1 • Introduction to seabed fluid flow

> Discovery commences with the awareness of anomaly, i.e. with the recognition that nature has somehow violated the paradigm-induced expectations that govern normal science.
>
> Kuhn, 1970

This chapter introduces the concept that seabed fluid flow is a widespread and important natural process. It has important consequences for subseabed and seabed geological features, and also for marine biological processes, and the composition of the oceans. Seabed fluid flow provides both hazards and benefits for human activities, and it is recognised that some sites are precious and need protection.

Earth scientists remember the 1960s as the decade of the plate tectonics 'revolution'. In the same decade, the discovery of two remarkable seabed features; hydrothermal vents and pockmarks, provided evidence of extensive emissions of fluids from the seabed. Since then there has been a growing awareness that dynamic geological processes, driving the exchange of fluids across the seabed–seawater interface, are of fundamental importance to the nature and composition of the 'marine system'; not only to marine geology, but also to the chemical and biological composition of the oceans. Today as in the geological past, seabed fluid exchange is as important as the interactions between the oceans and atmosphere. Gas bubble streams and columns of coloured or shimmering water, mineral crusts and chimneys, and biological communities that thrive without the aid of sunlight are all evidence of 'seabed fluid flow'.

Spectacular discoveries made during investigations of ocean spreading centres like the East Pacific Rise and the Mid-Atlantic Ridge have turned upside-down concepts of how our planet works. On the continental shelves, and more recently in the deeper waters of the slope and rise, the oil industry has not only driven technological advances, but has also been responsible for an increasing awareness of the fundamental role of fluids in sedimentary processes. Tryon *et al.* (2001) pointed out that: '*Subsurface fluid flow is a key area of earth science research, because fluids affect almost every physical, chemical, mechanical, and thermal property of the upper crust*'. They went on by saying that research in the deep biosphere, gas hydrates, subduction zone fluxes, seismogenic zone processes, and hydrothermal systems all are '*directly impacted by the transport of mass, heat, nutrients, and other chemical species in hydrogeological systems*'.

Mankind's activities, particularly during the last century, have resulted in increasingly serious pollution of the marine environment. Some of the principal causes relate to the petroleum industry, yet natural processes have been responsible for petroleum 'pollution' for a far greater period of time. In the Bible God instructed Noah to make an ark and '*coat it inside and out with pitch*' (Genesis 6:14). Indigenous populations from parts of the world where seeps occur have made good use of the special properties of natural petroleum products; Native Americans in California used 'asphaltum' to caulk their canoes, hold together hunting weapons and baskets, for face paints, and even chewing gum (USGS, 1999). The 'eternal flames' of natural gas seeps in Azerbaijan and elsewhere are central to the Zoroastrian faith.

Such seepages gave the first indications of the presence of petroleum in most of the world's petroleum-producing regions (Link, 1952). Indeed, Link considered that at least half the reserves proved by 1952 were discovered by drilling on or near seeps. But petroleum seeps are not confined to the land. Great lumps of floating tar, such as that illustrated in Fig. 1.1, caused the Romans to call the Dead Sea *Mare Asphalticum*, and early navigators of the Gulf of Suez, the Gulf of Mexico, the Californian coast, and many other parts of the world's oceans discovered oil slicks and tar-polluted beaches centuries before the modern oil industry was

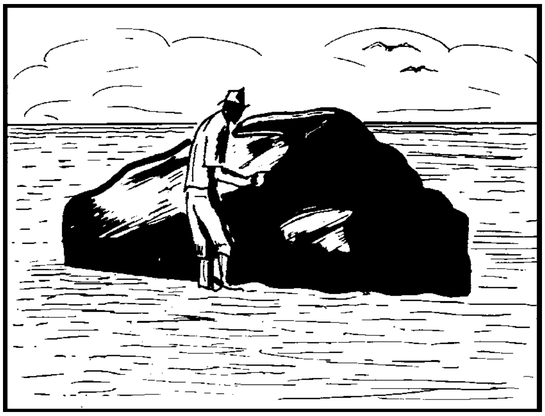

Figure 1.1 A giant lump of tar found on the shore of the Dead Sea. Numerous warm groundwater seeps are known to occur in the area. It seems that there are also hydocarbon seeps. (From Hovland and Judd, 1988; sketched from a photograph in Landes, 1973.)

founded and oil-powered ships and tankers were introduced (Soley, 1910; MacDonald, 1998). Kvenvolden and Cooper (2003) reported that natural seepage introduces between 0.2 and 2.0 × 10^6 (best estimate 0.6 × 10^6) tonnes of crude oil per year into the marine environment. This is about 47% of all the crude oil currently entering the marine environment; mankind is responsible for the rest. Hornafius *et al.* (1999) estimated that the present-day natural hydrocarbon seeps in Santa Barbara Channel, California are a significant source of air pollution, the flux being '*twice the emission rate from all the on-road vehicle traffic in Santa Barbara County*'.

