Offshore Petroleum Developments in Northwest Europe —An Update

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Summary
The North Sea has been the focus of attention during the last decade for petroleum developments on the continental shelves of northwest Europe. The North Sea petroleum basin is ranked as one of the richest in the world.

Production of North Sea gas commenced in 1966 and North Sea oil in 1971. By the early 1980s, 20 per cent of Western Europe's total oil requirements will be supplied by the North Sea. This will have beneficial effects not only on the economies of the United Kingdom and Norway (which will be self-sufficient in oil) but will also buy time to develop alternate sources of energy.

A characteristic of North Sea petroleum development programs is their high cost making North Sea oil the most expensive conventionally produced crude oil to date. To meet the demands of sea and climatic conditions, new offshore production technology has evolved.

In the northern North Sea, the favorable condition which exist for large reserves of oil include adequate Jurassic source rocks, good shale seals and large structures with highgrade sand reservoirs (mainly of Middle, Upper Jurassic, and Tertiary age) developed in a long north-south trending medial graben. Upper Permian salt seals large accumulations of natural gas in sandstone reservoirs of Lower Permian age in the southern North Sea. Similar tectonic and sedimentary relationships may exist in other basins of the northwest European shelf (off northern Norway, western Ireland, southwest and west UK) and these areas will receive future exploration attention.

Resumé
L'attention s'est concentrée, durant la dernière décade, sur la Mer du Nord pour les développements de l'exploitation pétrolière au niveau des plateformes continentales du Nord-Ouest de l'Europe. Le gisement de pétrole de la Mer du Nord est considéré comme l'un des plus riches du monde.

La production de gaz naturel de la Mer du Nord a commencé en 1966 et celle du pétrole en 1971. Au début des années 1980, 25% des besoins en produits pétroliers de l'Europe Occidentale seront fournis par la Mer du Nord. Ceci profitera non seulement aux économies du Royaume Uni et de la Norvège (dont la production se suffira alors à elle-même), mais permettra de gagner du temps pour développer des sources alternatives d'énergie.

L'une des caractéristiques de ces programmes de développements pétroliers en Mer du Nord, c'est leur coût élevé qui fait du pétrole fourni par la Mer du Nord l'un des plus chers parmi les pétroles bruts produtis à ce jour selon les méthodes habituelles. Pour faire face aux exigences des conditions maritimes et climatiques, une nouvelle technologie de la production au large des côtes s'est développée.

Dans la partie septentrionale de la Mer du Nord, l'existence de conditions favorables à de grandes réserves de pétrole incluent des roches jurassiques adéquates, de bonnes couches de schistes étanches, de vastes structures contenant des réservoirs de sable à haute teneur (principalement du Jurassique Moyen, Supérieur, et de l'Age Tertiaire), se développant en un long fossé médian orienté Nord-Sud. Des sels du Permien Supérieur recouvrent de manière étanche de grandes accumulations de gaz naturel dans des réservoirs de grès du Permien inférieur, dans la partie méridionale de la Mer du Nord. Des relations tectoniques et sédimentaires similaires peuvent exister dans d'autres bassins de la plateforme continentale du Nord-Ouest de l'Europe (au large des côtes du Nord de la Norvège, de l'Ouest de l'Irelande, de l'Ouest et du Sud-Ouest du Royaume Uni), et ces régions feront l'objet d'études en vue d'explorations prochaines.

Introduction
Petroleum developments of the last decade in the waters off northwestern Europe are dominated by the recognition of the North Sea as one of the great petroliferous areas of the world (Thomas, 1975; Watson and Swanson, 1975; Anon., 1975). These and future developments will have important effects on the geographic distribution of some of Europe's supply of oil and promise great economic benefits to the nations sharing this new found wealth.

This article has been prepared from a generalist's vantage point against a background that is dynamic and continuing to evolve. Its aims are: a) to provide the Canadian geological community with the latest information concerning offshore exploration, reserves, production and development operations, exports, expenditures and future investments, etc., in northwestern Europe, and b) to summarize the "new" geology of the North Sea basin, and c) to indicate to the reader the direction that offshore exploration in Europe is heading, so the trends of new exploration and develoment frequently reported in the news media can be followed.

Exploration, Reserves, Production Status, and Investments
Exploration. During the past ten years, exploration activities in the North Sea have defined four major oil and gas provinces (Fig. 1); 1) a northern (or Brent) province (both U.K. and Norwegian waters) where more than 70 percent of the North Sea oil found to date occurs in Middle Jurassic sand reservoirs; 2) a central province where oil and gas occur in Tertiary and Upper Jurassic sandstone reservoirs; 3) a southern Norwegian or Ekofisk province where oil and associated gas occurs in Tertiary and Upper Cretaceous carbonate, and 4) a southern province (mainly U.K. and Dutch waters) where natural gas is produced (since 1966) from Permian sandstone reservoirs.

In spite of a record number of wells drilled during 1975 (170 exploratory and appraisal wells completed including 31 new field discoveries), exploration activity and interest (predominantly in the UK and Norwegian sectors - see review by King, 1976) has begun of late to wane in the North Sea because of worldwide economic ills, major revisions of tax policies, uncertainties over government export (Norway) and ownership provisions (UK), a threefold increase in capital costs (C. A. Brown, 1976; Trimble, 1976) and because most of the seismically more obvious prospects currently under license have probably been drilled. Certainly, as far as Great Britain is concerned, the North Sea is emerging from the exploration into the development stage, although activity has continued at a high level as obligation and appraisal wells are drilled. By July, 1976, operators had made 11 new discoveries in the UK sector. The most exciting recent discoveries have been in UK quadrant 16, in the vicinity of the Brae discovery in 1975 (FIg. 2). Brae field may be one of the biggest in the North Sea with reserves of more than one billion barrels of oil and 2 to 3 Tcf associated gas. (For Canadian participation, see Petersen, 1976.) Mangus is the most northerly field so far discovered in water 580 feet deep.

