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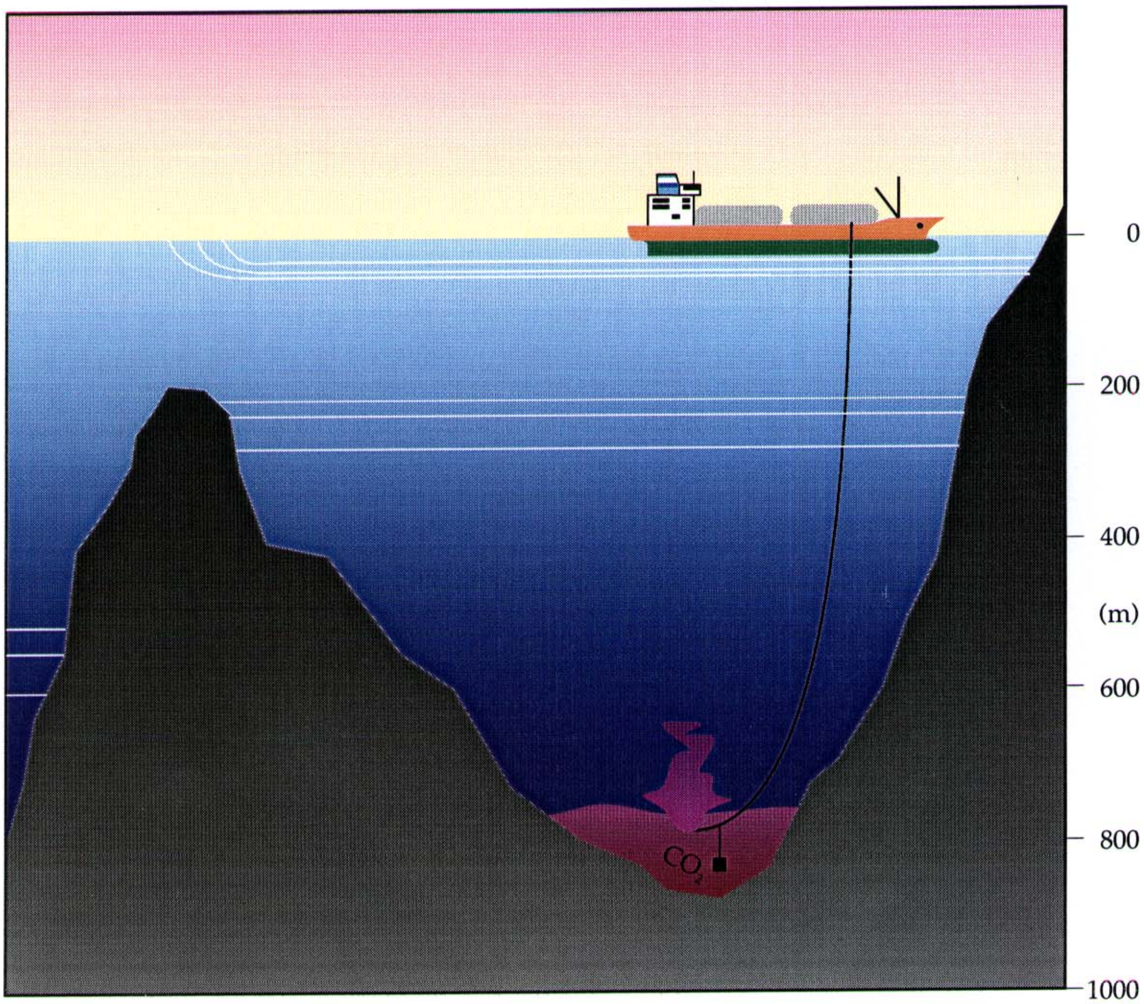
Norwegian fjords as potential sites for CO_2 experiments

A preliminary feasibility study



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REPORT

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Abstract

While deep open ocean locations probably will be those finally selected if large-scale CO_2 deepwater disposal in general will come into effect, deep Norwegian fjords may represent better locations for doing small-scale experiments with CO_2 deposition. In-situ experiments to study plume dynamics and chemical/biological impact are seriously needed. This initial feasibility study treats the physical, biological and legal constraints that an experiment in a fjord will have to adapt to. Several smaller or larger fjord basins with depths exceeding 500 m exist in western Norway. The report gives guidelines to what steps should be further taken in order to establish an in-situ CO_2 experiment in a fjord. 26 different basins have been identified in terms of max. depths, municipal adherence etc. Variations in deepwater hydrographic conditions are relatively small from fjord to fjord. Data on the dynamical states as well as on deep water biology are in general lacking, and is suggested to perform a baseline study in a limited selection of fjords that will be further evaluated prior to a final selection. User conflicts and legal aspects must not be overlooked, and a complete EIA study will most probably be required before starting any CO_2 experiment in a fjord.

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1. CO_2 havdeponering	1. Oceanic CO_2 disposal
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3. Dypvann	3. Deep Water
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by

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Preface

In November 1996 NIVA, the Norwegian Institute for Water Research, was asked by NEDO, the New Energy and Industrial Technology Development Organization of Japan, to perform an initial study and evaluation of the possibility to conduct a small-scale experiment with deep disposal of CO_2 in a suitable Norwegian fjord. The Contract for the study was signed by NIVA on December 6 and countersigned by NEDO on December 16, 1996.

Initial contacts between NEDO and NIVA were established with the assistance of Dr. Peter Haugan of the Geophysical Institute, University of Bergen. Dr. Haugan has also made contributions to the present report, particularly on the physical oceanography of fjords.

The following persons from NIVA made contributions to the report: Torgeir Bakke treated the aspects related to marine biology and Jan Sørensen gave an overview of legislation and formal procedures. Vilhelm Bjerknes reviewed some literature on the physiology of fish and other marine species, especially related to CO_2 exposure. Einar Nygaard and Petter Wang were responsible for the graphics/lay-out, while Inger Midttun edited the report. Lars G. Golmen described background issues and the physical oceanography of fjords in addition to coordinating the project activities.

Mr. Tadashi Sakuramoto coordinated NEDOs correspondence with NIVA, while Director Mashami Takayasu of NEDOs Global Environment Technology Department took the first formal initiatives to establish contacts. Constructive ideas about the CO_2 subject were exchanged between NEDO (Director Takayashu and Dr. Y. Fujii) and NIVA (L. G. Golmen) during a meeting 7. March 1997 in Oslo where the future of CO_2 ocean sequestration experiments was the main topic.

Several institutions/persons outside of NIVA have contributed with useful (informal) information, including -Ministry of Environment (B. Nordby and L. H. Skagestad),-State Pollution Control Authoritiy, (O. A. Follum), -National Centre for Environmental Impact Assessment, (S. R. Husby), -County Governor's Environmental Department in Hordaland, (H. Kryvi), -the Biological Station of Trondheim (O. Vadstein), -Hydrogas Norge (R. Nesje and P. Kværum).

NIVA has internally supported the study through Grant No. E-97423, 1997.

Contents

ANNEX. FACTS ABOUT A HYDROGAS CO_2 TANKER

Summary

This report deals with the issue of disposal of industrial CO_2 in the ocean as means to prevent further atmospheric build-up. This issue has recently been subject to numerous theoretical feasibility studies initiated by international organizations like the IEA and driven mainly by USA and Japan. However, several questions especially related to technical outlet design, to the physical behavior of the discharged gas in the ocean and to the environmental impact from the gas release still need to be resolved prior to any international acceptance of industrial CO_2 ocean disposal as a regular method.

Proposals have already been made to perform pilot tests in deep ocean locations like Hawaii and measure environmental impacts with relatively small CO_2 discharges. It has been argued that impacts may be hard to measure in such open locations, and therefore the alternative to run a pilot study in a deep fjord e.g. in Norway was put forward at a recent IEA workshop. In December 1996, NIVA; the Norwegian Institute for Water Research was contracted by NEDO; the Japanese New Energy and Industrial Technology Development Organization, to make a short study on the possibilities and obstacles, to use the deepest basin of a deep fjord in Norway, as a test site for a controlled CO_2 discharge of limited size and duration.

The proposed experiment is to inject or sprinkle liquid CO_2 at large depth from e.g. a ship by a hose or pipeline with a specially designed nozzle. It has been proposed to inject at a rate of 0.1 - 1 kg/s over a total duration of 1-2 weeks, and to measure *in situ* physical and environmental effects underway and afterwards. The CO_2 droplets, being lighter than the ambient seawater, will initially rise in the water column while being dissolved in the seawater. The CO_2 enriched seawater thus formed will be slightly denser than ambient, and will sink beyond its injection depth. Model studies on such droplet plume dispersal indicate a max. rising distance of about 100 m. At water temperatures of around 5-10°C (-this may be normal for deep water in fjords), pure CO_2 will exist in liquid form at pressures corresponding to ca 400 m or deeper. This means that injection should take place at 500 m or deeper in order to avoid CO_2 changing into gaseous phase.

With this minimum depth requirement, the coastal counties from Stavanger to Trondheim have been searched for fjords where depths are exceeding 500 m. This coastal region is where most, if not all deep fjords with sills are found in Norway. 26 individual fjord basins have been identified according to the county and fjord they belong, max. depth and municipal adherence. Most basins will adhere to more than one municipality, but each identified basin is confined to only one county. However, the fjord as a whole may be divided among several municipalities and two counties in some cases.

The deepest identified basin is about 1300 m, and several have depths of 700-1000 m. The horizontal area and the deep water volume vary significantly from basin to basin. Some of the larger identified basins actually have two or more deep regions separated by sills deeper than 500 m, that each may be topographically suitable for a CO_2 experiment. Most of the deep basins are separated from the coastal water by very deep sills, i.e. several hundred meters sill depth.

This report gives a brief review of the hydrography and currents in the deep basins. Only a few of the identified fjords are subject to some kind of regular monitoring. In such cases focus is most often laid on shallower and more productive waters. Deep water samples have only been collected occasionally in some basins. The water density stratification is weak. Oxygen depletion that is commonly observed in deep water of basins with shallow sills probably only rarely occurs in the deep basins considered in this report.

Deep current measurements in the identified basins or at adjacent sills hardly exist. For the deep water exchange in fjords with significantly shallower sills and basin depths than for those fjords identified in this study, numerous measurements and models show that water exchange is occurring intermittently, with stagnation periods of several months to a year or more. It has been anticipated that the water exchange of very deep fjords are governed by similar forces and dynamics, but timescales are probably different.

Anyhow, the dynamics will be quite different from the open ocean locations considered previously as CO_2 disposal sites. New models describing the far field dispersion of the CO_2 plume will have to be made. Existing models for shallower fjord basins have been reviewed. Some of these may be regarded as a starting point. But they will need adaptations, refinements and validation based on a set of true measurements in a limited number of preselected fjords prior to an experiment.

As for the physics, reports from investigations on deep water biology of Norwegian fjords are scarce. Available information suggests that the mesopelagic ecosystems are fairly rich, including some predatory fish. Several pelagic species perform substantial vertical migration, on various timescales. The sediment macrofauna contains all major benthic animal groups, but the numerical dominance by a few species is higher in the fjords than at similar depths on the coast outside. This may be due to larger sedimentation rates in the fjords. Some typical bottom dwelling predatory fish (ling, tusk) are also of some commercial value for fishing. In general there is a distinct dissimilarity in many cases for the deepwater fauna between the fjords and the adjacent coastal waters, with little cross-communication. Thus, the benthic communities may be particularly sensitive and vulnerable to environmental perturbations that a CO_2 experiment may imply if not designed and scaled properly.

The possibility for local concern and user-conflicts in connection with a CO_2 experiment should not be overlooked. Fjords including many of those identified in this study have many user-interests, including aquaculture, fishery, tourism and recreation. The local interests such as the Municipal Council(s) as well as the County Governor's Environmental Department should be involved in the early stages of planning of an experiment. The State Pollution Control Authority (SFT) shall evaluate new activities that may cause even temporary pollution, before issuing any permission. The State Pollution Act and the Planning and Building Act may come into effect, and EIA requirements are laid down in both.

The study suggests that a selection process to find a suitable fjord should start with shortening the list of identified fjords based on topographic and technical requirements. A thorough description of legal aspects and comparing/weighing of user-conflicts among a limited number of pre-selected fjords should then be performed. A few fjords with the lowest conflict potential may then be subject to further evaluation, which probably must include an EIA prior to the final necessary approval.

A CO_2 experiment in a fjord will open possibilities for research on both short and long-term effects on deep sea animals. Contrary to the open-ocean alternative, long term effects may be monitored even after only a small and short-lasting CO_2 injection in basins where the water circulation is weak. In addition to the proposed Baseline Study on deep water hydrography and currents, which will be accompanied by work on numerical models, biological mapping and experiments on exposure to different CO_2 and pH levels should also be performed. The latter should include examination of physiological stress due influence on the acid-base regulation, respiration, metabolism and subsequent effects.

Thoroughly designed biological experiments as part of the Baseline Study accompanied by field observations and measurements during and after the experiment should aim at establishing a set of threshold values for exposures in effect, that also will have a definitive relevance for future open ocean CO_2 disposals.

1. Introduction

1.1 General background

It has been suggested to dispose of industrial CO_2 emissions in the ocean in order to reduce climatological 'greenhouse' effects.

CO_2 disposal in the ocean will alter the chemistry of the impacted sea water and its physical characteristics like density. This in turn may lead to changes in local water circulation and impact on biota, and it is pertinent to evaluate the possible environmental impacts before any large scale disposal is started.

The nature of the CO_2 ocean-land-atmosphere interactions is very complicated. Serious considerations about CO_2 and global warming did not appear before the late 1950s, although the warming had been noted already in the 1930s. Certain aspects of CO_2 and its role as a climate regulator was published by the Swedish scientist Svante Arrhenius before 1900 and in 1938 the English meteorologist G. S. Calendar asserted in a paper that since 1890 the atmospheric CO_2 level had increased by ca 10 %, and that this rise could explain the temperature increase in the same period (Weart 1997).

Convincing evidence are showing that changing land use and increasing emissions of CO_2 to the atmosphere globally over the past 200 years are causing primary effects such as

- increased globally averaged atmospheric temperature,
- increased sea-level,
- increased sea surface acidity (lower pH).

These effects in turn may cause a cascade of secondary effects that affects climate, ecosystems and human habitations. Models are predicting an increase of atmospheric temperatures within the next 100 years of ca 2° C, and a sea level increase of 0.5 m. An acidification of ocean surface water expressed as a pH reduction of 0.1 pH units has probably already occurred (Haugan and Drange, 1996), and this trend is further projected to approach 0.5-1 pH units in the next century.

1.1.1 International programmes

The International Energy Agency (IEA) and its Implementing Agreement, the Greenhouse Gas R&D Programme (IEA GHG Programme), has during the recent years sponsored a series of specialist workshops to assess the knowledge status and the need for new research in the field of CO_2 ocean disposal or sequestration (IEA 1996).

In 1995, the IEA/OECD ministerial level statement regarding the establishment of CTI (Climate Technology Initiative) was announced at the first Conference of Parties (COP 1) of UNFCCC (United Nations Framework Convention on Climate Change) in Berlin. The first follow-up meeting of CTI was held in Paris. The CTI has the main purpose to enhance the cost effectiveness of efforts to meet the demand for developing more climate-friendly technologies.

In order to implement concrete projects under the CTI several Task Forces have been established. The Task Force 7 will as one of its sub-tasks specifically treat the issues related to CO_2 disposal. (Other items covered by this Task Force are hydrogen production, separation/removal of greenhouse gases from energy plants and similar types of research).

1.2 CO_2 ocean disposal experimentation

Potential effects of CO_2 emissions on climate have motivated investigation of mitigation options including direct ocean storage of CO_2 (Haugan and Drange, 1992). Direct ocean storage would involve transport of CO_2 to large depth and releasing it in the ocean in gaseous, liquid or solid form. Dissolution of CO_2 in the ocean (Haugan et al., 1995) would perturb the local chemistry even more than invasion from the atmosphere.

