Steven A. Murawski · Cameron H. Ainsworth
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Dana L. Wetzel *Editors*

Scenarios and Responses to Future Deep Oil Spills

Fighting the Next War

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Foreword and Dedication

Global production of liquid fossil hydrocarbons was 34 billion barrels in 2017,[1] with production increasing an average 1.1% per year during the preceding decade (BP 2018). Maintaining and increasing production now involves expansion into "frontier" areas including nontraditional terrestrial and aquatic realms. Marine oil exploration and production has advanced steadily offshore since its inception in the Gulf of Mexico in the 1930s (Murawski et al. 2020). For the first time, in 2017, more crude oil was generated from ultra-deep (>1 mile deep) waters of the Gulf of Mexico than in shallower waters (Murawski et al. 2020). This trend to deeper production is occurring in all major marine oil provinces of the world.

The *Deepwater Horizon* (DWH) oil spill was the world's first ultra-deep well blowout, but likely not the last. Deep well fields in the Gulf of Mexico now extend to depths nearly twice that of DWH. Ultra-deep wells present unique technical and environmental challenges. Because of the immense depths and pressures, ultra-deep wells are more complex, risk-prone, and expensive to construct and maintain as compared to equivalent shallower facilities. Notwithstanding these issues, and depending on the price of oil, the volumes of oil produced at ultra-deep wells can be enormously profitable, yielding many times the production rates of those inshore (Murawski et al. 2020).

The purposes of this book are to synthesize relevant science related to potential oil spills in frontier marine domains and to project the fate and impacts of simulated ultra-deep blowouts. No two spills are alike, and the conditions of the next ultra-deep well blowout will be different from both the DWH and the shallower Ixtoc 1 experiences. Prior to DWH, response planning for marine oil spills primarily assumed a scenario similar to the last major marine oil spill in the United States – the *Exxon Valdez* tanker accident in Alaska. Thus, responders were generally unprepared for the scenario of a deep and unconstrained well blowout in terms of infrastructure and basic science to reasonably inform the use of novel response measures.

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[1] One stock tank barrel = 42 gallons = 158 l; includes crude oil, shale oil, oil sands, and NGLs (natural gas liquids, the liquid content of natural gas where this is recovered separately)

Rather than concentrating on unresolved issues remaining post-DWH, we simulate spills in the Gulf of Mexico regions where oil and gas exploration and production may in the future occur (e.g., deep water in the eastern, western, and southern Gulf). Likewise, we consider spills in other frontier areas (e.g., off West Africa and in the Arctic). These location-specific simulations of oil fates and their relative impacts on ecological communities and economic activities (fishing) differ from the DWH scenario in fundamental and important ways. Under alternative conditions of oil type, gas/oil ratios, water depth, etc., oil fate and effects will vary still. The point of these simulations, and the importance of closing existing research gaps, is that conditions will be different and therefore response strategies must be nimble to effectively deal with the next ultra-deep oil well blowout, pipeline rupture, tanker-platform collision, industrial sabotage incident, or whatever the scenario may be. Assuming a replay of DWH will surely repeat the cycle of anticipating the next "war" by preparing for the last. Having a fuller repertoire of science applicable to a wide array of idiosyncratic conditions is the key to anticipating and effectively responding to the next spill of significance.

Despite the nearly $1 billion spent on relevant science since the DWH accident, there remain a number of critical science gaps that preclude consensus on best options to prevent or at least more efficiently respond to the next major spill. A short list of recommended science priorities and policy options is discussed. Nevertheless, there will always be uncertainty concerning the physics, chemistry, geology, and ecology associated with particular ultra-deep well blowouts. Perhaps as important to closing the science gaps that remain, identifying the attributes of locations that are too risk-prone or too ecologically or economically sensitive to permit oil exploration and production should be a priority. Should all frontier areas where oil and gas resources are technically feasible to recover be produced? This is the domain of policy, and informing the consequences of policy choices is the province of environmental science as characterized in the chapters that follow.

Much of the science synthesized in this volume was a result of support and funding from the Gulf of Mexico Research Initiative (GoMRI). The GoMRI enterprise was funded through a $500 million grant established in the wake of the DWH accident. Many of the authors and all of the coeditors of this book are members of the Center for Integrated Modeling and Analysis of Gulf Ecosystems (C-IMAGE), one of the several research centers supported by GoMRI. Authorship of this volume also includes contributions by members of other GoMRI-funded centers, as well as those from government, academic, and private research organizations. We are deeply grateful to the leadership, staff, and research board of GoMRI for supporting these efforts to better understand the science of deep oil spills and to synthesize that science into actionable alternatives to inform government and industry.