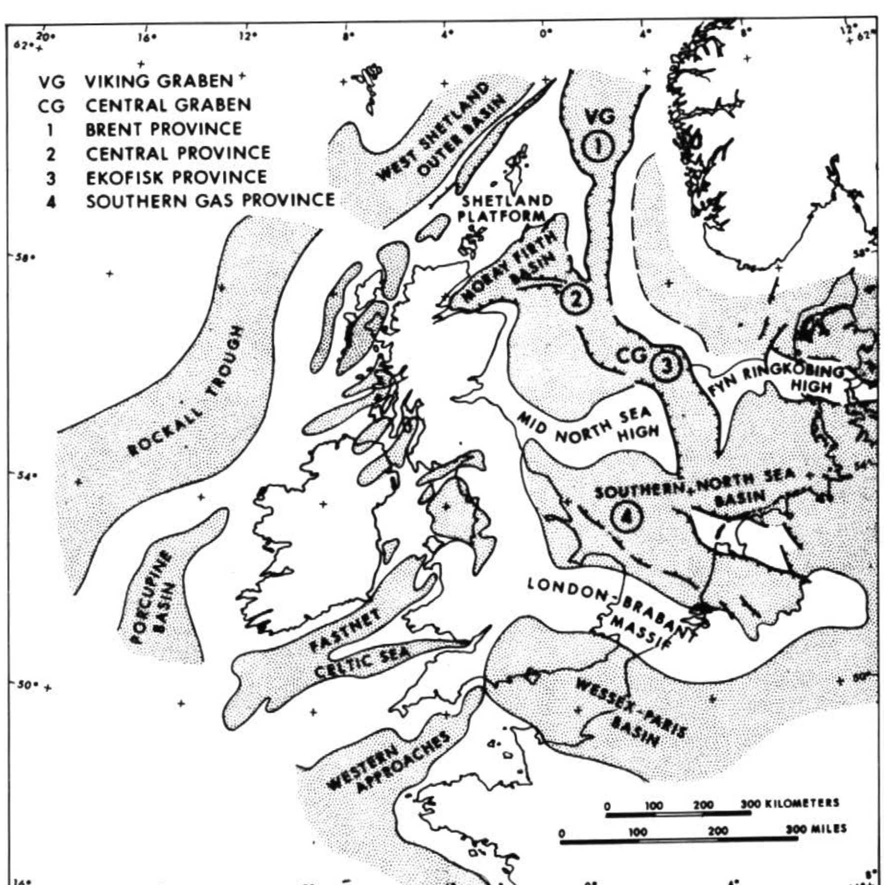

Figure 1
Major basins and North Sea Provinces.

Reserves. Published proven reserves in the North Sea amount to 20 to 25 billion barrels of recoverable oil mainly in the Norwegian and British sectors, and 60 to 90 trillion cubic feet (Tcf) of nonassociated natural gas exluding 58 Tcf assigned to the super-giant onshore Dutch Groningen field discovered in 1959. Reserves of natural gas associated with known oil fields totals 25 Tcf. The proven reserves of crude oil in the North Sea comprise three percent of the world total (H. Brown, 1976, p. 25).

As many as 12 oil fields may be credited with recoverable reserves of 500 million barrels (giant status) or more; Statfjord, the largest, has recoverable oil reserves of 3.9 billion barrels and associated gas reserves of 3.8 Tcf. Some 13 gas fields may each have reserves of one Tcf or more. One of these, Leman, with reserves of more than 10 Tcf, is the world's second largest offshore gas field after Iran's 'C' structure (130 Tcf) in the Persian Gulf.

Estimates of ultimately recoverable reserves are difficult to evaluate, but the UK Department of Energy (1976) estimates total discovered and undiscovered recoverable reserves from the British continental shelf will be between 22 billion (3 billion tons) and 33 billion (4.5 billion tons) barrels (current U.S. reserves 32.7 billion barrels). Estimates for Norway suggest figures of more than 50 billion barrels (6.8 billion tons) from the Tampen Spur (vicinity of Statfjord) area alone (Finstad, 1976) but Norwegian government estimates range form 23 to 30 billion barrels (3.1 to 4.1 billion tons) ultimate reserves for the area south of latitude 62°N. Recent estimates are that the Voring and nearby Helgeland basins (north of 62°N) between them could contain 30 billion barrels (4.1 billion tons) of oil or its equivalent in gas (Cranfield, 1976). A reasonable estimate (by Shell) of ultimately recoverable reserves from the North Sea south of 62°N is 35 bbo and 110 to 150 Tcf of gas (3000 to 4000 billion cu m).

Production and Developments. Crude oil production, which began in 1971 from Norway's Ekofisk field, reached 220,000 barrels of oil per day (from Ekofisk, Britain's Forties and Argyll, and Denmark's Dan), and natural gas production from the southern North Sea averaged 3.7 billion cubic feet per day at the end of 1975 (mainly Britain's Leman, Inde, and Hewett). Recent developments in the southern North Sea have been largely in the Dutch sector • (proven and probable reserves 11.3 Tcf or 323 billion cubic meters) where two fields (L/10-L/11, K/13) came on stream in 1975 to 1976. A third offshore field, K/6-L/7, will be producing in 1977. Annual yield from these fields is expected to be 8.9 billion cubic metres (0.86 Bcf per day).

Twenty-one oil fields (14, including Argyll, in the British waters; 6, including 5 in the Ekofisk complex, in Norwegian territory, and 1 in the Danish sector) are being developed or have production platforms ordered. The development of two fields, one gas (Frigg) and the other oil (Statfjord), has been the subject of the first international unitization agreements signed by Norway and Britain in 1976.

Seven fields are produding (Ekofisk, Dan, Forties, Auk, Argyll, Beryl and Montrose) and these will be joined in 1976 by Brent and Piper (both in the UK sector). By year end, production should average 665,000 barrels of oil per day (bopd) with just over half (340,000) being produced from the Britsh sector, about one-fifth of the total current British consumption (1,700,000 bopd).

By the mid1980s, several sources suggest North Sea productions could reach a peak of 5 to 6 million bopd (about 25% of total world offshore potential at the time or equivalent to just over 10% of current free world crude production). This would rank it the second most important offshore oil province in the world after the Persian Gulf, capable of 6 to 7 million bopd in addition to its onshore production. North Sea natural gas production may reach 9 to 12 bcf per day.

