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Invited Commentary

THE INTERNATIONAL SYMPOSIUM ON WETTABILITY AND POROUS MEDIA – PAST, PRESENT, AND THE FUTURE

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ABSTRACT

Classic work of capillarity in porous media was first reported by soil scientists and hydrologists over 100 years ago. Since then, the discipline has expanded significantly and includes diverse applications. Producing and optimizing subsurface petroleum reservoirs are one such application that have been the focus of much research and discovery for the past century while geological storage of carbon and hydrogen are emerging applications. The Wettability Symposium is a premier international meeting that has gathered a community of scientists and engineers interested in the affinity of fluids for surfaces in porous media. With a few exceptions, the Wettability Symposium has been held every two years since 1990. Even though the meeting has traditionally focused on petroleum systems, there is awareness in the community of the significance of wettability in various applications, including subsurface systems for carbon and energy storage contributing to the transition to low carbon intensity and net-zero energy systems of the future. This paper provides a brief history of the meeting, held October 2023 in Laramie, Wyoming, along with a summary of the discussions, identified gaps, and future perspectives.

KEYWORDS

Wettability Symposium, History, Research Trends, Future Perspectives

1. INTRODUCTION

The 15th International Symposium on Wettability and Porous Media, often referred to as the Wettability Symposium, was held from October 23 to 25, 2023 in Laramie, Wyoming, USA. It hosted 45 participants from around the globe, including five members of the National Academy of Engineering of the USA. The symposium focused on descriptions, measurements, and models of reservoir wettability, pore-scale models of flow and wettability properties in permeable media, alterations of wettability and physical

mechanisms that underlie these changes, and state-of-the-art core preservation and restoration techniques to improve quality of laboratory data. Here, we highlight the history of the meeting, the state-of-the-art, the outstanding questions, and the future directions of the meeting.

2. BACKGROUND & HISTORY OF THE MEETING

The Wettability Symposium (see **Figure 1** for the original logo) has a rich history that began at the Petroleum Recovery Research Center (PRRC) at the New Mexico Institute of Mining and Technology, also referred to as New Mexico Tech (NMT) (39). Kenneth Ford became President of NMT in 1975 (20) and spearheaded the founding of the Petroleum Recovery Research Center at NMT and the construction of the PRRC building soon after its founding. The building bears the name of John M. and Esther L. Kelly (39). John Kelly was a petroleum engineer and a petroleum geologist, who was later appointed as the Assistant Secretary of the Interior for Mineral Resources in January 1961 by President John F. Kennedy (30). John Kelly was an original champion of the founding of the Center. Most of the hydrocarbon production in New Mexico is in the northeast and the southwest corners of the state (16). After much discussion, the center ended up being centrally located at NMT. Kenneth Ford hired Professor Joe Taber, from the University of Pittsburgh, to start the center in June 1976 as the 1st Director of PRRC (22). Norman Morrow joined PRRC at Joe Taber's invitation in September 1976 as Head of Basic Studies, later referred to as the Petrophysics and Surface Chemistry Group. He was honored at the 15th Wettability Symposium for "lifetime contributions to the field of wettability and interfacial science."

Figure 1: The Wettability Symposium logo – the isotherm for double layer repulsion and van der Waals attraction.

In response to uncertainty in oil supplies from Southwest Asia (Middle East), the administration of President James E. Carter allocated significant funds to be disbursed amongst universities for research related to petroleum systems. Spurred by this federal investment, Norman Morrow's research Group, joined by John Chatzis, published extensively on the trapping and mobilization of oil at strongly water-wet states (7). This work expanded to include the effect of wettability on the oil recovery from crude oil/brine/rock (COBR) combinations. Soon after, Jill Buckley joined the Group working on crude oil chemistry and its effect on wetting (7). At the same time, work expanded to the recovery of gas from very low permeability sands. Fundamental studies of capillarity and wetting were continued through a more than 30-year collaboration with Geoffrey Mason of the University of Loughborough. The work on COBR combinations showed that mixed wetting states induced by crude oil typically resulted in significant oil recovery. Interest in these results led to an industrial consortium and federal funding, including a Department of Energy (DOE)-funded project on Reservoir Wettability in 1988. The first project meeting was planned for September 1990. Jake Rathmell, from ARCO (Atlantic Richfield Company) (7), a strong supporter of the Petrophysics Group's work, asked if a presentation from an ARCO researcher, Gary Gerald, could be included in the meeting. This triggered invitations for the affiliated companies to make presentations and all accepted. When the final program for the meeting was shown to George Stosur from DOE, he noted the number of supporting companies from abroad, commented: "there was one thing wrong – it should be called an International Symposium." Thus, the first meeting was named the "International Symposium on Reservoir Wettability and its Effect on Oil Recovery" and was hosted by Norman Morrow and Jill Buckley in September 1990 at NMT (25). Overall, the meeting was a great success. The scientific committee comprised Jill Buckley (NMT, USA), Norman Morrow (NMT, USA), George Hirasaki (Rice University, USA) and Louis Cuiec (Institut Français du Pétrole (IFP), France).

