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DETAILED SEA BED MAPPING FOR A PIPELINE ACROSS THE NORWEGIAN TRENCH

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ABSTRACT

In 1976, two years after the discovery of the Statfjord oil field in the North Sea, the Statoil/Mobil Group decided to go ahead with an evaluation of the feasibility of laying a submarine pipeline from Statfjord to the western coast of Norway.

Due to the rough nature of the Norwegian west coast and unexpected features (pockmarks) in the Norwegian Trench, the Statfjord-Norway pipeline route called for a detailed sea floor mapping.

For the general mapping, boomer, sparker, side scan sonar and pitch, roll and heave-compensated echo sounders were used.

For the detailed surveying of the rocky shore approach areas, a dense profile grid with the above-mentioned systems was used in addition to manned submersibles carrying video equipment and precision profiling equipment. In all, nine shore approach routes were studied, of which three were subject to manned submersible surveying before one shore approach route was selected.

Valuable experience was gained in the course of the survey programme, including experience on the complexity of submarine navigation in rugged terrain, automatic mapping systems and the difficulty of producing side scan sonar mosaics over large areas.

1. — INTRODUCTION

The Statfjord field, 160 km west of the Norwegian coast, in the northern North Sea was discovered in February 1974, and was declared commercial in August of the same year. The Norwegian part of the field is owned by the Statoil/Mobil Group of which Statoil (the Norwegian State Oil Company) owns 50 % and the field operator Mobil Exploration Norway Inc., owns 15 %.

In 1976 the Norwegian authorities requested an evaluation of the feasibility and the cost of two alternative crude oil transportation systems from the Statfjord field, namely, offshore loading by oil tankers, and pipeline transportation across the Norwegian Trench to a shore based terminal on the west coast of Norway.

Statoil undertook the pipeline project on behalf of the Statoil/Mobil Group. The main objectives of the project, which was termed the Statfjord Transportation System Project, were to study the feasibility and cost of installing, constructing and operating a large diameter (36 inch) crude oil pipeline from Statfjord to a terminal processing plant on shore. The project has posed a range of engineering questions, most of which were related to pipelaying in water depths of 300 to 350 m in the Norwegian Trench.

2. — REQUIRED ROUTE INFORMATION

One main objective of the project was to locate and describe an acceptable pipeline route. This necessitated a comprehensive program for acquisition of all necessary hydrographic and geophysical data. It was evident from the start of the project that the greatest routeing problems would be presented by the rugged sea floor in the coastal region, where crystalline bedrock constitutes the major part of the seabed. A large dia-

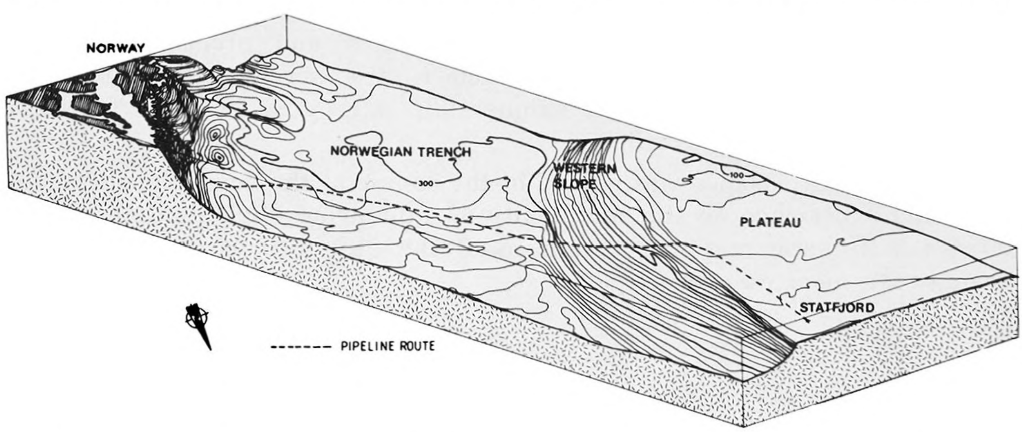

Fig. 1. — A perspective view, looking from the north at the Norwegian Trench (vertical scale enhancement).

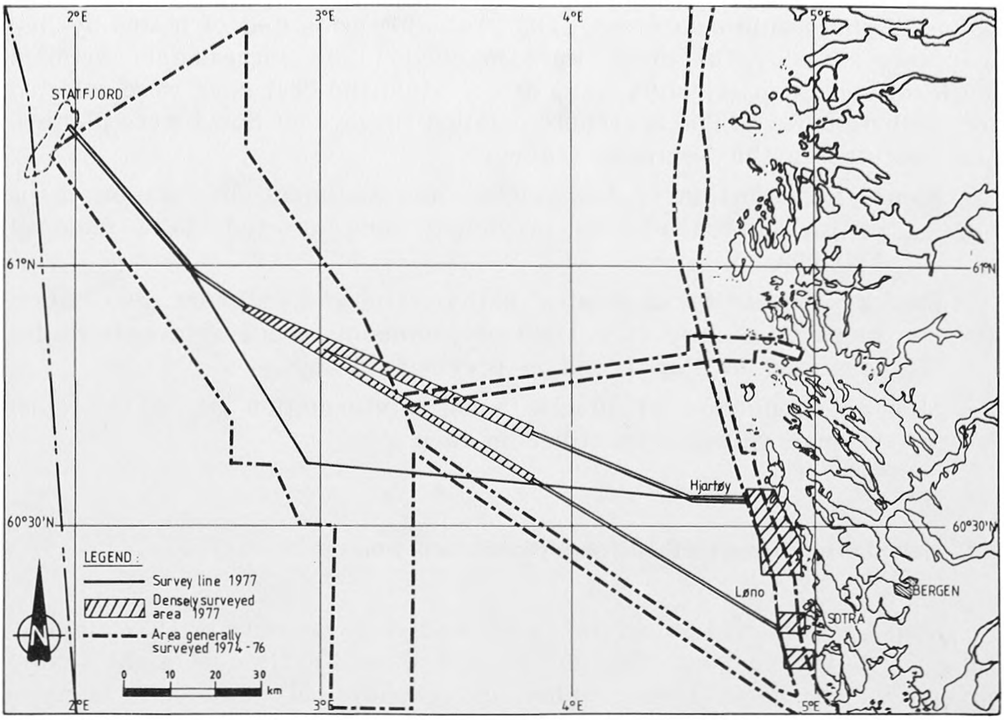

FIG. 2. — Map showing areas surveyed and the location of Statfjord and Sotra.

meter submarine pipeline requires a route which is devoid of horizontal sharp bends, (curvature radii should not be less than about 2 km). Since the vertical bending tolerance of the pipe is also relatively small, the route should preferably not present any abrupt changes in slope. Furthermore, the pipe should be able to rest upon a seabed, ideally consisting of gravel, sand or clay.