Latest production estimates indicate the United Kingdom will achieve self-suficiency in crude oil production by 1980 (although there are some doubts about how long this will persist) provided no prolonged delays occur in development, and demand remains depressed. Crude production in 1980 is anticipated to between 1.9 and 2.3 million barrels per day (95 to 115 million tons per annum). As a perspective, the Alaska Alyeska pipeline will eventually transport two million barrels a day. Peak offtake from the UK sector in the 1980s may average three million bopd (150 million tons per annum) and could place Britain among the top ten oil produders in the world (see Howitt, 1974). By 1987, Norwegian production should peak at 1.4 million bopd (73 million tons per annum) with over half coming from the Statfjord field. By 1984, maximum total productive capacity from Statfjord could be 900,000 bopd, which is greater than any current producing rate of any offshore oil field in the world. This is well below the official "ceiling" of 90 million tons of hydrocarbons a year which the government has set as the right level with regard to the Norwegian economy.

In comparison, current Canadian production is just under 1.5 million bopd (total production in 1975 was 525 million bo). Cumulative production has reached eight billion barrels of oil and proven oil reserves are 7.1 billion barrels. From 1980 to 1990, potential productivity of Canadian crude oil and equivalent is estimated at 1.6 to 1.3 million bpd (NEB, 1975) and net oil imports could range from 40 per cent (1985) to 68 per cent (1990) of Canadian oil demand (see Minister of Supply and Services, 1976, p. 118). Canadian natural gas production was 2.5 Tcf in 1975 (6.8 Bcf per day).

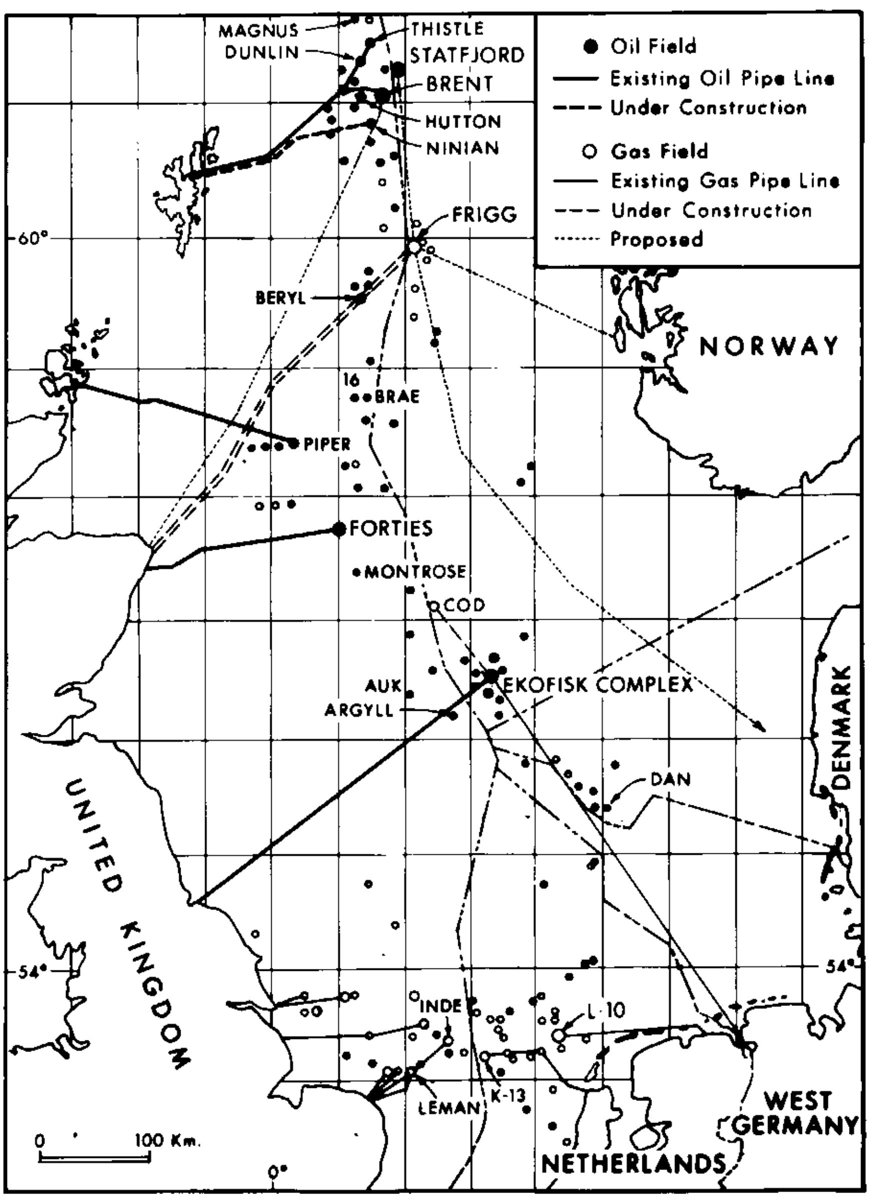

Figure 2
Location map of North Sea discoveries.

Production and Delivery Facilities. Two types of production platform structures are built: the heavy gravity structure of prestressed or reinforced concrete, and the more traditional steel platforms, called template structures or sea jackets which must be anchored to the sea floor by piles. Thistle A (606' high) and Brent A (502' high) are the largest jackets placed to date and are in water up to 530 feet deep. (Hondo platform, Santa Barbara channel, California, is in 850' of water, in place July, 1976). Gravity structures, such as the Condeep, Seatank, Doris, and Andoc designs, contain storage cells for up to 1.5 million barrels, and their sheer weight (up to 400,000 tons) assures their survival in 30 m (100 foot) storm waves. Several concrete structures have either been installed (Beryl A, Brent B, and Brent D) or are being constructed for installation in water 145 m deep, including the world's largest concrete gravity structure, the UK Ninian field central platform, which will be installed in 1978. Cost estimates for some concrete platforms run as high as $800 million (Statfjord A) to $1 billion each.

