Applied Geoscience in Shale Exploration and Production

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PREFACE

In the early days of modern exploration, following World War II, a clear distinction was made between the various disciplines involved in the search for hydrocarbons. The geologists would initiate the process by gathering regional data and propose areas of interest. The geophysicist would soon follow with proposals for regional 2-D seismic lines. Following a structural interpretation of the data, the geology would be superimposed, the particular blocks acquired, and the engineering staff would take up the task of proposing the wells, drilling, and producing the hydrocarbons. Communication between the disciplines was sparse, and rarely would one question members of different disciplines. Often they were on different floors and rarely interacted. Today the opposite prevails, yet there is still some level of mistrust. With rare exceptions, most professionals lack the exposure to various disciplines until they reach senior management levels, and then they are rotated to supervise areas they are unfamiliar with.

The objective of this textbook is to bridge that gap by providing sufficient background in the various disciplines to have meaningful interaction among the parties involved.

I am indebted to the thoughtful readers who contributed time and effort to edit portions of the textbook. In particular I would like to thank Dr. Kurt Marfurt, professor at the University of Oklahoma in Norman, OK, and Dr. Yoginder Chugh, professor at Southern Illinois University in Carbondale, IL. Mr. Tom Venetis assisted in the editing of the text and the efforts are appreciated.

INTRODUCTION

Continuing advances in petroleum technology have altered the simplistic view proposed by the followers of Hubbert (1949). Hubbert assumed that, with conventional onshore drilling and shallow offshore shelf drilling, oil production worldwide would peak by the 1970s. Later, Hubbert modified this estimate to the year 2000. More recently, HSBC Bank predicted in 2016 that the world oil production prognosis would peak at 21 billion barrels per year in 2016 and begin a 7% decline per year, reaching a minimum in 2040 of 3.4 billion barrels per year (Fustier et al., 2016).

While timing for *peak oil* predictions proved popular with some, four key factors were not taken into consideration that modified the prediction of both the maximum peak production and when that peak would be achieved:

- Development of accessible economic three-dimensional seismic surveys and advanced processing techniques that significantly reduced drilling risks and extended existing fields
- Ability to drill into deep formations and in ultradeep water, which led to discoveries of major accumulations worldwide
- Reduction of oil demand by using renewable energy sources and making engines more energy efficient
- Technology to exploit unconventional resource shale oil and gas in many traditional basins that significantly increased oil production in several countries

The last of these four contributions is the focus of this book. What new technology yet to be discovered will further improve recovery? The challenge is to produce the hydrocarbons from both conventional and unconventional resources plays, particularly shales, at the lowest possible cost, in an environmentally sound manner—and thus maximize profits and minimize liabilities. The newly developed technologies for unconventionals can also be used in conventional oil and gas fields to improve production.

fracking, microseismic, logging, multicomponent seismic, and rock physics have opened new avenues of investigations previously considered only as academic exercises. Seismic processing has advanced to the point where attributes related to sweet spots can be identified and mapped. With the proliferation of four-dimensional seismic (i.e., repeated three-dimensional seismic over the life of the field), the progressive depletion of the reservoirs can also be mapped, thereby improving the harvesting of the hydrocarbon resource.

STATEMENT OF OBJECTIVE

In the assessment of shale resource plays, it becomes evident that a multidisciplinary approach is critical, as well as for advanced conventional development. The first rule of an integrated study is that all participants must learn to speak the different languages used by each profession and understand the subtle cultural differences specific to each discipline. The second rule is that all team participants must be familiar with the techniques used by the various disciplines, to optimize their integration.

An example of language differences is the scale factor. A sedimentologist can describe massive sandstone bedding on a decimeter scale, whereas to the geophysicist a massive sandstone is a package 10–20 m thick; moreover, to the engineer, the massive sandstone is a continuous sand unit with no discernable internal barriers and with similar measurable reservoir parameters. The proliferation of technical language and techniques in the fields of geoscience and engineering and the subsequent use of contractions can lead to confusion and ultimately foster distrust. For example, an engineer might overhear the following conversation between a geophysicist and a petrophysicist: "My AVO signature is clearly class III and suggests 'a,' 'b,' and 'c.'" The petrophysicist might reply, "But my LMR plot, based on the well logs, suggests that for the depth range in question, it is more likely to expect a class II AVO, and that may modify your interpretation." In this example, the engineer needs to understand the impact on the amount of free gas in the reservoir, a topic that was never mentioned in this conversation between the two geoscientists, who are essentially speaking different languages.