In order to learn more about the technical possibilities and limitations of direct storage, and about the effects of increased CO_2 on ocean ecosystems, *in situ* experiments are contemplated (Ormerod and Angel 1996). Existing theoretical CO_2 disposal evaluations have mainly focused on the deep ocean, where expected impacts may be hard to document by experiments or direct monitoring.

While full scale direct ocean storage, if ever implemented, would have to take place in the deep ocean (Haugan and Drange, 1995), fjords have been suggested as experimental sites because fjords in many respects may be viewed as miniature oceans with physics, chemistry and echosystems which are simpler than those of the deep ocean, but still quite similar.

At the same time fjords of reasonable size may be manipulated and monitored in an experimental period. Full blown ecological experiments would probably need to last several years in order to observe potential chronic effects of CO_2 addition on echosystems.

A more technically oriented experiment with limited ecological scope, where the major efforts would be concentrated within approximately one month, might be considered first. Such an experiment would address some areas of uncertainty associated with ocean storage options, such as CO_2 droplet dissolution and buoyant droplet plume dynamics and intrusions and interaction with ambient diffusion. Still we think that the environmental aspects will have to be taken into serious consideration, and that physical and environmental issues should be dealt with, in parallel.

1.3 Scope of the study

The objective of this report is to provide basic information necessary for evaluating Norwegian fjords as potential sites for a limited CO_2 sequestration experiment.

The following items are parts of the Scope:

- Review the present status of CO_2 ocean disposal literature, and extract/describe texts that may be relevant for a fjord experiment.
- Give an overview of deep fjords in Western Norway that may be suitable for a CO_2 experiment.
- Describe the physical environment and physical processes in fjord basins.
- Briefly describe the marine biology of fjords.

- Suggest experimental set-up for monitoring of physics and biology. i. e. Baseline studies, monitoring during the experiment, and post-experiment monitoring/verification, including model developments and validation.

- Describe the legal and formal procedures that a proposal for a CO_2 experiment in a Norwegian fjord will have to adapt to.

- Describe in general the infrastructure, commercial and other interests in fjord municipalities that an institution performing a CO_2 experiment will have to consider.

- Suggest further actions to elaborate a proposal for a specific experiment in a Norwegian fjord.

Many research proposals, reports and journal articles related to CO_2 ocean disposal have been published the past few years. Several of these are mentioned in this report. However, it has not been our intention to review or repeat these articles in detail. Special focus has been laid on previous text items that may be directly relevant to a fjord experiment. Otherwise we have attempted to adapt present knowledge of fjords to the CO_2 disposal issue, but it is beyond the Scope to go into much detail under each topic. If a next step is taken towards a decision to really perform a CO_2 study in a Norwegian fjord, a more detailed description will have to be made, probably also including an EIA.

2. Description of a potential CO_2 experiment

2.1 Physical constraints and logistics

Attention is restricted to fjords which are deeper than 500-600 m so that pure CO_2, if released near the bottom would be in liquid rather than gaseous form (Fig. 2.1). This is the most realistic direct ocean storage option for future application, since dissolution of gaseous CO_2 closer to the surface is expected to lead to rapid outgassing and undesirable impact in productive near surface waters.

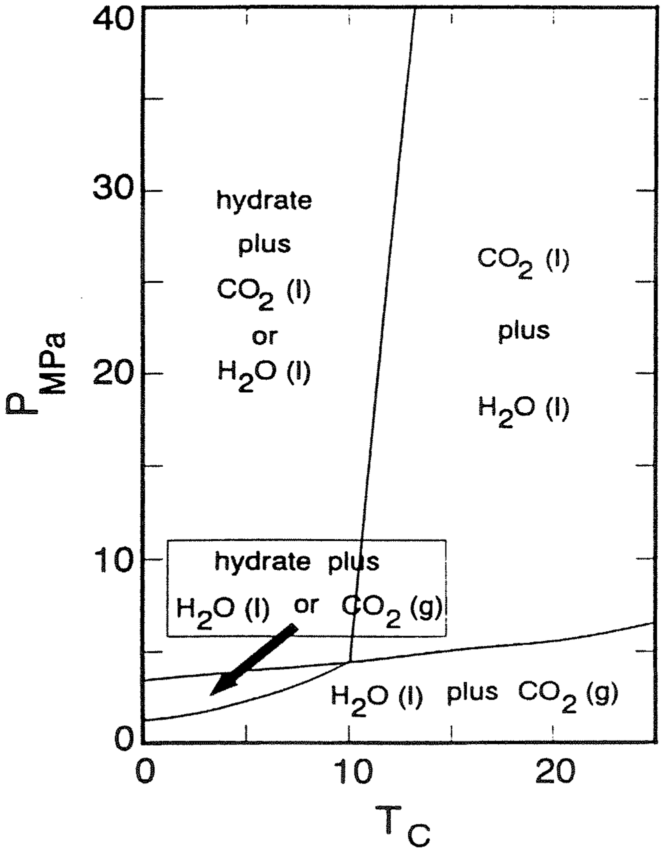


Figure 2.1. Diagram showing phase relations for the CO_2-H_2O system, as function of pressure and temperature (°C).
1 Mpa corresponds to ca 100 m water depth. From Wadsley (1995).

The experiment could be performed by releasing CO_2 via a vertical pipe from a ship or a floating platform or barge, alternatively from shore via pipeline. Tentatively a CO_2 rate of order 1 kg/s, which is ca 1 % of the rate from a 700MW-1GW gas power plant, is assumed realistic in an experiment.

As an example it can be mentioned that the Norwegian company *Hydrogas* operates 3 ships, each with a capacity to carry ca 1000 tonnes of liquid CO_2, which are stored cooled in large high-pressure cargo tanks. See Information a *Hydrogas* ship in the Annex of this report. One such ship may probably be allocated to a fjord experiment. With a 1 kg/s disposal rate, the 1000 tonnes will correspond to a total duration of ca 12 days. The ships are particularly busy in the summer season (deliverance's to breweries, greenhouses). The winter season may thus be most suitable in terms of availability of CO_2 and ships. The Hydro industrial plants in Porsgrunn, SE Norway (ca 100 km SW of Oslo), are a prime source of CO_2 in Norway.

Alternatively CO_2 may be transported in automobile cargo trucks. Each truck has a capacity of 20-30 tonnes. For a 1000 tonnes experiment this will correspond to on the order of 50 shipments.

2.2 Technical description

It seems that disposing of the CO_2 from a special ship is be the most interesting option. *Hydrogas* operates ships that probably may be used. The logistics will require special attention to the pipeline or hose, which will have to be insulated in order to keep the gas cool and liquid.

If conducting the experiment in the cool season, sea-surface temperatures of 5° C or lower may be expected, and maximum temperatures at intermediate depths will be around 10° C. Even during summer the temperatures will be significantly lower than e.g. at Hawaii. Thus previous technical calculations on the hose/pipeline will have to be redone, probably rendering lower requirements for heat insulation.

Logistics requirements moreover will involve equipment for navigation/positioning of the ship, hose and nozzle. Details on this will have to be worked out, according to the concept being studied (fixed or towed pipe). Surface currents in fjords may be significant due to the combined effects of freshwater runoff, wind and tides. Design criteria should be 1-2 knots for surface currents. The deep currents will be less strong, but will anyway affect the drag on the submerged pipe or hose. Keeping the nozzle in a steady position and at constant depth (fixed pipe) may require some form of bottom anchor attached to the nozzle.

2.3 CO_2 disposal rate

The nominal CO_2 rate of 1 kg/s which has been suggested as a suitable rate for a short-time experiment is equivalent to almost $2x10^6$ mole C/day. The natural carbon concentrations in ocean waters is around 2 mole Cm^{-3}. Injection in e.g. 10 days could then double the natural carbon concentration in a volume of 10^7m^3, e.g. in a layer of 10m depth with a horizontal extent of 1 km x 1 km, or effectuate a 10 % increase of the carbon levels in a volume 10 times larger, which may be comparable to a fjord basin. Note in this context that a 10 % increase of total carbon concentration is a considerable perturbation of the chemical state of the water.

Near surface ocean waters today have total carbon concentrations which are 2-3 % higher than in pre-industrial times due to the invasion of anthropogenic carbon from the atmosphere. To affect a sizable portion of the larger fjords like the Sognefjord would require injection for much longer periods than 10 days. E.g. three years (1000 days) could give a 10 % increase in 10 km^3, which is a small fraction of the total volume of the fjord but could cover the entire area if confined to a 10-20m layer.

These calculations are of course too simplified in that exchange of water has been neglected. It seems however, that simple, confined, small fjord basins systems may be perturbed after a short experiment period to the extent necessary to measure chemical and environmental changes.

3. Physical oceanography of fjords

3.1 General

Typically the larger fjords of Western Norway are oriented in the E-W direction, cutting into the central mainland from the west coast that is facing the North Sea. In the vicinity of the mouth or entrance of the fjord, a shallow region or sill commonly is found. This sill restricts the deep water circulation to intermittent or episodic events only, with long periods of stagnation in between.

Fig. 3.1. illustrates the different hydrographic regimes that may exist in a fjord. The layers above sill depth will be subject to relatively frequent renewal, which is driven partly by density variations and internal waves in the Coastal waters (Mysak 1980) and partly due to freshwater runoff and tides.

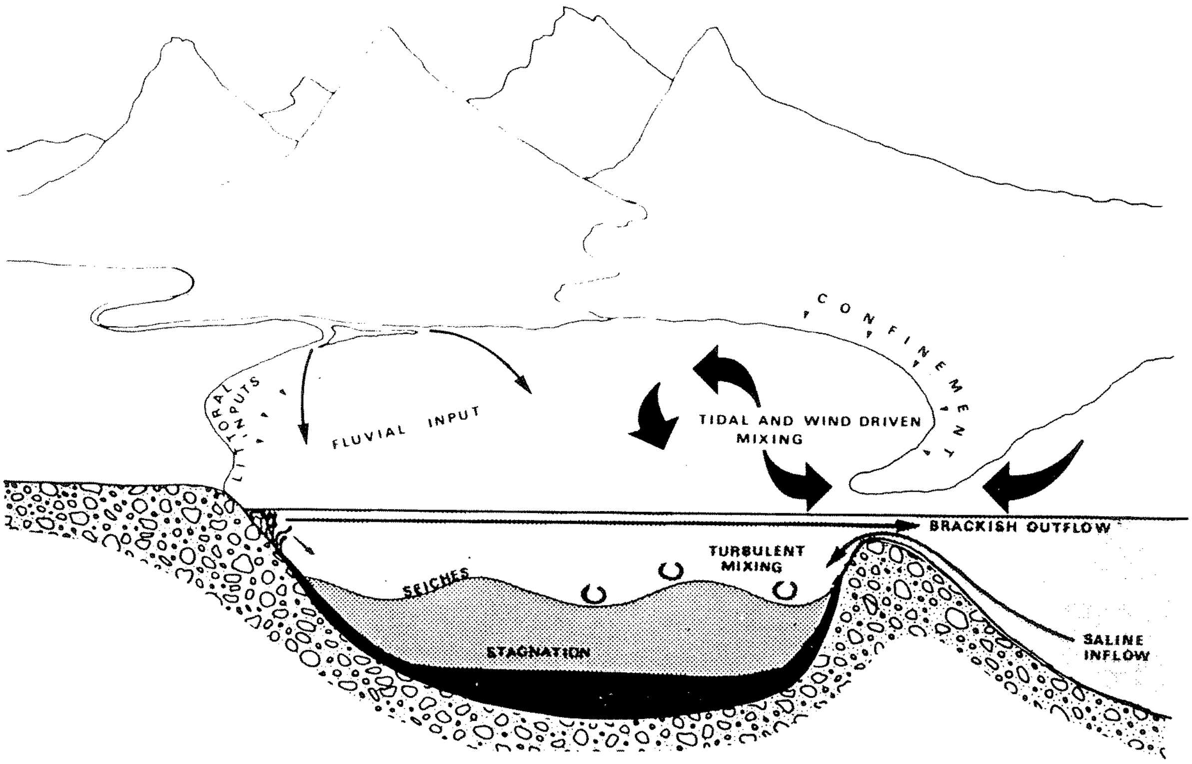


Figure 3.1. Schematic diagram of various environmental factors in deep fjords. From Pearson (1980).

A primary well defined pycnocline marks the division between the brackish surface layer and the intermediate water. Between the homogeneous deep water and the intermediate water a secondary pycnocline prevails throughout most of the year. At both these interfaces (pycnoclines) internal gravity waves may exist more or less permanently. It is expected that these also affect the internal deepwater circulation, and thus will have to be taken into account and monitored in a CO_2 experiment.

The deep water and sediment chemistry may vary according to the actual topography, the organic load and other factors (Aure and Stigebrandt 1989). Many sill fjords experience seasonal oxygen depletion in the deep water, sometimes leading to anoxia with H_2S. Fig. 3.2 illustrates such a fjord (example taken from NIVAs data from the Inner Oslofjord (Bjerkeng 1994). Other fjords may have permanent anoxia.

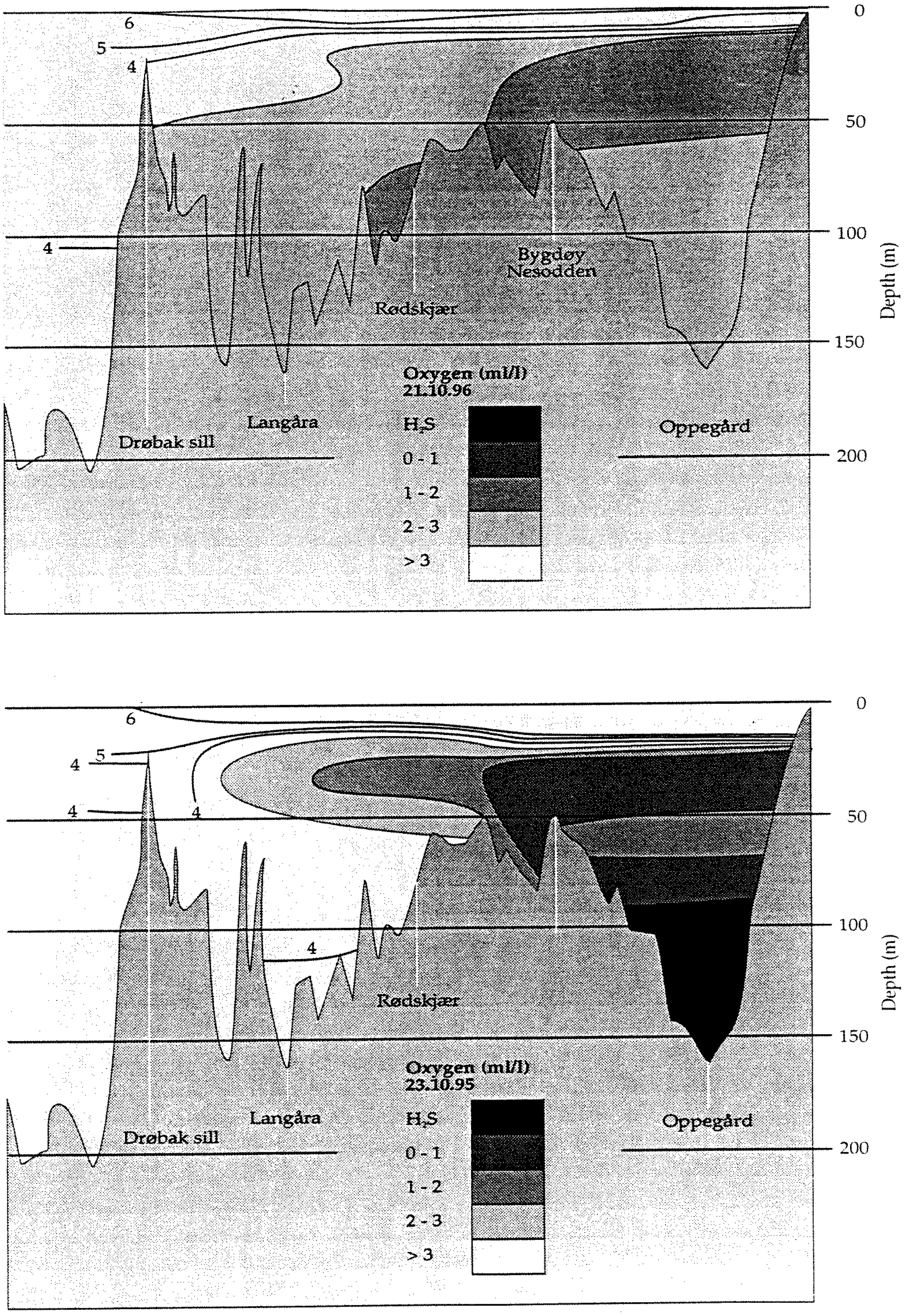


Figure 3.2. Example of a fjord (Inner Oslofjord) that exhibits intermittent oxygen depletion with H_2S in the deep water. Conditions from one year to the other may vary considerably. The figure was kindly provided by Jan Magnusson, NIVA.