Petroleum seeps are not the only form of seabed fluid flow that has been known for thousands of years. Taniguchi *et al.* (2002) identified the following ancient reports of submarine groundwater discharge:

- The Roman geographer, Strabo, who lived from 63 BC to AD 21, mentioned a submarine spring (fresh groundwater) 2.5 miles offshore from Latakia, Syria (Mediterranean), near the island of Aradus. Water from this spring was collected from a boat, utilising a lead funnel and leather tube, and transported to the city as a source of fresh water.
- Pliny the Elder (first century AD) reported submarine '*springs bubbling fresh water as if from pipes*' along the Black Sea coast.
- Pausanius (second century AD) told of Etruscan citizens using coastal springs for 'hot baths'.

Historical accounts tell of water vendors in Bahrain collecting potable water from offshore submarine springs for shipboard and land use.

Considering the long history of knowledge of petroleum and freshwater seeps, it is perhaps remarkable that hydrothermal vents and chemosynthetic biological communities have been discovered so recently. However, they are not the only features hidden in the ocean depths, out of reach of all but the most recent technology. Vogt *et al.* (1999a) made a comparison, highlighting the progress made in one decade between the contents of *The Nordic Seas* (Hurdle, 1986), and current understanding. They noted that: '*Two thirds of that 777-page volume was devoted to topography and geology . . . yet the words "methane", "hydrate", "pockmark", "gas vent or seep", "chemosynthesis", and "mud volcano" do not appear even once in the 42-page subject index*'.

The development in the mid 1960s of the side-can sonar and towed photographic cameras made widespread high-resolution seabed mapping possible, while the parallel development of high-resolution seismic profilers extended this mapping to include the sub-seabed sediments and rocks. More recently multibeam echo sounders (MBESs), manned and remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), and many more sophisticated instruments have enabled more rapid and detailed inspection of survey areas and individual seabed locations. These developments have enabled the pace of discovery to increase progressively. Features that were only recently regarded as geological curiosities are now known to be widely distributed geographically, from the coasts to the ocean depths, and through geological time. It is amazing how far knowledge of the seabed has advanced in little more than 60 years since the following words were written:

> In 1911, Fessenden made the first attempts to determine depths by sonic methods, and from about 1920 sonic depth finders have been in use with which soundings can be taken in a few seconds from a vessel running full speed. This new method has in a few years completely altered our concept of the topography of the ocean bottom. Basins and ridges, troughs and peaks have been discovered, and in many areas a bottom topography has been found as rugged as the topography of any mountain landscape.
>
> Sverdrup *et al.*, 1942

Figure 1.2* Seep bubbles emerging from the seabed. This photograph, taken in 1983, shows the first seeps identified in the North Sea, at Tommeliten (Block NO1/9, North Sea). The location is situated above the Delta salt diapir. Gas bubbles emanate from small, funnel-shaped craters in the sand-covered seabed. (From Hovland and Judd, 1988.)

Today's technology facilitates not only detailed 3D mapping, but also sampling and visual inspection, revealing features Sverdrup could not have dreamed of. This technology now permits an appreciation of how widespread emissions of water, petroleum fluids, and hydrothermal fluids are; it also enables associated features such as mineralised chimneys and chemosynthetic biological communities to be sampled and investigated. Only now is the importance of the natural processes responsible for them being realised in marine science.

It was through our curiosity towards pockmarks that we became aware of the importance of seabed fluid flow. An initial appraisal of pockmarks, in Chapter 2, is an account of the pockmark investigations of the Scotian Shelf and the North Sea that provided us with a preliminary insight into seabed fluid flow. This research, undertaken in the 1970s and 1980s, led us to realise the significance of pockmarks as indicators of fluid flow, and documented North Sea gas seeps (Figure 1.2) and the associated carbonates and benthic fauna for the first time. Chapter 3 (supported by maps provided in the web material) is a review of some key sites around the world that have provided evidence critical to the development of our present understanding of seabed fluid flow. It emphasises the relationship between the natural processes (geological, biological, physical, and chemical) involved, and shows that the study of this topic is not possible without crossing traditional scientific discipline boundaries. It is clear from Chapter 3 that seabed fluid flow is widespread, and that various types of fluid are involved. This book is concerned with three main types of fluid:[1] hydrothermal fluids