The aim of the first reconnaissance survey, along the west coast of Norway in 1974, was to locate any possible seabed features in the crystalline nearshore areas providing an obvious approach route to shore. The survey was run with boomer and echo sounder, but did not result in the identification of any clear-cut approach route.

After surveys both nearshore and offshore in 1975 and 1976, the island of Sotra near Bergen (figure 2) was chosen as the potential pipeline landfall area, due mainly to the deeper waters further north in the Norwegian Trench, the width of the coastal zone, and the possibilities of finding a suitable terminal area on Sotra Island. All the survey work performed between 1974 and 1976 was done by Geoteam A/S, Norway.

3. — DETAILED NEARSHORE SURVEYS — 1977

A narrowing-down method was applied for the detailed hydrographic and geophysical mapping of the areas identified in the coastal zone as potential shore approach areas. The procedure consisted of a step-by-step mapping, whereby the areas were mapped to an increasingly detailed level, for each step rejecting some areas, while the best ones were selected for further surveys. The nearshore detailed surveys off Sotra were planned and executed in the following sequence :

Step 1 : Production of bathymetric and sediment distribution maps of the approach areas previously not surveyed, to a scale of 1:10 000.

Step 2 : Production of detailed bathymetric and sediment distribution maps to a scale of 1:5 000 of promising shore approach routes identified in Step 1 and in previous surveys.

Step 3 : Production of precise seabed information along the most promising routes identified in Step 2.

3.1. Nearshore survey methods, equipment and time

Step 1 was carried out in the spring and early summer of 1977 employing a 64 ft fishing boat. Positioning was done by "line of sight" radio navigation, the main hydrographic and geophysical equipment being a pitch, roll and heave compensated echo sounder, a surface towed sub-bottom profiler (boomer), and a side scan sonar (figure 3). The sonar fish was towed at a mean altitude of 40 m above the rugged sea floor. The line spacing in Step 1 was set to 150 m. The main profiling direction was N-S in order to detect promising geological formations running E-W. The data processing, interpretation, plotting and contouring was carried out on land. Further details on the equipment are given in table 1.

In Step 2, five potential shore approach routes became subject to more detailed mapping in the summer of 1977. The same ship and equipment were used as in Step 1, except for one area where the vessel and equipment from the offshore survey were used. A 32 ft cabin cruiser equipped with a roll compensated echo sounder and a boomer was used to map areas close to shoals, islands and shore. The positioning of the small vessel was done with two theodolites. The line spacing in Step 2 was 75 m generally, and about 25 m along identified potential route corridors.

Step 3 was begun in the autumn of 1977 with an evaluation of the detailed 1:5 000 maps produced in Step 2. None of the routes which were identified could provide any solutions avoiding some sea floor preparations prior to pipe laying. The final step in the shore approach mapping sequence, therefore, called for a thorough examination and precise documentation of the critical sections of the potential routes.

Following this evaluation three areas were chosen for survey and mapping by manned submersibles, two outside Løno Island, and one further north in the Hjartøy area. The information gained by the submersible surveys was then subject to thorough engineering analyses for selection of the best pipeline route.

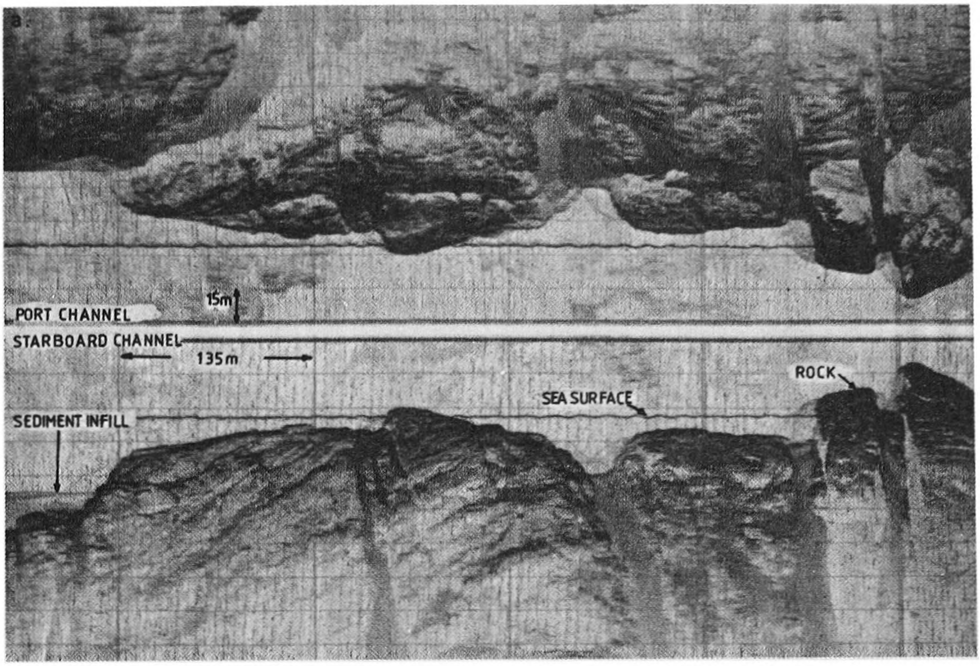

FIG. 3a. — Side scan sonogram of a nearshore area.