One objective of this book is to bridge these cultural barriers across disciplines and improve communication among various industry professionals. A second objective is to ensure that sufficient knowledge is available to readers to facilitate conversations with their counterparts in the various disciplines and to contribute to the discussion of all aspects characterizing a reservoir and affecting its management. It is also important to enable professionals to read the literature from the various disciplines on related topics and determine their importance and relevance to their current study.

2

SHALES, CLAY MINERALOGY, AND ASSOCIATED FEATURES (SURFACE AND SUBSURFACE)

TAKEAWAY

- Definition of shale based on grain size and mineralogy and significance
- Response of shale to gamma-ray log
- Clay minerals—mineral composition and significance, with focus on smectite/illite structure
- Mineral composition–based definition of brittleness
- Diagenesis of smectite and relationship to overpressure and free gas
- Porosity, permeability, and organic content response in shales
- Tools used in the study of shales and their applications: XRD, XRF, SEM, TEM, CEC, DTA, EDAX, QEMSCAN, IBM-SEM, FTIR, CT scan, and Langmuir isotherm

GENERAL PRINCIPLES

All professionals involved in the study of the shale resource play require an accurate definition of the shale, including its physical and chemical properties. At the same time, it is important to understand how the data are obtained to determine their accuracy and limitations of the definition. In addition, establish what questions to ask to improve the definition of these attributes.

There are several distinct ways of classifying shales and determining their properties. To the sedimentologist, grain size (<3.9 mm) and mineralogy are critical and equally important. Shales are mainly composed of clay minerals known as

Shale mineralogy

The second definition of shales is based on composition. Surprisingly, this definition is not as robust as one might expect. Shales are rarely pure clay minerals. In fact, clay minerals themselves can be either allochem or authigenic (autochem). The term *allochem* is more commonly applied to carbonates, and it is used to distinguish carbonates transported into the environment from those produced in situ, which are considered *autochem*. However, the terminology applies very well to shales, and allochem is analogous to detrital clays. It is important to establish if the clay fraction is an allochem or an autochem. Usually, the autochem has a significantly smaller grain size and can be separated by the hydrometer method described previously. The autochem in shales refers to diagenetically generated or biologically derived clays. Shales can also contain silica particles as either detrital quartz grains or fossil precipitates (e.g., sponge spicules and radiolaria). Moreover, they can contain varying amounts of carbonate, either as pure calcium carbonate ($CaCO_3$) from foraminiferal tests (shells) or mixed with autochem clay minerals, often originating from algae and bioturbation. Several tools are used to establish the mineral composition of the shale including x-ray crystallography, x-ray fluorescence, electron microprobe, calibrated well logs (to a certain extent), and other techniques discussed later in this chapter. The overall composition of resource shales can be plotted on a ternary diagram (fig. 2–3) and compared to other shale resource plays. Importantly, as figure 2–3 shows, there are no unconventional shale plays with a very high clay fraction.

Ternary plots are available for the composition of most of the world's shales. Several of the major North America shales are shown in figure 2–3. There is a wide range of compositions, and no unique composition provides a better candidate shale resource play. Each has its own benefits and deterrents. The most important aspects of studying analogue basins are to determine the differences and similarities between your current study area and those of other basins and to establish the most appropriate tools to define the specific problem in your area of study.

The higher the clay content is, the more ductile the shale will be—and therefore more difficult to frac. The presence of carbonates has significant impact on diagenesis and compaction of the shale. Understanding the composition of the shale is crucial in unraveling basin history, investigating overpressure, and designing proper completion techniques. New classification of shales are being proposed to combine aspects of composition. Terms like *siliceous-mudstones* and *mixed clay poor mudstones* have been proposed by Donovan (2017).

target at a single point, causing the electrons in the specific atom to be elevated to a higher energy state. Once the beam is relaxed, the electron returns to its original energy state but in the process emits a unique x-ray wavelength signal that identifies the element (in a similar fashion as the XRF tool). This technique allows for a more detailed analysis of the internal chemistry of the object under investigation (figs. 2–17 and 2–18). SEM combined with EDAX has been applied to geological studies for over 50 years.

