were, however, only very generally understood prior to subsurface exploration and even then were incompletely understood or communicated as exploration proceeded because of confidentiality considerations, with individual operating companies arriving at conclusions which were principally limited to their concession area blocks or traded data. This, understandably, led to the development of company-centered informal stratigraphic nomenclature schemes whose principal objective was to facilitate operations within the individual company's concession and not for ultimate communication in journals. It was inevitable that such approaches should result in the proliferation of expediently designed informal nomenclature schemes that regrettably have been extended beyond their intended in-house usages

Table 1 Stratigraphic succession of Yemen from west to east



to neighboring and distant concession areas through data exchange (Beydoun 1997).

As more successful new hydrocarbon discoveries were made by some operators, increased activity by hopeful newcomers resulted in further adaptations and modifications to informal in-house-oriented usage.

More critically, the question of nomenclature has gradually taken on the aspect of essentially being a subsurface problem where instrumental-based characteristics (wire line logs and/or seismic reflectors) are increasingly replacing lithological descriptions and lithostratigraphic correlations (Beydoun 1997).

This confused history of stratigraphic nomenclatural problems is not confined to Yemen, when new subsurface data independently obtained by rapid hydrocarbon exploration has often advanced beyond existing geological syntheses built solely on surface data. In an attempt to improve this, a unifying of the lithostratigraphy by the Yemen Ministry of Oil and Mineral Resources, by Ministerial Decree No. 4 for 1995, established the Yemen Stratigraphic Commission.

The Mesozoic basins in Yemen formed during two separate rifting events. The first event occurred during the Kimmeridgian-Berriasian and was followed by a period of thermal subsidence and a second rifting event during the Hauterivian-Barremian (Ellis et al. 1996).

The basins appeared to open from west to east with the Marib Basin dominated by Late Jurassic and Early Cretaceous fills followed by the Masila and Jiza' Qamar Basins filling progressively with younger sediments. Source and reservoir rocks were deposited as both pre- and syn-rift sediments, forming rift-oriented traps during rifting within horsts and tilted fault blocks. Hydrocarbon production within the Masila Basin is predominantly from Early Cretaceous Qishn Formation sands trapped in the hanging wall of rotated fault blocks sealed by tight by tight limestone of the overlying Qishn Formation (Beydoun 1997).

The pools are sourced from Jurassic marine shales in adjacent downfaulted lows, which allowed migration of hydrocarbons into the overlying and adjacent reservoirs. The Qishn Clastic Member at Nexen's Masila fields represents deposition in a fluvial to tidal flat environment, producing reservoir sandstone with porosity greater than 20% and permeability in excess of 1 Darcy. Qishn Formation sands have produced at rates of up to 12,670 b/d of 29–33° API gravity oil with little dissolved gas (Bosence 1995).

The study area

The Masila area is located in the Hadhramaut region in East Central Yemen (see Fig. 2). Oil was first discovered in the area in late 1990 with commerciality being declared in late 1991 and oil production commenced in July 1993. By the end of December 1999, the daily production rate approached 210,000 STB/D of very low GOR oil under partial to full water drive. Cumulative production is over 400 million STB (Canadian Oxy Co. 2001). Total known oil-in-place exceeds 1.6 billion STB, with proved ultimate recoverable oil reserves approaching 900 million STB. In addition, the reserve estimates (proved, probable, and possible) are in excess of one billion barrels of recoverable oil (Canadian Oxy Co. 2001).

The lower Cretaceous sequence is divided, from base to top, into Saar and Qishn Formations, of which the Qishn consists of two members: lower and upper. About 90% of the reserves are found in the lower Qishn Clastics Member of the Qishn Formation. The remaining 10% of the reserves are found in at least seven other distinct reservoir units including clastics and carbonates, ranging from late Jurassic to early Cretaceous age, in addition fractured Cambrian granitic basement rocks (Canadian Oxy Co. 2001). The distribution of the remaining reserves and further reservoir development program must await a detailed 3D geological model.

In this paper, we describe a general modeling process that improves reservoir understanding and performance forecasting of which integration of geological and geophysical data using geostatistical methods is well established. This integration leads to better reservoir characterization by utilizing a comprehensive data sets with low vertical resolution based on the seismic data, conditioned to a limited dataset with high vertical resolution based on well data.

Reservoir flow modeling involves upscaling from geological models, mostly with very large numbers of cells, and use of fast software platforms to edit those models as new data becomes available. In addition, these models should be tied to system models which include well-bore and surface facilities models to properly forecast the achievable rates and expected recoveries.

Geological setting

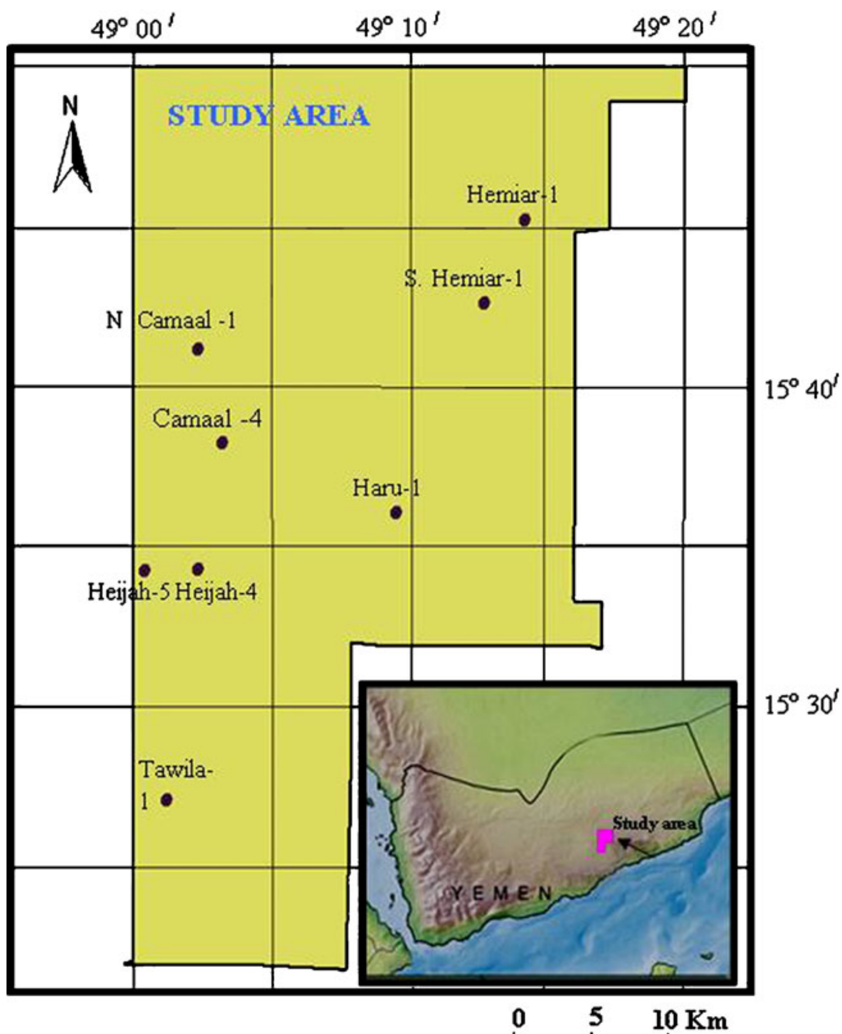
The sequence outcrop of the Masila Basin is dominated by Cenozoic sediments (Fig. 3). The Jurassic limestone has been penetrated only in the offshore wells (Haitham and Nani 1990). Less abundant are Cretaceous sandstones, that from the oldest outcropping sediments. The Oligocene–Miocene syn-rift sediments of the Shihr Group outcrop mostly in the coastal area (Bosence 1995, Watchorn et al. 1998) and Quaternary Volcanics outcrop in the eastern area of the basin. The general stratigraphy of the study area, from oldest to youngest, is mentioned in Fig. 4. The following summary represents the stratigraphy and basin evolution of the Masila Basin area and is based on previous and published studies by Putnam et al. (1997); and Beydoun et al. (1996).

Fig. 2 Location map of the study area

Pre-Cambrian The basement of the Sir-Say'un Basin consists mostly of metamorphosed Precambrian to lower Cambrian sediments. This basement complex is unconformably overlain by middle to upper Jurassic sequence.

Kohlan formation During the middle–late Jurassic, sandstones were deposited widely across the area now occupied by Yemen, with thick sedimentation within depositional lows of pre-Jurassic topography. These thick sandstone

Fig. 3 Location map of Masila and adjacent basins



deposits are known as the Kohlan Formation (Fig. 4) and include siltstone, sandstone, and conglomerate with thin limestones and green clay.

Shuqra formation The Shuqra Formation of upper Jurassic age, Oxfordian to Kimmeridgian, consists predominantly of a platform carbonate with reefal buildups. The Shuqra Formation is generally composed of limestones, including lime-mudstones, wackestones, and grainstones.

Madbi formation The Madbi Formation is generally composed of porous lime grainstone to argillaceous lime mudstone, of which the lithofacies represents deposition within an open marine environment. This unit is classified into two members, of which the lower member is commonly argillaceous limestones and sandstones and forms a good reservoir in some oil fields of the Masila Basin (Canadian Oxy Co. 2003). The upper member of the Madbi is composed of laminated organic rich shale, mudstone, and calcareous sandstone. This member is a prolific source rock in the Masila province (Mills 1992).

Naifa formation In general, the Naifa is formed mainly of silty and dolomitic limestone and lime mudstone with

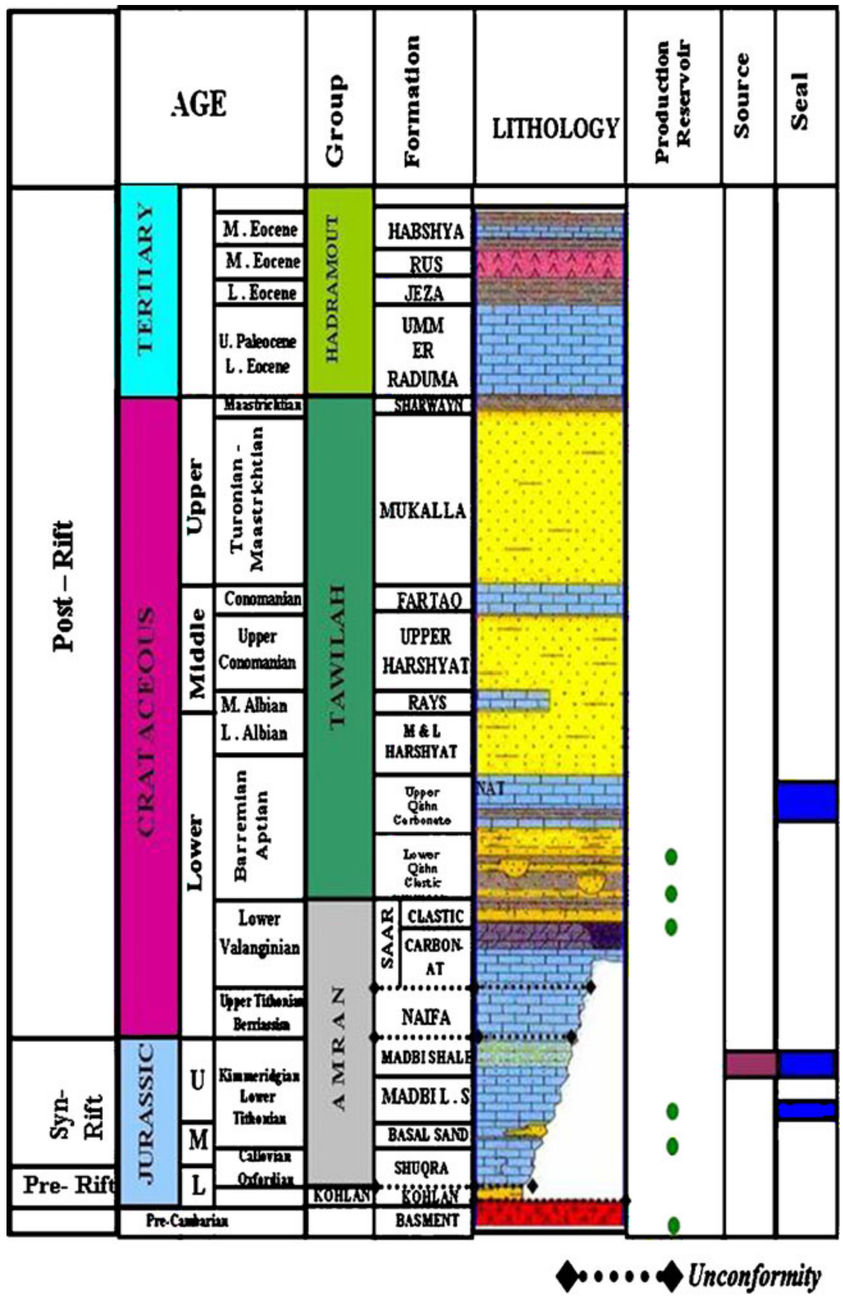


Fig. 4 Litho-stratigraphic column of study area, Yemen

wackestone and chalk. The upper part of the formation is composed of very porous clastic carbonate overlain by the Saar dolomite facies. The formation was deposited as chalk and lime mudstones in shallow water to deep water marine conditions.