This volume is dedicated to the 11 men who lost their lives aboard the MODU (Mobile Offshore Drilling Unit) *Deepwater Horizon* on April 20, 2010:

Jason C. Anderson, age 35
Aaron Dale Burkeen, age 37
Donald Clark, age 49
Stephen Ray Curtis, age 39
Gordon L. Jones, age 28
Roy Wyatt Kemp, age 27
Karl D. Kleppinger, Jr., age 38
Keith Blair Manuel, age 56
Dewey A. Revette, age 48
Shane M. Roshto, age 22
Adam Weise, age 24

The work described herein has been undertaken with the goal of preventing such accidents from ever happening again and reducing risks to the environment and people should they reoccur. In this way, we honor those whose lives were lost that they helped stimulate national and international action to make marine oil and gas production safer. The families of those who lost their lives in the *Deepwater Horizon* accident expect and deserve nothing less.

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The C-IMAGE research consortium, January 2014, Mobile, Alabama

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Overview

Photo Credit: C-IMAGE Consortium

Chapter 1
Introduction to the Volume

Steven A. Murawski, Cameron H. Ainsworth, Sherryl Gilbert, David J. Hollander, Claire B. Paris, Michael Schlüter, and Dana L. Wetzel

Abstract Ultra-deep water production of oil and gas – from depths greater than 1 mile (1500 m) – comprises an ever-increasing proportion of the world's supply of hydrocarbons. In the Gulf of Mexico, ultra-deep production now exceeds that from shallower waters. The ultra-deep domains of the world's oceans are home to unique and highly sensitive communities of animals, are characterized by extremes in environmental conditions (low temperatures, high pressures), and are exceedingly challenging regions in which to work safely. *Deepwater Horizon* (DWH) was the world's first and largest ultra-deep water well blowout and likely not the last. In the wake of that incident, scientific research and industrial development have been focused to better understand the ultra-deep domain, to lessen the likelihood of accidents there, and to better respond to future incidents. This volume summarizes trends in the development of ultra-deep drilling, synthesizes the state of knowledge relevant to ultra-deep oil spill prevention and response, and contrasts the effects of simulated ultra-deep spills in the frontier regions of the Gulf and elsewhere. Recommendations for additional research and public policy changes to lessen the likelihood and impacts of future spills and to improve oil spill response are provided.

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1.1 Introduction

Major industrial/environmental disasters – and responses to them – have elicited a wide variety of reactions, including, in some cases, paradigm shifts in oversight, industrial safety practices, legislation, and even political change (Wilson 1973; Jasanoff 1994; Sheail 2007; EVOS 2012; Fidler and Noble 2012; Revkin 2013); no more so than the compelling cases of marine oil spills. After the *Torrey Canyon* tanker grounding and spill off the Cornwall Coast of England in 1967, there were major changes in the international regulation of tanker traffic carrying crude oil. As well, "lessons learned" from that accident were applied during subsequent spills, including foregoing the use of large quantities of detergents, used in quantity during the *Torrey Canyon* spill, in the response to the *Amoco Cadiz* oil spill off Brittany, France, in 1978. Similarly, in the aftermath of the *Exxon Valdez* tanker spill in Prince William Sound, Alaska, in 1989, the US Clean Water Act of 1972 provisions regulating oil spill preparedness and response were updated and memorialized in the Oil Pollution Act of 1990 (OPA-90). While tanker-based accidents have plummeted since those high-profile accidents (Ramseur 2010), the offshore oil industry has become more reliant on ultra-deep sources, particularly for crude oil (Murawski et al. 2020a), and on pipeline transfers from offshore fields to refineries. After the catastrophic *Deepwater Horizon* (DWH) accident in the Gulf of Mexico (GoM), the oil industry has become more cognizant of the need for rapid response to uncontrolled blowouts in ultra-deep waters (≥1500 m), inventing and deploying new "capping stack" configurations (Wood Group Kenny 2016) and equipping blowout preventers with the capability to more efficiently treat uncontrolled blowouts with sub-surface dispersants injected (SSDI) directly into multiphase oil/gas/water flows exiting from blown-out wells. Additionally, and notwithstanding the open questions that persist regarding the efficacy and effects of SSDI (e.g., NASEM 2019; Murawski et al. 2020b), the common perception among regulators and the oil industry is that SSDI was effective in reducing the presence of volatile organic compounds in the vicinity of response workers (Gros et al. 2017) and that the environmental trade-offs of sequestering oil in the deep sea by the application of SSDI outweigh the costs of oil spill mitigation of surfacing oil (French-McCay et al. 2018). The experimental use of SSDI may be one of the enduring legacies of DWH given the few tools available at the time to respond to large, uncontrolled spills in such extreme environments. Clearly, the next deep oil spill response "war" will begin where the DWH spill scenario ended. Despite the ambiguous evidence of the utility of some of the novel approaches used in that response (Gros et al. 2017; Paris et al. 2018; NASEM 2019), government and industry are preparing to conduct large-scale SSDI to combat future uncontrolled deep blowouts.

