Chapter 1
INTRODUCTION

CONSTITUTIVE MODELS AND CHALK

Computing power has advanced significantly in the years since soil mechanics and rock mechanics first became mature fields. Probably the single most significant source of progress in engineering computational power is the development of the finite element method to solve boundary value problems. The accuracy of solutions available via finite element analyses is dependent on and limited by many factors, one of which is the ability of the material model used in the finite element code to accurately predict the stress-strain or constitutive behavior of the material.

Geomaterials present certain distinctive difficulties to scientists and engineers who attempt to characterize their behavior. The behavior of geomaterials is complicated by several factors including: they are multi-phase materials which are influenced by both their solid and fluid components; they are typically pressure-dependent; they are heterogeneous and often anisotropic; and they often show different behaviors due to time-dependent factors. As a result of these factors, geomaterials display significant nonlinearities in their constitutive behavior.

Soft rocks are a group of geomaterials which is characterized by a moderately deformable solid matrix, less deformable than soils but more deformable than hard rocks. Typically, soft rocks exhibit irreversible deformations or failure when subjected to strains on the order of one percent. A good understanding of the geomechanical properties of soft rock has been shown to play a significant role in the ability to predict the response of deformable multiphase (solid and fluid) geosystems to man-induced disturbances, including applications in petroleum engineering, mining engineering, and civil engineering.

In addition to developing an accurate constitutive model, the robustness and efficiency of a finite element code depends on the ability to implement the constitutive equations which comprise the mathematical model into a finite element package. In finite element calculations, strain increments for a given loading step are input to the constitutive driver, and the corresponding stress increments consistent with the constitutive behavior of the material are returned to the main finite element code. The efficiency and accuracy of a finite element code may suffer if stress increments cannot be calculated for a given set of strain increments.

Development of integration procedures for the constitutive equations is therefore a key component of constitutive model development.

The petroleum reservoirs of the southern North Sea are examples of deformable multiphase geosystems referenced above. The reservoirs in the southern sector of the North Sea are composed of a single solid phase (chalk) and three fluid phases (water, oil, and air or gas). Interaction of the solid and fluid phases during petroleum recovery operations have led to unexpected behavior in the reservoir. Subsidence rates within the North Sea reservoirs greatly exceed the subsidence rates which were expected, on the basis of experience gained from similar operations in non-chalk reservoirs. A brief history of petroleum recovery operations in the Ekofisk field of the Norwegian North Sea follows in the next section to provide perspective on the importance of the constitutive behavior of chalk to the observed field-scale behavior in the Ekofisk field.

The petroleum reservoirs of the southern North Sea are composed of chalk. Chalks of the North Sea and surrounding areas have biological origins. Chalks are formed from the fossilized remains of planktonic algae, and their mineral composition is almost entirely calcite; as stated above, small amounts of silica and clays are usually present. The fossilized algae which make up chalk are arranged in disk-shaped coccoliths, approximately 2-20 μm in diameter. Each coccolith is made up of many platelets (Figure 1.1). The coccoliths are weakly cemented together into larger spherical structures called coccospheres. Coccoliths are commonly observed in chalks recovered from reservoir chalks, but intact coccospheres are rarely recovered. Coccoliths and coccospheres contain a large fraction of void space which has been preserved in the North Sea chalks; reservoir chalks which are located at depths of 3000 m and which have been subjected to great effective overburden pressures on the order of 30-40 MPa still exhibit very high porosities of 30 to 45 %. Although the average porosity of North Sea chalks is quite high, the pore throats or connections between individual pores are small, usually 1-5 μm in size. A scanned electron microscope image of a typical North Sea-area chalk is shown in Figure 1.2; a coccolith shown in the image is approximately 7 μm in diameter. The microscopic structure of North Sea chalks, which produces high porosities and small individual pore spaces, strongly influences their macroscopic mechanical behavior.

Many constitutive models for soft rocks have been formulated and reported in the literature. The model developed here is sufficiently general to be applied to any soft rock, but the emphasis of the research is related to chalk. Some aspects of chalk behavior are unique among soft rocks. One or more components of the chalk model developed herein may be unique to chalk and need only be deleted to apply the model to any soft rocks.

