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REGIONAL CRUSTAL MOVEMENTS ON THE NORWEGIAN CONTINENTAL SHELF

ELOCS Report 1-3

by

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CONTENTS

The regional tectonics has changed quite markedly across the continental shelf within the post-Mesozoic period and in Fig. 2 the pattern of uplift and subsidence, as well as the associated tectonics, is illustrated for four periods: the Palaeocene, the Upper Eocene, the Oligocene-Miocene, and the Pliocene-Quaternary. Modern studies of tectonic provinces reveal regional consistency of tectonic behaviour, in particular with respect to the orientation of the principal horizontal compressive stress. Palaeostress orientations can be broadly inferred from the pattern of contemporary fault movements. The changing tectonic development of the region reveals a changing stress regime through the post-Mesozoic period. The tectonics and land level movements of these four periods are discussed below.

The Palaeocene

Immediately prior to the opening of the North Atlantic rift, the prevailing stress regime had a NE-SW oriented principal horizontal extensional stress, as revealed by the orientation of Hebridean dyke swarms in northern Britain. At the time of the Hebridean vulcanism Scotland and the Shetland platform became uplifted and marginal normal faulting developed both along the eastern margin of the Shetland-Faeroes basin and along the West Viking Graben Boundary Fault. A lesser amount of uplift occurred across Western Scandinavia at this same period (see Appendix 3), and was also probably associated with some marginal faulting. To the south of Norway strike slip and transpression along the Tornquist Zone and in the Central Graben may have continued from the Upper Cretaceous into the early Paleocene (see Appendices 1 and 2). Continued compression and north-easterly directed overthrusting was taking place in Spitsbergen at the western end of the Canadian Arctic Eurekan orogenic belt.

At the end of the Palaeocene the main North Atlantic rift developed as a line of subaerial volcanoes and NE-SW oriented dyke swarms, which contributed an enormous volume of eruptive products, as found in the Balder formation of the North Sea.

The Upper Eocene

In the Eocene the new oceanic crust began to subside beneath sea-level although elevated marginal islands remained along the edge of the ocean, comprising sections of continental crust permeated with basaltic intrusives and covered with lava flows - as at the Møre Platform and the Vøring Plateau (see Appendix 1). In the North Sea subsidence was concentrated along the Viking Graben and the centre of the Central Graben. At the end of the Eocene a major phase of northerly directed compression to the rear of the Pyreno-Provencal orogeny passed through Western Europe. Some component of this movement connected via transcurrent faults, with the North Atlantic spreading ridge. Extensional rifts also began to develop in the Alpine foreland, principally the main NNE-SSW oriented Rhine Graben. Continued extension and subsidence along this structure from the Upper Eocene through to the Lower Miocene provides an important constraint on the orientation of the regional stress field. Inversion of the Sole Pit trough continued (after a phase in the Upper Cretaceous) in the southwest North Sea and reflects a north-easterly directed compression (Appendix 2). Such compression also caused the minor inversion of some NE-SW and N-S structures in the Norwegian sector of the North Sea. Subsidence continued in the Møre and Vøring Basins at this period. Compressional tectonics ended in Spitsbergen and a transcurrent fault system had developed a short distance to the west of the islands - the northerly transform of the Norwegian Sea spreading ridge.

Oligocene-Miocene

From the Upper Eocene the spreading direction of the Norwegian Sea became rotated, after spreading had ceased in the Labrador Sea. For a period of about 15 million years the Jan Mayen block rotated anticlockwise with spreading ridges to both east and west. At this period of pronounced changes in relative plate motion, compressional tectonic features developed along much of the eastern edge of the Norwegian Sea, to the north of the Jan Mayen Fracture Zone, which remained as a dextral transcurrent fault all along its length. Large inversion structures (see Appendix 2) can be traced from the Molde High in the south to the Senja Ridge in the north, accommodating one or two kilometres of intraplate compressional strain. All these inversions are oriented approximately NNE-SSW suggesting WNW-ESE directed compression. In Spitsbergen however, at this same period, there was extensional tectonics with the formation of a deep rift along the western margin of the islands. This rift is oriented NNW-SSE. This extension, allied with the compression along the boundary further to the south, demonstrates the geometrical incompatibility between the amount of new crust being generated at the spreading ridge, and the actual vectors of relative plate movement.

