

ENERGY IN THE AMERICAS: CRITICAL REFLECTIONS ON ENERGY AND HISTORY

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Seismic Innovations: The Digital Revolution in the Search for Oil and Gas

Tyler Priest

During the 1920s, the lion's share of global oil production came from lands that rimmed the Gulf of Mexico and Caribbean Sea, with Texas, Mexico, and Venezuela dominating the world oil market. Nearly one hundred years later, the Gulf-Caribbean continues to yield prodigious amounts of oil and attract huge investments. Although not as dominant as before, this region nevertheless has demonstrated remarkable endurance as an oil province. What explains its staying power?

Obviously, the size of the petroleum resource is a determining factor. But someone still has to extract that petroleum in a cost-effective way and locate new reserves to offset depletion. In recent decades, as chapters by Joseph Pratt and Linda Hall in this volume reveal, resource nationalism in Mexico and Venezuela largely prevented those countries from achieving this. As a result, both have suffered steady production declines. The US portion of the Gulf of Mexico, by contrast, has experienced wave after wave of new discoveries and development, expanding from the shallow "tidelands" out beyond the edge of the continental shelf into 10,000-foot water depths in the middle of the Gulf. The underlying key to this expansion was the application of digital technology to geophysical exploration.

This chapter shifts the focus in this volume away from the role of the state in shaping energy development and outcomes, to the role of business and technological innovation in discovering the largest reserves of conventional petroleum in the recent history of the Americas. Government actions and policies assisted the growth of the US Gulf of Mexico offshore industry through a transparent property rights regime, generous fiscal terms and access, minimal safety and environmental regulation, and import protection.¹ But the driving force in this story was the digital transformation of seismic technology, which increased the accuracy and lowered the costs of finding oil. Long before digitization altered everyday lives through personal computing and the Internet, it reshaped the geoscience of oil exploration. The digital revolution happened earlier in the oil industry than in other established industries, and earlier in geophysical exploration than in any other part of the oil industry.² What we now call “Big Data,” a term coined in the 1990s to describe the challenge of storing and processing massive amounts of digital information, was something that the oil industry first encountered in the 1960s in trying to harvest digital acoustic data from beneath the surface of the earth.³

Petroleum seismology was born on the US Gulf Coast, and subsequent digital advances were all developed in the waters of the US Gulf of Mexico. The commercialization of digital seismic technology could have emerged elsewhere in the world, but the particular geology and marine environment of the Gulf were uniquely conducive to it. The marginal costs of applying novel ideas and expensive new technologies were lower offshore than on land. The gradual slope of the shelf and relatively calm waters allowed for incremental approaches to solving problems. The deep-seated salt domes and sedimentary layers underlying the coast and continental shelf of the Gulf of Mexico hold vast amounts of petroleum, but they are geologically complex, with massive overlaying salt sheets, highly faulted and steeply dipping beds, and numerous but thin sandstones in which hydrocarbons are difficult to pinpoint. Oil extraction here depended on continuous advances in technology.

As the Gulf yielded riches in the form of hundreds of oil and gas fields of varying size and productivity in gradually deeper waters, exploration technology continued to be refined and improved at a steady pace. Companies operating there became accustomed to seeking technological

solutions to exploration challenges.⁴ The entrepreneurs who commercialized leading edge technologies, however, were usually not the oil operators themselves; early on, those operators moved away from developing their own seismic instruments and running their own seismic crews. Instead, they purchased these services from geophysical contractors who invested in research to gain their own competitive edge and who interfaced most closely with cutting-edge work coming out of the universities and professional organizations.

Geophysical contractors became a bellwether service industry, the first hired in booms and the first fired in busts. In helping to reduce financial risk for oil firms, geophysical contractors ended up assuming an inordinate amount of that risk themselves. While oil firms jealously nurtured in-house expertise to interpret, reprocess, and correlate ever-larger streams of seismic data, the acquisition and primary processing technologies developed by contractors spread throughout the global oil industry. After leading the charge into the deep waters of the Gulf, advanced digital seismic techniques found successful application elsewhere. In the Americas, this can be seen most spectacularly in the deep waters off Brazil and most recently off Guyana and on the Mexican side of the Gulf of Mexico, which has further extended the life of the Gulf-Caribbean as a major oil-producing region.

The Gulf Coast Origins of Petroleum Seismology

In the 1920s, oil explorers began applying new methods and instruments to search for oil-bearing structures deep in the ground. Most importantly, companies adopted seismology, the practice of measuring acoustic wave velocities through elastic layers in the earth's crust in order to better understand earthquakes. During the First World War, the German military had tested the technology for locating enemy artillery. Afterward, oil companies began deploying a unique new instrument, the refraction seismograph, in a similar way, but with the objective of determining subsurface features that might lead them to oil.⁵

Refraction worked particularly well in locating Gulf Coast salt domes. Salt is impermeable and thus good at trapping oil deposits. In a refraction survey, a charge of dynamite set off near the surface created a sound wave

that travelled through the earth and was picked up by a series of distant seismometers, or “geophones.” These waves travelled through soft formations, such as sand and shale, in underground arcs at a known velocity. A hard or more compact formation, such as a salt dome, would transmit the waves at a much faster rate, in effect refracting them like a prism. Refracted waves would arrive at the geophone relatively fast, often indicating the presence of salt, and possibly oil.

The most ambitious and successful effort to commercialize seismic exploration came from the Tulsa-based Geophysical Research Corporation (GRC), an Amerada Petroleum affiliate established in 1925 by one of the geophysical industry’s founding fathers, Everette DeGolyer.⁶ Expanding rapidly and spreading its crews far and wide, Amerada’s GRC established itself as the leading seismic contractor in the United States, especially on the Gulf Coast. In the late 1920s, GRC set two important historical precedents for the business of geophysical contracting. The first was the inauguration of marine operations across the swamps, lakes, and open bayous of southern Louisiana. The second was the commercialization of the reflection seismograph.

