Persistent Prospects of the Permian

Lots of geoscience remains to be done in the Permian Basin of West Texas and southeast New Mexico. Plenty of Permian prospects remain to be analyzed.

And that might seem a little strange.

Production from the basin began more than 100 years ago. The Permian is one of the most explored and drilled regions of the United States. But somehow, this long-time oil and gas producing area has once more emerged with new promise.

Diamondback Energy hammered that point home again in February when it announced a $26-billion deal with Endeavor Energy Resources LP to combine their Permian Basin resources.

Once the deal closes, Diamondback expects to have 816 million barrels of oil equivalent production per day and around 838,000 net acres. That includes approximately 6,100 prospective drilling locations with break-evens below a $40 a barrel West Texas Intermediate oil price.

It was just the latest move in a sweeping Permian Basin consolidation. Last year, ExxonMobil agreed to buy Pioneer Natural Resources for more than $60 billion. Occidental Petroleum then announced its acquisition of privately held CrownRock LP for $12 billion.

All of that activity aims at building substantial positions in the Midland Basin area of the Permian, where Endeavor Energy's horizontal drilling operations focused on Martin, Howard, Midland, Glasscock, Upton and Reagan counties of West Texas.

Unconventional resources development brought new exploration life to the Permian Basin by 2010, earning it designation as a super basin. But that was only the first phase of the basin's resurgence.

During the following decade it became the mainspring of increased U.S. oil production, with most of the new crude output coming from the prolific Spraberry, Wolfcamp and Bone Spring formations, according to the U.S. Energy Information Agency.

Expanding Interest

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Today, "you continue to see development of the Wolfcamp and the Leonardian sections" in the Permian, said Tim McMahon, tight oil resource assessment project manager and principal investigator for the Bureau of Economic Geology at the University of Texas at Austin.

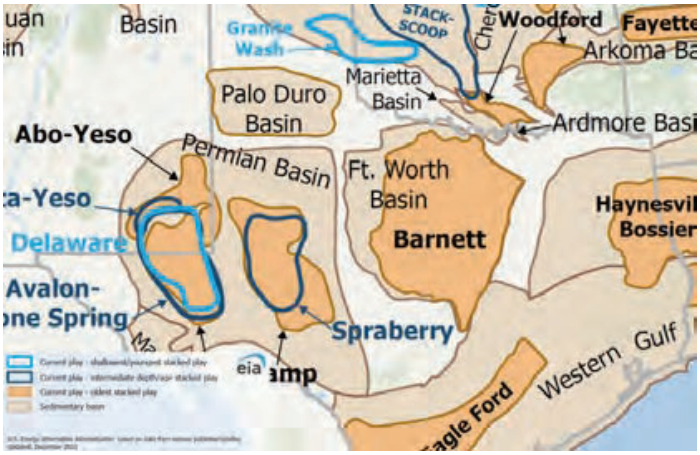
"Certainly, those have been of interest for some time, but we see some interest now in expanding that, going up into the Avalon (formation) in the Delaware Basin," he noted.

The Barnett formation below the Wolfcamp also has drawn attention recently, this time for oil production potential. That play now spreads over several counties in West Texas, in the Midland Basin. And "there's been some discussion: Do some of the Pennsylvanian rocks have potential in the deep basin?" McMahon said.

Above the Leonardian, "you also see some things going on in the Guadalupian section," in the Delaware Mountain Group, Artesia Group and San Andres, he noted.

Other Permian operators are targeting transition zone development, "where you get a lot of water but also a lot of oil," McMahon said.

"This is on the Central Basin Platform within the San Andres formation and includes both transition zones and residual oil zones. Companies are drilling horizontal wells to extract oil from the transition zone



on the formation, usually using (enhanced oil recovery) techniques as well," he observed.

"This has been going on since at least the mid-2010s, but shows how application of unconventional technologies can be used to produce additional hydrocarbons from older conventional fields," he added.

Ongoing Geoscience

Through its history, Permian exploration has demanded new rounds of geoscience. The Conventional Permian Basin lasted from about 1920 to 1970 and was analyzed using conventional interpretations.

As production went into decline, the Mature Conventional Permian emerged. Recovery geology and engineering began to dominate, until roughly 15 years ago. Then the Unconventional Permian Basin appeared, requiring a new approach.

Thirty years ago, Permian operators might dismiss formations that were too shaly or tight or wet. Today, some of those same formations are targets for development. In addition to recent work in the Barnett, potential zones of interest include the Avalon, Canyon, Clear Fork, Cline, Glorieta, Morrow, San Andres, Woodford, Yates and Yeso formations.

Diamondback Energy had earlier reported evaluating two shale intervals within the Clear Fork for potential horizontal development, while noting that conventional pay intervals in the Pennsylvanian Strawn and Atoka formations could add significant reserves.

"I know there are people looking at the Avalon in the Delaware Basin and they may be looking at the equivalent Clear Fork in the Midland (Basin)," McMahon said.

"Clear Fork is one of the areas where the nomenclature gets really weird," he added.

Disparity in stratigraphic nomenclature is nothing new in the U.S. Midcontinent region. In the Permian Basin, part of the issue involves the change from shelf to basin facies, McMahon said.

"The Middle and Upper Clear Fork on the Northwest Shelf and CBP are supposedly the time-equivalents of the Lower and Middle Spraberry in the Midland Basin, with the Glorieta equivalent to the Upper Spraberry," he noted.

"However, you will see the interval above the Upper Spraberry – we use Upper Leonard for this – sometimes referred to as Lower Clear Fork shale, with Glorieta and Upper Clear Fork above the Middle Leonard," he added.

In the Pennsylvanian section, the Wolfcamp D designation is commonly used within the industry, "but stratigraphic nomenclature would have that as the Cline shale. Below that, the Cisco may be locally named Tannehill, Croton or Stockwether, with similar local names within the Strawn," McMahon said.

"These changes make it difficult when mapping on a regional scale, which is a key component in evaluating resource potential and the focus of my group's research," he said. "Where you still need some work is sorting out the stratigraphy as you go from the deep basin to that upper shelf," especially with steep sides to an uplift.