The global oil industry is rapidly expanding exploration and production into "frontier" areas including the ultra-deep realm (Pinder 2001), regions of the world that are ill-equipped to muster both vigorous industry oversight and large-scale oil spill response (e.g., in the developing world), and some of the harshest environments on earth (e.g., the Arctic; Noble et al. 2013; Suprenand et al. 2020). Expansions into both the geographic and technological (Jin and Castais 2016) frontiers of oil and gas development beg the question regarding the state of preparedness of governments, industries, and the independent science community to anticipate likely oil spill scenarios, reduce or eliminate risk factors, and better prepare for and more efficiently respond to spills in the future.

Using the DWH disaster as a point of departure, this volume considers the questions of oil spill risk reduction, anticipation of the circumstances of future accidents, and oil spill response, from a variety of perspectives. The DWH oil spill occurred at a water depth of 1500 m in the relatively quiescent spring and summer of 2010. How would the scenario have changed had the spill occurred during a different season? Winters in the northern GoM have predominantly northern winds as illustrated by the drifter experiment conducted from the DWH site in January and February described in Haza et al. (2018), showing strong southerly forcing with many drifters moving toward the Yucatan shelf. Likewise, how would have the response and environmental effects of the spill changed if a strong and persistent hurricane had occurred or if the Loop Current system had not formed a strong eddy blocking normal transport to the Florida Straits? While the DWH blowout occurred at about 1500 m, the deepest oil lease in the northern Gulf is nearly twice as deep (2960 m; Murawski et al. 2020a). How would the behavior of released oil and gas and the response scenario have differed had the spill occurred at these extreme depths? Similarly, the oil type involved in the DWH spill (Louisiana Sweet Crude, or LCS) is one of many crude oil types both in the Gulf and elsewhere that are the objects of ultra-deep drilling. Had that accident occurred with a heavier, more viscous, more sulfur-rich ("sour") crude, how would these have altered the characteristics of the spill, its impacts, and the efficacy of response measures?

With respect to locations of future oil spills in the GoM, all three countries (USA, Mexico, Cuba) are now exploring in or developing ultra-deep fields (Murawski et al. 2020a). In the case of the USA and Mexico, spills close to their maritime boundaries (Fig. 1.1) doubtlessly will impact and require multinational responses only peripherally evident for DWH. Currently, a congressionally mandated moratorium in the US eastern GoM (Fig. 1.1) prohibits activities in the region where the highly dynamic Loop Current (Sturges and Lugo-Fernandez 2005; Weisberg and Liu 2017) flows eventually into the Florida Straits and up the Atlantic Seaboard as the Gulf Stream. If oil production occurred along the Florida Escarpment (Fig. 1.1), how would a spill there behave in relation to Loop Current dynamics? Are the risks to ecosystems and livelihoods of a catastrophic spill in the moratorium area (Fig. 1.1; e.g., Nelson and Grubesic 2018) greater than in the western and central GoM?

In the western GoM, both the USA and Mexico are aggressively pressing ocean drilling into the Perdido formation (BOEM 2017; Murawski et al. 2020a and Locker and Hine 2020). A major spill at the Perdido formation would doubtlessly impact