Reflection seismology offered more seductive possibilities than refraction.⁷ It measured the time it took for a wave to travel from the sound source at the surface to an underground layer and back again to the surface. An acoustic wave would be reflected or bounced back toward the surface, much like an echo, from any place where there was a change in the elastic properties of the medium through which the wave travelled. Using a series of recordings and knowledge of wave velocities through various formations, the reflection method made it possible to plot the contour and depth of reflecting layers.⁸

In the 1930s and ’40s, reflection seismic surveying transformed the business of petroleum exploration in nearly every oil region in the United States. In 1930, Everette DeGolyer and two associates responsible for the development of the reflection seismograph, John Karcher and Eugene McDermott, left Amerada and GRC to form a new venture, Geophysical Service Inc. (GSI). Still other GRC employees left to start new geophysical companies. During the 1930s, more than thirty US seismic contracting firms appeared, many of which could trace their lineage to GRC or GSI. In

1933, Henry Salvatori left GSI to form the Western Geophysical Company, which would become GSI's chief competitor.⁹

Reflection seismology's greatest economic impact was on the Texas-Louisiana Gulf Coast. Several technical refinements, especially sonograph recording, ultimately gave the reflection seismic method much broader range along the coastal plain and into the Gulf of Mexico.¹⁰ New capabilities for detailed geophysical prospecting accelerated the pace of wildcat leasing and land acquisition all along the Gulf Coast. Seismic surveying did not stop during the Second World War, but military and industrial mobilization diverted scientific minds away from investigating improvements in seismic technology to other priorities. After the war, companies made a big push both to expand surveying offshore in the Gulf of Mexico and to upgrade seismic capabilities.

In the late 1940s and early 1950s, the move from onshore leasing conducted by private and public landowners to offshore leasing by competitive auctions held by state and federal governments placed an even greater premium on geologic and geophysical capabilities, as incentives for speculative leasing were fewer, and costs higher, offshore. Oil firms and service companies had made rapid strides in learning how to drill and log wells. Still, drilling and producing hydrocarbons from deeper water offshore would entail steeply rising development costs, which mandated greater accuracy and economic efficiency in exploration.

Seismic surveying on the water nevertheless promised advantages over surveying on land. For one, companies did not have to contend with individual property holders or imposing topography, giving recording surveys potentially much greater speed and scope. In the early post-war years, operations in the Gulf of Mexico were conducted on modified shrimp boats or war surplus vessels. Establishing accurate shot and geophone positions and handling heavy, bulky geophones and cables designed for land operations, all from small vessels bobbing in offshore swells, proved difficult. By the early 1950s, radio-positioning systems such as "RAYDIST" (for *radio* and *distance*), based on advances made during the Second World War, had enabled accurate surveying, but it also added to the costs of deploying a small fleet of boats.¹¹

The economies of surveying improved greatly with the construction of larger, purpose-built ships that combined all shooting, recording, and

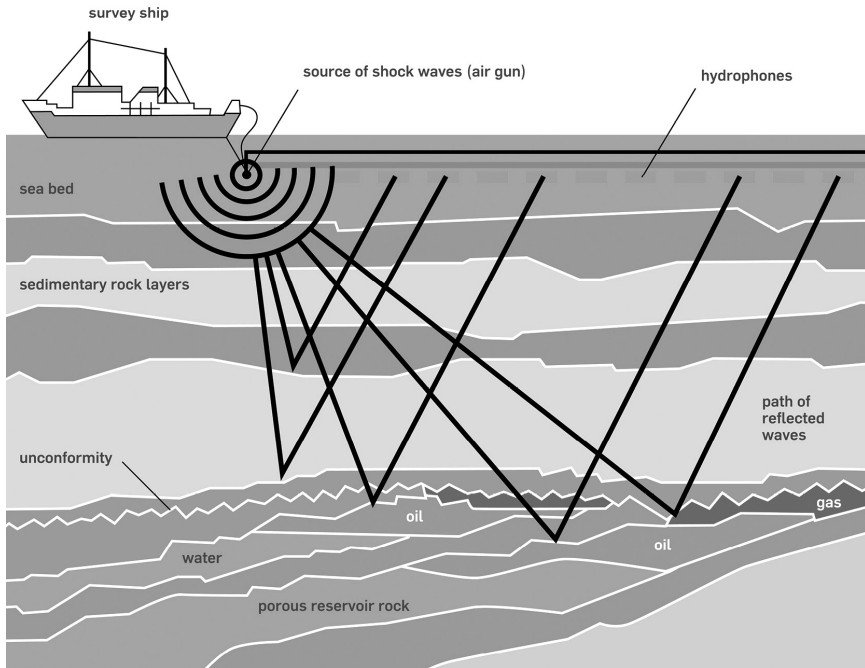


Figure 7.1 Offshore Reflection Seismic Survey Diagram

Source: Image courtesy of Kris Energy

surveying operations in a continuous operation. The breakthrough that made this possible was the oil-filled seismic “streamer,” a cable towed behind a boat with electrical wires and “hydrophones” that recorded and relayed seismic data to the vessel. With neutral buoyancy in water, the “Pavey” streamer, named after one of the men who patented it, could be adjusted to any depth. Because of its pressure-sensitive characteristics, the streamers were unaffected by cable motion and could be “yo-yoed” from a storage reel off the end of the boat. This meant that shots could be recorded one after the other from a moving boat, rather than having to stop the boat for each one.¹²

The next logical step was building bigger boats that could perform all the surveying functions continuously through rough waters. The

single-ship operation that became the industry standard by the late 1950s could record seismic profiles every one-half to two minutes continuously and cover up to 65 miles per day. This compared to 50 miles covered *per month* on dry land. The cost of a water crew in 1955 far exceeded that for a land crew (\$60,000–\$100,000/month versus \$15,000–\$25,000/month), but the higher rate of data acquisition by the new marine exploration techniques yielded a much lower cost per profile obtained, as little as one-third of the land cost by the 1960s. An offshore seismic survey simply offered much greater economies of scale in seismic data acquisition than onshore.¹³

Oil firms both ran their own seismic crews and contracted out for seismic services. The contractors' stock-in-trade was their instruments and the quality of their records. Nearly every company built and used its own instruments. Oil firms hired contractors by the month on "time-and-materials" contracts. Each seismic crew had a person designated as "the computer," someone who managed the seismic sections recorded on photographic paper, which were metre-long strips covered in reflection squiggles. The computer washed and hung the strips to dry, converted time data to depth, made all sorts of corrections for various factors, and then plotted this information profile on a two-dimensional, subsurface cross-section. The cross-section would be handed over to the seismologists, who would draw the geologic inferences on a contour map. All this was extremely tedious and time-consuming, not to mention vulnerable to human error. The successful contractors were those who could provide quality data at the lowest cost per month. But the time-based contract meant there was no incentive to exploit fully the increased productivity (i.e., reduced cost per mile or per profile) made possible by the single-ship operation. Company crews operated on a similar basis.¹⁴

From 1952 to 1958, geophysical contractors found themselves caught between rising costs and declining revenues.¹⁵ They responded in four possible ways: (1) they went out of business or sold to a competitor; (2) they continued cutting costs to the point of sacrificing quality, which often resulted in the first option; (3) they tried to change the contracting model; or (4) they looked to new technological advances to give them a leg up on competitors. Of the two strongest companies that emerged from this

period, Western Geophysical pursued both the third and fourth options, and GSI embraced the fourth in the most ambitious way.