Saar formation This deposit conformably overlies the Naifa Formation and is composed mainly of limestone with some mudstone and sandstone. Oil companies classified the formation into lower Saar carbonates and upper Saar clastics.

Qishn formation The term "Qishn Formation" was first defined by Beydoun (1964) and further refined in Beydoun (1966) and Beydoun and Greenwood (1968) and is used widely by operating oil companies in the Yemen. The Barremian to Aptian age range for the Qishn Formation was confirmed by samples analyzed in 1994. It is suggested that the Qishn Formation be divided into four easily separated members as follows. The lowest two members of the Qishn Formation are the laterally equivalent "clastic member" and "lower carbonate member." All the members defined herein pass laterally into a clastic dominated section in Western Yemen (Holden and Kerr 1997). The upper member, with the proposed name "carbonate member," is, as its name suggests, a unit predominantly of limestones with subordinate dolomites. Underlying the "carbonate member" is a widespread mudstone unit, the "shale member."

Clastic member The term "clastic member" is proposed for syn-rift, fluvial, and shallow marine sandstones and mudstones and subordinate limestones of Barremian age. The proposed type well is Sunah-I well from 1,675 to 1,935.5 m below KB. The lithology of the unit consists of subequal amounts of sandstones and mudstones, the latter being more common in the lower part of the unit in thicker well sections (Holden and Kerr 1997).

The upper boundary is within mudstones of the "shale member." The boundary is marked by a downhole decrease in gamma ray values and increase n sonic velocity. The lower boundary may be with sandstones and mudstones of the proposed "Furt Formation," older carbonates, or upon basement. The boundary with the "Furt Formation" is marked by an overall downhole decrease in sonic velocity and the sands of the "Furt Formation" exhibit a higher gamma ray value. The boundary is also marked by a downhole change from carbonate stringers, which are predominantly limestone in the Qishn Formation "clastic member" to dolomite in the "Furt Formation" (Holden and Kerr 1997).

The lower boundary is unconformable with sediments equivalent to the upper part of the Lower Barremian being absent. The boundary with the older carbonates (Sa'ar, Nayfa, or Shuqra Formations) is marked by a sharp downhole increase in sonic velocity.

The distribution and thickness of the "clastic member" has been recognized in 12 of the Simon Petroleum Technology (1994) study wells. The thickness varies from 761 m in the A1 Furt-I well to 20 m in the Hami-lX well. The "clastic member" can be distinguished east of the Kharwah-I well and west of approximately 50° E. To the west of the Kharwah-1 well, the section cannot be differentiated due to the well's proximal location and the subsequent dominance of clastic material throughout the Qishn Formation (Holden and Kerr 1997).

Regional correlation suggests that the "clastic member" is a lateral equivalent of the "lower carbonate member," the latter being deposited in deeper marine conditions away from areas of sediment source. The environment of deposition is an alluvial fan/braid-plain to meander plain fluvio-deltaic sandstones with common shallow marine sandstones and mudstones. These pass laterally into the shallow to locally deeper marine lime mudstones and carbonates of the "lower carbonate member" of the Qishn Formation (Holden and Kerr 1997).

Lower carbonate member The term "lower carbonate member" is proposed for syn-rift offshore marine limestones and subordinate mudstones of Barremian age. The unit is named after its dominant lithology and its stratigraphic position below the "shale member" and the "carbonate member." The proposed type well is Masila-lX well from 3,240 to 3,400 m below KB. The proposed reference well is Al Furt-1 well from 2,553 to 3,314 m below KB where the lithology consists of limestones and subordinate mudstones, with the latter being more common in the lower part of the unit. The upper boundary is with the mudstones of the "shale member" and as such is marked on the wireline logs by a sharp downhole increase in sonic velocity and decrease in gamma ray values (Holden and Kerr 1997). The lower boundary in the proposed reference section, the Al Furt-1 well, is with the mudstones of the "Furt Formation." In this section, the boundary is marked by a sharp downhole increase in gamma ray values and decrease in sonic velocity. The boundary is thought to be unconformable with sediments of intra-lower Barremian age being absent. In the type well, Masila-lX, the "lower carbonate member" overlies the carbonates of the Sa'ar Formation which exhibit higher sonic velocities than those of the "lower carbonate member." The wireline log character at the boundary in the type well is exaggerated as a basal mudstone unit is present in the "lower carbonate member." The lower boundary in the type well is also unconformable, with sediments of upper Valanginian to probable lower Barremian age absent (Holden and Kerr 1997).

The distribution and thickness of the “lower carbonate member” has been recognized in three of the Simon Petroleum Technology (1994) study wells. The thickness varies from 160 m in the Masila-lX well to 761 m in the Al Furt-1 well. The “lower carbonate member” can be distinguished east of approximately 50°E. The carbonates and mudstones of the “lower carbonate member” are lateral equivalents of the “clastic member,” which was deposited in more marginal areas. The environment of deposition for the lime mudstones and carbonates of this unit is shallow to locally deeper marine. These interdigitate with the fluvio-deltaic to shallow marine clastics of the “clastic member” of the Qishn Formation (Holden and Kerr 1997).

After the marine transgression that deposited the Saar Formation, a reduction of sea level resulted in erosion of the Valanginian deposits. In the Hautevivian to Barremian time (late early Cretaceous), braided-plain to fluvial and shallow marine sediments were deposited in the Say’un-Al Masila basin and mainly contains basal Lower Qishn clastic member. This basal unit is followed by the deposits of shallow marine shale and carbonate sediments that accumulated in the Barremian–Aptian time and forming the upper shale and carbonate members of Qishn Formation. The Qishn Formation is divided into two members, termed the lower Qishn clastic and upper Qishn carbonate members (Fig. 4).

The upper Qishn carbonate member consists of laminated to burrowed lime mudstone and wackestone interbedded with terrigenous mudstone and black fissile shales. These sediments were deposited in deep water under alternating open and closed marine conditions (Beydoun et al. 1996). The lower Qishn clastic member forms the main reservoir rocks in the Masila area. Oil companies classified the Qishn Formation into the following units: lower Qishn clastic (S1, S2, and S3), and upper Qishn carbonate. The upper Qishn consists mainly of carbonate rock with red shale beds at the base of which the red shale beds are considered to be one of the main seismic markers at the Masila area (Holden and Kerr 1997).

Shale member The term “shale member” is proposed for a widespread mudstone unit of Upper Barremian age thought to represent a maximum flooding event. The “shale member” contains the deepest marine microfaunas recovered from the Qishn Formation and is named after its dominant lithology. The proposed type well is Masila-lX well from 3,232 to 3,240 m below KB. The proposed reference well i*s* Sunah-1 well from 1,657.5 to 1,675 m below KB. The lithology of the unit consists predominantly of mudstones with minor limestones. The upper boundary is with the limestones of the “carbonate member” and as such is marked on the wireline logs by a sharp downhole decrease in sonic velocity and increase in gamma ray values. The lower boundary of “shale member” is with the carbonates and mudstones of the “lower carbonate member” or the sandstones and mudstones of the “clastic member.” The boundary is therefore marked on the wireline logs by a downhole decrease in gamma ray and increase in sonic velocity values. The distribution and thickness of the “shale member” has been recognized in 12 of the Simon Petroleum Technology (1994) study wells. The thickness varies from 40 m in the Al Furt-1 well to 5 m in the Thamoud-1 well. The environment of deposition of the marine shale and is thought to represent deepening associated with a maximum flooding event (Holden and Kerr 1997).

Carbonate member The term “carbonate member” is proposed for a widespread carbonate unit of Lower Aptian age, overlying the “shale member” and is named after its dominant lithology. The proposed type well is Masila-lX well from 3,125 to 3,232 m below KB. The proposed reference well is Sunah-I well from 1,560 to 1,657.5 m below KB. The lithology of the unit consists predominantly of limestone with subordinate mudstones. The unconformable upper boundary is with the mudstones and sandstones of the Harshiyat Formation, the boundary being marked by a downhole increase in sonic velocity and decrease in gamma ray values. The lower boundary of the “carbonate member” is with the mudstones of the “shale member.” The boundary is therefore marked on the wireline logs by a downhole increase in gamma ray values and decrease in sonic velocity (Holden and Kerr 1997).

The “carbonate member” has been recognized in 13 of the Simon Petroleum Technology (1994) study wells for which the palaeofacies distribution is illustrated in Fig. 16. The unit occurs to the east of the Kharwah-1 well which is

Table 2 Available data which are the most important aspects of building any 3D model

Data		Formats	Type
Wells data	Well headers	(Well heads (*.*))	Well
	Well deviations	(well path deviation)(ASCII)(*.*)	Well
	Well logs	(Well log (LAS 3.0) (*.las)	Well
Well tops		(ASCII) (*.*)	Well tops
3D seismic data		Seisworks Horizon Pick (ASCII) (*.*)	Lines

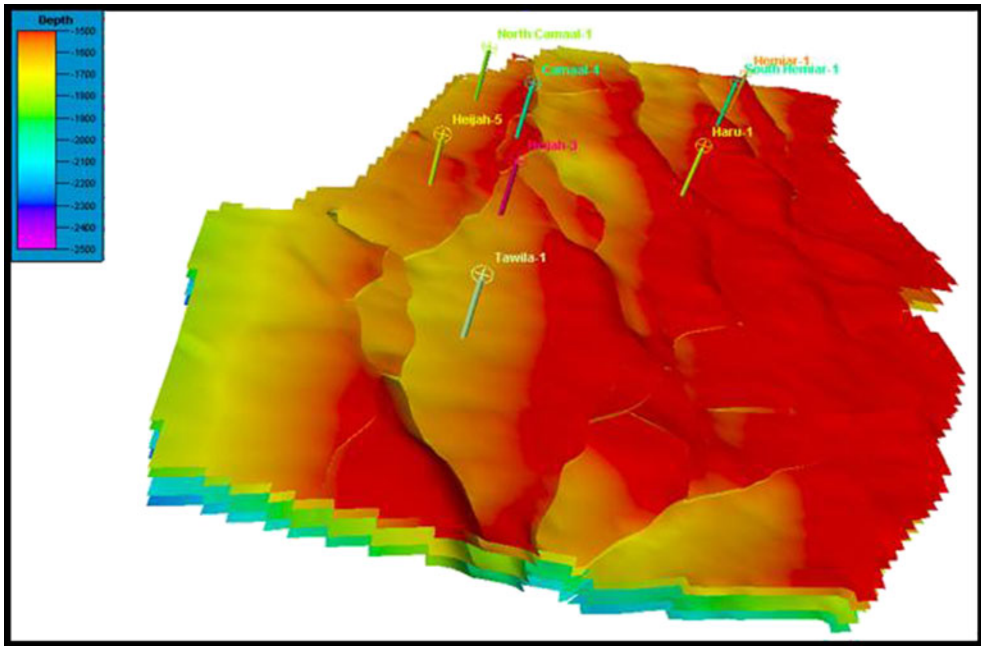


Fig. 5 Structural model of the Masila area, showing the relationship between the major fault and selected horizons in the basin: pre-fault top of basement (*blue surface*); syn-fault tops of the upper Qishn, and lower Qishn members and Saar Formation (*red*, *yellow*, and *green surfaces*)