[1] It is not uncommon in the literature to find '*gas and fluids*' mentioned as if they are separate phases. They are not. The Oxford English dictionary defines a fluid as '*a substance that is able to flow freely, not solid or rigid*', and specifically states that this includes both liquids and gases. So, throughout this book when we refer to fluids we mean both gases and liquids. However, direct quotes do not necessarily conform to this standard.

generated by the circulation of seawater through the cooling igneous rocks of ocean-spreading centres and submarine volcanoes; gases, particularly methane, generated in marine sediments; and groundwater flowing from catchment areas on land. Perhaps it is normal to deal with each of these fluid types separately. However, although major differences, for example in temperature and chemical composition, result in contrasting behaviour, many processes and associated features are either common, or so closely related that it is hard to consider one without mentioning the others. So, we consider the cycles of generation, migration, and utilisation or escape of these three fluid types, pointing out the similarities and contrasts between them, and the overall significance of seabed fluid flow. Our objective is to be inclusive rather than selective.

It is remarkable how common seabed fluid flow is. As we show in Chapter 4, the examples described in Chapter 3 come from every seabed environment from coastal waters down to the deep ocean trenches. Also, seabed fluid flow is integral to every marine plate-tectonics setting: hydrothermal venting is part of the system that cools igneous rocks at plate boundaries; mud volcanoes and seeps permit the compaction of sediments trapped in the accretionary wedges (prisms) of convergent boundaries; buoyant hydrocarbon fluids escape from intra-plate sedimentary basins through seeps. The nature and origins of the various types of fluid (discussed in Chapter 5) are largely a function of these contexts, and the geological and biological processes operating in them. So, where igneous processes dominate, hydrothermal fluids are formed by the interactions between pore fluids and hot rocks. In sedimentary basins the most significant fluids are hydrocarbons, particularly methane, formed by the degradation of organic matter held within the sediments.

At this point it is appropriate to clarify some terminology. The word ‘biogenic’ is commonly used, particularly by geoscientists, when referring to methane that has been derived by the activity of micro-organisms, as opposed to ‘thermogenic’ methane, derived from processes occurring deeper within the sediments. However, in the biological sciences ‘thermogenic’ methane is also regarded as being ‘biogenic’ because the source materials are of organic origin; thus ‘biogenic’ is distinct from ‘abiogenic’, formed without the involvement of living organisms. We will avoid this confusion by avoiding the word ‘biogenic’ altogether. Instead we distinguish between ‘thermogenic’ and ‘microbial’ methane. This also avoids the use of ‘bacterial methane’, which is generally incorrect as microbes, ‘minute living beings’, which generate methane, are actually archaea, not bacteria. However, although these are definitions we stick to, quotations from other authors may imply something different; we do not wish to modify other people’s words.

Methane, formed during sediment burial, is buoyant and therefore inclined to migrate towards the surface. Although seepage is a natural result of this migration, geological conditions often result in the formation of accumulations. In deep water, temperature and pressure conditions favour the formation of gas hydrates that also inhibit migration. In order to understand the distribution of seeps in both space and time it is essential to appreciate how and why these accumulations form, and how to identify them. We address these issues in Chapter 6. Diatremes, mud diapirs, gas chimneys, and mud volcanoes form as a result of the pressure that builds up in some subseabed gas accumulations. However, the nature of the migration mechanism is dependent on the stress environment within the sediments. In some places migration is a much more gentle process, and the plumbing system may lead to pockmarks, or to seeps with no associated seabed morphological features at all. As we discuss in Chapter 7, the style of migration and seabed escape is determined by interactions between many factors. Fluid flow is clearly a dynamic process.

Perhaps the most amazing biological discovery of the twentieth century was made in 1977 when deep-ocean chemosynthetic communities were found at the Galapagos Rift. Until then it was inconceivable that life could exist without benefiting from the Sun’s energy. Although such communities are probably rare, they are clearly widespread and, as we discuss in Chapter 8, they are not confined to ocean spreading centres or to hydrothermal vents. The principal effect of petroleum seeps, particularly those of the shelf seas, might be expected to be the pollution of the seabed sediments and the overlying waters. This is not the case. Similarities between hot-vent and cold-seep communities are remarkable, as is the suggestion that the first life on Earth may have relied on chemosynthesis. Is photosynthesis a relatively recent adaptation?