In the mid-1950s, Western Geophysical introduced new ways of contracting that shifted incentives toward productivity and spurred the firm's fantastic growth during the next two decades. Founded in Los Angeles in 1933 by GRC/GSI veteran Henry Salvatori, Western started running marine crews in 1938.¹⁶ In 1956, under the visionary leadership of Vice-President Booth Strange, Western began bidding marine jobs on a "turn-key" basis—on a per-mile cost rather than a per-month cost. This freed Western's crews from client restrictions such as "no overtime." The ships and instruments were still the largest expense, so paying overtime or double-time wages did not appreciably add to overall costs, especially per mile. Oil companies accepted the new arrangement because they received a more concrete estimate for the data acquired and delivered. Meanwhile, Western's productivity and profits soared. The company then invested profits in better equipment and added more personnel, further increasing productivity and lowering the cost per mile.¹⁷

Not long after the introduction of the new bidding model, Strange persuaded Western's board to approve gathering data without a contract—that is, on a speculative, or "spec," basis. This was in response to growing pressure by some oil companies to do "group shoots," which dramatically reduced contractors' profits.¹⁸ In 1956, at the end of the contract to shoot proprietary data for Union Producing in the Gulf of Mexico, Western made a deal to keep gathering data on a non-exclusive, non-proprietary basis over acreage Union was interested in nominating at the next federal offshore lease sale. Union would pay a fraction of the cost, and Western would be able to resell the data to other interested companies.¹⁹ The price per increment of data to each company would be substantially less than if the job were done on a proprietary basis. Companies started buying, and Western expanded its spec data shooting, selling data for some areas twenty to thirty times.²⁰

Western took more commercial risks than competitors such as GSI and made a reputation as the leader in spec data. In addition to being able to resell the data, spec shooting had other benefits. It kept seismic crews working continually, thus cushioning operations against cyclical swings in demand for data from oil companies.²¹ Spec shooting also drove

Western to invest more in research and development, because spec data competed not only in price, but also in quality. In 1960, when Salvatori sold the company to Litton Industries, Western gained access to deeper pockets for making these kinds of investments. Booth Strange took over as president, and in 1965 he relocated the company from Los Angeles to Houston, where Western could be closer to the centre of the oil business and focus its operations and research in the booming Gulf of Mexico.²²

The mid- to late 1950s proved to be the most fertile period of invention perhaps in the entire history of seismic imaging. Inventions came from varied sources, but they combined to lay the ground for the revolutionary move from analogue to digital technology. First, the introduction of continuous velocity well logs (sonic logs)—in which the velocity of sound measurements within a well bore was matched to rock density—allowed for greater precision in locating the origin of seismic reflections. Even more important, starting in 1955, was the replacement of paper records by magnetic tape in seismic recording. Magnetic tape could record signals in analogue over a wide range of frequencies and play them back using different “filters” to adjust for time delays caused by surface effects and path geometry.²³

Cross-sections prepared from analogue magnetic-tape playback changed the way seismic data were processed as well as collected. Most importantly, magnetic-tape playback provided a means for economically applying the “common-depth-point” (CDP) or “horizontal stacking” method of acquisition and processing. Patented and developed by Harry Mayne of Petty Geophysical, CDP stacking involved taking tapes of individually corrected seismic traces from different sound source and recording stations, each equally offset from the same reflection point or mid-point, and then combining or “compositing” these traces. Stacking enhanced the desired or “primary” reflections and filtered out unwanted “multiple” reflections or “noise.” The CDP method dramatically improved the accuracy of seismic surveying and the delivery of quality data.²⁴ After presenting and marketing the CDP technique at the 1960 international meeting of the Society for Exploration Geophysicists (SEG), Mayne and Petty licensed it to the most technologically advanced oil firms in the industry. Still the main signal-to-noise enhancing technique today, CDP stacking was a watershed that divided previous seismic exploration from

all subsequent innovations and paved the way for the conversion to digital technology.²⁵

Magnetic recording and CDP shooting led to additional refinements and improvements in seismic acquisition, which, again, found their most productive use offshore in the Gulf of Mexico. Magnetic recording made it possible to employ other sound sources to replace the thousands of tons of dynamite exploded every year in the Gulf. Dynamite was costly, time-consuming, and dangerous to deploy; it also killed or disturbed aquatic life, leading to conflicts with shrimpers, fishermen, and oystermen.²⁶ Beginning in the late 1950s, many companies experimented with new types of sound sources, such as mechanical/hydraulic vibrating mechanisms and gas exploder devices. By the mid-1960s, air guns, pioneered by a young engineer at Lamont Geological Observatory, Stephen Chelminski, proved to be safest, simplest, and most reliable. They eventually became the source of choice.²⁷

The Digital Revolution

Magnetic recording, with its capacity for storing seismic information in reproducible form, generated interest in what one geoscientist referred to in the 1950s as “mechanized automatic means of data processing,” or simply “computing.” Conventional methods of seismic data processing involved tedious human computational labour. In the mid- to late 1950s, analogue seismic-data-processing computers made their appearance, which relieved the human computer of some of the busy work in processing and plotting cross-sections. Efforts to digitize analogue magnetic recordings soon followed, largely to assist in filtering unwanted noise. The logical extension of this technology was the direct digital recording and processing of seismic data.²⁸

The shift from analogue to digital, however, was not immediate or seamless. The transition required companies and contractors to replace outmoded equipment with expensive new computers and adopt entirely new ways of doing things, which oil companies often resisted.²⁹ But thanks to research breakthroughs and savvy methods of marketing digital technology by GSI, the digital revolution finally transformed the industry during the early 1960s, expanding oil companies’ understanding of

the subsurface and increasing their accuracy in finding oil and gas. This lowered the considerable risks of exploration in the Gulf of Mexico, where digital seismic technology was commercially introduced.