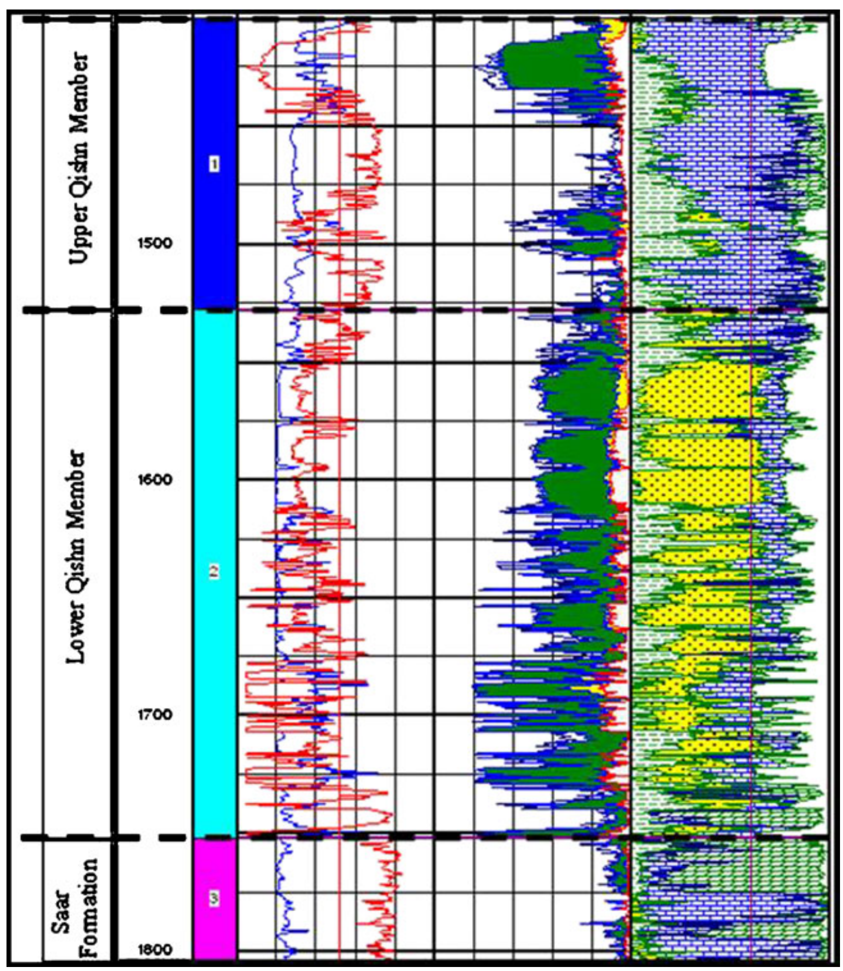


Fig. 6 Masila oilfield reservoirs

an indication of the extent of marine influence in the Early Aptian. To the west of Kharwah-1 in marginal settings, the Qishn Formation is undifferentiated. The thickness varies from 229 m in the AI Furt-1 well to 13 m in the Al Qarn-1 well. The “carbonate member” consists of shallow marine, with subordinate deeper marine, carbonates and mudstones, shallow subtidal lime grainstone shoals, and coral/rudist buildups. Similar shallow water carbonates were deposited across Saudi Arabia and Oman forming the Shu’aiba Formation (Hughes-Clarke 1988).

Late lower Cretaceous–Tertiary Formations The late lower Cretaceous–Tertiary Formations consist of clastic (Harshiyat Formation) and carbonate (Fartaq Formation) interbedded each other suggesting lacustrine to marginal marine depositional settings. A similar pattern of sedimentation occurred during the late Cretaceous time (Coniacian though Campanian), when fluvial systems domain (Mukalla Formation). These fluvial deposits prograded southeast in the Al-Masila Basin. Transgression culminated in the latest Cretaceous (Mastrichtian), when carbonate deposits were developed (Sharwan Formation). In the late Paleocene, transgressive shale deposits of the shammer member were deposited at the base of the carbonates of the Umm Er-Radhuma Formation. The carbonates deposits continued to accumulate during the early Eocene, followed by anhydrites of the Rus Formation during the middle Miocene. A rise in the sea level during the middle to late Eocene resulted in

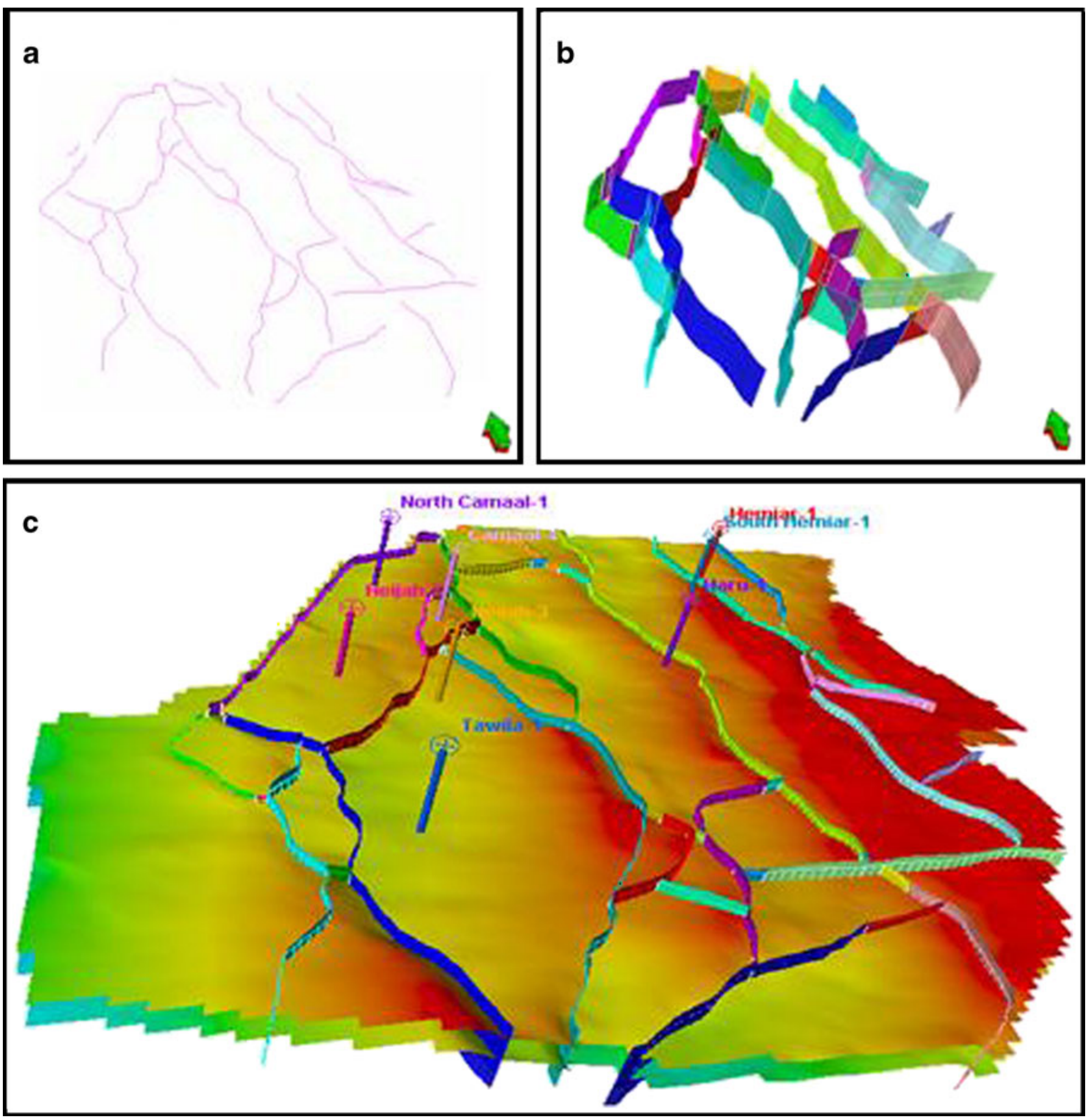


Fig. 7 Fault model show **a** faults outline system, **b** fault surfaces, and **c** surface-appended of the horizons in the Masila oilfield

widespread carbonate deposition of the Ghaydah Formation which graded into shallow marine fine-grained clastics of the Habashiya Formation.

Available well data One of the most important aspects of building any model is to understand the data and checking the quality of the files built from such data (Table 2).

1. Wells Data:

Wells data are imported in three steps:

   a. Well-Heads data: A well-heads file must be created to specify the top position of the well and length of the well path
   b. Deviation data: If the well is not vertical, a file containing the deviation survey must be imported describing its path
   c. Well-Logs data: Eight wells (Fig. 3) that cover the whole study area were selected based on the different log types (petrophysics parameters logs in LAS format)

2. Well-Tops data
3. Seismic data

Both 2D and 3D seismic can be imported as SEG-Y format. There is no limit to the size of the seismic file.

Generalized procedure for building the geological The processes of building 3D geological models are:

1. Geological and geophysical modeling—construction of the geological framework
2. Reservoir characterization—distribution of the geological units, rock, and fluid properties
3. Reservoir flow modeling—upscaling (or upgridding) and flow modeling

Geological and geophysical modeling

From a purely physical point of view, the interpretation of seismic surveys is non-unique and requires continuous calibration and ground truthing by geology outcrop and wellbore data. High frequency, ultra sonic P- and S-wave velocities, density, porosity, and natural gamma ray are routinely measured, either in the laboratory from plugs drilled in the outcrop, or in situ from wellbore logging tools. The construction of the seismic outcrop model for sequence stratigraphy is conventionally built in several discrete steps: (1) construction of a quantitative lithologic model, (2) determination of petrophysical properties, (3) construction of the impedance function, and (4) convolution of the impedance function with a seismic signal.

This process begins with the creation of a geological framework of the structure and reservoir architecture from seismic data and well logs (if the structure has been penetrated by wells). In this process, horizon maps of the top and base of the structure are generated from seismic data tied to well markers, if available. Additional horizons should be added as needed between the top and base horizons to aid in the vertical layering of the model. The main goal in geological and geophysical modeling is to represent all major geological features, such as faults, flow barriers, etc., that are likely to affect the connectivity of the reservoir. Geological modeling should be conducted on a software platform that can be readily updated. In this case, we used Petrel software to building 3D geological model.

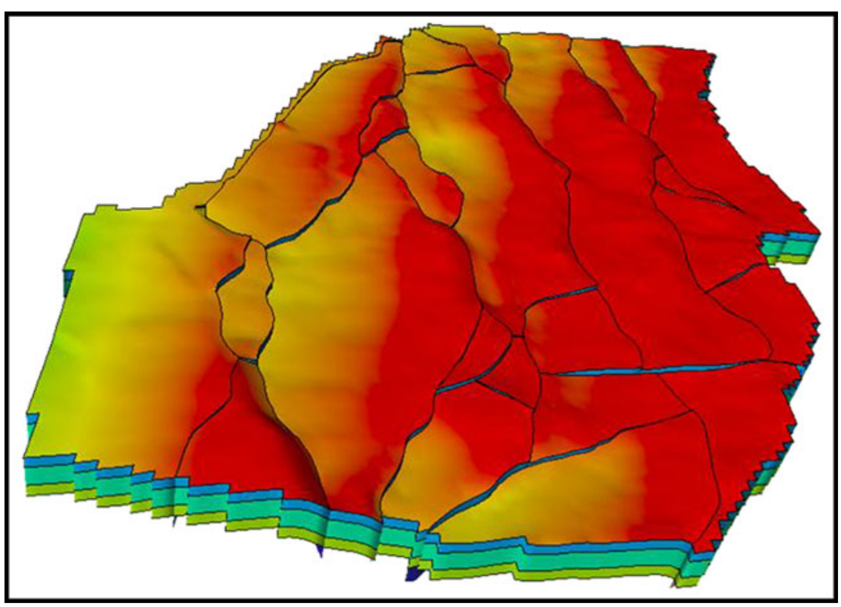


Fig. 8 3D structural model includes faults, stratigraphy geometry of the reservoirs of the study area

The structural framework represents the overall geometry of the reservoir and is the backbone for designing the 3D grid that will contain all the geological/petrophysical information and the generated reservoir properties. It includes two main elements, structure surface and faults, and defines the relationship between topographical those and the interpreted well data. Most geological (static) models are eventually converted into flow (dynamic) models.

Reservoir characterization Volumes of research have been published on reservoir characterization and the value of applying geologic parameters to porosity and permeability questions to determine reservoir compartments.