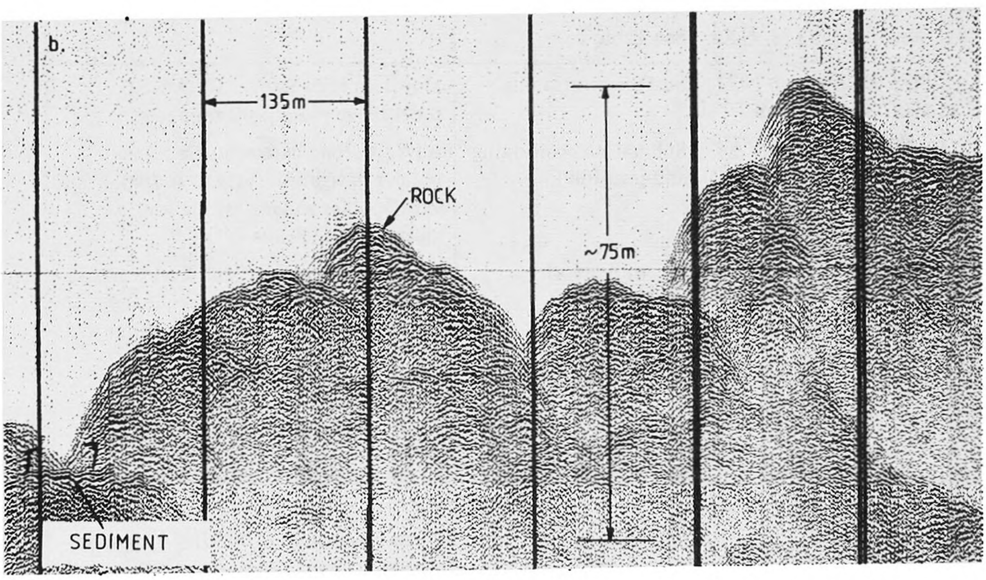

FIG. 3b. — The corresponding sub-bottom profiler record (see fig. 3a).

The manned submersible surveys were carried out in two stages with two different contractors. One survey was done late in 1977, the other one early in 1978. The main instruments carried by the submersibles were precision bottom-profiling systems and video tape systems. Further equipment details are given in Table 1. A profile grid with a line spacing of 25 m was run in critical route sections, while only one profile was run along the other parts of the promising approach routes. Some submersible tracks for the Løno area are shown in figure 7b.

Table 1

Mapping sequence, time, vessel, contractor, survey systems and equipment specifications for nearshore surveys conducted in 1977 and 1978

Mapping sequence, time, vessel and contractor	Survey system	Type and specification
Step 1, Spring 1977, M/K *"Lotroll"* 64' former fishing boat, Noteby-Blom Joint Venture, Norway	Positioning Echosounder Sub bottom profiler Side scan sonar	Motorola Mini-Ranger III (MRS), short range radio positioning. Simrad EK-S scientific, 38 kHz, 7° beam angle transducer, papertape and analogue datalogging. Pitch, roll and heave compensation by use of a gyroplatform made by the Continental Shelf Institute, Trondheim. EG & G Uniboom system (500 Hz at 300 J). Analogue and magnetic tape recording. Klein Hydroscan model 400(100 kHz). Analogue paper recording.
Step 2, Summer 1977, M/K *"Lotroll"*, *"Pegasus"* 32' Noteby-Blom Joint Venture, Norway Sonarmarine Ltd. U.K.	Same as above Positioning Echosounder See Table 2	Same as above Intersection by two Wild theodolites. Atlas 470, 33 kHz, 6° beam angle, roll stabilized transducer.
Step 3a, Autumn 1977, M/S *"Vickers Vanguard"*, 269' support ship with two minisubmarines : "Pisces II" and "Pisces VIII". Vickers Oceanics Ltd., U.K.	Surface positioning Submarine positioning and position log Precision depth profiling Video recording Stereo photography Sub-bottom profiler Side scan sonar	Motorola Mini-Ranger III (MRS), short range radio positioning. ATNAV, long base acoustic transponder navigation system. A dual axis Doppler sonar position log, mounted on "Pisces II". Combination of precision Digiquartz pressure sensor and high frequency short range echo sounding system. Sub-Sea Systems under-water camera, Sony recorder. Two 35 mm UMEL Deep Sea cameras. Parametric sub-bottom profiling system, 7° beam angle. Klein Electronics (100 kHz), magnetic tape recording, mounted on "Pisces II".
Step 3b, Spring 1978, M/S, *"InterSub Three"*, 249' support ship with one minisubmarine : *"PC 1201"*. Kvaerner Intersub, Norway.	Surface positioning Submarine positioning Precision depth profiling Video recording	Motorola Mini-Ranger III (MRS), short range radio positioning. PA21, long base acoustic transponder under-water navigation system. Combination of precision CZ9029 pressure sensor and ELA precision depth sounder Type DS11 (170 kHz). Hand-held Sony camera, Sony recorder. Video shot through the dome-shaped plexiglass nose of "PC 1201".

4. — DETAILED OFFSHORE SURVEYS — 1977

It has been generally known that the sea floor in the northern North Sea is generally even and consists of soft clay in the deeper parts (Norwegian Trench). It was also known that the sea floor in some areas has a varying degree of roughness in the form of gullies and local depressions. The surveys in 1974 and 1976 showed that these seabed features were of a similar type to features, termed pockmarks, observed in the British North Sea. Pockmarks are local depressions of a circular, oval or irregular shape, varying in diameter from less than 10 m to 300 m, and ranging in depth below the main seabed level from 1 m to 10 m.

The purpose of a detailed offshore survey in 1977 was therefore twofold :

a) To produce detailed bathymetric profiles and information on soil types and thicknesses along the chosen offshore pipeline route corridor.

b) To map the position, size, form and distribution of pockmarks in an area of the pockmarks region. This was done primarily for route alignment, but also in order to attempt to unravel the mode of pockmark formation. The area chosen as a pockmark reference area was mapped such that a later resurvey of the area would enable the detection of possible changes in the pockmark pattern. The areas mapped offshore are shown in figure 2.

4.1. Methods and equipment used offshore

The vessel employed for the detailed offshore survey (see table 2) was a 185 ft former stern trawler. The survey was run on a 24-hour basis.

Table 2

Survey systems, type and specifications on the offshore survey conducted in the summer of 1977 with M/T Criscilla, a 185′ former stern trawler. The contractor was Sonarmarine Ltd., U.K.

Survey system	Type and specifications
Positioning	Hi-Fix/6 with Decca Pulse 8 as back-up system. (Decca Trisponder nearshore).
Echosounder	O.R.E. Model 323 A with shallow-towed, heave compensated, 9° beam angle transducer.
Sub-bottom profiler	Modified Huntec deep towed boomer (540 J) with analogue paper and magnetic tape recording.
Side scan sonar	Sonarmarine deep towed sonar fish with modified Kelvin Hughes 48 kHz transducers. Range : 375 m and 750 m.

