Deeper Waters: How Science and Technology Pushed Exploration to Greater Depths*

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Introduction

Today, there are 31 sedimentary basins worldwide that produce or have economic discoveries in deepwater, in terms of both modern water depths and reservoir type (Figure 1). Exploration wells have now been drilled in water depths up to 11,155 feet (Pelotas Basin, Uruguay) (Figures 2 and 3), and the deepest offshore production at present is 9656 feet (northern Gulf of Mexico).

We all know successful deepwater production has profound economic impact. Sometimes, however, it is difficult to grasp how profound the economic impacts are. To get an idea, consider that the total gross income collected by the U.S. federal government from offshore oil and gas resources averaged $8 billion per year from 2005 to 2014, according to the Congressional Budget Office. That is compared to $3 billion from onshore resources for the same period.

How did our industry move into deepwater provinces in the past seven decades? What were the drivers behind this multibillion-dollar investment of resources?

The global story of deepwater petroleum exploration is not one that has a great deal of intrigue, like the Teapot Dome scandal or other early (mis)adventures in petroleum geology. Likewise, our story never had a master plan. Rather, this is a tale of gradual evolution – one in which the role of technology and science are inextricably linked to the economic need to discover new resources for an expanding global population.

New Technology and Science

The desire to explore in greater water depths required new seismic technology to accurately image the subsurface, new scientific disciplines to analyze the geology and geophysics, and new technology to drill and develop resources.

For example, with the development of common-depth-point seismic and digital recording in the mid-1960s, vast amounts of 2-D marine seismic information began to be collected. The continued improvement in acquisition, in terms of streamer design, allowed for improved subsurface imaging. This new information, in turn, presented new kinds of geology that had not been imaged before. The fields of seismic and sequence stratigraphy evolved from evaluation of these data, heavily influenced by early exploration of the North Sea and other basins. Meanwhile, the recognition of geophysical "bright spots" on seismic reflection data was critical to exploration success in deepwater, and it became one of the technical drivers in moving into progressively deeper-water frontier provinces for drilling.

Finally, the development of innovative drilling technology and production techniques were also essential to making deepwater economical.

Defining Terms

Like many geologic disciplines, there is a tremendous amount of jargon for deepwater. So let's define two terms. First, let's use the term "turbidite" to refer informally to any sedimentary gravity flow deposit regardless of water depth for deposition. Second, "deepwater" has two definitions. The geologic definition refers to water depths where sediment gravity flows tend to dominate, which generally means greater than 300 meters (although lakes are the exception). The engineering definition considers deepwater to be where fixed platforms can no longer be used for development. Instead, some sort of floating development structure is required; typically this is greater than 1500-feet water depth. I will use the second definition throughout this article.

Pioneers in Sedimentology

The important first step in deepwater exploration was the recognition that turbidite reservoirs exist. Ironically, some of the first oil fields discovered in the world were in turbidite reservoirs. Some of the reservoirs discovered in western Pennsylvania were likely in Devonian turbidities. Many of the giant fields in California discovered in the late 1890s and early 20th century had turbidite reservoirs. Examples include the southern San Joaquin, Los Angeles and Ventura basins. In 1930, Royal Dutch Shell discovered the supergiant Poza Rica field in onshore Mexico. The field produces from primarily Lower Cretaceous base-of-slope carbonate debrites and some turbidites. The Poza Rica field has the largest stratigraphic trap in conventional deepwater deposits.

However, in all of these examples, it was not until the late 1940s and '50s that the correct depositional setting of the reservoirs was recognized. Select companies began to realize that many of their fields in fact had deepwater turbidite reservoirs.

Manley Natland (Figure 4) did pioneering work in the early 1930s in several southern California basins. From modern marine studies, he recognized that the deepwater benthic foraminifers living in offshore basins in the Los Angeles area were also found in the shales encasing the coarser-grained sands and conglomerates in the nearby Plio-Pleistocene reservoirs and outcrops of the Ventura basin. Natland was so intrigued by these processes that he altered the bottom of his swimming pool to create ridges to simulate the effects of irregular bathymetry of the Neogene Los Angeles Basin, and then poured sand and mud into the pool to generate turbidity currents. (His son Martin confirmed this story in July, 2016.)