After the first meeting, Alistair Fletcher visited the PRRC to propose, with Kenneth Sorbie (Heriot Watt University), that they hold a follow-up meeting at Heriot Watt University in Edinburgh, Scotland. The second meeting was held in September 1992 in Edinburgh, Scotland (25). Sixty people attended from seven countries. There were 23 presentations with extended abstracts. Among them Clayton Radke

presented a study illustrating how thin wetting film forces, pore size, and capillary pressure interplay to describe the development of mixed wettability in rocks (27). This study subsequently became the basis for the incorporation of mixed wettability states into pore network models.

The Scientific Program Committee for the Heriot Watt meeting declared the meeting should be held every two years and asked Norman Morrow, who had joined the University of Wyoming (UW) that fall, to organize the next meeting in Wyoming. Subsequently, the third meeting was held in Laramie in September 1994 (25); 92 people attended from fourteen countries, and UW published the proceedings, comprising 35 papers (36). The 4th meeting was hosted by Louis Cuiec (IFP, France) in Montpellier, France in September 1996 (25). This meeting coincided with the annual meeting of the Society of Core Analysts (SCA), where Norman Morrow was honored with the SCA's Technical achievement award (7). Håkon Rueslåtten (Statoil, Norway) who was present at the 1996 Wettability meeting agreed to organize a 5th meeting, which was held in June 1998, in Trondheim, Norway (25). The 6th meeting was hosted by Jill Buckley (PRRC) in September 2000 in Socorro, New Mexico, USA (25). In 2000, Norman Morrow visited Australia as part of a Society of Petroleum Engineers distinguished lecture tour. Against that backdrop, Lincoln Patterson (the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Melbourne) proposed that the following wettability meeting be held in Australia. Various possibilities were considered. The compromise was to hold the 7th meeting at Freycenet, Tasmania in March 2002 (25). This meeting seeded a strong association with researchers in the Department of Applied Mathematics at the Australian National University in Canberra. The 8th meeting was hosted by George Hirasaki in May 2004 at Rice University, in Houston, Texas, USA (25). At George Hirasaki's request, Norman Morrow spoke on the history of the meeting at the symposium dinner. Also, Louis Ciuec who had recently retired from IFP was honored for his contributions to the understanding of reservoir wettability. Papers presented at the Wettability Symposium from 1996 to 2004 were published as five theme-issues of the *Journal of Petroleum Science and Engineering*, edited by either Norman Morrow or Jill Buckley (9, 10, 11, 34, 35). Subsequently records of the symposium, subject to permission, were made available as manuscripts and/or slide presentations.

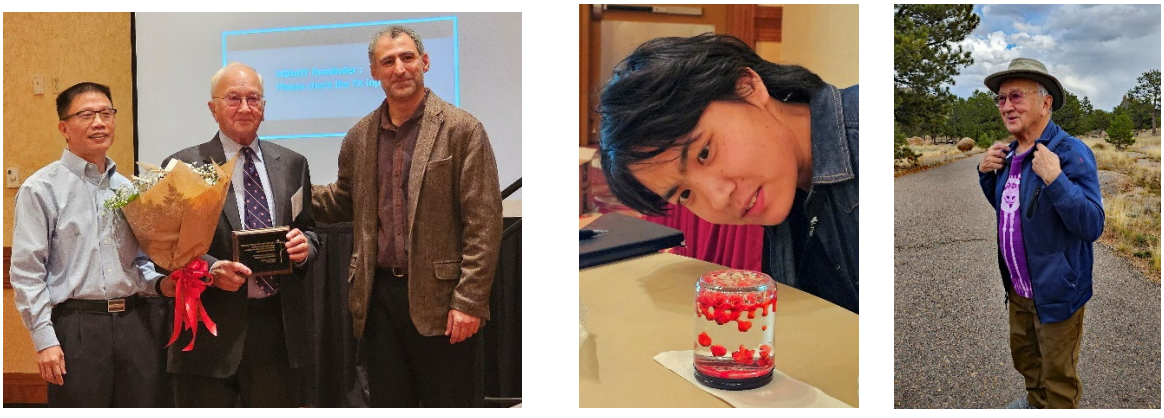
Arne Skauge (Norsk Hydro, Bergen, Norway) hosted the 9th Wettability meeting in Bergen, Norway in 2006 (see **Fig. 2**). Through encouragement by Arne Graue (University of Bergen), new collaborations were established between Geoff Mason, Douglas Ruth and the UW researchers with Martin Fernø and