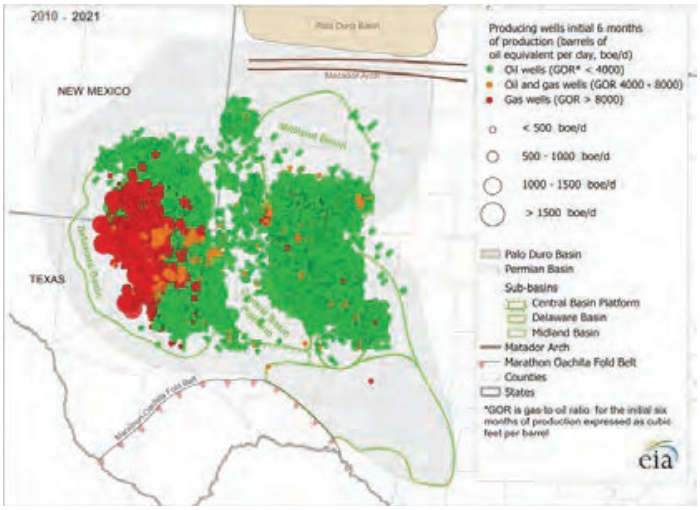
Ongoing work for geoscientists in the Permian includes deciphering the basin's thermal maturity, which McMahon described as "challenging."

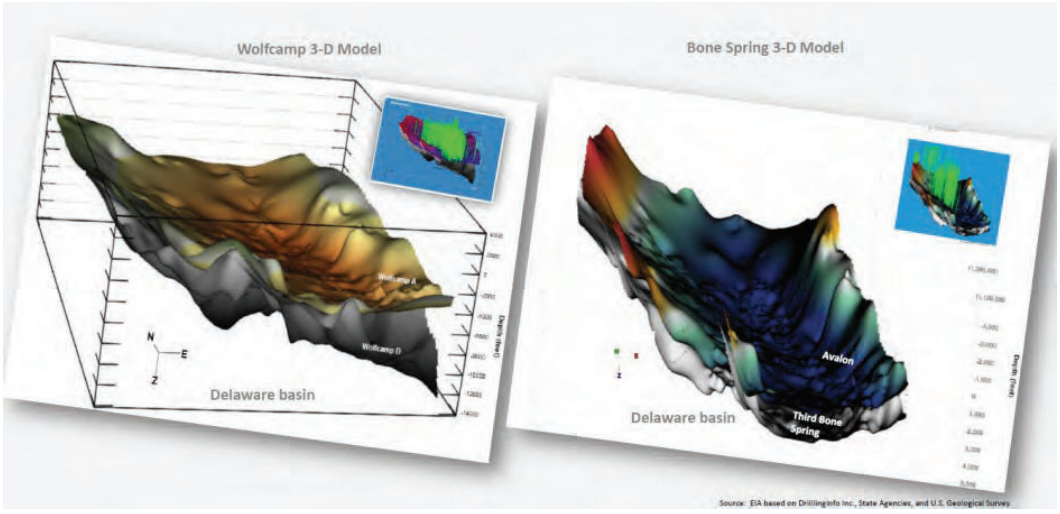
"The thermal history's a little bit unusual," for instance in the Delaware Basin, where the deepest zones may have been the hottest, he noted.

"It does appear to be uplifted, possibly tilted, and how does that affect how we look at it?" he said.

There's also the question of nailing down reservoir and play extent: "These things in the Permian Basin don't always have great lateral connectivity in the

See **Permian** page 15 ▶





Attend, Learn, Succeed! AAPG Global Training Events

4th Edition: Stratigraphic Traps of the Middle East
Al-Khobar, Saudi Arabia | 4–6 Mar. 2024

The workshop will continue to provide opportunity for attendees to receive up-to-date knowledge about stratigraphic trap exploration of the Middle East covering the prolific Gulf region and surrounding areas, exposure to regional and global stratigraphic case studies. It is also an opportunity for all professionals to share state of the art-technologies utilized to detect and produce these complex-yet-rewarding traps.

Carbon Capture, Utilization, and Storage (CCUS) 2024
Houston, Texas | 11–13 Mar. 2024

As hosts of the Carbon Capture, Utilization, and Storage (CCUS) 2024, 11–13 March 2024 at the George R. Brown Convention Center in Houston, Texas , the Society of Petroleum Engineers (SPE), the American Association of Petroleum Geologists (AAPG), and the Society of Exploration Geophysicists (SEG), are excited to once again join forces to offer the industry's leading event for CCUS management and development. This meeting continues to be best chance you'll have to gain insights into the technical and business aspects surrounding CCUS. Help lead the way for successful net-zero operations, developments, and opportunities.

AAPG Spring Student Expo
Norman, Oklahoma | 15 Mar. 2024

The School of Geosciences, with support from the AAPG Foundation, will be hosting the AAPG Spring Student Expo on Friday, March 15 at the National Weather Center in Norman, OK. The Expo will feature short courses, a scientific poster competition and networking with industry professionals.

AAPG/GESGB – Business & Exploration Opportunities Show (BEOS)
London, UK | 26–27 Mar. 2024

The Business Exploration Opportunities Show (BEOS) is a two-day event jointly conceived by the AAPG and the GESGB, which brings together the best of APPEX and PROSPEX into one great show. BEOS is an important multifaceted platform at a critical time to reach out to a broad and diverse audience of stakeholders in the International Upstream Exploration and Business Development / New Ventures part of the Industry.

GCAGS/GCSSEPM's GEOGULF 2024
San Antonio, Texas | 10–12 Apr. 2024

AAPG Gulf Coast Sectional Conference in San Antonio, Texas. Technical Sessions, short courses, events, and field trips relating to most topics associated with Gulf Coast Geology.

Cross Regional Carbonates and Mixed Carbonate Systems Symposium
Palermo, Italy | 22–24 Apr. 2024

This Symposium marks a collaborative event that brings together AAPG Europe and AAPG Middle East, with a central focus on carbonates and mixed carbonate systems worldwide, while highlighting their significance within these two regions. The primary objectives are an overview of controls that govern the evolution of these systems in time and space and the characterization and prediction of their properties across scales. Through overview presentations and case studies, the symposium will address these systems with emphasis on new scientific developments equally as on exploration and characterization of the subsurface in the era of sustainability.