Besides pipelines (Fig. 2), production delivery systems include the Single Point Mooring Buoy (SPM) and articulated mooring tower (Beryl) systems from which oil is loaded directly into tankers. Some schemes are hybrid: that is they use both storage and unloading facilities, e.g., the Spar-buoy at Brent. Subsea completions are another option enabling reduced investment in expensive platforms and many novel, unconventional means of producing oil from the North Sea are being offered to the industry. New schemes are particularly important for the smaller North Sea fields such as Argyll, where wells are seabed completions and the oil is produced onto a floating production platform adapted form a semisubmersible drilling rig.

Exports. In early May, 1976, Britain exported its first crude oil from the North Sea Forties Field, and Britain will continue to be an oil trading nation even when domestic North Sea crude production is sufficient to meet projected internal demand in the 1980s. Trading will continue because North Sea crude oil is at a premium. It is of high quality, light gravity (30° to 50° API), and contains only a small amount of sulphur (less than 0.4%). Furthermore, to satisfy domestic marketing patterns, refinery runs require a mix with about 65 per cent lower grade (high sulphur) crude.

By 1980, the UK will also have a sufficient surplus after supplying its own and Europe's needs, of ethane, propane, and butane, an important feedstock for the petrochemical industry, to export 3.3 million metric tons/year of these gases in liquefied form to the US and Canada.

Expenditures and Future Investments. Characteristic of North Sea exploration and development, as it is in many "frontier" areas, is the long lead time and the large capital investment required for development. Since the start of operations in the North Sea, the petroleum industry has spent some five billion dollars on exploration and development. By 1980, the industry is projected to require from 15 to 25 billion dollars at 1976 prices (some 10 per cent of worldwide finding and development expenditures 1975 to 80) for development alone. (Development drilling is expected to peak 1979 to 80, C. A. Brown, 1975). For comparison, sums over $20 billion have been estimated (1975) for Canadian Arctic petroleum development, including exploration, to prove up threshold reserves as well as pipeline costs of $4.5 to 7.5 billion to pipe gas from Arctic islands. As a rule of thumb, investment costs for oil fields under development in the North Sea are between $1.00 to 3.25 per recoverable barrel (see MacKay and MacKay, 1975; Heritier, 1975, p. 38). Including exploration, operation, and development expenditures, the cost of North Sea oil ranges from $4 to 7 per barrel. In determinations of commerciality, most of these costs must be offset by discounted future after-tax revenues.

For example, the Esso Petroleum Company-Royal Dutch Shell Group expect to spend more than $6 billion over the next five years in developing their joint venture oil fields in the British North Sea. A major enterprise is the development of Brent, Cormorant, and Dunlin fields (total productive capacity of 800,000 bopb by 1982) and the construction of a joint liquids pipeline to a terminal (operational by 1978) at Sullom Voe, the largest of the Shetland Islands, and a gas pipeline to the Scottish coast north of Aberdeen. Some 3.5 billion dollars will be needed to develop Brent field and recover some two billion barrels of liquids and three trillion cubic feet of gas. This is the second most costy private enterprise project of any kind undertaken in the world after the Alaska pipline which will cost $7.7 billion. Investment in these fields will be approximately $7,500 per daily barrel (pdb) of peak production. Expenditures for the Ninian field (one billion barrels recoverable oil) have been placed at $14,700 to 19,230 per average daily barrel of production (Investment costs for Alberta tar sands crude were estimated in 1974 at $10,000 to 15,000 pdb - now probably $30,000 pbd - versus $100 to 250 pdb for the large Middle East fields). Among other major projects, Ekofisk oil and gas development costs are over $4.5 billion; Statfjord oil field, $4.8 billion; Frigg gas field, $2.6 billion; Forties oil field, $1.7 billion. Financing for these ventures is a top corporate problem.

To protect North Sea investments and to protect alternative energy sources should the world market price collapse, the European Economic Community has recommended to EEC Council of Ministers that the nine nation community adopt a $7.00 (minimum) import price for oil in line with the International Energy Agency agreement. The effect of a fall in world oil prices on supplies of North Sea oil has been analyzed by Robinson and Morgan (1976).

Future Pipeline Developments. Beside the Brent pipeline system mentioned above, two other major pipeline schemes have been suggested to recover the natural gas associated with many of the larger oil fields and to make economic development of smaller gas fields possible.

One concept in the Norwegian sector involves a large diameter pipeline running 1,000 km south from the Statfjord Field, through Odin, Heimdal, Sleipner, and fields in the Ekofisk area to the continent, with a landfall in Denmark or Germany. Called the Statfjord trunkline, the pipeline would move 200 billion cu.m/year (2 Bcf/d) and could not come onstream before 1984. It would cost between three and four billion dollars at 1976 prices. Gas reserves along the gathering line are estimated at 300 billion cubic meters (10.6 Tcf).

A minimum 2.9 billion dollar network of gas pipelines has been tentatively recommended by the UK Department of Energy (May, 1976) to bring ashore associated gas from the northern basin of the British North Sea, including those fields to the east of the Shetlands and those in the approaches to the Moray Firth basin. If feasibility is confirmed by futher studies, this line may be operational by 1982 with a capacity of 1.5 bcf/d of natural gas and nine million tons a year of natural gas liquids.

Recent Legislation and Future Awards. In the United Kingdom, two major pieces of legislation were enacted in 1975, and further progress was made to assure major government participation in offshore oil fields. The Petroleum Taxation Bill provides for a petroleum revenue tax (PRT) to be levied on profits (see Kemp, 1976) and the creation of the

British National Oil Corporation by the Petroleum and Submarine Pipelines Bill. The BNOC became operative at the beginning of 1976 and at the same time acquired all the exploration rights and staff of the National Coal Board. The government has repeatedly emphasized its determination to obtain 51 per cent participation in all commercial fields and early in 1976, announced its first agreement with Gulf Oil Corporation and Continental Oil Company. These agreements include an option which allows BNOC to buy 51 per cent of the crude produced at market prices.

Under new legislation (1976) the BNOC and British Gas Corporation are able to apply, as sole licensee, for offshore licenses without waiting for formal licensing rounds. The fifth-round license awards, due this year will involve 71 blocks in the North and Celtic Seas, and the western approaches of the English channel. Unlike previous licensing rounds, this will be the first time the government will be guaranteed participation in any oil finds.

