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Foreword

The Arabian Tectonic Plate contains the world’s most prolific petroleum province, namely the Arabian Gulf–Mesopotamian–Zagros Fold and Thrust Belt Basin (named the Arabian plate basin in this publication).

In the early decades of the 20th century, production mostly came from carbonate Cenozoic and Mesozoic sediments. However, there were numerous major productions in supergiant fields from Mesozoic siliciclastic reservoirs in the northern part of the Arabian Gulf (onshore and offshore). The picture was to change drastically during the last two decades of the 20th century, as exploration of deeper and dominantly siliciclastic Paleozoic sediments accelerated discoveries of significant siliciclastic reservoirs in Ordovician, Silurian, Devonian, and Permo-Carboniferous formations. The hydrocarbons of the Paleozoic reservoirs were mostly sourced from prolific basal Silurian hot shales. However, post-Paleozoic reservoir hydrocarbons were essentially sourced from both Silurian and Jurassic shales with subordinate contributions from other source rocks scattered throughout the stratigraphic column.

The economic development of these prolific siliciclastic reservoirs would not have been possible without an improved understanding of the geological controls on reservoir performance. Significant risks are associated with the exploration and development of siliciclastic reservoirs in the Arabian plate, but these can be mitigated through the use of multiple techniques such as sedimentology, sequence stratigraphy, biostratigraphy, chemostratigraphy, and seismic interpretation.

Literature on the Arabian plate siliciclastic reservoirs is scattered over a dozen or more geological journals, whereas some of it is not readily accessible or found within unpublished company reports. This Memoir documents a series of advanced and specialized studies within the Arabian plate, providing insight into its unique siliciclastic reservoir systems and serving as a classic reference book for geoscientists in the oil industry and academia alike. In addition, papers published in this memoir will provide good analogues for studies undertaken in other regions.

The following chapters of this Memoir show that the understanding of siliciclastic reservoirs of the Arabian plate has been aided by technological advances in reservoir exploration, characterization, and modeling. It is hoped that this will serve as a reference for geoscientists in the coming years and that it may inspire young professionals to take an interest in the subject.

The Editors
About the Editors

Homoud R. AlAnzi

Homoud R. AlAnzi is a professional clastic sedimentologist and sequence stratigrapher working for the Geological Operations Department of Saudi Aramco since 2000. He is actively involved in high priority operational sedimentology and reservoir quality description studies from different stratigraphic intervals throughout the geological column in Saudi Arabia. Homoud has also conducted many long term clastic sedimentological studies from offshore and onshore fields of Saudi Arabia. These cover multiple depositional systems including fluvo-deltaic, shallow marine, aeolian, continental, and glacial paleoenvironments. He produced detailed depositional models for these depositional systems in order to determine the lateral extent of reservoirs and to identify the exploration targets. Homoud is a subject matter expert and key member of many Saudi Aramco Exploration Organization technical committees, such as Prospect Quality Optimization Team, Quantitative Seismic Prospect Generation Team, Strategic Portfolio Optimization Team, and Petrophysical Workflow Initiative, where he contributed to the evaluation of prospects.

Since 2008, Homoud has been heavily involved in providing highly specialized clastic sedimentology and sequence stratigraphy training to young professionals and peer geoscientists. This has included lectures, core workshops, production of guidebooks, leading/co-leading field trips in Saudi Arabia, Kuwait and Australia, and mentorship. He was assigned as divisional technical publication committee chairman where he reviewed and evaluated many technical contributions submitted for international publications.

Homoud obtained his B.Sc. degree from the University of Kuwait in 1999 and an M.Sc. degree from the Australian School of Petroleum, Adelaide University, Australia in 2008. He has presented, published and co-published on the Paleozoic and Mesozoic of Saudi Arabia and the Cenozoic of Australia. He was selected as Saudi Aramco representative and technical program committee member for regional conferences that were organized by the AAPG, EAGE and GEO.

Riyadh (Ray) A. Rahmani

Riyadh (Ray) A. Rahmani is a consulting petroleum geologist based in Calgary, Alberta, Canada. Rahmani holds a BSc in Geology from the University of Baghdad (1965), an MSc from the University of British Columbia (1968) and a PhD from the University of Alberta (1973). He has 45 years of worldwide experience within the petroleum industry (Canada, USA, North & East Africa, and the Middle East) and government geological surveys. He has previously worked with RAK Gas (Ras Alkhaimah, UAE), Crescent Petroleum (Sharjah, UAE), Saudi Aramco (Saudi Arabia), Sirte Oil (Libya), Canadian Hunter Exploration, Alberta Geological Survey, Kuwait Institute for Scientific Research, Geological Survey of Canada, and Shell Canada.

