Summary of the AAPG–SPE–SEG Hedberg Research Conference on "Fundamental Controls on Flow in Carbonates"

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A joint AAPG–Society of Petroleum Engineers–Society of Exploration Geophysicists Hedberg Research Conference was held in Saint-Cyr sur Mer, France, on July 8 to 13, 2012, to review current research and explore future research directions related to improved production from carbonate reservoirs. Eighty-seven scientists from academia and industry (split roughly equally) attended for five days. A primary objective for the conference was to explore novel connections among different disciplines (primarily within geoscience and reservoir engineering) as a way to define new research opportunities. Research areas represented included carbonate sedimentology and stratigraphy, structural geology, geomechanics, hydrology, reactive transport modeling, seismic imaging (including four-dimensional seismic, tomography, and seismic forward modeling), geologic modeling and forward modeling of geologic processes, petrophysics, statistical methods, numerical methods for simulation, reservoir engineering, pore-scale processes, in-situ flow experiments (e.g., x-ray computed tomography), visualization, and methods for data interaction.

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MEETING FORMAT

The conference was organized into four thematic sessions on the first two days (fundamentals, measurement and detection of flow on laboratory to field scales, uncertainty and prediction, and novel modeling and simulation techniques); a field trip on the third day was preceded by a dedicated poster session that introduced the geology of the area, whereas the ice breaker featured guest lectures on innovation and complex adaptive leadership, as well as a panel discussion. Given the challenge of cross-disciplinary communication, delegates were encouraged to adopt a beginner's mind, challenging the status quo and exploring basic questions that the establishment might have overlooked. Stepping back and slowing down to promote effective conversations among different disciplines was emphasized upfront. Several delegates noted that technical jargon was a significant barrier to novel thinking in the way that it impeded effective communication among disciplines during the meeting. Cross-disciplinary interactions were encouraged by several further mechanisms, representing a shift from more common Hedberg Conference formats. Overall, the conference started with substantial guidance to promote engagement. As the week progressed, the conference format became less structured as delegates learned more about each other and pursued the development of research ideas. For a group of free-thinking research scientists, early deliberate orchestration of interactions was an unusual experience. The objective, however, was to ensure that delegates did not fall back on established connections, to promote new connections and to engage all delegates (particularly non-native English speakers). Some of the techniques used resemble methods used in Open Space Technology to promote self-organization in a framework of simple guidelines (Owen, 2012). Nick Obolensky (Vth Dimension) and Julian Birkinshaw (London Business School) helped to kick off the meeting with introductions related to innovation. Birkinshaw discussed "Where Ideas Come From," while Obolensky led sessions related to "Complex Adaptive Leadership" and "Self-Organization." Delegate feedback commented on the value of these nonscientific contributions, recommending that similar efforts might be worthwhile for future conferences. The techniques encouraged delegates not only to think about the science and technology but also to consider how situations and interactions were impacting their ability to connect and innovate. Several of the approaches had been tested previously through the ExxonMobil-Academic $(FC)^2$ Alliance (Agar, 2009), but this Hedberg Conference provided an opportunity to evaluate these methods in a large group of academic and industry researchers, many of them meeting for the first time. A panel discussion, led by Professor Martin Blunt (Imperial College London), Donatella Astratti (Schlumberger), and Brodie Thompson (ExxonMobil) then emphasized why innovation is needed for carbonate reservoirs and what keeps the scientific community from achieving it.

From the start of the week, delegates were asked to consider new research opportunities in the form of proposals for collaborative multidisciplinary research involving academic and industry representatives. A strong emphasis was placed on the development of bold new ideas regardless of budget and present-day technical feasibility. The motto for the week was "Build your spaceship to Mars!," encouraging delegates to think beyond incremental developments on their current line of research and to explore new and unfamiliar areas. During the first three days of the conference, delegates could propose a potential "venture group" by posting an idea or research direction and inviting others to sign up. Essentially, the conference provided a market place to sell and buy into ideas with a view to consolidating a limited number of teams later in the week to discuss forefront research proposals (Figure 1). Although many high-quality and informative presentations and posters were presented, the emphasis was very much on the future. To support the development of venture groups, 13 keynote presentations were delivered over the first 2 days to introduce provocative thinking, novel research, and case studies related to each of the four half-day themes. The presentations were followed by poster sessions (~15–20 posters per session). Nearly all delegates who were not giving keynote presentations contributed a poster, creating a rich library of ongoing research primarily related to geoscience, flow prediction, and production in carbonate reservoirs. Abstracts for the talks are now available on AAPG Search and Discovery and were distributed electronically to the delegates. In addition, many delegates volunteered to make their talks and posters available in electronic format after the conference via a secure Web site at Heriot-Watt University.

Posters (Figure 2) provided a starting point to identify connections and future research opportunities. Speed dates were used at the start of each poster session as a means to identify connections. These 8-min exchanges required the poster presenter to deliver key research messages, needs, future directions, and opportunities. Some delegates noted that posters commonly have more writing on them than can be easily absorbed and that the focus on a few key points helped to drill quickly into what really mattered. After 4 min, the audience (that had self-organized around the posters in each session) was asked to provide feedback on common interests and connections that they

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could identify and ways that they might help. For some, this felt a little different because their usual mode of interaction is to interrogate the science as opposed to identifying opportunities. The fundamental science was still important, but delegates were being asked to think on their feet about potential mutual gains. In the open format poster session that followed, delegates were asked to identify three to five posters that could offer opportunities for research collaboration on a common theme. A simple numbering system enabled the rapid acquisition of data and mapping of networks (Figure 1). Delegates agreed to share information on connections to posters, although it was recognized that large differentials in the apparent popularity reflected might exist. It was emphasized that network maps of connections did not represent any evaluation of the scientific or technical merit of a given poster. First, delegates might not even recognize the opportunities associated with cutting-edge research. Second, to a large extent, connections tend to reflect the interests of delegates instead of the opportunities for commercialization. Some biases also arose from the position of posters in the meeting room and timing of sessions. Recognizing that the process was far from perfect, the network maps still offered some early insights to potential hubs for venture groups. Several poster presenters also commented that the networking process helped to identify novel connections that they had not previously considered. Following a spectacular introductory boat trip along the coast between La Ciotat and Cassis on the first day of the conference, a mid-week field trip provided the transition from orchestrated presentations and poster sessions to more informal interactions. Led by the faculty and students at the Université Aix-Marseille, the trip focused on Cretaceous carbonate outcrops near Orgon and Cassis. The diverse group of delegates was introduced to analogs for Middle East carbonate reservoirs, examples of fault zones in carbonates, facies in various ramp settings, outcrop fracture studies, and multi-kilometer–scale overviews of carbonate sequences.

The fourth morning of the conference provided additional time for delegates to review the venture group proposals and to consolidate into 12 or less groups. Starting with more than 20 proposals, self-organized mergers and acquisitions condensed fairly quickly down to just five venture groups (see below). Breakout discussions with interim report outs were used to shape research proposals by each venture group for the next day with final presentations delivered on the last morning (Figure 1).

The following section summarizes key points from each of the sessions including all keynote oral presentations and posters. To avoid unnecessary repetition, some posters are discussed in a different session from the one in which they were presented.

