Petrophysics Beyond Petroleum – *Emerging Technologies*

As the world attempts to pivot away from fossil fuels that have fueled the extraordinary economic growth of the 20th century, creating the so-called developed world that the developing world wants to emulate, the petroleum industry faces three broad crosscurrents on its future: (1) double down on continued production of such fuels as some desire, (2) abandon 100 years of geoscience/petrophysical technologies and related human resources to join the bandwagon of "clean" renewables, primarily intermittent solar and wind, as others insist on, or (3) potentially repurpose their technologies and even develop new ones for an assured, broad-based, low-carbon energy future. Petrophysics, aka well logging, offers a unique perspective in this context. Low-carbon energy options identified by the Intergovernmental Panel on Climate Change include: (i) continued fossil fuel use with carbon capture and sequestration (CCS), (ii) nuclear power, and (iii) (several of the) renewables, which would require drilling and geological assessment. Thus, petrophysics remains of interest.

Despite the commonality, however, hydrocarbon E&P is primarily geared towards extracting fluids, while low-carbon energy options would involve the extraction of fluids, including novel ones, such as geologic hydrogen, and extraction of minerals from rocks. Additionally, low-carbon energy options bring a critically important component that must be addressed, namely, the geological internment of consequential byproducts of energy generation, such as CO_2, highly radioactive nuclear waste—almost on a millennial timescale—and various heavy metals from renewables, all often under extreme conditions. Clearly, standard petrophysical techniques may not suffice.

Several of these issues were discussed at a Special Session during the SPWLA 64th Annual Symposium, pointing to the need for significant advances in petrophysical technologies. The special focus section of the present volume of the journal initiates a broader discourse on these requisite advances in a connected way through the four papers in this section. Key points of the four papers are noted next, and common attributes are identified.

Nuclear Logging in Geological Probing for a Low-Carbon Energy Future – *A New Frontier*?
Badruzzaman

The author notes that nuclear logging techniques, because of their ability to initially characterize a formation and later monitor fluids in it downhole, offer an inherent advantage and would be applicable in all three low-carbon energy options. The author discusses tests of nuclear in monitoring CCS projects and shallow-scale monitoring of radionuclide movement in a nuclear waste repository. However, several physics issues still need attention. He then postulates the use of nuclear techniques in renewables, for example, to locate and quantify downhole the needed critical minerals using recently developed inelastic/capture n-gamma mineralogy techniques. This approach would likely allow targeted extraction of critical minerals, thereby avoiding indiscriminate drilling and potentially mitigating reported mineral-extraction-related human rights abuses. The author discusses potential sources of geologic hydrogen, another potential renewable, and proposes an approach to delineate it from natural gas; both may be present in the subsurface together. The author recommends a number of hardware and software advances to address the challenges that will arise in these applications. He suggests switching to advanced electronic radiation source tools for both formation characterization and monitoring. Electronic sources would be inherently safer and provide additional information, such as mineralogy, effective porosity, etc. Several novel concepts on such sources are under development.

The author further recommends the examination of two novel nuclear-based techniques: (i) associate particle imaging (API) postulated to identify, a priori, sources of casing leaks in wells used to extract gas from hydrogen or methane storage, and (ii) muon-based deep probing to monitor nuclear waste repositories over long time intervals. The muon-based technique offers a tantalizing possibility: seismic-scale probing using nuclear without likely challenges from utilizing seismic techniques to monitor waste repositories.

Petrophysical Analysis for Supporting the Search for a Claystone-Hosted Nuclear Repository
Strobel

The author relates the story of Germany's process of selecting nuclear waste repository sites, where petrophysical techniques play a key role. Germany has shut down its nuclear power generation program and has 11,000 tons of high-level waste (HLW) that must be disposed of. Germany's new search process for HLW storage sites is unique. It calls for a "complete, comparative search of the whole German deep underground without bias or predisposition." The author identifies the complexities of their potential containment rocks—allochthonous and autochthonous rock salt, claystone, and crystalline rock—and notes the lack of sufficient advanced logs such as those from nuclear magnetic resonance (NMR) and neutron activation that may be needed for a comprehensive assessment of such a diverse set of potential repositories. He utilizes conventional logs, such as gamma ray, neutron, density, resistivity, etc., and approaches, such as the construction of variograms, to gain insights and demonstrate how even the limited NMR data they have add to that insight. An ideal logging suite, according to the author, would include neutron activation logs for clay mineralogy, NMR tools with short T_2 spacing for clay porosity and characterization, epithermal neutron data as the NMR log-quality control, density, and PEF logs, and acoustic logs that contain directional shear-wave data for geomechanical assessment. The author notes, "one would only consider claystone with a low total organic content," for organics "could facilitate the transport of nuclides," a point Badruzzaman also noted.