Rahmani has conducted numerous outcrop and subsurface-based regional and field scale sequence stratigraphic and facies studies of clastic reservoirs in petroleum basins of a variety of tectono-stratigraphic settings spanning the entire Phanerozoic.

His fields of interests are clastic reservoir characterization, sedimentology, sequence stratigraphy and basin analysis. Rahmani has taught clastic depositional systems and sequence stratigraphy of sandstone reservoirs since 1973, both in the classroom and in field seminars to his work colleagues and society conferences and meetings, in Canada and worldwide. Working as a consultant for the past 14 years, he has taught these subjects both as public courses and private in-house seminars to petroleum professionals in Saudi Arabia, Indonesia, Egypt, Tunisia, and Turkey. He is a member of the AAPG, IAS and SEPM.
Ronald J. Steel

Ronald J. Steel has more than 30 years of experience in research aimed at using clastic sedimentology to address problems in basin analysis and clastic reservoirs and particularly deciphering the signatures of tectonics, climate, sea level change and sediment supply in stratigraphic successions. He headed the Geology Research of Norsk Hydro in Bergen, Norway, before becoming a professor of Sedimentology and Reservoir Geology in University of Bergen, Norway. He has held the position of Wold Chair of Energy in the Geology and Geophysics Department of the University of Wyoming (UW), US, and was an Interim Director of the Institute of Energy Research in UW. He is currently a Professor and Davis Centennial Chair of the Geological Sciences in UT Austin and an Honorary Professorial Fellow at Heriot-Watt University, UK.

Osama M. Soliman

Osama M. Soliman is a passionate geologist with 35 years of experience working in both academia and in the petroleum industry. In 1995, he received his Ph.D. from Memorial University of Newfoundland, where he specialized in clastic sedimentology and sequence stratigraphy. He worked for Amoco Canada and Petro-Canada on prospect generation in Alberta, Atlantic rift basins, Algeria and Tunisia.

In 2002, he joined Saudi Aramco and was employed by the geological technical services division, where he worked on numerous Paleozoic, Mesozoic and Tertiary clastic reservoirs of Saudi Arabia. He described many cores and developed detailed models for diverse glacial, aeolian, fluvial, deltaic, shelf-margin and deep marine reservoirs. More recently, he has worked on exploration projects in the Red Sea region. He developed tectonostratigraphic models to guide the search for stratigraphic traps in syn-rift reservoirs, and is increasingly involved in teaching and mentoring young professionals.
Acknowledgments

The editors sincerely thank the Exploration Management of Saudi Aramco for supporting efforts toward the publication of Arabian plate reservoirs. We also thank the reviewers for their dedication in providing valuable comments and careful reviews of the submitted manuscripts. Their reviews have greatly improved the scientific content of this Memoir.

Many thanks to Beverly Molyneux, Cecilia Whitehurst, and the AAPG staff for reviewing the AAPG Memoir proposal and granting the necessary approvals to publish this Memoir.
Reviewers

Abdullah, Fawzia
AlAnzi, Homoud
AlDuaiji, AbdulAziz
AlKhalifa, Mohammad
AlMasrahy, Mohammed
Backhouse, John
Baniak, Greg
Cantrell, Dave
Craigie, Neil
Davies, Roger
Diggs, Tim
Droste, Henk
Franks, Stephen
Gerard, Jean
Gomez-Perez, Irene
Hampson, Gary
Hawat, Ahmed
Heward, Alan

Johnson, Howard
LeNindre, Yves-Michel
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May, Michael
Maynard, James
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Porebski, Szczepan
Rahmani, Riyadh
Ratcliffe, Ken
Rowe, Harry
Sharp, Ian
Soliman, Osama
Steel, Ron
Sutcliffe, Owen
Van Buchem, Frans
Van Hoof, Tom
Wells, Martin
Introduction

Homoud AlAnzi
Geological Operations Department, Saudi Aramco, Dhahran, Saudi Arabia (e-mail: homoud.anzi@aramco.com)

Riyadh A. Rahmani
RRC Petroleum Consulting, #415, 59-22 Ave, SW Calgary, Alberta, T2S 3C7, Canada (e-mail: rahmani44@hotmail.com)

The idea of publishing this AAPG Memoir 116 stemmed from an AAPG Geo-Technology Workshop (GTW) entitled “Siliciclastic Reservoirs of the Middle East,” which was held in Kuwait in March 2015. The presentations that were delivered at the workshop represented the starting point for the editorial committee members to solicit papers from those who presented at the workshop. However, many active Arabian plate geoscientists were not present at the AAPG GTW, and so it was decided to extend the reach of this memoir far beyond the AAPG GTW that was held in Kuwait. Specifically, the geographic coverage; the number of geoscientists, academics, and companies contributing to the memoir; and the stratigraphic intervals addressed all represent an enlargement of the overall scope of the memoir. The editorial committee members issued a call for contributions from all those who have worked in the siliciclastic reservoirs of the Arabian plate from academia and the oil industry.