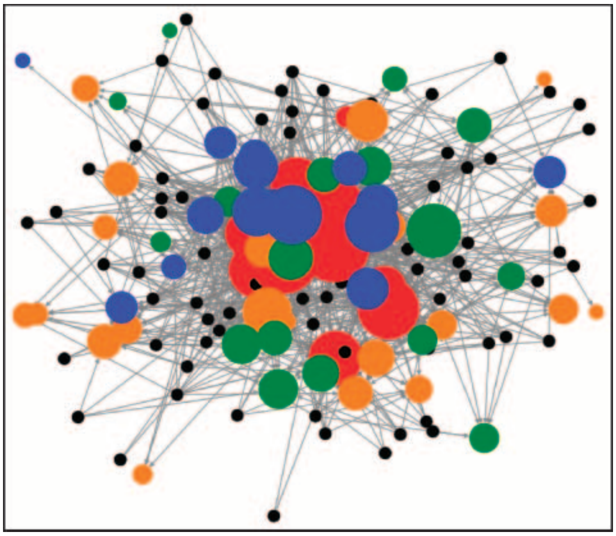

Figure 1. Example network of individual delegates (black dots) and their connections to posters in all four poster sessions for the first two days. The posters common to a given poster session are represented by dots with a common color (i.e., red, green, blue, or orange). The size of the circles represents the in-degree, that is, the number of delegates who identified a connection to a given poster. These displays were used to provide early indications of research interests and potential links that could underpin venture groups. Data presentation by Laura Wegener.

EMERGING THEMES RELATED TO FUNDAMENTAL PROCESSES

Joyce Neilson (University of Aberdeen) and Olivier Gosselin (Total/Imperial College) led the first session on "fundamentals." Key messages included the following:

- Future research needs to emphasize the fundamental physics and chemistry controlling fluid movements in carbonate rocks. Some of this research is currently limited by technical capabilities (e.g., imaging).
- Expansion of pore-scale simulation research is stimulating further discussion related to multi–scale-modeling approaches, more rigorous approaches to upscaling, and improvements for reactive transport modeling (RTM).
- The creation and destruction of porosity involve fundamental processes affecting all carbonates. Significant advances are still needed to develop reliable simulations of porosity evolution.
- Insights to first-order processes and their relation to original mineralogy and stratigraphy may offer ways to simplify porosity and permeability prediction.
- Knowledge creation related to the processes controlling stylolite formation and fracture aperture development is opening up paths to improved prediction and representation in flow models.
- Many alternatives available for flow and mechanical modeling tools that can offer improvements on the current state of industry technology exist. A state-of-the-art summary would benefit many researchers (see also Session 4 below).

Methods to Predict and Control Wettability

Discussions emphasized the need for more research on the fundamental physics and chemistry controlling fluid movements in carbonate rocks. In particular, presentations highlighted the relationship of wettability to pore structures, how wettability varies with pore surface, and how we can use this knowledge and smart water to change the wettability of pore throats to increase permeability. One approach discussed in Martin Blunt's (Imperial College) keynote presentation introduced pore-network modeling as a means to study the impact of wettability and connectivity on waterflood relative permeability. This approach involves computing flow through binarized images, solving the Stoke's equation for slow viscous flow, tracing streamlines through the pore space, and moving particles combined with a random displacement. Agreement between simulation results and experimental neutron magnetic resonance (NMR) measurements reinforces confidence in the method. A further experimental study of wettability, that of Kristian Mogensen and Søren Frank (Maersk), looked at different scales to constrain the impact of heterogeneities. Their results highlighted the function of surface reactivity and roughness on wettability and the potential to modify pore-throat roughness (and wettability) through carefully designed acid jobs. Surface electrical charge was proposed as another influence on the wetting behavior of carbonates by Matt Jackson (Imperial College). He discussed the use of the streaming potential coupling coefficient as a way to probe the surface electrical charge properties of carbonate samples

Figure 2. Speed dating at the posters.

saturated with brine and crude oil. The method also offers a way to explore whether changes in surface charge and wetting state are responsible for improved oil recovery during controlled salinity water floods. The importance of being able to visualize directly the distribution of residual phases in the rock pore space based on plug nanometer-scale studies was discussed by Mark Knackstedt (Australian National University). His multiscale imaging approach not only provides insights to recovery mechanisms but also can support the development of upscaling methods for flow properties from pore to plug to core scales. Masa Pradonovic (University of Texas at Austin) also revealed submicron porosity characteristics of carbonate rocks through her ion beam microscopy studies (see more below). An identified challenge for the wettability theme was the need for a set of recommendations or guidelines to represent relative permeabilities for (fractured) multiporosity carbonates with complex diagenetic evolution. Furthermore, current image resolution for tomography imposes limitations on pore-scale visualization and modeling. This said, the potential for pore-scale modeling approaches to advance RTM was highlighted as a promising future research area.

Processes Controlling Porosity Development

The creation and destruction of porosity involve fundamental processes affecting all carbonates and represent a cornerstone of carbonate geoscience research. Without appropriate constraints for modeling parameters, simulations of porosity evolution remain exploratory at best. Starting with the fundamental assumptions used in numerical models, Simon Emmanuel (Hebrew University) discussed the shortcomings of empirical rate laws of dissolution for dissolution in heterogeneous carbonates. Suggested improvements have been developed based on combined atomic force microscopy and numerical modeling studies of dissolution rates and mechanisms. Linking to comments on pore-scale modeling above, these results are now being used to propose techniques to integrate pore-scale heterogeneity with reactive transport models. The large number of complex interactions involved in diagenesis were noted as a key challenge for simulations. However, a contribution by Adrian Immenhause (Ruhr University Bochum) emphasized the first-order controls of original mineralogy on dissolution (the aragonite vs. calcite seas issue). The recognition of carbonate mineralogy as one of a limited number of factors that exerts an overriding influence on diagenesis may offer a way to simplify diagenetic models. In the absence of robust simulations of porosity evolution, a tendency to fall back on common assumptions (rules of thumb and anecdotes) for porosity and permeability development also exists. Whereas some may argue that sequence boundaries tend to localize significant porosity and permeability development, Robert Goldstein (University of Kansas) presented a different view: reductions in porosity and permeability at sequence boundaries are also predictable on the basis of depositional facies and thus can improve subsurface models. Cementation as a process that can destroy overall permeability was further highlighted by the concept of diagenetic backstripping (Rachel Wood, University of Edinburgh) as a means to identify diagenetic tipping points during the evolution of carbonate reservoirs during burial that can be linked to fluid migration histories. Discussions extended to porosity and cementation in stylolites and fractures. Einat Aharonov (Hebrew University) identified categories of stylolites; the mechanisms controlling their evolution; and their impacts on large-scale strains, spatial distributions of porosity, and potential flow. A proposed upscaling approach also offers a new way to incorporate core-scale observations of stylolites into field-scale models. The processes controlling fracture aperture development were also addressed. As a key impact on fracture flow predictions, appropriate definitions of fracture aperture populations remain elusive. In response to this challenge, novel approaches to evaluate the impacts of stress and fluid reactivity on apertures were shared by Derek Elsworth (Pennsylvania State University). His experimental results suggest that both the fluid chemistry and characteristics of the fracture surfaces influence whether the fracture aperture is likely to increase or reduce with time. The direction of flow along fractures can also impact whether their apertures decrease or increase. Gareth Jones (ExxonMobil) showed the strong impacts of thermal gradients on dissolution and cementation rates in convective flow models (variable density fluid flow coupled with thermodynamic reactions) for nonmarine carbonates. Weak gradients along strata have little impact; however in fault zones, stronger thermal gradients promote faster dissolution when flow is directed up the fault but more cementation when flow is directed down the fault. These thermal gradient effects have the potential to drive locally an order-of-magnitude difference in permeability. Whereas each of the studies above focused on a particular aspect of carbonate porosity, Rudy Swennen (KU Leuven) promoted the need to integrate and coordinate studies of various carbonate pore networks to realize gains for both academia and industry. He highlighted the ad-hoc nature of reservoir studies undertaken to meet industry needs for the short term, the small size of academic research groups, and the lack of a full spectrum of required expertise in any given group. In his view, the coordination of a consortium of multiple research groups to develop a structured database on this theme can offer significant advances in terms of standardization of data and broader access.