Some of the most spectacular seabed scenery is associated with seabed fluid flow. At some locations the

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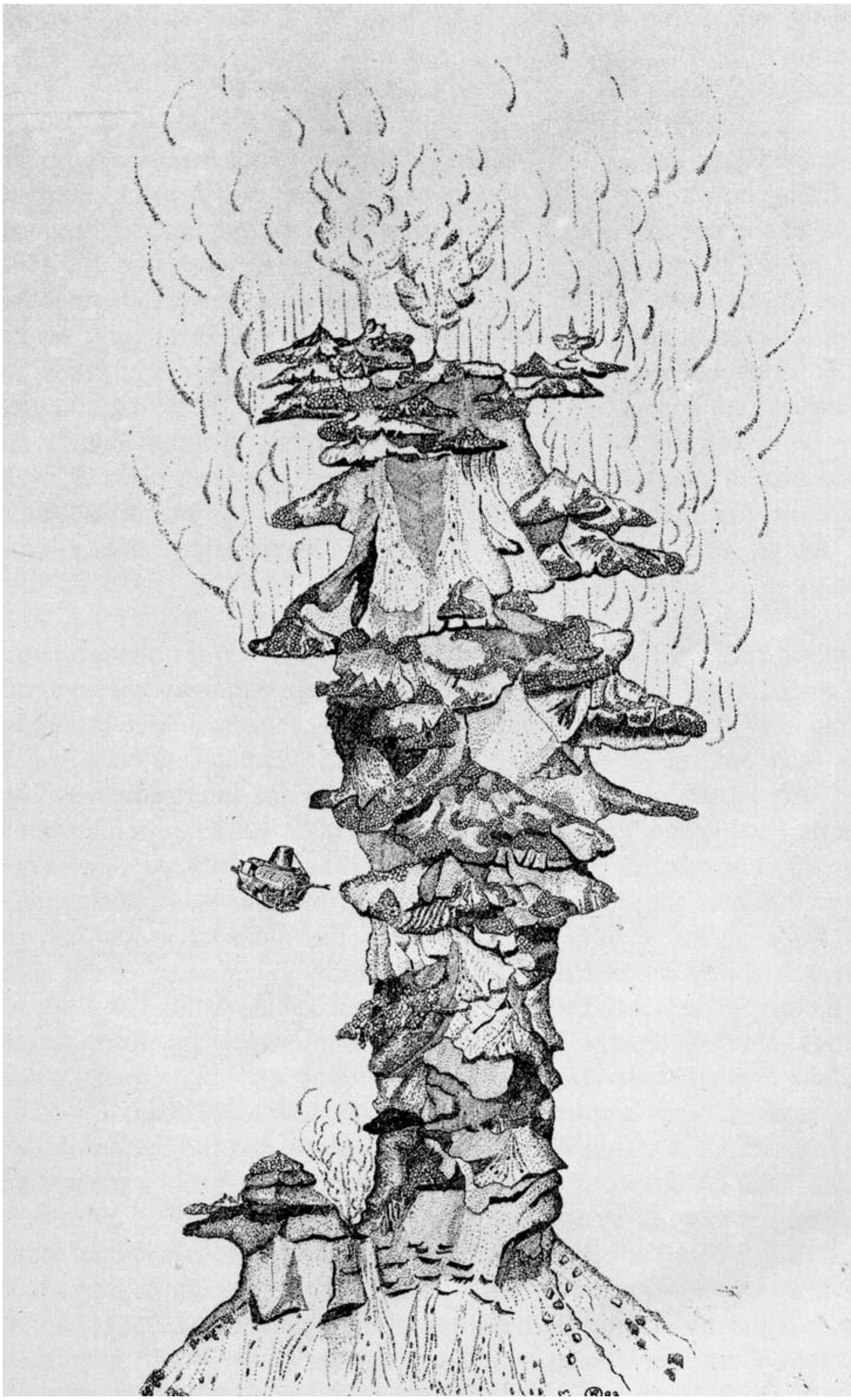

Figure 1.3 Godzilla, a 45 m high sulphide mound with flanges on the Juan de Fuca Ridge. The submersible Alvin is drawn to scale. (Reproduced with permission from Robigou *et al.*, 1993.)