Figure 2: 9th Wettability meeting, 2006, Bergen, Norway. An outing in Bryggen: From right to left: Felicity Mason (deceased), Evren Unsal, Xina Xie, Bev Ruth, Douglas Ruth (deceased), Kenneth Sorbie, Geoff Mason (deceased), Jill Buckley, Norm Morrow, Tien Fan. *Photo printed with permission of all individuals, or direct relations of deceased, shown above.*

Åsmund Haugen of the University of Bergen. The Abu Dhabi National Oil Company expressed interest in holding the 10th meeting in Abu Dhabi, in 2008 (24). The 11th meeting was held in 2010 at the University of Calgary and was hosted by Barry Bennett and Steve Larter from the Department of Geochemistry. Further continuation of the meetings was proposed by Reza Barati at the University of Kansas, who hosted the 12th Meeting in 2015 (51). The 13th meeting was held in 2018 at the University of Texas at Austin, USA, hosted by Kishore Mohanty. The 14th meeting was initially scheduled for 2020, but with the onset of COVID, the meeting was postponed to 2021. Skule Strand (Stavanger, Norway) hosted an on-line meeting in 2021, which coincided with 7th IOR Norway meeting at the National IOR Centre of Norway in Stavanger (40).

The 15th meeting was brought back to the University of Wyoming (UW) by Saman Aryana (14, 23, 38). In recognition of the broad reach of interfacial science in various applications and the evolving nature of questions of relevance, the name of the gathering was changed to the "International Symposium on Wettabililty and Porous Media". It was sponsored by the UW Center for Global Studies of the Global Engagement Office, the Department of Chemical & Biomedical Engineering at UW, and the Petroleum Research School of Norway (NFiP). Under the leadership of Arne Graue, NFiP enabled support from Norway for 10 international students from various parts of the globe to attend this meeting (38).

The scientific committee comprised Saman Aryana (UW), Anthony R. Kovscek (Stanford University), Vladimir Alvarado (UW), Maša Prodanović (UT-Austin), Josephina Schembre-McCabe (Chevron Corp.), Steffen Berg (Shell Global Solutions International B.V.), and Reza Barati (University of Kansas) (14). The lifetime achievements and scientific contributions of Norman Morrow were honored (see **Fig. 3a**). The meeting was organized as a single session, offering ample opportunities for connection and networking. These included daily breakfasts, coffee breaks, lunches, a conference dinner, a hands-on "Build Your Own Reservoir Model" exercise led by M. Prodanović (see **Fig. 3b** and the **Supplementary Material**, available online, for details), and a hiking trip. Notably, the meeting featured a trip to Vedauwoo, situated at an altitude of 8,000 feet in the Medicine Bow-Routt National Forest near Laramie (see **Fig. 3c**). Most of the attendees completed the classic hike around Turtle Rock. Overall, the meeting was a great success and spurred much discussion about the past, present and future of the discipline. The remainder of this paper provides a summary of the topics discussed in the meeting, the research questions that were emphasized, and potential future directions.