Simulation of Flow and Fundamental Geologic Processes

In addition to direct investigations of the fundamental physical and chemical processes that impact flow and rock properties in carbonate reservoirs, the first session introduced some of the challenges related to the development of appropriate proxies and their representation at different scales in models (pore scale to full-field scale). Issues surrounding the scaling rock and fluid flow behavior, as well as multiscale modeling techniques, were raised commonly. As an example of a way to capture the fundamental physics while reducing computational cost, Masa Pradonovic (University of Texas at Austin) demonstrated a novel two-scale network model to connect flow on pore and microporosity scales. Moving to a coarser scale, Jim Jennings (Shell) sought a way to simplify. He proposed a generalized approach for permeability averaging through the use of power averaging. This approach provides flexibility to range between harmonic and arithmetic means, using exponents estimated by the Ababou conjecture and applying these, stepwise, to random permeability fields containing different anisotropies. At an even coarser scale, Cedric Griffiths (Commonwealth Scientific and Industrial Research Organization) addressed multiscale forward stratigraphic modeling as a way to gain insights to appropriate upscaling techniques for rock properties and to predict rock properties between wells.

Highlighting the numerous improvements needed to advance flow simulation for carbonate reservoirs, Olivier Gosselin's (Total/Imperial College) keynote presentation challenged delegates to pursue improvements or alternatives to dual porosity models for fracture-flow simulations. No resistance to this proposal was voiced at the conference, and several alternatives were highlighted in subsequent talks and posters (discrete fracture-matrix modeling, lattice

Boltzmann, cellular automata (CA), network (ball and stick model), Langrangian, and continuous time random walk (CTRW) [see below]). Ensuing discussion of discrete fracture network (DFN) models raised questions concerning the current state of geomechanical modeling as a means to generate fracture populations, their connectivity, and the value of coupling fluid flow to geomechanics. Reinforcing the need for a review of geomechanical modeling tools, Gosselin also highlighted new approaches that are under development (e.g., incorporating fluid flow into geomechanical simulations and attempts to incorporate fracture propagation and realistic fracture aperture distributions in discrete fracture matrix [DFM] models). The problem, however, is that, while numerous geomechanical modeling efforts are being pursued, interested parties are challenged to find the time and resources to evaluate all of them, and little consensus on the most promising research avenues appears to exist.

Although many people are familiar with the application of DFN simulation approaches for fractured carbonate reservoirs, the application of the CTRW method, which is well established in the groundwater community and has been used in physics since the early 1970s, was less familiar to many of the delegates. The CTRW approach has been applied in many different fields, but examples of its application to subsurface flow in hydrocarbon reservoirs are more limited. In his keynote presentation, Ruben Juanes (Massachusetts Institute of Technology) introduced the CTRW method as a novel way to look at anomalous flow and particle velocity, emphasizing flow in fractured porous media. In his example, the CTRW was being used to validate a spatial Markov model on a lattice network that explicitly captures the multidimensional effects associated with changes in direction along the particle trajectory. Potential applications of this approach include forecasting and risk assessment of the drained reservoir volume or time to breakthrough in fractured reservoirs directly from DFN models. This approach avoids the need for lengthy dynamic simulations on conventional corner point grids and the difficult task of upscaling the DFN.

A wide-ranging conversation on various aspects of modeling permeated discussions throughout the conference. Comments reinforced the need to improve the integration of static and dynamic data and the types of dynamic data needed to calibrate models for a given scale with a given recovery process. In addition, the relative merits of more simulations and more sophisticated simulations versus a move to simpler approaches were debated. The fact that conclusions from simulations may arise from an input that is not being tracked carefully was duly noted. Discussions also drew attention to the fact that reservoir simulation models step forward linearly in time whereas much of the inherent flow physics operates on multiple time scales, that is, it happens much faster than a single simulation time step (and hence would be represented incorrectly) or is much slower (and hence the simulator calculates that nothing happened in part of the reservoir volume). This not only makes the use of computational hardware inefficient but also simplifies the flow physics, potentially leading to erroneous results and production forecasts.

EMERGING THEMES RELATED TO MEASUREMENT AND DETECTION OF FLOW AND ROCK PROPERTIES

Laura Pyrak-Nolte (Purdue University) and Matt Jackson (Imperial College) chaired a session on various approaches to measure and detect flow and rock properties from plug to play scales. Key points from this session were as follows:

- Petrophysical experiments are revealing further complexities in terms of rock and fluid impacts on acoustic signatures—there is much more to do.
- Petrophysical assumptions for clastic rocks do not necessarily apply in carbonates caused in part by the multiple scales of heterogeneities that exist in carbonates. Novel experiments are highlighting additional insights to controls on distinct paths for porosity and permeability development in carbonates and offer improvements for established petrophysical parameters.
- An opportunity exists to pursue more subsurface experiments to validate modeling (flow and seismic) and interpretation of seismic signatures, to learn more about what happens between wells, and to measure flow properties directly.

- Linking different measurements over different scales is a major challenge for monitoring and detection of flow. Opportunities exist to develop better tools for subsurface monitoring and better tools for seamless data integration.
- Various inversion methods and integration of all available data types (geophysical, geologic, and production and/or engineering data) can help to reduce uncertainties. No single approach can tell us what we need to know.
- We need to remember that operations also impact flow—it is not just geology and fluids.

INSIGHTS FROM NOVEL PETROPHYSICAL EXPERIMENTS

The overlap in length scales of discrete elements in carbonate rocks together with changes induced by factors such as stress, fluid content, and reactive fluid flow make it particularly challenging to interpret the geophysical signatures of flow behavior and to tie petroacoustic responses to rock properties. In her keynote presentation, Laura Pyrak-Nolte (Purdue University) used results from time-lapse imaging of Austin chalk samples to promote three key areas for future research on seismic wave behavior: (1) in layered media in the transition zone between ray theory and effective medium theory, (2) for layered systems with two competing anisotropic sources, and (3) in layered fractured systems that are geochemically altered over time. The experimental results highlighted several issues related to the influence of different rock and fluid characteristics on acoustic properties. Fracture-specific stiffness will change as a consequence of precipitation and reduction of a fracture aperture, whereas the locations of fractures in a layered medium will impact interpretations of specific stiffness. Changes in flow paths, fluid saturation (velocity dispersion), and fluid substitution (seismic anisotropy) will also influence the seismic response.