scenery is provided by carbonate chimneys associated with methane seeps, at others by chimneys of hydrothermal metal sulphides. Exceptional examples stand metres tall; *Godzilla*, a structure on the Juan de Fuca Ridge, towers 45 m above the seabed, belching black smoke from its chimneys (Figure 1.3). Mineral precipitation, the subject of Chapter 9, results in changes to the composition of flowing fluids, whether by microbial utilisation, as in the case of methane-derived authigenic carbonate (MDAC), or precipitation as a result of a sudden change in temperature (as at hydrothermal vents). As we see in Chapter 10, the fluids that escape contribute to the composition of the overlying water column, adding heat as well as metals or hydrocarbons; nutrients and substrates that can be oxidised by microbes in the water also contribute to biological productivity. If seabed fluid flow were a rare phenomenon, then these contributions would be of little consequence. However, given the widespread distribution shown in Chapters 3 and 4, perhaps the composition of the oceans has been significantly influenced by geological contributions. Seeps and mud volcanoes may also influence atmospheric concentrations of methane, particularly in shallow water where gas bubbles can survive a journey to the sea surface. Vast volumes of methane are sequestered by seabed gas hydrates during interglacial periods, and may be released during glaciations, so it seems possible that variations in the seabed flux of geological methane moderates the extremes of global climate change.

In the final chapter we discuss both the implications of seabed fluid flow for mankind, and the effects of offshore activities on seabed fluid flow. Marine geohazards include slope failures and drilling hazards associated with shallow gas, and the possible implications of seabed eruptions for seabed installations and shipping. However, seabed fluid flow offers benefits too. The mining of metals from hydrothermal ore deposits on land is a major industry, and active hydrothermal vents provide useful information for mining, as well as having future potential as a resource. The energy potential of gas hydrates has encouraged significant research programmes in several countries, and the oil industry makes use of seeps in petroleum exploration. A more recent concern to marine science is the vulnerability of benthic ecosystems associated with seabed fluid flow. International legislation is now affording some protection; for example, the European Union's *Habitats Directive* has identified '*sub-marine structures made by leaking gas*' as a habitat worth protecting.

In this book we suggest that seabed fluid flow is of fundamental importance to the marine environment and the working of our planet. It is widespread, dynamic, and influential. Although it is essentially a geological process, it affects marine ecology, ocean chemistry, and the composition of the atmosphere. The seabed does not mark the limit of the marine system. Fluids flowing out of the seabed contribute to and, we argue, play a significant role in ocean processes and the global carbon cycle.

2 • Pockmarks, shallow gas, and seeps: an initial appraisal

> The North Sea's fattyness is, after its saltiness, a peculiar property, . . . It should be assumed here that in the ocean as on land there exists, here and there, seepages of running oily liquids or streams of petroleum, naptha, sulphur, coal-oils and other bituminous liquids.
>
> Translated from Erich Pontoppidan, 1752

This chapter begins with a review of the pioneering work undertaken on the Scotian Shelf, off eastern Canada, by L. H. King and his colleagues at the Bedford Institute of Oceanography. However, having 'cut our teeth' in the North Sea, the pockmarks and seeps here have become the standard against which we compare those of other areas. Consequently it is appropriate to review our early studies of North Sea pockmarks. This provides a historical perspective on pockmark research, and indicates how this early work led us to the conclusions that pockmarks and seabed seeps are important geological phenomena and indicators of processes associated with seabed fluid flow. In some cases the sites we visited early on have been the subjects of further work. This is also reviewed here.

By the end of this chapter it becomes clear that seeps and pockmarks, along with the associated carbonates and biological communities, are components of the important hydrocarbon cycle.

2.1 THE SCOTIAN SHELF: THE EARLY YEARS

Pockmarks were first described on the continental shelf offshore Nova Scotia, Canada by King and MacLean (1970). Subsequent work in this area was reported by Josenhans *et al.* (1978). Pockmarks were found to be present over an area of 3000–4000 km^2 in the Roseway, LaHave and Emerald basins, and two smaller basins. From echo sounder and side-scan sonar records, and from visual observations made from the manned submersible 'Shelfdiver', the features were described as cone-shaped seabed depressions that bottomed at a well-defined point. In plan, most are elongate with a preferred orientation that, on average, is north–south. No raised rims were present, but the pockmark edges were found to be sharply defined, the slope changing from horizontal to an estimated 30° within a distance of only 0.5 m.