(a) (b) (c)

Figure 3: 15th Wettability meeting, October 2023, Laramie, Wyoming: (a) Norman Morrow's Lifetime Achievement Award. From left to right: Jason Tong, Norman Morrow, and Saman Aryana; (b) Participant Xuesong Ma inspecting the result of her "Build your own reservoir model" Exercise; and (c) Norman Morrow leading the Vedauwoo outing on Monday, October 23, 2023. *Photos printed with permission of individuals shown.*

3. SUMMARY OF DISCUSSIONS, TOPICS, AND IDENTIFIED GAPS & FUTURE PERSPECTIVES

The 15th meeting comprised three invited talks by George Hirasaki (Rice University), Clayton Radke (University of California Berkeley), and Steffen Berg (Shell Global Solutions International B.V.), (38) scheduled talks, and a panel discussion on the energy transition with panelists: Anthony Kovscek (Stanford University), Abbas Firoozabadi (Reservoir Engineering Research Institute), Eugene Holubnyak (UW), and Vladimir Alvarado (UW) (**Fig. 4**). During dinner, Norman Morrow presented the history of the Wettability Symposium and his thoughts about the future directions of porous media and wettability research. The presentations collectively showcased the state-of-the-art and recent advances in the understanding of wettability in porous media, particularly in the context of oil recovery and CO_2 sequestration. They demonstrated the significance of surfactants, pressure conditions, and advanced measurement techniques in altering and assessing wettability in different types of reservoirs.

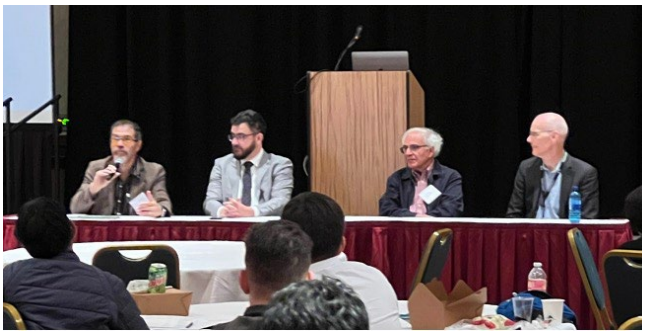


Figure 4: A Panel Discussion on the Energy Transition. From left to right: Vladimir Alvarado, Eugene Holubnyak, Abbas Firoozabadi, and Anthony Kovscek. *Photo printed with permission of individuals shown.*

The topics discussed and the speakers at the meeting are listed below.

- Gilsonite, a Solid Bitumen with Asphaltene having Exceptional Properties: *George Hirasaki, Rice University (invited talk)*
- Improving Multiphase; Pore-scale Transport Simulations on MicroCT Images Using Super Resolution Generative Networks: *Yulman Perez Claro, Stanford University*
- Microcalorimetric Study of Wettability Alteration of Outcrop Carbonates: *Jacquelin Cobos, University of Bergen*
- Investigating the Wettability of Caprocks with Supercritical Carbon Dioxide and Brine as a Function of Pressure: *Foad Haeri, U.S. Department of Energy National Energy Technology Laboratory*
- Pore-scale Assessment of Effects of Fluid Configuration and Wettability Alteration on Relative Permeability: *Ruoyi Li, UT Austin*
- Two-phase displacements in microchannels of triangular cross-section: *John Oakey, UW*
- Ion-Exchange-Induced Dissolution in Salinity-Altered Waterflooding of Carbonate Reservoirs: *Clayton Radke, UC Berkeley (invited talk)*
- Bridging adsorption behavior of CH_4-CO_2 binary systems across scales: *Lingfu Liu, UW*
- Wettability alteration for carbonate formations in West Texas: *Bruno Reinoso, UT Austin*
- Contact Angle measurements through micro-CT and ESEM: Technique validation and measurements on synthetic/real systems: *Paola Ceragioli, ENI*
- Experimental Study of Wettability Alteration and Its Effect on Oil Recovery with Chemical Injection in Unconventional Shale and Tight Rock Reservoir: *Tom Tang, Chevron*
- Experimental and numerical investigation of foam in fractured media: *Maša Prodanović, University of Texas at Austin*
- Hydrate film formation in subsea carbon storage: *Wen Song, UT Austin*
- CO_2 Storage in Deep Saline Aquifers on the Texas Gulf Coast: Early Characterization of Wettability, Capillary Pressure and Relative Permeability: *Behrooz Raeesi, BP*
- Caprock Wettability Under CO_2 Geostorage Conditions: *Alex Lee, ExxonMobil*

