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Mustapha Meghraoui · Narasimman Sundararajan · Santanu Banerjee · Klaus-G. Hinzen · Mehdi Eshagh · François Roure · Helder I. Chaminé · Said Maouche · André Michard *Editors*

Advances in Geophysics, Tectonics and Petroleum Geosciences

Proceedings of the 2nd Springer Conference of the Arabian Journal of Geosciences (CAJG-2), Tunisia 2019

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About the 2nd Springer Conference of the Arabian Journal of Geosciences (CAJG-2), Tunisia 2019

The Arabian Journal of Geosciences (AJG) is a Springer journal publishing original articles on the full range of Earth sciences in partnership with the Saudi Society for Geosciences. The journal focuses on, but is not limited to, research themes which have regional significance for the Middle East, the Euro-Mediterranean, Africa, Asia and some other regions of the world. The journal receives on average 4000 submissions a year and accepts around 1000 papers for publication in its 24 annual issues (acceptance rate around 25%). It benefits from the participation of an editorial team of 100 international Associate Editors who generously help in evaluating and selecting the best papers.

In 2008, Prof. Abdullah Al-Amri, in close partnership with Springer, founded the Arabian Journal of Geosciences (AJGS). In 2018, the journal celebrated its 10th anniversary. To mark the event, the founder and Editor-in-Chief of the AJGS organized the 1st Conference of the Arabian Journal of Geosciences (CAJG) in close collaboration with Springer on 12–15 November 2018. The conference was an occasion to endorse the journal's long-held reputation

and brought together 450 authors from 70 countries, who work in the wide-ranging fields of Earth sciences. The dynamic four-day conference in a stimulating environment in Hammamet, Tunisia provided attendees with opportunities to share their latest unpublished findings and learn about the latest geosciences studies. The event also allowed attendees to meet and talk to the journal's editors and reviewers. Three field trips were organized alongside the conference, and many participants enjoyed the wonders of the geology of Tunisia.

In a continuation of the successful 1st CAJG, the 2019's conference aimed to bring geoscientists from all over the world to present and discuss their most recent findings. The 2nd CAJG was an occasion to publish the newest findings in its proceedings by Springer and a special issue in the AJGS, with a clear mission to drive greater North-South (Europe-Africa) scientific cooperation and to open doors to new and enriching collaborations with geoscientists based in Asia and the Americas. The 2nd CAJG devoted a special session (workshop) to studies focusing on unraveling the undiscovered oil and gas resources in the Mediterranean and North Africa. Many international experts took part in the discussion.

The conference covered all cross-cutting themes of geosciences and focused principally on the following 15 tracks:

- Track 1. Atmospheric Sciences, Meteorology, Climatology, Oceanography
- Track 2. Biogeochemistry, Geobiology, Geoecology, Geoagronomy
- Track 3. Earthquake Seismology and Geodesy
- Track 4. Environmental Earth Sciences
- Track 5. Exploration & Theoretical Geophysics, Seismic & Well Logging Methods, Mathematical Geosciences
- Track 6. Geo-Informatics and Remote Sensing
- Track 7. Geochemistry, Mineralogy, Petrology, Volcanology
- Track 8. Geological Engineering, Geotechnical Engineering
- Track 9. Geomorphology, Geography, Soil Science, Glaciology, Geoarchaeology, Geoheritage
- Track 10. Hydrology, Hydrogeology, Hydrochemistry
- Track 11. Marine Geosciences, Historical Geology, Paleoceanography, Paleoclimatology
- Track 12. Numerical and Analytical Methods in Mining Sciences and Geomechanics
- Track 13. Petroleum and Energy Engineering, Petroleum Geochemistry
- Track 14. Sedimentology, Stratigraphy, Paleontology, Geochronology
- Track 15. Structural Geology, Tectonics and Geodynamics, Petroleum Geology

The dynamic four-day conference provided more than 400 attendees with opportunities to share their latest unpublished findings and learn the newest geosciences studies. The event also allowed attendees to meet and discuss with the journal's editors and reviewers.