AAPG Southwest Section Annual Convention
Abilene, Texas | 27–30 Apr. 2024

2024 SWS-AAPG Annual Convention
Join us in the key city for the 2024 SWS-AAPG Annual Convention hosted by the Abilene Geological Society. Stay tuned for more information coming soon.

Offshore Technology Conference (OTC) 2024
Houston, Texas | 6–9 May 2024

Since 1969, the Offshore Technology Conference (OTC) has served as a central hub convening energy professionals from around the world to share ideas and innovations, discuss, debate, and build consensus around the most pressing topics facing the offshore energy sector. Whether it's oil and gas, solar, wind, hydrogen, and other marine resources, these conversations will be centered around the innovations that could help shift and drive the world's energy mix.

Optimizing Exploration Workflows: Bridging Expertise between the Rockies and the Andes
Calgary, Canada | 9–10 May 2024

AAPG's Canada and Latin America & Caribbean Regions invite you to join us for a geosciences technology workshop (GTW) that features a series of technical presentations, roundtable discussions, and networking opportunities with technical experts from throughout the Americas. The event is designed for geologists, geophysicists, technologists and business development professionals interested in exploring the potential for hydrocarbons and other resources in complex geological environments

Latin America Carbon Capture, Utilization, and Storage (CCUS) 2024
Rio de Janeiro, Brazil | 22–23 May 2024

Plan now to be a part of the first SPE AAPG SEG event focused on CCUS potential in Latin America! Join us in Rio for a multidisciplinary program featuring technical presentations, panel discussions, keynote talks and an exhibition highlighting work, future challenges and opportunities for energy professionals in Carbon Capture, Utilization and Storage.

2nd Edition: Geological Process-Based Forward Modeling
Abu Dhabi, UAE | 27–29 May 2024

This workshop will bring together invited experts and interested researchers from both industry and academia to concentrate on all technical aspects related to geological process-based forward modeling. Six sessions spread over a period of 3 days will be dedicated to key challenges, finishing with a concluding session to define the best practical way forward.

AAPG Europe Regional Conference 2024
Krakow, Poland | 28–29 May 2024

On behalf of the Organizing and Advisory Committees, we invite you to join us in Krakow, Poland, for the annual AAPG European Regional Conference, to be held from 28–29 May 2024. This meeting will have sessions which fit the general geological setting of the Carpathians and its foreland in Poland but also the broader East European Craton including various Ukrainian basins with highlights on the salt tectonics, clastic, carbonate reservoirs and structural geology. Call for abstract is now open.

Unconventional Resources Technology Conference (URTeC)
Houston, Texas | 17–19 Jun. 2024

The Unconventional Resources Technology Conference (URTeC) continues to be the best opportunity you'll have to exchange information, formulate strategic ideas and solve problems to manage and optimize your unconventional resource plays. Leveraging from all technical backgrounds and disciplines, URTeC is critical to you and your business by delivering the science, technology, and commercial opportunities on what's working with our current business environment.

From Frontier to Discoveries: Namibia's Journey to Major Oil and Gas Discoveries
Houston, Texas | 17–19 Jun. 2024

The Unconventional Resources Technology Conference (URTeC) continues to be the best opportunity y

SEG | AAPG International Meeting for Applied Geoscience and Energy (IMAGE)
Windhoek, Namibia | 22–24 Jul. 2024

Plan now to join us from 22–24 July 2024 in Windhoek, Namibia for the AAPG Geosciences Technology Workshop, From Frontier to Discoveries: Namibia's Journey to Major Oil and Gas Discoveries.

AAPG International Conference and Exhibition (ICE)
Muscat, Oman | 30 Sept.–2 Oct. 2024

Hosted by PDO, ICE 2024 will bring together a global audience of technical professionals, decision makers, academics and government representatives working in both the traditional oil and gas sector as well as on energy transition and sustainable development initiatives. Organized for the first time in the Middle East, the event can leverage Oman's exploration and production plans and incredible geology and will offer a global and regional multidisciplinary technical program that covers the advance, innovation and discoveries in our industry.

AAPG/EAGE/SEG Digitalization in Geosciences Symposium
Khobar, Saudi Arabia | 21–24 Oct. 2024

The primary objective of this symposium is to facilitate knowledge sharing and collaboration among professionals who are engaged in implementing digitalization technologies and machine learning algorithms in geoscience applications. The joint effort of EAGE, AAPG and SEG societies aims to set up industry standards on reproducible AI and distribute key solutions on: data standardization and optimization, data quality, storage and model accuracy assessment, performance profiling, code optimizations, pervasive real-time and remote monitoring and more for advanced prototyping and delivery.

AAPG Mid-Continent Section 6th Biennial Field Conference
Fort Hays, Kansas | 18–20 Oct. 2024

AAPG, Fort Hayes State University Geosciences and Kansas Geological Society host the 6th Bi

AAPG Energy Summit 2024
Uruguay | 19–21 November 2024

Plan now to join us in Uruguay for the Latin America and Caribbean Energy Summit, an executive level event connecting decision makers working to provide reliable, affordable, and sustainable energy for communities throughout the Americas and beyond. Enjoy keynote presentations and panel discussions with industry and government leaders who will share insights about E&P activities, decarbonization strategies, and technological advances shaping the region's energy future. Meet privately with current and future partners at the Business-to-Business session held on-site during the event.

AAPG.org/events

Energy Economics and Technology: Did You Know There's a Committee for That?

For many years the Energy Economics and Technology Committee of AAPG's Energy and Minerals Division has been "a hidden resource under the AAPG umbrella," in the words of co-chair Jeremy Platt.

The Committee issues annual, sometimes biannual, reports. Because information relating to the Committee's purview floods in on a daily basis, Platt said, the group focuses on important recent or sometimes historical events, rather than trade news or forecasting.