The deeper fjords that are of interest in the present study in general have a deep sill which does not impose a serious restriction to water exchange as do shallow sills. At least the water quality of the deep fjords is expected to be satisfactory in terms of dissolved oxygen content. However some basins do exhibit seasonal reduction in oxygen. The lack of regular monitoring of Norwegian fjords in general may disguise the fact that several fjords actually may exhibit seasonal oxygen reduction.

During periods of stagnation slow vertical diffusion cause a gradual reduction in sea water density, thus preconditioning this water to renewal by denser water from outside. A reduction less than 1 sigma-t units may be sufficient that a renewal may take place.

Deep water renewal is expected to occur in late winter or spring. Prior to this, dense coastal deep water is upwelled at the coast and then circulated across the sill and into the deep basin. The actual density of the inflowing water and the basin water will determine if the new water flows along the bottom, or interleaves in the water column.

In terms of a CO_2 experiment, where dense CO_2-enriched water is expected to collect in a bottom layer, both the slow diffusion with gradual reduction of density and the density difference between inflowing water and bottom water must be determined by combined modeling and measurements.

After assessing density of the CO_2-enriched water, statistical approaches may be taken in order to compute the renewal time, based on long-term data on sea water density in the coastal water (Stigebrandt 1992).

In summary, the physics and dynamics of the deep water of fjords may be said to behave differently from the open ocean, especially in terms of intermittence. This topic is addressed further in sections 6.2 and 6.3.

3.2 Overview of deep fjords

We have compiled maps showing all parts or basins of fjords where depths exceed 500 meters. The maps are based on a digital bathymetic database (GEBCO 1994). Fig. 3.3 shows South Norway and the areas selected for further description. Figs. 3.4 - 3.8 show more detailed maps of the different counties between Stavanger and Trondheim.

It may be seen that fjords deeper than 500 m are found in every county and map shown. The number varies from a few to several fjords in each county. Some of these fjords are subject to further physical description below. It may be seen from the overview below that information on deep water currents and dynamics in general is lacking, while some data on hydrography do exist, at least for some fjords.

3.2.1 Salhusfjord

The Salhusfjord (fjord No. 7 in Fig. 3.5) is the nearest location to Bergen (barely) meeting the depth criteria with a flat bottom at approximately 550m water depth. Typical salinities, temperatures and oxygen levels below 200 m are 34.95 psu, 7.5°C and 5 ml/l respectively (Helle, 1975), with little seasonal variability but potential interannual variations. This area has for several years been studied extensively in conjunction with planning of the recent (1994) construction of a partially floating bridge across the fjord. Variable near surface currents are documented and should be taken into account when planning marine operations in conjunction with an experiment. The location close to an intersection between several interacting fjord systems complicates the regional circulation pattern compared to a simple fjord, and would imply fairly substantial logistics to monitor flow of carbon enriched water on scales longer than a few days and kilometers. On the other hand, easy access and well documented environmental conditions could make it a favoured site for small scale experiments.

3.2.2 Sognefjord

The Sognefjord (fjord No. 5 in Fig. 3.6) 60 km north of Bergen is the longest (176 km), deepest (1300 m) and largest (525 km^3) Norwegian fjord system, with depths larger than 600 m in a section of more than 150 km length. The sill depth is 165m. Typical basin water salinities, temperatures and oxygen levels are 35±0.05 psu, 6.75±0.25°C and 5.5±0.5 ml/l respectively (Fig. 3.9) (Hermansen, 1974). The upper layers exhibit significant seasonal variations mainly due to seasonal variations in freshwater input and air temperatures (Rustad 1978). Seasonal variations in the basin water are small, but interannual variations may exist related to episodic renewal of the partially stagnating basin water, gradually becoming lighter than coastal or Atlantic water because of vertical mixing within the fjord.

In periods with little renewal of basin water, oxygen levels would drop below the interval mentioned above, although hardly towards oxygen deficiency. Hermansen (1974) describes an event in 1970 where oxygenated and cold (6°C) water, slightly fresher (34.90 psu) than the basin water, intruded into the main Sognefjord basin and spread out along the bottom renewing at least one third of the entire fjord volume in a matter of months.

3.2.3 Hardangerfjord

The Hardangerfjord (sites No. 2 and 3 in Fig. 3.5) 40 km south of Bergen is the second largest fjord in Norway (223 km^3). Its sill depth is about 150 m. It has a maximum depth close to 900 m and is more than 600 m deep for about 70 km of its length. Typical salinities, temperatures and oxygen levels in basin water are 35 psu, 6.8 °C and 5-6 ml/l respectively (Sælen, 1962). Fig. 3.10 shows the salinity distribution for August and February 1956. Cold water inflows from the coast occur in Hardangerfjord in a similar way as in the Sognefjord.

3.2.4 Jøsenfjord

The Jøsenfjord (fjord No. 3 in Fig. 3.4) in the inner parts of the Ryfylkefjord, 120 km from Bergen and 50 km from Stavanger is an example of a rather small, well protected, simple fjord far from the coast. It has a width of just over 1 km and is deeper than 600 m for a length of about 8 km. Its effective sill depth is approximately 100 m. Typical basin water salinities and temperatures are 34.95±0.05 psu and 6.75±0.25 °C respectively (Svendsen, 1981).

3.2.5 Boknafjord and Nedstrandsfjord

Boknafjorden (Fjord No. 1 in Fig. 3.4) and Nedstrandsfjorden (Fjord No. 2 in Fig. 3.4) have max. depths of 621 and 756 m respectively. These fjord areas have been subject to substantial hydrographic monitoring in the 1970's and 1980's in connection with impact studies on fresh water discharges (Svendsen 1981, Lie et al. 1992), and are also subject to regular monitoring (Aure et al. 1993). Fig. 3.11 shows a hydrographic section (December 1982) from the head of the Hylsfjord to the coastal area. Deep water salinities exceed 35 psu, and corresponding temperatures are 6-6.5 °C.

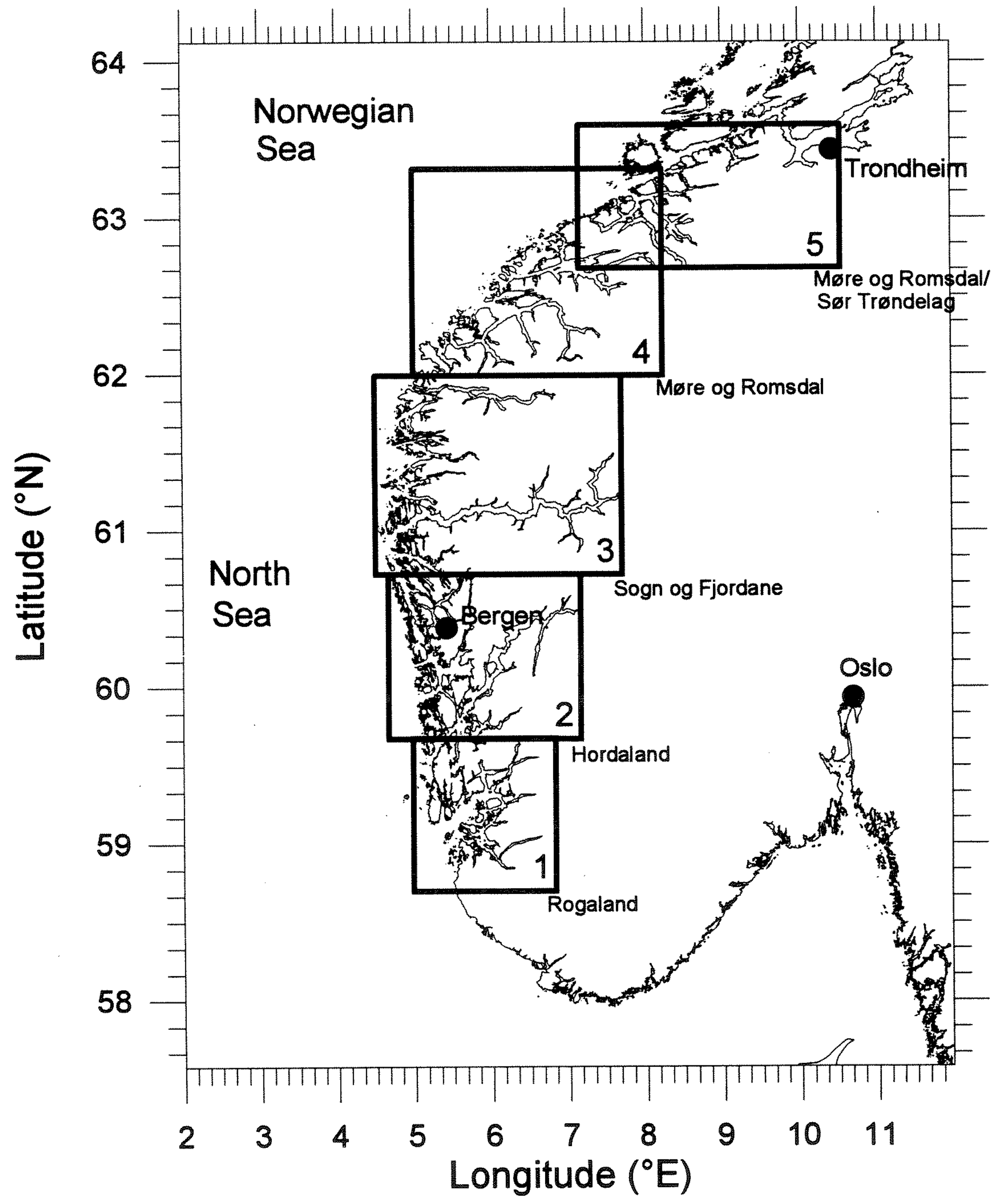
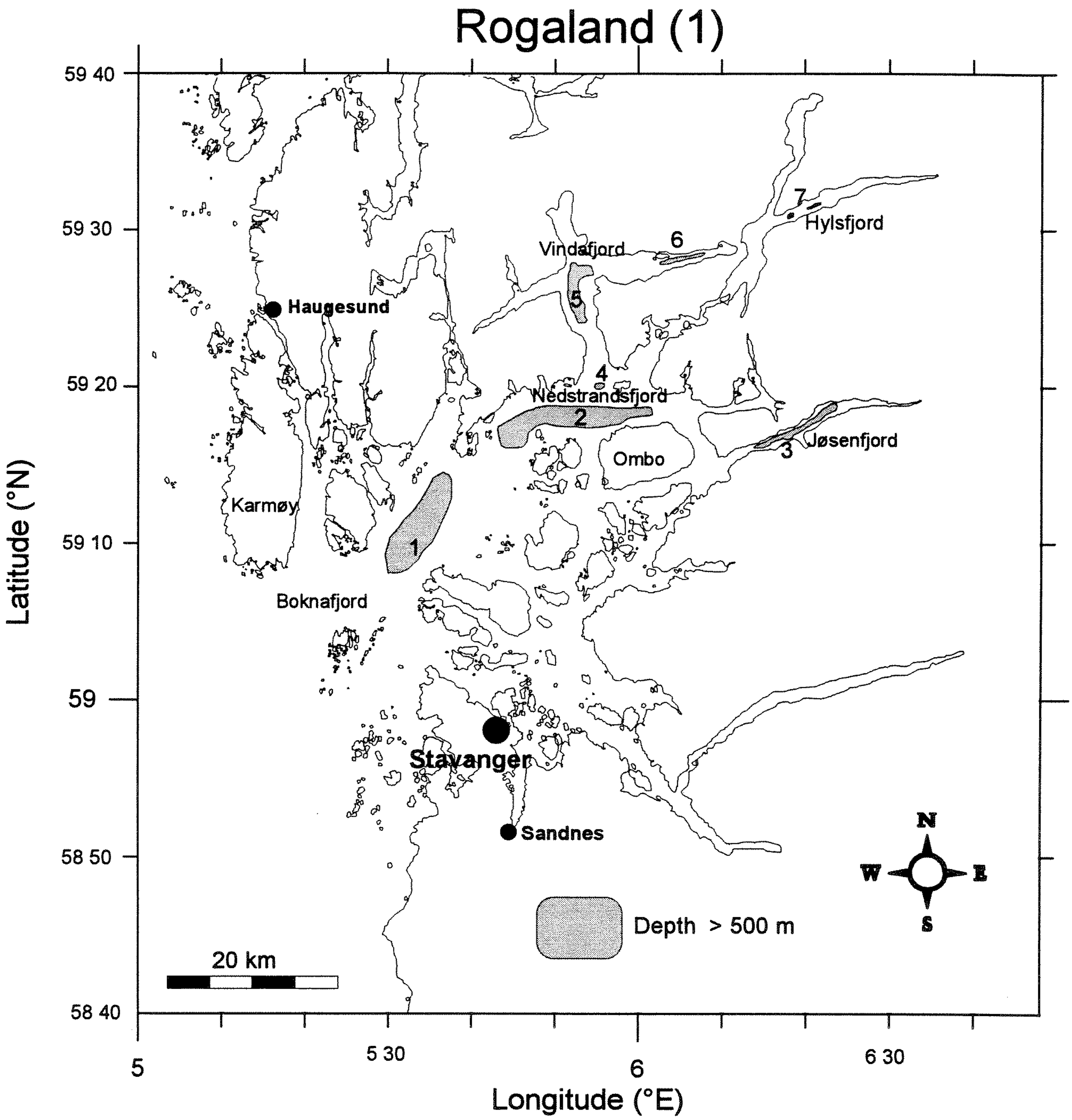
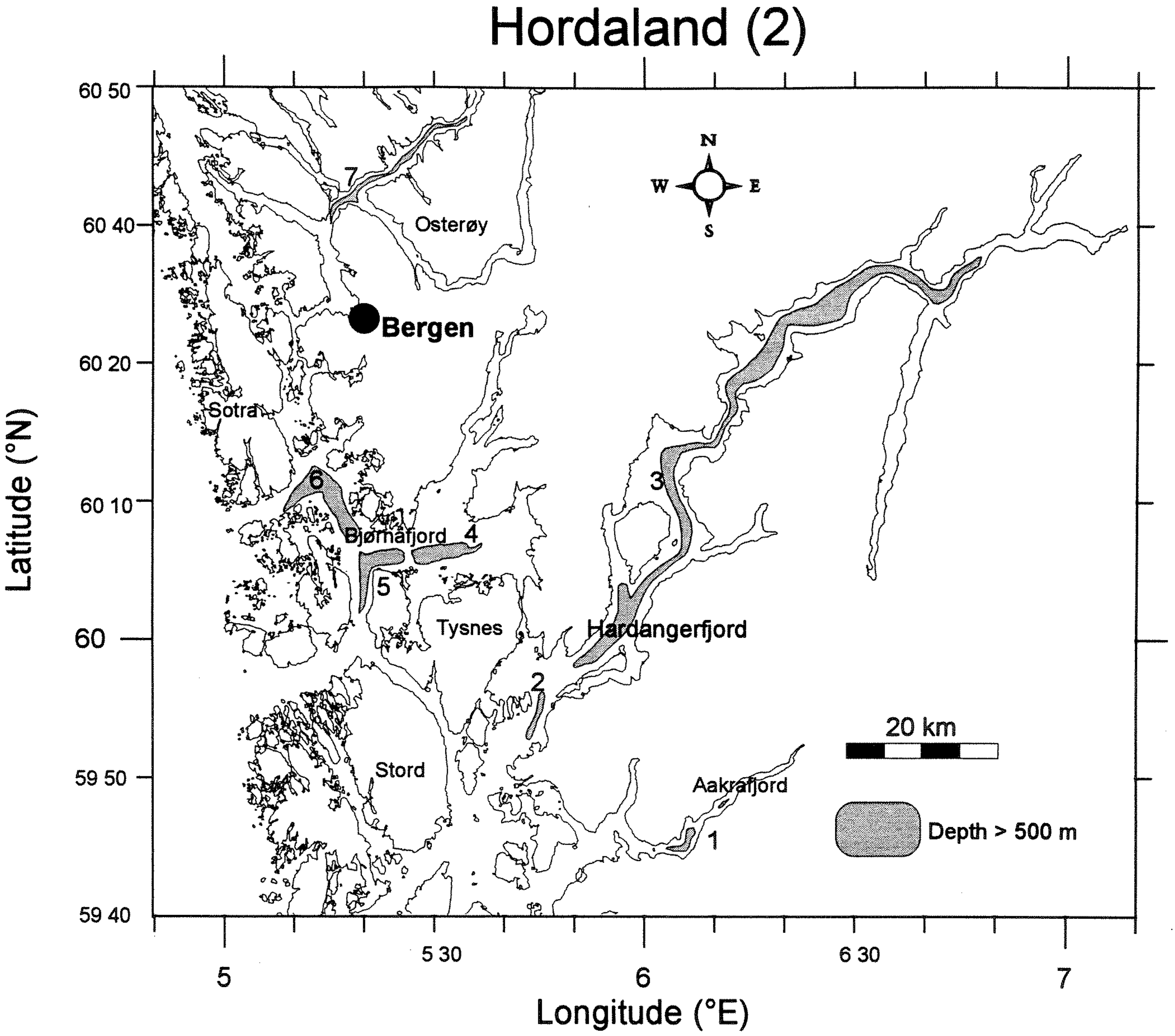