Bridging illite forms as authigenic illite (fig. 2–21). When present, it can significantly reduce permeability in fracture systems. SEM can also detect characteristics of the organic material in the sample. Organic material has the unique characteristic that its porosity increases with maturity, thereby creating additional storage space; this is most likely due to hydrocarbon expulsion (Löhr et al., 2015), which will be discussed in chapter 7. Loucks et al. (2009) have reported an excellent comparison between the size of the organic material nanopore and the size of a methane molecule (fig. 2–22). The efficiency of the nanopores as storage space for gas is evident. The SEM image may be enhanced using the ion beam milling (IBM) technique or the more advanced focused ion beam milling (FIB) described in the next section.

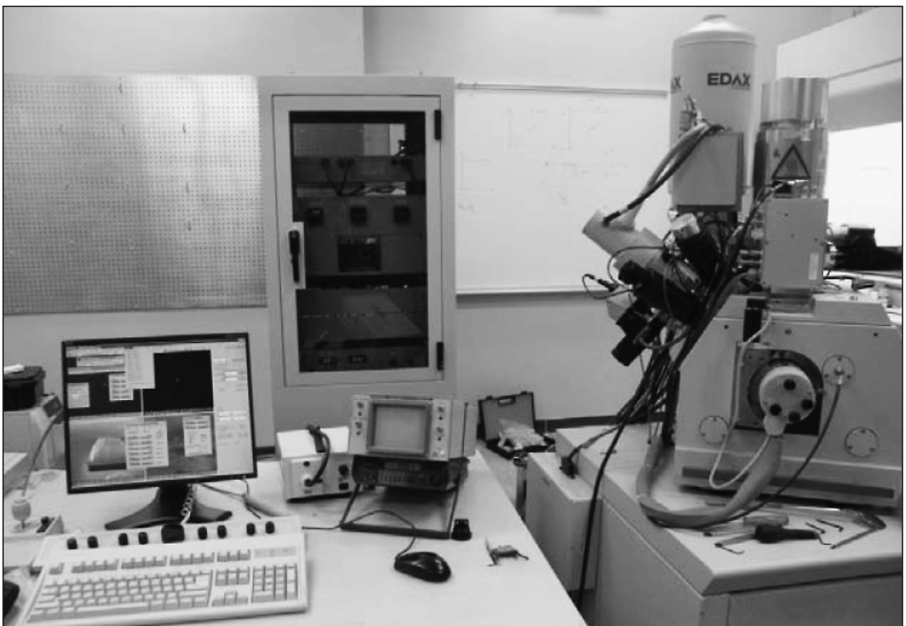

Fig. 2–17. SEM/EDAX unit at University of Houston nanotechnology laboratory, combined with focused ion beam (FIB) milling (Photograph published with permission from the University of Houston)

text. We now understand that the biostratigraphy can be dated via ash flows. What other faunal assemblages can we use?

If foraminifera had been abundant and well preserved throughout geological history, then the analysis of stressed environments and paleoecology would have been simplified. Foraminifera have a distinct disadvantage: They became very abundant and widespread from the Cretaceous onward, developing in the Jurassic. Prior to the Jurassic microfauna, the world was affected by several great mass extinctions punctuating the end of the Devonian, the end of Permian, and the end of the Triassic. Ammonite zonations are most often referenced for the Cretaceous and Jurassic sediments. Van Hinte (1976) attempted to unify the age dates of the Cretaceous stages, and other investigators are continuously updating the limits.