A BRIEF HISTORY OF EKOFISK

More comprehensive accounts of the history of petroleum exploitation at Ekofisk can be found in several references (Sulak and Danielsen, 1989; Sulak, 1991; Gutierrez et al., 1995). The Ekofisk field is located in the central graben of the southern Norwegian North Sea (Figure 1.3). Geologically, the field is an anticlinal structure with its fold axis in the north-south direction; locally, Ekofisk is an elliptical dome-like structure which serves as the geological hydrocarbon trap. The field covers an area of approximately 6.9 km (east-west) x 9.3 km (north-south). The field is composed of two highly porous petroleum-bearing strata, the Ekofisk Formation and underlying Tor Formation, whose combined thickness ranges from 225 to 300 m and which are separated by a lower-porosity tight zone (Figure 1.4). The reservoirs are composed of fine-grained chalks of Danian and Maastrichtian age (in the Cretaceous and Tertiary periods) which contain minor amounts (typically <5 %) of noncarbonate minerals, usually silica and clays. Porosity in the reservoirs is typically between 30 and 45 %, and is typically 10-20 % in the tight zone. Intragranular permeability in reservoir chalks is quite small, but the field permeability is greatly enhanced by an extensive fracture network. The overburden consists of approximately 3000 m of relatively impermeable claystones and shales, with little interbedded sand (Figure 1.5). Nagel (1998) provides a characterization of the overburden at Ekofisk. Water depth at Ekofisk is less than 100 m.

The Ekofisk field, discovered in 1969, was the first of many petroleum reservoirs discovered in the chalk fields of the southern North Sea. Production started in 1971, and a large gravity-based structure (GBS) was installed to serve as the center of recovery operations (the Ekofisk complex) in 1973; the structures consist of three production platforms, a terminal platform, a hotel, and a 1-million-barrel storage tank. Gas produced as part of recovery operations began to be re-injected in 1975, and gas injection has historically continued at rates which depend on a variety of factors.

Unexpected production-related seabed subsidence was discovered in 1984. At the time, it was estimated that approximately 3.0 m of subsidence had occurred. To protect the petroleum recovery structures, all platforms were raised by 6.0 m in 1987, and a protective seawall was installed around the GBS in 1989. In addition to gas injection, water injection began in 1987 in an effort to prevent depressurization and associated compaction of the reservoirs. Expansion of the waterflooding projects occurred in 1989, 1990, and several subsequent years. Seabed subsidence has been monitored closely following its discovery, and has continued at rates of 10-40 cm/year, depending on location within the reservoir, to the current magnitude of 9+ m underneath the GBS. The magnitude of reservoir compaction measured at Ekofisk is somewhat greater than the magnitude of seabed subsidence.

Originally, the potential for production-related subsidence was believed to be minimal due to the great depth of the reservoir. Although reservoir compaction related to production was anticipated, it was thought that the effects of compaction would not be propagated through the great thickness of the overburden to the seabed. Analysis of the compaction-subsidence interaction indicated that a subsidence-to-compaction ratio (S/C) of 0.5 was obtained using the model of Geertsma (1973). History matching and forward modeling efforts concluded that less than 6 m of seabed subsidence would occur, at a decreasing rate, during the expected operational lifetime of the field (until 2011); it was from this projection that the structural remediation measures were designed. After subsidence continued at a faster-than-expected rate, further modeling of the compaction-subsidence interaction, then resulted in a predicted S/C of 0.8 assuming a rigid basement exists upon which subsidence occurs. This S/C ratio appears to be a more accurate representation of observed field conditions, since seabed subsidence has already exceeded the maximum predicted subsidence on which structural remediation plans were based.

Other petroleum reservoirs, most notably the Valhall field, in the chalk fields of the North Sea have also undergone subsidence. However, the geometry of the other fields is more favorable as related to seabed subsidence than that of Ekofisk. The subsidence problems at Ekofisk are of much greater magnitude than at other North Sea chalk fields.

Another phenomenon contributing to the continuing subsidence is the “water weakening” effect. It has been observed for approximately 20 years that chalk strength is decreased substantially in the presence of water as compared to its strength when oil-saturated. The result of petroleum recovery and waterflooding operations is that the water content in reservoir chalks increases continually as time passes, resulting in additional reservoir compaction. The reservoir compaction resulting from water weakening is a constitutive response of chalk that has been termed “water effect strain.”