Reservoir characterization attempts to describe the physical properties of oil reservoirs through the use of many different data types. Several sources of geological and geophysical data measure the reservoir volumes at different scales. It is our purpose to integrate these datasets. The primary tool for probing the entire reservoir is 3D reflection seismic surveying. While 3D seismic data cover the entire reservoir volume, the wavelengths are typically 10–100 m because most

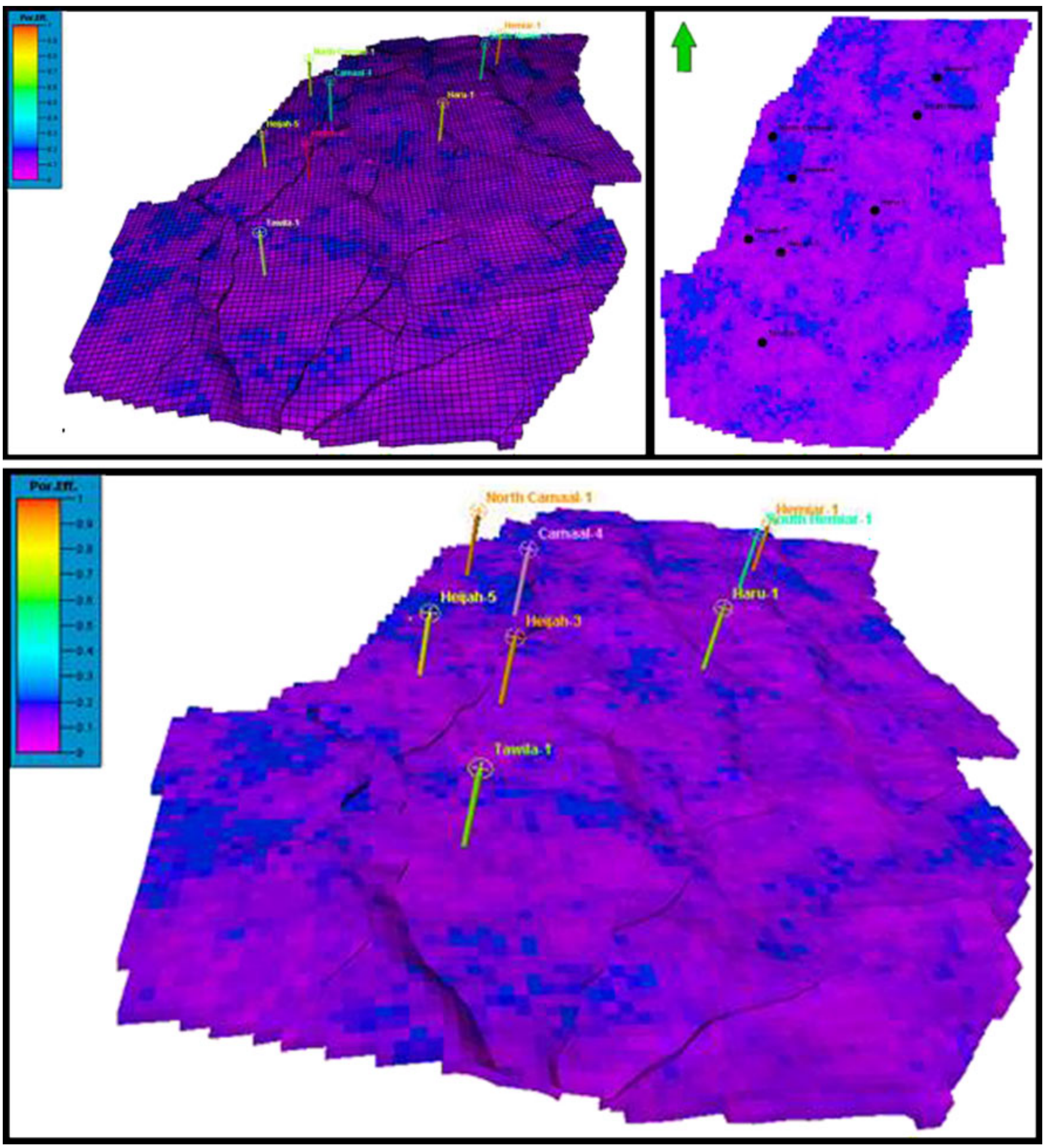


Fig. 9 Petrophysics model (porosity) output from view: **a** 3D gridding model, **b** horizontal slice SGS, **c** color-coded according to porosity of the upper Qishn member in the study area

seismic frequencies for surface data are in the 5–100 Hz range.

Well logs and core measurements usually are made on the scale of 0.1–1.0 m. Although the scale of resolution is quite fine, the volume of investigation is small, confined to within a few meters of the borehole. To fill in the "missing wavelengths" between borehole data and surface seismic data, we can acquire borehole seismic data. Such data, gathered by using seismic sources and receivers to fill the wavelength gap, would include vertical seismic profiling and cross-borehole seismic surveys. The key is to characterize the reservoir's physical properties by integrating the various data sets with different wavelengths.

Reservoir characterization is the process of integrating various qualities and quantities of data in a consistent manner to describe reservoir properties of interest at inter-well locations. For reservoirs, reservoir characterization is the process of integrating seismic data of various qualities and well data of limited quantities in a consistent manner to assign

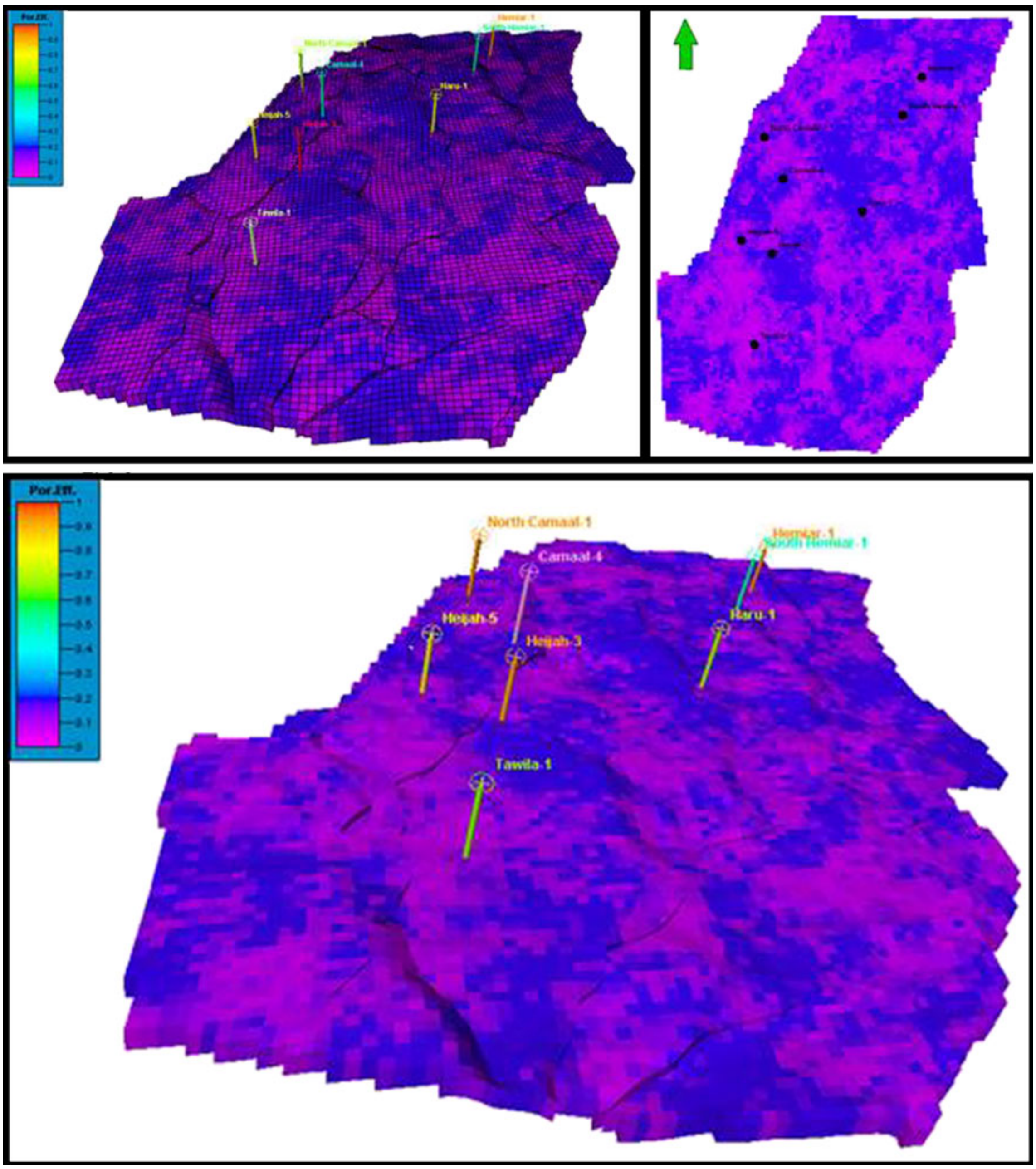


Fig. 10 Petrophysics model (porosity) output from view: **a** 3D gridding model, **b** horizontal slice SGS, **c** color-coded according to porosity of the lower Qishn member in the study area

reservoir properties to a large extent of the reservoir using the seismic data. Geostatistics is especially useful in the characterization of reservoirs because it is a technique that enables the propagation of reservoir properties in a manner that is statistically coherent and consistent. It allows the application of concepts such as trends and variability of properties as well as subjective interpretation in the description of reservoir. The basic inputs in the reservoir characterization process are the geological framework, well log data, seismic amplitude data, well test data, and any other data which can be correlated to rock properties, such as porosity, permeability, saturation, thickness, and lithofacies. The simplest geostatistical methods applicable to reservoirs are the sequential simulation techniques. These are Sequential Gaussian Simulation (SGS) and Sequential Indicator Simulation (SIS). SGS is generally used to distribute continuous properties such as porosity, permeability, saturations, net-to-gross ratios or net thickness, gross thickness, etc. Meanwhile, the SIS was chosen to distribute three facies types in each reservoir interval: shale, sandstone facies, and carbonates facies by using the flags created in

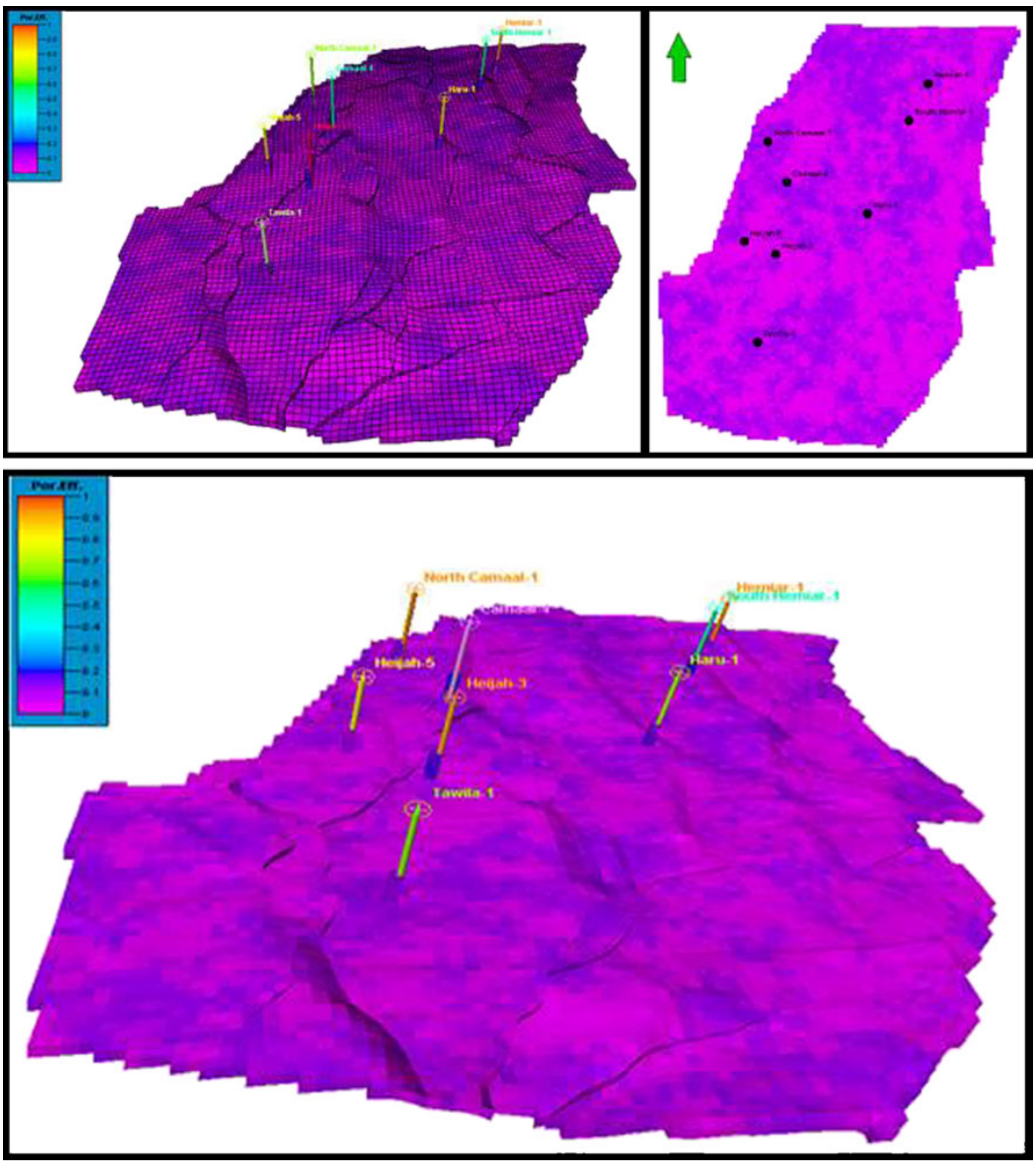


Fig. 11 Petrophysics model (porosity) output from view: **a** 3D gridding model, **b** horizontal slice SGS, **c** color-coded according to porosity of the Saar Formation in the study area

ptrophysical information (Fig. 6). Reservoir properties, such as initial water saturations, porosities, permeabilities, and facies, were upscaled into model cells along the well paths from processed well logs.