The Arabian plate owes its richness in hydrocarbons to the following unique combination of geological conditions:

1. Deposition of thick and organic-carbon-rich, fine-grained source rocks in the Ordovician, Silurian, and Jurassic.
2. Climatic and tectonic settings conducive to deposition of very thick siliciclastic and carbonate reservoir rocks. In the case of the thick clastic reservoirs, there were, additionally, large Gondwana catchment areas to provide significant sediment influx and low enough topography for regressive coastlines to build across extensive shelf platforms.
3. Climatic settings conducive to deposition of exceptionally thick evaporitic seal rocks in addition to thick, fine-grained seal rocks.
4. The perfect timing of tectonic deformation and hydrocarbon migration events conducive to maximum and optimal creation of trapping conditions.

Many of the numerous producing siliciclastic reservoirs of the Arabian plate form giant and supergiant fields. In fact, some combine to form the largest offshore field in the world, the Safaniya oil field in the northern Arabian Gulf offshore of Saudi Arabia. Other giant and supergiant oil fields, in southern Iraq and Kuwait, for example, contain hydrocarbons trapped in Mesozoic siliciclastic reservoirs. In addition to the classic Mesozoic siliciclastic reservoirs, large discoveries have been made in the Paleozoic siliciclastic successions since the mid-1980s. These Paleozoic sandstone reservoirs form important productive intervals in the Arabian plate but have often been overshadowed by the younger, more prolific carbonate plays.

This memoir incorporates studies on a wide variety of topics of these prolific siliciclastic reservoirs of the Arabian plate, including regional and field-size petroleum potential, sequence stratigraphy, depositional systems, palynostratigraphy, chemostratigraphy, outcrop-to-subsurface analogues, petrography, diagenesis and fluid evolution, reservoir properties, geological controls on reservoir development, reservoir modeling, reservoir performance, reservoir management, and petrophysics.
The papers are arranged stratigraphically from oldest to youngest and are grouped based on geologic time eras, as follows (Figure 1):

**PALEOZOIC ERA**

In Chapter 1, Rahmani and co-authors reconstruct the Devonian gas-bearing Jauf Formation depositional systems using subsurface and outcrop data, emphasizing key regressive deltaic and transgressive estuarine shorelines as well as associated fluvial, paralic, and shelf deposits. They demonstrate the importance of the fundamental (building block) 4th-order shelf transiting sequences and the larger 3rd-order host sequences in the very extensive outbuilding and aggradation of the Devonian Arabian shelf. The Jauf Formation is an excellent example of a high sediment supply dispositional system with low accommodation.

The study also draws contrasts between the Jauf Formation development in the outcrops of northwest Saudi Arabia (including carbonate embayments) and that in the subsurface of the eastern and southeastern parts of Saudi Arabia (wave-dominated strandplains and deltas and tide-influenced estuaries), where there was stronger fluvial supply. The Devonian Jauf shorelines show truly spectacular regressive and transgressive transits for hundreds of kilometers (hundreds of miles) across the wide shallow shelf that sloped gently off the Arabian shield.

In Chapter 2, Ramseyer and co-authors address the relationship among porosity-reducing diagenetic processes, that is, compaction, cementation, and pressure...
solution, the pore-fluid evolution, and tectonic activities affecting clastic rocks of the late Carboniferous to early Permian Al Khala Formation of Oman. This was determined by applying petrography, fluid-inclusion microthermometry, isotope and trace-element geochemistry, hydrochemical modeling, and basin modeling techniques.

In Chapter 3, Soua provides a chemostratigraphic correlation workflow to help resolve the Perm-Carboniferous Unayzah Group stratigraphy in central Saudi Arabia. The correlation workflow is developed based on specific changes in elemental ratios found within glaciogenic, fluvial, eolian, and coarse-grained alluvial sediments. The rationale behind this chemostratigraphy study is that the Unayzah Group lacks high-resolution biostratigraphic control, and so attempts at regional lithostratigraphic correlation fail because of strong similarities in wireline log signatures between sandstone units encountered throughout much of the Paleozoic section. The study also defines the boundaries of the Unayzah Group and Basal Khuff Clastics (BKC).