The seabed subsidence at Ekofisk, then, is due to at least two complex phenomena. The reservoir compaction is due to constitutive behavior of the chalk, and the seabed subsidence is due to effects of reservoir-overburden geometry and to changes in pore pressure and effective stress in the reservoir. Although the bulk of this dissertation is concerned with constitutive behavior of chalk and other soft rocks, the effects of reservoir geometry on Ekofisk subsidence will be examined via finite element analysis in Chapter 9.

DOCUMENT ORGANIZATION

The remainder of this document describes the formulation and implementation of the constitutive model for chalk and other soft rocks, and is arranged as follows. Chapter 2 describes different types of constitutive models, and summarizes the basic equations of elasto(visco)plastic constitutive models. Chapter 3 contains a description of the mechanical behavior of chalk and of other soft rocks. Chapter 4 consists of a review of published constitutive models for chalk, including models for elastoplasticity, time- and rate-dependence, and pore fluid effects. In Chapter 5, a one-dimensional rate-dependent model for chalk and soft rocks is developed, then extended for three-dimensional effects and compared to experimental data. Chapter 6 contains a description of a newly proposed constitutive model for chalk including all yield and failure mechanisms (except pore fluid effects), correlations to index parameters, and comparisons to experimental data. Chapter 7 contains a state-of-the-art review of integration procedures for constitutive equations and a detailed description of a new integration procedure. Chapter 8 contains a description of pore-fluid dependent behavior and water weakening in chalk, provisions in the model for pore fluid effects, and comparisons to experimental data. Chapter 9 contains finite element analysis of field problems related to chalk using the new constitutive model. Chapter 10 summarizes the results, presents conclusions of the research, and examines unresolved issues and potential future directions for the work.

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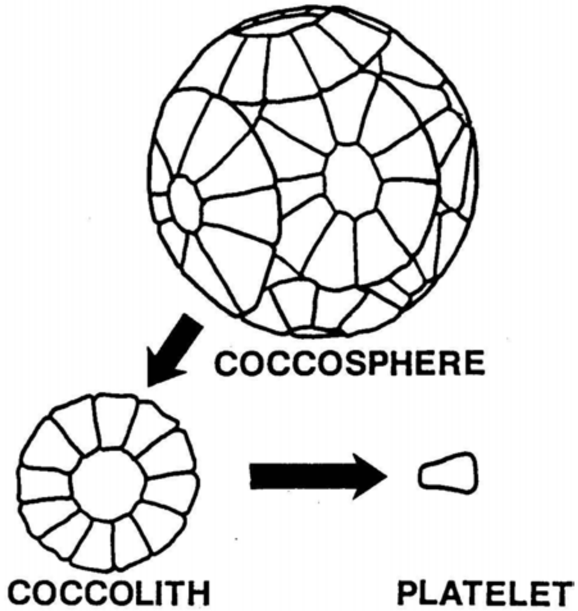

Figure 1.1. Microscopic chalk structures: coccospheres, coccoliths, and platelets (Sulak and Danielsen, 1989).