More than 710 short contributing papers to the conference were submitted by authors from more than 74 countries. After a pre-conference peer review process by more than 500 reviewers, 462 papers were accepted. These papers are published as chapters in the conference proceedings which consist of four edited volumes, each edited by the following group of Arabian Journal of Geosciences (AJGS) editors and other guest editors:

Proceedings Volume 1: New Prospects in Environmental Geosciences and Hydrogeosciences

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Helder I. Chaminé: School of Engineering—ISEP, Polytechnic of Porto, Porto, Portugal
Md Firoz Khan: Department of Chemistry, Faculty of Science, University of Malaya, Kuala Lumpur, Malaysia

Proceedings Volume 2: Advances in Geophysics, Tectonics and Petroleum Geosciences

Proceedings Volume 3: Recent Research on Geomorphology, Sedimentology and Geochemistry

Proceedings Volume 4: Research developments in Geotechnics, Geo-Informatics and Remote Sensing

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Preface

The diversity of the geological and geophysical structures and its components are major markers of the evolution of our planet. Field and laboratory studies leading sometimes to discoveries are a necessary step to unveil the outstanding variety of rocks, their transformation and deformation that may enhance our understanding of the Earth's formation. Previously forming a large part of the Pangea, the African continent and its conterminous domains such as the Arabian Plate, the Mediterranean and Indian Ocean regions conceal a wealth of indicators on the plate tectonics and mineral resources. The continent that seems stable displays seismic ruptures, active tectonics and volcanoes as a testimony of the still alive telluric activity and as a warning for the building of proper mitigation plans against catastrophes mainly due to anthropic occupations. The development of research programs in geology and geophysics is becoming a real challenge for the Earth environmental settings.

Four sections spanning a large spectrum of geological and geophysical topics form the content of conference tracks presented during the 2nd CAJG. The proceedings volume presents here a series of research methods that are nowadays in use for measuring, quantifying and analyzing the targeted geological domains. Remote sensing with high-resolution satellite imagery, seismology, geochemistry, theoretical geophysics and related profiles with tomographic images, earthquake geology with times series radar interferometry and related geodetic-GPS campaigns, well-logging contribute to scrutinizing the Earth tectonic architecture. Several contributions are from young researchers that often benefited from training sessions during previous meetings. Fundamental questions that address the genesis and evolution of our planet are built upon data collection and experimental investigations under physical constitutive laws which are the conditions for a successful scientific research. These multidisciplinary approaches combined with the geodynamics of tectonic provinces and investigations of potential zones of natural resources (petroleum reservoirs) provide the basis for the economic development.

Strasbourg, France — Mustapha Meghraoui
Muscat, Oman — Narasimman Sundararajan
Mumbai, India — Santanu Banerjee
Bergisch Gladbach, Germany — Klaus-G Hinzen
Trollhättan, Sweden — Mehdi Eshagh
Rueil-Malmaison, France — François Roure
Porto, Portugal — Helder I. Chaminé
Alger, Algeria — Said Maouche
Paris, France — André Michard

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About the Editors

Mustapha Meghraoui (Ph.D.) is a senior research scientist (Physicien 1ère Classe) at the IPG Strasbourg (France). He leads the "Active Tectonics and Paleoseismology" group of IPG Strasbourg and develops programs in the study of earthquake faulting, seismotectonics, paleoseismology, paleotsunami and geological hazards. He has played a significant role in the identification of earthquake faulting in intraplate and interplate tectonic domains. He teaches active tectonics and paleoseismology to Master I and II degree students and conducted more than 12 Ph.D. theses at the University of Strasbourg. He has been a coordinator and PI in previous and current scientific projects in Europe and Middle East (EC-funded PALEOSIS ENV4-CT97-0578; SAFE EVG1-2000-22005, RELIEF EVG1-2002-00069, APAME ICA-CT-2002-10024, TRANSFER EC GOCE Contract No. 037058, FP7-ENV.2013.6.4-3-ASTARTE), in Algeria (PNE, ACI, CMEP) and in Africa (IGCP-601, IGCP-659 Seismic Hazard and Risk in Africa). He is elected President of the African Seismological Commission, Freeman of the city of Chlef (ex El Asnam, Algeria), Honor Medalist of Aristoteles University (Thessaloniki, Greece), Merit Medalist of the Italian Ministry of Interior and Honor Medalist of the Turkish Geological Society. He is a founding member of the Algerian Academy of Science and Technology and author and co-author of about 98 peer-reviewed scientific publications in international journals, with 2967 citations and an H-index of 37 (ISI Web of Science).

