Cambridge University Press
978-1-107-02717-6 - Oil in the Environment: Legacies and Lessons of the Exxon Valdez Oil Spill
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PART I

INTRODUCTION AND BACKGROUND

INTRODUCTION

Every oil spill is different from the ones that preceded it. This is due in part to differences in the spill itself – the nature of the oil and the circumstances of the release – but it also stems from differences in the context of the spill – the setting, the resources at risk, and how people respond to the spill. All of these factors affect how science is brought to bear on investigating the spill and its consequences.

The two chapters in this section consider these factors in two ways. Chapter 1 (to which many of the authors contributed) introduces the environmental setting of the *Exxon Valdez* oil spill, what happened during the spill and to the oil that was released, the cleanup responses and the launch of scientific studies, and the regulatory and legal context of the spill responses and studies. Separate discussions consider: the characteristics of crude oil; the importance of assessing exposure of biota to the oil in gauging potential effects; the thorny issue of defining "impact," "effect," "injury," and "recovery"; and the legal issues that followed from the spill.

In Chapter 2, Paul Boehm, Erich Gundlach, and David Page take a broader view. When oil is released in a marine environment, it immediately begins to undergo transformations resulting from a variety of physical and chemical processes. Although these changes are continuous, they can be separated into three overlapping phases that align with shifts in the focus of scientific studies over time. Recognizing these phases can help to plan which studies to conduct, and when. This, in turn, can facilitate an efficient and effective allocation of research efforts.

CHAPTER ONE

Introduction and background

John A. Wiens

1.1 Introduction

In the aftermath of an oil spill, the effects on the environment and wildlife are often painful to see. After the initial emotional impact come the questions: What wildlife and environments are at risk, and when will they recover? How can the oil be removed without causing further harm? Is it safe to eat the seafood or to be on the beaches? What will happen to the oil? Science can offer objectivity, rigor, and focus in addressing such questions, helping to separate fact from fiction, evidence from conjecture. A science-based approach defines potential spill effects and then formulates testable hypotheses, follows an unbiased study design, collects and analyzes data using rigorous methods, and interprets the results with a mind open to alternative explanations that evolve during the investigations. This is how good science is done.

Conducting science following the *Exxon Valdez* spill was not always easy, however. Along with everyone else, the first scientists on the scene were distraught over what they saw – shorelines awash with oil, oiled seabirds and sea otters (*Enhydra lutris*) struggling to survive, and fisheries closed for fear of contamination. It was challenging to come up with good, objective study designs. The remote location of the spill and the wide variation among places in the spill zone complicated data collection. Studies conducted at different times or of different durations produced different results, and relationships documented at different spatial scales did not always match. Study designs often seemed to be confounded by other factors or uncontrolled sources of variation at every turn, making it difficult to separate changes in the environment due to the oil spill from changes due to other, unrelated factors.

This book is about how the investigations of the *Exxon Valdez* oil spill carried out by multiple parties met these challenges. Much was learned in the process. These lessons and scientific insights provide essential guidance for designing responses and assessing the consequences of future spills or, indeed, of any large environmental disruptions.

In this introductory chapter, we set the stage by describing the geographical, physical, environmental, and cultural settings of the *Exxon Valdez* spill. We discuss the event and what happened to the oil over time. We emphasize the importance of

Oil in the Environment: Legacies and Lessons of the Exxon Valdez *Oil Spill*, ed. J. A. Wiens. Published by Cambridge University Press.

documenting the pathways by which organisms might be exposed to oil or its toxic[1] components and the value of clear, operational definitions of *impact*, *effect*, *injury*, and *recovery*. Finally, we touch very briefly on the regulatory and legal context of responses to the spill.

1.2 The setting: the northern Gulf of Alaska and Prince William Sound

The northern Gulf of Alaska (GOA), in the northeastern corner of the Pacific Ocean, is bounded to the east by southeastern Alaska and to the west by Kodiak Island and the Alaska Peninsula (see Map 1, p. v). It is a diverse, highly productive ecosystem that includes one of the world's largest fisheries (Spies, 2007; Gaichas *et al*., 2009).[2] Because Prince William Sound (PWS) was the most heavily oiled part of the northern GOA and the vast majority of scientific studies of the effects of the *Exxon Valdez* oil spill were conducted there, we focus on the Sound throughout this book.