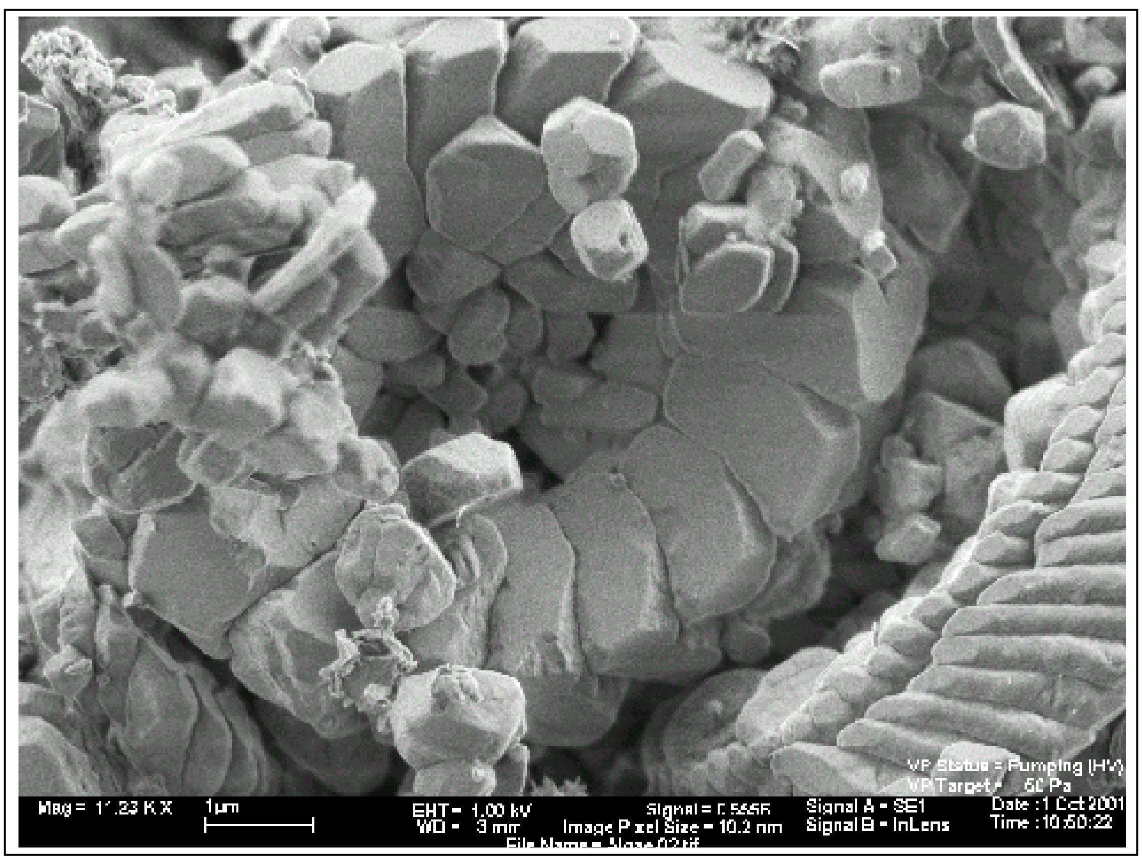

Figure 1.2. Scanned electron miscroscope image of the Lixhe outcrop chalk, which has properties similar to those of a typical North Sea chalk. Note the coccolith at the center of the image (Risnes et al., 2003).