Prof. Dr. Narasimman Sundararajan graduated in Mathematics from the University of Madras followed by a M.Sc. (Tech) and Ph.D. in Geophysics from Osmania University, India. He began a career as Research Scientist in the National Laboratory under Council of Scientific & Industrial Research and later switched over to teaching in Osmania University where he became Professor in 2004. Currently, he is Professor Geophysics in the Department of Earth Sciences, Sultan Qaboos University, Oman. He has published more than 90 research papers in the leading international journals. He has authored a book and a couple of chapters besides edited volume for Springer Publishers. He supervised successfully several Ph.Ds in Geophysics as well as Mathematics. He brought out a few innovative tools for processing and interpreting of various geophysical data besides a mathematical concept called "Sundararajan Transform." He implemented several research projects including one on Uranium exploration. He is Member of XIV Indian Scientific Expedition to Antarctica during 1994–1995. He introduced a valid and viable approach to multidimensional Hartley transform in contrast to the definition of Prof. R. N. Bracewell from Stanford University, USA. For his overall significant research contribution, the Government of India has conferred upon him the National Award for Geosciences in 2007. His research interests are varied and wide including geophysical data processing, mineral and ground water exploration, earth quake hazard assessment studies, etc. In 2015, he has joined the editorial board of *Arabian Journal of Geophysics* as Associate Editor. Currently, he is working as Chief Editor responsible for evaluating submissions in the field of theoretical and applied geophysics.

Prof. Santanu Banerjee is associated with Indian Institute of Technology Bombay since 1999. He supervised several research projects on sedimentology and stratigraphy of Indian sedimentary basins. Along with his collaborators, he attempted a correlation of Precambrian sedimentary successions across the world. He also carried out several research projects on petroleum geology sponsored by oil companies. His research interests include and petroleum geology, microbial mat structures in Precambrian siliciclastics, origin of glauconite and sequence stratigraphy. He has published more than 120 papers in peer-reviewed journals and books and edited two books. He is currently country Ambassador of Society for Sedimentary Geology (SEPM). He is one of the Topical Chief Editors in *Arabian Journal of Geosciences* and Associate Editor-in-Chief of the *Journal of Palaeogeography*. He also serves the editorial board of the *Journal of Earth Systems Science* and *Journal of Indian Association of Sedimentologists*.

Klaus-G. Hinzen's main interests are local earthquake seismology, engineering and particularly archaeoseismology; he worked on source mechanisms of induced and teleseismic earthquakes at the Ruhr-University, Bochum (Ph.D. thesis). During 11 years at the Federal Institute for Geosciences and Natural Resources (BGR), Hannover, he gained experience in seismic in situ testing methods and the modeling of the dynamic behavior of underground openings. In several projects, he developed methods to reduce environmental effects of blast vibrations. In 1995, he became director of the Earthquake Geology Division of the Institute for Geology and Mineralogy of University of Cologne (BNS). The division runs a local seismic network in the northern Rhine area (NRA) which he expanded to 40 seismic stations including a strong motion network and monitoring of Cologne Cathedral. In several projects, the first instrumental earthquake catalog of the NRA was published, historical and palaeoseismological studies were made and a ground amplification model for the southern Lower Rhine Embayment was developed. Since two decades quantitative archaeoseismic studies based on laser scan surveys and discrete element modeling in the Rhine area, Turkey, Greece, Italy, Israel and Tunisia are in the focus of his work which continues after his retirement in 2018.

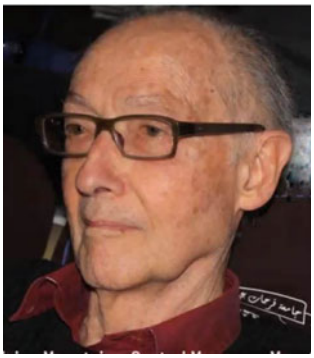
Mehdi Eshagh received his B.Sc. in Surveying Engineering in 1999 from Islamic Azad University, Iran, his M.Sc. in Geodesy in 2002 from K. N. Toosi University of Technology, Iran, and his Ph.D. in Geodesy in 2009 from the Royal Institute of Technology (KTH) in Sweden. In October 2010, he was appointed as Docent/Associate Professor of Physical Geodesy/Space Geodesy at KTH and, since 2013, has been Professor of Geodesy at University West, Sweden. He has taught a variety of courses in surveying engineering at different levels of education, from high school to Ph.D. programs, since 1999. His research interests are mainly in the fields of physical geodesy, in particular geoid and gravity field determination, satellite gravimetry and gradiometry, adjustment theory, satellite orbit determination, geodetic network optimization and design, theories of isostasy, Moho and density contrast determination and sub-lithospheric stress modeling using gravimetric data. He has published and co-authored over 150 original articles, monographs, text-books, edited books, special issues and conference abstracts. He is Founder and Editor-in-Chief of the *Journal of Geodetic Science* and is currently Editor of the *Journal of Geodesy and Geomatics Engineering*and the *Arabian Journal of Geosciences*.