1.2.1 Geography and geology

Prince William Sound is a large, semi-enclosed estuary ecosystem east of the Kenai Peninsula and south of the Chugach Mountains of the Pacific Coast Ranges (see Map 2, p. vi). It is a place of stunning natural beauty surrounded by rugged mountains (see frontispiece). Tidewater glaciers calve icebergs into its northern reaches. Human settlements are sparse and scattered – only five were documented in the 2010 US census: Valdez (population 3976), Cordova (2239), Whittier (220), Tatitlek (88), and Chenega (76). There are some 4800 km of shoreline in an area of only 9000 km^2 (Adams *et al*., 2002), with forests, high tides, and winter storms restricting most rocky beaches to narrow strands. Islands and shorelines on the western side of PWS are sharply dissected by numerous bays and deep fjords, whereas topography and bathymetry on the eastern side of PWS are more gradual, and the shoreline is less dissected (see http://www.charts.noaa.gov/OnLineViewer/16700.shtml).

Water from the Alaska Coastal Current enters PWS from the GOA through Hinchinbrook Entrance and leaves through Montague Strait and Knight Island Passage (see Map 1, p. v) 2 to 3 weeks later (Royer *et al*., 1990). PWS is also fed by melting glaciers in the surrounding watershed and by coastal rain and snowfall (which can exceed 4 m in normal years and more than 10 m in exceptional years). Most of the glaciers, particularly large ones such as the Columbia Glacier, are in the mountainous areas bordering PWS to the north and west. They are responsible for most of the freshwater entering PWS.

The complex flows and mixing of fresh and marine water, combined with daily tidal fluctuations of up to 6 m, create the foundation for substantial marine productivity. This productivity varies considerably among locations, but it is higher where the Alaska

[1] To paraphrase Paracelsus, who lived in the sixteenth century and provided the basis for both modern medicine and ecotoxicology, there is nothing that is not a poison – depending on the dose. The word "toxic" is used in various chapters of this book with this reality in mind – the chemicals associated with spilled oil can be toxic or they may not be, depending on the dose.
[2] Additional details about the oceanography, geology, and biology of the GOA are provided in Mundy (2005) and Spies (2007).

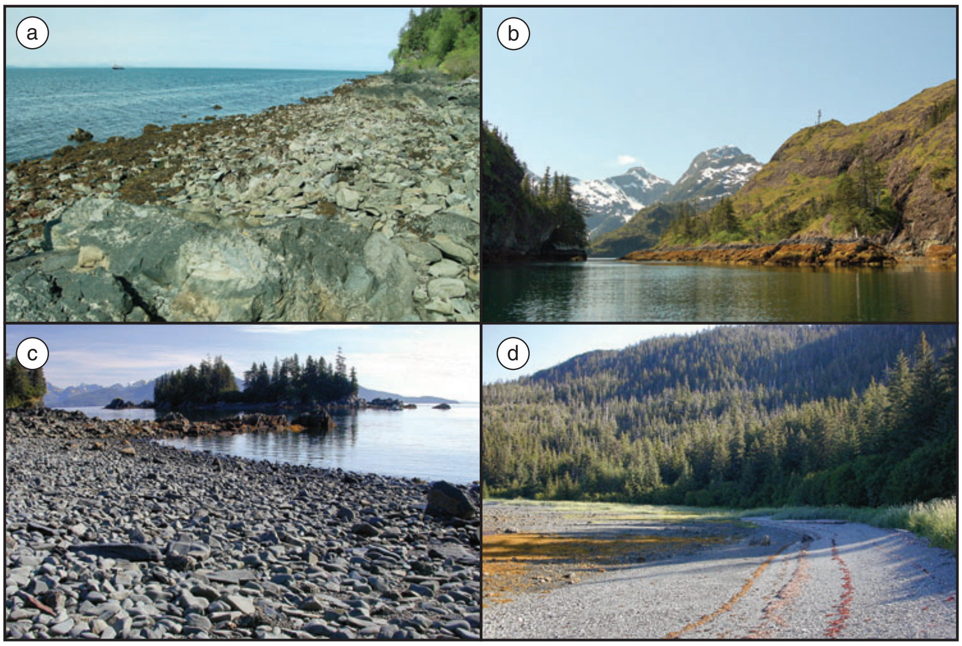

Figure 1.1 Examples of shoreline types in PWS. (a) Exposed bedrock/rubble, north Smith Island, 2007. (b) Sheltered bedrock/rubble, southeastern Herring Bay, 2007. (c) Exposed boulder/cobble, northeastern Evans Island, 2002. (d) Mixed pebble/gravel, Foul Pass, Ingot Island, 2004 (Photos: David S. Page).