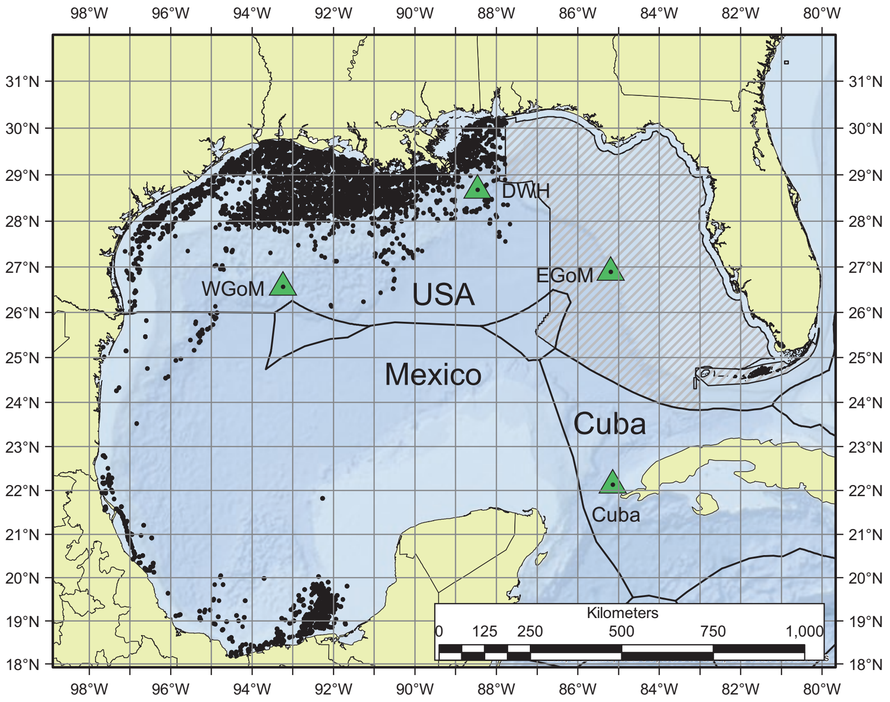

Fig. 1.1 Map of the Gulf of Mexico illustrating the exclusive economic zones (EEZs) of the USA, Mexico, and Cuba. Black dots are the current (2018) locations of oil and gas infrastructure. Triangles are the locations of simulated oil spills in the Gulf that are analyzed herein. Hatched area is the region of the congressionally mandated moratorium on oil and gas development, in place until 2022

US and Mexican ecosystems and a variety of particularly vulnerable species including the Kemp's ridley (*Lepidochelys kempii*) turtle population and their nesting areas at Rancho Nuevo, Mexico (Bevan et al. 2016), migrating sea- and land-based birds, fisheries, and other public uses of coastal areas. Again, how would the impacts and responses to such a spill differ from those of DWH? As the Ixtoc 1 spill demonstrated, oil spills in the SW GoM can have extended footprints and in the extreme advancing to the USA-Mexican border and beyond (Soto et al. 2014; Sun et al. 2015).

The Cuban government and its partners in the global oil and gas exploration and production industries continue to search for lucrative offshore quantities within the Cuban EEZ (Slav 2017; Fig. 1.1). While a number of exploration wells so far have not apparently discovered economically recoverable quantities of oil and gas, this effort continues. Because of the strategic location of Cuba at both the entrance and exit of the GoM (Fig. 1.1), there is a concern that spills at either location would result in broad-scale transport beyond Cuba's territory, and impacts on migratory species.

1.2 Focus of the Book

This volume has three main foci: (1) to summarize the state of knowledge of relevant physical, chemical, geological, and biological properties and processes in the environments where ultra-deep drilling and development are occurring, (2) to simulate and contrast likely scenarios and impacts of hypothetical spills occurring in frontier areas of the GoM and elsewhere, and (3) to evaluate the state of information and recommend additional high-priority science necessary for reducing the likelihood of catastrophic deepwater accidents and for mounting more effective responses to ultra-deep spills should they occur.

The volume overview (Murawski et al. 2020a) provides a narrative history of oil and gas development in the entirety of the GoM and illustrates the evolution from shallow-to-deep sourcing. Recent trends in the GoM mirror those globally (Pinder 2001), as facilitated by rapid advances in oil and gas drilling and production technologies. A petro-geological analysis of the GoM (Chap. 3) provides spatial context for the processes involved in oil and gas formation across geological epochs and provides strong evidence for likely targets of future oil and gas exploration and production in the next several decades (Locker and Hine 2020; BOEM 2017).

Because of the enormous investment in GoM research following the DWH spill, we now have measurements of oil-derived contaminants and associated indicators for broad spatial swaths of the GoM and, in some cases, time series of a variety of oil indicators in the regions of the DWH and Ixtoc 1 blowouts (Lubchenco et al. 2012; Soto et al. 2014). These indicators will be enormously important as broad-scale (but *not* facility-specific) baselines for analyzing the impacts of future spills. Some time series show declining trends in oil contamination levels and recovery of biota 9 years after DWH and nearly 40 years after the Ixtoc 1 spill, while the events remain recorded in continually sequestered, chronologized bottom sediments, in biota and, surprisingly, in GoM waters (Chanton et al. 2020).