Investigations into digital seismic surveying began with the Geophysical Analysis Group (GAG), organized in 1952 at the Massachusetts Institute of Technology (MIT). In 1951, a twenty-year-old graduate student in mathematics at MIT, Enders Robinson, applied a time-series analysis to the task of enhancing the quality of seismograph records, something never tried before, and came up with a method of “deconvolution,” which was a way of filtering desired seismic signals from other noise signals that corrupted them. The basic problem was that acoustical wavelets were reflected with varying amplitudes from hundreds of subsurface reflecting horizons. Hence, a single seismic trace recorded at the surface consisted of a continuous series of overlapping reflections that were difficult to distinguish from one another. This was an especially troublesome problem in offshore seismic prospecting. Seismic signals tended to reverberate in the water layer between the seabed and water surface, producing a “ringing” noise so strong it often masked the desired reflections from the subsurface. Robinson’s study proved that numerical filtering could separate data and noise just like electronic filtering, but in a much more precise and high-powered fashion. What deconvolution did, in essence, was provide better resolution for imaging seismic signals.

Based on this revolutionary discovery, the Office of the President at MIT sponsored GAG, and the following year a consortium of twenty oil and geophysical companies took over funding the group. Between 1952 and 1957, the GAG group attracted some of MIT’s brightest graduate students, most of whom subsequently specialized in geophysics. At first, the group mainly used analogue recordings to perform deconvolution. However, having access one hour per week to MIT’s first digital computer with stored program architecture, the “Whirlwind,” and, later, Raytheon’s British Ferranti Mark 1 computer, they found that all analogue methods could be done by digital seismic processing and with much greater accuracy.³⁰

The conversion to digital was years away, not least because oil companies were still skeptical about the technology’s commercial applications, even after publication of Enders Robinson’s path-breaking thesis,

“Predictive Decomposition of Time Series with Application to Seismic Exploration,” reproduced as *GAG Report No. 7* in July 1954.³¹ In spite of the oil industry’s reticence, GSI forged ahead to commercialize digital seismic technology. During the Second World War, GSI had diversified into electronics, becoming a major contractor to the US military as a maker of submarine detection devices, airborne magnetometers, and radar. This led to the creation in 1951 of a new company called Texas Instruments (TI), with GSI reorganized as TI’s geophysical subsidiary.³² That same year, GSI’s president, Cecil Green, a towering figure in the geophysics profession who had an eye for spotting talent, worked with Robert R. Shrock of MIT to organize a summer “co-operative program” designed to give selected college students an orientation in applied geophysics working with crews in the field.³³ The combination of GSI’s pipeline to MIT and TI’s aggressive approach to electronics innovation propelled GSI into the digital vanguard.

Dr. Kenneth Burg, GSI’s technical vice-president, grasped the potential of the emerging computer revolution and initiated research into digital seismic processing at TI’s Central Research Laboratory in Dallas.³⁴ To support this effort, Burg hired a large crop of geophysics PhDs from MIT, including former members of GAG. Headed by Mark Smith, GSI launched a special research effort in 1954 to adapt the newly recognized statistical communication theory developed by Robinson to reflection seismology. Milo Backus, one of the MIT PhDs, devised a unique deconvolution solution to the water reverberation problem using something called a “multiple analyzer and eliminator,” a crude sort of “digital filter implemented in analog form,” as Backus described it, to reduce multiple reflections.³⁵ According to Mark Smith, “this approach was very successful and helped to give GSI a competitive edge in many important offshore areas.”³⁶

Between 1956 and 1958, GSI’s digital seismic investigations broke important new ground. After testing digital processing methods on a hybrid analogue-digital computer called the *seisMAC*, TI’s research department—renamed the Data Systems and Earth Sciences Department—designed and built an analogue-to-digital converter and TI’s first digital computer. Programmed for seismic processing, the data analysis and reduction computer used two thousand vacuum tubes and measured six by three by twenty-four feet. As Mark Smith noted, “it began to look to GSI as though the equipment end of the geophysical business was starting to

wag the dog, and that the misconception was developing that a major step in hardware alone would substantially change the effectiveness of seismic exploration.”³⁷

Smith, in turn, instituted a comprehensive R&D program that addressed all aspects of the reflection seismic problem. He focused on locating stratigraphic traps, which were a key objective in the sedimentary basin of the Gulf of Mexico. Stratigraphic traps are features that accumulate oil due to changes in rock character rather than because of structural aspects such as faulting or folding of the rock. Up to that point, reflection seismology was only useful for finding structural traps. GSI-TI’s “Stratigraphic Trap Program” aimed to introduce digital recording in the field (instead of recording in analogue and converting to digital) and integrate it with continually improving digital processing software and techniques, so that the recorded seismogram would provide a closer approximation of the particular geology and stratigraphy.³⁸

Dovetailing with this effort was the rapid development of another breakthrough technology in the 1950s, the semiconducting transistor, which replaced vacuum tubes, first as a sound amplifier in many kinds of electronic devices, and then as electronic switches in digital computers. Both applications had a pivotal impact on seismic surveying. Transistors fabricated from germanium and eventually silicon were smaller, lighter, and increasingly more powerful than vacuum tubes. Developed and licensed by Bell Laboratories, early transistors were relatively costly and thus found commercial application initially in small, portable, and lower-power-consuming devices, such as hearing aids, radios, and, by 1958, seismic receivers. Transistorized geophysical equipment significantly lightened the load for field crews.³⁹

By the late 1950s, thinner, faster, and more reliable transistors enhanced digital computing. In 1954, TI introduced the first commercial silicon transistor and in 1957 became a major supplier of transistors for IBM computers. Then, in 1958, TI pioneered a major advance with the integrated circuit made of a single semiconductor material.⁴⁰ By 1960, most new computer designs were fully transistorized with integrated circuits. At TI’s seismic branch in Houston, J. Fred Bucy, who would later become president of TI, led the development of the first digital field recording

system, the DFS-9000, which was integrated with an all-transistorized computer called the TIAC (Texas Instruments Automatic Computer).⁴¹

In launching this “total seismic system,” as GSI called it, the company faced an uphill climb, first to produce it within TI, and then, as with other seismic innovations, to market it to a dubious oil industry. Even though digital recording promised to eliminate the time and costs of converting analogue data, the front-end costs of the system were much higher, and oil companies and contractors alike preferred tried and true methods of recording in analogue. A digital recording set cost more than \$100,000; converting to digital meant completely replacing equipment.⁴²