François Roure is a graduate of the Ecole Normale Supérieure of St-Cloud, France, and holder of Doctorate in Sciences from the University of Paris VI. He joined the IFP's GeologyGeochemistry-Geophysics Division in 1984, following a 4-year career at the CNRS. His research is predominantly focused on the study of sedimentary basins (architecture and geodynamics, thermicity, oil-bearing systems, fluid/rock interactions and reservoir characterization). He was selected as an extraordinary professor from IFP at the Free University of Amsterdam (VU) and then in Utrecht. He is former Editor of Tectonics, and he also chaired for 10 years the working group on sedimentary basins in the International Lithosphere Program (ILP). He has contributed more than 100 articles and published in prestigious international journals. In 2010, François Roure was honored by the European Association of Geoscientists and Engineers (EAGE), which selected him as the winner of the2010 Wegener Award, as a recognition of his contribution to the geoscientific research in the area of petroleum exploration of frontier areas and the search for new reserves, particularly in mountain belts. He is the current chief editor for Track 15 of the *Arabian Journal of Geo-Sciences*.

Helder. I. Chaminé is skilled Geologist and Professor of Engineering Geosciences at the School of Engineering (ISEP) of the Polytechnic of Porto, with over 32 years' experience in multidisciplinary geosciences research, consultancy and practice. He studied geological engineering and geology (B.Sc., 1990) at the Universities of Aveiro and Porto (Portugal), respectively. He received his Ph.D. in geology at the University of Porto in 2000 and spent his postdoctoral research in applied geosciences at the University of Aveiro (2001–2003). In 2011, he received his Habilitation (D.Sc.) in geosciences from Aveiro University. Before joining academy, he worked over a decade in international projects for mining, geotechnics and groundwater industry and/or academia related to geodynamics and regional geology, hard-rock hydrogeology and water resources, engineering geosciences and applied geomorphology, rock engineering and georesources. His research interests span over fundamental to applied fields: GIS mapping techniques for applied geology, structural geology and regional geology, engineering geosciences and rock engineering, slope geotechnics, mining geology and hydrogeomechanics, hard-rock hydrogeology, exploration hydrogeology, urban groundwater and hydromineral resources. He has interests on mining geoheritage, history of cartography, military geosciences and higher-education dissemination, skills and core values. Presently, he is Head of the Laboratory of Cartography and Applied Geology (LABCARGA|ISEP), Senior Researcher at Centre GeoBioTec| U.Aveiro and Centre IDL| U.Lisbon, as well as belongs to the executive board of the M.Sc.+B.Sc. Geotechnical and Geoenvironmental Engineering (OE+EUR-ACE Label) and the Department of Geotechnical Engineering (ISEP). Currently, he

belongs to the board of the Technical Committee of Environmental Geotechnics of the Portuguese Geotechnical Society (SPG) and IAH—Portuguese Chapter. He was a board member of the APGeom—Portuguese Association of Geomorphologists (2009–2013), APG - Portuguese Association of Geologists (2020), and SPG (2016–2020). He was a consultant and was responsible over 70 projects of rock engineering, applied geology, hydrogeomechanics, slope geotechnics, mining geology, exploration hydrogeology, hard-rock hydrogeology, water resources, urban groundwater and applied mapping (Mozambique, Portugal and Spain). He has been co-authored over 220 publications in indexed journals, conference proceedings/full papers, chapters, technical and professional papers. He co-edited over 15 special volumes, as well as is presently evolved in editing themed issues for three international journals (Geotechnical Research ICE, Springer Nature Applied Sciences and Water MDPI). He has a wide activity as a referee for several international journals. He served as invited Expert Evaluator of Bologna Geoscience Programme for DGES (Portugal) and Scientific Projects Evaluation for NCST, 2017–2019 (Kazakhstan) and NRF|RISA, 2019 (South Africa), as well as Coordinator of "Geology on Summer/Ciência Viva" program at ISEP, since 2005, for geosciences dissemination. He has been also active with teaching and supervising of many Ph.D., M.Sc. and undergraduate students. He has been on the editorial board, among others of *Arabian Journal of Geosciences* (SSG +Springer), *Hydrogeology Journal* (IAH+Springer), *Euro-Mediterranean Journal for Environmental Integration* (Springer), *Springer Nature Applied Sciences* (Springer), *Mediterranean Geoscience Reviews* (Springer), *Geotechnical Research* (ICE), *Geosciences* (MDPI), *Revista Geotecnia* (Portugal) and *Geología Aplicada a la Ingeniería y al Ambiente* (Argentina). He integrates as moderator or session chair in several conferences, workshops and meetings. Currently, is in organizing/scientific committee of the 3rd International Workshop on Natural Hazards—NATHAZ'22 (Terceira Island, Azores, May 2022).