Further laboratory studies of petrophysical properties introduced several novel approaches to improve the link between petroacoustic signatures and the rock properties while highlighting the distinct approaches required for carbonate rocks. Efforts to improve constraints on porosity and potential permeability were targeted by Elizabeth Bemer (Institut Français du Pétrole) via a micromechanical model. By capturing microstructural characteristics, Bemer is able to compute theoretical velocities and compare these with experimental petroacoustic measurements. This, in turn, enables inversion for optimal parameters such as pore aspect ratio. The limitations of Archie's law when applied to carbonate rocks were further highlighted by two studies from Geosciences Montpellier: using a synchrotron facility to image connected porosity and percolation clusters, Charlotte Garing (Geosciences Montpellier) illustrated a flow dependency on the critical pore size connecting the percolating network instead of the electrical formation factor or tortuosity. Discussion reinforced the need to integrate three-dimensional (3-D) imaging with core-scale geophysical properties as a consequence of the fine-scale heterogeneities (below that of the integration volume of the borehole geophysical methods) and the strong influence that these heterogeneities have on the hydrodynamic properties of the rock. In addition to pore sizes, geometry, and connectivity, reactive surface area was introduced as a new controlling parameter. Philippe Gouze (Geosciences Montpellier) presented controlled dissolution experiments to show how the pore structure changes in different ways with dissolution regimes (representing different rates of dissolution). One consequence of this is the development of distinct porosity-permeability relationships within different dissolution regimes. The importance of links between chemical and physical processes was further emphasized by Tiziana Vanorio (Stanford University) in a discussion of time-varying elastic parameters. Laboratory-based time-lapse experiments with high-resolution imaging illustrated the changes in P- and S-wave velocities resulting from injection-induced dissolution. By recognizing distinct styles of porosity-permeability modification for each carbonate facies during dissolution, an opportunity to reduce the number of parameters to model permeability and velocity trends exists. A case study from the Campos Basin, Brazil, also targeted ways to distinguish porosity and permeability associated with different facies. Abel Carrasquilla (Universidade Estadual do Norte Fluminense) discussed the integration of laboratory petrophysical measurements with conventional logs as a means to quantify permeability and classify electrofacies. Focusing on ways to reduce the costs associated with NMR logs, the study attempted to simulate the NMR profile through the use of other conventional logs and artificial intelligence (neural network approaches proved to work better than other methods). Results for porosity were shown to be reasonable, but permeability prediction was more challenging.

Seeing More

The issue of linking different measurements over different scales was raised again in the context of directly imaging faults and fractures or predicting their presence from bulk volume seismic attributes. Sampling, scaling, and resolution issues limit any ability to cross-validate seismically derived fracture attributes with geologic observations of fractures. A keynote presentation by Donatella Astratti (Schlumberger) introduced various seismic attributes and time-lapse seismic data as a means to capture information on the connectivity of fracture networks. Using a chalk reservoir example, she illustrated the need to differentiate distinct generations of structures caused by their significantly different impacts on flow and their different responses to stress. Integration of the production history with the comparisons of repeated surveys was used to link changes in fault images to qualitative interpretations of changes in fault-flow behavior. A related keynote by André Revil (Colorado School of Mines) discussed time-lapse joint inversion of geophysical data as a way to reduce the nonuniqueness of the inverse problem. Using a combination of two inversion methods (active time-constrained and structural time-lapse inversion) to simulate the inversion of cross-hole data, Revil showed the potential advantages for monitoring changes in partial saturation during the production of oil from carbonate reservoirs. Recognized benefits were the reduction in spatial artifacts in the tomograms relative to other inversion methods as well as improvements for the use of time-lapse inversion of seismic and resistivity data performed independently. Enru Liu (ExxonMobil) also made a strong case for further measurements to examine the interwell space while ensuring a full understanding of the physics, limitations, and complementary nature of tools and techniques used to acquire information on different scales. In an effort to link laboratory data to field-scale seismic velocity variations and interpretations of fracture populations, Richard Gibson (Texas A&M) presented a model for effective seismic velocities in media with isotropic or aligned fracture sets. His method expresses the stress dependence of fracture compliances to the increasing contact area of rough-surfaced fractures. This provides a way to represent changes in seismic anisotropy caused by variations in stress fields while relating fracture distributions to changes in seismic amplitudes. Discussion noted, however, that whereas the presence of fractures may be determined from bulk attributes, the precise location of a given low-offset fault or large-opening mode fracture may be needed to understand specific impacts of discrete structures on flow. Ralf Oppermann (OPPtimal Exploration and Development) addressed this challenge through new workflows for automated fault extraction that integrate very high-resolution 3-D seismic image processing results with detailed calibration. A key paradigm shift here is the move from subjective interpretation to objective measurements, which can highlight faults in seismic data and decrease a reliance on stochastic approaches. He showed examples where high-resolution fault extraction enabled the identification of multiple seismic fault penetrations in wells that were ground-truthed with image log data and directly linked with productivity and/or sweet spots or unfavorable fluid flow effects (drilling fluid losses, water channeling, well-to-well shortcuts, and compartmentalization). Four-dimensional ground-penetrating radar (GPR) as a technique to image fractures in near-surface settings were reported by Mark Grasmueck (University of Miami). One of his previous studies focused on the Solvay quarry (Cassis) that was visited during the conference field trip. In a further quarry study, time-lapse GPR was used to show the impacts of deformation bands on near-surface flow of water. The presence of baffles caused the water to spread, but some deformation bands provided connections between strata on meter to decimeter scales. The potential use of diffractions for imaging fractures and karst was also considered by Grasmueck. It was suggested that a combination of 3-D GPR and ray-born synthetic modeling can be used to decipher the signatures of unmigrated diffractions. Seemingly incomplete and asymmetric diffraction circles visible on time slices actually contain dip information of crosscutting fracture systems. Diagenetic impacts on the elastic properties of carbonates were also included. Using seismic-scale examples of carbonate reservoir analogs from the Southeast Basin in France, Renaud Toullec and Francois Fournier (Université Aix-Marseille) presented forward seismic models of depositional and diagenetic heterogeneities. Following a program of detailed sampling and petrophysical measurements, their study shows that sequence boundaries and unconformities will not necessarily correspond to changes in the seismic signal. Furthermore, a diagenetic overprint can generate nondepositional reflector terminations and abrupt lateral polarity changes.

The Integration of Geophysical Monitoring with Production Data

Several delegates sought ways to maximize the value of insights from seismic data through integration with other monitoring techniques and routine production data (e.g., more common use of cross-well tomography and wells that monitor above and below reservoirs). One approach proposed by Matt Jackson (Imperial College) discussed the use of spontaneous potential (SP) in hydrocarbon reservoirs during water flooding to detect and monitor water encroaching on a well through the use of SP and electrodes installed permanently downhole. The technique has the potential to detect increasing water saturation several meters to tens to hundreds of meters away but is still looking for developments of appropriate hardware and interpretation methods and a better understanding of the coupling coefficients involved (these relate gradients in water phase pressure, salinity, and temperature to gradients in electrical potential). In addition to novel monitoring techniques, considerable energy exists around the need to acknowledge the uncertainty in 3-D and four-dimensional seismic data and ways to reduce this uncertainty through joint inversion with other geophysical data. As a method to capture 3-D petrophysical properties from inverted prestack seismic data, Andrew Curtis (University of Edinburgh) showed a neural network approach for fully probabilistic inversion techniques. A key advantage of this approach was an ability to represent the uncertainty associated with rock and fluid property maps derived from seismic (such as variations in effective pressure, bulk modulus, density of hydrocarbons, random noise in recorded data, and the petrophysical forward function) while realizing significant computational efficiencies.

Frequent calls for better tools to integrate all the different types of data across multiple scales emphasized the need for smoother mechanisms to update models with monitoring and survey data. Moving on from geophysical insights, an interesting case study from Saudi Arabia and Kuwait (Nicole Champenoy and Scott Meddaugh, Chevron) was used to broaden the picture by drawing attention to the less commonly recognized variables that impact fluid flow. These include well deliverability, historical operations, completions, facility constraints, and reactivity. Champenoy and Meddaugh emphasized that, without appropriate measurements and monitoring, it can be hard to determine which of these has the most impact. Moreover, these factors are not necessarily at the front of a geologist's mind when considering controls on flow. A further case study shared by Rick Wachtman (ExxonMobil) showed how a comprehensive measurement and surveillance program combined with geologic modeling was used on the Means field residual oil zone to assess recovery efficiency and potential flow streams. In this case, repeated simulations identified key factors such as proxies for fractures, high-permeability leached zones, and ratios between vertical and horizontal permeabilities as requirements to obtain a match to production histories. Complementary models were used to estimate fieldwide flow streams of a water-alternating-gas flood, providing an estimated extension of field life by 20 yr.