European sedimentologists Phillip Kuenen, Carlo Migliorini and their students also did pioneering deepwater research at the same general time. Their seminal work in outcrops and flume tanks began to gain acceptance in the late 1940s and '50s. By the 1960s, critical outcrop studies by

Arnold Bouma, Emiliano Mutti and Franco Ricci-Lucci (Figure 5) led to the development of facies classifications that were essential for the correct depositional interpretation of deepwater reservoirs. Later work in the 1970s by several workers continued to advance the understanding of depositional processes and facies association.

Three Key Basins

Initially, three areas were key to the successful transition of exploration into deepwater: the North Sea, the northern Gulf of Mexico and Brazil. The reservoirs discovered in these basins were essential for the recognition that deepwater reservoirs could produce at high and sustained rates, which were critical to making these plays economic.

The exploration story for deepwater sandstones began in earnest with the early oil discoveries in the North Sea basin. Although the modern water depths do not exceed 400 meters, the discovery of turbidite reservoirs in a number of fields was an essential step in the understanding of deepwater reservoir systems, impacting future deepwater exploration. After the 1958 United Nations treaty divided the North Sea into economic zones by country, exploration gradually moved from onshore into the shelf region. Marine seismic acquisition grew throughout the 1960s.

Ironically, two of the first fields discovered in the Central Graben of the North Sea were in turbidite reservoirs. First, Ekofisk was discovered in 1969, where the main reservoirs are lower Paleocene resedimented chalk turbidites. Then, the following year, the Forties field was discovered in upper Paleocene sandstones.

There was considerable internal discussion at BP, the operator, about the depositional origin of the Forties reservoir sandstones – were they shallow marine or deep marine? After a few years, the data collected for the field began to point toward a major delta-fed, base-of- slope deposit. Specifically, the reservoir was encased between deeper water microfaunal and palynological assemblages, distinct clinoforms prograded across the top of the deeper water reservoir systems, and associated sedimentologic studies were pointing toward sedimentary gravity flows. With the discovery of Forties, a number of other deepwater reservoirs were quickly discovered associated with the Paleocene systems as step-out from Forties; these included such fields as Maureen, Andrew, Montrose, Frigg, and Nelson.

Additional turbidite discoveries were made in the syn- and post-rift Jurassic and Lower Cretaceous strata: Magnus, the Brae complex, Britannia and Claymore fields. About 25 percent of the historical production in the U.K. North Sea has come from turbidite reservoirs.

GOM and Bright-spot Technology

In the northern Gulf of Mexico, exploration after World War II continued to move into deeper water depths across the shelf. Offshore Louisiana in 1947, Kerr McGee drilled the first well that could not be seen from land. The progressive movement of exploration into deeper water depths on the shelf continued for the next 30 years. The first significant discovery off the shelf was the 1975 Cognac Field in 1030 feet of water; the reservoirs were primarily upper slope and deltaic sands.

The major technical driver in moving exploration into the upper slope and deeper water was the use of bright-spot technology, initially developed by Mike Forrest and colleagues at Shell, and independently developed at Mobil. This approach was especially effective in discovering fields both on the shelf, as well as in deeper water. The larger fields were discovered beginning in the mid-1980s to early ‘90s and include Auger, Mensa, Mars, Ram Powell, and Ursa. Today, the northern deepwater Gulf of Mexico has 226 fields and discoveries; all but four of them are in turbidite reservoirs. Yearly production in 2014 was 416 million barrels of oil and 688 billion cubic feet of gas.

The movement into deepwater was gradual at first, limited by drilling technology. Drill ships became necessary to drill in much greater water depths. Specialized ships were initially developed for the Deep Sea Drilling Project Scientific Drilling Program in the 1960s. By the mid-1970s, several drill ships were built and used by industry.

Initial record water depths for drilling were in eight basins globally between 1970 to 1984. However, from 1987-2011, all record water depths were in the northern Gulf of Mexico (Figures 2 and 3).