The main hydrographic and geophysical equipment was : a precision echo sounder with a shallow towed, heave compensated transducer, a deep towed, depth compensated, high resolution boomer and a deep towed, single channel, high resolution side scan sonar (figure 4). In the pockmark area the line spacing was 135 m in order to provide sufficient overlap and coverage from both sides. In the remaining offshore pipeline route corridor the line spacing was 600 m.

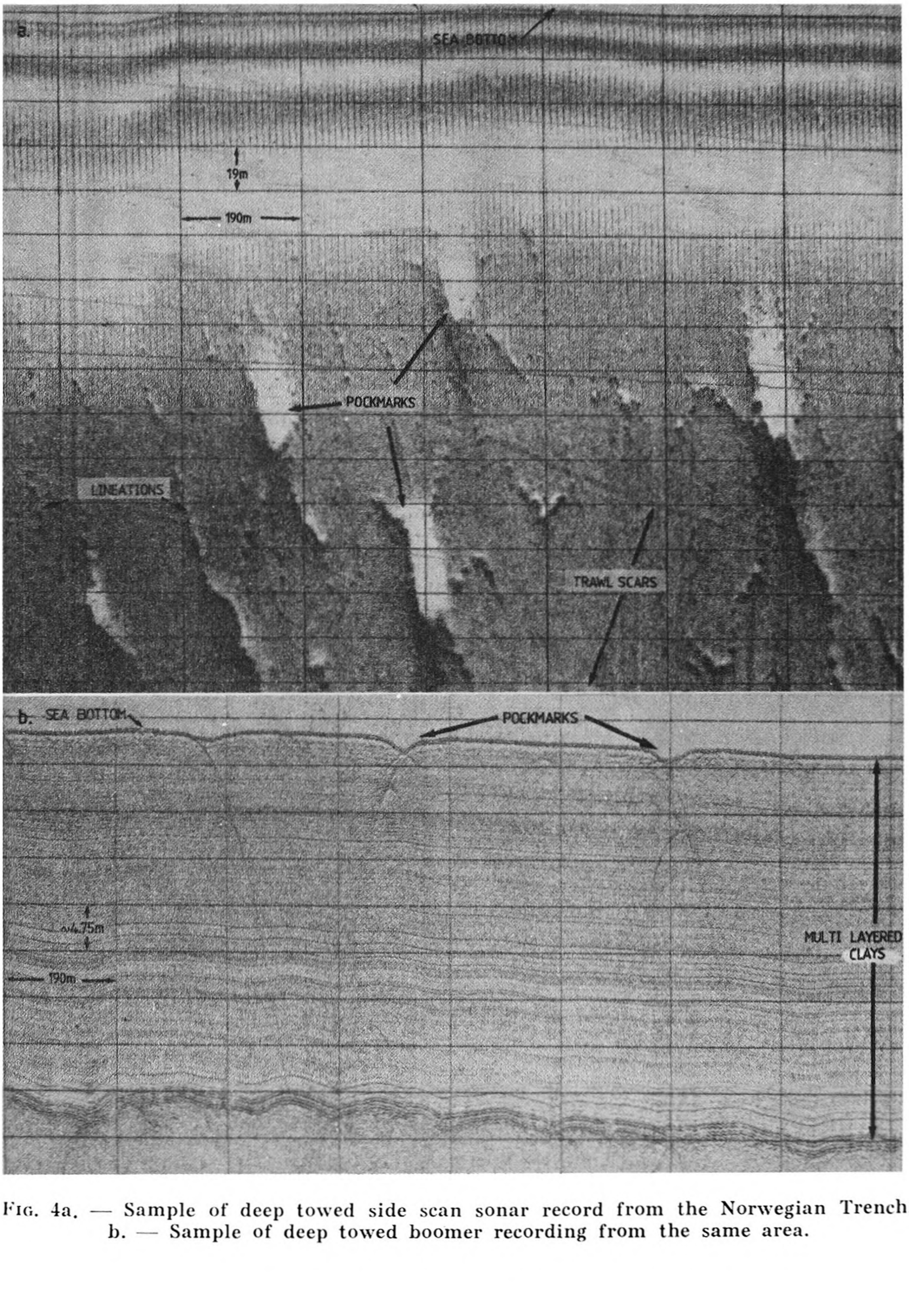

FIG. 4a. — Sample of deep towed side scan sonar record from the Norwegian Trench.
b. — Sample of deep towed boomer recording from the same area.

5. — SURVEY RESULTS AND EXPERIENCE

5.1. Nearshore

The field work in Step 1 of the nearshore surveys took $1\frac{1}{2}$ months, during which 900 km of bathymetric and geophysical profiling was carried