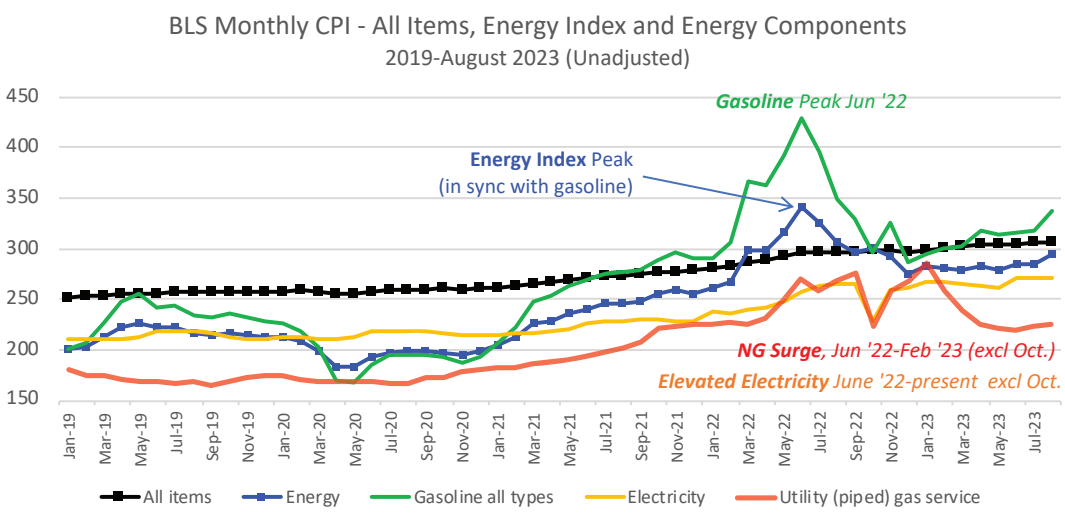
With reports available dating as far back as 2005, "Our contributors have included, from time to time, individuals with remarkable reputations in energy analysis. Having myself spent a nearly 40-year career working alongside such individuals, our approach has been to tap fine minds regardless of individuals' geoscientific credentials or lack thereof," Platt said.

The Committee's latest submission, released late last year, is a departure of sorts, being both up to the minute and focused on one topic: "Energy and Inflation."

"The topic of inflation and connections to oil have been on people's minds for a long time, not least since the midsummer 2022 spike in oil prices," said Platt.

Pratt said it's no surprise that "as far as the general public is concerned and the tracking of big numbers, the story is dominated in most years and months by oil, by gasoline at the pump. Yet it is interesting to see how some of the components have changed since the pre-pandemic year of 2019."

"By components? Gasoline, natural gas, electricity," he continued. "My own background was deeply involved in fuels used for electricity – uranium, coal and for several decades, natural gas, which had once been shunned. So it was quite interesting to learn that, unlike oil and natural gas, from a consumer's point of view, electricity costs recently have just gone up and up, even though natural gas – to which its wholesale costs are joined at the hip – have fallen sharply into its habitual very unattractive (from a producer's point of view) territory."



Origin Story of the Committee

The Committee began by the fall of 1998 after recommendations within EMD by Platt and Keith Murray and later executive actions. Its aim was to provide an avenue within AAPG to advance understanding of the interplay of energy markets and technologies of supply and demand. The means for doing this has been to tap experts with different backgrounds and perspectives, to organize topical sessions principally at annual meetings, and to develop annual reviews with commentary on selected themes and guidance on important references. The importance of providing this service owes to the essential need for energy in people's lives, the magnitude of shifting policies and fundamentals, the unease and uncertainty that never goes away, and the need to participate in discussions and learnings to stay on top of one's profession.

The group quickly began making significant contributions and has continued to do so in the decades since.

"The Committee's first big splash," Platt said, "was a full-day forum at the 1999 annual meeting on 'Gas in the New Electric Market.' Natural gas was beginning to play a central role in the economics of power generation … The industries – oil, gas and electric power – were becoming tied together. Explosive advances in efficiency and cost-effectiveness of power generation technology, coupled with deregulation of that industry, led to burgeoning growth in the use of natural gas."

Hydraulic fracturing wasn't on the radar yet, he explained, while natural gas and coal presented considerable uncertainties.

"Many were surprised that reserves of seemingly scarce natural gas were proving to be much greater than expected," said Platt. "Past AAPG President Bill Fisher was one of the first to document this. And as today, coal generation was widely seen to face waves of regulatory hurdles, even though coal supply had undergone shocking growth due to the phenomenal attributers of the Powder River Basin deposits. In a sense, the Powder River Basin had become, for coal, what the Permian Basin is today is for U.S. oil and gas, if not more so."

Understanding Energy Economics

Energy economics can only be understood by bridging separate fields, Platt explained, be it geology and economics, exploration and engineering, and "with the advent and urgency of mobile and stationary energy storage, such disciplines as solid-state physics, electrochemistry and the outlook for the costs of battery materials and EV penetration."

Still profound is the continuing interplay of natural gas and coal in the commodity market, both on a nearly seasonal basis and, within the past decade, in response to gas' superior economics.

The Committee has been a major force behind many important events, exploring emerging opportunities and controversies as they buffet the industry.

The Committee was a principal organizer of AAPG's 2012 Geosciences Technology Workshop in Golden, Colo., on "Hydraulic Fracturing – New Controversies, New Plays." It organized the panel, "Energy Transition: Oil and Gas in the Crosshairs," at the 2021 International Meeting for Applied Geoscience and Energy, bringing perspectives from Wall Street finance, the auto industry and the power sector.

And it was with great anticipation that it organized a workshop and field trip to examine the special markets of natural gas liquids, centered on the pre-eminent storage and price-setting hub just 30 miles east of downtown Houston, Mont Belvieu – only to be scuttled by the pandemic.

As these few examples attest, energy economics and technologies are constantly changing, and it should not be surprising that the purview of the Committee remains at or near the top choice in surveys of AAPG members. This situation is ironic since, like many volunteer organizations, the Committee has always had difficulty engaging members to conduct the actual work, thus relying on aforementioned experts from outside the geoscientific community, Platt said.