Underground Hydrogen Storage in Porous Media: The Potential Role of Petrophysics
Okoroafor, Sekar, and Galvis

Through a simulation study, the authors identified reservoir depth or current pressure, reservoir dip, and flow capacity as the key geological and reservoir engineering parameters that influence underground hydrogen storage. Permeability was a key parameter impacting hydrogen productivity in depleted gas fields. The authors demonstrate the value of petrophysical data and geomechanical analysis. Their analysis shows how hydrogen storage would differ between storage in depleted gas fields vs. saline aquifers and how that may also contrast with natural gas storage. Their study revealed that monitoring stress changes would be significantly more important than monitoring changes in the strain. They conclude that hydrogen injection into and withdrawal from saline aquifers in critically stressed rocks can result in increased incidents of microseismicity. The authors noted that formation testers, imaging tools, density tools, etc., will be key to reducing uncertainties in hydrogen storage sites. They call for devising novel neutron measurements to detect hydrogen in the subsurface—Badruzzaman suggests an approach for this in his paper—and using time-lapse monitoring, electromagnetic surveys, and seismic data to monitor hydrogen in porous media.

Automatic Geological Facies Analysis in Crust-Mantle Transition Zone
Morelli, Yang, Machara, Cai, Moe, Yamada, and Matter

This paper tested a new automatic facies analysis technique—FaciesSpect—against two older techniques to understand the lithology change across the complicated crust-mantle transition zone in a deep-drilling program off Oman. FaciesSpect is a newer and unsupervised technique that utilizes high-resolution borehole image logs and up to three petrophysical logs, with analysis performed in a prescribed manner. FaciesSpect results are easier to compare with core-based lithologies. Several boreholes were drilled, including four across the crust-mantle transition zone. Slim and conventional wireline logs, electrical image logs, geochemical spectroscopy logs, and core data were acquired for input into the study. The authors demonstrated that the easier-to-interpret FaciesSpect technique compared well with the other two more established techniques. The analysis showed that Fe and Ca curves from geochemical log data obtained using an advanced (n-gamma) spectroscopy tool that utilizes both inelastic and capture data were suitable inputs to represent the crust-mantle transition.

The technique identified dunite, harzburgite, and gabbro, potential source rocks for geologic hydrogen, identified from core data as the dominant lithology in the study well. This is potentially a key finding since these rocks can be major sources of geologic hydrogen. The authors suggest that their technique can also possibly support the evaluation of potential geological repositories for nuclear waste disposal, which Strobel discusses in his paper. They identify different rock types, such as

fractured, deformed, and massive, that may aid in understanding CO_2 leakage potential in CCS projects. The technique can also potentially be used to assess formations for hydrogen storage, which is the topic of Okoroafor et al.'s paper. Clearly, the Morelli et al. approach will be valuable in facies analysis across applications discussed in the other three papers.

In conclusion, the papers in the special focus section have identified several emerging petrophysical techniques that, if successfully deployed, will significantly advance the state of the art of petrophysics, making them usable in the low-carbon energy future envisioned to mitigate global warming and potential climate change. This would allow access to major CO_2-free energy resources, such as nuclear, geologic hydrogen, and critical minerals for renewables, potentially without human rights abuses currently prevalent in accessing these minerals. The emerging petrophysical techniques could simultaneously offer ways to monitor the sequestration of associated waste products. Thus, the benefits of these emerging petrophysical techniques would be more consequential than those the world derived from their predecessors in the petroleum era.

Low-carbon energy generation will be a major achievement for humanity, for it will help avoid climate change that can make our planet uninhabitable. But will that transition be sustainable and just? If not, we must push technology and societal compacts to achieve such a future. As we weigh these issues, let's ask ourselves: Could we petrophysicists push the envelope of our craft to be a determinant of that future?

Best regards,
Ahmed Badruzzaman
Guest Editor