Coastal Current creates warmer and more saline waters to the east and south than in the glacial waters to the north and west (Royer *et al.*, 1990).

The principal sources of subtidal sediments in PWS are streams and rivers to the east of PWS. Some of these sediments come from areas containing active natural petroleum seeps, such as those to the east of the Copper River delta near Katalla (Map 2, p. vi; Chapter 6). In addition, the Copper River discharges an estimated 107 million tons of sediment into the Alaska Coastal Current annually (Reimnitz, 1966). Suspended sediments are transported westward along the coastline, some entering PWS through Hinchinbrook Entrance (Royer *et al.*, 1990), where they fall to the seafloor. Local sediment input from glaciers, by comparison, is small (Sharma, 1979).

Shorelines in PWS are generally narrow, although there are large tidal flats in some eastern parts of PWS. Metamorphic rocks form island landmasses in the central part of western PWS. The intertidal zone is often steep, particularly on islands bordered by deep fjords. Hillsides above the tidal zone are similarly restricted by rocky cliffs that abut dense forest. The underlying geology is composed of sedimentary rocks that are interbedded with volcanic rocks (both extrusive and intrusive; Wilson and Hults, 2008). Shoreline substrates in PWS are diverse, ranging from small pebbles, gravel, sand, and mudflats (in a few places) to large boulders, exposed rocky shelves, cliffs, and steep talus slopes (Fig. 1.1).

Shoreline substrates in western PWS differ from those of eastern PWS. The spill zone shoreline – located entirely in western PWS – consists largely of sheltered and exposed bedrock and bedrock/rubble, with boulder/cobble/gravel and mixed pebble/gravel beaches making up almost all of the remaining shoreline (Chapter 6). The sand/gravel beaches that dominate the eastern part of PWS are largely absent (Page *et al.*, 1995).

Most shorelines are eroding; consequently, unless protected by surface bedrock/rubble or boulder/cobble/gravel armoring, shoreline sediments tend to be coarse.

1.2.2 The environment

Severe winter storms buffet the shorelines of PWS. Where wave exposure is low, the distribution of shoreline plants and invertebrates is determined largely by competition for space, predator–prey interactions, and resistance to physical stress. Where wave exposure is high, loose sediment particles – or even small boulders – can become missiles in high waves (Shanks and Wright, 1986). Logs, ice, and glacial bergs may further scour the shoreline, disrupting biotic communities and creating spaces open to colonization. The dominance of physical stress and disturbance results in a mosaic of species whose existence in a location is less a function of their competitive edge than their colonizing ability, the timing of their breeding cycle, and the vagaries of wave action and shoreline disturbance (Connell, 1961; Paine, 1966; see Chapter 11, Fig. 11.1).

Weather and ocean conditions in PWS are affected by broad-scale oceanographic phenomena, such as El Niño–Southern Oscillation events (Mantua *et al*., 1997; Mantua and Hare, 2002), as well as changes operating over longer periods (Finney *et al*., 2002). El Niño events have become more frequent, and La Niña events less frequent, since the 1970s (Trenberth and Hoar, 1996, 1997). Recent warming and freshening of waters in the northern GOA, possibly associated with increased coastal freshwater flows from melting glaciers and wind forcing associated with climate change, have led to a westward shift in oceanic isotherms that may have broad-scale, regional impacts (Royer and Grosch, 2006). Sudden shifts in atmospheric and broad-scale oceanographic conditions ("regime shifts") have occurred in the northern Pacific several times in the last 50 years (Peterson and Schwing, 2003; Litzow, 2006), leading to shifts in species' distributions, community composition, and food chains (Francis and Hare, 1994; Anderson and Piatt, 1999; Trites *et al*., 2006; Springer, 2007). In addition to the large regime shifts of 1976–77, major regime shifts occurred in 1989 (the year of the *Exxon Valdez* spill) and 1998 (Hare and Mantua, 2000; Overland *et al*., 2008). The Pacific Decadal Oscillation, which has broad-scale effects on sea-surface temperatures, has also undergone at least one phase shift since 1989 (Yatsu *et al*., 2008). This phase shift caused changes in freshwater input into the northern GOA, affecting salmon and other keystone species (Royer *et al*., 2001).