Reservoir flow modeling The geological formation of petroleum involves a complex network of coupled RTM (reaction, transport, mechanical) processes. These processes are interdependent on chemical reactions, mass transport and fluid flow, and mechanical forces at work in the earth. The computer model should take these interactions into account, using iteration (continuous feedback) procedures to simulate the changes that occur in nature. Predicting the permeability of the rock is a particularly important task because the type and degree of connections between pores influence the ability of a well to produce natural gas and crude oil. The volume of interconnecting pores can be increased significantly by fracturing. The degree of fracturing is related to the stress, fluid composition, fluid pressure, and thermal histories of a given rock layer.

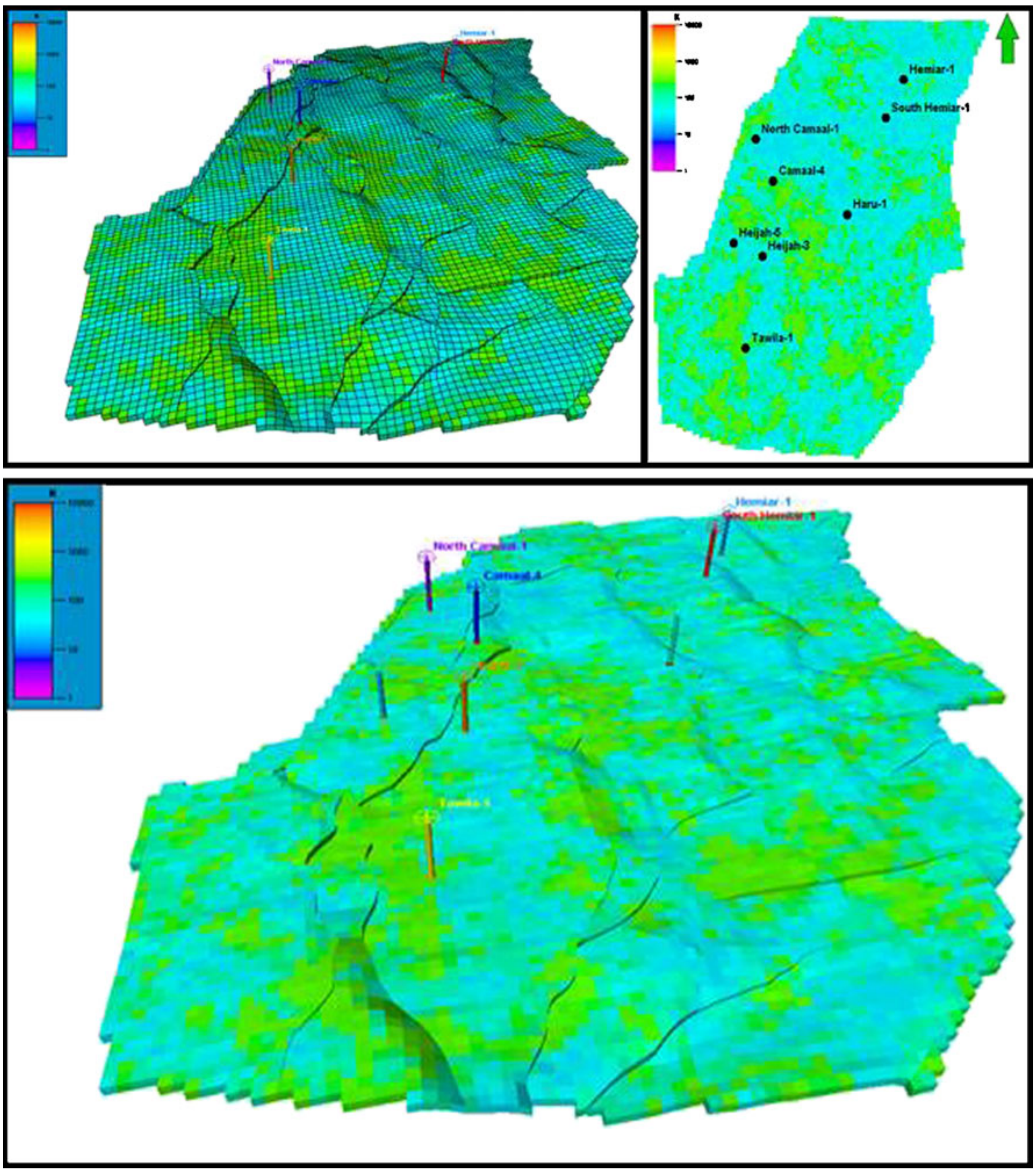


Fig. 12 Petrophysics model (permeability) output from view: **a** 3D gridding model, **b** horizontal slice SGS, **c** color-coded according to permeability of the upper Qishn member in the study area

Integrated flow modeling presents the formulation, development, and application of an integrated flow simulator. Integrated flow models make it possible to work directly with seismically generated data at any time during the life of the reservoir. An integrated flow model combines a traditional flow model with a petrophysical model. We have to understand the properties of porous media within the context of multidisciplinary reservoir modeling and present the technical details needed to understand and apply the simulator to realistic problems.

For example, tidal sandstone reservoirs contain significant intervals of hydrocarbon-bearing heterolithic facies characterized by the presence of tide-generated sedimentary structures such as flaser, wavy, and lenticular bedding (millimeter to centimeter sand–mud alternations). The reservoir properties (sandstone connectivity, effective permeability, and displacement efficiency) of these facies using 3D models reconstructed directly from large rock specimens. The key control on reservoir quality is the connectivity and continuity of the sand-

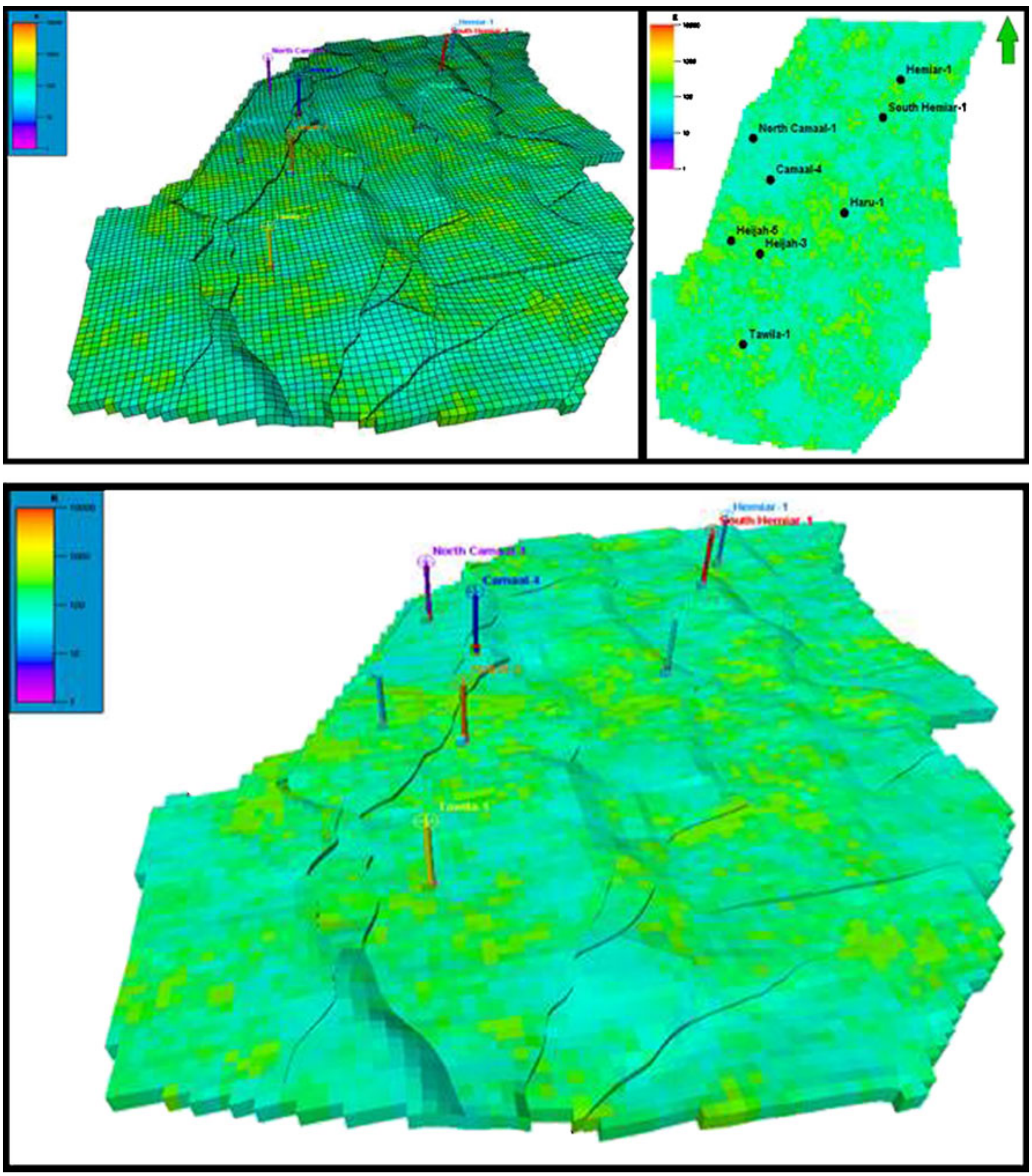


Fig. 13 Petrophysics model (permeability) output from view: **a** 3D gridding model, **b** horizontal slice SGS, **c** color-coded according to permeability of the lower Qishn member in the study area

stone and mudstone layers. If the sandstone layers form a connected network, they are likely to be productive even at low values of net-to-gross (about 0.3–0.5). This may explain why the productivity of low net-to-gross, heterolithic tidal sandstones is commonly underestimated or overlooked. Connectivity is the dominant control on the transition between productive (pay) and nonproductive (nonpay) heterolithic facies. However, connectivity is difficult to characterize because core plugs sampled from the subsurface are too small to capture connectivity, whereas 2D outcrop measurements can significantly underestimate the true 3D value.

Reservoir flow modeling converts the static geocelluar model created through the process of geological modeling and reservoir characterization into a dynamic model with fluid properties and flow parameters. The first step is transforming the static geological model into a dynamic model. This is the upscaling (or upgridding) process. Upscaling is the process of reducing a geological model with a large number of cells into a model with a much

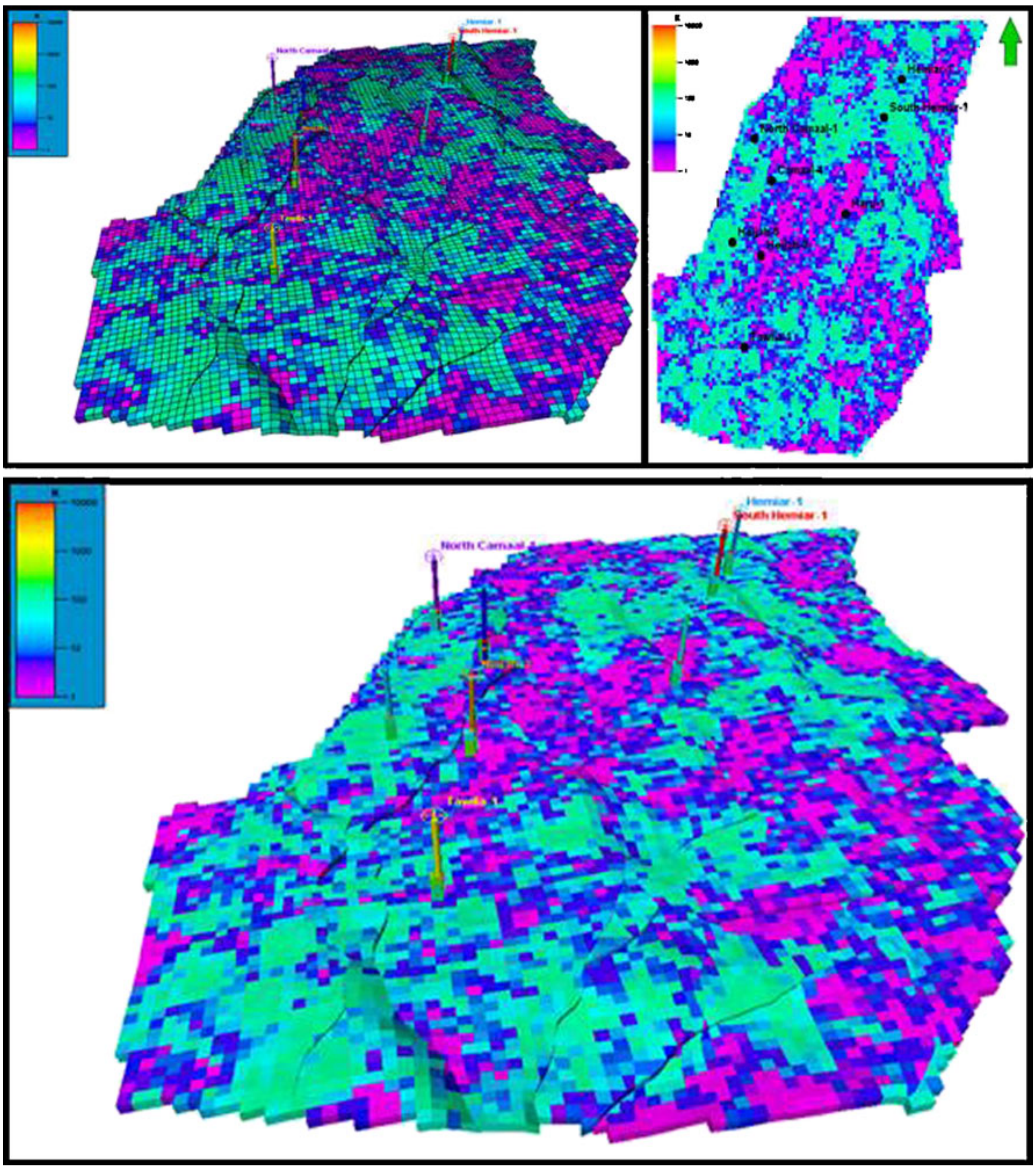


Fig. 14 Petrophysics model (permeability) output from view: **a** 3D gridding model, **b** horizontal slice SGS, **c** color-coded according to permeability of the Saar Formation in the study area

smaller number of cells while retaining key geological heterogeneities and features.