Several delegates wanted to learn more about the extent to which fracture and fault patterns are validated by modeling and/or monitoring data. The following presentations helped to fill in some knowledge gaps while highlighting limitations and opportunities to do more. In a more data-limited case study than the preceding examples, Stephen Smart (Hess) emphasized the importance of early conceptual models to develop ideas for the 3-D distribution of fracture intensity. Subsequent integration of robust data sets across various scales and several iterations with reservoir performance data were used to construct and refine a dual-porosity simulation model for offshore East Java. In an assisted history matching example, Arnaud Lange (Institut Français du Pétrole) demonstrated the use of connectivity information from production data to characterize seismic and subseismic fault networks. By examining possible correlations between water breakthrough time and connectivity, Lange was able to identify the most probable fault network realizations to match the production data. Given the sensitivity of flow simulation results to different fault network realizations, the method can help to focus on the most likely scenarios. Thomas Finkbeiner (Baker Hughes) provided insights to fracture-flow properties on production time scales through geomechanical modeling of a carbonate reservoir. Key developments in this study emphasized permeability changes associated with depletion and/or injection, fracture property variations (i.e., weak vs. strong fractures), as well as the impact that would be predicted had all fracture sets been assigned the same mechanical properties and stress sensitivity. It was noted that, in carbonates where fractures may be stiffer and less stress (pressure) sensitive, stress impacts on production and injection may be far less pronounced relative to reservoir rocks containing more stress-sensitive fractures. The impact of a single fracture on well-test responses was explored by Bander Al-Quaimi (Saudi Aramco). Numerical simulation (dual porosity), inspired by a real field example, was used to generate a spectrum of well-test responses for different scenarios related to a fracture located between two wells. The results showed the impact of permeability contrasts between the fracture and the matrix in different layers as well as the connection of the fracture to different layers.

Monitoring Flow on Local to Regional Scales

Whereas most of the discussion focused on production time scales, a novel contribution by Apollo Kok (Maersk) illustrated the concept of an "oil-on-the-move system" in which hydrocarbons are neither structurally nor dynamically trapped but still represent viable accumulations as they continue to migrate. This work has supported the development of a regional oil migration atlas based on oil expulsion, vertical migration, aquifer flow, and residual oil saturations. By performing numerical simulations of oil migration and comparing the results with known accumulations, several opportunities and potential leads were identified in the Danish North Sea Chalk.

EMERGING THEMES RELATED TO UNCERTAINTY AND PREDICTION

Giovanni Bertotti (TU Delft), Gareth Jones (ExxonMobil), and Jeroen Kenter (Statoil) chaired the third session on uncertainty and prediction. Key points from this session included the following:

- First principle and robust geologic concepts are lacking in reservoir models for reasons such as (1) poorly defined integration of geologic attributes and static and dynamic properties (multiscale pore system) and resulting conversion to rock types, (2) inadequate nongeologic geostatistical simulation techniques and fear to deviate from hard data in data-poor scenarios and, (3) lack of techniques to fast track model building and dynamic simulation of a wider range of models in a shorter period of time.
- Workflows need to identify early the function of diagenetic modification on static and dynamic properties. Consequently, improved knowledge of diagenetic processes and related spatial trends as well as diagenetic modeling capabilities are needed to reduce uncertainty in matrix characteristics and property distributions. Organization of the few existing data sets and a concerted effort to acquire new multiscale diagenetic and/or pore system data sets will be required to validate model capabilities and realizations. Geologic databases capturing depositional rock-type assemblages from analogs, their spatial juxtaposition rules and morphometric trends, will support the detection of diagenetic modification and help to constrain pre-drill scenarios.

- Reservoir (or petrophysical) rock typing needs to go beyond basic rock classifications (e.g., texture and fabric) and incorporate many more geologic factors (e.g., diagenetic attributes, certain fracture types, juxtaposition rules, and spatial trends) while integrating static and dynamic data.
- One size does not fit all—local (and when needed, refined) models may still be needed to explain flow behavior even with substantial geologic data and insights across a producing field. This is because heterogeneity varies spatially and generally increases with data quality and quantity.
- Variations in fracture densities are unlikely to be fully captured by well data or properly predicted from analogs. Fracture prediction needs to include an understanding of the evolution of mechanical properties as a function of primary depositional and diagenetic factors. Mechanical modeling of carbonate rocks is still limited by the identification of appropriate mechanical properties to assign to models at different scales. Representation of depth-dependent fracture mechanisms and the evolution of rock strengths during platform development provide examples of the types of model improvements needed.
- Current geostatistical techniques and practices tend to obscure the relationships between geologic concepts and permeability distributions in reservoir models. Significant opportunities to go beyond entrenched methods for geologic modeling and to invest in new and innovative techniques and workflows exist. In addition, a need for a wider range of models to be tested and/or other techniques to fast track simulation exists.
- A clear need to take the art out of reservoir quality predictions and to develop more rigorous and concept-driven workflows exists. Expert opinions are rarely objective, but subjectivity can be good if it is recognized and used appropriately. The key is to be aware of the factors influencing expert opinions.

Uncertainty in the Matrix

Several presentations and posters addressed a range of characteristics in different carbonate facies, to predict them and to capture key attributes in geologic models and flow simulations. As a way to "take the art out of reservoir quality predictions," Dave Cantrell (Saudi Aramco) issued the challenge to develop quantitative process-based tools that would allow the prediction of reservoir quality ahead of the bit. Based on a pilot in the Sha'aiba, he outlined a multimodel approach to generate the initial reservoir quality (forward stratigraphic modeling) including environmental constraints (e.g., water depth, initial bathymetry, temperature, sediment accretion rates, and wind speeds) and the superimposed diagenetic modifications (calibrated kinetic cementation model). Although initial results for porosity were within two porosity units, the project has not evolved yet to the point where predicted dynamic properties and trends can be contrasted with subsurface data. Related discussion reemphasized that the origin of multiscale carbonate pore systems remains poorly understood and requires improvements through research on diagenetic modeling and the development of guidelines.

Anita Csoma and Hesham El Sobky (ConocoPhillips) developed the diagenetic theme further to predict anhydrite cementation of the karst system in the San Andres Formation. When compared with deterministic petrophysical methods and other statistical approaches, a modular neural network method proved to be superior for the determination of anhydrite abundance. Given the potential impact of cemented karst features on recovery, predicted volumes and distribution of anhydrite were used in a geocellular model to delineate anhydrite-filled karst networks via multiple-point geostatistics with customized training images. Two case studies provided fundamental observations related to the distribution and origin of dolomitized reservoir intervals and their commercial significance. From Brazil, Mary Raigosa Diaz (Baker Hughes) focused on dolomites that form the best reservoir units in the Sergipe subbasin. Detailed paragenesis identified the top of high-energy carbonate banks that were subjected to complete dolomitization as the prime reservoir candidates. Reporting on the characteristics of a less commonly encountered environment in carbonate reservoirs, Ray Mitchell (ConocoPhillips) pointed out that production from the Bakken petroleum system comes mainly from interbedded, mostly dolomitic carbonate intervals interpreted to be of mostly continental origin. The mixed siliciclastic and carbonate sediments in the Three Forks Dolomite were deposited mainly by eolian processes with heterolithic bedding (dolomite silt and mudstone) formed during wet periods. Further characterization efforts used satellite images of modern isolated carbonate platforms (Philippe Ruelland, Total) to derive lateral variations in environments of deposition to generate training images for multiple-point geostatistics. Direct sampling was used to develop facies models synchronously with models of matrix porosity before diagenesis. Overall, this cluster of posters demonstrated the increasingly sophisticated use of data to characterize matrix properties, together with the effective use of modern and recent carbonates to inform our understanding of the distribution of carbonate heterogeneities over a range of scales.