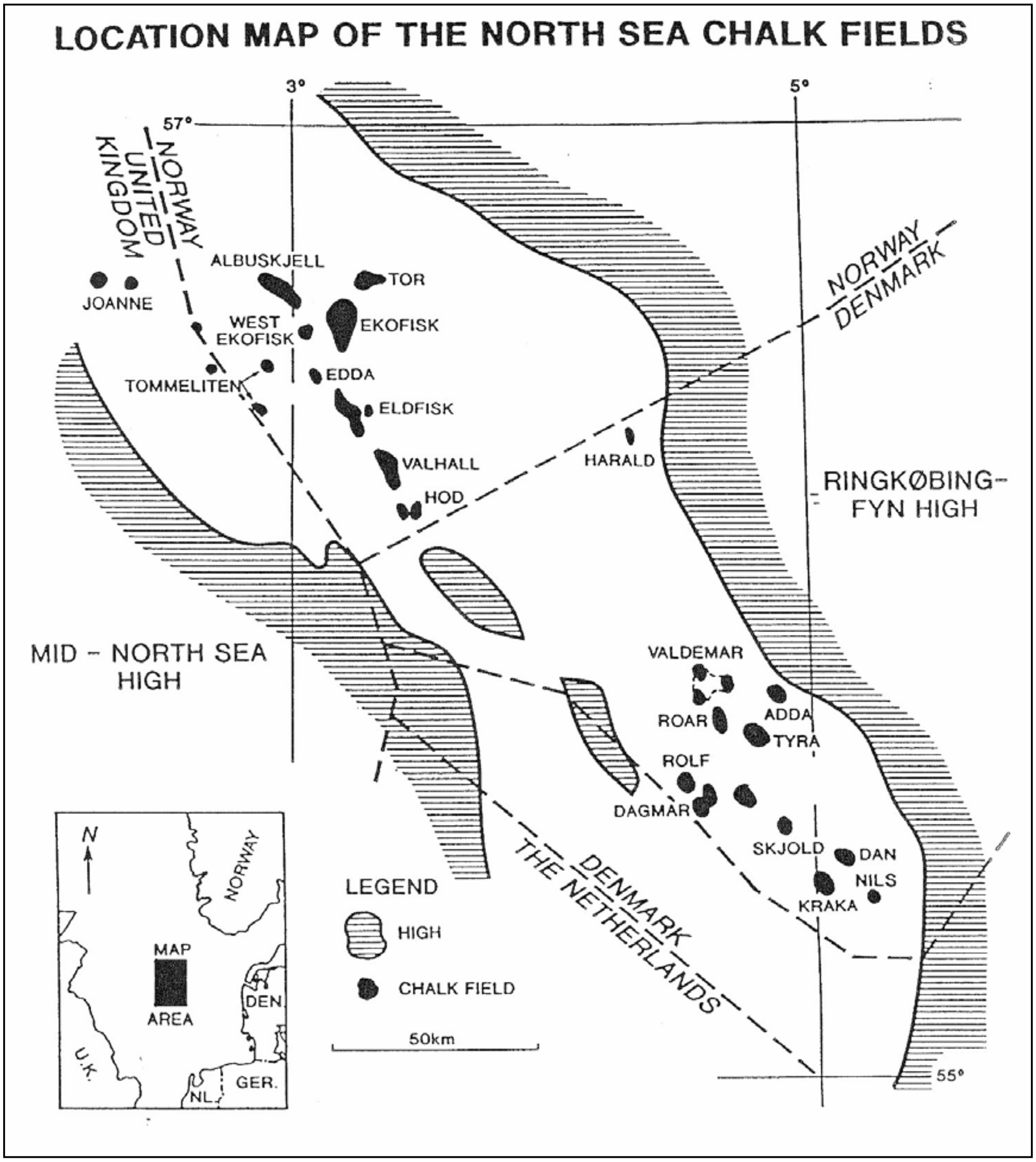

Figure 1.3. Location of petroleum reservoirs in the chalk fields of the southern North Sea (after Lind et al., 1992).