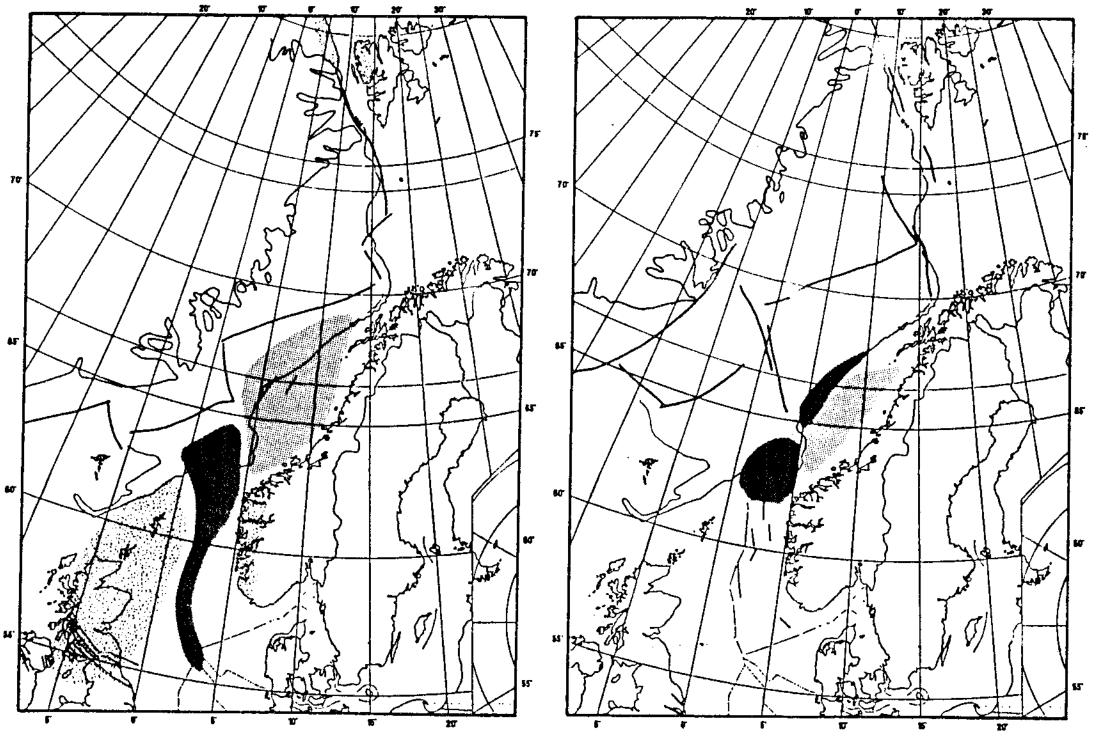
At this same period Western Scandinavia began to rise in a broad fold, controlled by density changes probably in the asthenosphere (see Appendix 3). This uplift carried with it the eastern margins of the major offshore sedimentary basins. The erosion of these basins contributed large quantities of sediments. In the Oligocene sedimentary depocentres in the North Sea reflect a complex pattern - the region lying in the midst of diverse tectonic environments with the uplift of Norway to the north-east and the continued inversion of the Sole Pit to the south-west. It is, as is pointed out in Appendix ~~2~~1, also the only period during the Tertiary where a rapid subsidence of the Witch Ground Graben occurs. The orientation of this graben suggests a local stress field with an E-W principal compressive stress. However, in the Miocene a NW-SE principal compressive stress is indicated by the beginnings of extension along NW-SE oriented faults in the lower Rhine Graben. The rapid subsidence in the Central Graben is probably mostly induced by sediment loading by the products of erosion from the rising Scandinavian mainland (see Appendix 1). The general trend of the subsiding graben does however not contradict a NW-SE principal compressive stress.

Along the mid Norwegian shelf inversion was coming to an end along the more northerly and southerly inversions, and as the uplift of mainland Norway continued across the present Barents Sea enormous quantities of easily eroded Tertiary and Mesozoic sediments poured across the by now subsiding Senja Ridge, the Senja Fracture Zone and down onto the Lofoten Basin.