To market the new system and obtain the initial financial support to manufacture the equipment and develop field experience, GSI agreed to give two of the oil companies most interested in the technology, Mobil and Texaco, a two-year contract (1961–3) for exclusive use of GSI digital crews and equipment. If the technology proved itself, Mobil and Texaco would have a jump on competitors. However, seismic software and signal processing were not part of the exclusive agreement, which allowed GSI to make marketing presentations in all the petroleum centres around the United States showing the latest processing developments, thus “whetting the industry’s appetite” for the full digital service.⁴³

And whet it, it did. After the exclusive period, during which GSI made dramatic improvements to all aspects of the integrated system, company after company signed up for digital crews. GSI had convincingly demonstrated that the greater dynamic range and processing flexibility of digital recording and processing allowed for a much fuller exploitation of CDP shooting and the tremendous seismic signal-to-noise enhancements it provided. In 1964, GSI experienced a 58 per cent growth in revenue, driven largely by the new digital business.⁴⁴

Although some of GSI’s digital crews worked on land (mainly for Texaco), the “real bread and butter was in digital marine work,” especially in the Gulf of Mexico.⁴⁵ GSI’s marine business grew fairly quickly to twenty-six crews operating with a fleet of more than fifty seismic vessels.⁴⁶ In 1964, GSI opened its first regional TIAC data centre in New Orleans to handle growing business in the Gulf of Mexico.

There were several reasons for the intensive application of digital seismology offshore. First, offshore exploration was already growing at the

expense of land work in many areas of the world, and the Gulf of Mexico was a proven oil region with a lot of unexplored territory. The aforementioned economies of scale offshore meant that the increase in marginal cost of digital equipment over analogue was smaller than on land. The higher volume of data acquired offshore was ideal for digital data processing. Most importantly, the digital system brought offshore geology into clear focus in ways that it did not on land. The amazing resolution of high-powered deconvolution allowed geophysicists, for the first time, to pinpoint Gulf region salt domes and stratigraphic traps, the main objective of the digital research program at GSI. “They just came out and hit you in the eyeball,” marveled Milo Backus. “The whole structural picture was quite different from what they had seen out there before. That was a major thing in the Gulf of Mexico.”⁴⁷

In the mid-1960s, as digital seismic surveying gained industry acceptance, and as a new generation of digital computers emerged, geophysicists acquired ever-improving tools to visualize offshore geology. Existing contractors, such as Western, and new competitors, such as Digicon and Seiscom Delta, quickly developed and marketed their own digital systems and versions of deconvolution.⁴⁸ In 1964, IBM introduced its 360 series computer, and the more serious exploration-minded oil companies began installing huge banks of them in newly established data centres. Geoscientists started transferring large volumes of data from bookshelves and filing cabinets into computers, and computer programmers generated new processing algorithms (Milo Backus at GSI was the mastermind behind many of the first ones). As computing costs dropped exponentially during the next several years, oil firms were able to process vast amounts of seismic data at ever-increasing speeds, greatly enhancing their capabilities in geophysical and geological interpretation.

In the late 1960s, these evolving capabilities led to a critical advance in exploration in the Gulf of Mexico. Binary-gain digital recording systems were enabling geophysicists to measure and quantify the “relative wave amplitudes” between seismic traces for the first time.⁴⁹ This measurement was sometimes referred to as “true amplitude recovery.” Up to that point, seismic techniques only helped delineate structures, stratigraphy, and traps; operators still had to risk sinking a well to determine if oil and gas existed in those features. But the new digital seismic data revealed

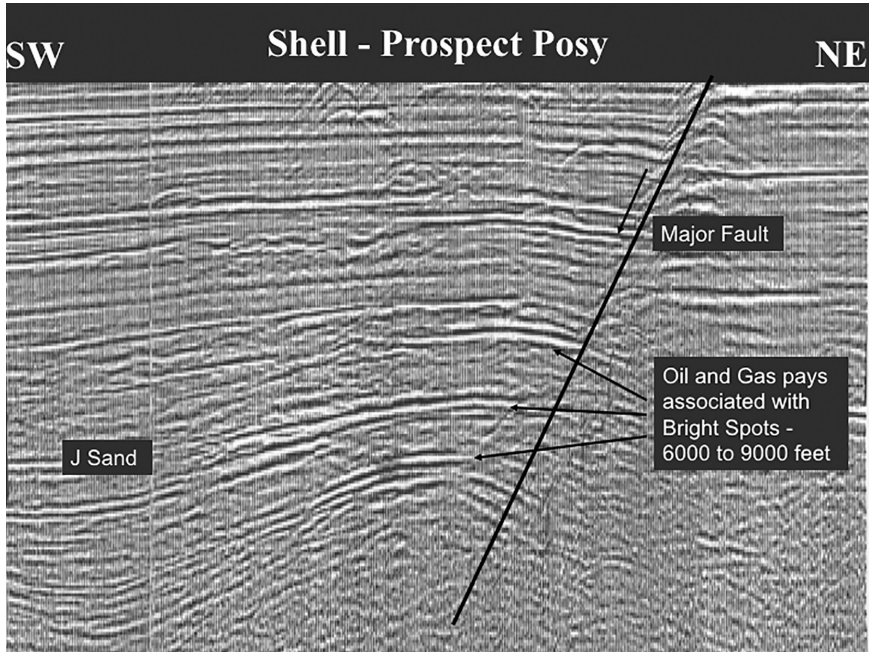


Figure 7.2 Shell Oil Bright Spot Seismic, Posey Prospect, Eugene Island 330 Field

Source: Image courtesy of Mike Forrest

striking “amplitude anomalies” that suggested the tantalizing prospect of “directly detecting” hydrocarbons that might be associated with them. Shell Oil and Mobil Oil were the first companies to identify and quantify such anomalies and factor them into their bids for offshore leases. Mobil referred to them as “hydrocarbon indicators.” Shell called them “bright spots,” because they seemed to light up on the seismic record.⁵⁰ “Direct hydrocarbon indicators” (DHI) has since become the industry’s standard technical term.