Gulf of Mexico’s sediments faithfully record not only climate proxies but evidence of volcanic eruptions, human interventions, and, importantly, a chronological history of the use of hydrocarbons over the past century or so (Santschi et al. 2001). Sediments also record large-scale oil spills and their impacts on benthic infauna (Brooks et al. 2020; Schwing et al. 2020; Montagna et al. 2020). The use of novel and advanced technological approaches revealed a persistent carbon isotopic signature of large-scale oil spills in the water column (long after the oil was dissolved, diluted, or transformed; Chanton et al. 2020) which aids in separating oil spill effects from naturally occurring hydrocarbon sources.

The application of “omics-based” “big data” approaches to microbial community analyses provides a quantitative framework for evaluating the resilience of such communities to large-scale contaminant exposure and reveals the opportunistic nature of methanotropic and oil-consuming bacteria when applied to significant spills (Kostka et al. 2020). During DWH there were many proposals to cultivate and release oil-consuming strains of bacteria into the environment to enhance the rate of degradation of oil and other hydrocarbons. However, naturally occurring strains of the bacterial genome responded quickly to the available food source resulting in relatively rapid degradation. The issue of whether the presence of dispersants retarded or accelerated this process remains a significant uncertainty (Kleindienst et al. 2015; Prince et al. 2016; NASEM 2019).

Isotope analyses of fish and other tissues reveal natural tracers documenting fish migratory pathways and thus exposure potential to localized and broad-scale oil spills (Peebles and Hollander 2020). As well, isotope analyses document biogeochemical pathways that trace petro-carbon through trophic food webs once spilled (Patterson III et al. 2020). Toxicological baselines for GoM fishes now extend throughout the Gulf's continental shelves (Pulster et al. 2020) and into the mesopelagic realm (Romero et al. 2018). Interpreting the significance of contaminants in biota is facilitated by combining field-derived data with laboratory-based exposure trials (Mitchelmore et al. 2020; Raimondo et al. 2020) and aided by modeling studies (Paris et al. 2020a). Impact studies from previous spills, when combined with extensive collections during and after the DWH spill, provide a much more complete picture of both static and dynamic components of environmental baseline parameters, thus allowing much more precise evaluations of the relative exposures and impacts from future GoM spills.

The second focus of this volume is understanding mechanisms of oil spill dynamics under differing circumstances, including physical processes influencing sedimentation and transport of oil (Foekema et al. 2020; Daly et al. 2020). Formation of oiled marine snow ("MOSSFA") was a pathway for sedimentation of significant quantities of oil in both the cases of DWH and Ixtoc 1 (Brooks et al. 2020), resulting in negative effects on benthic habitats and biota (Schwing et al. 2020; Montagna et al. 2020). Both of those spills occurred seaward of riverine deltaic systems (Fig. 1.1). Although the antecedents of MOSSFA formation are not precisely known (Daly et al. 2016), they likely require high concentrations of phytoplankton, fine particle sediments, and oil. Indications are that oil and dispersants result in the production of extracellular polymeric substances (EPS) a glue-like substance enhancing oil/mineral aggregate formation. The oil and gas industries of the GoM and elsewhere are pushing much further offshore, into less productive waters with lower sediment loads. Under these circumstances would we expect as strong MOSSFA events to occur if a sub-surface blowout occurred there (MacDonald et al. 2020; Armenteros et al. 2020; Daly et al. 2020; Berenshtein et al. 2020a)? The specific location of oil spills as well as ancillary environmental conditions (depth, temperature, oil type, season, hydrodynamics, and other factors) is likewise critical in determining the outcomes with respect to spill impacts and severity. A series of oil spill simulations, using the CMS modeling package (Paris et al. 2013, 2020a, b; Berenshtein et al. 2020a, b; Murk et al. 2020, Sutton et al. 2020; Frasier 2020; Chancellor et al. 2020), are described for four GoM locations in frontier oil development areas (Fig. 1.1). These include additional simulations at the DWH site using different seasonal and flow condition sites, as well as eastern, western, and southern GoM locations (Paris et al. 2020a). These simulations are used to rank the relative impacts of the spills on several metrics including the degree of shoreline impact, including ecosystem implications (Berenshtein et al. 2020a). Importantly, one of the stated reasons for using SSDI is to minimize the degree to which shorelines and coastal areas are oiled (French-McCay et al. 2018). However, spills in the deep central Gulf may result in relatively little weathered oil reaching shorelines (Berenshtein et al. 2020a).