Figure 3.3. Map of South Norway, with frames showing the different maps in Figs. 3.4-3.8.



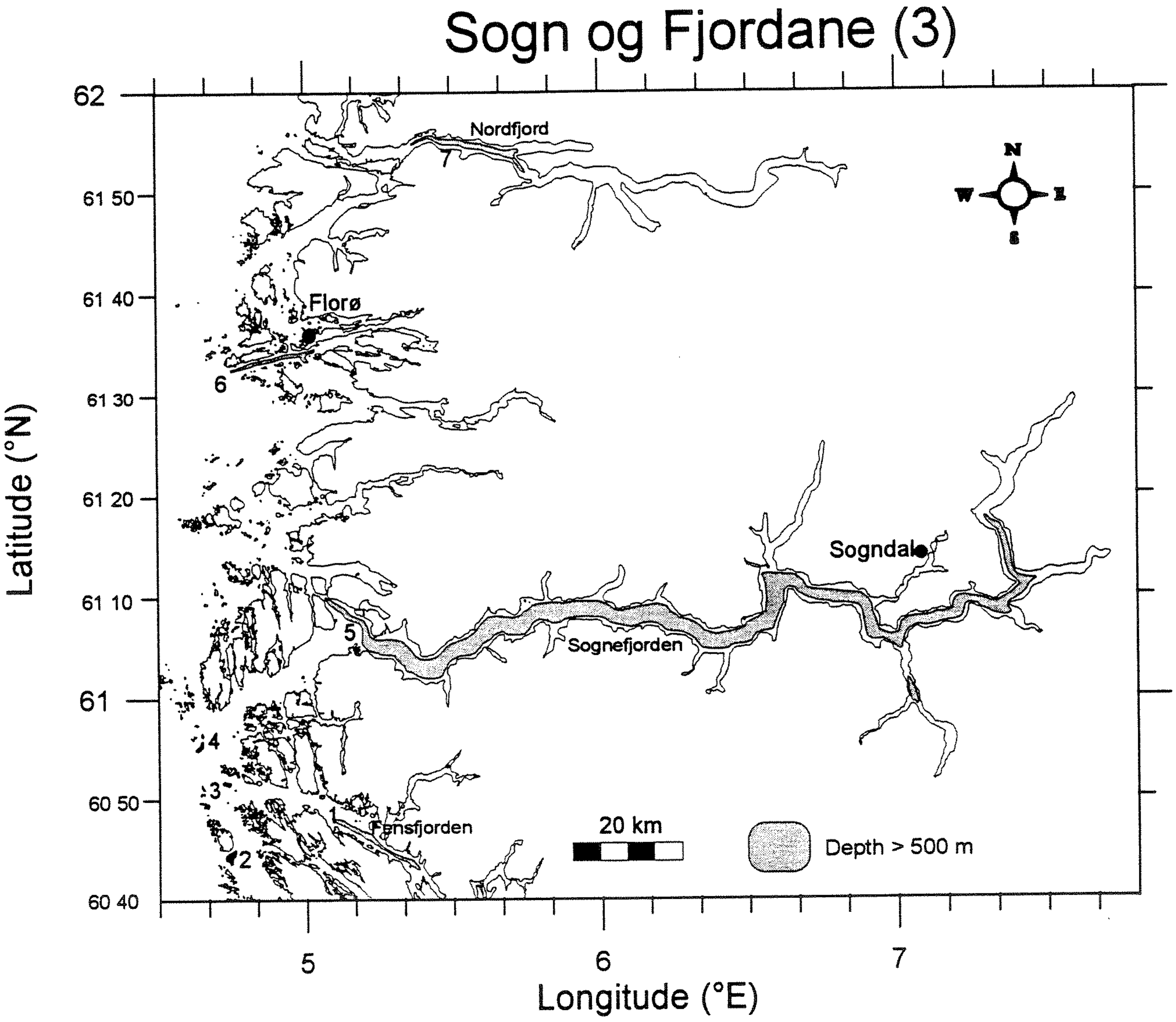
Number	County	Municipality	Fjord	Max Depth (m)
1	Rogaland	Rennesøy/Bokn/Finnøy	Boknafjord	621
2	Rogaland	Tysvær/Finnøy/Suldal	Nedstrandsfjord	756
3	Rogaland	Hjelmeland	Jøsenfjord	664
4	Rogaland	Suldal	Nedstrandsfjord	527
5	Rogaland	Suldal/Vindafjord/Tysvær	Vindafjord	712
6	Rogaland	Suldal	Vindafjod	700
7	Rogaland	Suldal	Hylsfjord	504

Figure 3.4. Map of Rogaland County, showing fjords with depths > 500 m. The table underneath shows max. depth of each basin and the municipalities to which the fjord basins belong.



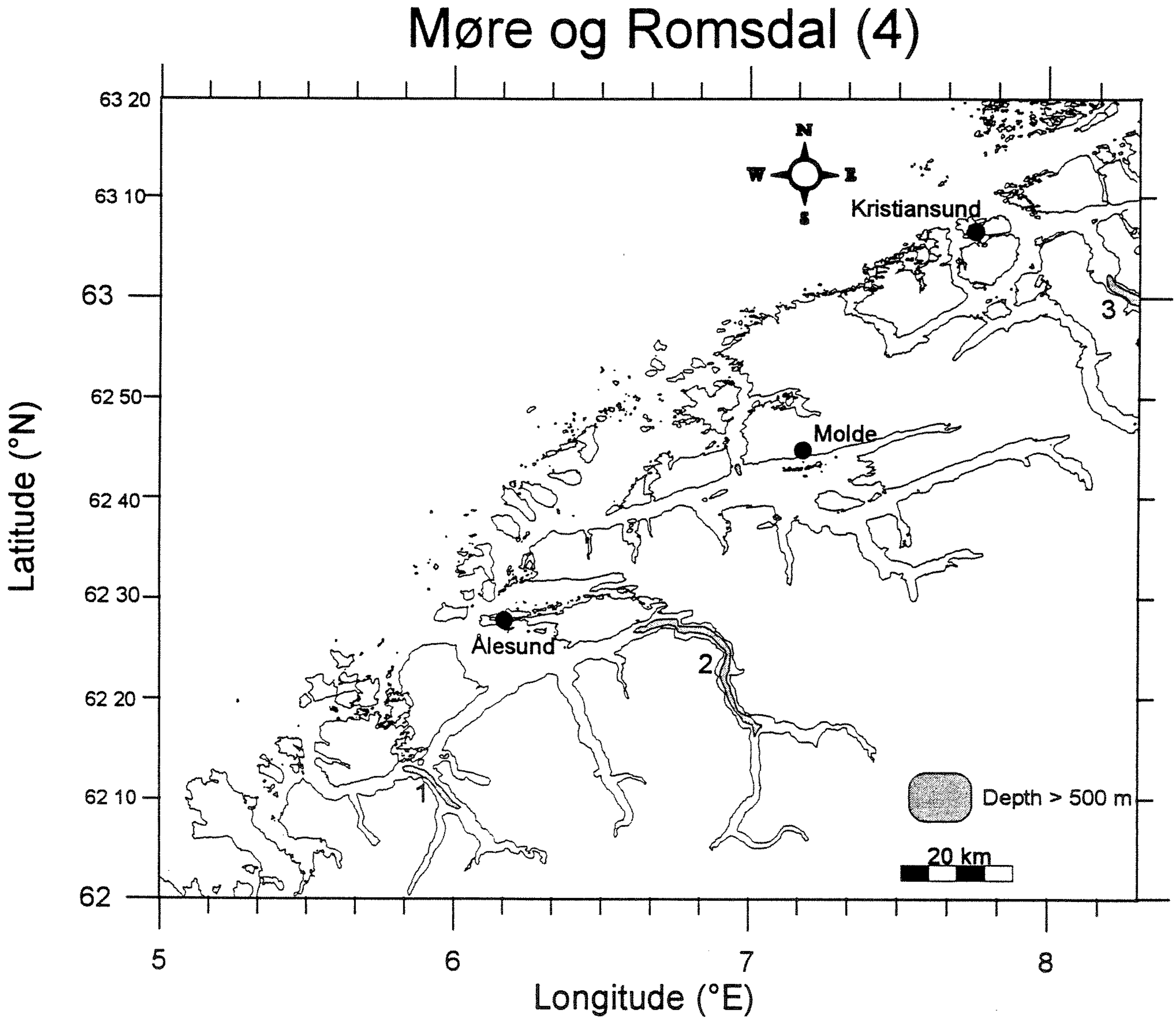
Number	County	Municipality	Fjord	Max Depth (m)
1	Hordaland	Etne/Kvinnherad	Aakrafjord	630
2	Hordaland	Kvinnherad/Tysnes	Hardangerfjord	514
3	Hordaland	Kvinnherad/Jondal/Odda/Granvin/Kvam	Hardangerfjord	859
4	Hordaland	Fusa/Tysnes/Os	Bjørnafjord	593
5	Hordaland	Tysnes/Os/Austevoll	Bjørnafjord	572
6	Hordaland	Os/Fana/Sund/Austevoll	Korsfjord	678
7	Hordaland	Lindås/Osterøy/Bergen	Osterfjorden	640

Figure 3.5. Map of Hordaland County, showing fjords with depths > 500 m. The table underneath shows max. depth of each basin and the municipalities to which the basins belong.



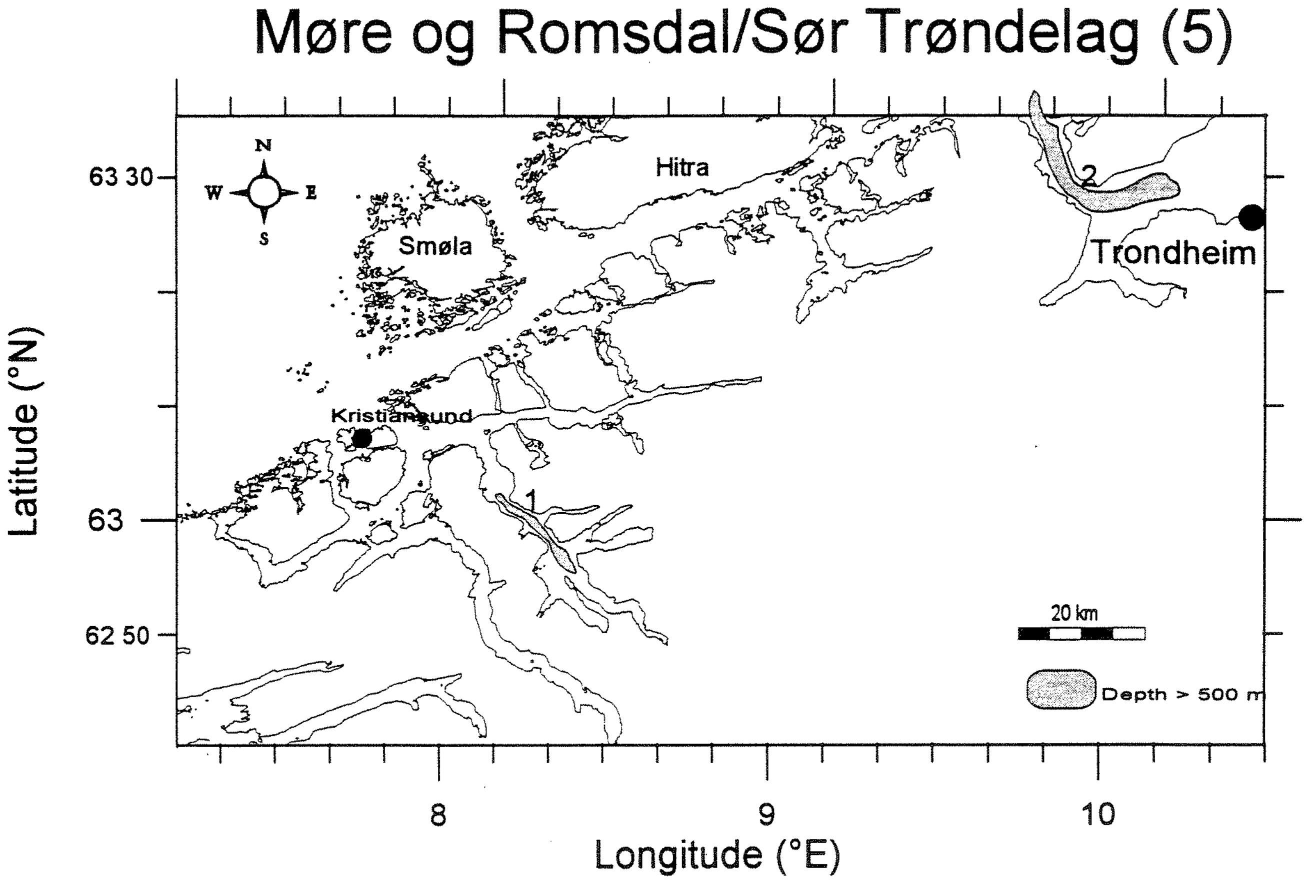
Number	County	Municipality	Fjord	Max Depth (m)
1	Hordaland/Sogn og Fjordane	Lindås/Masfjorden	Fensfjorden	680
2	Hordaland	Fedje	Fedjefjorden	576
3	Hordaland	Fedje	Fedjefjorden	525
4	Sogn og Fjordane	Solund	Sognesjøen	557
5	Sogn og Fjordane	Gulen/Høyanger/ Leikanger/Lærdal/ Sogndal	Sognefjorden	1303
6	Sogn og Fjordane	Flora	Rekstafjorden	554
7	Sogn og Fjordane	Bremanger/Gloppen/ Eid	Nordfjord	591

Figure 3.6. Map of Sogn og Fjordane County, showing fjords with depths > 500 m. The table underneath shows max. depth of each basin and the municipalities to which the basins belong.