Once the bright spot interpretation, or DHI, method was refined and disseminated in the early 1970s, it had a giant impact on the business of exploration in the Gulf. Being able literally to “see” hydrocarbons on the seismic section before ever drilling a well eliminated the questions of whether hydrocarbons existed in a certain location or what the drilling

targets were. The remaining questions were whether the target was big enough or if the hydrocarbons would come out the ground fast enough. Reducing the “dry hole factor” changed the way companies allocated risk and capital in their general strategic approach to offshore oil. If a bright spot scan reduced the odds of drilling a dry hole on a prospect from three out of five to two out of five, managers could afford to bid more for attractive leases or use the money saved by avoiding dry holes to invest in drilling and production technologies for deeper water. The advances in seismic amplitude analysis were one of the most important products of the digital revolution for the exploration business, moving the industry into 1,000-plus-foot water depths in the 1980s and ’90s.

One caveat about bright spots—the technique worked only for certain kinds of geology. The clastic sedimentary rocks found in deltaic regions like the Gulf Coast—and, as oil explorers would later learn, along the Atlantic Ocean margins of Brazil and West Africa—were well-suited to this kind of interpretation. Hard-rock areas elsewhere were not. Bright spot interpretation and the digital seismic revolution helped oil companies overcome the water depth and cost limits that had stalled offshore development in the Gulf. In the late 1970s, the Brazilian state-owned oil firm, Petrobras, which Gail Triner writes about in this volume, also used bright spot amplitude analysis to help identify prospects in the offshore Campos Basin that ultimately contained more than twelve billion barrels of oil. By 1995, Petrobras was producing a million barrels a day from the Campos Basin, establishing Brazil, for the first time, as a major oil-producing nation.⁵¹

Three Dimensions

The move from two-dimensional (2D) to three-dimensional (3D) seismic technology was decisive confirmation of the revolutionary potential of digital technology in the oil business. The concept of 3D seismology had existed since the earliest days of geophysics. Geoscientists have always sought to visualize the subsurface in three dimensions, not two. All seismic surveys, when they produce a subsurface contour map, are conceived of in three dimensions. By the early 1970s, the arsenal of digital

data recording and processing techniques had taken exploration to an unprecedented level of sophistication, but imaging was still 2D.

Exxon claims to have shot the first 3D seismic survey over the Friendswood field south of Houston in 1967. Esso Production Research presented the results at an SEG meeting in 1970.⁵² It was a presentation that displayed a model based on data gathered from well logs and 2D seismic surveys, and it used a special fibre optic viewer to simulate depth in three dimensions. Although Exxon later received the Distinguished Achievement Award from the SEG for “inventing” and developing 3D methods, this was not actually 3D technology as it came to be properly understood and practised. As GSI’s Robert Graebner put it, “3D involves gathering data in a spatial sense so that you can put together that data from wherever it reflected with another piece that came from that same spot.”⁵³ This means doing 3D “migration.” Migration is the geometric repositioning of the return signal to show the exact subsurface location where the seismic wave reflects, as opposed to where it is picked up by the geophone. To position events accurately in three dimensions was a massive computational challenge. It required building a mathematical and physical model governed by the so-called wave equation, which is a hyperbolic partial differential equation that describes the propagation of waves.⁵⁴ This is not what Exxon (Esso at the time) was doing in the Friendswood field in 1967.

The density of spatial seismic coverage required to produce a 3D image magnified the computational challenge of migration. A detailed 2D seismic survey might collect data in a grid spaced at one-kilometre intervals, whereas a 3D survey would require a much tighter grid, by at least an order of magnitude, to get any kind of accurate detail. By the early 1970s, computing power and digital seismic acquisition and processing techniques had developed to a point where this was finally possible. But, as with every major step forward with geophysical technology, the constraint on commercializing this concept was cost. And again, it was GSI that pioneered the technology and successfully marketed it to industry.

In early 1972, an important brainstorming session took place at GSI headquarters in Dallas. The principals were research scientist William Schneider, Milo Backus, then director of research, and Robert Graebner and M. E. “Shorty” Trostle, both executives. To fund an experimental survey to test the idea, the GSI executives enlisted the support of six large

oil companies—Chevron, Amoco, Texaco, Mobil, Phillips, and Atlantic Richfield. They selected the Bell Lake field in southeastern New Mexico and West Texas, which was “a structural play with nine producers and several dry holes.” Bell Lake had sufficient well data so that 3D data could be correlated with subsurface geology.⁵⁵ The results of the 3D survey were stunning. They not only confirmed the field’s nine producers and three dry holes but also indicated several new drilling prospects in this mature area. As the *Midland Reporter-Telegram* later reported:

When the petroleum history books are written, Milo Backus, M. E. “Shorty” Trostle, and Bob Graebner (of GSI) [Schneider should also have been mentioned] may stand in significance alongside Howard Hughes and his rotary bit, the Schlumberger brothers and their logging machine, and Earl Halliburton and his idea for pumping cement behind the casing of oil wells. Because when the final tally is made, the impact of 3D on the oil industry will be in the billions.⁵⁶

It took considerable time for the tally to mount. Many oil companies could not justify the cost of the 3D survey. Even a modest sampling of the data acquired in a 3D survey generated a huge number of paper sections to examine and interpret. Computers were limited in power to handle more advanced and accurate algorithms. The commercial viability of 3D seismology for *exploration*—that is, looking for new, wildcat fields—was still in the future. The expense of a 3D survey was prohibitive in an area with a relatively high probability of drilling a dry hole. GSI’s Bob Graebner, however, made an increasingly convincing case that the bottom-line results of a 3D survey could be worth the cost for *developing* producing fields and *defining* already discovered reservoirs.⁵⁷

Again, as with the introduction of digital recording and processing, the most value could be added offshore, where the marginal cost of doing a 3D survey was smaller than on land. The Gulf of Mexico, the most mature offshore producing region in the world, was where oil companies and contractors cut their teeth on 3D and devised ways to bring down costs. Better instruments, wider arrays of hydrophone streamers, larger vessels, faster navigation, and on-board processing all reduced costs and improved



Figure 7.3 GSI's 3D Seismic Pioneers

Bill Schneider, Milo Backus, Bob Graebner, and Jack Pizant, co-authors of the 1966 SEG Award-winning paper "A New Marine Processing System."

Source: Photo courtesy of Degolyer Library, Southern Methodist University.

data acquisition. Most importantly, advances in computing power spurred the market for 3D surveys. The emergence of interactive computer workstations permitted geophysicists to see results in computer screen images with three dimensions and reduced the time to interpret a 3D survey from months to weeks.