The resilience potential of ecological resources; efficacy of response measures, including fishery closures; and the potential sensitivity of deepwater fish communities, sea turtle populations, and marine mammals are evaluated, with particular reference to resources potentially affected by ultra-deep blowouts (Sutton et al. 2020; Frasier 2020; Chancellor et al. 2020). Oil and gas facility siting and oil spill contingency planning historically have used environmental sensitivity indices (ESIs) to reserve particularly unique areas from siting consideration or to note where special precautions in spill response and mitigation should occur (Jensen et al. 1998). Chancellor et al. (2020) outline a quantitative approach to EISs specifically taking into account deepwater resources and economic dependencies. Unique environmental and human community sensitivities applicable to oil and gas development in frontier Arctic ecosystems are discussed in Suprenand et al. (2020).

The third focal area of this book considers oil spill risk reduction as well as preparations for, and responses to, future ultra-deep spills. Given the controversial use of dispersants as a response measure, applied at the sea surface, and as SSDI, the state of knowledge of the efficacy, mode of application, and environmental and human health effects are reviewed (NASEM 2019; Murawski et al. 2020b). Despite the hundreds of millions of dollars spent on research and oil spill preparedness and prevention in the wake of DWH, there remain important unresolved scientific questions related to the siting of deepwater facilities to reduce risks of catastrophic spills. Likewise, gaps in research exist in spill prevention, preparedness, response, injury assessment, and ecosystem restoration (ICCOPR 2015; Murawski 2020).

1.3 Final Thoughts

The advent of ultra-deep oil and gas production carries with it enormous potential benefits as well as significant – and asymmetric – risks. The use of novel drilling and production technologies, in largely unexplored frontier regions, and with significant unknown, unknowns regarding oil and gas behavior at extreme pressures and temperatures, contributes to the increased risks of ultra-deep water development. Understanding the behavior of oil and gas under these extreme conditions as well as the efficacy of response and mitigation measures can be partially informed by past experience, but:

> "It is often said that the military… are always preparing to fight the last war rather than the next one". – Erwin Canham, 12 January 1945, Christian Science Monitor

In this regard, the next deep oil blowout and ensuing spill, wherever it may happen, will likely occur under fundamentally different conditions than have the two previous sub-surface mega-blowouts (DWH and Ixtoc 1; Fig. 1.1). While the previous 80+ years of experience in oil exploration and production from the GoM have included responses to literally hundreds of oil spills (Ramseur 2010), a 3000 m blowout will be unlike any previous. Furthermore, the physical oceanographic conditions, appropriateness of response technologies, and the specifics of the casualty will require nimble response approaches informed by rigorous pre-spill planning and anticipatory research. Likewise, the types of significant accidents occurring in other frontier regions of oil and gas development (the Arctic, off developing nations, and in relation to novel recovery strategies, e.g., Jin and Castais 2016) also remain in the realm of “unknown-unknowns.” Preparations for such accidents must include scenario analyses and training exercises that are informed by sophisticated modeling tools, experimental and field-level data collected under realistic ambient conditions, and deep understanding of the inherent environmental and human risks of drilling such areas in the first place, as well as the response options available. As the industry extends into *ignotas aquas* of frontier marine oil and gas regions, so too practical scientific research must be forthcoming to support the policy and response decisions necessary to minimize to near zero the risks of such catastrophic events. Furthermore, additional research and active dialog between government regulators, industry, and independent scientists are urgently needed in order to deploy effective, efficient, and environmentally sound response approaches applicable to ever-evolving deepwater scenarios. It is to this task that this book is dedicated.

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Chapter 2
Deepwater Oil and Gas Production in the Gulf of Mexico and Related Global Trends

Steven A. Murawski, David J. Hollander, Sherryl Gilbert, and Adolfo Gracia

Abstract The marine oil industry in the Gulf of Mexico (GoM) began in 1938 with the construction of the first oil well platform built in 4 meters of water, a mile off the Louisiana coast. The Mexican marine oil industry began in the 1950s with exploration and low-level production off the city of Tampico in the state of Tamaulipas. The discovery of the massive Cantarell oil field off Campeche in 1976 led to rapid expansion of the Mexican industry, surpassing US production of GoM-derived oil. Total annual oil production from the GoM peaked in 2003 at 1.6 billion barrels, but has since declined to about 1.2 billion barrels. Production at the Cantarell field peaked in 2004 and has since declined by 90%. Both the US and Mexican oil industries have focused more recently on deepwater plays to support production. The US oil production by lease depth showed a steady offshore migration through the 1990s but a dramatic rise in ultra-deep (e.g., ≥1500 m water depth) production beginning in the 2000s. In 2017, 52% of US oil production was from ultra-deep wells. Beginning in 2013, Mexico liberalized its policies to allow international cooperative ventures for exploration and production, particularly focusing on deepwater sources. Several large discoveries off Mexico since 2015 portend higher offshore production in the 2020s when these fields come online. In the US GoM, marine-derived natural gas production has declined by 79% since 1997, to about 1 trillion ft^3 in 2017, reflecting rapid increases in land-based gas sources from hydraulic fracturing, which are less expensive to produce that marine-derived gas. Over the next decade, shallow-water sources of oil and gas in the US GoM will be phased out or reduced in importance as additional ultra-deep sources are developed. In the US GoM these include plays in depths to 3000 m and potentially deeper off Mexico. Ultra-deep sources occurring in the "Golden Triangle" between West Africa, Brazil, and the GoM will likely dominate global ultra-deepwater production, but other frontier