Pliocene-Quaternary

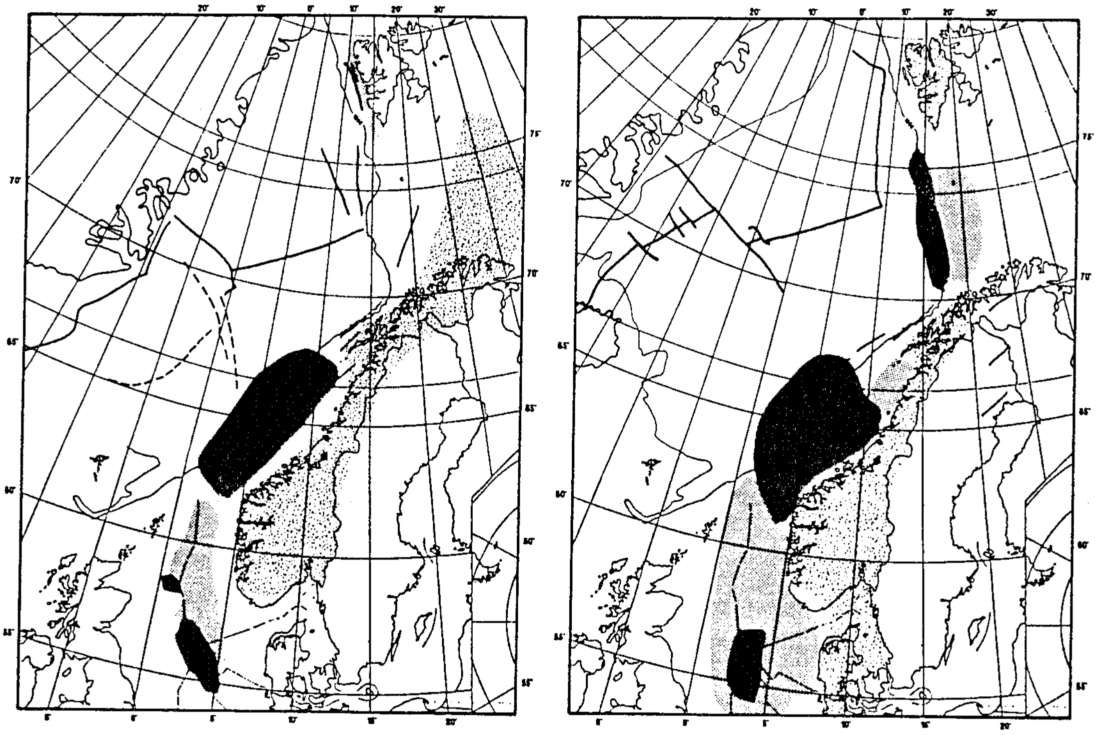
During the Pliocene-Quaternary rapid subsidence took place across much of the southern central North Sea interconnecting the Lower Rhine Graben and Central Grabens. Some evidence exists however, which relates this interconnection with the expansion of deltas from the Rhine river into the central North Sea, the subsidence being induced by sediment loading and compaction (Appendix I). The predominant stress field across alomost all of Europe had become NW-SE directed. To the north of the North Sea the Møre Basin and outer Plateau began to subside very rapidly - due to a combination of lithospheric cooling and subsidence from the adjacent now extinct Aegir ridge, and the original Møre Basin. Mimicking this behaviour is the subsidience of the Vøring Basin and Vøring Plateau which, although not as large as that of the Møre Basin, also spread to include the Trøndelag Platform and the Nordland ridge (Appendix 1). However, further to the north around the Lofoten margin, unlike the situation to both north and south, there was no subsidence on the margins of the continental shelf, and the northern end of the Molde High as well as presumably both the outer Lofoten inversion and Lofoten islands themselves, appear to be under continued compression and uplift (Appendix 2). Post-glacial reverse faulting of a similar orientation to these inversions is located across northern Sweden, Finland and Norwegian Lapland. The Barents Sea margin remained passive but not subsiding through this period, while Spitsbergen became uplifted, apparently as the result of the easterly migration of the Knipovich spreading ridge.

While the repeated glaciations and their corresponding impact on sediment stratigraphy and land- and sea-levels continue to obstruct the resolution of contemporary long term tectonic 'signal' from the ice-age 'noise', there remains some evidence that western Scandinavia continues to rise, as it has done since the Oligocene (Appendix 3). Intraplate tectonic deformation is to be found along several sections of the continental margin of a similar form to that which has persisted for much of the past 40 million years. Those locations which provide the borders between areas of uplift and subsidence (see Fig. 2), as well as those regions that are suffering internal strain, must remain as areas most prone to sudden fault movements and the generation of earthquakes.



Palaeocene

Upper Eocene



Oligocene - lower Miocene

Upper Miocene - Quaternary

░ Uplift ▒ Subsidence ■ Rapid Subsidence ___ Faults and dykes (Palaeocene)

Fig. 2 Regionalisation of the crustal movements on the Norwegian Continental Shelf

APPENDIX I

SUBSIDENCE ON THE NORWEGIAN CONTINENTAL SHELF

by

Carl Fredrik Forsberg

1. INTRODUCTION

The Norwegian Continental Shelf has been undergoing subsidence for extended periods during the past 60 million years (The Tertiary and Quaternary). The subsidence has however, varied from place to place and from one time period to another. The aim of this report is to review the subsidence history of the Continental Shelf and to evaluate this history with respect to the possibility of present subsidence-induced relative crustal movements.

While the main period of interest for this study is the past 60 million years special attention is given to the past 20 million years (the post Oligocene). Reference is also made to events prior to the Tertiary (the Mesozoic) to assist in complete understanding. The report first covers general information on the large scale tectonics of this period, subsidence quantification and subsidence mechanisms before reviewing the geological history of the shelf.