Before workstations, images produced from a 3D survey were basically "a sandwich of 2D cross sections linked by horizontal slices."⁵⁸ Workstations finally rendered seismic images in 3D shapes that corresponded to the subsurface features, and with increasing speed. By the early 1980s, all the major seismic contractors and several major oil companies had developed their own systems. New companies formed to focus entirely on the seismic workstations business, led by Landmark Graphics, GeoQuest, and others associated with Schlumberger and Halliburton.⁵⁹ Eventually, these contractors developed special rooms called "visualization centres" that displayed seismic images in three dimensions. Using stereoscopic glasses, viewers could immerse themselves in 3D seismic images constructed from projections on the walls, ceiling, and floor, and actually walk through a moving perspective of the subsurface.⁶⁰

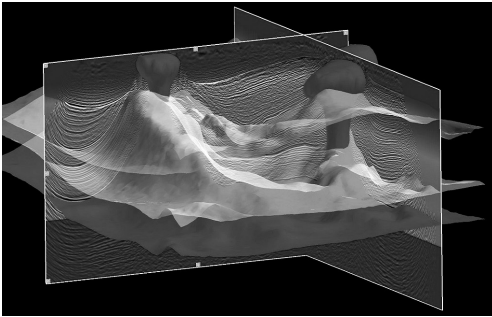


Figure 7.4 3D Seismic Image with Salt Domes in Deep Blue

Source: Photo courtesy of Paradigm.

In the 1990s, the market for 3D surveys exploded, first in the Gulf of Mexico and then in other marine areas such as the North Sea. In 1989, only 5 per cent of the wells drilled in the Gulf relied on 3D; in 1996, nearly 80 per cent did. Companies acquired the majority of that data between 1990 and 1993.⁶¹ Data acquisition was made easier beginning in the early 1990s by the deployment of the US Navy's global positioning system (GPS) in place of conventional radio positioning systems. By the late 1990s, oil firms increasingly used 3D data not only for field development, but for exploration as well. As majors such as Shell began to divest from older producing properties in the shallow waters of the Gulf's continental shelf in favour of new "deepwater" prospects (in water greater than 1,500 feet), smaller firms purchased the older properties and redeveloped them with significant reserve additions using 3D data. Graebner conservatively estimates that 3D *quadrupled* the oil and gas reserves in the Gulf of Mexico.⁶²

As the majors moved into deepwater, where a single well could cost \$50 million or more, it made perfect sense to have 3D coverage before drilling. However expensive a 3D survey was, that was little more than a rounding error when applied to the overall cost of exploring and producing in deepwater. More significantly, 3D gave oil firms nearly pinpoint accuracy in discovering oil and gas. Wildcatting success rates without 3D were typically no higher than 30 or 40 per cent (three or four out of every ten wells struck pay). By most accounts, 3D boosted wildcat drilling success to 60 or 70 per cent. The savings from drilling three or four fewer \$50 million dry holes out of every ten added up very quickly. Investment bank Salomon Smith Barney estimated that 3D technology accounted for 46 per cent of falling exploration and production costs between 1995 and 1997, far more than any other oil field technology.⁶³

Ongoing Innovations

Ironically, just as the forty-year effort to exploit the digital potential of seismic exploration was bearing fruit in what *Business Week* called “a Golden Age of technology,” the geophysical contractor business took a dive.⁶⁴ The demand for seismic crews had been relatively weak since the oil bust in the mid-1980s. The sharp oil price drop and wave of oil company mergers beginning in 1998 further slashed demand. Compounding the problem, contractors found themselves swimming in an excess supply of data—what one analyst described as “data indigestion.” The diffusion and commodification of 3D seismic technology generated intense competition. Speculative shooting, pioneered by Western Geophysical, and so-called multi-client surveys, had become the dominant mode of acquiring and selling data, and both became less profitable.

In a multi-client deal, a group of oil customers would fund a seismic shoot in advance, but the real profits were earned over time from reselling the data (after usually a six-month exclusive period). This kind of deal emerged in the Gulf of Mexico during the leasing boom that started in 1995. However, if the data turned out to be of little value, or if demand fell due to slashed exploration budgets, then the seismic contractors operating with less than 100 per cent funding were on the hook. To win business, contractors would agree to lower their “pre-funding” requirements to 35 or 40 per cent, taking on greater risk and essentially subsidizing seismic exploration for the oil companies.⁶⁵

The result was a massive contraction and consolidation in the geophysical contractor business that lasted for a good part of the 1990s. Forty years of innovation could not protect GSI, which was sold to Halliburton in 1988. Six years later, Halliburton sold the remnants of its GSI assets to Western Geophysical, which itself underwent a series of reorganizations and mergers before resurfacing in 2000 as Western Geco, a business unit of Schlumberger. Over the long run, the oil companies, many of whom were initially skeptical about leading-edge innovations in seismic technology, enjoyed most of the benefits from the subsurface vision digitally engineered by firms such as GSI and Western.

While geophysical contractors were the first to be fired in the downturn, they were also the first to be hired in an upturn. During the oil boom

that lasted from 2002 to 2014, the marine seismic business recovered and thrived once again. This expansion pushed exploration into new geological frontiers, most spectacularly beneath massive layers of salt in deep-water. The subsalt play began first in the Gulf of Mexico in the late 1990s, and then spread elsewhere, especially offshore of Brazil, spurring successive rounds of innovation in digital seismic acquisition, processing, and interpretation.

Although developed in the 1970s, 3D technology was still in its infancy by the late 1990s, and it matured in many directions. More complex 3D migration algorithms, such as 3D “prestack” time and depth migration and “reverse-time migration,” provided ever-greater precision necessary for imaging through wave-distorting bodies of salt. To overcome the data constraints that still inhibited subsalt exploration, contractors introduced “multi-azimuth” (MAZ), “wide-azimuth” (WAZ), and “full-azimuth” (FAZ) seismic surveys, acquiring data from several vessels at a time that recorded data in multiple azimuths (the angle of linear horizontal direction), rather than merely along one narrow azimuth from one vessel. Steadily increasing computing power allowed geophysicists to extract more and different kinds of information from richer sets of data obtained through MAZ, WAZ, and FAZ seismic surveys.⁶⁶