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regions will doubtlessly be explored. The inherent risks of catastrophic well blowouts at extreme depths will increase as the productivity of oil facilities increases exponentially with water depth.

Keywords Ultra-deep oil · Congressional moratorium · Gulf of Mexico · Cantarell

2.1 Introduction

This book considers the potential impacts and responses to another large-scale, deepwater oil spill occurring in the Gulf of Mexico (GoM; Fig. 2.1) or elsewhere in the world. We synthesize many published research studies and especially focus on scientific investigations conducted during and after the *Deepwater Horizon* accident (Lubchenco et al. 2012). While the focus of the book is on factors controlling the fate, distribution, and ecological consequences of such spills, equally important

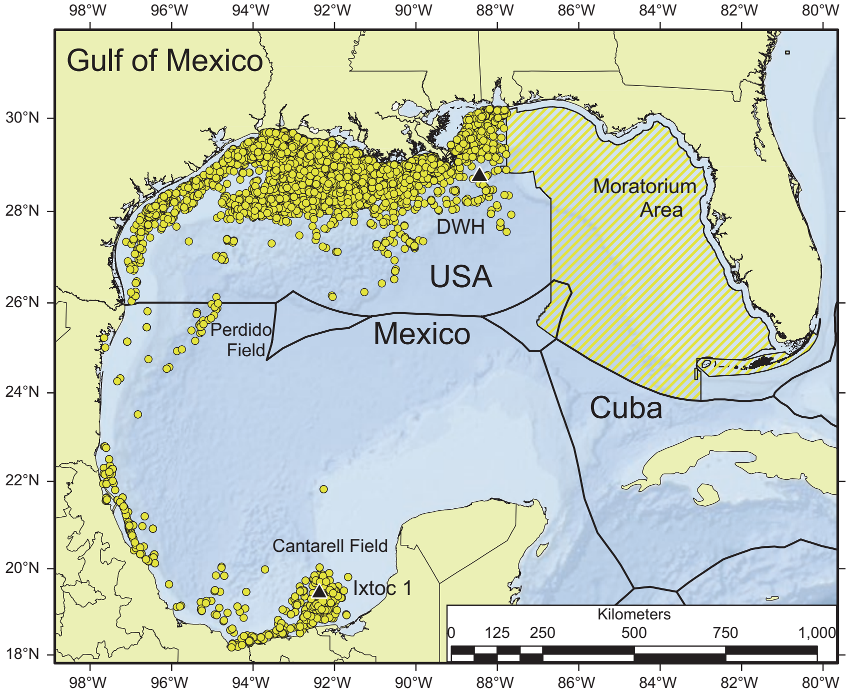

Fig. 2.1 Geographic distribution of offshore oil and gas infrastructure facilities (yellow circles) in the Gulf of Mexico (GoM), 2017. (Data are from BOEM and PEMEX). Also illustrated are the exclusive economic zone (EEZ) boundaries between the USA, Mexico, and Cuba, as well as the US Congressional moratorium boundary on new oil and gas drilling (applicable until 2022). The locations of the Ixtoc 1 and *Deepwater Horizon* (DWH) oil blowouts are plotted as black triangles

considerations are where and under what circumstances such a deepwater blowout might again occur. Using the eight-decade history of marine oil and gas exploration and production from the GoM, including documentation from the USA and Mexico, we review the history and trends in spatial distribution, production, utilization, and management of the Gulf's oil industries. We also provide global perspectives on deepwater oil development and thus where in the world deep spill responses are most likely to be necessary.