Number	County	Municipality	Fjord	Max Depth (m)
1	Møre og Romsdal	Volda	Voldafjorden	697
2	Møre og Romsdal	Sykkulve/Stordal/ Stranda/Spjelkavik/ Skedje	Storfjorden	684
3	Møre og Romsdal	Halsa/Tingvoll/ Surnadal	Halsafjorden	534

Figure 3.7. Map of Møre og Romsdal County, showing fjords with depths > 500 m. The table underneath shows max. depth of each basin and the municipalities to which the basins belong.



Number	County	Municipality	Fjord	Max Depth (m)
1	Møre og Romsdal	Halsa/Tingvoll/ Surnadal	Halsafjorden	534
2	Sør Trøndelag	Agdenes/Rissa/ Trondheim	Trondheimsfjorden	617

Figure 3.8. Map of northern parts of Møre og Romsdal and of southern parts of Sør-Trøndelag county, showing fjords with depths > 500 m. The table underneath shows max. depth of each basin, and the municipalities owning the fjord area.

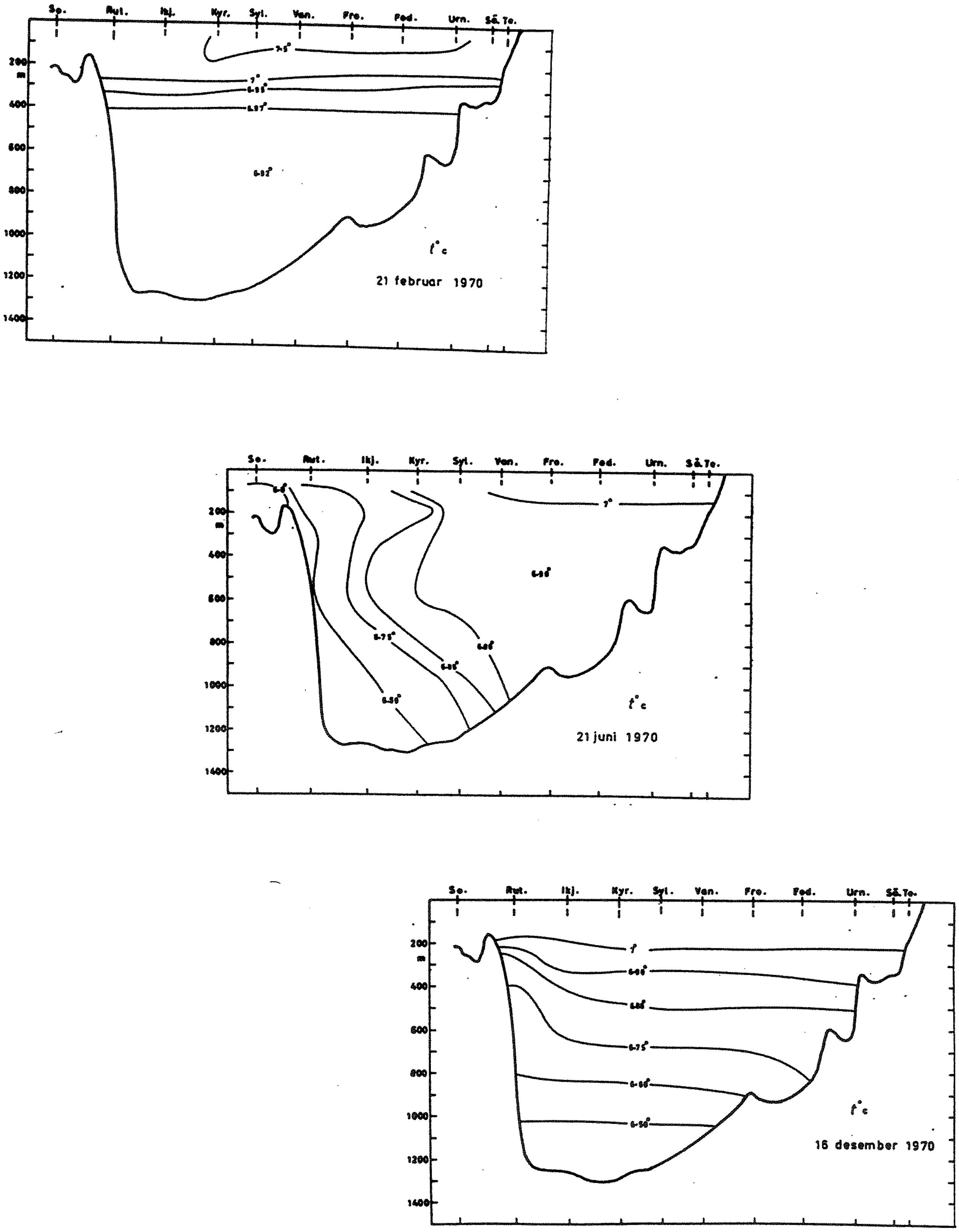


Figure 3.9. Temperatures in the Sognefjord, 1970. From Hermansen (1974).

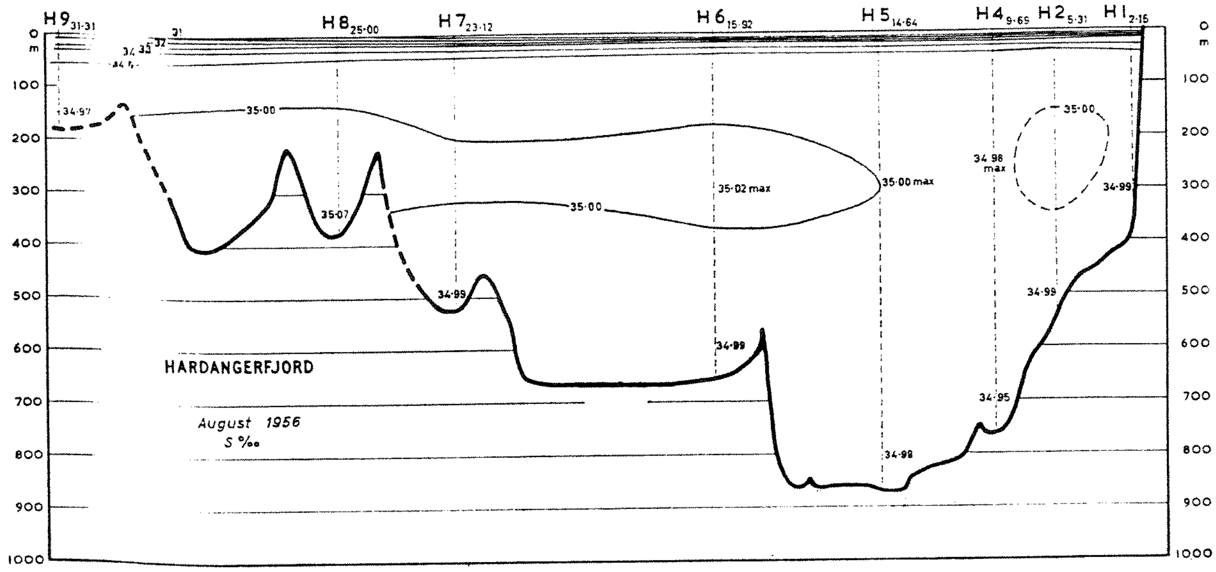


Fig. 2. Distribution of salinity in a longitudinal section of the Hardangerfjord, August, 1956.

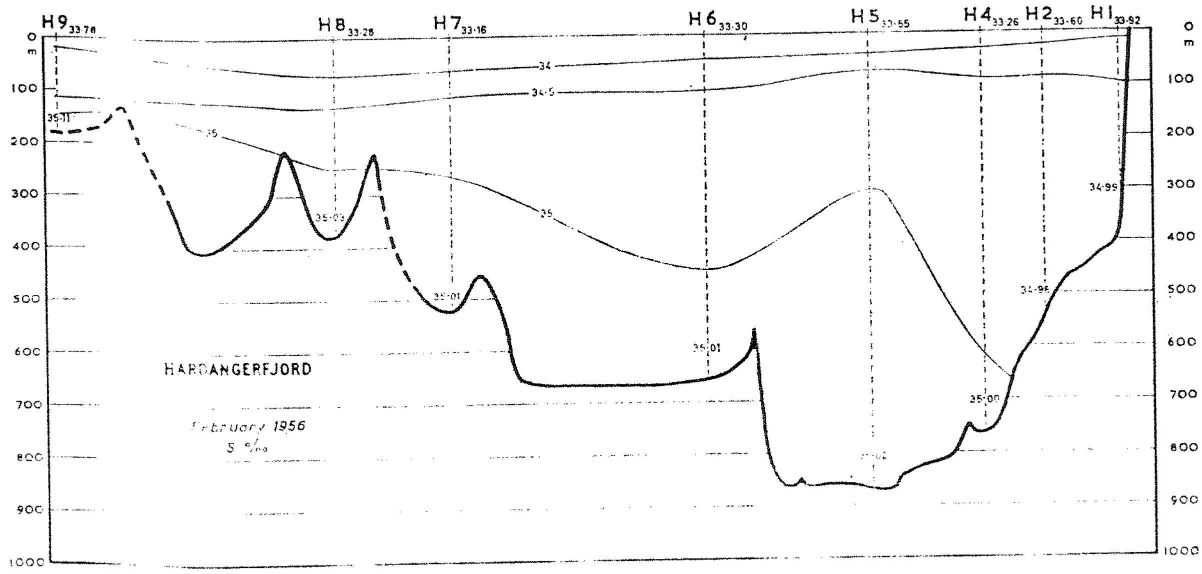


Figure 3.10. Salinities in the Hardangerfjord, February and August 1956. From Sælen (1967).

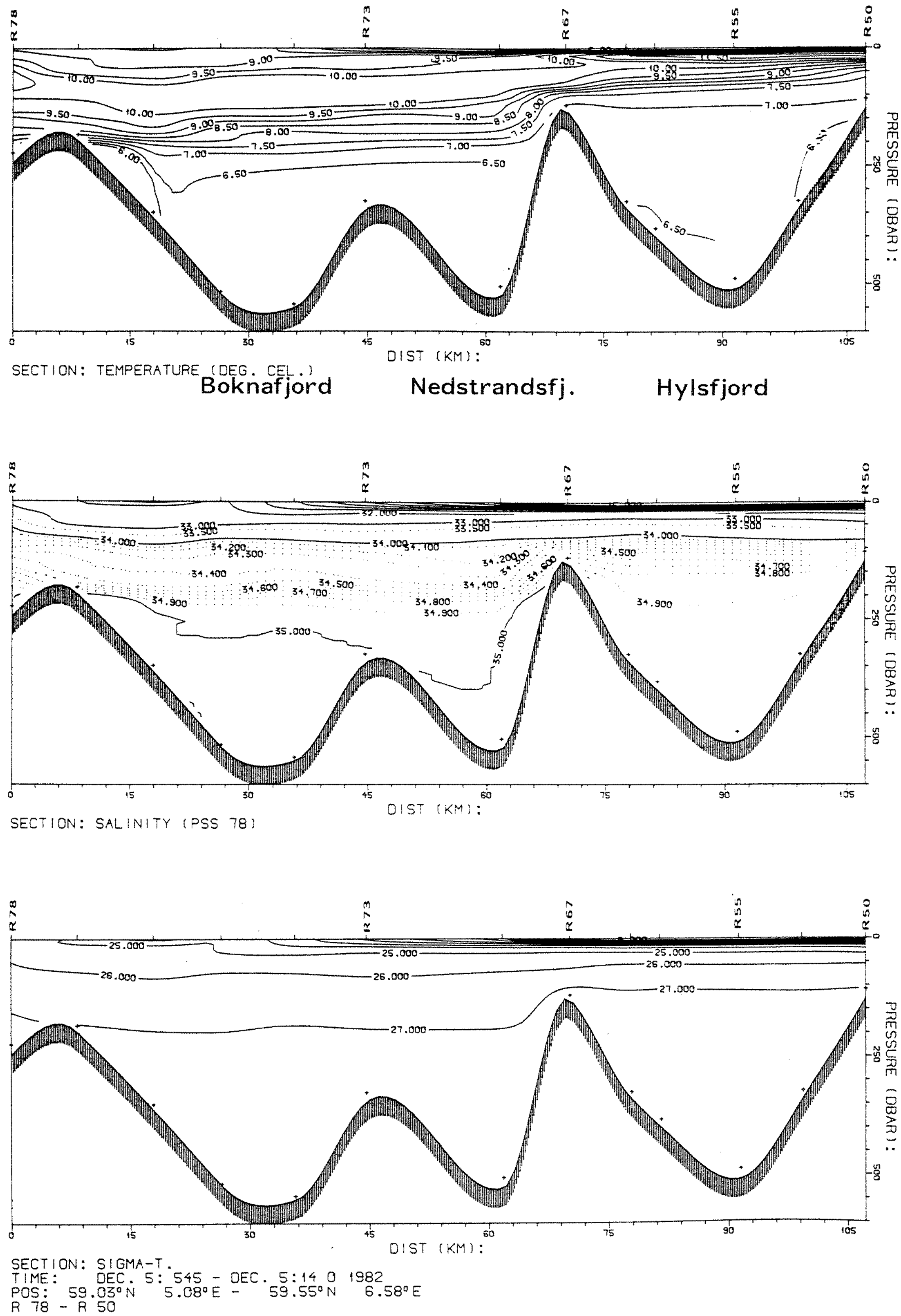


Figure 3.11. Vertical sections of temperature, salinity and sigma-t covering the Boknafjord and Nedstandsfjord. From Svendsen and Golmen (1987).

3.2.6 Other fjords

The above does not constitute a survey of all possibilities, but should be viewed as examples of both large and small fjords. Some other potential sites are mentioned briefly here.

Nordfjord (Fig. 3.6) north of the Sognefjord is the third longest Norwegian fjord (90 km). The inner basin of Nordfjord is separated from the outer parts by a secondary sill of 125m depth. Inner basin water may remain undisturbed for periods up to a decade during which oxygen content in basin water may be reduced below 50 % from near saturation levels (Sælen, 1967).

Locations like the **Korsfjord** (No. 6 in Fig. 3.5) close to Bergen have sufficient depths, but with a much more open environment than e.g. the Salhusfjord and Jøsenfjord. Such locations close to the coast may be subject to severe sea state and weather conditions, and would typically be exchanging water with the coast more rapidly so that many of the advantages expected from a confined and sheltered fjord location would be lost.

Fjords further north or east along the coast and also fjords in northern Norway are generally shallower, with the exception of very open coastal areas sometimes having 'fjord' names. Also the Inner Oslofjord is excluded because of its shallow depth.

4. Deepwater ecology of fjords

4.1 Introduction

This chapter discusses the feasibility of investigating biological effects of CO_2 deposition in deep fjords on the local animal populations and communities. It also discusses to what extent results from such studies are relevant for judging effects on oceanic deep water communities. As an introduction, a general description of the ecological features of deep Norwegian fjords is given. The description does not intend to characterize each individual fjords identified as potential site for a CO_2 experiment, mainly because the information being necessary for assessing the feasibility of such an experiment is general for all the fjords.

4.2 General ecological features

In broad sense the ecosystems in fjords may be divided into pelagic and benthic ecosystems, which again may be divided into vertical strata corresponding to the main water bodies. Hence the pelagic systems may be split into epipelagic (0-150 m) and mesopelagic (deeper than approx. 150 m) strata, of which the latter may be influenced by the deepwater deposition of CO_2. The deep water basins represent a potential refuge for local pelagic organisms in a fjord, and offers a homogenous environment with respect to temperature and salinity. The pelagic ecosystems in deeper parts of Norwegian fjords are fairly rich, and typical numerical dominants among the larger zooplankton forms are pelagic shrimps (*Phasiphaea multidentata* and *Sergestes arctica*), euphausids (*Meganyctiphanes norvegica*, *Thysanoessa* spp.), mysids (*Boreomysis arctica*), and chaetognaths (*Sagitta elegans*, *Eukrohnia hamata*). Other important zooplankton in the deepwater at certain seasons are copepods (*Calanus finnmarchicus* and *Euchaeta norwegica*). Typical mesopelagic predatory fish are *Benthosema glaciale* and *Maurolicus muelleri*. Several of the species perform substantial diurnal or seasonal vertical migration, even into the upper advective layers of the fjord, but many populations still seem to sustain their position in the fjord rather than being swept over the sill to the coast outside (Kaartvedt et al. 1988).