Mark Skalinski (Chevron) and Jeroen Kenter (Statoil) discussed several shortcomings in the classification and use of carbonate rock types, including the need to incorporate diagenetic attributes and modification; integrating multiscale and multimodal pore types, including fractures; integrating dynamic data; and the lack of appropriate geostatistical tools. Examples from Tengiz and First Eocene (Wafra) reservoirs were used to illustrate the application of a new workflow designed to optimize petrophysical rock typing and the generation of carbonate reservoir models. Petrophysical rock types are defined as (1) the category of rocks characterized by specific ranges of petrophysical properties, (2) exhibiting distinct relationships relevant for flow characterization, (3) identified by logging surveys, and (4) linked to geologic attributes like primary texture or diagenetic modifications. The objective of this approach is to determine the petrophysical rock types that control the dynamic behavior of the reservoir while optimally linking the geologic attributes (depositional and diagenetic attributes and their hybrid combinations) and their spatial interrelationships and trends. Michel Rebelle and Cecile Pabian Goyheneche (Total) also showcased an approach to integrate reservoir geology, seismic data, engineering, and petrophysics as a more sophisticated workflow for reservoir rock typing. Jim Markello and Rick Wachtman (ExxonMobil) showed a new sequence-stratigraphic–based reservoir architecture for the Lisburne field that was developed in the context of Late Pennsylvanian regional and global controls on tectonics, climate, eustasy, ocean circulation, and geologic history. The improved framework helped to guide the content of geologic models and simulations to achieve reasonable performance matches. However, even with substantial geologic and production data, the single framework could not capture local differences that impacted specific flow directions, connectivity lengths, and rates on the sector scale. A key message was "one size does not fit all."

Complementary outcrop studies of the Urgonian carbonate platform in southern France by Philippe Léonide, Francois Fournier, and Jean Borgomano (Université Aix-Marseille) suggest that early cementation influenced the preservation of tight and/or microporous units that compartmentalize the platform vertically and laterally. An association between the early diagenesis and major sequence boundaries has been recognized. By combining petrographic, diagenetic, and isotope geochemistry, they have been able to identify links among pore-type distributions, micrite diagenetic patterns, and sequence stratigraphy in microporous-dominated carbonate reservoir analogs that may offer predictive capabilities. A further example of outcrop modeling was presented by Maria Mutti (University of Potsdam) based on a Jurassic carbonate ramp in Morocco. In this case, the focus was the development of a geostatistical database of geobodies and the choice of appropriate statistical modeling algorithms to represent the spatial organization of different hierarchical scales of heterogeneity. A truncated Gaussian simulation algorithm was used to represent depositional environments because of the gradational and linear trends observed between geobodies. However, the sequential indicator simulation was used for lithofacies distributions because of its flexibility in handling spatially independent lithofacies elements.

Uncertainty in Fractures

Delegates continued to wrestle with long-standing issues related to the prediction of fracture networks and ways to capture uncertainty in their characteristics and distributions in the subsurface. Bertrand Gauthier's (Total) keynote presentation focused on the need to know more about fracture networks between wells and at the scale of a reservoir model cell. Outcrop studies can complement information on fractures at a well by providing insights to the factors controlling fracture populations, which can then underpin qualitative concepts or quantitative relationships. A detailed quarry study in the Southeast Basin, France, used to construct a digital fracture network, provided several useful lessons, including the following: (1) fracture data from wells may not really be hard data because they cannot capture the full spectrum of variability in fracture densities and (2) identified relationships among one-dimensional, two-dimensional (2-D), and 3-D representations of the same fracture network may simplify the extrapolation of well data to 3-D properties in the subsurface. A broader evaluation of fracture populations across the Southeast Basin of France was reviewed by Juliette Lamarche (University of Provence) and Bertrand Gauthier (Total). The study offered a departure from more traditional mechanical stratigraphy, indicating that geographic position was more important for the mechanical properties of the carbonates than depositional facies, with early diagenesis potentially locking in mechanical differentiation of the rocks. Regional fracture patterns were also considered to be mostly unrelated to large-scale structural events. In contrast, sedimentologic controls on fractures were the focus of Chris Zahm's (Bureau of Economic Geology) presentation. Nine vertical mechanical facies associations were linked between core and outcrop studies of facies in transgressive- and highstand-systems tracts. Both rock fabric and porosity were found to be key influences on rock strength. The vertical mechanical facies associations constrained a mechanical framework for subsurface dual-porosity simulation models and ultimately supported a pressure match to well tests and fieldwide production. In another fractured carbonate reservoir case study, Alex Assaf and Richard Steele (BG Group) addressed uncertainty in a severely heterogeneous carbonate field in North Africa. They developed multiple models (fully compartmentalized, fully open faults, and partly compartmentalized) to explore a spectrum of scenarios. Further reductions in uncertainty were realized by integrating pressure transient analysis and numerical modeling of near wellbore effects that provided critical feedback and led to a geologically appropriate history match. Michael Welch (Rock Deformation Research Ltd.) reported on his quest to predict fractures based on outcrop studies in chalk. Examples from southeastern and northeastern England provided insights to the larger structural influences on the locations of fracture corridors and emphasized the way that rock strength (reflecting different porosities in chalk) and pore fluid pressure will impact fracture failure modes (shear or tensile). Prediction of fracture populations in flat-topped carbonate platforms was addressed by Giovanni Bertotti (TU Delft). In this case, fracture generation scenarios (stress and mechanisms) were represented by first-order 3-D finite-element modeling. Key uncertainties included (1) the stress conditions that control the formation of stylolites and transitions from mode 1 to mode 2 fractures, (2) the appropriate bulk mechanical properties for a platform-scale model, and (3) the difficulty of predicting the number and dimensions of fractures. Important factors represented by this work were the depth dependence of fracture formation and large sensitivities to assumed paleostress scenarios. A further geomechanical study related to a steep-rimmed carbonate platform was presented by Vincent Heesakkers (Chevron). Two-dimensional finite-element modeling was used to represent stepwise carbonate platform development with appropriate constitutive models to reflect the different strength of facies during synsedimentary fracture development. Based on studies of the Canning Basin and the Guadalupe Mountains, such models offer insights to early fractures in large carbonate resources such as Tengiz and Karachaganak. Dave Healy (University of Aberdeen) shared insights to the variability of fault-zone properties based on outcrop analogy from Malta. The overall objective of this ongoing research is to constrain the natural statistical distributions in all of the pore-system attributes, as well as their spatial variation with respect to depositional faces and tectonic damage. In a related study, Joyce Neilson and Dave Healy (University of Aberdeen) showed how effective medium theory is being applied to translate the frequency range from ultrasonic data from fractured rock to seismic scales. As such, this work supports a way to link the fracture porosity and fault properties in the Malta study to acoustic signatures and to determine how property variations are manifested in petrophysical attributes. Based on the preceding presentations, an interesting discussion developed surrounding the importance of production data as a way to provide a check on the validity of the initial geologic predictions and interpretations and, possibly, to identify their flaws. However, the time-lag between insights from production data and the development of a geologic model makes such validation less feasible. A possible solution lies in the definition of proxies to signal the quality of the model as early as possible. The sooner a shortcoming in the model is identified, the less damaging are the consequences: fail fast!