The surficial sediments of the Scotian Shelf range in thickness from a few metres to over 200 m. They consist of five formations of which the oldest, the Scotian Shelf Drift, is mainly glacial till. The basins are infilled with Emerald Silt, a fine-grained, muddy sediment, predominantly silt but locally sandy and containing some gravel. This is overlain by the mainly-Holocene LaHave Clay, comprising homogeneous, loosely compacted marine silty clay that locally grades to clayey silt. These three sediment units are illustrated on the seismic profile (Figure 2.1), where it can be seen that the younger two thicken towards the deeper parts of the basin. King and MacLean (1970) found that the pockmark distribution is related to the distribution of the LaHave Clay. However, pockmarks are not found throughout this area, neither are they restricted to this sediment type. Some are found in the Emerald Silt and a few small, isolated pockmarks have been reported in the Sambro Sand (medium- to fine-grained sand, moderate to well sorted, with up to 20% silt and clay-sized material) near the edge of the Emerald Basin (Josenhans *et al.*, 1978). Pockmarks are not found in the intervening Sambro and Roseway banks, and, with the exception of a slight overlap in the Roseway Basin, they overlie the coastal plain sediments. These are a thick sequence of well-stratified, seaward-dipping Tertiary and Cretaceous sediments that wedge out against the basement rocks along a line subparallel to the coast. The basement

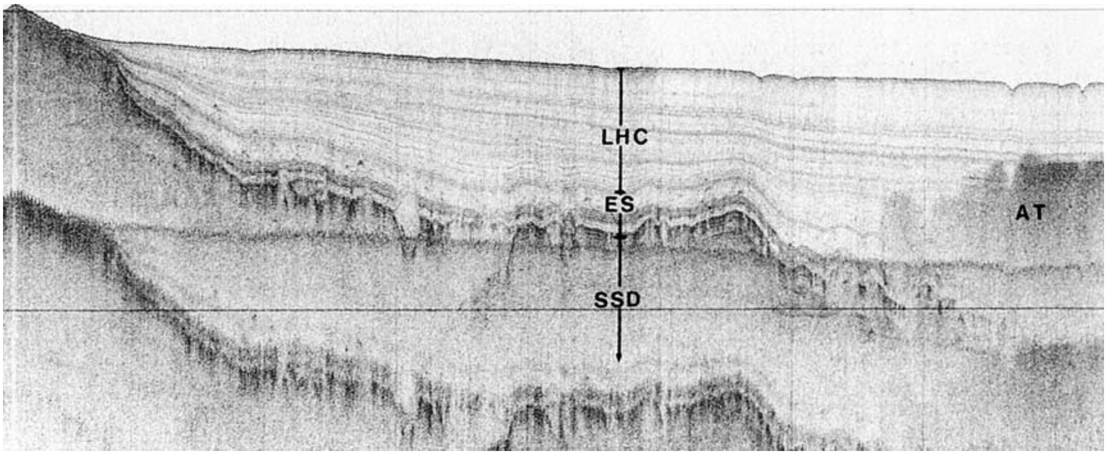

Figure 2.1 A shallow seismic record from the Scotian Shelf. LHC = LaHave Clay, ES = Emerald Silt, SSD = Scotian Shelf Drift, AT = acoustic turbidity. Note how the turbidity decreases below pockmarks. (From Hovland and Judd, 1988; courtesy of L. H. King.)

rocks comprise folded Cambro-Ordovician metasediments and granitic intrusions of Devonian age.

The pockmarks in the three basins are similar, but King and MacLean found those of the Roseway Basin to be more numerous (200 per km^2) and smaller (15–30 m across and 3–6 m deep) than those of the Emerald and LaHave basins (45 per km^2, 30–60 m in diameter and 6–9 m deep). A more detailed study of a small (150 km^2) area in the Emerald Basin (Josenhans *et al.*, 1978) indicated that pockmark density and size were related to the surficial sediment type and thickness, more but smaller pockmarks occurring in the silts, fewer and larger pockmarks in the clays. The largest pockmark they recorded lay in the LaHave Clay and measured 300 m long, 150 m wide and 15 m deep.

King and MacLean (1970) considered that '*the crater-like nature of the pockmarks strongly suggests that they are erosional features*'. After discussing various possible mechanisms, they concluded that the association with the underlying coastal plain sediments suggested a link and surmised that water or gas rising from these sediments (or underlying coal-bearing Upper Carboniferous strata) to the seabed was the most likely cause or agent. Although the currently known petroleum fields on the Scotian Shelf lie further seaward, considerable updip migration cannot be ruled out. It was further envisaged that water currents would disperse suspended sediment, and that the pockmark walls would slump, enlarging the feature, until a stable slope developed. The preference of pockmarks for fine-grained sediments was considered to reflect the inability of escaping fluids to percolate through such sediments without disturbing them. In contrast, percolation could occur in areas such as the Roseway and Sambro banks where coarse sediments are present. Josenhans *et al.* (1978) observed that elongate pockmarks are aligned with their long axes parallel to the dominant tidal flow, which has an oscillating tidal component of 10 cm s^{-1} with a major axis oriented north to northwest, and a residual current flow of 3 cm s^{-1} from the north.