For the pre–Upper Jurassic, fusulinids (extinct in the Upper Permian) and conodonts (extinct in the Triassic) are used to establish correlations and bracket sequences. Conodonts have two advantages: Speciation and wide diversity allow for excellent correlations; and possibly the most important aspect is their composition (Hautmann, 2012). Because of their calcium carbonate phosphate content, conodonts are insoluble in acid and sensitive to heat, resulting in color changes. Being less soluble in mild acids, they can readily be separated from limestone beds. In shales, they often require considerable sample size to provide a good assemblage. After careful documentation of the conodonts, it was observed that a coloration index could be established and readily related to equivalency with other maturation indices such as Fourier transform infrared (FTIR) spectroscopy (see chap. 2). Results from FTIR spectroscopy can be translated into an equivalent vitrinite reflectance value and other maturity indices. Vitrinite is available only in sediments younger than the Carboniferous. In chapter 7, maturation criteria will be discussed in greater detail. For now, conodont coloration variations, called *conodont alteration index* (CAI), have been tabulated and cross-referenced to other maturation tools. The temperature ranges for the alterations can be carefully calibrated by heating samples of immature conodonts (fig. 3–2). Because a significant portion of the world's resource shales lie in the Paleozoic, having an independent means of establishing the maximum temperature attained during burial allows for an accurate prediction of expected reservoir fluids.

Conodonts are unique fossils. Even though they have been described for over a century, their origin was not known until the 1980s, when an elongate soft-bodied fossil was discovered in Scotland with conodonts in the mouth region (Barrick, n.d.). For example, the conodont biozone ages were used to correlate the Devonian to the Lower Carboniferous of the western United States and, by extension, Western Canada (fig. 3–3).

RATES OF DEPOSITION

Biostratigraphy is used in estimating rates of deposition. Care must be taken to understand the impact of sedimentary compaction on these estimates. Given that caveat, an example is used from the Texas-Louisiana Gulf Coast. A well in Calcasieu Parish, Louisiana, shows the first appearance of the benthic fauna *Siphonia davisi* and *Cibicides jeffersonensis*. Importantly, when the first appearances occur, they are part of a group of fauna commonly associated in the same strata. Because their ages are well documented, the rate of sedimentation can be clearly established (fig. 3–10). The ages are provided by Paleo-Data (2017), based on thousands of wells studied in the Gulf of Mexico region. This interval has a rate of deposition of 26 mm per 1,000 years.

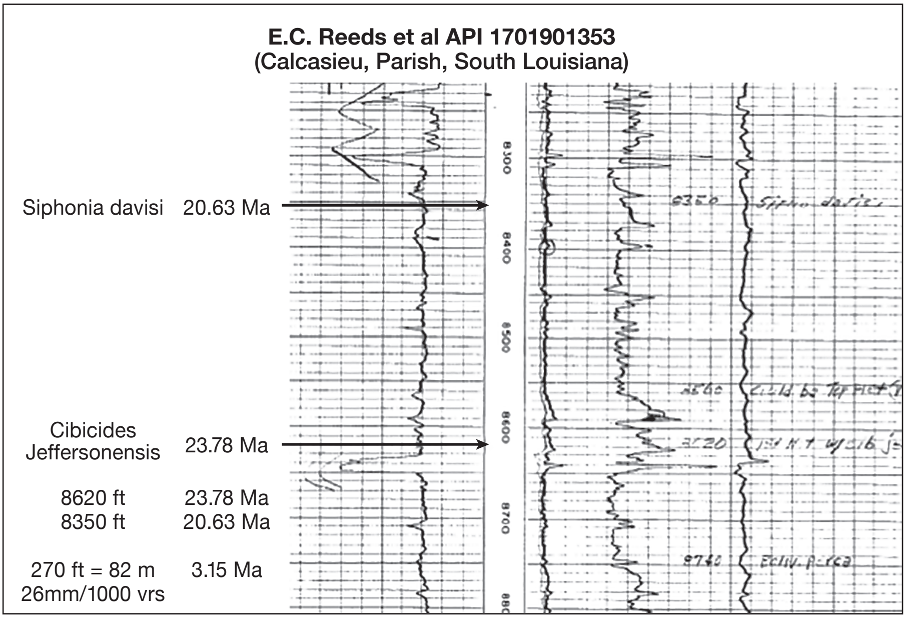

Fig. 3–10. Rate of sedimentation calculation calculated on an individual well in South Louisiana

The calculation for rate of deposition is critical to establish the burial history of the basin for both temperature and pressure. Deltas have sedimentation rates averaging 1,000 mm per 1,000 years. Stable shelf sediments may have rates as low as 50 mm per 1,000 years (Sadler, 1999). It is important to use this information on the burial history plots with care. The following assumptions are needed: first, the interval is not faulted; second, there are no unconformities; and third, there is no compaction or compaction is corrected. Corrections for each of these conditions may have to be integrated.