Dr. Said Maouche is currently Professor of structural geology and earthquake geology at the Centre de Recherche en Astronomie, Astrophysique et Geophysique (CRAAG) in Algeria. He is the author of more than 50 publications peer-reviewed journals. He serves as reviewer in several international journals. His research falls in different areas of interest: currently works on active tectonics, earthquakes, neotectonics and coastal tectonics, geology and geomorphology, tsunami deposits, floods and environment.



André Michard is a graduate of the Ecole Normale Supérieure, holder of the Agrégation of Natural Sciences (1955) and holder of a doctorate in Earth Sciences from the University of Paris Sorbonne (1966). He is an emeritus professor from the University of Paris-Sud (Orsay) since 1999. He began his academic career in the latter university, just launched, in 1958, after a Ph.D. thesis in the Western Alps, and kept working in the Alpine belts (Alps, Oman, Taurus, Cuba) until the early 2000s. He discovered Morocco in 1966 as a professor at Mohamed-V University, Rabat, and immediately fell in love of the geology of the country. His first works concerned the Variscan metamorphic domains of the Western Meseta. Once appointed professor at the University of Strasbourg (1968), he extended his Moroccan works to the Rif belt in connection with the Spanish geologists of the Betics. He published a first overview of Moroccan Geology in 1976 ("Eléments de Géologie marocaine"; 3rd edition in 2001, also translated in Japanese) and a second one co-authored by a large panel of Moroccan or European specialists, in 2008 ("Continental evolution: the Geology of Morocco"). In the meanwhile, he collaborated with several Moroccan academics in research programs targeting the High Atlas, Anti-Atlas and the Saharan domains. Based on this experience, he was the linchpin of the editing program of the "Nouveaux Guides géologiques et Miniers du Maroc" (2011, vol. 1–9). In the last decade, he co-authored also some 20 articles dealing with the structural geology, geodynamics, stratigraphy, paleontology or geoheritage of the various regions of Morocco. From the beginning of his academic activity, he has contributed more than 100 articles published in prestigious international journals. The first West African Craton and Margins International Workshop (Dakhla, Apr. 2017) has been dedicated to André as a tribute for his jubilee of works in Morocco.

Dr. Abdullah Al-Amri holds a B.Sc. in Geology (1981) from King Saud University (KSA), a M.Sc. in Applied Geophysics (1985) from the University of South Florida (USA) and a Ph.D. degree in Earthquake Seismology (1990) from the University of Minnesota (USA). He is currently Professor of Earthquake Seismology at King Saud University (KSU) and Director of the Seismic Studies Center at KSU, the Chairman of KSU's Geology and Geophysics Department and the President of the Saudi Society for Geosciences (SSG). He has received several international prizes and awards for scientific excellence and innovation. His research interests focus on crustal structures and seismic microzoning of the Arabian Peninsula. He has conducted more than 45 research projects, the most recent of which involved EM and MT applications in deep groundwater exploration of the Empty Quarter, and geothermal prospecting of volcanic Harrats in the Arabian shield. He has co-published 65 research articles in international indexed and refereed

journals and authored several books. In 2008, he, in close partnership with Springer, founded the Arabian Journal of Geosciences (AJGS) on behalf of the SSG. In 2018, Marquis Who's Who, the world's premier publisher of biographical profiles, proudly presented to him with the Albert Nelson Marquis Lifetime Achievement Award.

Earthquake Seismology and Geodesy (T3): IGCP-659 Meeting—Seismic Hazard and Risk Assessment in Africa

Swelling Performance of Paraffinic Crude Oil Under Carbon Dioxide Injection

Muslim Abdurrahman, Asep Kurnia Permadi, Wisup Bae, Ivan Efriza, Shabrina Sri Riswati, and Adi Novriansyah

Abstract

Paraffinic crude reservoir is one of an attractive options for co-implementation of CO_2-EOR and CO_2-storage activities. The effectiveness of oil recovery is affected by an oil swelling mechanism. The swelling performance of CO_2 in paraffinic crude is essential to be studied due to the difficulties to pursue miscible condition. This mechanism was investigated through the analysis of the swelling factor value from the swelling experiment. Moreover, the equation of state calculation (EOS) using Peng–Robinson equation was performed to predict the minimum miscibility pressure (MMP) of the crude sample for investigating swelling trends toward this point. Results from the experimental test reveal a slow process of oil swelling due to CO_2 injection, which is implied from the low swelling factor value. The EOS calculation shows a large MMP value, which was impossible to reach under reservoir condition. Extrapolating extraction-condensation trend indicates no occurring extraction which means that the main mechanisms for this crude type was dominated by viscosity and interfacial tension reduction. Although it was impossible to pursue the MMP, the utilization of CO_2 in paraffinic crude may bring a positive impact on the oil recovery process.