"The door is always open," he emphasized. "One of the most rewarding collaborations was when our Dieter Beike, a petroleum engineer with a rich industry background, jumped on board and soon became co-chair."

The Committee's "bread and butter" remains its annual reviews, he said. Beginning about 2000, and ending with its 2018 contribution, these were periodically co-published in the journal Natural Resources Research.

Other major contributions from the Committee include 2022's review: "Transition Framework and Questions."

"That deep dive on the energy transition, as noted, was issued in November 2022. The review followed a very similar outline to one presented at the AAPG September 2021 annual meeting, when AAPG partnered with the Society of Exploration Geophysicists under the entity called 'IMAGE,'" Platt said. "That in turn was based on interviews and research throughout 2021, so that by November 2022 we had been pursuing this topic of the energy transition for over a year and a half and had exhausted all the low-hanging fruit and ourselves (and myself)."

"Another year has gone by, but I haven't seen anything to dislodge or replace the insights included in that major review," Platt added.

In the Market for Experts

The Committee's main goal, he said, is to "stay on top of a bucking bronco and remain relevant, continuing to advance understanding of complicated markets and other developments, and organize occasional topical sessions and other events."

"To do this, it will be important to find co-workers and successors to keep up the work," Platt reiterated. "Those who have the connections, or can make and sustain them, to experts across industry and the consulting community will be a great asset. With such individuals, the Committee will continue to serve as a forum for learning, doing the legwork for those who don't have the time or position to do this all themselves but appreciate the destination. The notion of symbiosis is at the heart of this, namely providing forums shaped by individuals' professional needs, where they

Continued on next page ▶

The Committee report is available on the AAPG website. Go to the 'Divisions' tab at the top of the page, and the EMD button is the second of the four listed there, then find the 'Committees' tab on the right side under 'Navigation.' Then click 'Energy Economics and Technology Committee' at the center of the page, then find the 'Activity & Reports' tab, under the Committee's reports can be found, the most recent being "Energy Economics and Technology Report: Energy and Inflation."

Some of the key information in the report is as follows:

The Bureau of Labor Statistics is the arbiter of all facets of U.S. inflation. Broad inflation in 2022 as measured by the Consumers Price Index (CPI) reached 9.1 percent, the highest since the 1970s when the CPI hit 12.3 percent and 14.8 percent. Energy accounted for 33 percent of the growth in inflation by mid-2022 over the previous year. BLS' tracks of the raw components of energy are shown in this chart. The lion's share of energy's contribution usually gasoline, Natural gas was important both last summer and into the winter, whereas electricity's share has shown little volatility, climbing steadily. Other BLS data compiled in the report quantify the relative importance of each of these components to the national CPI.

The Committee addressed the principal questions about the energy transition toward decarbonization in its 2022 report. Drawing on current research and interviews, it summed up the key factors directly affecting the oil and gas industry in this fashion. Oil's fate is largely caught up in vehicle electrification and other means to reduce fossil fuel use. The power sector will struggle to run away from natural gas, which it has embraced as a game-changer over coal. Hydrogen gets much attention and might draw heavily on natural gas whose fate is caught up in what is portrayed as a horserace between methods of "reforming" natural gas or resorting to brute force electrolysis.

New Kitchen, Many Chefs, Missing Ingredients

Oil / Transportation

An EV story -- a mix of tech, regulatory-push and demand-pull

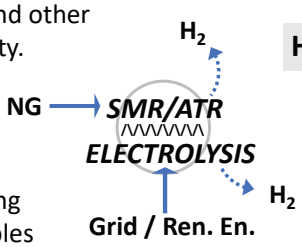
Down the road? Fuel cells, Biofuels, Alternate mobility – at scale?

What to watch? Batteries and other approaches to range anxiety.

Nat. Gas / Power Gen.

A messy story

Tried and true: Fuel switching (NG for coal) and Renewables



Hydrogen / Industry

A "test kitchen"

Industrial hubs as incubators

What to watch? Carbon capture, low-C fuels, H_2

A cauldron of approaches: H_2 blending, low-C fuels, 4th Gen. (new) nuclear, Allam Cycle, transmission

What to watch? Carbon capture, long(er) duration storage, H_2

Landscape of oil and gas in the energy transition

◀ Continued from previous page

can shape AAPG to serve their own evolving geoscientific/economic interests. Only then does AAPG remain a relevant priority in their lives," Platt said.

Predictions

What does the future hold for energy markets and technology?

"A short answer is 'more of the same, but different,'" answered Platt. "This means understanding the scale and extent of possible changes in transition, serving vital needs to bring perspective on such changes which are often nearly unrestrained fantasies produced by well-intentioned scenarios quantified by vast computer models and data collections."

More specifically, Platt said that "hydrogen realities will need more attention. Autothermal reforming, the Allam Cycle in power generation, the promise and constraints on renewables, the faltering steps toward carbon sequestration, all these will need to continue to be tracked. Will they rise above the forest floor and make a difference?"

Embedded in this is appreciating the oil and gas industry's remarkable technical proficiency and the role that the private sector has played in transformations, he said.

"This is not a statement of capitalistic political philosophy but the reality of what it takes to steer investment at scale. How will the tension and promise of 'demand pull' be reconciled with 'regulatory push' in any serious grappling with climate change?" Platt explained, citing the shale revolution as illustrative of this tension.

"One certain conclusion is that Big Oil's negative reputation has done it no good in making the case that it is a vital part of the solution, and not the problem," he added. "This has led to efforts to nip off fossil fuels at the bud, on the easy-to-snip supply side, without giving serious attention to the demand. Time and again, when demand gets ahead of supply, fuel insecurity and intolerable price escalation will take primacy over all other considerations. Anticipating this, tracking how this plays out, sticking to objective facts and data, and steering clear of advocacy will be central to sound understanding going forward. Not an easy course."

CCUS

from page 7

CCUS deployed more broadly and to have global penetration, because doing projects in Europe and the United States is way too insufficient," he said.

"Unless we get this to places like Indonesia, India and China, we're not going to do anything with the climate. We will be a bunch of people in the developed world patting ourselves on the back for doing fun little science projects. That's not what it's about," he said.

McConnell said international energy companies could be a part of the solution to global emissions reduction.