The geocellular model is used directly in the flow simulation mode. In practical cases, especially for large geological models, some degree of upscaling is usually necessary. The key here is to minimize the amount of upscaling that has to be done. This is achieved principally during the geological modeling phase by selecting a grid system that is transferable to the flow modeling phase while capturing and retaining key geological features. A practical approach is to select an areal (x, y) grid system for the geological model which is retained for the flow model while upscaling only in the vertical (z) direction as the geological model is transformed into a flow model.

Field example: Masila reservoirs

The Masila reservoirs are located in Hadramaut region of Central Yemen (Fig. 2). The lower Cretaceous sequence consists of three main reservoirs, from top to base, the upper Qishn, and lower Qishn members and Saar

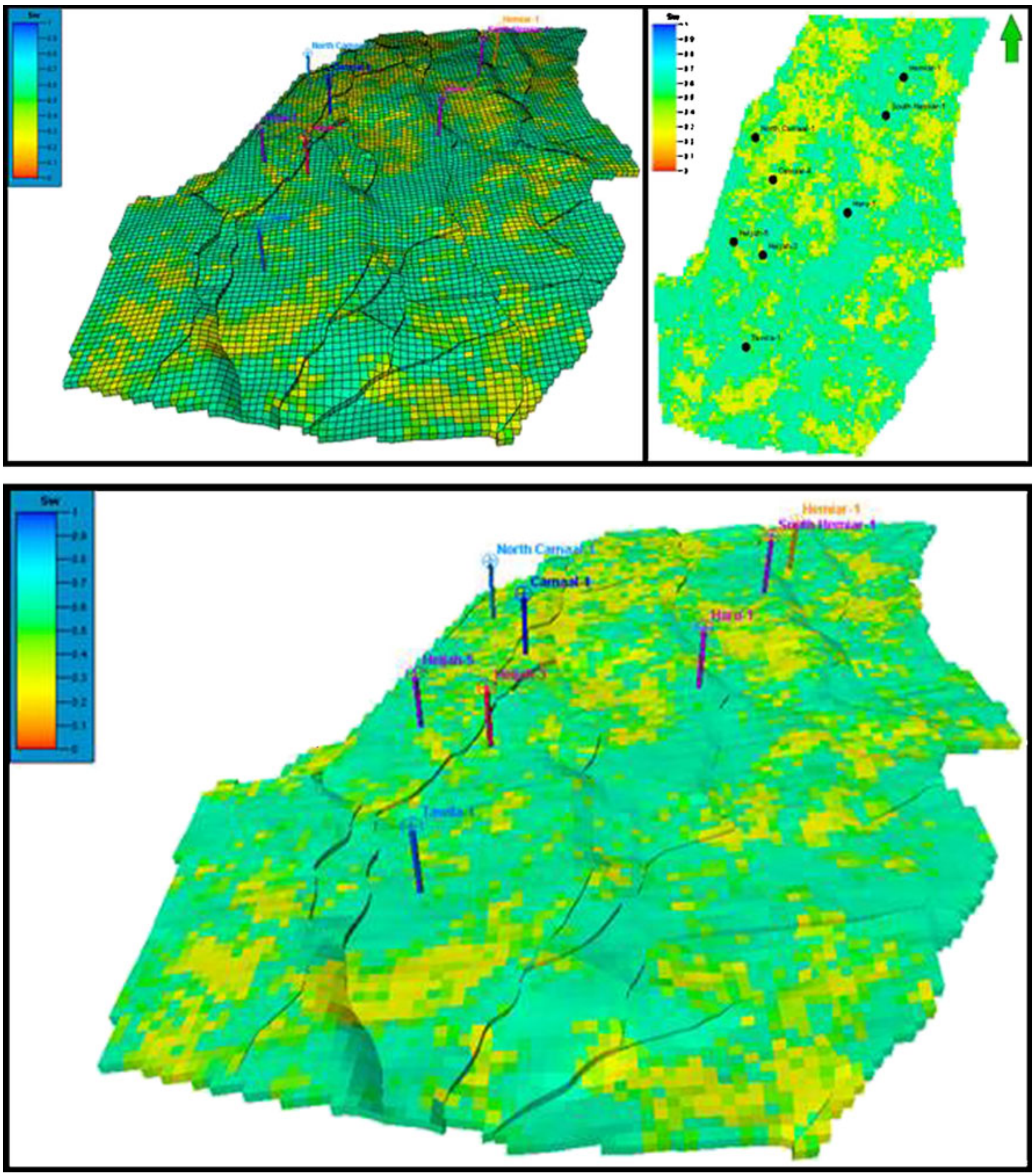


Fig. 15 Petrophysics model (water saturation) output from view: **a** 3D gridding model, **b** horizontal slice SGS, **c** color-coded according to water saturation of the upper Qishn member in the study area

Formation as shown in Fig. 20. The models described here were built for the lower Cretaceous reservoirs.

Geological modeling The stratigraphy of the studied reservoir can be summarized as follows, from top to bottom:

Upper Qishn Member (red surface)
Lower Qishn Member (green surface)
Saar Formation (yellow surface)

Extensive datasets were used to construct the geological model of the reservoir. These include:

1. Geological structures (major horizons, permeability barriers, fluid contacts, etc.).
2. Fault polygons for all major faults
3. Processed log data for eight well penetrations
4. Well log-data (porosity, permeability, saturations, etc.)
5. Seismic data

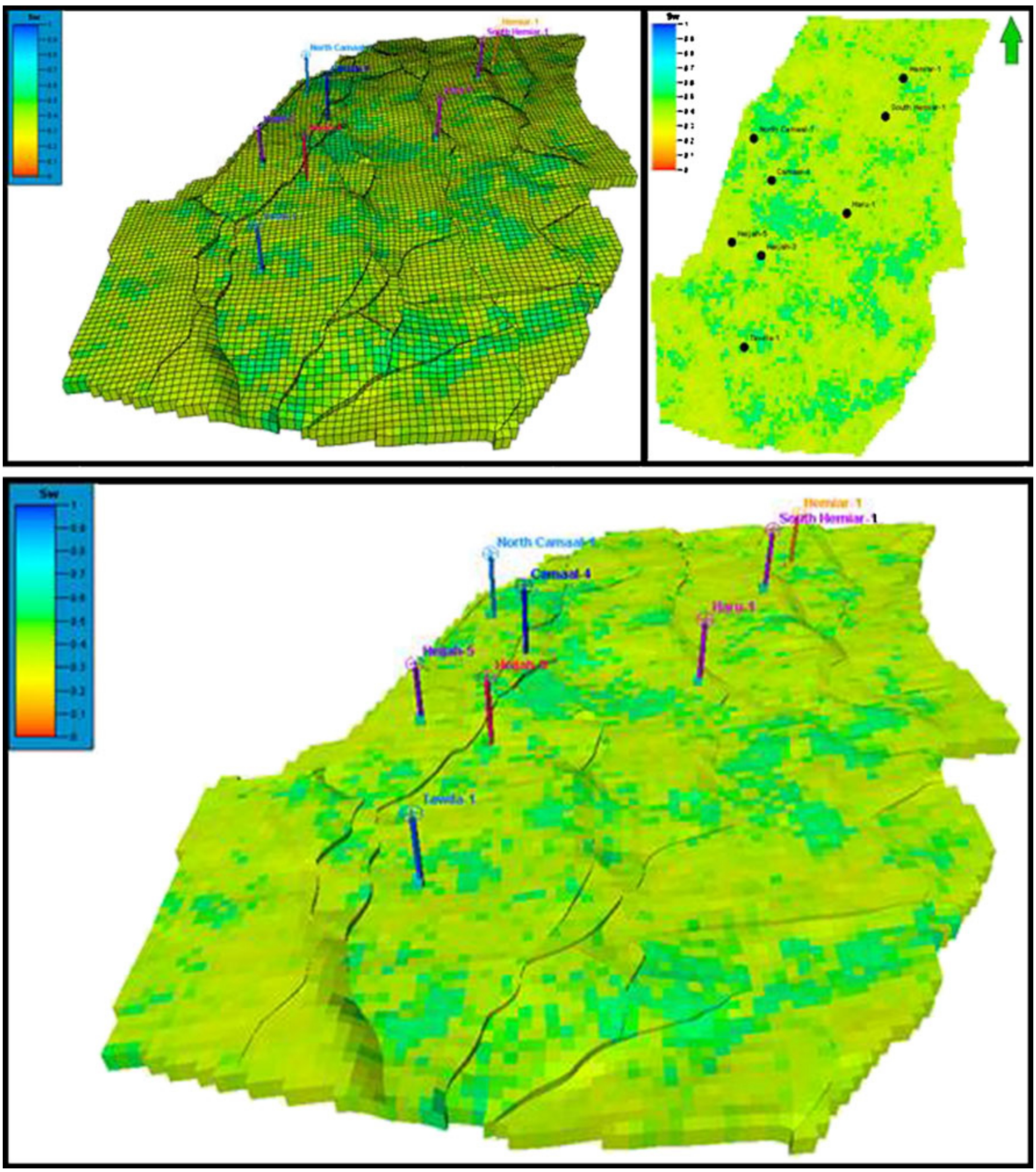


Fig. 16 Petrophysics model (water saturation) output from view: **a** 3D gridding model, **b** horizontal slice SGS, **c** color-coded according water saturation of the lower Qishn member in the study area

The top and base structure maps were digitized and transformed into surfaces, as shown in Fig. 5. The main geological feature in this field is a system of faults (shown in Figs. 5 and 7) that divides the field into eastern and western sections (Fig. 6). The fault system, as well as other smaller faults, was modeled as vertical fault surfaces (Figs. 7 and 8).

Petrophysical model An accurate model of the reservoir geology is a crucial input to the complete field development planning process. Without it costly decisions like the placement of wells and future predictions about production volumes, using reservoir simulation, will be wrong.