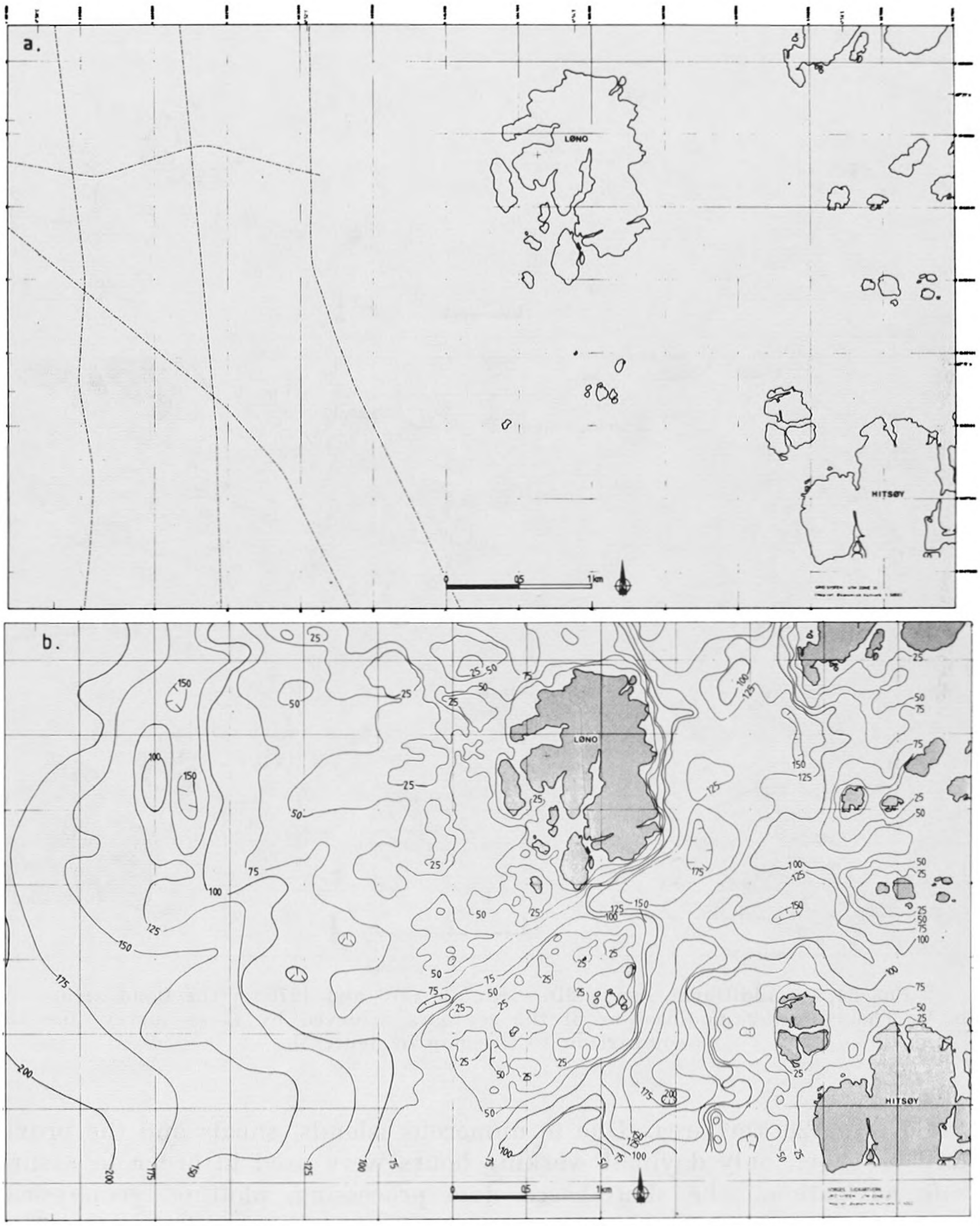

Fig. 5a. — Reconnaissance profiles run in 1974 in one of the nearshore areas close to the Island of Løno west of Sotra main Island.
b. — Bathymetric map of the Løno area. The map is produced from soundings done by the Norwegian Hydrographic Office around 1930.

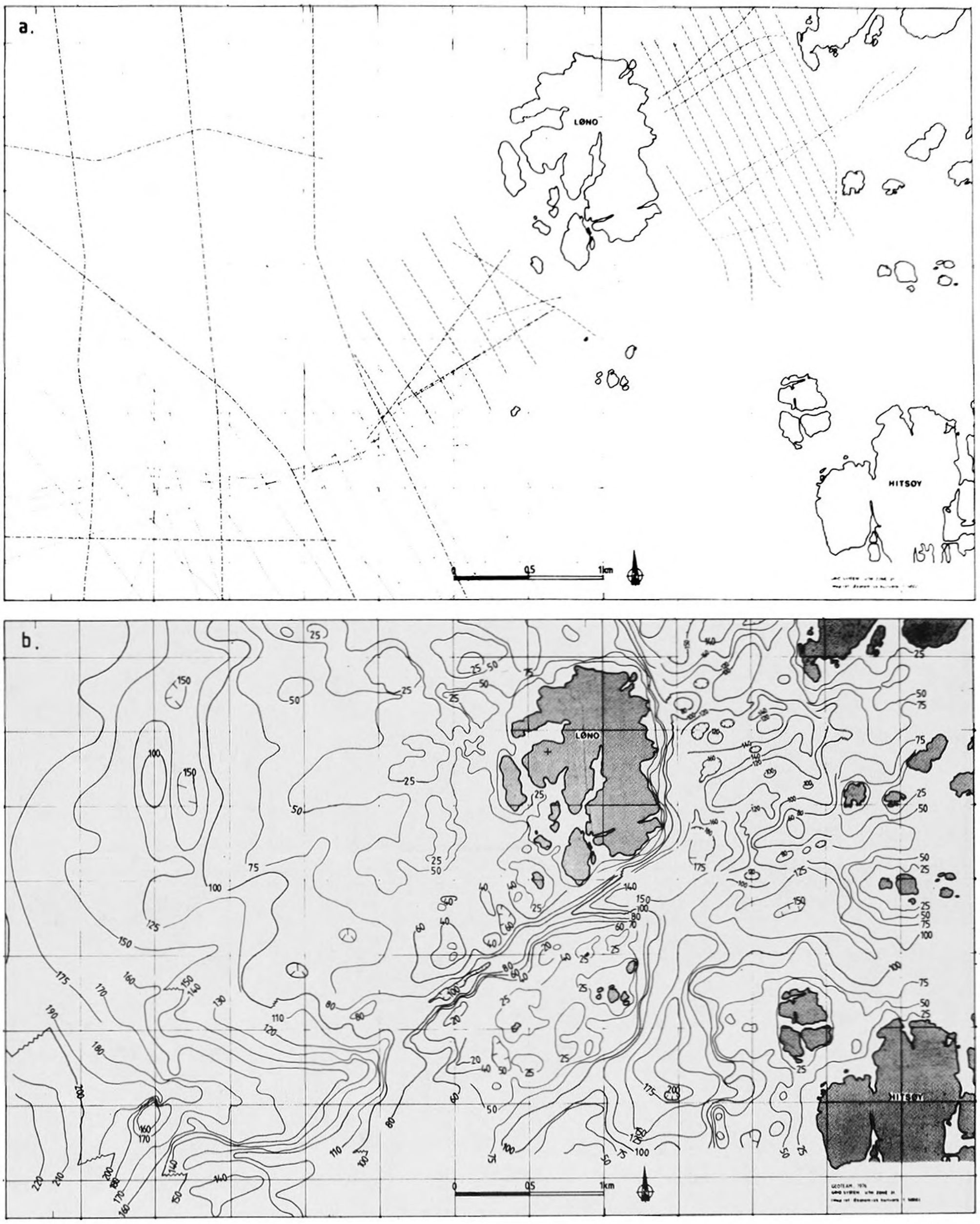

FIG. 6a. — Additional survey lines run in 1975 and 1976 in the Løno area.
b. — The resulting modification of the contours achieved by these survey lines in comparison to the map in figure 5b.

out over a 120 km² area. Due to numerous islands, shoals and the proximity to shore, only daylight working hours were used in order to assure safe navigation. The shore-based data processing, plotting, geophysical interpretation, and contouring were commenced two weeks after the field work started. A set of three map sheets to a scale of 1:10 000 were thus completed. The map sheets contained information on bathymetry (with a contour interval of 10 m), the soft sediment thickness and its distribution, the distribution of rock and coarse sediments and the sea floor morphology.