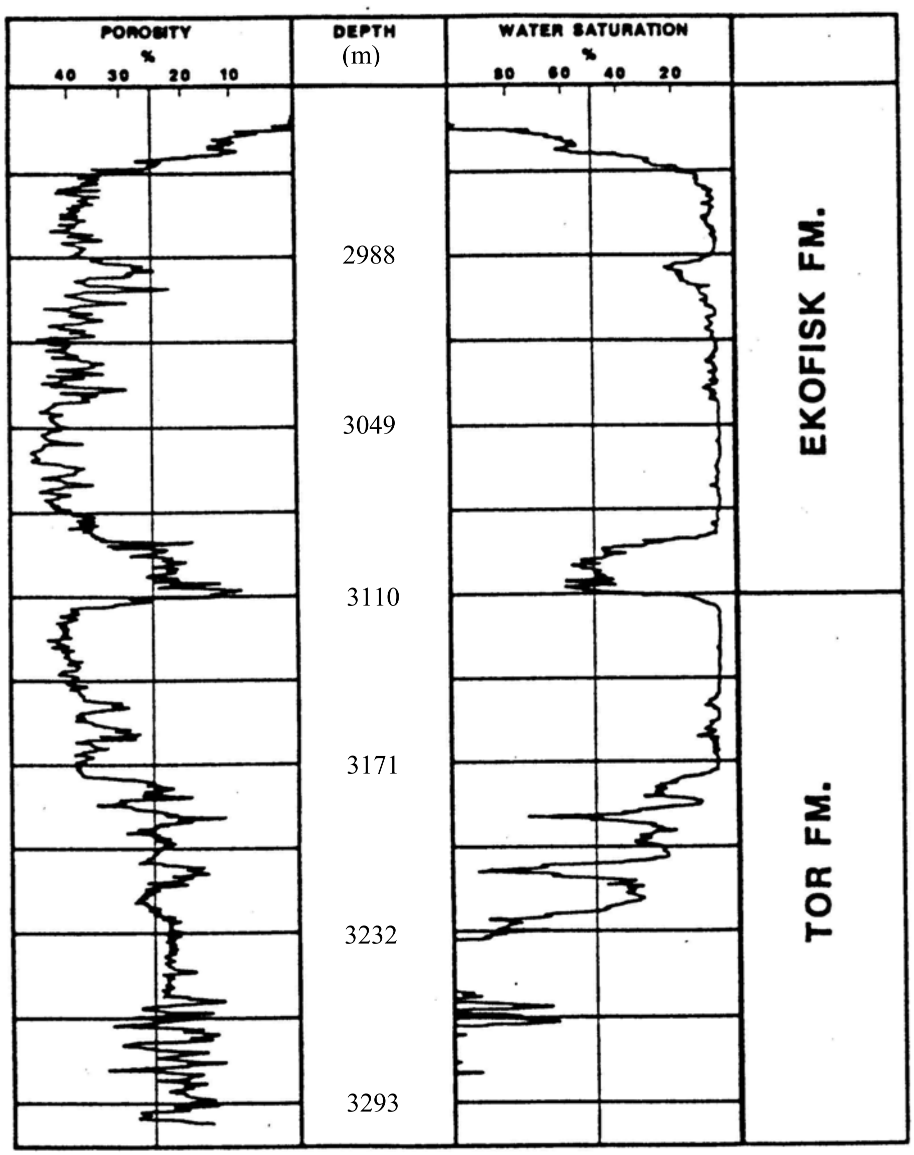

Figure 1.4. Porosity and water saturation log of the Ekofisk field. Note the high porosity of the Ekofisk and Tor Formations, and the less porous tight zone between (after Sulak and Danielsen, 1989).

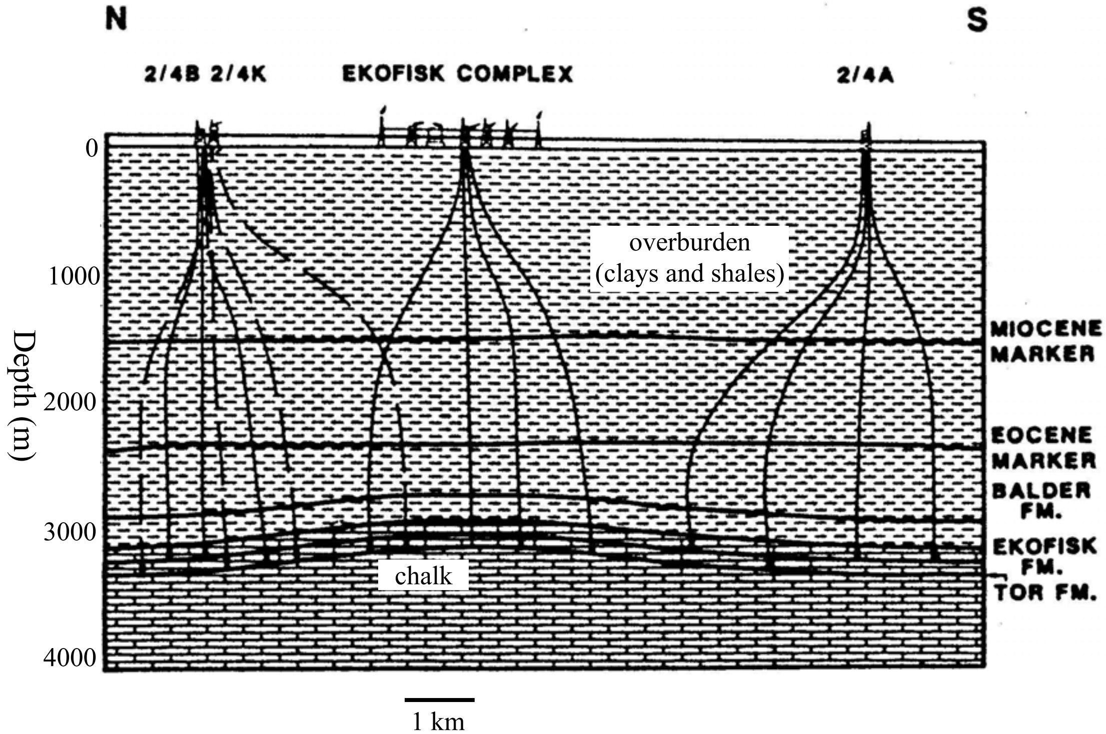

Figure 1.5. Stratigraphic cross-section of the Ekofisk field and overburden (after Sulak and Danielsen, 1989).