- From Low Salinity Ion-Tuned Waterflooding studies to more general insights into the Wettability matter, transversal within the Energy world: *Paola Ceragioli, ENI*
- Relevance of the Spatial Wettability Distribution: *Steffen Berg, Shell (invited talk)*
- Interfacial Elasticity Increase and Efficient Oil Recovery from Brine Injection: *Taniya Kar, RERI*
- Temperature-Dependence of Crude Oil-Brine Interfacial Rheological Properties: Vladimir Alvarado, UW
- CO_2 Foam Mobility Control for Enhanced Oil Recovery and CO_2 Storage: *Hilde Halsøy, University of Bergen*
- Spontaneous Imbibition in Layered Petroleum Reservoirs: *Akshit Agarwal, IIT Delhi*
- Mechanistic surfactant wettability alteration model for reservoir simulators: *Leonard Chang, Chevron*

The presentations explored various aspects of subsurface engineering, with a particular focus on wettability and porous media. They encompassed a range of studies, each contributing to a deeper understanding of fluid dynamics in petroleum reservoirs and the implications for enhanced oil recovery (EOR) techniques and CO_2 sequestration.

4. RESEARCH TRENDS & APPLICATION FIELDS

One dominant trend is to understand wettability more consistently as a multi-scale problem (6, 44). Advanced imaging techniques and numerical simulation models form an effective tandem for understanding solid-fluid interactions in rock-oil-brine systems. However, due to the multiscale nature of wettability changes, and their effects from the molecular level to pore/grain scale and beyond, experiments and numerical methods must continuously inform each other. This meeting serves as a critical platform for facilitating that exchange. Beginning in the mid-2000s, research on improved oil recovery (IOR) using brine with controlled ionic composition—referred to in the industry by various terms such as low salinity waterflooding and smart waterflooding—has primarily focused on wettability. This work has addressed both instrumental (19) and methodological aspects (8). The environmental and economic benefits of low salinity ion-tuned waterflooding as an IOR/EOR technique was a significant topic of discussion. Within the same application range, there is also a growing trend towards tighter rocks. Physical insights borrowed from oil and gas systems are then applied to describe and understand the renewables space, emphasizing the multiscale aspects of wettability.

Next to the traditional application fields associated with hydrocarbon recovery, there is a range of new application fields where wettability is an important parameter. One important consideration within the framework of COBR is the role of interfacial fluid-fluid phenomena. Wettability, a complex set of fluid-surface interactions, is often studied under preconceived assumptions on fluid-fluid interactions. However, phase mobility and consequently multiphase fluid flow in porous systems involves fluid-fluid as well as fluid-solid interactions. In this regard, quasi-static or equilibrium properties, such as interfacial tension, and dynamic properties at the fluid-fluid interface, resulting from modification of the water chemistry, are intertwined to regulate fluid mobility. Three presentations during the symposium in Laramie shed light on the associated responses. Clayton Radke presented early evidence that contact-angle measurements can be affected by fluid-fluid interfacial viscoelasticity. Taniya Kar showed that enhancement of interfacial elasticity leads to improved oil recovery. Vladimir Alvarado demonstrated through spinning-drop measurements that interfacial elasticity builds up at high temperatures.

The wettability of caprocks in the context of CO_2 sequestration under varying pressures was another noteworthy topic. Understanding caprock integrity in CO_2 storage scenarios is paramount for assessment of long-term safety and security of sequestered carbon.

Adding chemicals and increasing pressure in tight oil reservoirs was shown to enhance spontaneous imbibition and significantly improve oil recovery. Low concentrations of anionic surfactants were shown to be effective in recovery strategies. High pressure conditions were shown to reduce the pore size and increase the driving force for imbibition. Wettability considerations in the form of receding and

advancing angles directly impact flow and displacement behavior in drainage and imbibition, respectively.

Presentations included numerical simulation results of fluid flow in layered petroleum reservoirs using the MATLAB Reservoir Simulation Tool (MRST). The models included capillary-driven flow and considered the possibility of capillary breakthrough in the cap rock. Fluid propagation velocity varies in each layer, with the wetting fluid penetrating further in low permeability layers due to high capillary forces, with relevance to fluid dynamics post-CO_2 injection in CO_2 sequestration operations. Presentations also included a mechanistic surfactant wettability alteration model for reservoir simulation. For optimizing surfactant formulations in oil recovery, it is important to capture various geochemical reactions and the dynamics of wettability alteration. Another study used microcalorimetry to assess wettability alteration in carbonate rocks. This research showed dynamic rock-fluid and fluid-fluid interactions upon crude oil injection into carbonate rocks, providing insights into the interfacial phenomena affecting wettability in porous media.