Although Josenhans *et al.* (1978) favoured gas escape as the pockmark-forming process, they could find insufficient evidence to support present-day gas escape from shallow seismic reflection profiles, echo sounder profiles, side-scan sonar records, the analysis of piston core samples (reported by Vilks and Rashid, 1975), or hydrocarbon sniffer data. This led them to conclude that the Scotian Shelf pockmarks are largely relict features.

2.2 NORTH SEA POCKMARKS

The first North Sea pockmarks were discovered in 1970 by Decca Surveys during a rig-site survey in preparation for exploration drilling at BP's Forties field. The following year they were found off the Norwegian coast during a research survey (van Weering *et al.*, 1973). Indications

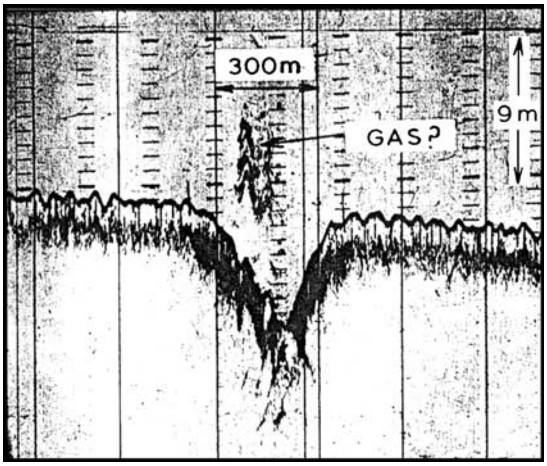

Figure 2.2 Echo sounder profile of a North Sea pockmark. The water-column target was thought to indicate seeping gas. However, more recent data have shown that this is actually a shipwreck, see Section 11.5.1. (From Hovland and Judd, 1988; image courtesy of BP).

of gas seeps from pockmarks were also recorded in the early 1970s (Figure 2.2), but it was not until 1983 that positive proof of gas seepage was obtained (Hovland *et al.*, 1985; 1987).

2.2.1 History of discovery

In 1971 the Netherlands Institute of Sea Research (NIOZ) conducted a survey in the Norwegian Trench between Oslo and Bergen, using a hull-mounted 3.5 kHz sub-bottom profiler. The main objective was to map the thickness of the surficial sediments. Side-scan sonar was not used, but the seabed notches were correctly interpreted as pockmarks by comparing them to the pockmarks of the Scotian Shelf. From this survey it was evident that there are pockmarks along most of the Norwegian Trench, including some parts of the Skagerrak. This conclusion has been confirmed by subsequent work. Indeed, it is now known that pockmarks are present throughout most of the area covered by the youngest sediments, the Kleppe Senior Formation, although they are generally most common along the western slope of the Norwegian Trench. The NIOZ also discovered that pockmarks are extensive in the Witch Ground Basin of the UK sector of the North Sea (Jansen, 1976).

During the period 1974–8 the British Geological Survey (BGS) undertook a research programme to find out more about pockmarks in an area that was then attracting increasing attention from the oil industry. This programme was concentrated in the South Fladen area, northwest of the Forties field in UK blocks 15/28 and 21/3 (i.e. blocks UK15/28 and UK21/3), on the southern side of the Witch Ground Basin. Ten investigations were undertaken. They included gravity and vibrocore sampling, drilling, visual inspection using the unmanned submersible (ROV) Consub, *in situ* geophysical (seismic-velocity and electrical-resistivity) measurements, geophysical surveys (side-scan sonar and seismic profiling) and geochemical studies of core samples and seawater. The results were summarised by McQuillin *et al.* (1979) and referred to by Fannin (1979) and McQuillin and Fannin (1979). Subsequent analyses of the data acquired during some of the surveys were undertaken by Judd (1982). The results of this and some subsequent work (including the regional mapping of the UK continental shelf by the BGS) are reviewed in Section 2.3.1.

These early surveys were intended to obtain basic information to delimit the area in which pockmarks occur, and to give some indication of the mode of formation. In particular it was felt necessary to establish whether or not the process of pockmark formation might be hazardous to offshore installations. During these surveys a range of features were identified, including evidence of the presence and migration of gas. Many of them had not been recognised before, so a terminology was developed to describe them – see Sections 2.2.4 (pockmarks) and 6.2.2 (gas).