An additional 1900 km of profiling in Step 2 yielded detailed maps for five areas to a scale of 1:5 000 with a contour interval of 5 m, and seabed information as mentioned for Step 1.

The step-wise surveying and the resulting improvement of the bathymetric information is illustrated in figures 5 to 7 from the Løno area, one of the potential shore approach areas.

In Step 3, 63 km of manned submersible surveying yielded detailed depth profiles, continuous video recordings, stereo colour photographs, and some side scan sonar information along three potential shore approach routes in two landing areas. This information provided a route description enabling the construction of detailed depth profiles to a scale of 1:2 000 along critical sections of the routes.

The experience gained during the two-year mapping sequence described for the coastal zone may be summarized as follows.

a) *Time and costs*

The main lesson learnt in the course of the project was not to underestimate the mapping requirements. Even though it was known that the coastal zone would present the greatest routeing problems, more time than at first anticipated was spent in search of a shore approach route.

The search for an easy shore approach route became a search for a technically feasible route which required the least amount of sea floor preparations prior to pipe laying.

b) *Side scan sonar handling*

Prior to the field work in Steps 1 and 2 it was known that the side scan sonar handling would require a lot of effort in order to acquire good results in the nearshore area. In order to tow a standard sonar fish at an optimum mean height over the rugged terrain, each line was carefully planned on hydrographic charts. A winch operator with direct communication to the bridge was employed. Fairly good records were acquired from a total of 2100 km of nearshore side scan towage. The sonar fish only grazed a submarine mountain top once. This happened on a line where no problems were expected and the winchman had gone for lunch. Instead of employing an extra man for the winch, it would be much better with either a steerable fish or a fast winch operated directly by the side scan sonar operator.

c) *The echo sounder system and vessel*

It was difficult to find an ideal combination of vessel and echo sounder for the nearshore area. A narrow-beam transducer is required for rapid depth variations. This again calls for a stable platform. However, a large

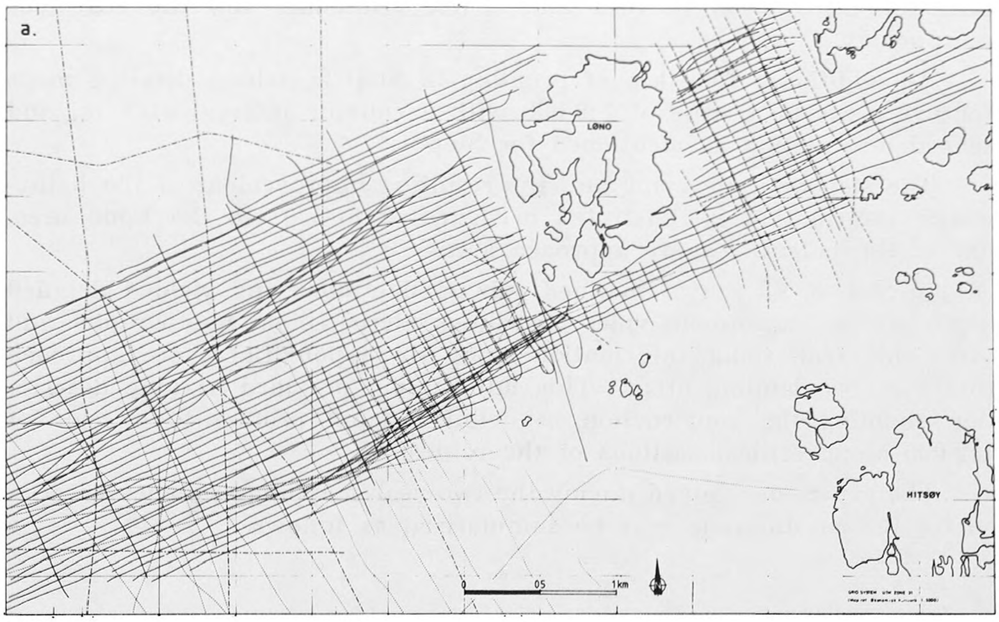

FIG. 7a. — Detailed nearshore route survey lines run during mapping Steps 1 and 2 in 1977 and previously, in the Løno area.

(stable) vessel cannot operate as close to shore as required. A compromise solution was therefore chosen. A narrow-beam transducer was installed in a fairly small vessel, together with a pitch, roll and heave sensor. The transducer's movements were compensated for in the data processing done on-shore. This solution led to a reduced sea state tolerance for the survey, which had to be interrupted when the vessel's roll (in particular) became too large.

d) *Submersible operation*

In the rugged nearshore terrain the long base acoustic bottom navigation system turned out to be difficult to operate due to shadowing of paths and multiple reflections of transponder pulses. Even though maps to a scale of 1:5 000 were provided, and great care was taken in planning, both contractors had problems at first finding locations for the bottom transponders which gave good positioning. Quite some time was spent at the beginning of each survey in a trial and error process of transponder positioning.

The end result was a fairly narrow transponder pattern where the transponders were placed 10-20 m above the sea bottom. Field time could have been saved if a numerical simulation model had been at hand, whereby the optimal long base transponder positions could be computed in relation to the topography and the water temperature lapse rate.