5. NEW TECHNIQUES AND METHODS

Over the past decade there has been a tremendous improvement in experimental, modelling and conceptual capabilities. Several presentations highlighted our capability to determine in situ contact angles using X-ray computed micro-tomography (micro-CT). This technique was initially introduced by Prodanović et al. in 2006 (41) and was further automated and refined about a decade ago by the Imperial College group (2, 5). One of the key advantages is that contact angles can be studied in situ also at operating conditions in terms of pressure and temperature.

When measured at the end of imbibition, the resulting contact angle distributions often approximate a Gaussian shape, with a width of around 100 degrees (37). This width is roughly consistent with the interval between the maximum advancing and minimum receding contact angles observed on rough surfaces (37). Event-based contact angle distributions are significantly narrower (37), providing a different perspective regarding to which extent contact angles are dependent on displacement versus being an independent input. The latter is more the intrinsic contact angle and is accessible via a range of new microscopy techniques operating at the nanometer scale including atomic force microscopy (AFM) (19). Using force-distance mapping with AFM, wetting maps representing the work of adhesion (which can be translated into an intrinsic contact angle) were obtained.

In addition to micro-CT and AFM, the discussions included scanning electron microscopy (SEM) techniques such as environmental scanning electron microscopy (ESEM) and their application in understanding rock-fluid interactions and wettability assessment. While SEM has been instrumental to obtain details about surface topography, ESEM, and also cryoSEM techniques, allow the study of fluid-solid contacts in situ (46). Images reveal that the contact angles observed using micro-CT likely represent effective configurations, though the underlying microscopic details are more complex.

The experimental images are there both for characterization and input to numerical models on the pore scale. For that purpose, images from natural rocks are used, along with tests on synthetic sandstone, carbonates, and tighter synthetic rocks. These tests were presented at the symposium, offering new insights into wettability assessment in reservoir engineering.

On a conceptual level, there has been significant advances in the description level of wetting. Two decades ago, Morrow and Mason's groundbreaking work extended the Young-Laplace description from planar surfaces and spherical droplets to more complicated geometries (29). More recently, this has been further advanced to a universal description of wetting through the use of integral geometry along with thermodynamic considerations (48).

In contrast to effects of fluid-solid interactions, buildup of fluid-fluid interfacial viscoelasticity has been shown to suppress phase-trapping by preventing snap-off of the non-wetting phase (4, 32, 33). This has become possible thanks to the development of new interfacial rheological tools such as the double-wall ring interface rheometer (12). These measurements have already contributed to model the interfacial

force balance that is able to explain the competition between capillary and dynamic interfacial effects such as non-wetting phase choke-off (21).

Micro-CT studies in combination with pore network modelling suggest that the 3D distribution of wetting might be more important than average contact angle. Three-dimensional wettability maps obtained by X-ray computed micro-tomography (18) show a non-uniform distribution of water and oil-wetting pores. Pore network modelling studies show that in more homogeneous rock, the spatial distribution of wetting has a major influence on the pore filling sequence and resulting saturation distribution and relative permeability (15). Both studies suggest a spatially correlated wetting distribution, very different from what is traditionally assumed as input for pore-scale simulation. Using the advanced atomic force microscopy techniques, it could be understood that the different faces of clay minerals do indeed exhibit a different response to ionic composition of brine (19) and that the redox conditions can have a significant impact on wettability (52, 54).

6. OPEN QUESTIONS, KNOWLEDGE GAPS, & FUTURE DIRECTIONS

In summary, spontaneous imbibition in tight oil reservoirs is a complex and multifaceted process, influenced by factors such as fracturing fluids, surfactants, nanoparticle additives, capillary forces, and the geological characteristics of the reservoirs. Ongoing research and experimental studies continue to deepen our understanding of this process, with a focus on enhancing oil recovery and addressing the challenges posed by the unique properties of tight oil reservoirs. These studies collectively advance the understanding of wettability in porous media, particularly in the context of oil recovery and CO_2 sequestration. They demonstrate the significance of surfactants, pressure conditions, and advanced measurement techniques in altering and assessing wettability in different types of reservoirs. Despite these advancements, there remain gaps in fully understanding the nano and microscale interactions in porous media, especially under varying chemical and pressure conditions. The complexity of these interactions poses challenges in accurately modeling and predicting fluid behavior in porous structures. Despite progress regarding quasi-static multiphase fluid flow at low capillary number, previously less explored mechanisms, such as interfacial viscoelasticity, have been shown to participate in the fate of fluid distributions and phase displacement. Future research may focus on developing more sophisticated models and experimental techniques to better understand and manipulate wettability in porous media. This includes exploring the effects of different chemical additives, pressure conditions, and reservoir characteristics on wettability alteration.