1.1 Large scale tectonics

Figure 1-1 shows the position of the Norway's continental shelf in relation to the two major plate boundaries in the area during the early Tertiary, i.e. the Alpine Orogeny and the rifting in the North Atlantic. The North Sea can be seen to be wedged inbetween these boundaries whereas the remainder of the Norwegian continental margin is in closer proximity to the North Atlantic rift.

The rifting of the early Atlantic ocean was the last phase of a long period of extensional tectonics which had produced the graben systems of the North Sea. The history of the North Atlantic (see Fig. 1-2) can be summarised as follows: During the Cretaceous rifting developed in the old continent consisting of Eurasia, Greenland and America. First Greenland separated from North America and subsequently, beginning in the Palaeocene, from Eurasia. By the early Eocene ocean crust began to develop along the line of the Norwegian Sea. The rifting was accompanied by intense vulcanism along most of the continental margin as the crust was thinned through extension and hot mantle material approached the surface.

A major change in the configuration of the North Atlantic occurred during the late Eocene through to the Oligocene when the spreading axis shifted west from the now extinct Aegir ridge to the Kolbeinsey ridge, close to Greenland. The spreading ridge in the Labrador Sea, between Greenland and Canada, also became extinct during this period. As a consequence of this change in configuration, the relative directions of movement between Eurasia and Greenland changed. No major changes have since occurred in the configuration of spreading in the North Atlantic, although there is some evidence that the Knipovitch ridge is moving eastwards (between Sptsbergen/Barents Sea and Greenland).

1.2 Subsidence quantification

In order to infer subsidence from geological data the original (presubsidence) morphology of any rock formation used as a reference must be known. If successive sedimentary layers were originally horizontal and close to sea level, then the isopach maps of the area reflect the relative regional subsidence. This requires that the sedimentation rate is equal to the subsidence rate, i.e. excess sediments are transported out of the region. If the sedimentation rate is lower than the subsidence rate a starved sedimentary basin results, and excessive subsidence may be mistakenly estimated for a later period when the basin again becomes filled. Eustatic sea level changes can also confuse a subsidence history as high sea levels increase the areal extent of potential sediment traps as well as providing a more elevated sedimentary baseline in alredy existing depocentres. Compaction of sediments due to the weight overlying deposits will also cause apparent subsidence in the absence of any sinking of basement.

1.3 Subsidence mechanisms

Subsidence of an area is generally a result of isostatic loading. This can result from

tectonic extension
lithospheric cooling
sediment accumulation

1.3.1 Tectonic extension and lithospheric cooling

A tectonic extension appears to be resultant of a thinning of the lithosphere according to the model of McKenzie (1978). The initial uprising of asthenosphere beneath the lithosphere and the thermal expansion of the lithosphere may or may not cause a period of initial uplift. This is followed by subsidence as the thinned lithosphere cools and deepens and therefore increase in density. The period of extension is usually relatively shortlived (less than 20 mill. years) and associated with intense faulting. The period of subsidence due to lithospheric cooling is longlived (approaching 200 mill. years). The North Sea subsidence has been successfully modelled using lithospheric cooling as the driving mechanism by several authors (e.g. Wood and Barton, 1983; Schlater and Christie, 1980; Jarvis, 1984). The purpose of these models, however, has not been to give a detailed picture of the tectonic development in the area but to provide a simple relationship between the extensional phase of basin development with the subsequent subsiding phase which can be used in predicting the maturity of hydrocarbons within the different basins. Long-term subsidence may become perturbed if a new tectonic event occurs within the basin. A renewed phase of lithospheric heating and extension will cause a new subsidenc curve to become overprinted. A phase of basin compression and inversion will cause crustal and lithospheric thickening and therefore suppress long-term subsidence.

The Norwegian Continental shelf has suffered two main periods of extension i.e. during the Carboniferous to Triassic (400 - 280 mill. years ago) and during the Jurassic to Early Cretaceous (200 - 100 mill. years ago).

The Carboniferous to Triassic extension is in many places obscured by thick sedimentary layers or salt diapirism and did not influence the Barents Sea and adjacent areas. This is only of minor significance to this study as the thermal effects of this early history have almost completely decayed.

The Jurassic to Early Cretaceous rifting (Kimmerian rifting) was cause of most of the present structures seen on the Norwegian shelf (Fig. 1-3) and the longterm subsidence which has persisted until the present. The subsidence was at first probably concentrated near the centres of rifting (Jarvis, 1984) and later spread as the thermal effects associated with the rifting affected the neighbouring areas. The thermal subsidence was therefore probably at first fault related with a subsequent gradual transition to crustal flexuring.

Vulcanism is often associated with extensional regimes due to the thinned lithosphere allowing the high temperature asthenospeheric mantle material closer to the surface. In some cases fractures due to tensional stresses may allow the extrusion of magmas as exemplified by the opening of the North Atlantic during the early Tertiary.