Keywords

CO_2 • Paraffinic oil • Immiscible displacement • Swelling factor • Minimum miscibility pressure

1 Introduction

As an alternative option to store carbon dioxide (CO_2), main component of greenhouse gas (GHG), oil reservoir is an attractive storage candidate because CO_2 can be used as an enhance oil recovery (EOR) agent, known as CO_2-EOR (Gozalpour et al. 2005). For over two decades, CO_2-EOR has successfully recovered residual light oil (Zhang et al. 2019). As CO_2 is well known to solve wax problem in production facilities (Yang et al. 2019), CO_2 capability in paraffinic crude oil reservoir should be tested. Paraffinic oil contains a large amount of wax. This oil type has gravity more than 25° API or still in the range of medium to light oil, where CO_2 flooding is still acceptable. High wax content is the reason of the time consumed by CO_2 solubilization process (Abdurrahman et al. 2019). This is similar to mechanisms of CO_2 injection in heavy oil. (Li et al. 2013). Even though the mechanism is similar, viscosity of paraffinic crude is lower than that of heavy crude in reservoir conditions. Therefore, the strategy to implement CO_2 in this type of crude should be different, including its swelling performance.

The objective of this paper was to study CO_2 swelling performance of paraffinic crude under CO_2 injection. This parameter was analyzed by interpreting CO_2-Oil swelling factor, a ratio of observed oil level at specific injection pressure to initial oil level. The swelling factor is useful in the condensation-extraction analysis and MMP estimation (Abdurrahman et al. 2015). Peng–Robinson equation of state (EOS) calculation was used to predict the MMP and analyze the possibility of an extraction mechanism to occur in miscible condition.

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2 Methodology

This experimental study utilized a crude oil sample from central Sumatra basin. The sample has an API gravity of around 30 or included to the medium-light oil. The bubble point pressure, pour point temperature, wax, and asphaltene contents are 113 psi, 105–110 °F, 33 wt%, and 13 wt%, respectively. The percentage of heptane plus ($C_7H_{16}^+$) was around 90 mol% at reservoir condition (Table 1). The crude was sampled at 1200 ft. depth, and the reservoir pressure was approximately 500 psi (Abdurrahman et al. 2019).

The swelling factor apparatus consists of a syringe pump for CO_2 injection, high-pressure-high-temperature (HPHT) optical cell, camera, and PC for observation. Crude oil is placed inside the optical cell which was located in the air-bath. The temperature inside the air bath was maintained constant by adjusting a heater temperature to reservoir condition (136 °F). CO_2 was injected continuously into the cell at constant pressure. Crude level inside the optical cell was recorded by using camera and recorded into numerical data by computer. The experiment was repeated for certain injection pressure, starting from 300 to 3300 psi.

Before predicting the MMP under EOS calculation, the fluid should be modeled and verified by matching the bubble point pressure and reservoir temperature with the previously reported data (113 psi; 136 °F). A simulation study was performed to estimate the sample MMP. EOS by Peng–Robinson was used under WINPROP module in CMG software. (CMG software 2014). Hydrocarbon composition in Table 1 and reservoir temperature were needed as an input parameter for this module. The MMP determination was performed by selecting multiple contact miscibility modules in the software. For a designated solvent, i.e., pure CO_2 and range of pressure, the MMP was determined at a certain temperature. In MMP, no mix envelope was found in the ternary diagram.

3 Results and Discussion

Figure 1 shows the swelling factor plot over the injection pressure where two trends of swelling factor data were recorded in this test, i.e., the swelling factor tends to increase with 0.14% per 1000 psi at low pressure region (300–1900 psi) and to decrease with 6.5% per 1000 psi in the range of 2000–3300 psi, which is lower than light crude oil swelling factor (Abdurrahman et al. 2015). These trends are similar to condensation and extraction-condensation phenomena (Wang 1986). The MMP was not achieved in this experiment based on definition by Abdurrahman et al. (2015).