An important trend has been the abrupt increases in the water depths for drilling during short time periods: 2,000 to 5,000 feet (1975-79), 5,000 to 7,000 (1981-84), 7,600 to 9,000 (1998-99), and 9,000 to 10,000 (2000-03) (Figures 2 and 3).

In addition to drilling, new development technology was necessary to develop these large fields. Subsea tiebacks, now a common production technology, got their start in the North Sea. Likewise, underwater pipelines, tension leg platforms, floating platforms and floating production storage offloading units have been essential technologies.

Brazil and Petrobas

Brazil is also a very important part of this deepwater story. Petrobras drilled its first onshore discovery in 1954; by 1968, the first offshore well was drilled in 10 meters of water in the Espirito Santo Basin, testing a structure that had alternative interpretations of a salt diapir or an igneous intrusion. The well was unsuccessful but proved the presence of evaporites in the continental platform, creating expectations of a new frontier with structures and plays similar to the Gulf of Mexico. In 1968, the Guaricema Field in the Sergipe-Alagoas Basin was discovered in a water depth of 20 meters; similar to some of the North Sea discoveries, there was considerable internal discussion as to the environment of deposition of the reservoir. Bill Fisher, working as a consultant, suggested that the reservoirs were, in fact, deepwater sands; this observation led to a change in exploration paradigm for potential reservoirs.

In 1974, Petrobras discovered the first oil field in the Campos Basin in Albian carbonates, and in less than a year the exploration focus moved to siliciclastic reservoirs in shallow waters, which were interpreted as turbidite sands deposited from Late Cretaceous to Mid-Tertiary. By 1982, Petrobras had drilled successfully in the upper slope in the Campos Basin in about 400 meters of water.

The next big jump happened in 1984 when drill ships were brought to the Campos Basin and the Albacora (1400 feet) and Marlim fields (2800 feet) were discovered. These two major discoveries opened an entirely new deepwater frontier in the South Atlantic.

More than 40 fields in the deepwater of offshore Brazil are in Lower Cretaceous to lower Miocene turbidite-related reservoirs. In 2015, the daily production in the Campos Basin from these deepwater sand reservoirs was nearly 1 million BOE/day.

Continued Evolution in Seismic Data

Another major jump for deepwater exploration happened during the early to mid-1990s, when marine 3-D seismic became routinely available for regional evaluations, and countries began to allow deepwater exploration in areas previously inaccessible.

For example, the 3-D seismic data collected along the West African margin led to major discoveries in Angola, Congo, Gabon, Equatorial Guinea, and Nigeria. These new seismic data also stimulated companies to reassess their concepts of how deepwater sedimentary systems operate. The depositional models that had been developed with 2-D seismic data needed modification where the 3-D data could very accurately image the depositional elements. Meanwhile, the need for 3-D seismic to image the geology below thick allochthonous salt led to cost-effective development of pre-stack depth migrated data. In addition, companies began to reassess deepwater outcrops to help construct accurate reservoir models. Flume studies also began to increase in complexity as companies tried to replicate the interpreted processes of the gravity flows. 4-D seismic (repeat 3-D) also became an essential tool for imaging the movement of fluids during field development in many productive basins.

Continental and Shallow Marine Reservoirs

Although most deepwater fields and discoveries have turbidite sand reservoirs, a number of reservoirs deposited in shallow marine to continental environments have been discovered in modern deepwater (greater than 1500 feet). All of these reservoirs represent deposition in the earliest portion of these margins’ tectonic development. The most notable are the pre-salt Lower Cretaceous reservoirs in the Santos and Campos basins in Brazil and their mirror image basins in offshore Angola (Kwanza and Namibe). Reservoirs are mainly microbial carbonates, coquinas and cherts deposited in rift lakes. Those fields already produce more than 1 million BOPD in the Santos and Campos basins. Other discoveries include: Upper Jurassic eolian reservoirs in the northern deep Gulf of Mexico; Upper Jurassic fluvial-estuarine reservoirs in the Bay du Nord, offshore eastern Canada; Lower Cretaceous lacustrine deposits in the northern Falkland- Malvinas Basin; Lower Cretaceous shallow to marginal marine reservoirs in offshore Senegal; middle Miocene carbonate buildups in offshore Egypt; and upper Miocene carbonate reservoirs west of the Philippines.