Early in 1976, the Dutch government announced new terms for future offshore license awards whereby the state will take a 50 per cent share in gas discoveries, and licensing terms are stiffened.

Two features distinguish the Norwegian North Sea oil scene: the State has been heavily involved from the first discovery and the policy has been to slow exploration and exploitation deliberately. Allocations are expected for about nine blocks which are under negotiation.

Tectonic Framework

Throughout Europe, the North Sea, and over the offshore margin west of Britain, geological and geophysical data have shown a well defined pattern of deep, linear, sediment-filled troughs, up to 50 km (30 miles) wide and 320 km (200 miles) long, separated by fault-bounded platforms of continental crust (Fig. 1). This pattern may represent a number of wholly or partially failed spreading systems (De Windt, 1976).

To date, much of the commercial oil and gas found in the northwest European shelf has been associated with the thick sediments infilling these fault-bounded troughs in the North Sea area. As all of them have a common origin they are fundamentally similar in architecture and sedimentary development. Consequently favourable prospects for the discovery of oil may exist in other troughs and on the flanks of platforms west of the British Isles (Naylor and Monterey, 1975).

North Sea. A pattern of long linear troughs can be delineated which comprise the Mesozoic basins of the North Sea (Fig. 1; Whiteman *et al.*, 1975). These Mesozoic troughs are filled with thick wedges of sediment up to 10 kilometres thick, ranging in age from Permian to Cretaceous. The troughs are separated by regional positive features, such as the London-Brabant platform, the mid-North Sea high, and the Ringkoping-Fyn high upon which the sedimentary sequences are much thinner or absent (Ziegler, 1975).

The North Sea basin, floored mainly by metamorphic rocks of Caledonian age, thus includes many structures formed, not only by regional tectonic movements but also by movement of Permian salt (Fig. 3). Both have influenced patterns of sedimentation regionally.

Viking-Central Graben. A major structural element, the Viking-Graben system, occurs in the centre of the North Sea, and parallels the Norwegian-United Kingdom median line. It is within this system that most of the oil in Jurassic, Upper Cretaceous, and Tertiary reservoirs has been found.

The Viking-Central Graben, and other North Sea rift systems, began to develop during the Permo-Triassic (after Hercynian or Variscan orogeny). Its evolution continued throughout the Mesozoic period as the Asian-European-American megacontinent began to break up, and became dormant only in Late Mesozoic (Middle Cretaceous) times as the centres of active crustal separation shifted westwards to follow the line now occupied by the North Atlantic Ocean and Labrador Sea (see Laughton, 1975). Upper Cretaceous and Tertiary strata were deposited in relatively unfaulted simple basins. Cretaceous units are widely transgressive; those of the Tertiary are restricted areally and associated with broad folding. Paleozoic and Mesozoic highs in the mid- and northern-North Sea lost their identities and sank with the development of the late Mesozoic and Tertiary basins (see Kent, 1975).

The North Sea basin is the site of at least three mega-cycles of sedimentation. Significant unconformities occur within the stratigraphic sequence, and petroleum is produced from both below and above these regional unconformities. The major regional unconformities occur in conjuction with the Carboniferous-Permian (Hercynian), Jurassic (late Kimmerian), and early Tertiary (Laramide) orogenies.

Stratigraphy and Sedimentary Facies

For the purposes of this study, economic basement for petroleum is considered to be the Permian. Oil has been found, however, in the Devonian Old Red Sandstone associated with Permian and Triassic reservoirs at Argyll field, and natural gas has been tested from sandstones in the Upper Carboniferous Coal Measure series (Westphalian) in some wells in the southern North Sea. In any event, very few boreholes have penetrated below the Permian and it appears, from onshore exposures, that the Devonian underlies the Permo-Trias, with the Carboniferous generally absent except in southern UK and Dutch waters.

Permian. During the Lower Permian, two main sedimentary basins existed: one to the north of the mid North Sea - Ringkoping - Fyn High, the other to the south in which Rotliegendes clastics were deposited.

The bulk of the Rotliegendes consists of unfossiliferous red beds in which crossbedded aeolian dune sands, fluviatile/wadi, sabkha, and desert-lake environments are recognized (Glennie, 1972; Marie, 1975). The aeolian dune sandstones are the principal reservoirs in the large southern North Sea gas fields (Leman, Inde) but lateral variation in facies is marked (see Smith *et al.*, 1974).

In the northern portions of Dutch and the western portions of German waters, igneous effusives are relatively widespread in the Lower Rotliegendes associated with volcanic vents. Permian volcanics are also known onshore (Smith *et al.*, 1974) from Devon and the Midland Valley of Scotland.

The Upper Permian is composed of Zechstein carbonates and evaporites up to 750 m thick which exhibit both platform facies (including sabkha carbonates which display pelletoidal-oncolitic fabric and stromatolitic laminations with abundant replacement anhydrite, and oolitic dolomites and local algal and bryozoan mud-mounds or "reefs") and true basin facies. Within this basinal sequence, a major fourfold vertical cyclicity can be recognized, which is best developed onshore in Germany and can be recognized in the southern North Sea basin (Brunstrom and Walmsley, 1969).

The Zechstein is important in connection with accumulation of hydrocarbons in the North Sea because the halites act as a cap rock (seal) for the Rotliegendes sandstone and later halokinesis caused structural deformation influencing the development of traps. The carbonates provide suitable reservoirs for oil where leached below the Kimmerian unconformity (e.g., Auk, Argyll).

Triassic. The fourfold sub-division of the Triassic (Bunter, Muschelkalk, Keuper and Rhaetic) of continental Europe can be recognized throughout the southern North Sea where Triassic strata attain a thickness of 1500 m (5,000 feet). Triassic nomenclature has recently been revised in the UK sector to accommodate the absence of the Muschelkalk to the west (see Rhys, 1974; Brennand, 1975).