The deeper fjord basins on the west coast of Norway have characteristically very steep sides (up to 40-50° slope) and a flat bottom which is covered with a layer of sediment that may be several hundred meters thick. The sediments are in general finer than at similar depths on the shelf outside. The fjords are relatively young (about 10 000 years old) and have been gradually colonized from the coastal ecosystems outside (Brattegard 1980). The sediment macrofauna contain all major benthic animal groups (e.g. polychaets, molluscs, crustaceans and echinoderms), but the number of species and the diversity of two of the major groups, the molluscs and the crustacean amphipods have shown to be clearly lower in the fjord than at similar depths on the shelf outside (Buhl-Mortensen and Høisæter 1993, Buhl-Jensen 1986). The numerical dominance by a few species is also higher in the fjords. One possible reason may be that the shelf represents a more diverse habitat in food resources and grain size composition than the deep fjord bottoms, which again may support more species. Also the fjord bottoms have higher sedimentation rates and hence larger food input which may favour a few opportunistic species to the exclusion of others (Buhl-Mortensen and Høisæter 1993). Conspicuous predatory fish associated with the basin bottoms are ling (*Molva molva*) and tusk (*Brosme brosme*) which to some extent are harvested commercially from the fjords. Other species which should be mentioned are *Merluccius merluccius*, *Micromesistus poutassou*, *Chimaera monstrosa* and *Coryphaenoides rupestris*.

The deep basins of the open Norwegian fjords have a distinct soft bottom mollusc fauna consisting of mainly lusitanian-boreal species (Buhl-Mortensen and Høisæter 1993). Few of the species are common to the North Sea or the European shelf, but many forms reappear on the lower shelf or the upper slope of the western Mediterranean. They seem to have appeared in the fjords between 8 000 and 9 000 years ago (Thomsen and Vorren, 1986), probably as a result of a period of influx of warm saline Atlantic water as the climate improved after the last glaciation. Hence, the bottom fauna in the deep basins seem to be relatively little influenced by that of the shelf outside, and the basin bottoms may be regarded as 'islands' more or less isolated from the available recruitment pool of nearby bottoms. The fact that, at least for one important animal group - the molluscs, loss of species from the basin community not easily will be replenished by new recruits of the same species from the nearby shelf areas, makes these benthic communities particularly vulnerable to manmade perturbations.

4.3 Impacts on fish from CO_2 disposed in deep water.

Many Norwegian fjords have the feature of sill basins, where the ecological effects of CO_2 deposition will have a limited distribution due to limited water exchange. However, even a moderate rise in CO_2 may be lethal to the most sensitive species. Although the number of species with acute sensitivity may be small, even tolerant species may suffer. Long term, sub-lethal effects at the ecosystem, population and individual levels are likely. In this section the present information on physiological effects of elevated CO_2 on fish is discussed, and an approach to the study of threshold levels is proposed.

4.3.1 Biological impacts

Elevated CO_2 levels in ambient water will affect the physiology of fish and other animals. Present knowledge ranges from effects on acid-base regulation to influence on respiration, excretion, energy turn over, and mode of metabolism. The main properties and biological impacts of CO_2 in water may be summarized in the following points:

- Compared to all other gases, CO_2 is very soluble in water (at 0°C, CO_2 is 35 times more soluble than O_2, and is still 25 times more soluble at 30°C).
- CO_2 affects pH, so that release of CO_2 into seawater results in increased concentrations of H^+ (lowered pH).
- The fact that most natural water has little CO_2 content makes CO_2 levels in fish blood low compared to air-breathers.
- Fish cannot regulate its respiratory system by changes in CO_2 level (as air-breathers do), but must sense O_2 changes instead.
- CO_2 may be excreted as HCO_3^- (from the kidney) as well as molecular CO_2 (from the gills), depending on the environmental pH and carbonate levels. This is a way of regulating blood pH (physiochemical buffering).

The effect on the physiology of marine fish species of increased concentrations of CO_2 in sea water, and the associated effects of increased HCO_3^- and pH, is dependent, not only on the magnitude of those increased concentrations, but also on the tolerance of the particular marine animal.

4.3.2 Tolerance and biological response

Information is limited on the tolerance and physiological responses of most species. However, fishes can be grouped in two broad categories, having different taxonomies and ecologies (Pörtner and Reipschläger 1996):

- Pelagic fishes which inhabit the water column. These can be further divided into species inhabiting inshore waters and off-shore oceanic waters. This group is adapted to constant, low CO_2 concentrations, and are expected to have a low tolerance to fluctuations in CO_2 and pH.
- Demersal (benthic) fishes which, as adults spend their lives on, or close to the sea bed, and can tolerate variations in CO_2 resulting from varying oxygen consumption and anaerobic metabolism of bacteria and fauna.

Many Norwegian fjords are sill basins with low water exchange, and therefore low O_2 content in the lower part of the water column. One may therefore expect a deep water fauna of high CO_2 tolerance in these fjords, reinforced by low water temperature and thus reduced metabolic rate. However, long term exposure of high CO_2 concentrations may lead to sub-lethal or even lethal effects even on tolerant species.

4.3.3 Threshold levels

Threshold values represent a useful tool for the evaluation of the biological impacts from a certain ambient parameter on a certain species or test organism. The threshold value may be defined as mortality rate (response) related to a certain dose (concentration and exposure time), or to the appearance of specific physiological, behavioral or physical disorder that can be related to the impact parameter. Experiments for the study and determination of tolerance levels of CO_2 exposure should be planned and designed to exclude disturbances from other ambient parameters like temperature, O_2 etc., which should be kept constant.

Long term exposure of rainbow trout to elevated CO_2 (50-60 mgL^{-1}) leads to severe kidney damage, characterized by calcification and granuloma formation in kidney and stomach, followed by secondary lesions, a condition mentioned as nephrocalcinosis. The condition has been observed in farmed rainbow trout *(Oncorhychus mykiss)* both in freshwater (Smart et al. 1979) and in sea water (Bjerknes et al. 1994; Poppe et al. 1995). The underlying mechanisms are not completely understood. Increased blood bicarbonate, due to physiochemical buffering, could lead to increased urinary excretion of bicarbonate with a subsequent rise in urine pH, which may again lead to precipitation of calcium hydrogen phosphate. Similar conditions have been reported from other fish species (e.g. turbot, *Scophthalamus maximus*), and is often referred to as "hepato-renal syndrome".

4.4 Feasibility of effects measurements

One main purpose of a CO_2 experiment in a Norwegian fjord is to study the impact on the natural communities, populations and individuals, under conditions as close to the real situation as possible. This means that the effects of CO_2 enrichment preferably should be studied *in situ*. The feasibility of doing effects studies directly on populations at 400+ m depth is rather low. *In situ* studies of metabolic activities of deep water species have been made (examples given by Shirayama 1995). But in general the technology available for *in situ* studies will cover various types of remote qualitative and quantitative sampling procedures (by e.g. grabs, sleds, trawls, and plankton nets), which give species compositions, abundance and biomasses, possibly coupled to optic or acoustic instrumentations giving spatial informations primarily of dense aggregations of plankton and fish. The sensitivity of these methods to detect any impact of CO_2 depend on the effects being manifested as changes in species composition, abundances and spatial distribution (behavior). In many cases one must expect that this implies lethal effects, i.e. individuals will have to disappear to give effects on species compositions and abundances. As long as the idea of such an experiment is not to push the system to lethality, there is reason to doubt that effects can be detected *in situ*. There are, however, a couple of possibilities that still should be discussed further.

If sublethal biological effects of CO_2 shall be ecologically significant, they should directly or indirectly lead to changes in population growth and reproduction. Individual size and biochemical composition (e.g. lipid content and/or fatty acid composition) of important pelagic and benthic species represents in a sense the integrated effect of past growth conditions, and can be measured on samples taken by conventional means. Also population structure of certain forms (such as crustaceans): relative abundance of various stages and fecundity of adult females, may be studied on basis of conventional samples, and should reflect impact of ecological significance. An experimental situation where the time of impact onset is under control, makes it easy to perform 'before impact' sampling to define the baseline situation, and then 'during impact' and 'after impact' samplings to study changes relative to the baseline. A similar design has been used with success in the Ryfylkefjord project to study the effects of freshwater effluents from a hydroelectric power plant on the fjord zooplankton by switching the effluent on and off (Lie et al. 1992).

Studies have shown that the tropic system of the deeper pelagic ecosystem of fjords in Western Norway is strongly influenced by the optical conditions in the water (Kaartvedt pers. inf.). Two neighbouring fjords Lurefjorden and Masfjorden have clearly different mesopelagic ecosystems, and the cause is believed to be the influence of differing optical conditions on the most important visual predators, mesopelagic fish, which have a strong structuring influence on the whole ecosystem. One may therefore envisage that if a strong CO_2 enrichment in the deep fjords changes the optical quality of the water, such profound tropic changes may occur. If physical considerations suggest that such optical changes may occur due to CO_2 enrichment, such tropic changes should be looked upon in a fjord experiment.

Although many experimental studies have been done on the effects of CO_2 (and of pH) on marine organisms in general (cf recent reviews by e.g. Stenevik and Giske 1997 and Magnesen and Wahl 1993), there may still be aspects of the sublethal effects of CO_2 on deep Norwegian fjord organisms which ideally should be studied in laboratory experiments. Examples are effects on behaviour and on metabolic functions. The relevance of such studies relies not only on the creation of a realistic exposure scenario, but also on the feasibility of obtaining live organisms from these deepwater communities and keep them in the laboratory in such a way that they function normally. For the latter it is essentially unknown to what extent the decompression from 4-500 m depth to the 1 atm laboratory situation will influence the functions and responses one will study. Leaving this, it is clear from past experiments that several species from the deep basins of the fjords in western Norway may be used successfully in experiments. Examples are the copepods *Calanus finmarchicus* (Hirche 1983) *Chiridius armatus* (Alvarez and Matthews 1975), and *Euchaeta norwegica* (Båmstedt and Holt 1978) the euphausid *Meganyctiphanes norvegica* (Bakke unpubl.), benthic decapods such as *Munida tenuimana* (Vea 1977) and *Pontophilus norwegicus* (Vartdal 1976), and bivalves such as *Abra nitida* and *A. longicallus* (Wikander 1980). All these species have been kept in aquaria for extended periods of time and have been used for e.g. feeding and growth experiments. The possibility of running impact experiments adjoined to or prior to a main CO_2 experiment in the fjord should therefore be good.

4.5 Are biological effects of CO_2 in fjords relevant for deep ocean ecosystems?

Although there is considerable advection over the sills of western Norwegian fjords, the deeper basins may, as pointed out earlier, in some respect be isolated units with community compositions different from those at similar depths on the shelf slope outside. Differences lie in species composition and abundances, resulting in differences both in diversity and dominance patterns. It is therefore a question how relevant any effects shown in these fjord ecosystems are for assessing potential effects on the deeper continental slope ecosystems outside, and even more questionable on general deepwater oceanic ecosystems.

Effects of CO_2 are mediated through lowering of pH (Stenervik and Giske 1997, Magnesen and Wahl 1993), which may have a toxic effect on the fauna or a hampering effect on the production of calcareous structures. The tolerance will vary from one species to another. There seems to be a clear dissimilarity in benthic species composition and community structure between the fjord basins and the continental slope. This implies that effects related to individual benthic species in the fjord have limited direct relevance to the benthos outside. For the mesopelagic ecosystem there are reasons to believe that the fjord may reflect oceanic species composition better. For instance the dominant herbivore species in the pelagic food chain, the copepod *Calanus finmarchicus*, is in general common at seasons in the deep water in the fjords as well as on the shelf edges bordering both the Norwegian Sea and the deep water west of the British Isles, and with approximately the same pattern in vertical migration (Kaartvedt pers. inf.). Also Matthews and Bakke (1977) mention that the deepwater pelagic community of Korsfjorden south of Bergen is dominated by oceanic forms. Therefore any effects on these species should be directly relevant to the mesopelagic community outside.

If the CO_2 disposal cause effects on the community level (e.g. changes in tropic dynamics, shift in relative abundance of feeding types, changes in diversity and dominance patterns) such results should also be transferable for the mesopelagic community due to the similarity in structure with it's oceanic counterpart. Whether community effects in the benthic system are transferable, is more uncertain, due to the clear difference in community structure between the fjords and the continental slope. Any attempt to judge whether the fjord basin benthic community as such is more or less sensitive to a CO_2 impact than the slope community is considered speculative.

In conclusion it is difficult to evaluate the degree of transferability of effects found in the deepwater fjord ecosystems before one know what kind of effects are provoked by a CO_2 deposition. This reservation is, however, not more severe than one should have concerning transfer of other experimental results to a real situation, and should not in themselves be taken as a cause for abandoning a CO_2 deposition experiment in a deep fjord basin.

5. Potential User-conflicts - Legal and Administrative Aspects.

5.1 Introduction

Experimental CO_2 disposal in a Norwegian fjord represents a new activity for which there exist no experiences regarding user-conflicts and no standard administrative procedures, routines and requirements. A close contact and cooperation with the relevant decision-making authorities during the planning process would therefore be mandatory. Hence, it is difficult to predict the possibilities of obtaining a permit/concession and which requirements that have to be met. Eventually, it is also difficult to forecast what kind of limiting clauses (e.g. threshold values for pollution) on the project that would be forwarded, and if they would be acceptable from the project point of view.

This preliminary assessment of the possible user-conflicts and the legal and administrative aspects related to the planning of the project is based on available background information and informal contacts with the authorities.

5.2 The Process of Selecting Project Sites.

The first step in the project preparation and planning would be to sort out alternative sites for the experiments based on specific selection criteria. Fjords with depths >500-600 meters and also meeting other specific requirements are assumed to be physically suitable. Some fjord areas, all situated on the western coast in Norway are subject to attention in this report. E.g.

- Salhusfjord
- Sognefjord (the largest fjord in Norway)
- Hardangerfjord
- Jøsenfjord.

The next step would be to contact the municipalities that have jurisdiction over the fjord areas to find out if they are willing to assess the possibility of “hosting” the project and to discuss possible premises. Since the administrative borders between municipalities often follow the midline of a fjord, the afflicted area would often be shared between two or more municipalities. The authorities at county level (County Municipality), responsible for coordinating inter-municipal activities, and the County Governor, should also be notified.

If the municipalities are positive, it will be necessary to have a formal approval from the Municipal Council before one continues with any further and more detailed planning of the project. If, on the other hand, the municipalities are negative and unwilling to support the project, then the chances are probably small that a higher administrative level will overrule their decision.

5.3 Local Concern

An in situ experiment with CO_2 disposal in a Norwegian fjord would undoubtedly cause concern about possible environmental impacts and the consequences for both commercial and public user-interests in the area. The fjords are multiple use areas and also play an important role for local community life and for local identity. Any experiments with uncertain or negative consequences would therefore be a sensitive matter.

The municipalities will evidently be interested in the environmental costs of the project compared to the benefits. The local outcome from the project must be pointed out (revenues, jobs, taxes, spin-off activities etc.). It would definitely be a challenge to put forward convincing arguments and create incentives for using a fjord as site for an international experiment if the benefits for the local community (or even for the nation) are uncertain. It would probably create a lot of scepticism and resistance at local Government level and among the user-organizations (e.g. the local fishermen's organization), local Non-Governmental Organisations (NGO's) and among the population in general.

5.4 User-conflicts

Disposal and Storage Options - Relative conflict Level

The possible environmental impacts and user-conflicts will depend on which disposal technology and storage options that are selected, and on the characteristics in the selected fjord.