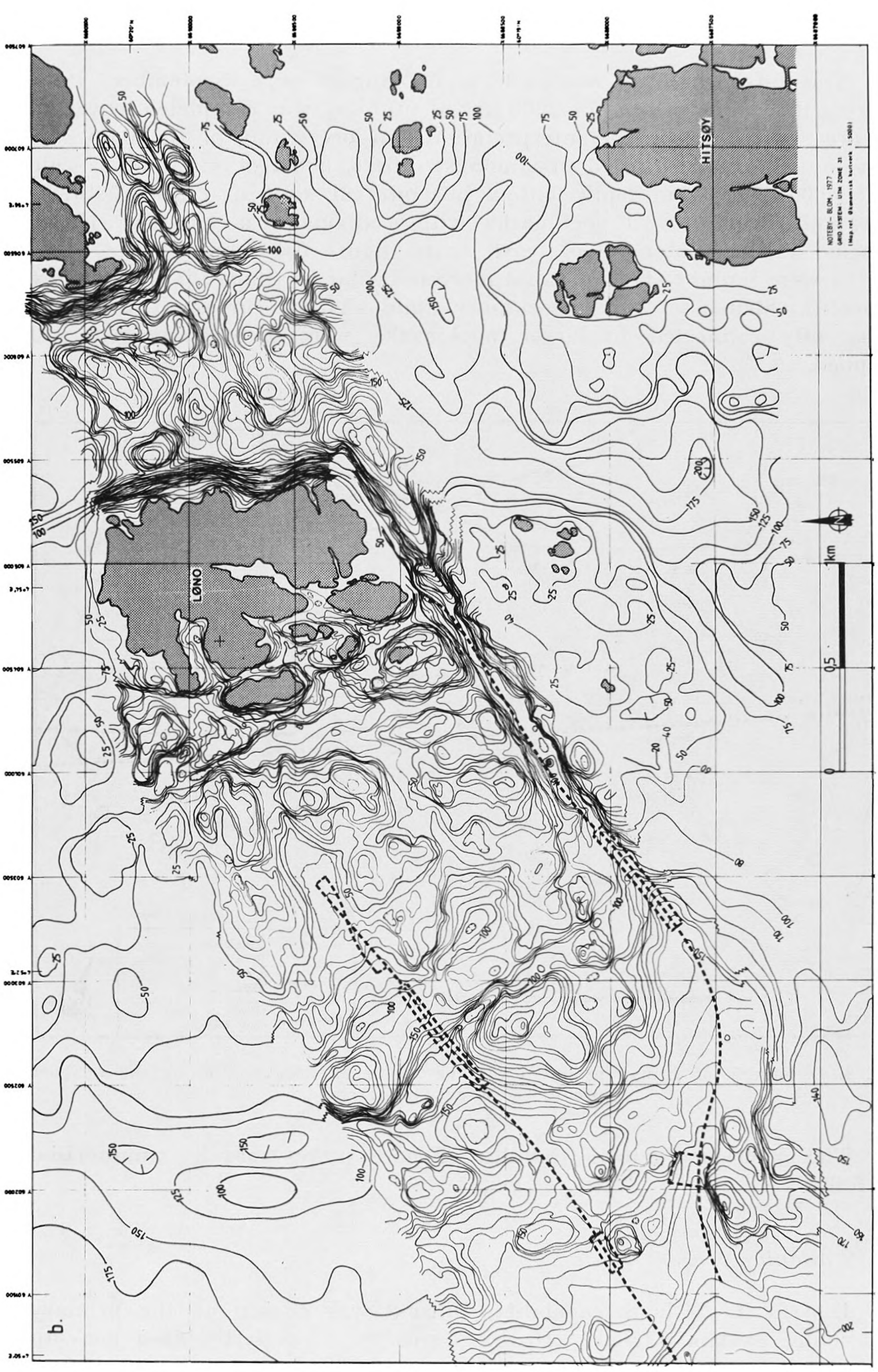

FIG. 7b. — The final bathymetric map of the Løno area resulting mainly from the 1977 survey lines. Some manned submersible tracks are also shown for the two routes in this shore approach area.

5.2. **Offshore**

The offshore field work done in August and September 1977. During this period a total of 2900 km of profiling was completed, covering an area of 350 km². The interpretation and processing of the data was done onshore and resulted in, amongst others, a set of maps at a scale of 1:10 000, with 2 m depth contour line interval, showing sediment thickness and structure, all pockmarks with a diameter larger than 10 m, wrecks, and the intensity of trawl scars (figure 8). Some of the pockmarks were found to be somewhat more irregular in shape than previously expected. Strings of small pockmarks and shallow furrows (lineations) apparently connected to larger pockmarks were also discovered and mapped.

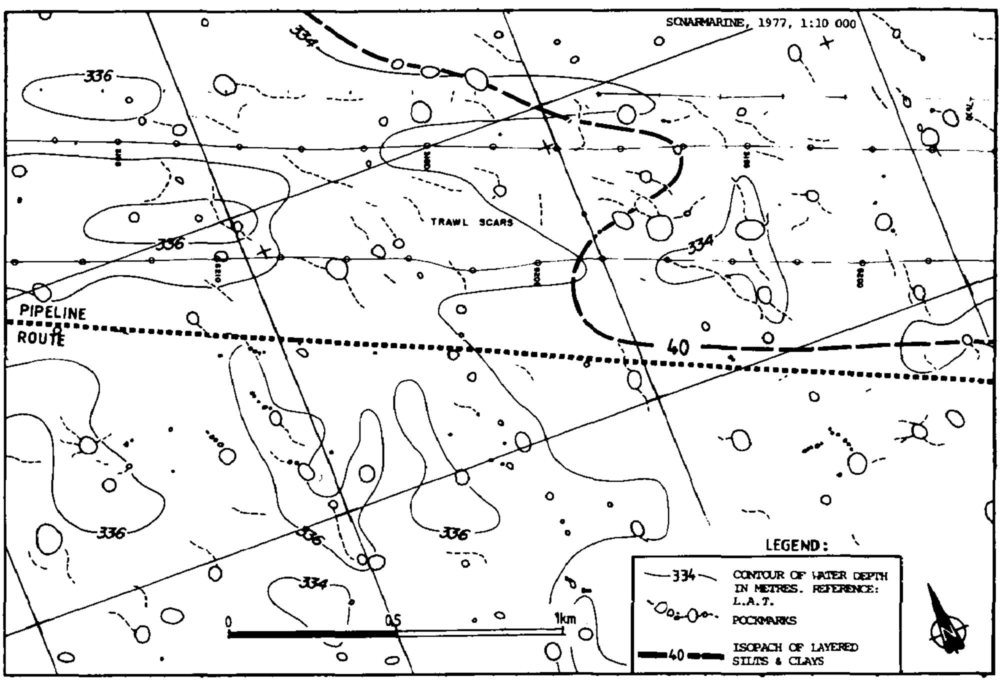

FIG. 8. — Sample of a map produced for the pockmark area and along the offshore route in the Norwegian Trench.