"International energy companies have that footprint all over the world. They operate everywhere, not just in Houston," he said. "And many of these industries have many of the necessary capabilities and competencies to address issues associated with CO_2 emissions."

Kendall agreed.

"Considering the skills, tools and infrastructure needed to develop CCUS projects, I can't imagine an industry that is better suited to advance CCUS, whether it be subsurface modeling and analysis, drilling and operating CO_2 injection wells, or the development of pipelines and surface facilities," he said.

Kendall looks forward to sharing Denbury's story at the CCUS event in Houston on March 11.

"We are at a fascinating crossroads. Ever-increasing global energy demand is intersecting with the need to reduce global CO_2 emissions. CCUS can mitigate billions of tons of CO_2 emissions annually, but we are still in the early innings," he said.

"Our industry is set to lead in CCUS, and I'm excited to share perspectives with the conference attendees."

For information about the CCUS event and to register visit: CCUSEvent.org.

Geophysical Corner

Working with Imbalanced Data in Machine Learning Algorithms

Bridging the gap between real and optimal in seismic interpretation

While scientists and workforces are becoming more at ease with the term "machine learning" and less reluctant to use these methods, there are still many uncertainties about their correct use and output understanding. Therefore, there is a need to explain what might be happening in the so called "black boxes" and the potential causes for high errors and misclassifications. If not well understood, these issues can lead to incorrect interpretations and economic losses.

We would dare to say that 80 percent of any machine learning method, especially unsupervised, relies on input data preparation: the principle of "garbage in, garbage out" applies. So, it needs to be understood not only what kind of data it is, but how it can be optimized. The amount of data, their relationships and quality are just a few aspects to consider in order to do this. The first aspect is in focus here, since disparities in data (imbalance) can result in significant errors.

The term "imbalance" in data refers to the differences in proportions between classes. In this sense, the class that has the majority of records or instances will be called "negative class," and the underrepresented or minority class will be named "positive class."

Most of the geological settings we are used to studying are indeed imbalanced. Imagine a deepwater setting in which channel complexes are usually surrounded by shales in a major proportion, or as another example, a setting in which salt tectonics dominate and salt bodies will represent that negative class. Since a perfect dataset would only exist in a utopian world, we need to understand our data and how to optimize results without biasing or overfitting our models.

To understand the impact of the class imbalance we need to first understand the degree of imbalance between classes, and second, we need to understand the overlap between classes. The degree of imbalance (also known as IR) is obtained by relating the total number of negative class examples and the number of positive class examples. Figure 1 shows an example of how shale facies represent the majority of a training dataset (also known as MTD) used to predict deepwater channel facies. Here, five facies are used as labels. If we relate background "shale" to any of the other facies we would see that it doubles or triples them, creating an imbalanced dataset.

However, when we sum up all the channel facies and MTD, they will be almost proportional to the background shale, suggesting that we should simplify our labels.

The type of machine learning technique we intend to use should also be considered. Supervised methods count on error metrics given by the fact that input and output are known. However, in the case of unsupervised ML techniques, only the input is known, and the selection of the right number of clusters is still under debate. So, we will provide general guidance based on our experience on what to do with each type of method for seismic facies interpretation.

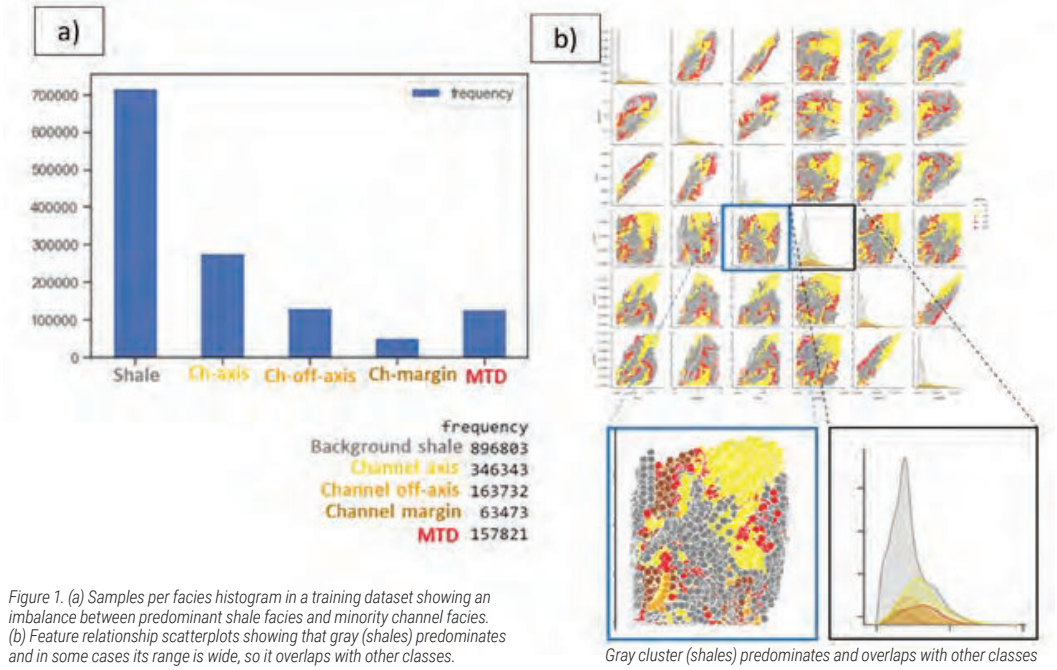


Figure 1. (a) Samples per facies histogram in a training dataset showing an imbalance between predominant shale facies and minority channel facies. (b) Feature relationship scatterplots showing that gray (shales) predominates and in some cases its range is wide, so it overlaps with other classes.