Figure 2 displays the bubble point pressure of the crude sample in the fluid model phase envelope from the WINPROP module, where the generated fluid model was

Table 1 Hydrocarbon composition of the crude sample in this study

Component	Mole%	Component	Mole%
Hydrogen sulfide (H_2S)	0.00	Iso-Butane (i-C_4H_{10})	0.90
Carbon dioxide (CO_2)	0.56	n-Butane (n-C_4H_{10})	1.57
Nitrogen (N_2)	0.00	Iso-Pentane (i-C_5H_{12})	1.56
Methane (CH_4)	0.67	n-Pentane (n-C_5H_{12})	1.50
Ethane (C_2H_6)	0.67	Hexanes (C_6H_{14})	0.35
Propane (C_3H_8)	1.51	Heptane plus ($C_7H_{16}^+$)	90.71

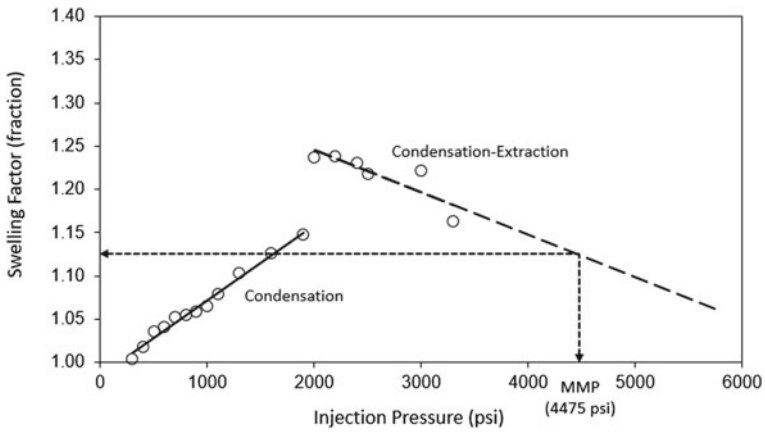

Fig. 1 Oil swelling factor at various injection pressure values

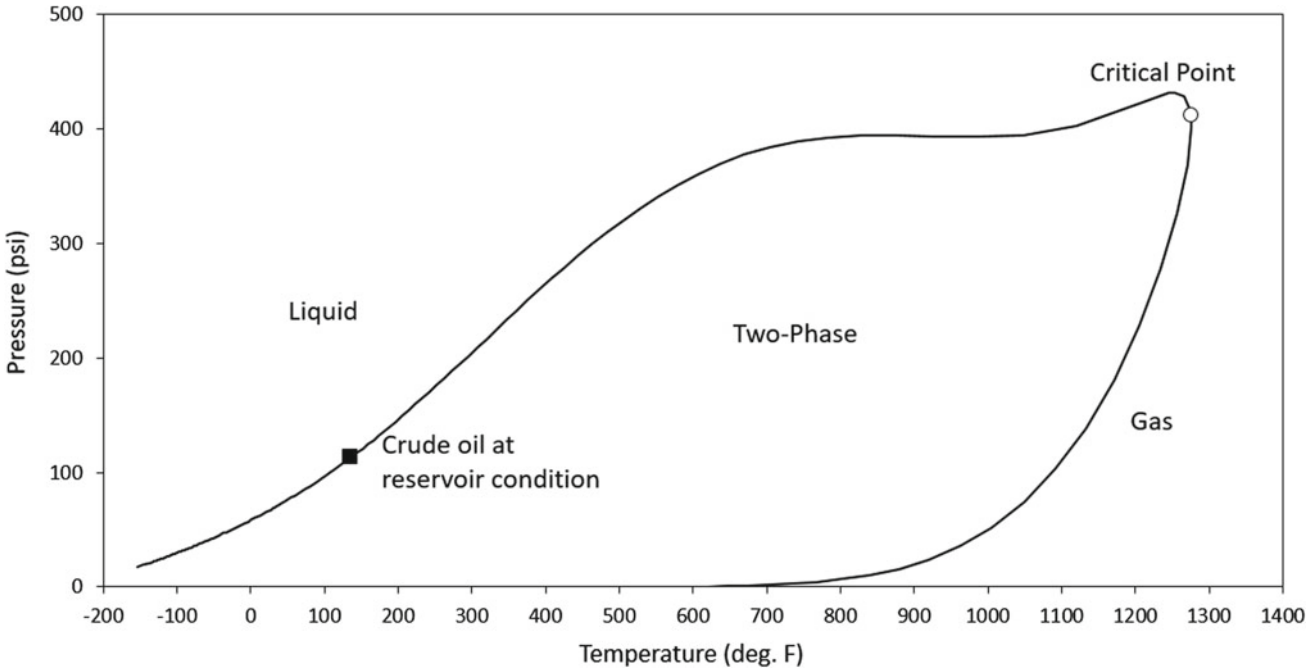

Fig. 2 Pressure–temperature diagram of crude oil sample

matched with the crude oil sample. The MMP calculation by Peng–Robinson EOS in WINPROP module yielded a large value (4475 psi), which means a displacement scenario is under immiscible condition with its reduction of oil viscosity and oil swelling due CO_2 dissolution mechanisms (Li et al. 2013). The ternary diagram in Fig. 3a indicates the change of the liquid line toward a vapor line by increasing the injection pressure. High pressure improves CO_2 solubility into oil, resulting high swelling factor (Abedini and Torabi 2014). In MMP condition (Fig. 3b), the vapor and liquid lines vanished, indicating miscibility already achieved, leaving a small portion of heavy component (represented as black dot in the ternary component) and Oil-CO_2 mixture (red dot in ternary diagram).