The Future?

At this point we must ask: what is next for deepwater exploration and development? The recent price downturn has had a significant global impact on the economics of deepwater. Many deepwater plays are not profitable in the current low-cost environment due to high capital and operating costs. Clearly, an increase in oil price and/or a decrease in operating expenses are essential for deepwater exploration and production to remain profitable in the future.

Acknowledgments

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Author

Paul Weimer (Figure 6) is an AAPG past president and holds the Bruce D. Benson Endowed Chair in the Department of Geological Sciences at the University of Colorado, and serves as the Director of the Energy and Minerals Applied Research Center. He began research on deepwater deposits in 1978 and has continued to prod the broad topic for many years since then. He was also the co-chair of the 100th AAPG Anniversary Committee.

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A history-based series, Historical Highlights is an ongoing EXPLORER series that celebrates the "eureka" moments of petroleum geology, the rise of key concepts, the discoveries that made a difference, the perseverance and ingenuity of our colleagues – and/or their luck! – through stories that emphasize the anecdotes, the good yarns and the human interest side of our E&P profession. If you have such a story – and who doesn't? – and you'd like to share it with your fellow AAPG Members, contact the editor, Hans Krause at historical.highlights@yahoo.com.

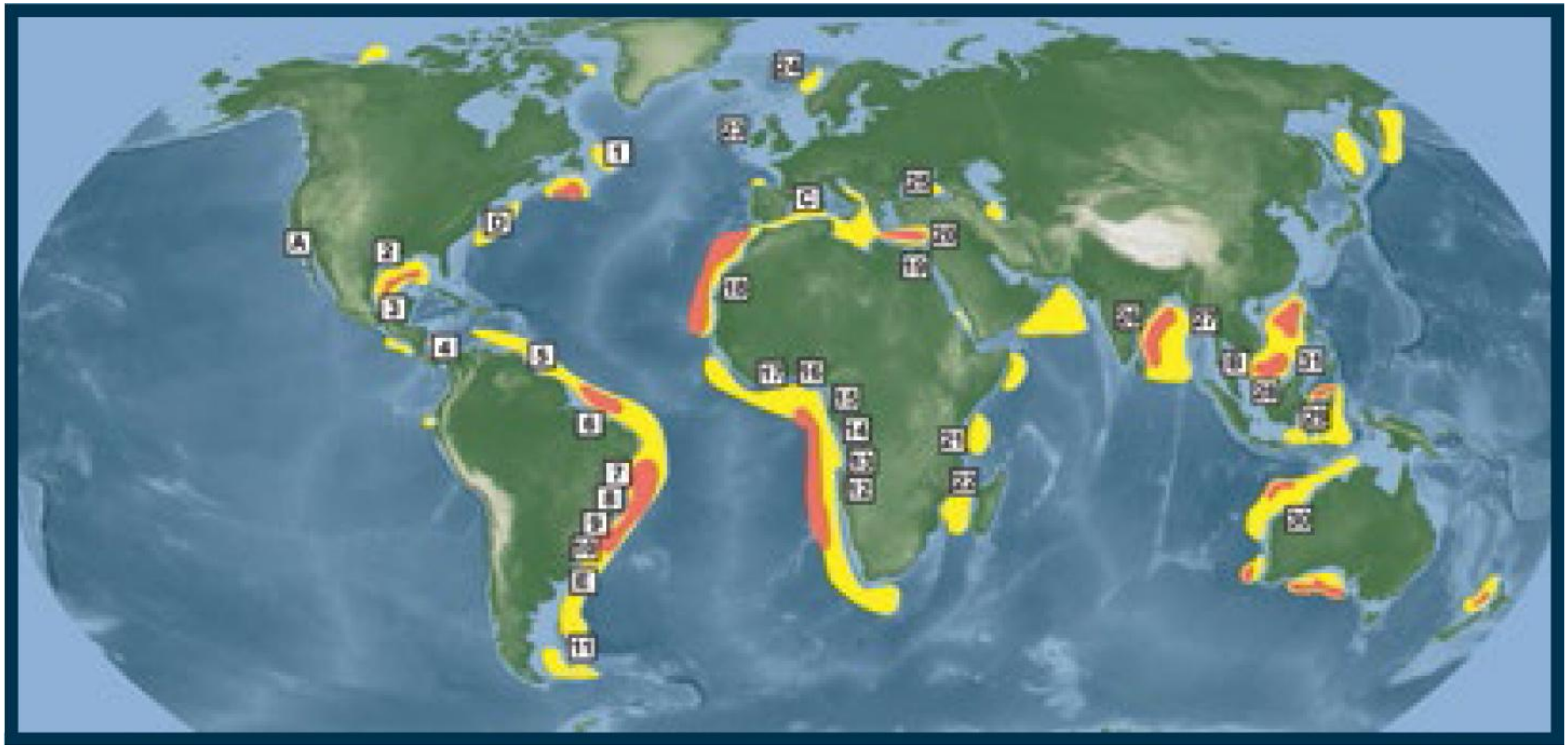

Figure 1. Global map of all basins in greater than 1500 feet water depth with fields or economic discoveries. 1. Eastern Canada. 2. Northern Gulf of Mexico. 3. Southern Gulf of Mexico. 4. Colombia. 5. Guyana. 6. Potiguar. 7. Sergipe Alagoas. 8. Espírito Santo. 9. Campos. 10. Santos. 11. North Falklands. 12. Angola. 13. Cabinda. 14. Gabon. 15. Equatorial Guinea. 16. Nigeria. 17. Ghana-Core D'Ivoire/ 18. Senegal-Mauritania. 19. Nile. 20. Levant. 21. Tanzania 22. Rovuma. 23. Shetlands. 24. Central Norwegian shelf. 25. Black Sea (Romania). 26. Krishna-Godavari. 27. Myanmar. 28. Brunei-Sabah. 29. Mahakam. 30. NW shelf- OZ (three sub-basins). 31. West Philippine Sea. Additional sites for drilling records (Figure 3) are shown: A=Santa Barbara (1970); B=Andaman Sea (1976); C=Gulf of Lion (1982); D=Baltimore Canyon (1983- 1984); E=Pelotas Basin Uruguay (2016). Areas with good exploration potential are shown in yellow (deepwater 1500-6000 feet) and orange (ultra-deepwater greater than 6000 feet).