2.2 History of Oil Development and Production in the Gulf of Mexico

Marine oil and gas development in the GoM was initiated in 1938 with the construction of a 320 × 180 ft wooden deck from which a drilling derrick sank a well in 4 m (14 ft) of water. The initial Superior-Pure State No. 1 well was located about a mile offshore of Creole, Louisiana (AOGHS 2018; Duncan et al. 2018). It successfully produced oil but was destroyed by a hurricane in 1940, then subsequently rebuilt, and put back into production. In 1947 Kerr-McGee drilled the first marine oil well out of sight of land in 6 m of water 10 miles from shore. This well would eventually yield 1.4 million stock tank barrels (=42 gallons, defined at sea level pressure) and 307 million ft^3 of natural gas (AOGHS 2018). By the end of 1949, there were 11 oil and natural gas fields in the northern GoM (AOGHS 2018). A critical management issue resolved in the 1940s and early 1950s was the ownership of so-called tidelands (Austin et al. 2008), finally investing the authority to sell leases and regulate the offshore industry extensive of state territorial waters, in the federal government, through the Outer Continental Shelf (OCS) Lands Act of 1953. The OCSLA defines the OCS as all submerged lands lying seaward of state coastal waters which are now under the US jurisdiction (Austin et al. 2008). The OCSLA thus substantially predated the establishment of the 200 nm exclusive economic zone (EEZ) by the USA in 1980 (Fig. 2.1), which asserted control over a wider variety of natural resources.

Between the 1940s and the 1970s, the US oil industry in the GoM gradually evolved to mid-continental shelf depths (Table 2.1) as technology advanced and larger plays of higher producing oil and gas were discovered. Annual oil production increased between the 1940s and 1970s from about 7 million barrels per year (MBPY) in the 1950s to about 290 MBPY in the 1970s (Table 2.1; Fig. 2.2). Throughout this period, the technology for exploratory drilling evolved but was primarily based on derricks fixed to the ocean bottom or so-called "jack-up" rigs, consisting of a platform the legs of which could be systematically lowered to the sea bottom to support drilling operations, but subsequently jacked up and moved to other locations. These types of MODUs (Mobile Offshore Drilling Units) are appropriate for water depths to about 200 m. During the 1970s to the early 1990s, total oil production was stable, but the maximum depths of wells increased to about 700 m in the 1980s and 1300 m in the 1990s. This necessitated the development of drilling

Table 2.1 Total oil production by decade and water depths of extraction from US waters of the Gulf of Mexico, 1948–2018

Years	Total production (million barrels)	Mean depth (m)	Median depth (m)	Maximum depth (m)	Proportion from ultra-deep waters (>1500 m)
1947–1949	0.28	7	6	17	0.00
1950–1959	70.24	17	14	59	0.00
1960–1969	1324.06	26	19	159	0.00
1970–1979	2888.99	42	34	399	0.00
1980–1989	2727.25	81	56	728	0.00
1990–1999	2966.50	250	79	1337	0.00
2000–2009	4261.41	869	790	2432	0.15
2010–2018*	3984.04	1346	1355	2936	0.41
2017	587.15	1510	1670	2936	0.52

Depths are the maximum lease block depths as reported to BOEM/MMS. The data for 2018 (*) include only the months of January and February

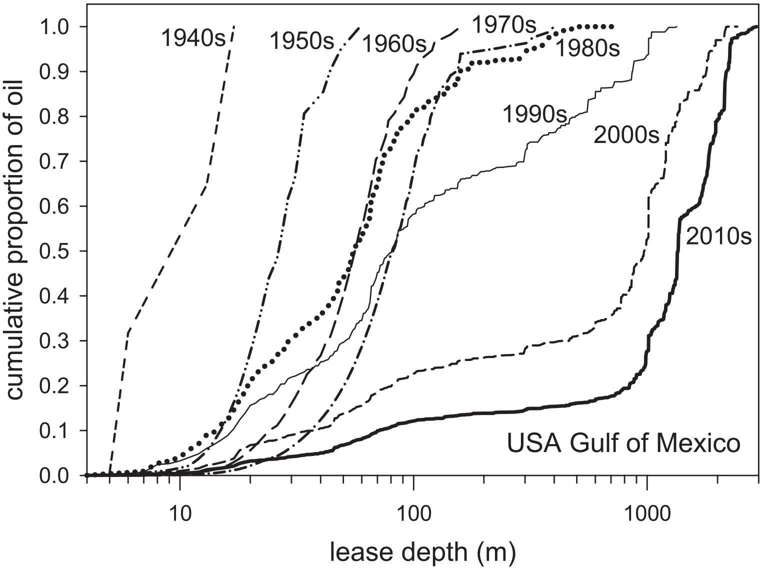

Fig. 2.2 Cumulative decadal oil production (Table 2.1) by maximum lease depth in US waters of the GoM, 1948–2017. (Data are derived from the Bureau of Ocean Energy Management (BOEM): https://www.data.boem.gov/)