The experience gained from the offshore survey may be summarized as follows.

a) *Positioning*

Due to its 24-hour capability, Pulse-8 was chosen as the primary positioning system offshore. Hi-Fix/6 was included partly as a back-up system, and partly to increase the accuracy in the pockmarks region. However, it turned out that Hi-Fix/6 was stable throughout 24 hours and was therefore used as the primary positioning system, and was operated in range-range mode. Pulse-8 was used for lane-setting (of Hi-Fix/6) and as a back-up system. During the survey Hi-Fix/6 seemed to provide a repeatability of 3-4 m, and an absolute accuracy of 10-15 m.

b) *Side scan sonar*

The increased knowledge about pockmark features resulting from this survey, was mainly achieved by the side scan sonar which was towed at an optimum altitude (15-20 m) above the bottom, regardless of the (actual) water depth. This was done with normal profiling speed (3-4 knots), with a fairly reasonable lay back of the fish (about 350 m in 300 m water depth).

An attempt was made to construct a side scan sonar mosaic picture of the pockmark area. However, the results were not as good as expected, and did not add significantly to the presentation of pockmark features.

c) *Deep towed sub-bottom profiler*

In relation to experience gained from previous surveys with standard surface towed equipment, it was found that the deep towed boomer (towing depth 100-250 m) gave two main advantages. Due to the proximity to the sea floor, the sound pulses travel through less water, reducing the amount of noise and attenuation, and thus providing an increased data quality.

The deep towed systems are less influenced by the sea surface conditions and are therefore less weather dependent. A disadvantage is, however, less position control.

6. — THE PIPELINE ROUTE

A route for a potential crude oil pipeline from the Statfjord field to the west coast of Norway has in the course of the project been identified and mapped in such detail that engineering on the pipeline could be performed. The route is shown in figure 9.

Along the offshore section, the pipeline route is aligned so that larger pockmarks will be avoided.

Many possible pockmark formation modes have been reviewed. The theories studied ranged from pockmarks being caused by biological activity to wartime depth charge explosions. It is presently believed that pockmarks are formed in soft clays by a particle-by-particle removal of material, caused by slow gas migration.

In the shore approach section the route is partly covered by sand and gravel. But rock blasting can however not be avoided and will be necessary in water depths down to about 40 m. Rock filling will also have to be done along some shallow water sections. In deeper water down to 240 m, long pipe spans and overstresses in the 36 inch pipe will be

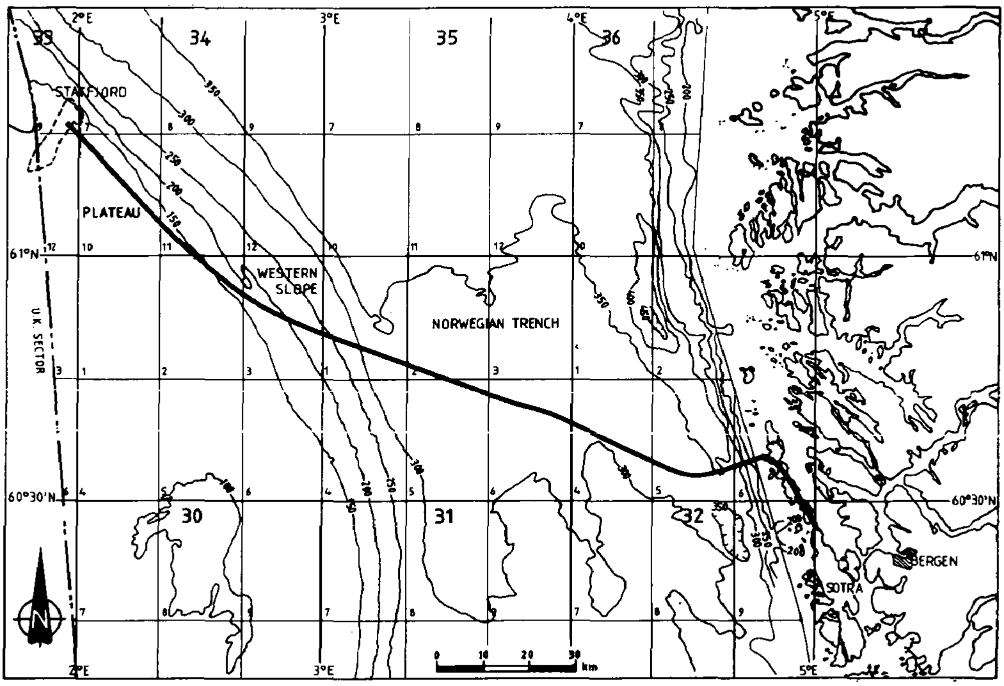

FIG. 9. — The overall pipeline route from Statfjord to Sotra Island.

prevented by the installation of special supports. Several boulder areas in the shore approach section will furthermore have to be cleared prior to pipe construction.

The total submarine length of the route is 183 km, with 99 km in water depths greater than 300 m. The maximum depth is 354 m only 8 km from the Norwegian coast. The pipeline route continues onshore in a length of 24 km from the landfall site to the terminal site. This part of the route includes 11 island-to-island water crossings and 3 tunnels.

The permanent transportation system for crude oil from the Statfjord field, whether offshore loading or pipeline, will be chosen later.

7. — CONCLUSIONS

Looking back on the survey period, from our (Statoil's) point of view, some improvements of the survey equipment and methods would have been desirable. The following items indicate some areas where we think that increased research and development could pay dividends.

For sub-area construction purposes there is a strong demand for quantified *areal* information, whereby interpolation of profile data is avoided. Such a possibility probably lies in the development of a "stereo" side scan sonar system or an acoustic "camera".

Moving into deeper waters there is a demand for a commercial deep-towed multisensor carrier incorporating good handling facilities, steering possibilities, and a reliable positioning system.

An obvious demand for the client is to increase the survey speed without reducing data quality. Using a combination of hydrographic and geophysical systems, a typical survey speed today is 3-4 knots. A 10 knot capability in deeper waters would obviously mean a great advantage. The multisensor carrier mentioned above could possibly provide an answer.

There is also a great need for improved submersible-mounted sub-bottom profiling and sonar recording systems, incorporating on-line processing of the data, whereby variations in the submersible's attitude are corrected for.

A great deal of time in the field could be saved with an improved submersible positioning system, giving immediate on-line positions. Submersible surveying is today a fairly slow and laborious process, due mainly to the fact that the submersible has to stop to get a reliable position fixing. There are, however, great expectations to the development of a commercial inertial navigation system, or a reliable doppler system.