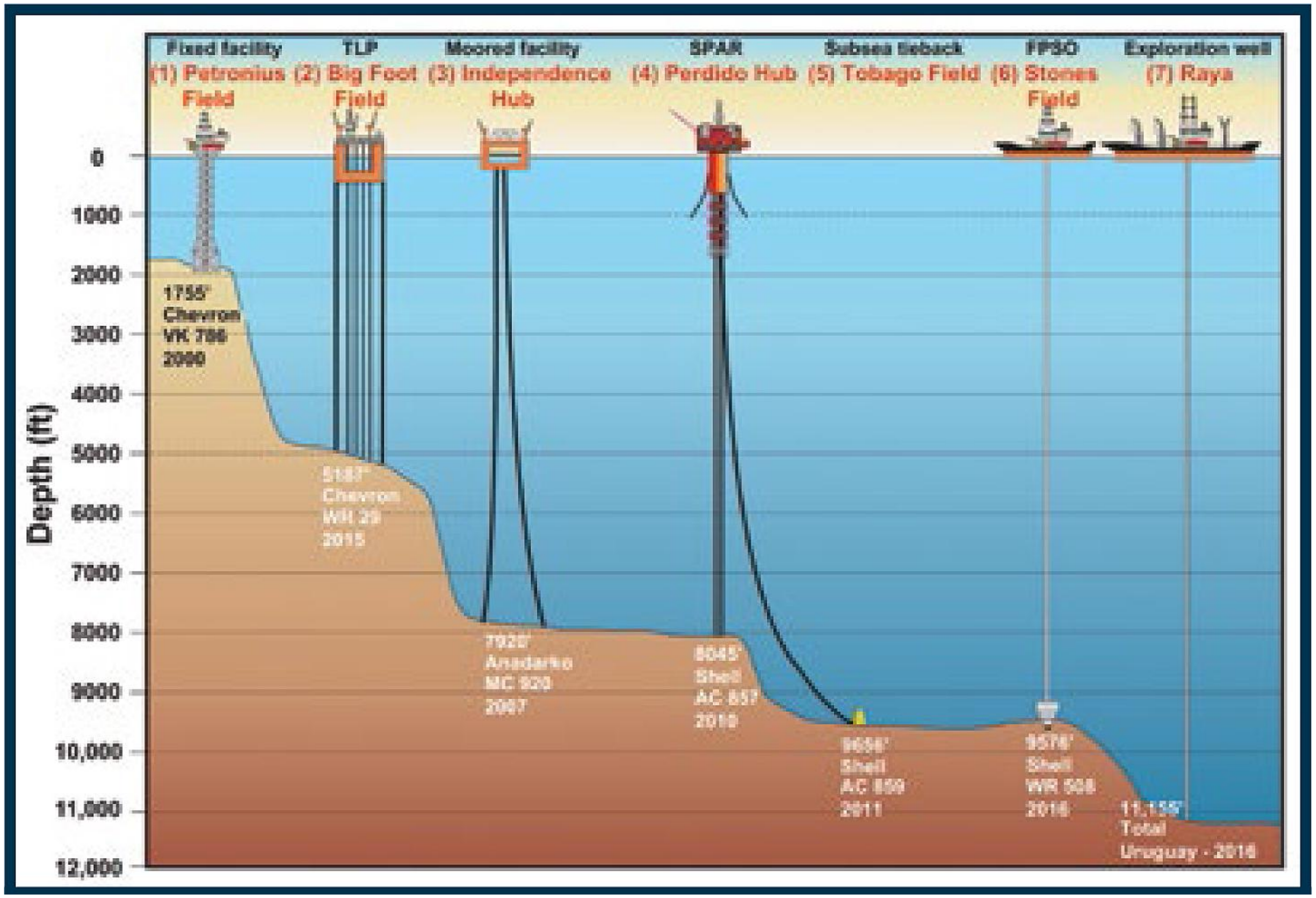

Figure 2. Schematic diagram showing the world-record water depths for exploration and development facilities, and years of first usage. TLP=Tension Leg Platform; FPSO= Floating Production Storage Offloading.