By referring to the swelling test result, the crude has a long extraction-condensation stage to pursue the MMP condition. Extrapolating the extraction-condensation trends to the expected MMP value from EOS calculation (Fig. 1)

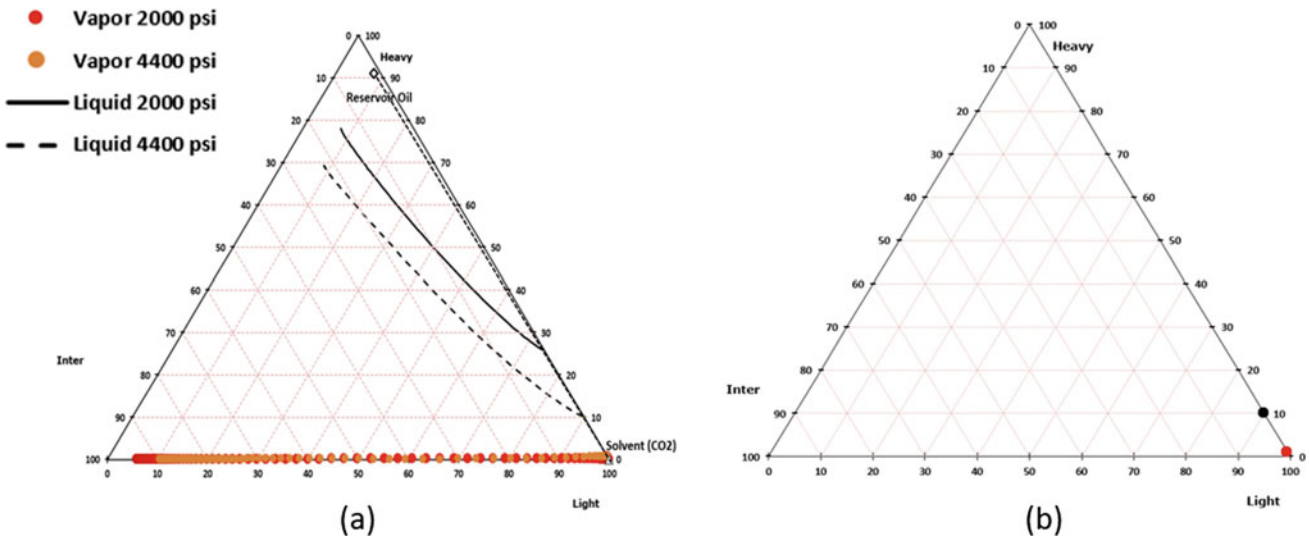

Fig. 3 Ternary diagram of fluid model at **a** 2000 and 4400 psi; **b** 4475 psi

results, the oil swelling factor was reduced from 1.24 to 1.12 (around 10% declined), which is still higher than the initial condition (1.00). Hence, the hydrocarbon extraction might not happen during CO_2 injection until the estimated MMP, and as a result, a CO_2 gas dissolves into oil, inducing the oil volume to increase. This phenomenon reduces the interfacial tension and viscosity, and the crude flows easier in porous medium (Li et al. 2013).

4 Conclusions

This paper combines the experimental and simulation work to study the swelling performance of paraffinic oil CO_2 injection. The swelling test led to two kinds of swelling factor trends which describe condensation and extraction-condensation phenomena. Both trends reveal low oil swelling factor, indicating the low capability of CO_2 dissolution. The MMP calculation by Peng–Robinson EOS limits the displacement process into immiscible scenario if the reservoir constraints are concerned. Long stages of extraction-condensation stage may have happened in the sample if the MMP from simulation was considered as MMP from the experiment. The CO_2 injection into this paraffinic crude may have ended in a CO_2 dissolution phenomenon.

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