The Bunter rests on the Zechstein conformably. It is a series of continental deposits of red mudstones and sandstones which spread widely over the Zechstein peneplain. The Bunter sheet sandstones of the southern North Sea, though exhibiting good reservoir properties, rarely contain gas because Zechstein salt prevents upward migration to them. Where the Zechstein is thin, cut by faulting or absent, gas produced from Carboniferous coal beds may have become trapped in the Bunter as it is in the Hewett gas field where salt does not occur. Here, the reservoir sands are of medium-coarse grade and locally contain well-cemented conglomeratic layers, probably of fluvial origin.

The Muschelkalk marks a temporary marine incursion from the south and east. The succession is variable but consists predominantly of interbedded clastic red mudstones with dolomite and anhydrite. Periods of evaporitic deposition alternated with distal flood plain and coastal sabkha conditions. Locally, sediments developed in a semi-marginal facies produced limestones, and anhydritic clays and mudstones. In the Dutch and German offshore, the Muschelkalk takes on the more classic development of limestones and dolomites.

The Keuper is typically composed of red-brown anhydritic mudstones and marls which sandwich the Keuper Halite

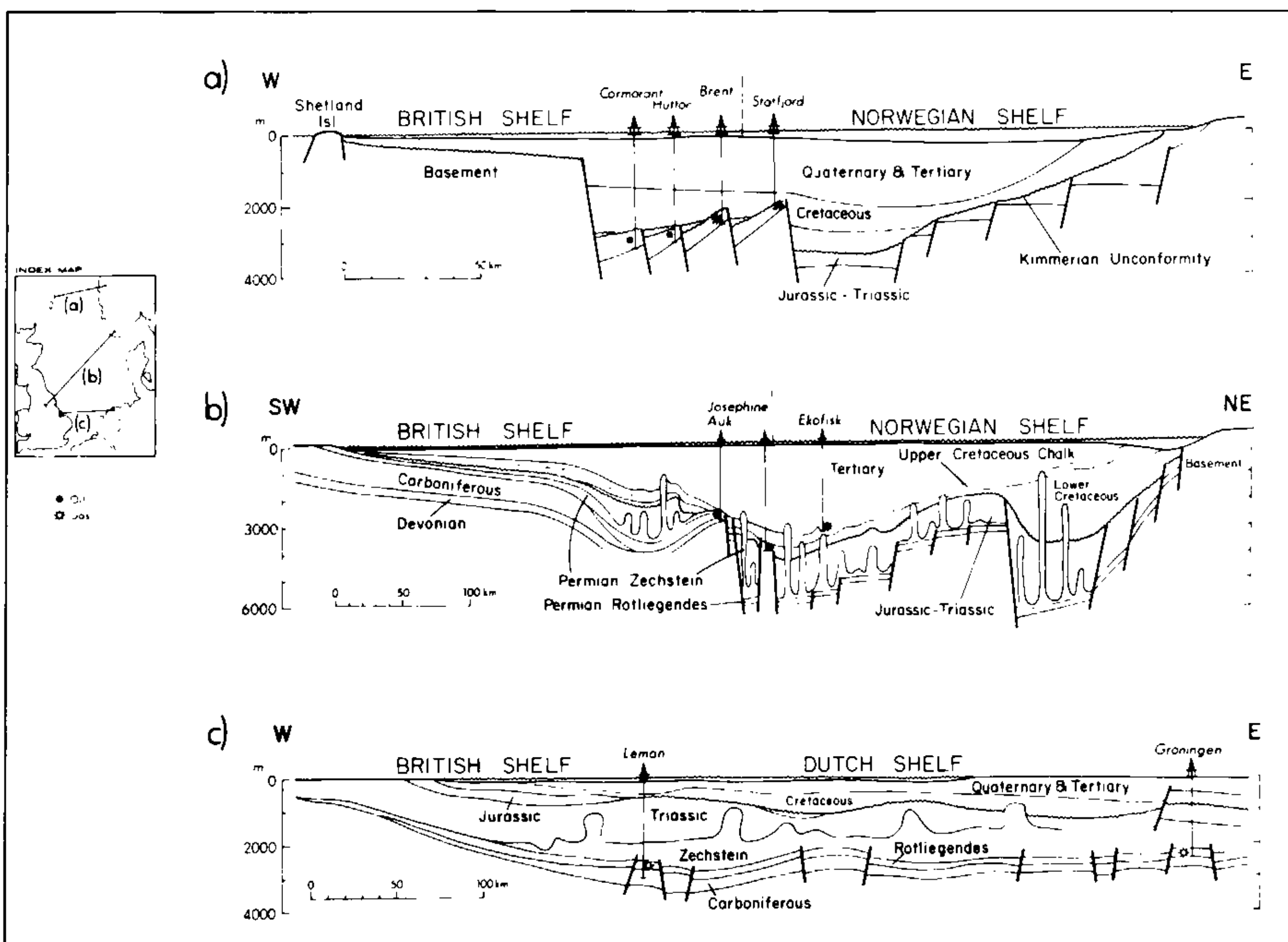

Figure 3
Schematic cross-sections (after Watson and Swanson, 1975; Schöneich, 1975).

Member, a restricted salt development. Terminating the Triassic sequence is the Rhaetic, of which the basal clays, and grey-green sands, mark the widespread marine incursion in northwest Europe preceding Jurassic times and representing "passage" beds between the continental Triassic and the predominantly marine Jurassic.

Jurassic. (Walmsley, 1975). Strata of Jurassic age are now the major petroleum prospect in the northern North Sea. They are essentially a sequence of marine shales and mudstones with occasional important developments of sandstone which exhibit rapid lateral changes in facies.

Regionally, the Jurassic succession demonstrates a major trangression, and marine shales of Liassic age are widespread. Locally, as in the northern North Sea, sand represents a part of the Lias (Hallam and Sellwood, 1976). During Middle Jurassic (Dogger) times a regression caused the deposition of oolitic and bioclastic limestones in the south, on the flanks of the London-Brabant platform, and deltaic and estuarine sands, sometimes with coals, in other localities. The Dogger (Bajocian-Callovian) thus includes a wide variety of facies which include important reservoirs, (e.g., Brent sand). The Upper Jurassic (Malm) is generally transgressive, culminating in the marine Kimmeridge Clay, a bituminous formation probably the major source rock for most of the Mesozoic North Sea oil (Fuller, 1975).