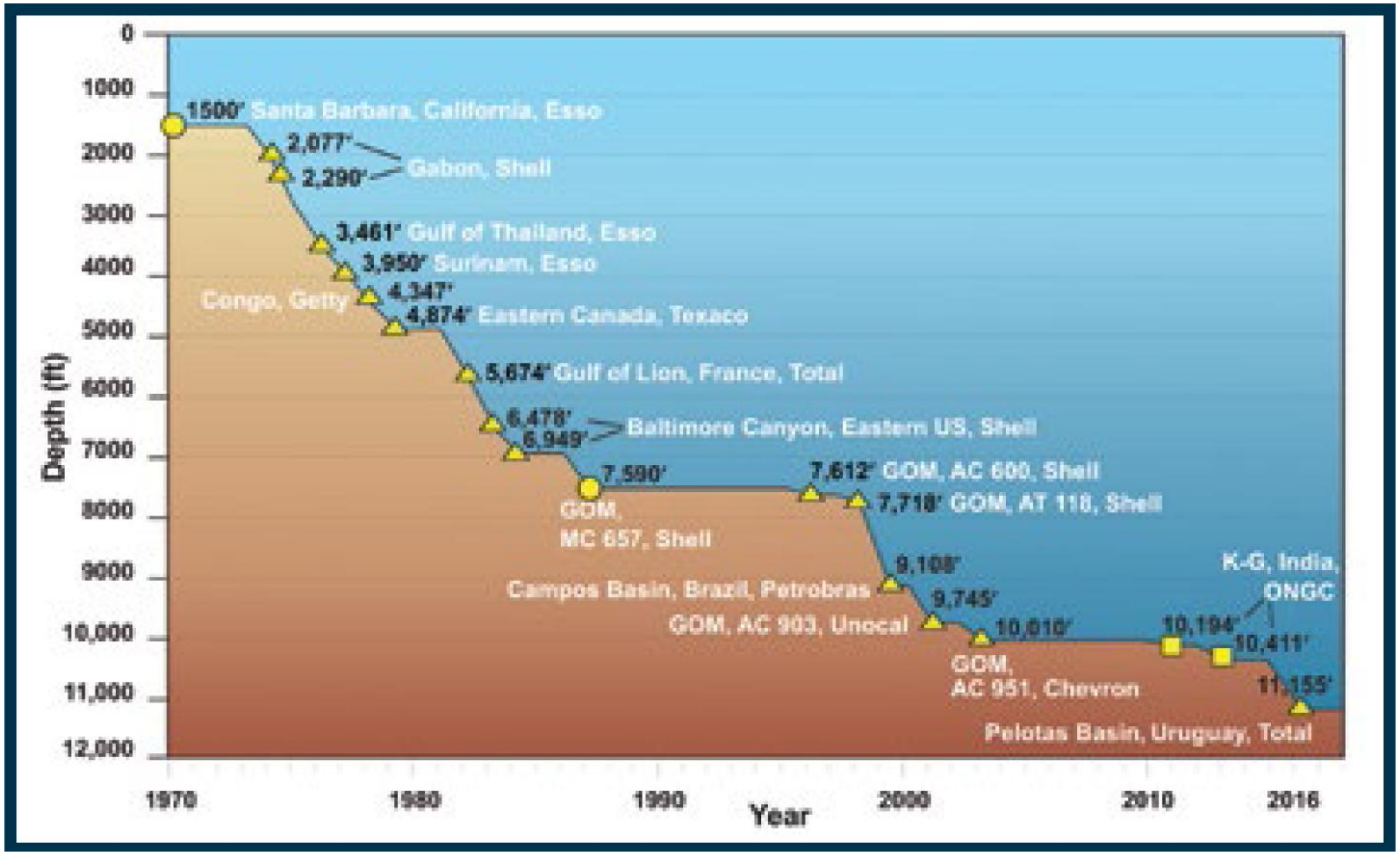

Figure 3. Record water depths for drilling by the end of each year. Location of wells and operator are indicated. GOM=Gulf of Mexico, AC=Alaminos Canyon, AT=Atwater Valley, MC=Mississippi Canyon, K-G=Krishna-Godivari. Triangles=dry holes, circles=producing fields, squares=discoveries. Locations of basins shown in Figure 1.

Figure 4. Manley Natland (with camera) filming the generation of turbidites in a flume at Union Oil Research Laboratory, Brea, Calif., January 1965. Photo courtesy of Martin Natland.

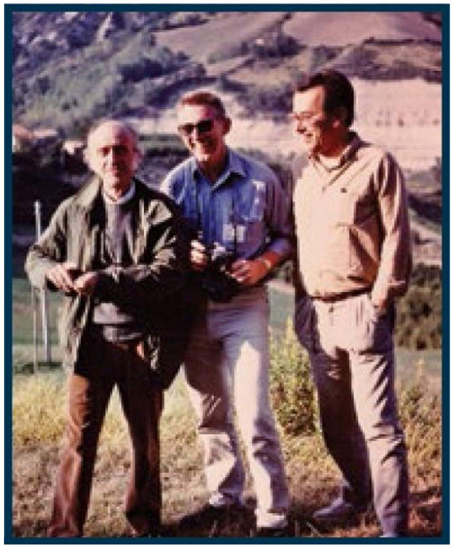

Figure 5. (From left) Emiliano Mutti, Arnold Bouma, and Franco Ricci-Lucchi in the Apennine Mountains, Italy, September 1988. Photo by Martin Link.

Figure 6. Paul Weimer.