A process or procedure used to interpret petrophysical (usually wireline log) data. Usually representing a set of equations, algorithms, or other mathematical processes, petrophysical models often have multiple routines. For example, a deterministic model might include routines that: calculate the shale volume, total porosity, effective porosity, water saturation, and permeability. The models have to be calibrated using core, production, test, and other datasets. Although many software packages contain ready-built petro-

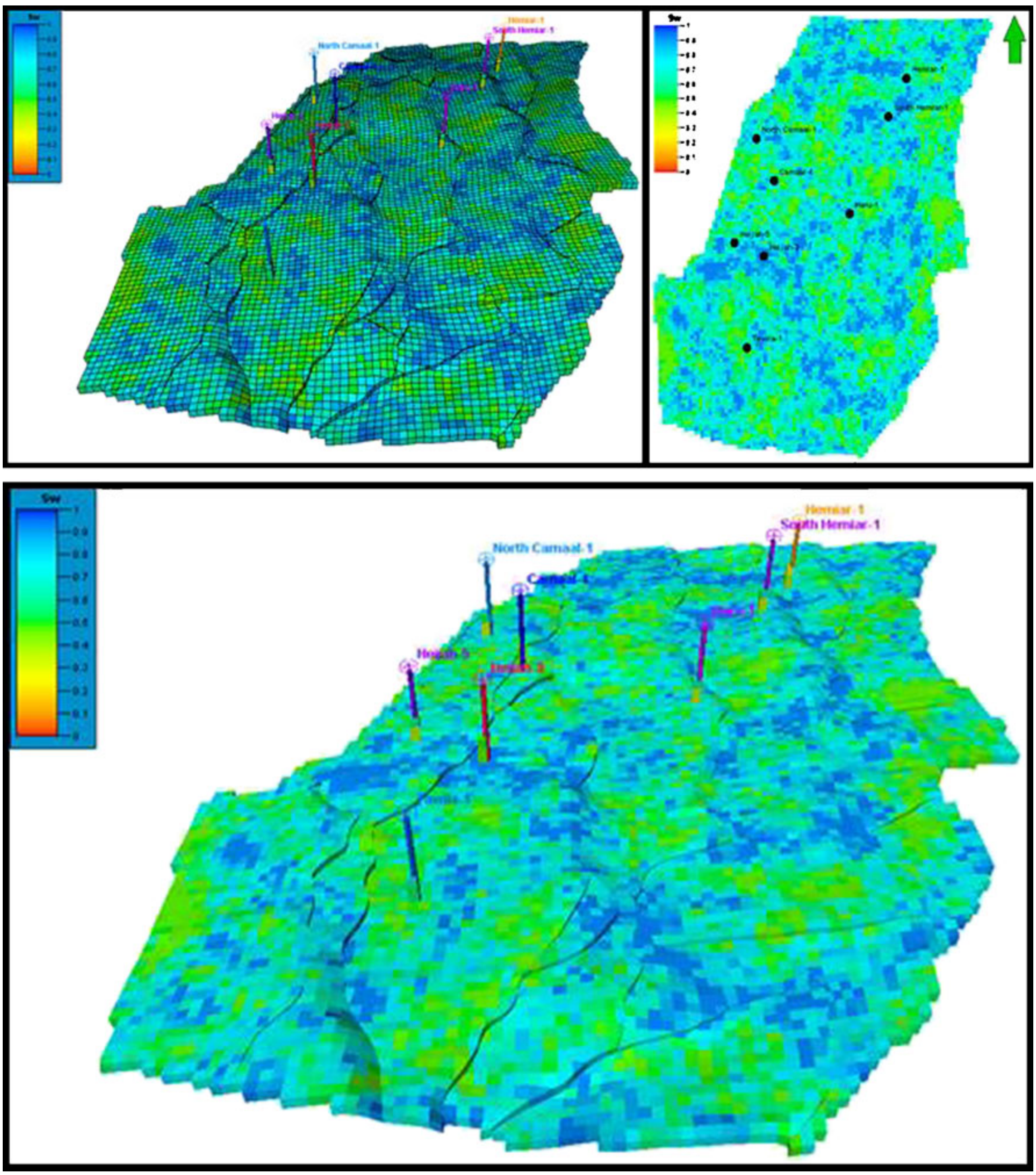


Fig. 17 Petrophysics model (water saturation) output from view: **a** 3D gridding model, **b** horizontal slice SGS, **c** color-coded according to water saturation of the Saar Formation in the study area

physical models or component routines that can be called upon, many log-analysis problems are unique and require that "built to purpose" models be constructed. Construction of new petrophysical models is normally driven by the data available and the nature of the problem to be solved.

Porosity values were distributed across the model using SGS. Similarly, water saturation and permeability were distributed with SGS with collocated on distributed porosity data.

Figures 9, 10, 11, 12, 13, 14, 15, 16, 17 is an example of the geological model showing the porosity, permeability, and water saturation distribution created by this process of the study area. Those models reflect that the porosity values were of the upper Qishn member range from 9.5% to 14.5% while the porosity model of the lower Qishn member (Fig. 10) reflects the porosity value is not exceeds 21.5%. Meanwhile, the porosity model of the Saar Formation (Fig. 11) reflects the porosity value is range

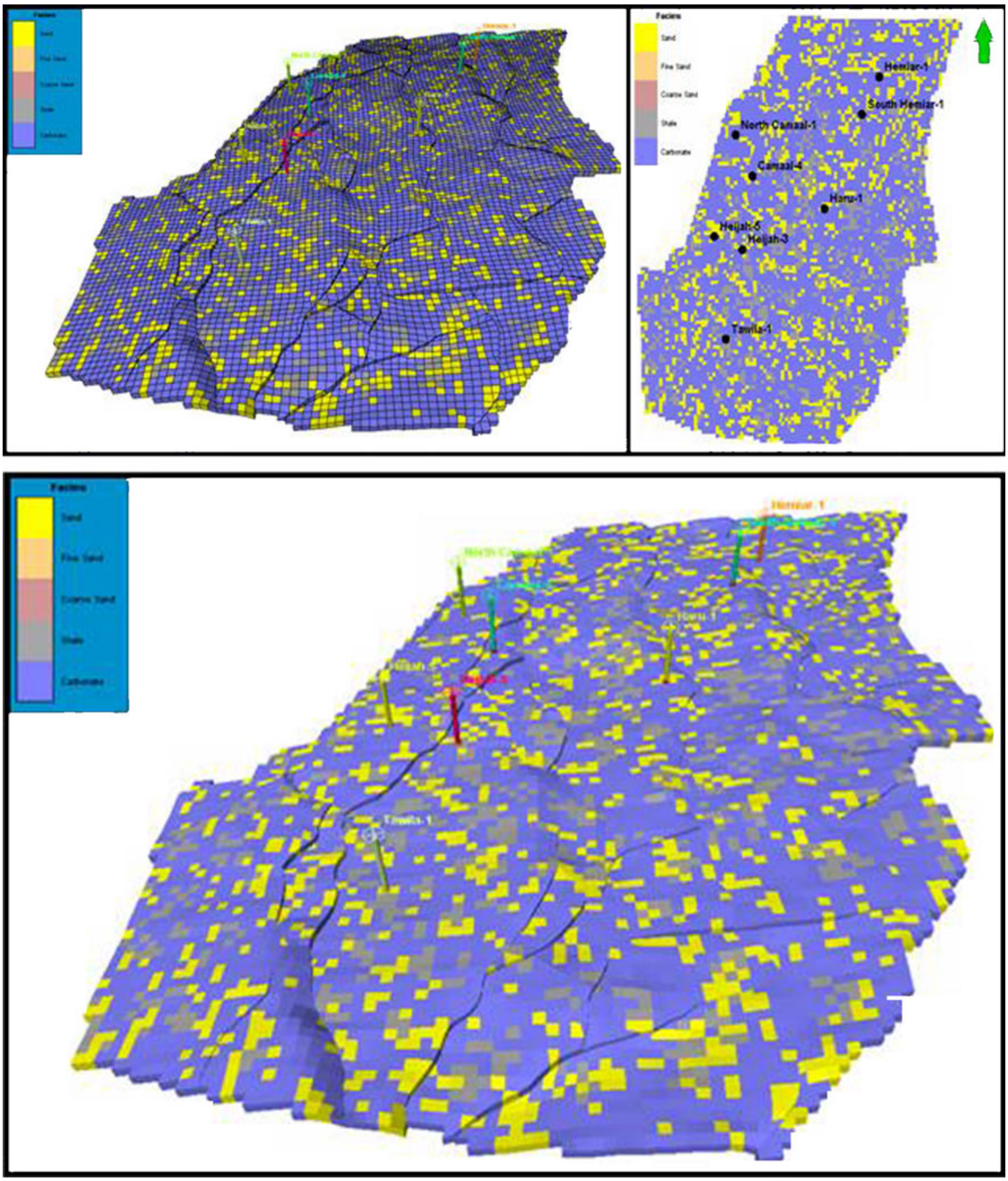


Fig. 18 Facies model output from view: **a** 3D gridding model, **b** horizontal slice SIS, **c** color-coded according to facies of the upper Qishn member in the study area

from 3% to 12%. Permeability is considered to be a function of porosity.

A set of equations was derived from well tests and porosity logs and used to populate the 3D grid. This method for deriving permeability distribution gives satisfactory results. In study area, the permeability model of the upper Qishn member (Fig. 12) reflects that permeability value ranges from 43 to 155 md while the permeability model of the lower Qishn member (Fig. 13) reflects that permeability value ranges from 100 to 380 md.

The permeability model of the Saar Formation (Fig. 14) reflects that permeability value ranges from 1 to 65 md. Water saturation is calculated based on distributions related to porosity ranges. These distributions condition perfectly the modeling of the water saturation for each porosity class. This fast and simple method allows the generation of a consistent water saturation

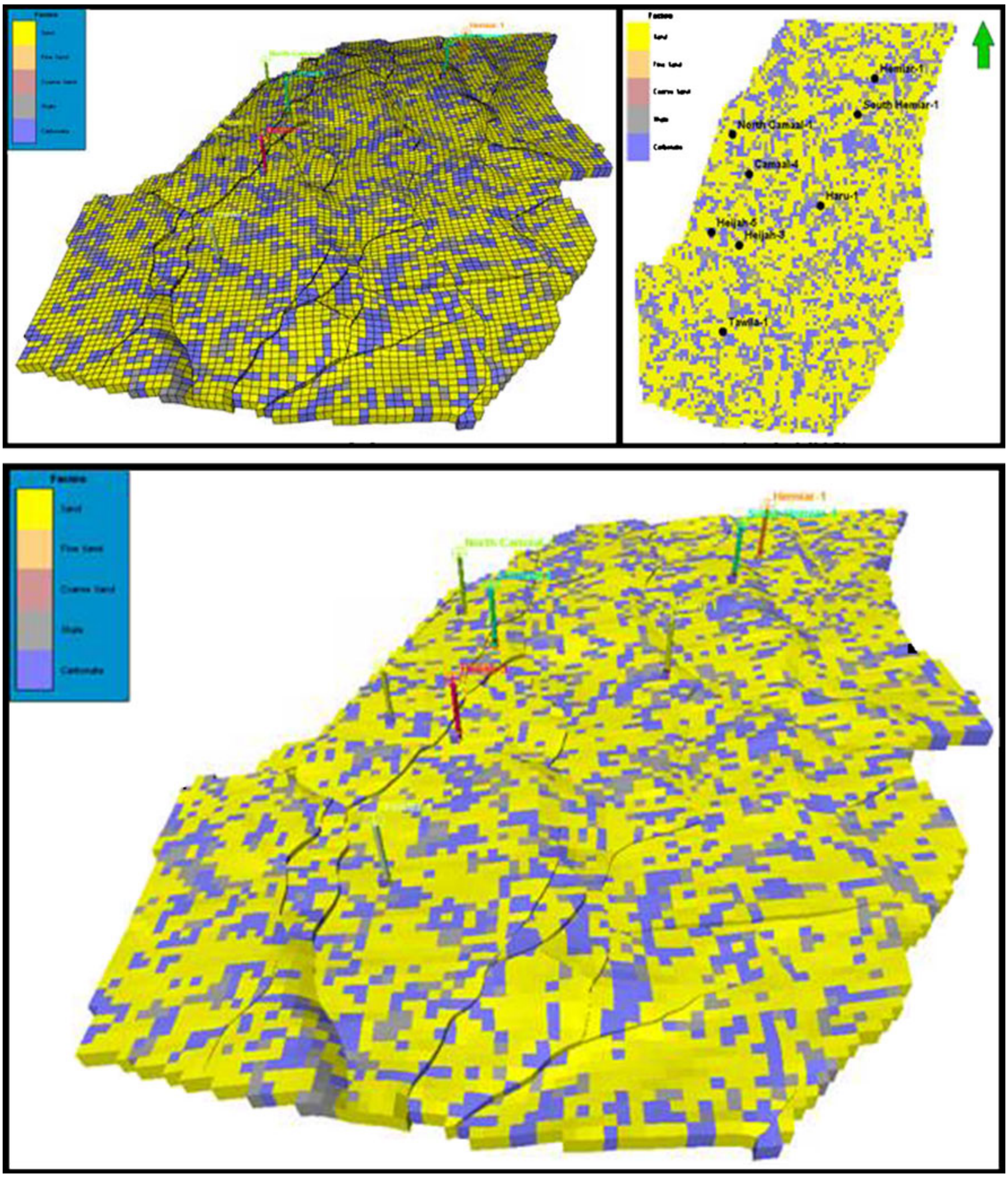


Fig. 19 Facies model output from view: **a** 3D gridding model, **b** horizontal slice SIS, **c** color-coded according to facies of the lower Qishn member in the study area

distribution that respects a realistic degree of correlation between porosity and saturation.

Meanwhile, the water saturation model of the upper Qishn member (Fig. 15) reflects that water saturation value ranges from 57% to 62% while the water saturation model of the lower Qishn member (Fig. 16) reflects that water saturation value ranges from 29% to 37%. The water saturation model of the Saar Formation (Fig. 21) reflects the water saturation value is range from 52% to 76%.