Uncertainty, Statistics, and Modeling

Brodie Thomson (ExxonMobil) provoked the audience by addressing the failure of carbonate reservoir characterization and modeling to define the distribution and continuity of permeability extremes and to represent our geologic concepts adequately. The current practice of geostatistical methods, he argued, tends to obscure the relationship between geologic concepts and the final (and noisy) permeability distribution in the model. The effects of averaging and stacking multiple geostatistical steps can obscure flow pathways, thin baffles, and many other subtle geologic features (e.g., thin-bedded and microporous intervals and stylolites). The presentation stirred considerable discussion, dividing the delegates into those who sought greater simplification and those who sought more (appropriate) geologic influence or concepts in the model. More unified support developed around the need for a wider range of models to be tested and other techniques to fast track simulations. In addition, it was recognized that this was an area of considerable entrenchment and that significant opportunities to think outside of the box exist.

Comments on the need to improve communication and integration across groups of experts reinforced the overall thinking behind the conference. In a related poster presentation, Andrew Curtis (University of Edinburgh) drew attention to the information scale gap that exists as a result of the tools and approaches available for subsurface sampling. Given the large geologic uncertainties that result from this gap, the function of expert opinions was reviewed, using examples to highlight a lack of objectivity that emerges because of group dynamics. Examples of the ways that opinions evolve in response to group dynamics have been tracked by software during discussions and raise concerns for consensus-driven outcomes. Expert elicitation, hence, is potentially a low-cost method to reduce overall uncertainties by improving the quality of how previous information is obtained and parameterized.

EMERGING THEMES RELATED TO NOVEL MODELING AND SIMULATION TECHNIQUES

The fourth session, chaired by Gary Hampson (Imperial College), Fiona Whitaker (University of Bristol), and Stephan Matthäi (Montan Universität Leoben) addressed novel modeling and simulation methods. Discussions returned to some of the initial comments related to the simulation of fundamental processes at the start of the meeting. Key messages from this session included the following:

- Models can serve to integrate different data sources across multiple scales, but techniques for upscaling across several orders of magnitude in a single model remain challenging. Multiscale models offer an alternative approach that allows significant fine-scale details to be captured while maintaining computational efficiency.
- Recognizing the caveats related to uncertainties in the previous session, it was still emphasized that a large amount of data are available to pursue modeling in a larger, more integrated, and strategic way, with strong opportunities to link field observations and hypothesis testing via numerical models and laboratory experiments.
- Many new (or less commonly used) modeling tools are available or on the horizon (discussed in this and other sessions). We need to develop the most effective ways to use them and to seek clever and more creative applications.

- An ability to compare different models through standardization approaches, to use common models as a basis for further analysis, and to conduct collaborative research on common reservoirs and outcrops can serve to increase the overall value of modeling.
- Outcrop studies are perceived to have waned in popularity, but these still have a function to play in geologic modeling and flow simulations. They provide low-cost opportunities to test out data handling and modeling techniques for different stratal and structural geometries. They can also provide reasonable geologic scenarios and assumptions for characteristics that are not easily constrained by subsurface data (e.g., fracture size distributions and effective fracture permeability).
- Fracture-flow simulations would benefit from guidelines to determine when fractures and similar small pervasive heterogeneities (e.g., stylolites and karst) should be explicitly represented versus being implicitly represented by effective properties.
- Fracture-flow simulations mostly ignore the impacts of fracture-associated diagenesis on sweep and fracture-matrix fluid exchange and struggle to assign appropriate aperture distributions. Further developments in RTM need to extend to fracture diagenesis as well as the matrix.
- The coupling of processes in models is recognized as important but has yet to be fully realized (e.g., integrated sedimentologic DFM-RTM geomechanical models).
- Developments in computational graphics and visualization offer ways to truly interact with data and models and provide opportunities to represent the associated uncertainty.
- The essentials of geologic heterogeneity and evolving flow patterns must be captured in a reservoir simulation for better production forecasting; however, this is normally not achieved with the current, industry-standard reservoir simulators.
- In light of the above, many geologic and simulation models constructed using standard tools and workflows are unnecessarily complex in some regard, simplistic in others, and their construction is too time intensive to allow assessment of multiple scenarios and uncertainty. New modeling and visualization tools can help to tackle these issues, but their effective exploitation probably requires a shift in the mindset of the user. It is commonly more useful to generate a suite of simple models that encompass different scenarios and uncertainty (while representing key heterogeneities and flow processes realistically) than to generate a small number of detailed models anchored to a single scenario, which may fail to represent key aspects of the system of interest.

Simulating Matrix Properties Over Different Scales

Further reinforcing the need to integrate different data sources across multiple scales, Chris Nichols (Shell) focused on inputs for upscaling based on information from core-plug to whole-core scales. Three case studies were used by Nichols to show how different data (core plug, logs, and core) can lead to different impressions of porosity and permeability. A key message here was the need to examine rock types in both the petrophysical and geologic space. This integration can help to determine approaches to handle different types of heterogeneities for a given rock type while shaping guidelines to upscale from core to log to cell scales. Michael Sukop (Florida International University) very effectively demonstrated how dense data–driven variograms from borehole images of relatively young carbonates in Florida appear to capture high-frequency stratigraphic cycles and can be used to generate 3-D volumes for borehole-scale lattice Boltzmann flow simulations and thereby extend the scale of application of direct flow simulation. Limitations of readily available geostatistical software to accommodate the complex variogram structure led to simulations that overrepresented the horizontal continuity and underestimated vuggy porosity. By expanding applications of the lattice Boltzmann method to borehole-scale simulations of flow for vuggy carbonates (much larger than the usual pore-scale applications), Sukop confirmed reasonable agreement with other experimentally derived estimates of permeability.

Advances for Fracture-Flow Simulation

Robin Hui (Chevron) introduced this theme with a keynote presentation on an in-depth sensitivity analysis using a DFM, where fractures and matrix are both represented in a dynamic model using an unstructured grid. The study highlighted the challenge of applying appropriate numerical approaches to the simulation of flow on a geologically driven grid structure. Whereas the DFM technology enables the inclusion of aperture and length-displacement scaling from outcrop-analog data, solid guidelines to determine when to draw the line between explicitly represented fractures and those represented by effective properties do not exist yet. Such decisions can be influenced by gridding and other software considerations and, also, by geologic rationale. Questions were raised concerning the value of running a DFM as opposed to conventional approaches and if different business decisions would have resulted from using more traditional dual porosity and/or dual-permeability simulation approaches. The need for a comparative study to determine these factors was also discussed. Wayne Narr (Chevron) generated much interest in his work characterizing syndepositional fracturing from the Devonian Canning Basin, features similar to those seen in the recent as well as reservoirs such as Tengiz but very different from fracturing that occurs after burial. Supporting the value of outcrop-based studies for the subsurface, the Canning Basin data compilations of fracture sizes and their relationships to stratigraphy have been shown to complement well data and provide useful guidelines to constrain flow simulations of the Tengiz field. A further case study presented by Jim Sylte (ConocoPhillips) demonstrated how dynamic data have been integrated for a period of 25 yr to monitor the influence of fractures and stylolites during waterflooding of the Ekofisk chalk reservoir. The duration of the study reinforces the value of continuing to reevaluate and integrate data with simulations as new technology brings further insights and as enhanced oil recovery projects pose new challenges. Iryna Malinouskaya (Université Pierre et Marie Curie) demonstrated the use of 2-D outcrop data from a Jurassic carbonate ramp in Morocco to calculate the 3-D tensor for fracture permeability. The approach is being used to explore the impact of different fracture network characteristics on effective permeability. In some cases, differences in fracture populations will have a substantial impact on the effective permeability, but in others, the details may not make that much difference. Ole Petter Wennberg (Statoil) showed the implications for fluid flow of the development of a cemented zone around a fracture and patchy matrix cement alone. Preliminary results indicate that cement distribution exerts a primary influence on simulation outcomes and that the presence of cement at the matrix-fracture interface should be factored into history matching and upscaling efforts. The study elegantly created anticipation for the Notre Dame de Beauregard outcrop, which was seen during the field trip. Following previous sessions in which fracture impacts were discussed, this session reinforced that the simplifications we commonly make about the effect of fractures on flow are problematic. This occurs not only on the reservoir scale for reservoir characterization and flow simulation, but also where fractures are represented in 2-D, ignoring fluid circulation in the fracture plane and incorporating simplistic assumptions about fracture apertures.