Gray cluster (shales) predominates and overlaps with other classes

Unsupervised Methods and Imbalanced Data

When using clustering algorithms, such as K-means clustering, self-organizing mapping (SOM) and generative topographic mapping (GTM), it is suggested to use seismic attributes suitable for the geological target. Analyze their statistical relationships and refine them if necessary, using a dimensionality reduction technique (for example, PCA, ICA, Shap values). Additionally, consider using a method such as an elbow plot to determine the optimal number of clusters. An elbow plot visualizes the relationship between the number of clusters and the explained variance, aiding in pinpointing where additional clusters yield diminishing returns in explaining the data's structure. An example is shown in figure 2, which depicts results and error using a ML technique (GTM) with three clusters where five were expected. Notice how error is reduced by using an optimal cluster number determined by an elbow plot. This suggests that, although

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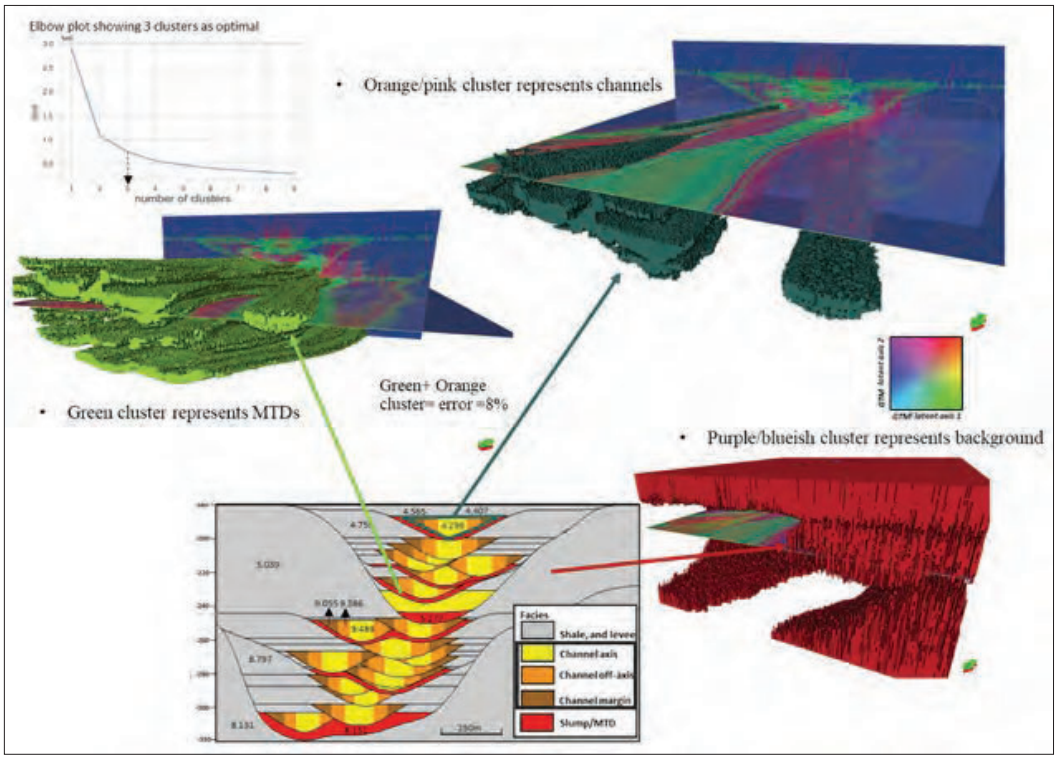

Figure 2. The elbow plot indicates that the optimal number of clusters is three, and GTM results reveal MTDs in a light green geobody (GTM green), Shale in red geobody (Purple/blue in GTM), and channel facies combined in dark green geobody (orange in GTM). This demonstrates that not every cluster has to represent single facies. The elbow plot is a valuable tool for estimating the optimal number of clusters. The number of clusters may be related to the quality and resolution of the data and distinctive patterns found.

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we intend to depict five facies, the data patterns end up forming three major clusters.

Interpreting these visually, we can see that one corresponds to the majoritarian shale facies, another represents the MTDs, and the third cluster represents the channel facies (axis, off-axis and margin) combined. It is important to remember that while we aim to identify all discrete facies, the properties of the seismic data (frequency, noise, resolution, etc.) and the type of seismic attributes used, as well as their parameterizations, play a fundamental role in the detailed or non-definition of different seismic facies.

Supervised Methods and Imbalanced Datasets

Supervised ML needs an input (labels, plus features) to train the model, allowing us to know the expected facies first and enabling numerical error estimation or performance evaluation.

Figure 2 displays a distribution of training data. By contrasting seismic attributes used as features, it becomes apparent that there is an overlap between shale and most of the channel facies. This overlap will result in misclassification of these facies with shale. One potential solution is to explore other features that create greater distinction between classes or to perform a resampling of the data.

Some of the methods we can employ to address imbalanced datasets include:

- The use of simple algorithms such as DBscan or K-means clustering with realistic labels or minimum classes: Another option is the use of boosting algorithms (such as random forests) which assign different weights to the training distribution in each iteration. After each iteration, boosting increases the weights associated with the incorrectly classified examples and decreases the weights associated with the correctly classified examples.
- Oversampling or undersampling: oversampling refers to appending to the original data set, while undersampling involves the removal of data from the original dataset, typically from the majority or negative set, to achieve the same proportion or balance. However, this method could introduce its own set of problematic consequences, which can potentially hinder learning.
- The use of correct statistical metrics: A confusion matrix is a popular tool for understanding and evaluating classification problems. It compares actual or original vs predicted values. The main diagonal shows the samples that were classified correctly, while the other fields help us understand where and to what extent misclassifications occur. While accuracy is normally the metric evaluated in confusion matrices, it places more weight on common classes than on rare classes. This can make it challenging for a classifier to perform well on rare classes when evaluating imbalanced datasets. In such cases, it is recommended to use the F score, which is a weighted harmonic mean between precision and recall. There is also a G score that, instead of a harmonic mean, uses a geometric mean.
- Receiver operating characteristic curve and area under the curve: ROC is used to analyze classifier performance by comparing the false positive rate on the x-axis versus the true positive rate on the y-axis. The closer the curve is to the upper-left corner, the better the classifier is. By calculating AUC, we can obtain a score for the classifier. A higher AUC score, closer to 1, indicates a good classifier with a top-left ROC curve. AUC lower than 0.5 can be considered as indicating a poor classifier. It's important to note that these methods are designed for binary problems and not multiclass scenarios, which are common in seismic facies. When dealing with multiclass scenarios, we may need to evaluate ROC or AUC per class, and it becomes sensitive to class skew, as the negative class would be a combination of N-1 classes.