MESOZOIC ERA

In Chapter 4, Davies and co-authors provide a regional perspective of the Arabian plate Mesozoic depositional systems. The paper examines the temporal and spatial extent of siliciclastic intervals within the otherwise dominantly carbonate Arabian shelf. These intervals contain important elements of petroleum plays, forming proven and potential reservoirs, source rocks, and seals. This study then compares them against known tectonic, climatic, and eustatic events affecting the Arabian plate that may have been acting independently or coincidently. This is to control siliciclastic input by means of hinterland uplift, influence on denudation and run off, incision and creation of sediment pathways, and accommodation space. A better understanding of the fundamental controls on siliciclastic input onto the Arabian plate will enable predictions of these key petroleum play elements and a better understanding of the subsurface risk associated with their occurrence.

In Chapter 5, Issautier and co-authors’ outcrop-to-subsurface study provides improved knowledge of the depositional geometries and age dating of the Triassic–Early Jurassic Minjur Formation from central Saudi Arabia. Combining outcrop and subsurface facies, stratigraphy, and available ages, the authors have contributed to an improved understanding of the stratigraphic architecture and depositional model for the formation. A highlight is the likelihood that continental spores and pollen reflect fluctuating dry and humid climatic periods. In addition, the sedimentary history of the Minjur Formation was punctuated by marine dinocysts and other saline algal occurrences, which constrain the ages and determine periods of marine transgression.

In Chapter 6, a study of the Early Cretaceous (Barremian) Zubair Formation is presented by Azim and co-authors concentrating on the Sabiriyah and Raudhatain fields in northern Kuwait. The study addresses the importance of depositional environment interpretation and sequence stratigraphic framework recognition in reservoir development and production strategies. The main conclusion is that distinct depositional barriers may give rise to multiple fluid contacts. The study also highlights the value of reservoir structure and fault patterns that control fluid redistribution.

In Chapter 7, another study of the Zubair Formation is covered by Wells and co-authors concentrating on the supergiant Rumaila oil field in southeast Iraq. The work addresses the economic development of the fluvial-dominated, tide-influenced deltas of Zubair Formation through improved understanding of the geological controls on reservoir performance and how this impacts reservoir management decisions. Thorough geological description and integration with dynamic reservoir data has enabled several key reservoir management decisions. For example, the identification and correlation of the mudstones that cause multiple moved oil–water contacts and hold back significant pressure enable the development of a perforation strategy where each reservoir flow unit is produced separately, avoiding cross-flow and lost production. The type, geometry, and connectivity of the paralic depositional elements define the reservoir architecture, which controls large-scale sweep efficiency and the habitat of remaining hydrocarbons. An improved understanding of these elements and their control on sweep has facilitated a successful infill drilling campaign.

In Chapter 8, Datta and co-authors study demonstrates a workflow to characterize the impact of heterogeneity in paralic deposits, from full field to core scale, that can be used for meeting the challenges of managing reservoir performance complexity in a supergiant field. The Upper Burgan Member of the Middle Cretaceous Burgan Formation is the reservoir of interest in their paper. The authors show that variations in depositional subenvironments in time and space generated heterogeneity ranging in scale from millimeters to tens of meters in the reservoir. The relationship of this to the permeability architecture of the reservoir is also discussed. The results provide insight into the nature of heterogeneity within a framework of reservoir connectivity. They also
provide high-quality input to larger simulation models and have greatly influenced reservoir management. This study proposes a methodology that is applicable to other reservoirs of varying connectivity.

In Chapter 9, AlAnzi and Tourqui characterize the depositional facies of the Middle Cretaceous Wara Member of the Wasia Formation in time and space from the Arabian Gulf. In this study, detailed core description, well log interpretation and correlation, sequence stratigraphy, depositional model generation, petrographic analysis, and reservoir quality assessment are integrated to gain a more comprehensive understanding of the potential reservoir quality and depositional geometries of this interval.

In Chapter 10, Keller and co-authors present results of a study on the Cretaceous sedimentary aquifers in Saudi Arabian (Biyadh-Wasia-Aruma) formations to better assess the storage volume of fossil groundwater, which is of fundamental importance for the hyper-arid kingdom. Besides the regional 3-D stratigraphic framework, the focus was on measurements of porosity and permeability of 150 samples and the interpretation of reservoir quality in terms of sedimentary facies and their diagenetic overprint.

CENOZOIC ERA

In Chapter 11, Tanoli and co-authors’ study on the lower to middle Miocene Jal Az-Zor Formation from subsurface data from northern Kuwait documents the lithofacies penetrated in five wells and discusses the environments of deposition. It also highlights high-frequency sequences and cyclicity within the formation. Results of biostratigraphy are incorporated for age dating. Regional implications are also highlighted in this paper.