Because pockmarks occur over such wide areas of the northern North Sea they have been a source of considerable interest to the oil industry. In the UK sector, many producing petroleum fields (e.g. Balmoral, Britannia, Forties, Ivanhoe, Piper, and Tartan) lie within the Witch Ground Basin, and several pipeline systems cross this area. Several fields (e.g. Troll, Veslefrikk, Snorre, and part of Gullfaks) are located at pockmarked sites in the deeper waters of the Norwegian Trench, and several pipelines (e.g. the Statpipe, Zeepipe, and Europipe systems) also cross the Trench. The work involved in site and route planning surveys for these installations has provided a considerable volume of data about pockmarks. Unfortunately, the operators retain much of this in confidence. Of the oil company data that have been released, Statoil produced the overwhelming majority. These include echo sounder, side-scan sonar records, shallow seismic reflection profiles, and sedimentological data from coring. Also, ROVs have been utilised for seabed inspections.

The vast majority of the survey data acquired prior to 1983 represent a form of remote sensing, using side-scan sonar, shallow seismics etc. As with all remote sensing, a proper interpretation cannot be made without ground-truthing. During two research cruises in 1983 and 1985, Statoil conducted detailed inspections of pockmarks using ROVs. The results of these, and some subsequent surveys, are discussed in Section 2.3.

2.2.2 Pockmark distribution

The North Sea can be subdivided into three bathymetric zones: the southern and northern North Sea (separated by the Dogger Bank), and the Norwegian Trench. For a long time no pockmarks had been located south of the 56° parallel. This was assumed to be a function of the seabed sediment types rather than being due to the absence of gas seepages. However, careful analysis of MBESs and shallow seismic data from the Zeepipe pipeline route data has revealed pockmarks in areas of sandy sediments and sandwaves. These are discussed in Section 3.5.2.

The seabed of the northern North Sea is a gently inclined plateau; water depths gradually increasing from about 60 m in the south to about 250 m in the far north, at the edge of the continental shelf. The largest of several basins within the plateau is the Witch Ground Basin. Here, water depths increase to more than 150 m. Many of the smaller basins are actually channels cut into the plateau sediments during the late Pleistocene and subsequently partially infilled. Sediment types on the plateau vary, but stiff glacial clays covered by varying layers of sand predominate. In contrast, the basins and channels tend to be characterised by soft, muddy sediments (Andrews *et al.*, 1990; Johnson *et al.*, 1993; Gatcliff *et al.*, 1994). The origin of the Norwegian Trench, where waters are as much as 700 m deep (in the Skagerrak), has long been debated. However, it is now generally believed originally to have been cut fluvially in the late Tertiary and subsequently deepened by glaciers and ice-sheets during the Pleistocene. It is an asymmetric trough in form. The western slope is smooth, whereas the landward side is steeper and frequently rugged (Holtedahl, 1993).

Most pockmarks are found in the three muddy sediment formations in the northern North Sea: the Witch Ground Formation, in the Witch Ground Basin, the Flags Formation of the smaller basins further north, and the Kleppe Senior Formation that occupies the floor of the Norwegian Trench. There are also pockmarks in equivalent sediments that infill or partially infill channels cut into the stiffer clays of the plateau. These sediments are all post-glacial and are similar in most respects. Indeed, Hovland *et al.* (1984) noted that both the Witch Ground and Kleppe Senior formations are remarkably similar to the Emerald Silt–LaHave Clay sequence of the Scotian Shelf. This comparison is valid in respect of their lithological characteristics, seismostratigraphic character, and depositional environment. Also, sedimentation has all but ceased in the basins of the Scotian Shelf, as it has in the northern North Sea.

2.2.3 Pockmark size and density

The density of pockmarks varies from area to area both within the North Sea and within the individual pockmarked areas in the North Sea. In the Norwegian Trench the density varies from 0 to about 60 per km^2 (counting only those that are more than 10 m across); the most densely pockmarked area of substantial size lies over the Troll gas field. The sizes of individual pockmarks in any given area are varied, but the only change in the range of sizes within the Trench is associated with the western slope, which is the only area in which elongated pockmarks are found. In contrast, the size and density of the pockmarks in the Witch Ground Basin vary, apparently in response to variations in the thickness and lithology of the seabed sediments (Long, 1986). In general, pockmarks are between 50 and 100 m in diameter with depths in the range 1–3 m. The highest densities (>40 km^{-2}) occur within bathymetric hollows characterised by sandy muds, but here sizes rarely exceed 50 m. In the deepest parts of the basin, where seabed sediments are pure mud, the density is 10–15 per km^2, but sizes are much larger (100–150 m). Both pockmark density and size tend to decrease towards the edges of the basin beyond the outcrop of the Witch Member and particularly where the Fladen Member becomes thinner and coarser. At the basin edge