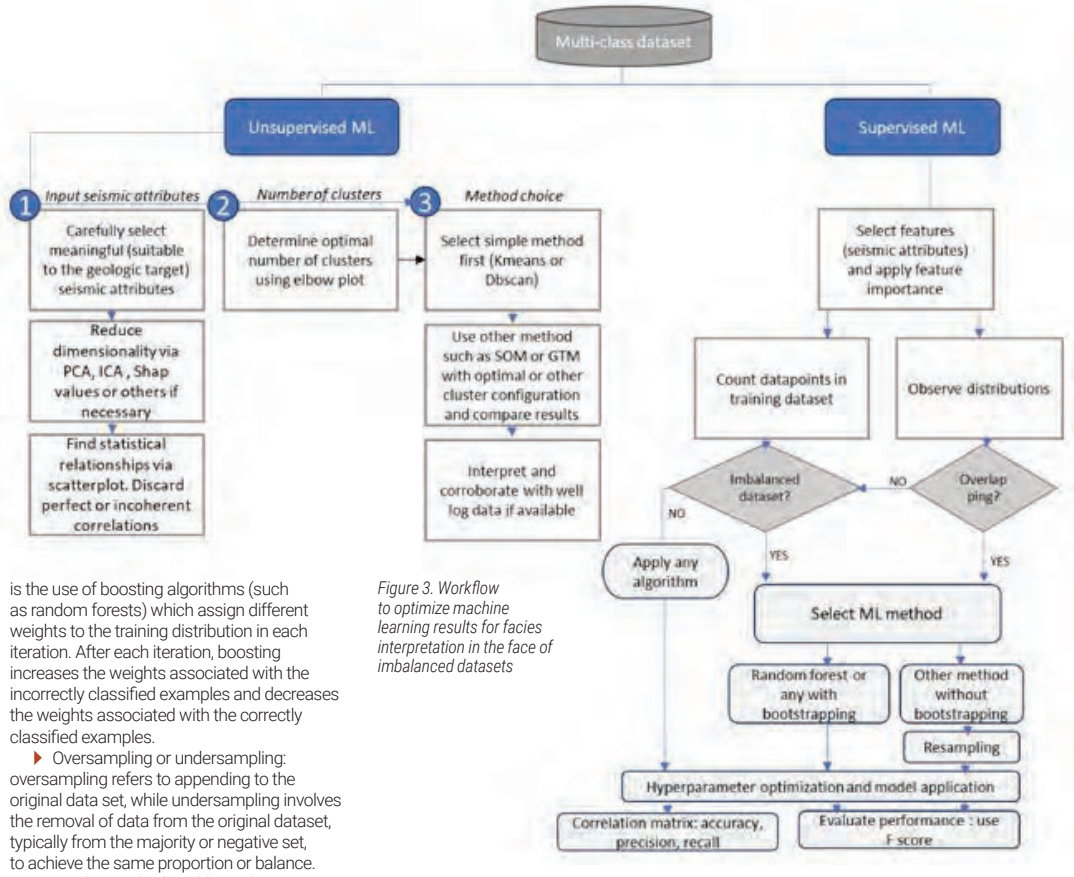

Figure 3. Workflow to optimize machine learning results for facies interpretation in the face of imbalanced datasets

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Conclusions

To summarize the recommendations provided here, we have created an easy-to-follow workflow (figure 3) that could be helpful for interpreters who are beginners in dealing with imbalanced data.

No dataset will ever be perfect, so very accurate models should arouse suspicion because they will probably reflect bias or overfitting problems. Also, not every imbalanced dataset will necessarily result in poor training data. As geoscientists, we need to use the tools such as seismic attributes and ML techniques intelligently, be aware of our data's limitations, apply best practices, including parameter optimization and, most importantly, recognize that in geology, nothing is perfect. Our understanding of the geological context and subsequent inferences still needs to be carried out. We believe that machines can't fully replace us, at least not yet.

(Editors Note: The Geophysical Corner is a regular column in the EXPLORER, edited by Satinder Chopra, founder and president of SamiGeo, Calgary, Canada, and a past AAPG-SEG Joint Distinguished Lecturer.)

Permian

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reservoirs. You may have it, and you may not," McMahon said.

And as always, results may vary. The Third Bone Spring sand in the Delaware Basin has been targeted for development but its Midland Basin equivalent, the Dean formation, doesn't draw as much attention, McMahon noted.

"The Dean might not be as good as the Third Bone Spring sand, which is the equivalent but might not have the same degree of prospectivity," he said.

In development drilling, the Permian has seen the same shift to longer laterals as other unconventional areas. So-called "horseshoe laterals" extend from a well then make a 180-degree turn and double back, to create a parallel lateral.

"Operators have been experimenting with new development techniques. People are starting to drill U-shaped wells (in the Permian), with the idea that you get more lateral in the area you're drilling," McMahon said.

Investments and Acquisitions

While the Midland Basin has gotten most of the recent attention and investment, operators continue to eye other prospect areas in the Permian, particularly in the less drilled and developed Delaware Basin.

The Delaware is typically defined as including all or parts of oving, Winkler, Ward, Reeves and Pecos counties in West Texas and Eddy and Lea counties in southeastern New Mexico, although parts of adjacent counties are sometimes included.

McMahon said his agency had created a comprehensive, color-coded chart of wells drilled in the Permian by year.

"You've got a lot more blank space in the Delaware (Basin). Even where it's been drilled, the density isn't as great," he said.

In U.S. oil production, an obvious and maybe inevitable 2024 headline would read, "The Permian Basin Re-emerges -- Again." Because of the basin's status as an exploration and production hot spot, companies have found it hard to put together any meaningful Permian acreage position without buying another operator.

McMahon said he knows of one company from outside the United States that made a substantial effort to build a position in the basin, but ultimately was forced to give up. That bodes even more consolidation to come, with deeper pockets and deeper expertise driving future Permian Basin development.