Relative environmental impact levels may be described as follows (E. Adams and H. Herzog, pers. comm.):

Storage Option	*Relative Environmental Impact*
Dry Ice	Low
Towed Pipe	Lowest
Droplet Plume	Low-Medium
Dense Plume	Highest
CO_2 Lake	Low

The most realistic option for fjord experiments seems to be the Droplet Plume, possibly in some combination with the Towed Pipe. It must be assumed that this will give little or no undesirable influence on the productive surface waters and minimum chance of e.g. rapid outgassing.

Common User-interests in Norwegian Fjords

Most local municipalities and e.g. the County Governor's Environmental Department will have databases and thematic maps showing both environmental interests and user-interests in the fjord areas, although the quality and the coverage actually vary considerably. Marine biodiversity, and reproduction areas for fish etc., are in general not registered systematically and the information is often uncertain. The Directorate of Fisheries and its local Advisory Services will have information on farm sites and areas of particular importance to fisheries. However, printed updates in the form of maps or reports are hard to get.

Aquaculture (fish farming) is an important economic factor in many fjords. Farm sites are generally established on a long-term basis, with basis in local Coastal Zone Management plans. Such plans have been made for many or most municipalities. The first plan of this kind in Norway was made by NIVA in 1984 (Elvestad and Sørensen 1985). Some zoning plans also cover larger areas, like the Southern Hordaland County (Bjerknes and Waatevik 1988).

Printed information (reports) or maps showing the present status for fish farming and fishing grounds may be difficult to obtain, as farm owners change from time to time, as also do the permits (consessions) for each farm. Fredly (1982) is an example of such a report, but this is will need an update.

A broad variety of different user-interests are to be found in Norwegian fjords (list not complete):

- local commercial fishery
- aquaculture
- spawning and breeding grounds
- biodiversity areas, nursery habitats
- nature protection areas
- recreational boating and fishery
- bathing and outdoor recreation
- tourism areas
- sand extraction
- sewage disposal
- emissions from industries
- transport/ship traffic
- harbours
- cultural heritage areas and objects
- military defence installations
- technical installations

Commercial fisheries may include the deep water in fjords (5-600 m depth in some cases). Prawn fisheries generally go to maximum 200-300 m. Other areas e.g. for spawning will generally be in much shallower waters. Many fisheries will be seasonal. So when proposing a CO_2 experiment, one may e.g. select non-conflicting seasons.

Potential User-conflicts

The potential conflicts associated with CO_2 disposal in a Norwegian fjord are expected to be limited to local or regional areas (involving two or more municipalities). National interests could, however, be said to be influenced in cases where e.g. rare species of benthic fauna and/or areas of national interest are affected directly or indirectly. The Espoo Convention regulates transboundary pollution, but impacts on other neighbouring nations from the project are unlikely to occur as long as it is located to a "closed" fjord system well within the national territorial boundaries.

Since the majority of the (environmentally dependable) user-interests are mainly associated with surface waters and the shore areas, the immediate conflicts of CO_2 enriched water at the fjord bottom should be limited, provided that the CO_2 will not dissolute high up in the water column or reach the surface.

Existing descriptions of possible impacts on the ecosystems and the environment are not very specific. Impacts of increased CO_2 levels on marine biology are largely unknown. Some marine organisms may be stimulated while others may experience severe problems, in particular close to the injection site, but possibly also over wide areas. Harvestable resources and commercial fish species like bream and ling might be affected. Grown up fish will probably be able to escape the area, but eggs and larvae will have more difficulties. A crucial question is whether the consequences will be irreversible (permanent damage on e.g. local species, biodiversity) or if the ecosystem will "repair" itself with time.

By experience, potential user-conflicts will be more evident in areas that are more densely populated or in areas with sensitive user-interests, e.g. that are highly dependent on the environmental quality. A relatively large part of the human settlements (towns, villages and scattered houses, farms and cottages) and economic activities are located in the vicinity of the fjord along the shorelines and on river deltas, although relatively sparsely populated areas with less conflict potential are not difficult to find. On the other hand, the more remote and "unspoiled" areas may have significant value for e.g. biodiversity and for recreational activities.

Aesthetic conflicts could occur. The psychological component should not be overseen. Public consciousness about a "polluted" fjord could reduce the recreational value and also cause problems for tourism, although this is very uncertain. Disposal close to popular and public areas should be avoided.

The CO_2 storage would possibly not inflict with private land property or stakeholder's interests directly since private ownership rights are limited to 2 meter's depth into marine water (this regulation does also apply for fjords).

Necessary technical installations like pipelines, pump stations etc. should also be taken into account. Introduction of technical installations on the shore area or in the littoral zone would normally represent a larger conflict potential than if located to areas that are regulated to e.g. industrial activities or where infrastructure facilities are already in place (buildings etc.). The Planning and Building Act (§ 17-2) generally bans building or constructing activities inside a 100 meter belt along the shoreline to the sea/fjord. This provision does not, however, apply to already built-up areas, nor to areas covered by Local Development Plan or Shore Plan. Releasing CO_2 from e.g. a ship or a floating platform will probably be less conflicting compared to installations (including a security buffer) that would occupy and cause permanent damage to shore areas.

Many municipalities have developed systems for integrated coastal zone management and planning (including fjord areas) and have made decisions for long-term exploitation and protection of resources and areas (§ 20-1).

The zoning plans will in many cases have juridical validity. All new activities will have to be measured to see if they are in accordance with the plans. After application, dispensations from the plan can be granted in special circumstances (§ 7).

Several deep fjord basins have been subject to legal/illegal dumping of ship wrecks and formerly also industrial waste. Ammunition from the 2nd world war was dumped in some deep fjords after the war, and may still represent an obstacle to the CO_2 experiments, if not being a security risk. Local port authorities, and the Norwegian Nautical Service should be contacted.

5.5 Legal Requirements for Environmental Impact Assessment (EIA).

The Pollution Control Authority may upon application grant permission/concession for activities which may cause pollution (authorized by the Pollution Act). EIA requirements are laid down both in the Pollution Act and in the Planning and Building Act.

The Pollution Act

The Pollution Act applies to pollution and waste in the external environment. § 13 states that "anyone planning activities which may lead to significant pollution (remarks: CO_2 disposal would most probably be regarded as significant pollution) in a new place, or planning major developments of a new character at a place where there is existing activity, shall notify the Pollution Control Authority at an early stage of the planning process". Furthermore it is stated that "the Pollution Control Authority may stipulate that anyone planning activities that are required to be notified to the authorities shall carry out an impact analysis in order to determine the effects the pollution will have".

The Planning and Building Act

EIA requirements are laid down in the Planning and Building Act, Chapter VII-a, and in the (newly revised) EIA-regulations. Disposal of CO_2 is not specifically listed among the activities that *have* to undergo EIA (Annex I), but also activities that *might* have significant impacts on the environment, the natural resources and the community, may have to undergo an EIA. The EIA is intended to ensure that any effects are taken into account in the planning of projects, and when a decision is taken as to whether and, in the event, under what conditions, a project can be carried out.

For the specific CO_2 disposal project the main responsible authority concerning EIA regulations would be the Ministry of Environment. After the developer has notified the Ministry about the project, the Ministry would decide whether an EIA has to be carried out or not. If the developer is instructed to do an EIA (which is most likely in this case), the first step would be to design a Draft Programme which describes the project, alternative sites, technical solutions, a screening of possible impacts, including a proposal on which further investigations that have to be undertaken to predict the consequences as precise as possible. Based on the conclusions, the Ministry will then determine the design of the EIA. In general it will have to be tailor-made for the specific project. The EIA procedures are shown in the diagram (Figure 5.1).

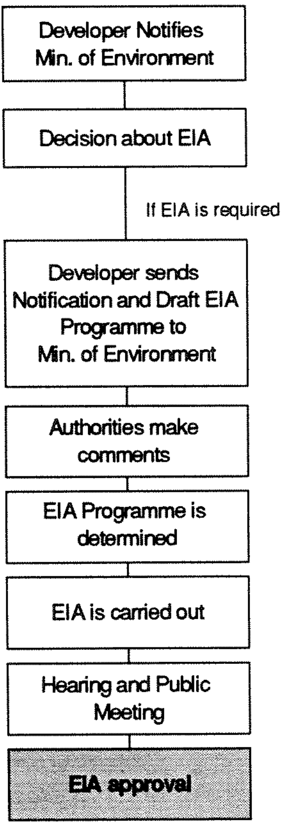


Figure 5.1. Diagram showing the EIA-procedures.

Accidental upwelling of CO_2 may be necessary to take into consideration. A risk analysis to measure the statistical risk of a "blow-out", possible impacts and preventative/abatement actions may be required.

The EIA process will have to involve all affected parties and the public. Expenses for producing a EIA Statement etc. have to be covered by the developer.

5.6 Experience from similar exercises

Although a CO_2 experiment may have some local impact this may by far be outweighed by the experiences gained for the future global CO_2 balance. In most real cases where mitigating environmental actions are called upon, there will be a 'give some-take some', and the benefits will have to be weighed against the expected cost or sacrifices for the environment. A CO_2 sequestration project in Norway (or even elsewhere) will be quite unique in kind. However, some lessons may perhaps be learned from other former or on-going projects in Norway with similar approaches or facets.

MARICULT is a Norwegian programme focusing on marine eutrophication, which has funding from both private industry (Norsk Hydro) and the Norwegian Research Council. Support is also provided through grants from EU (the MAST-III). The Comweb experiment under MARICULT (see Internet: http://www.maricult.org) will take place in a small embayment facing the Trondheimsfjord. It will involve artificial nourishment over the summer season by adding nutrients to the bay water. This in turn is expected to enhance primary and secondary production. Such a supply of nutrients has been subject to formal applications and procedures, and presently a hearing is going on. In terms of a future CO_2 experiment, it may be of value to study the results from that hearing.

Large scale liming of acidified lakes and rivers has been conducted over several years in southern Norway. This large-scale programme has been subject to thorough small-scale studies on effects and impacts on biota and strategy selections prior to executing large scale liming programs (Hindar and Rosseland 1991). In principle, the acidification may not be reversible. I.e. the former undisturbed state of the ecosystems may actually not be reached again even if the pH of the water is coming up to its normal value. In such a sense, the liming may be regarded as a large scale experiment, and lessons may be learned about the legal process prior to the launching of large-scale liming presently going on. Several governmental bodies are involved in this.

Fighting parasites on freshwater fish may involve non-selective poison treatment of a complete river system. Such treatment, although both destructive and debatable, has been conducted in Norwegian rivers with the approval of central environmental bodies.

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EIA-regulations, Planning and Building Act, Chapter VII-a. 13. December 1996.

IEA Greenhouse Gas R & D Programme: Ocean Storage of CO_2. Extracts from Workshop 3: International Links and Concerns.

6. Conducting a real experiment

As stated in previous chapters, selecting a specific site (fjord area) for a time-limited/space-limited CO_2 experiment will call upon actions on several levels. As indicated, an EIA study may have to be made. Such an EIA study may have to be performed in two stages:

1. An initial EIA based on a certain type of fjord, but not a specific one.

2. A second EIA based on an experiment in a selected, specific fjord.

Both EIAs will have to address and assess the physical, chemical and biological impacts based on the present knowledge, though without ending up in an indefinite loop of EIA-> lacking evidence-> new EIA etc.

6.1 Criteria for fjord selection

Almost all Norwegian fjords are U-shaped with steep sides and a fairly flat bottom with thick sediment layers. Depths may vary considerably along the length of a fjord as previously described. Most of the deep Norwegian fjords are characterized by a three layer stratification with an upper brackish layer of variable depth followed by an intermediate layer approximately down to sill depth or somewhat deeper, and finally the basin water below sill depth. Effective sill depths for the deeper fjords considered here are of the order 100-200 m.

Operations at around 600 m depth would then almost invariably take place in basin water. If the CO_2 dissolution process extends over a considerable vertical interval, or rates are large and monitoring continues long enough that ambient vertical mixing processes are allowed to act, CO_2 enrichment may also be observed in the intermediate layer, but main focus initially should be on the basin water.

It may be that focus first must be placed on the local conflict potential for each fjord area before any physical considerations are made. The selection criteria may rather be conflict related rather than related to physical or hydrographic considerations. As described in Chapter 5 there are conflict potentials that must not be overseen. A screening of a list of fjords in terms of conflict potential etc. may be the next step in the process of selecting a fjord.

6.2 Monitoring programme

The design of a monitoring programme directly in connection with a CO_2 experiment can to a large extent lean on previous proposals for open ocean monitoring. However, fjords may represent the opportunity to add new aspects and techniques.

Disposal of CO_2 in deep water of fjords will open possibilities for research on both short- and long term effects on deep-sea animals, including fish. Initially, experimental exposure of different deep-sea species to different CO_2 levels should be performed and followed up by the examination of physiological stress due to influences on acid-base regulation, respiration and metabolism, and subsequent detrimental effects.

Baseline study

Concrete data on the deep water and biota of the fjord selected for further evaluation (or a limited number of alternative fjords) may be lacking or at best be sparse. A measurement and sampling programme must therefore probably be conducted in advance of any final selection. Probably a programme covering several fjords will be the best way to go. Different projects may be run in parallel in order to save costs and time. In addition, this will render fully comparable datasets.

The sampling for the Baseline study should last minimum one year, covering all seasons.

The biological sampling should for example include

- Bottom samples for sediment and fauna characterisation.
- Fish catching with bottom line or nets.
- Sampling of mesopelagic organisms (plankton nets).
- Video camera survey (ROV or autonomous vehicle, manned submarine).

The physical and chemical sampling should cover (list not complete)

- Hydrography (i.e. seawater salinity and temperature vs. depth; profiling instruments and fixed moorings).
- Dissolved gases, especially O_2 and CO_2 (carbon chemistry, incl. pH and/or alkalinity).
- Currents at the sill and in the fjord basin proper (fixed instruments/moorings).

The institutions involved in marine investigations in Bergen already have wide experience with many types of instrumentation and sampling techniques. Several factories in Bergen are manufacturing instruments for the international market (e.g. Aanderaa Instruments). Thus performing a Baseline study in principle should be readily feasible, possibly with exception of the ROV study that may require some advance R&D and adaptations.

New techniques such as using autonomous profilers and passive drifters may have to be specially adapted. The method of measuring slow currents by means of neutrally buoyant floats (RAFOS, ALACE etc) has been widely used in the open ocean (see e.g. Golmen and Søiland (1995) for a review of this method). However, due to special acoustic conditions in fjords, some form of down-scaling and adaptation must be performed.

The baseline study should also include numerical modelling og deep water circulation, especially for proper scaling and optimizing of the measurement efforts. Theoretical and numerical models of renewal of basin water and of vertical mixing during stagnation periods (Gade and Edwards, 1980) exist for different types of fjords, and could be employed, in particular for mixing over seasonal and annual time scales. Stratification in basin waters of fjords is generally weak (as it is in deep ocean water below the thermocline), and would have to be measured in detail in conjunction with an experiment in order to understand intrusion dynamics and vertical mixing on time scales of days and weeks.

Experimental monitoring

In addition to the methods suggested for the baseline study, supplementary methods may be included, such as,

- Plume dispersion studies:
    - Tracer studies (rhodamine-B).
    - Echosounders: vertically and horizontally looking arrays.
    - Acoustic tomography, down-scaled.
    - Sediment traps.

Plumes of freshwater entering a body of seawater may be traced by traditional echosounders from the ship. NIVA has experience with this in previous plume monitoring programmes (Golmen et al. 1993). The use of specially designed echosounder arrays will require some advance R&D. Christian Michelsen Research (CMR) in Bergen has wide experience with their inverted 300kHz echosounders, which may be re-designed for the new study. Acoustic tomography used in a fjord may be more far-fetched, but in principle the two-phase liquid CO_2/seawater system could be detected in 3D by a suitable designed sound array (CMR manufactures already 2-phase flow monitoring instruments).