The geology of the Jurassic is complicated by a number of major epeirogenic movements (possibly associated with the early phases of the opening of the Atlantic) as well as eustatic variations associated with the Kimmerian orogeny to the south. At the same time and in particular during Lias and Dogger time, strong movement of the underlying Permian salt caused rapid variations in the thickness of the Jurassic over the central part of the Zechstein Basin. Subsequent widespread erosion at the end of this period removed much of these and older rocks, and Cretaceous sediments are now found resting unconformably on sediments ranging in age from Upper Jurassic to Paleozoic (Walmsley, 1975).

Fault-bounded troughs formed early in the Jurassic were filled with sediments, as for example the Viking Graben, but the maximum thickness of the fill cannot be assessed at present, for wells are confined to structurally high areas where the sequence is both thin and has been subsequently eroded. In the Central Graben area extensive Jurassic rift volcanism occurred where fissuring allowed the extrusion on the post-Bathonian succession of alkali basalts with affinities to oceanic crust (Gib and Kanaris-Sotiriou, 1976).

In the southern North Sea the total thickness of Jurassic (where fully represented) varies from 600 m (2,000 ft.) on the margins to 1,500 m (5,000 ft.) in the troughs. In this southern area, subsequent epeirogenic uplift and erosion has either removed the Jurassic or brought it close to the surface. Therefore it has little hydrocarbon potential.

Major subsidence of the Viking Graben and associated block faulting at the end of the Jurassic (Late Kimmerian tectonic phase) resulted in the development of a pronounced submarine topography. The blocks were only partly eroded and the grabens only beginning to fill with detritus when major movement ceased. Jurassic topography was then buried and preserved below thick argillaceous sediments of Cretaceous age. The prolific reservoirs of the northernmost North Sea (Brent Province) occur in Jurassic sands lying unconformably below Upper Jurassic or thick Cretaceous shales, (e.g., Brent, Statfjord) within uplifted and tilted fault blocks. These great oil bearing structures were formed during the Kimmerian tectonic phase (Pegrum *et al.*, 1975, p. 64).

The Rhaetian to Lower Jurassic Statfjord sands (possibly nonmarine) and the Dogger Brent sands (shallow marine-deltaic) form the main reservoirs for the major oil accumulations in the Viking Graben. However, their time equivalents are of less importance in the Central Graben to the south, where Upper Jurassic (Oxfordian-Lower Kimmeridgian) shallow water beach/bar sands constitute the major Mesozoic oil reservoir, (e.g., Piper field, Williams *et al.*, 1975). Upper Jurassic sands deposited in submarine fan complexes at the base of fault scarps bounding graben areas are also prospective hydrocarbon reservoirs (e.g., Brae).

Cretaceous. The original distribution of Lower Cretaceous (Neocomian) sediments in the North Sea is highly conjectural. Subsequent erosion removed these sediments from much of the area and it is not known if they were widely deposited or confined to the troughs (Walmsley, 1975). The sediments are mostly marine shales, with some sandstones, (e.g., in the Moray Firth) and limestones in the marginal areas around the pre-Cretaceous highs. Basal Cretaceous (Wealden) sands overlying the Kimmerian unconformity are oil and gas reservoirs in the Netherlands and Germany.

The Aptian-Albian marked a widespread transgression as waters flooded across Europe from the Tethys in the south and the Boreal Ocean in the north. In the North Sea Aptian-Albian sediments are widespread and are normally represented by marine shales which are thin (±75 m, ±250 feet) and commonly rest unconformably on rocks ranging from Jurassic to paleozoic in age, except in the Viking and Central Grabens which continued to subside rapidly and received thick shale deposits (up to 500 m).

Transgression continued through the Upper Cretaceous as the seas gradually submerged much of northwest Europe. The transgression reached its maximum extent during the Senonian (late Campanian), when only parts of central Europe, northern Scotland and Scandinavia remained as islands (see Hancock, 1969, 1975).

Over most of northern Europe, the Upper Cretaceous is developed as a pure white chalk composed largely of coccoliths free of detrital constituents. In the northern part of the North Sea, however argillaceous sediments predominate with only minor amounts of carbonate. These clays are draped over the pre-Cretaceous block topography and seal the underlying reservoirs.

Apart from the area of Zechstein salt where moving masses become diapiric, the Upper Cretaceous is fairly constant in thickness, ranging where fully developed from 600 m (2,000 feet) to about 1050 m (3,500 feet). The chalk itself, though highly porous, is actually impermeable and is therefore an unattractive reservoir. However, in certain areas, notably the Ekofisk area of southern Norwegian water, some permeability exists in the very clean uppermost Cretaceous Maastrichtian and overlying Tertiary Danian chalk (Mapstone, 1975; Hancock and Scholle, 1975), possibly caused by intensive fracturing (induced by underlying salt uplift) or early oil migration which retarded cementation and diagenesis in the chalk.

Intensive bioturbation is characteristic of much of the Maastrichtian chalk. At certain localites, in particular in Denmark, bryozoan bioherms occur (see Hancock, 1975, p. 510). Planktonic and benthonic Foraminifera are the most common microfossils and molluscan grains, sponge spicules, and rare echinoid fragments are the major megafossil components (Scholle, 1974). Flints, occuring as nodular layers, are the most conspicuous products of late diagenesis in the Maastrichtian chalk (Hakansson *et al.*, 1974).

Tertiary. Widespread epeirogenic uplift at the end of the Cretaceous (Laramide) led to a marked regression, leaving small basins in which successively younger chalk was deposited. The Danian formations are restricted to the centre of the North Sea basin. Basal Danian sediments are chalky limestones resting on Maastrichtian chalk, and grade upwards into a sand and shale sequence containing conglomerates of reworked chalk. From Danian times onwards, subsidence during the Tertiary (attaining about 3500 meters (11,500 feet) in the centre of the basin) has led to the present form of the North Sea (Walmsley, 1975).