Spatial variation is also pronounced. At a broad scale, the eastern and western parts of PWS differ not only in topography and depth, but also in habitat, as exemplified by variation in the number and length of salmon spawning streams (the east has more, longer streams; Wiens *et al*., 2010; Alaska Department of Fish and Game, 2012). At a finer scale of tens of kilometers, areas such as parts of Knight Island (see Map 3, p. vii) differ in both physical features (e.g., number of islands and islets, shoreline substrate, steepness of the adjacent land) and biological attributes (e.g., cover of intertidal rockweed, *Fucus* spp.). At even finer scales, stretches of shoreline may have a heterogeneous mixture of habitats within even a few tens of meters (e.g., Fig. 1.1c).

Natural ecosystems are unstable, and not all changes are gradual: single, unpredictable events can have profound impacts. This is perhaps nowhere more evident than in portions of western PWS, where the 5-minute, 9.2-magnitude Great Alaska Earthquake on March 24, 1964, and the consequent tsunami fundamentally altered the geomorphology, bathymetry, and ecology of PWS (Plafker, 1965; Haven, 1971; Losey, 2005). Many parts of PWS were uplifted, some, as around Montague Island, by as much as 10 m

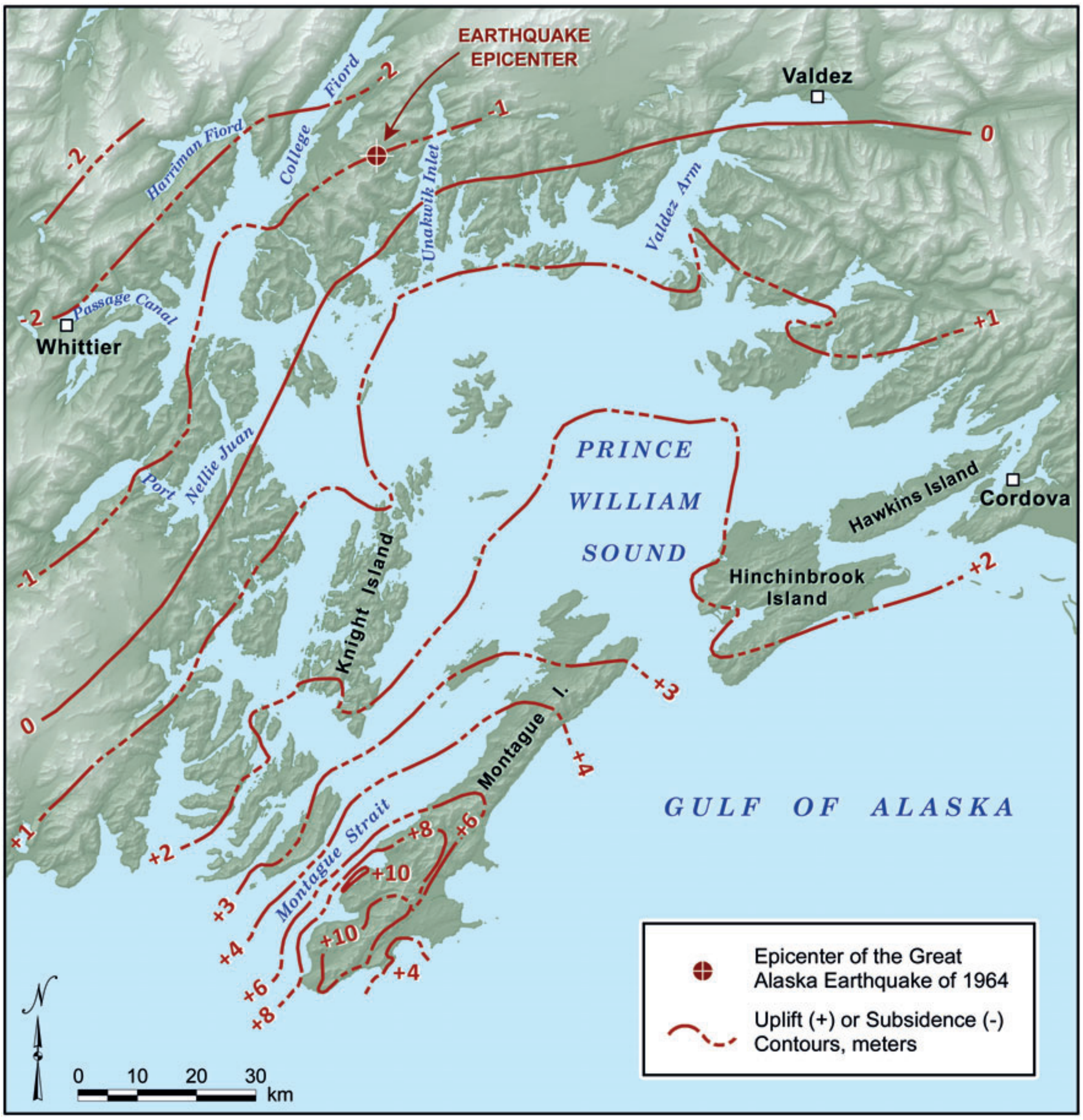

Figure 1.2 Ground deformation in Prince William Sound resulting from the 1964 Alaska earthquake (adapted from Plafker, 1969).

(Reimnitz and Marshall, 1965). The extent of uplift or subsidence varied substantially among different parts of PWS (Fig. 1.2; Haven, 1971). These changes had long-term effects on habitat suitability for a variety of organisms (Losey, 2005; Blanchard *et al.*, 2010).

The earthquake and tsunami also destroyed settlements and structures throughout PWS, including much of the towns of Valdez and Old Chenega Village (which was abandoned as a result), as well as canneries, sawmills, mines, and other facilities. Ruptured fuel-storage tanks released significant quantities of petroleum products into intertidal shoreline and subtidal areas (Wilson and Torum, 1972). These processes continue even now (Chapters 5, 6).

1.2.3 Human history