Facies model The act of modeling a reservoir using knowledge of the facies that make up the reservoir and the depositional environments that the facies represent. The depositional characteristics will suggest rules concerning the geometries of the facies and the possible relationships between facies, especially where the facies have been related to each other within a stratigraphic sequence or a cyclothem. Facies modeling is often an important component of geostatistical reservoir characterization and facili-

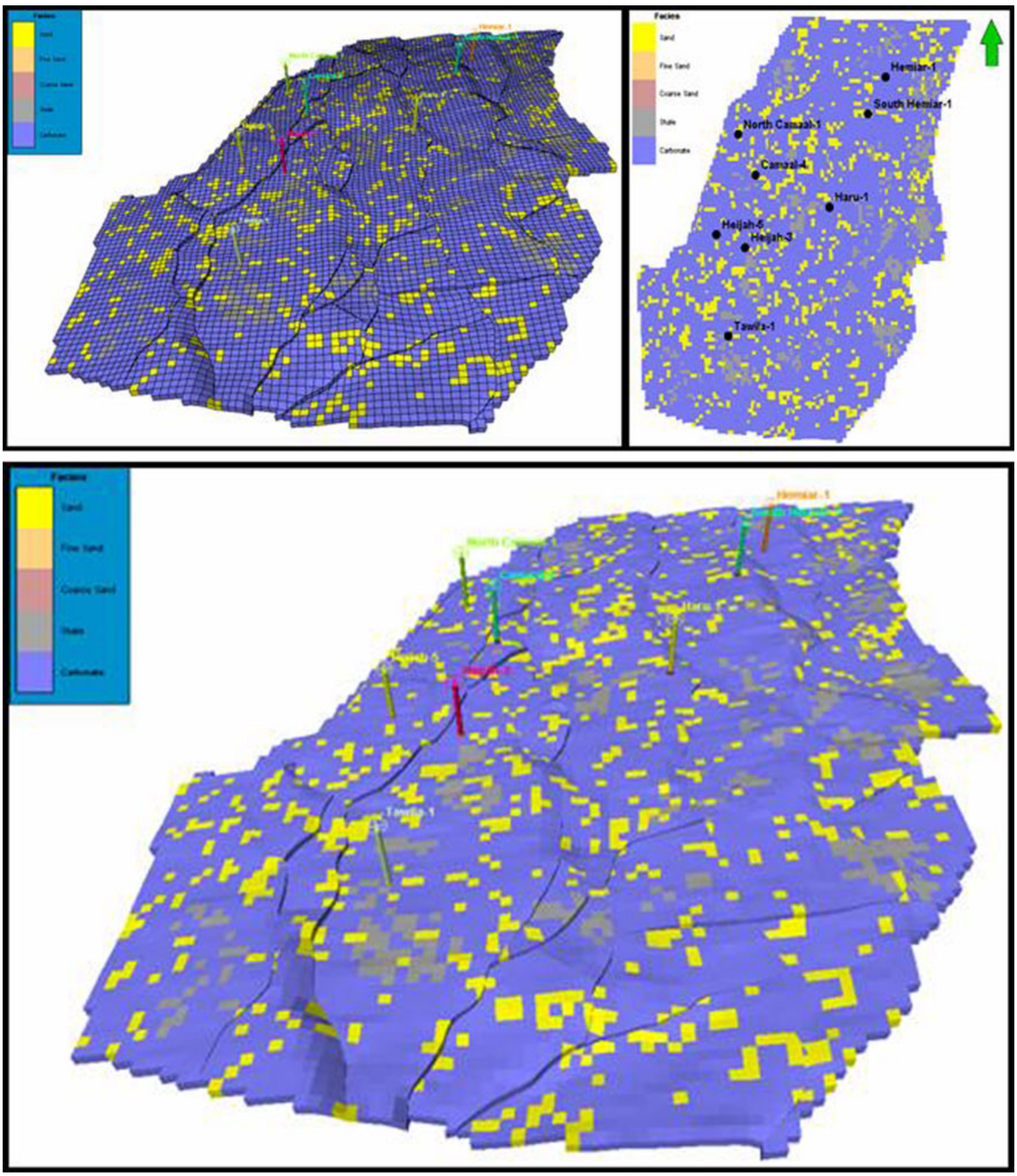


Fig. 20 Facies model output from view: **a** 3D gridding model, **b** horizontal slice SIS, **c** color-coded according to facies of the Saar Formation in the study area

tates construction of superior reservoir models for complex reservoirs.

Once the strata or layers are identified, the distribution of channel complexes versus overbank deposits within each strata represents second-order heterogeneities. The distribution of individual channels within each channel complex constitutes third order heterogeneities. Sequence stratigraphy allows such hierarchical classification of heterogeneities down to the bed set or bed level. This genetic hierarchy of heterogeneities within a given reservoir is best modeled through a hierarchical procedure. A hierarchical object-based procedure was applied to model the channel sand distribution in each layer. The key geologic input parameters are (1) the proportion of channel sand that could vary vertically and areally, (2) geometric parameters defining the channel thicknesses, widths, and sinuosities, and (3) well data. In this case, the layer proportions were assumed constant, realistic channel geometries were considered, and no well data were used to constrain the model.

Stochastic object modeling algorithm is used to simulate lith-facies using flow line trend maps generated from 3D seismic. Facies geobody characteristics were specified in the model as depositional objects and parameters for each interpreted object within flow lines (i.e., channel width, thickness, sinuosity, frequency, etc.) were provided from analog data. The geobody objects were then modeled against background nonreservoir facies (mudstone/siltstone and coal facies association) and conditioned to wells. Clean reservoir sands and marginal shaly sands are superimposed on top of the background facies; 3D seismic image interpretation using geomorphologic features, texture, appearance, and albedo variations can be further developed and merged with some seismo-facies classification may help generate realistic geological facies models. Porosity and other reservoir properties can now be simulated constrained by the more meaningful 3D litho-facies model which improves predictability of reservoir quality and fluid content.

The facies model of the study area (Figs. 18, 19, 20) show the upper Qishn member model is composed mainly carbonate with shale and a few of sandstone distributed at

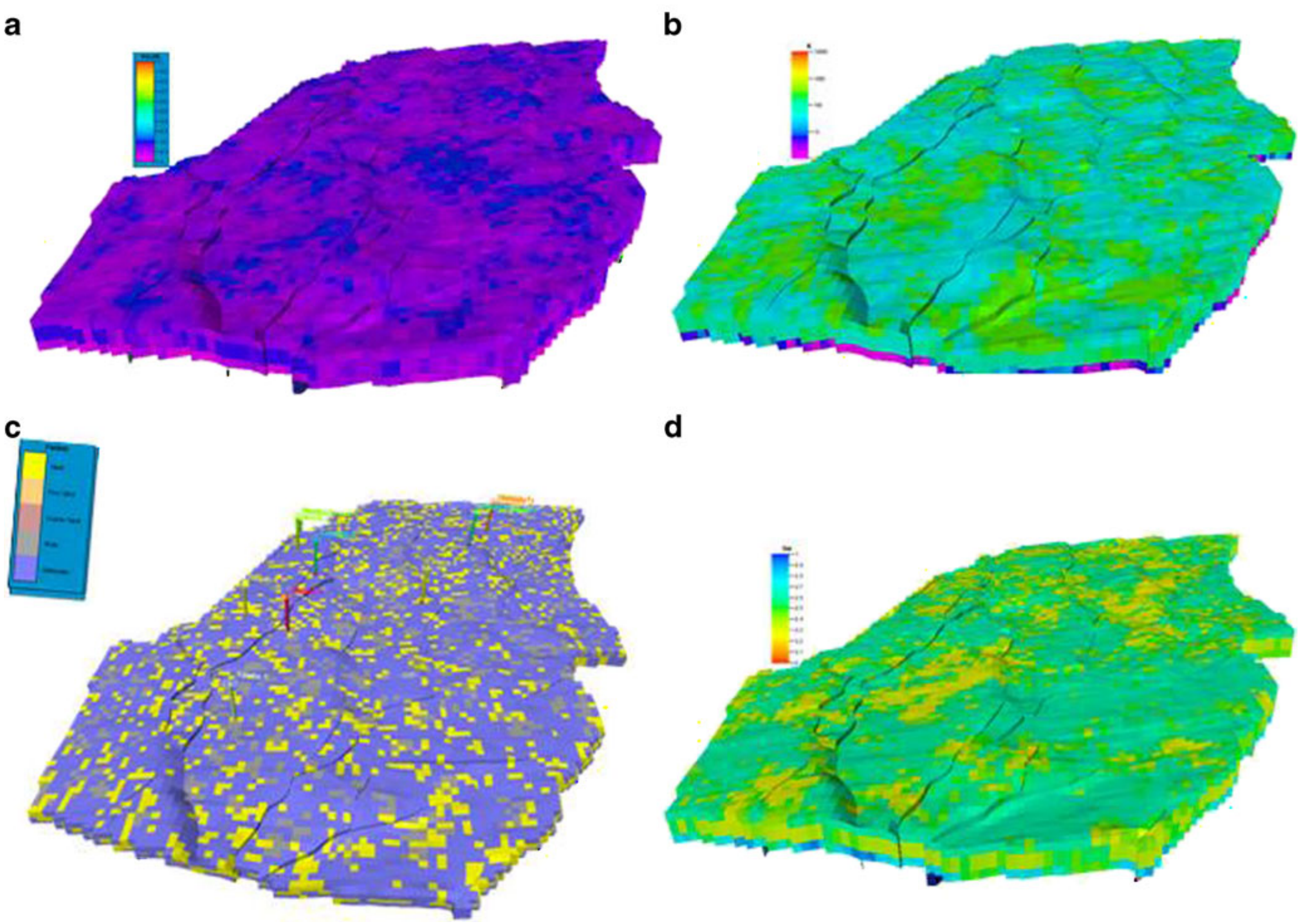


Fig. 21 Property modeling of lower Cretaceous reservoirs in Masila oilfield **a** porosity model, **b** permeability model, **c** water saturation model, and **d** facies model

the study area, while the facies model at the lower Qishn member shows is composed mainly sandstone with shale and carbonates. Meanwhile, the facies model the Saar Formation shows is composed mainly carbonates with shale and sandstone. It is concluded that this formation is highly carbonates facies.

Reservoir flow model The flow model is and advanced dynamic multifluid two-phase flow model. Integrated flow models make it possible to work directly with seismically generated data at any time during the life of the reservoir. An integrated flow model combines a traditional flow model with a petrophysical model. The properties of porous media have to be tested within the context of multidisciplinary reservoir modeling and present the technical details needed to understand and apply the simulator to realistic problems.

The Petroleum Engineering and Fluid Mechanics in Porous Media group performs research in several areas of petroleum engineering, including flow in porous media, reservoir simulation, reservoir characterization, drilling, pollutant transport, sustainable development of oil and gas reservoirs, and waste disposal.

The geological model was converted into a flow model with 750,000 ($500\times500\times3$) grid blocks. This flow model will be used to evaluate the productive potential of the lower Cretaceous reservoirs (Fig. 21)

Conclusions

1. The Mesozoic basins of Yemen vary spatially and temporally from the west to the east of the country. The interior rifts of the western and central areas are oriented NW–SE. The Sayun-al Masila Basin and Jiza'-Qamar basins are oriented progressively more east–west. A multitude of different names, different spellings, different usages, and different lithostratigraphic concepts has resulted in a plethora of lithostratigraphic names in Yemen, but the one accepted here is illustrated in Table 1.
2. The extensional Basin Phoenix extends 140º and is a possible extension to the western al Masila Basin of Yemen. It is a large asymmetric graben with strata dipping and thickening to the southwest with an estimated 3 km of upper Jurassic–lower Cretaceous syn-rift strata showing phases of footwall fan progradation.
3. In the fields of the Masila block, the early Cretaceous marine Qishn Formation provides both the reservoir sandstone and an overlying sealing tight limestone unit. The largest hydrocarbon volumes are reservoired in sands of the Qishn Formation sands of Barremian–Aptian age that have produced considerable rates of oil with little dissolved gas and are sealed by tight limestones of the Qishn Formation. The Qishn Formation comprises shallow shelf to fluvio-deltaic sandstones in Central and Western Yemen and is likely to be equivalent to the lower fluviatile sandstones of the Tawilah Group of Western Yemen, and to the east, it becomes more carbonate rich and passes into the purer carbonate facies of the Mahra Group.
4. Highly detailed reservoir properties from log analysis were augmented by similarly detailed seismic and stratigraphic correlations and integrated together in a 3D geological model and reservoir simulator to provide an accurate historical and predictive model for production optimization.
5. Building a coherent 3D geological model of a complex heavy oil field is a tremendous task that requires a multidisciplinary organization and approach, by an integrated team, at each stage of the process. To improve the description of the reservoir heterogeneity, all the available static and dynamic inputs must be introduced in detailed structural model, lithological grid, and petrophysical grids that are intimately related. Any modifications to match the dynamic constraints are discussed by the concerned team and introduced into the fine 3D geological grid as deterministic inputs. The integration of such inputs enhances considerably not only the static reservoir description but also the consistency of the future reservoir model which will better reproduce the observed field performance and facilitate at a later stage the production history matching process.

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