Great volcanic activity occurred during the early Tertiary and igneous extrusives are abundant throughout western Scotland, the Atlantic region and Greenland. A major Paleocene volcanic ash forms an excellent time marker, (pre-Lower Eocene transgression) associated with a seismic horizon picked over most of the North Sea

The combination of lithological, sedimentological, geophysical and paleontological data indicates a deep-water basin existed in the centre of the North Sea early in Tertiary times as a result of continued rifting and subsidence, as the British Isles rotated westward relative to northwest Europe. A prograding coastal-deltaic sandy facies advanced southeast from the Shetland Platform area towards the centre of the basin Instability of sediments produced gravity flows that formed submarine fan systems characterized by turbidity current and other mass-flow deposits. Sandstones of the upper and middle fan facies have good reservoir qualities and the Forties and Montrose fields are located in these sediments (Parker, 1975; Thomas *et al.*, 1974). During the Eocene, sand deposition continued in the coastal-deltaic environments but in the deeper water parts of the basin deposition was principally shale

Tertiary sediments were laid down at a time when vast orogenic movements were taking place in southern Europe (Alpine). These movements were of minor importance in the North Atlantic However, widespread subsidence together with eustatic changes in sea level led to repeated regressive phases within the overall transgressive seas of the Tertiary period.

Quaternary. Subsidence continued rapidly during the early Pleistocene with the deposition of marine clays, sands, and conglomerates with shell debris and lignites. Subsequent glaciation saw the entire area covered with ice from which a veneer of Boulder Clay was deposited.

Holocene sediments record the melting of the ice accompanied by a marked transgression and sediments largely composed of reworked glacial material.

Traps

Four major trapping situations exist in the North Sea (Blair, 1975; Walmsley, 1975). In the prolific gas province of the southern British and Dutch waters, gas was formed in the Carboniferous Coal Measures and migrated into the fractured and porous Permian Rotliegendes Sandstone (60 to 240 m thick) where it was trapped in faulted anticlines by an impervious Zechstein Salt seal above.

The traps of the Ekofisk complex (7 fields, 3 billion barrels recoverable crude and 12 trillion cubic feet of associated gas) comprise large domal anticlines at depths of 10 to 12,000 feet producing from fractured Lower Tertiary (Danian) and Upper Cretaceous (Maastrichtian) chalk. These structures were formed by the upward movement of Zechstein salt and are sealed by Tertiary mudstones

In the central North Sea, the reservoirs in Forties (2 billion barrels recoverable, on production since 1975, to peak at 500,000 bopd in 1977) and Montrose (100 million barrels recoverable) fields are primarily Paleocene (turbidite) sandstones located at depths of 8,000 feet (Thomas *et al.*, 1974; Fowler, 1975). The movement of pre-Cretaceous basement blocks has produced a draping effect in the tight Cretaceous chalk and Tertiary reservoir sands, which caused the development of low relief anticlinal traps.

In the northern part of the North Sea, the so-called Brent Province, Jurassic sandstones, which may be over 1,000 feet thick, form the reservoirs of many fields such as Statfjord (3.9 bbo), Brent (2.2 bbo) and Ninian (1.2 bbo) The Middle (Brent sand) and Lower (Statfjord sand) Jurassic reservoirs are westward dipping and preserved in fault blocks, and sealed up-dip by unconformable Upper Jurassic (Kimmeridgian-Callovian) and Cretaceous shales. Similar traps are developed in Zechstein carbonates below the unconformity at Auk and Argyll in the UK sector, west of the Ekofisk Province.

A fifth major trapping situation is developed along the eastern edge of the Shetland platform where thick (more than 500 m) sands of the Upper Jurassic occur as coalesced fan deposits at the base of submarine scarps (e g., Brae and Thelma discoveries)

Future Exploration Activies

Exploration will continue in the North Sea Basin and in three new major areas: 1) the south and west coasts of Ireland, 2) the Western Aproaches Basin, and 3) northern Norway. If Britain is to maintain self-sufficiency in oil through the 1990s, successful exploratory and development operations may be needed in deep water areas, perhaps, in water depths up to 6,000 feet. Attention on the British shelf will then be directed north of latitude 62°N in the North Sea basin and in the Rockall Trough and Platform among other areas.

In the Western Approaches Basin (see Blundell, in Yorath *et al*, 1975, p. 341-362) off Brest, three wells were drilled during 1975 to 1976 The first well, Lizenn 1, is reported to have penetrated Lower Jurassic limestones at 14,400 feet. The subsequent well, Lenkett 1, reportedly had oil shows in the Upper Jurassic which were not tested, and the third well, Brezell, was plugged and abandoned. Although the French and

British have still to resolve the median line here, some blocks are offered in the British sector in the 5th round awards.

Future exploratory activity by the industry off the west coast of the Republic of Ireland will be worth watching. In March, 1976, licences were awarded to several groups of companies, and drilling should begin in the Porcupine seabight (Bailey, in Yorath *et al.*, 1975, p. 331-340) by 1978. Further drilling is taking place in the western extremities of the Fastnet Basin, where encouragement for commercial hydrocarbon production has been given by the gas discoveries at Kinsale in Lower Cretaceous deltaic sandstones ("Wealden") with reserves of about one Tcf (production to commence 1978) and oil discoveries at Seven Heads (Robinson and Riddihough, 1975). Activity is anticipated in the Celtic Sea where several obligation wells from previous concession awards remain to be drilled by March, 1978.

The basins off northern Norway (Tromso, Hammerfest) may see exploratory drilling during the summer of 1978. These areas have potential in thick Mesozoic sections compatible with the stratigraphy of the northern North Sea (Sundvor and Nysaether, in Yorath *et al.*, 1975, p. 267-281). The government company Statoil will probably be assigned primary responsibility for drilling operations in cooperation with experienced private companies.

In the Spanish Mediterranean (Gulf of Valencia), several recently drilled wells have tapped oil trapped beneath Tertiary shales in karstified Mesozoic (Triassic - Lower Cretaceous) carbonates. Deep-water awards in 1975 will see exploratory tests in 1,800 feet of water during 1977. A discovery by Shell in May, 1976, on the narrow Spanish shelf of the Bay of Biscay is significant, and new awards will be made here in 1977.

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