Although people have occupied and altered coastal areas of PWS for millennia, human cultures of the ancient past are known from only a handful of archaeological excavations (de Laguna, 1956; Yarborough and Yarborough, 1996; Yarborough, 1997). These archaeological sites record eons of social adaptations to an ever-fluctuating maritime environment, including the remarkable skin-boat and sea-mammal hunting cultures developed by ancient maritime people (Fitzhugh and Chaussonnet, 1994; Yarborough and Yarborough, 1998). The oldest phase of occupation dates to 4400–3300 years before the present, and several other cultural phases followed before contact with Europeans and Americans in the eighteenth century.

The "postcontact" cultural history of the region began in 1741, when a Russian expedition led by Vitus Jonassen Bering, a Danish-born navigator in the Russian navy, landed just outside of PWS at Kayak Island. Georg Wilhelm Steller, a German naturalist and physician on the voyage, went ashore briefly (thereby becoming the first European to set foot on Alaskan soil), noted a small structure, and left trade beads and other items as token gifts, but he did not directly interact with the native people. (Steller also described what later became known as Steller's jay, *Cyanocitta stelleri*, and Steller's sea lion, *Eumetopias jubatus*.)

Russia's interest in PWS was not renewed until 1760, when sea otters had become scarce around the Aleutian Islands, which were much closer to Russia. In 1781, Grigory Shelikov and other merchants organized the North-Eastern America Company. The first Russian settlement in Alaska, at Three Saints Bay on the southeastern coast of Kodiak Island, was founded in 1784.

Meanwhile, fearing Russian expansion, Spain had been sending expeditions from Mexico as far north as PWS between 1774 and 1791. In 1790, explorer Salvador Fidalgo named Port Valdez. Also during this period, England sent Captain James Cook to find the Northwest Passage that would connect the Atlantic and Pacific oceans through the Arctic Ocean. Captain Cook arrived in PWS in 1778 and named many of its geographic features: Hinchinbrook and Montague islands, Bligh[3] Reef (the site of the *Exxon Valdez* grounding), and Sandwich Sound (later changed to Prince William Sound by the editors of Cook's maps).

The late 1700s to early 1800s featured warfare and epidemic disease among the indigenous people, creating widespread social upheaval. At roughly the same time, the maritime fur trade brought English, Spanish, French, Dutch, and American ships. The local, native cultures were fused into a new quasi-commercial, culturally mixed subsistence economy. Russian Orthodox communities of mixed Alutiiq, Aleut, and Euro-American ethnicity began to predominate, with the Alutiiq and Aleut members coming from areas to the west to hunt sea otters and seals.