These capabilities combined to propel further advances in data acquisition and processing. Along with the development of high-sensitivity ocean-bottom hydrophones, or “nodes,” these advances helped to improve on a kind of seismic amplitude analysis called “amplitude vs. offset,” or AVO, which is a way of measuring the variation of seismic reflection amplitudes with a change in distance between the shotpoint and receiver. The advances enabled geophysicists to estimate the velocity of not only “p-waves,” but also “s-waves,” known variously as secondary, shear, or transverse waves. P-waves travel longitudinally by compression in the same direction as sound; they have the highest velocity and move through both solid rock and fluid. S-waves travel perpendicularly to the direction of sound; they are slower and can only move through solid rock, thus requiring ocean-bottom receivers to be recorded. S-waves can detect important reservoir properties or subtle changes in lithology that p-waves cannot. Improvements in AVO analysis had a major impact on modelling reservoirs found with DHI or bright spots in young, poorly consolidated

rocks, such as those in the Gulf of Mexico. In relatively a short time, s-waves enabled oil and gas firms to find hundreds of millions of barrels of oil and tens of billions of cubic feet of gas that could not have been found with p-waves alone.⁶⁷

On top of advanced AVO modelling, technology moved along many different fronts. These include broadband data recording, simultaneous sound sources, wireless systems, higher channel counts, fibre optic streamers, and robotic ocean-bottom nodes. As computing power began to catch up with advances in seismic acquisition, the industry progressed toward “full wave-form inversion” (FWI), in which primary and shear waves, reflections and refractions, all contribute to the creation of a more fine-grained subsurface image from much better estimates of seismic velocity. FWI could obtain quantitative information from seismic data about rock properties, such as porosity, lithology, and fluid saturation, on a detailed scale.⁶⁸ Oil explorers closed in on acquiring the power to visualize, literally, the intricacies of subsurface geology before ever drilling a well.

Once again, the Gulf of Mexico was the proving ground for this latest trend in seismic innovation. Explorers used their expanded capabilities to uncover a whole new oil frontier in the subsalt strata, foldbelts, and Lower Tertiary formations of the “ultra-deepwater” (7,000- to 12,000-foot depths) Gulf of Mexico. By 2015, the US Department of the Interior counted 171 deepwater and ultra-deepwater fields discovered in the Gulf since the 1980s, containing an original 13 billion barrels of oil equivalent, with billions more classified as “contingent,” awaiting a development commitment from operators.⁶⁹

Beginning in the late 1990s, advanced digital seismic techniques animated other deepwater basins, enabling geophysicists to collect accurate images through the salt and decipher frontier geology. Many major discoveries followed, which helped allay fears about the adequacy of oil supplies for years to come. By 2006, the industry had discovered 60 billion barrels of oil in deepwater worldwide, production from which is still coming on line.⁷⁰ From 2007 to 2012, half of the 170 billion barrels of global conventional oil and gas discovered by the industry was in deepwater.⁷¹

West Africa accounted for a lot of this action, but seismic innovations have also reshaped oil prospects in the Americas. Most spectacularly, as Triner in this volume recounts, Brazil’s Petrobras announced in

late 2007 that it had discovered 7.5 billion barrels of oil in the “pre-salt” sediments of the Santos offshore basin. The company has since estimated pre-salt reserves across three basins to be 13 billion barrels. In May 2015, ExxonMobil used bright spot amplitudes to make a significant discovery in the Stabroek Block offshore Guyana (population: 770,000).⁷² The company followed that up with a string of additional discoveries in even deeper water, based on advanced 3D imaging, that totalled more than 8 billion barrels of oil equivalent by 2020. Geophysical surveying and drilling have also indicated “huge hydrocarbon potential” in the offshore basins of Brazil’s equatorial margin.⁷³ Finally, the expansion of leasing and drilling ever closer to the US-Mexico maritime boundary has played no small part in compelling Mexico in 2013 to end the seventy-five-year-old oil monopoly that barred foreign participation in the nation’s oil sector (see Hall in this volume). In January 2018, Mexico sold exploration rights to nineteen deepwater blocks for \$500 million. The ongoing digital revolution in seismic technology has illuminated new pockets of hydrocarbon resources across the Americas.

Conclusion

Beginning in the 1950s, technological advances in petroleum seismology transformed oil exploration into a high-tech business and turned the Gulf of Mexico into one of the most active oil-hunting areas in the world. The development of marine geophysical operations and a new model of contracting in the 1950s opened up new offshore vistas. The early introduction of magnetic tape recording and common-depth-point shooting in the late 1950s, closely followed by digital processing and recording in the early 1960s, led to continual improvements in seismic processing and interpretation, from the deconvolution of signals caused by reverberations in water in the late 1950s, to the direct detection of hydrocarbons in the late 1960s, to three-dimensional seismology in the late 1970s, to the emergence of full wave-form inversion in the twenty-first century.

The fifty-year project of digital innovation has had its greatest impact on the water, where the marginal costs of applying novel ideas and expensive new technologies were lower offshore than on land. The proving ground for digital seismic technology was the US Gulf of Mexico. But

geophysical techniques pioneered in the Gulf have also helped to open other deepwater basins around the world to petroleum extraction. In the Americas, from the Santos Basin off Brazil to the Mexican side of the Gulf, digital seismic innovations have led explorers to find billions upon billions of barrels of petroleum, much of which has yet to be coaxed from the ocean. This newly discovered offshore petroleum abundance, combined with the spectacular growth of oil and gas production from shale basins in the United States through hydraulic fracturing, which also benefitted from advanced digital seismic technologies, silenced alarms about an impending “peak” in global oil supply that had been so common in the early 2000s.⁷⁴

Ironically, just as the progress in seismic innovations reduced a great deal of the uncertainty in finding oil, other uncertainties arose to cloud the future of offshore exploration. The unreliability of future demand in a world desperately trying to shift away from fossil fuels to mitigate runaway global warming is obviously a big problem. Related to this is the ongoing price volatility of oil in a world without a mechanism to balance supply and demand. This volatility wreaks havoc on the investment decisions companies make in developing resources in high-cost environments like deepwater.⁷⁵ The first industry affected in a price downturn, like the one that lasted from 2014 to 2018, remained geophysical contractors. Among other casualties in this shakeout, the long-established French company CCG filed for bankruptcy, and Schlumberger sold off the seismic acquisition business of WesternGeco, whose ancestors, GSI and Western Geophysical, pioneered the digital revolution.⁷⁶ The supply and demand for digital data has turned out to behave a lot like oil, subject to endemic cycles of boom and bust.

NOTES

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 - 24 For Mayne’s personal account, see W. Harry Mayne, *50 Years of Geophysical Ideas* (Tulsa: SEG, 1989).
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