Biological experiments might include investigations of effects of CO_2 on the physiology of deep sea fish species. The development of calcinosis or related sub-lethal detrimental conditions after CO_2 exposure should be examined for adequate test organisms (i.e. selected deep water species) for the definition of critical threshold levels. Rainbow trout may be useful as a control organism.

The Norwegian Underwater Technology Centre (NUTEC), located in Bergen, Norway, possesses equipment for pressure testing where the ambient conditions in fjord deep-water can be simulated. A testing program including experimental CO_2 exposure to different deep water fish species to define critical limits may be designed in cooperation between NIVA and NUTEC.

Post-experiment monitoring

The monitoring after the experiment should technically duplicate the Baseline study, including most of the physical measurements. How long it should last, will depend on the results gained underway. But in principle it may have to last several years in order to document the rehabitation and reversion to the previous condition. However, it may gradually be down-sized according to the speed of the processes.

6.3 Models for assessment

6.3.1 Water circulation and mixing

As for open ocean experiments a fjord experiment should be accompanied by studies on water circulation. We assume that the existing models for dissolution of CO_2 droplets and possibly for dispersal of the CO_2 droplet plume (primary dilution phase) may be adapted to the fjord case, going through the validation steps. However, the far-field studies (secondary dilution phase) will need input from a different type of models than those used in the open ocean.

Models that describe the full nature of the dynamics of fjord basins hardly exist. This is due to the fact that the dynamic processes are not continuous, but intermittent and of varying nature (cause). This has lead to the development of random or stochastic approaches to interpret the dynamics (Gade, 1973). Empirical models covering also the intermittent water exchange cycles have been developed (de Yong and Pond 1988), but deterministic models for the specified fjords probably will have to be developed.

Regular features like internal waves, internal tides and resonance phenomena have been successfully modelled for fjords either by applying the traditional vertical mode resolution (eigenmodes & horizontal bottom) or the new technique of ray tracing (sloping bottom) (Cushman-Roisin et al. 1989, Tverberg et al. 1991). On the west coast of Norway tidal driven phenomena also in the deep water must be expected, and the above methods may be applied, one or the other, depending on the basin bathymetry.

Models incorporating intermediate water exchange between the fjord and the coastal water should be implemented, based on the knowledge of coastal dynamics (Mysak 1980, Klinck et al. 1981). Presently the University of Bergen is running the 3D Princeton Ocean Model (ECOM3D, Blumberg-Mellor model) on fjords, with sigma-coordinates. The resolution may still be inadequate. McClimans et al. (1992) and Røed (1993) brought a summary on the state-of-the-art of numerical model use and demand in Norway at that time.

Integrated ecosystem models that include deep water and CO_2 chemistry should be developed. Such models do exist, but will need refinements. NIVA has developed a complex model for fjords including physics (water exchange, internal mixing), water chemistry (nutrients, O_2/H_2S cycling etc.) and tropic levels including zooplankton and oysters. This model has successfully been adapted to the Oslofjord (Bjerkeng 1994), and recently also to other fjords.

7. Assessment of hazards

Conducting a small scale CO_2 sequestration project in a Norwegian fjord is unlikely to cause any accidents or imposing hazards to humans. Still security aspects probably will have to be evaluated and approved prior to an experiment.

Security aspects in connection with disposal from a moving ship may include:

- Handling of the pressurized CO_2 gas on board the ship
- Ship manoeuvring and local traffic control
- Contingency plans for nearby communities or inhabitants

A risk assessment for unintended and abrupt CO_2 leakage to the air should be made, at least briefly. By disposing the liquid CO_2 deeper than about 500 m the risk of producing CO_2 gas bubbles is diminished, and all CO_2 will be in the form of liquid droplets, hydrates or dissolved into the ambient seawater.

As max. depths of Norwegian fjords do not exceed ca 1.300 m, the liquid CO_2 will be lighter than ambient seawater, and no "CO_2-lake" at the bottom will form. However, the seawater that is enriched in CO_2 will be heavier than the ambient water, and is expected to either interleave deep in the water column or confine itself in a bottom layer.

Some lakes e.g. in Africa and in Japan are naturally enriched in CO_2 from volcanic activity via ground water. Serious accidents have happened due to physical disturbances in some of these lakes. As the interface between the deep high-concentration CO_2 water and the upper layer is forced upwards beyond the equilibrium pressure e.g. by internal waves, large amounts of dissolved CO_2 suddenly is released as bubbles that cascade towards the surface, entraining lots of water (Fig. 7.1).

Such a cascade of gas and water caused the sudden death of more than 1.700 people around the 208 m deep Lake Nyos in Cameroon in August, 1986 (Stager and Suau 1987). The deaths were caused by suffocation (asphyxiation) due to the heavy CO_2 gas cloud that dispersed near the ground in the areas below the lake (Golmen 1996).

Destratification of the water column due to seasonal cooling does not occur at any significant extent in the African lakes. Due to the colder climate, a similar CO_2-enriched lake in Japan (Lake Mashu) is subject to annual destratification and vertical overturning, which prevents excessive accumulation of CO_2 in the deep water (Ladbury 1996).

In principle similar gas outbursts from CO_2-saturated deep water may also occur in fjords if the CO_2 is dissolved in seawater in very high concentrations. Preventive actions to avoid this possibility should be documented before commencing any experiment.

Another type of potential hazard may be interaction with disposed weapons ammunition especially from after the 2nd world war. Probably not all sites are known, but several are registered and marked in the nautical charts.

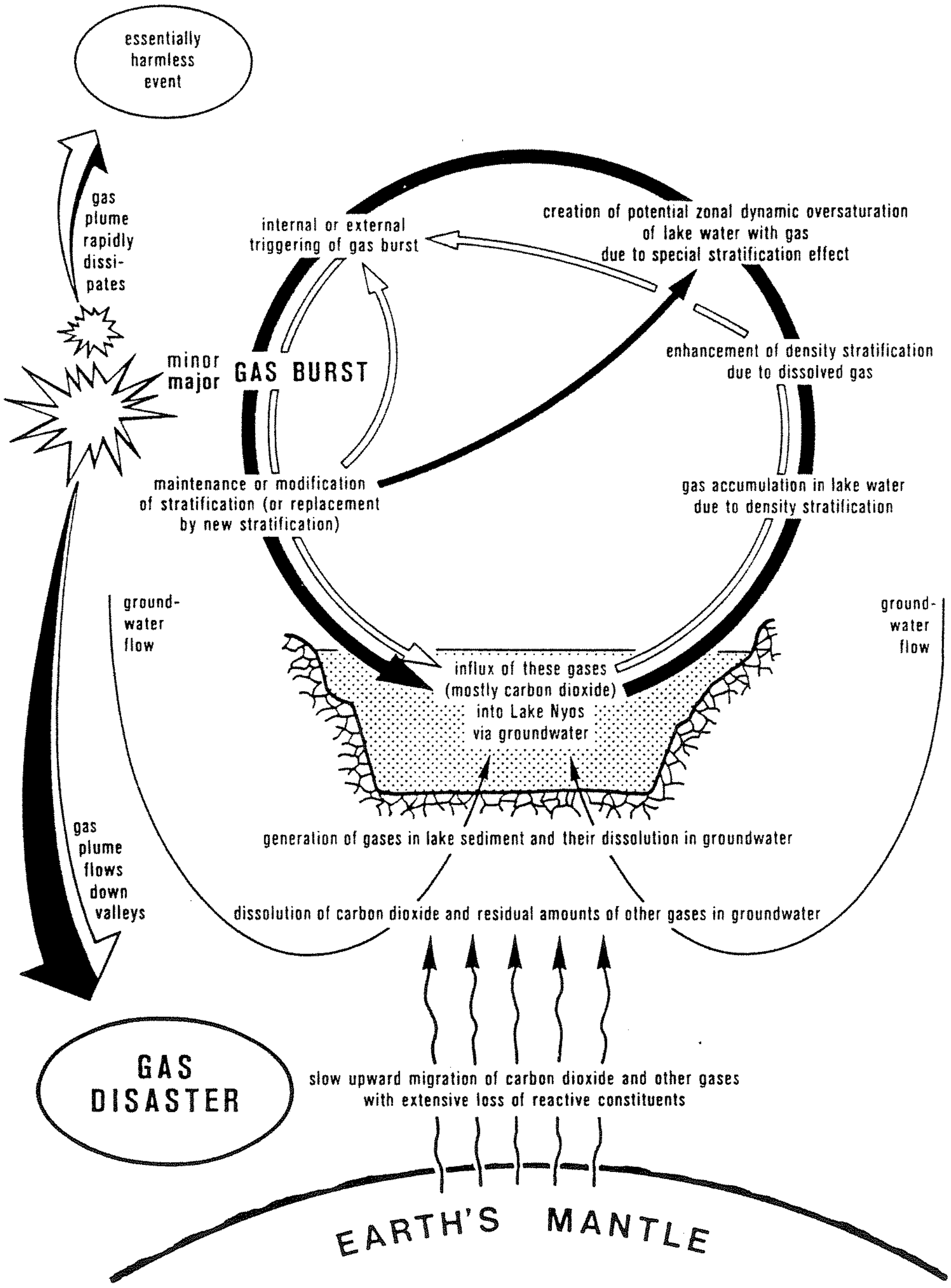

Figure 7.1. Flow diagram of the causes and mechanisms of the Lake Nyos gas disaster in 1986. Black or darkened arrows indicate cycles that may lead to major gas bursts. From K. Tietze, (1992).

8. Closing remarks

Geographic and hydrographic characteristics of fjords of sufficient depth to be suitable for CO_2 storage experiments, have been given. It is suggested that several suitable sites providing ocean-like, but sheltered environments, do exist along the west coast of Norway. The marine biological conditions at these sites are not investigated, but it can generally be assumed that biological communities similar to, but simpler than, those in open oceanic waters with the same temperature and salinity range are present.

For experiments with scope beyond the near field effects associated with the mode (droplet plume, dense plume) of storing CO_2, more information on water circulation, residence times and mixing would be required for a candidate site, such as one of the smaller fjords, or a particular location in one of the larger fjords. Material for further studies can be found in the given references and reports from unpublished investigations performed in conjunction with development of hydroelectric power plants, bridges, outfalls etc., and basic published and unpublished research including thesis work.

Short term experiments concentrating on the technical near-field aspects of CO_2 dissolution in seawater and on droplet plume dynamics could be performed essentially anywhere in the world. However, fjords have the benefit of providing a sheltered and accessible working area. In addition, even a short term CO_2 disposal experiment in a fjord opens possibilities for biological studies and longer term monitoring of impact and recovery.

Great caution needs to be taken to avoid irreversible damage, in particular to the benthic communities. An experiment with CO_2 enrichment only in the pelagic may be most realistic to avoid serious conflicts of interest and for logistical reasons. It is expected to give biological results of interest to deep ocean applications, in particular applications of the potentially most environment-friendly option, i.e. release from a moving ship (Haugan 1997).

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Annex

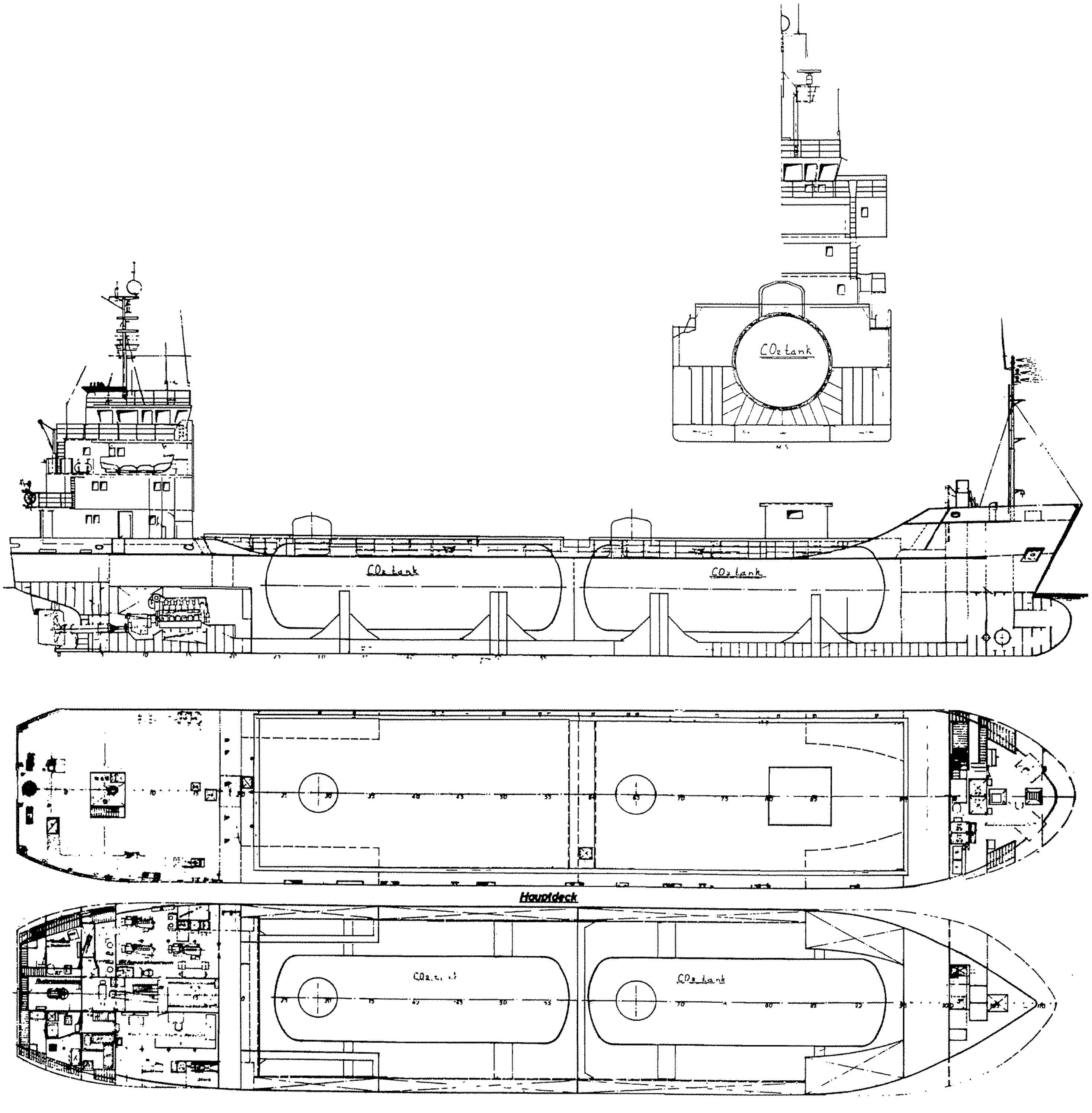
M/T "HYDROGAS"

CO$_2$ tanker

Flag:	NOR Register NIS
Call sign:	LAJC4 Port of reg: Oslo
Mob. phone:	094 71 503
Built:	1977 J J Sietas Schw, Hamburg,
Yard no:	834
Converted:	1987 from container vessel
Class:	DNV +1A1, Tanker for liquefied CO$_2$, E0, Ice 1B
Mdwt:	2060
Grt:	1089.9
Nrt:	766.14
L.O.A.:	72.00 Length pp: 65.20
Br molded:	12.83
Depth:	6.80
Draught:	Loaded 4.45 Ballast 3.65 m

Suitable cargo:	CO$_2$
Max cargo cap:	abt 900 tons CO$_2$
Hold:	2 CO2 tanks x 450 tons
Pumps:	2 x 175 t/hr against 16 bar
Main eng:	B&W Alpha 12V23LU 1739 BHp 1280 kW at 800 rpm
Aux eng:	1 Deutz F6L413R 68 kW , 77 kVA 1 Deutz F5L413R 57 kW, 63.5 kVA
Speed/Consump:	12.5 kn 6600 l GO /24 hr
Side thruster:	Forward 147 kW
Capacities:	GO abt 156 mt Water 43 mt Ballast 758 mt

M/T "HYDROGAS"



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