Reactive Transport Modeling

A keynote presentation by Nicole Champenoy and Scott Meddaugh (Chevron) discussed advanced methods to characterize permeability heterogeneity and to handle steamflood RTM. Based on 2-D RTMs, steam injection was predicted to drive calcite and brucite precipitation, dissolution of dolomite, and conversion of gypsum to anhydrite. Discussions emphasized the need to anticipate potential changes in flow behavior, the need to understand the physics of displacement, the need for technical knowledge to guide the use of various software tools, and the impact of grid design. Opportunities to develop more sophisticated RTMs were illustrated using examples of replacement dolomitization by Fiona Whitaker (University of Bristol), who also explored some of the hurdles that need to be overcome to generate more meaningful simulations. Such challenges include the feedbacks between depositional and diagenetic sediment texture, permeability and reactivity, the relative importance of various forcing mechanisms, and the sensitivity of an environmental system to changes in any of these forcing processes. Scenarios for dolomitization were also discussed by Conxita Taberner (Shell) in the context of density-driven flow. Two-dimensional RTM simulations were used to predict geometries (layered dolomite bodies vs. irregular fingerlike bodies) resulting from (1) hypersaline brine reflux and (2) thermally driven flow. Potentially beneficial links were evident within this cluster of posters, for example, RTM simulations offering a route to generate rules and to describe diagenetic geobodies that could usefully feed into geologic models. Enrique Gomez-Rivas (University of Tuebingen) proposed a crustal-scale mechanism for the emergence of a self-organized flow system that may explain the development of localized alteration such as hydrothermal mineralization along fault zones.

Advances in Geologic Modeling, Data Visualization, and Interaction Methods

Contributions related to static modeling of both matrix and fracture properties introduced significant developments. In this cluster of posters, Gregory Benson (ExxonMobil) exemplified the workflow for collecting and interpreting data from detailed field studies and LIDAR imaging to construct a geologic model of a Miocene outcrop in southeastern Spain. In ongoing efforts to ensure compatibility of various flow simulation studies, Benson introduced a "standard property calculator" as a means to standardize assignment of reservoir properties. Gary Hampson (Imperial College) demonstrated the principles and application of a pragmatic surface-based modeling approach. The approach is still limited by several factors, including selection of an appropriate level in the hierarchy, gradations in geologic characteristics, and the incorporation of fracture and diagenetic heterogeneities. Nevertheless, the technology offers improvements related to the next generation of unstructured mesh simulators. The surface-based modeling approach was applied by Peter Fitch (Imperial College) to a Jurassic ramp system to systematically investigate controls on patterns of multiphase fluid flow. In combination with experimental design techniques, the objective is to develop insights to the impact of heterogeneities on flow in carbonates as a means to support the prioritization of effort during geologic model construction. A completely different approach presented by Claude-Alain Hassler (Shell) used the numerically efficient cellular automata (CA) method. The technique provides a way to incorporate simple diagenesis in reservoir models. Although the CA method is widely used, its application to reservoir modeling has been very limited. Perceived benefits include improvements on classic variogram-based methods through the application of stochastic rules, straightforward conditioning to existing data, and capabilities to represent complex geometries.

Providing a link to the field trip, Jean Borgomano (Université Aix-Marseille) introduced work in the carbonates group of the University Aix-Marseille and their research on generic learning from outcrops that can be translated to relevance in the subsurface (e.g., correlation length scales and rules). Using mainly Cretaceous carbonates in the Provence region, the group has developed an impressive suite of sedimentologic, petrophysical, LIDAR, and seismic data integrated across multiple scales. It was emphasized that the required level of detail is not always obvious at the outset of a study and, echoing points raised in the first session, opportunities to link multiple models at different scales exist. This presentation also served to introduce several poster contributions by students and postdoctoral students at the University of Provence for a special session that recognized their contributions to field-trip organization and local logistics for the conference.

A strong contender for the most glamorous presentation, Mario Costa Sousa (University of Calgary) shared novel approaches to visualization and data interaction. Examples emphasized the need to interact with data as opposed to simply observing them, showing ways to tear apart or zoom into reservoir simulation model results and to construct 3-D objects from 2-D sketches. Discussions noted that such impressive visualization methods still have the potential to mask significant uncertainty and that geologists and engineers may be awed by the visualization, masking the underlying data; however, more flexible visualization would actually help to query simulation results more robustly. In addition, generalists (and others) examining data by these methods would benefit from simultaneous representations of uncertainty. The concept of a Google Earth style interface for zooming in and out of models was proposed during the discussion as a way to link data and models across different scales.

Venture Groups

Recharged from the field trip, delegates self-organized to form five venture groups from the 20 venture groups initially proposed. Each venture group comprised 10 or more delegates representing different disciplines (geology vs. engineering) and background (industry vs. academia). For the next day, each venture group came up with a well-defined research project with a clearly identified hypothesis, research goal, and research plan, including an idea for an end-product that could be rolled out to the industry.

The topics proposed were as follows:

1. Diagenetic and structural controls on flow models: The aim was to build a multidimensional matrix that will allow isolation of variables driving the resulting 3-D distribution reservoir quality properties useful both at exploration and production stages.
2. Geoprinting: The aim was to develop 3-D printing technology to create large-scale (tens of meters), integrated dynamic analog models for carbonate reservoirs to experiment with geology, fluid flow, geophysics, and geomechanics.
3. Disconnect between geology and reservoir characterization: The aim was to develop an app to fast track the creation and validation of 3-D reservoir models and test multiple flow and geologic scenarios.
4. Multiscale field experiment (from 10^{-6} to 10^{2} m^2): The aim was to study flow processes over more than eight orders of magnitude in length scale—from laboratory to field, including the excavation of the field site for reconstructing the 3-D geology—to revolutionize flow simulation tools used for reservoir predictions.
5. Wettability engineering: The aim was to develop a flexible toolkit that accurately predicts reservoir wettability at the pore scale and suggests the best recovery mechanism, based on the fundamental physics and chemistry, to increase production from carbonate reservoirs.

Crossing the Academic-Industry Divide

As noted above, this Hedberg Conference achieved many of its success measures, defining promising new research directions that are being shared with the global scientific community through this article and a special conference volume anticipated later in 2014. New connections were formed, and delegates developed interesting ideas for collaborations and research proposals. However, there is much that remains to be done to strengthen industry-academic collaboration. Discussion drew attention to the fact that industry-academic collaboration may be limited by the extent to which academics are aware of routine industry applications and the awareness of novel research advances in academia by industry representatives. These shortcomings limited the abilities of delegates to identify opportunities for research advances through collaboration. Several academics wanted to learn more about the basic modeling assumptions used in industry, the knowledge gaps, and the opportunities that might exist to contribute fundamental geologic data. Industry researchers needed opportunities to learn about the assumptions and methods implicit in novel modeling techniques and advances in fundamental science. In the experience of the conveners, this is a problem that extends far beyond the research needs for carbonate reservoirs. There was a call to be more organized and united in our data collection. Significant valuable data sets have been collected through the years both by industry and academia. Given this, it would be beneficial for the combined industry and academic community to adopt a coordinated approach in which the data would be more accessible and comparable, as per recommendations of Rudy Swennen (KU Leuven).

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