Advanced experimental techniques, such as nuclear magnetic resonance (NMR) (31), scanning transmission electron microscopy (STEM) (17), transmission electron microscopy (TEM/cryo-TEM), SEM (13, 53), and particle image velocimetry (PIV) (49, 50), together with models such as molecular simulations and lattice Boltzmann (LB) models (1, 28), offer promising avenues for fundamental discoveries. These tools and methodologies enable a deeper mechanistic understanding of interfacial science in porous materials and enhance predictive capabilities. Their applications are diverse, ranging from subsurface energy and carbon storage to separation processes and the extraction of rare earth minerals, extending to biomedical fields such as blood plasma membranes.

A key challenge in pore scale modeling is determining the spatial distribution of wettability (15). Techniques include spatial mapping of wetting using NMR, wettability anchoring experiments with imbibition capillary pressure measurements (42, 43), and inverse gas chromatography to derive spatial wetting distribution – an ongoing research focus. Another complex issue relates to wettability and contact line dynamics (3, 45, 47), which is especially challenging in strongly water-wet conditions characterized by fast Haines jumps, with an entrained wetting phase, and no clear contact line.

In numerical simulations, the non-wetting phase forms a moving contact line with the solid during the Haines jump (45). In physical experiments, the contact line gets pinned at the pore entrance, causing the non-wetting phase to expand into the pore body as a droplet. Initially, when the capillary number is higher than the critical value, the wetting phase gets entrained. Only later, as the velocity drops, contact

with the solid forms. Integrating these phenomena into numerical simulations poses significant challenges, necessitating a thorough understanding of their implications.

Additionally, the role of wettability on multiphase fluid flow does not correspond directly to the average contact angle. In dynamic experiments, for example, the contact angle may differ significantly from its equilibrium state and exhibit hysteresis that depends on displacement path, COBR interactions, and time. The spatial distribution of contact angles within the rock notably affects fluid relative permeability and capillary pressure, beyond the typical uncertainty ranges of average contact angle measurements.

Effective upscaling from pore scale to Darcy scale necessitates utilizing microscopic measurements of both the rock's structure, mineralogy, and wettability. Instead of depending solely on geometric contact angles, wettability should be assessed by examining the mineral-specific surface coverage of interacting fluid phases, thus avoiding associated issues with the advancing-receding contact line.

7. CONCLUSION

Putting things in perspective, in the 1970s, there were approximately 18 company laboratories in the US dedicated to oil production research. Since then, nearly all US production research laboratories have merged and/or closed. Research active company laboratories are now nearly all located outside the US. Nevertheless, the discipline of interfacial science and wettability remains as important as ever. In the context of the subsurface, wettability will continue to dominate the subsurface behavior in storage of sequestered carbon, hydrogen, and other energy carriers of the future. The format of the Wettability Meeting promoted interactions between experimentalist and modelers that is necessary for scientific advancement.

Looking forward, there is a general recognition in the community of the need to broaden the scope of the meetings to include a much wider range of topics. Additional topics of interest include water and nutrient retention and movement in soils, adsorption and transport in plant matter (roots and fungi for forests and grasslands), permafrost, and the key links that artificial intelligence can reveal within a huge body of rapidly growing and widely scattered literature on wetting and transport in porous media. For that reason, the 16th Wettability meeting is currently scheduled to take place jointly with the 4th Biennial Meeting of InterPore Australian Chapter in Sydney from the 28th to 31st of January 2025 (26).

STATEMENTS AND DECLARATIONS

Supplementary Material

Instructions on how to build your own reservoir model are available in the Supplementary Material, which can be downloaded online here.

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Author Contributions

All authors contributed to the preparation of this article, including the drafting, revising, author corrections, and final approval.

Conflicts of Interest

There are no conflicts of interest to declare.

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