Industrial-scale commercial whaling began in the mid-1800s, followed in the 1880s by the rapid development of commercial fishing and fish processing. Serbian, Italian, Scandinavian, and Midwestern American cultural influences affected life in PWS. Copper prospecting and mining, fur ranching, gold mining, fish salting and canning, infrastructural support, transportation services, and maritime supply (including petroleum products) transformed the region politically, economically, and culturally. This period saw considerable ecological and environmental impacts, and many industrial archaeological sites in the region date to this era (Wooley, 2002; see Chapter 5, Fig. 5.4).

[3] Named after Cook's sailing master, William Bligh, of *Mutiny on the Bounty* fame.

Salmon (*Oncorhynchus* spp.) and Pacific herring (*Clupea pallasii*) fisheries in PWS developed in the late 1800s and early 1900s, expanding rapidly with the demand for canned salmon during World War I. Canneries and other processing facilities were established at several locations throughout the western part of PWS. Overfishing caused fisheries to decline, and the last cannery in PWS ceased operating in 1959. In time, the fisheries recovered, and in 1988, the year before the *Exxon Valdez* spill, the PWS salmon fisheries harvested over 14.9 million fish (of all species), valued at approximately $80 million; at the same time, the Pacific herring fisheries harvested approximately 12 000 tons of herring roe and fish, valued at almost $12 million (Brady *et al.*, 1990).

A new era of human activity in PWS began on March 13, 1968, when Atlantic Richfield Company and Humble Oil and Refining Company (an Exxon company) announced their discovery of oil in Alaska's Prudhoe Bay, 1300 km from PWS. Four months later, an Atlantic Richfield–Humble team began to investigate the feasibility of a pipeline to carry Prudhoe Bay crude oil to the Port of Valdez for tanker transport to the lower 48 states. The Trans Alaska Pipeline Act became law on November 16, 1973; the first pipe was laid on March 27, 1975; and the first oil moved through the pipeline on June 20, 1977. The 122-cm pipeline still carries crude oil from Prudhoe Bay to the Alyeska Pipeline Service Company's PWS tanker terminal in Valdez, currently North America's most northern ice-free port.

1.3 The event: the *Exxon Valdez* oil spill

At 9:21 p.m. on March 23, 1989, the *T/V Exxon Valdez*, loaded with 53 million gallons (~200 million liters) of Alaska North Slope crude oil, cleared the dock at Valdez bound for Long Beach, California. Shortly after midnight, it grounded on Bligh Reef in PWS, spilling some 11 million gallons (40 million liters) of its cargo (Leschine *et al.*, 1993).[4] The spilled oil would affect some 2100 km of shoreline in PWS and the GOA (Neff *et al.*, 1995) (see Map 1, p. v). The spill path included only areas in western PWS, leaving the eastern side untouched. An estimated 40% of the spilled oil was stranded on 783 km of shoreline (about 16% of the total shoreline of PWS; Wolfe *et al.*, 1994; Neff *et al.*, 1995; Chapter 4). The remainder evaporated or was carried out into the GOA (Chapter 3).

1.3.1 What is crude oil?

One reason that every oil spill is unique is because each crude oil is itself unique in its composition and physical properties. Crude oils are natural products, complex mixtures of thousands of compounds made up of carbon and hydrogen (hydrocarbons), plus other compounds containing sulfur, oxygen, nitrogen, and metals. Because the oils have physical and chemical properties that affect their persistence and toxicity in the environment, defining those properties and how they change with time is essential to assessments of environmental impacts. Box 1.1 highlights some fundamental properties of petroleum crude oils and how they can vary with respect to their physical characteristics, chemistry, and extent of weathering. This box also provides some important technical details specific to Alaska North Slope crude, to which several chapters in this book refer.

[4] The circumstances and consequences of the *Exxon Valdez* oil spill have been discussed and reviewed from a variety of perspectives in a large number of publications (see online bibliography) and several books (e.g., Davidson, 1990; Keeble, 1991; Smith, 1992; Loughlin, 1994; Wheelwright, 1994; Owen *et al.*, 1995; Wells *et al.*, 1995; Rice *et al.*, 1996; Lebedoff, 1997; Leacock, 2005; Ott, 2005, 2008; Spies, 2007; Coll, 2012).