PERGAMON

Journal of Structural Geology 21 (1999) 1457–1475

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

Development of intraformational (Oligocene–Miocene) faults in the northern North Sea: influence of remote stresses and doming of Fennoscandia

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Received 7 January 1998; accepted 12 March 1999

Abstract

The post-rift Cretaceous sequence of the Horda Platform (eastern margin of the Viking Graben, northern North Sea) is overlain by Cenozoic silisiclastic sediments. Within the latter sequence (Hordaland Group; claystone and thinly layered sands), a system of intraformational faults with a strongly dominant NW–SE-trend are seen in a transgressive unit of late Oligocene age. Occasionally, the faults are associated with deeper pre-Tertiary structures, but generally there is no such connection. Still, this indicates that the Oligocene deformation involved reactivation of Mesozoic or even older faults. The base of the sequence is represented by an angular unconformity with a primary mean slope angle of 1.8° when the post-Oligocene tilting of the area is corrected for present. The faults have a dominant strike (NW–SE) deviating 45° with respect to the N–S-striking slope. The lowermost part of the late Oligocene sequence rests on an unstable unit where incipient clay pillows and diapirs are observed.

An evolutionary model including anomalously high fluid pressure, downslope gravity sliding, gravity collapse and regional tectonic stresses is suggested to account for the origin of the faulting observed. It is likely that a high fluid pressure, associated gravity collapse and downslope gravity sliding were critical for fault initiation. Still, the orientation homogeneity and parallelism of the fault system suggests that the deformation was influenced by a remote tectonic stress system related to ridge-push, doming of Fennoscandia and the differential subsidence of the North Sea.

This model contrasts to the deformation style seen further to the southwest in the North Sea, where complex fault geometries and cellular networks comprising polygonal prismatic and pyramidal forms are observed. The dominant deformation mechanism in these areas is believed to be failure due to an anomalously high fluid pressure, without the influence of remote tectonic stresses.

1. Introduction

Intraformational faults in late Cretaceous and Tertiary sediments are common in many places at the northwest European continental shelf. Rundberg (1989) regarded intraformational faulting in the northern North Sea in Oligocene sequences to have resulted from extensive deformation related to collapse and sliding of an unstable overpressured sequence, probably triggered by seismic activity along the Øygarden Fault Complex. Rundberg (1989) also observed shale diapirs in the Oligocene sequence. The two most important factors controlling the clay diapirism were thought to be the build-up of high fluid pressure and differential compaction, whereas Jordt (1996) related development of shale diapirs and associated faults in block 35/8 (situated north of the Troll Field) to rapid sedimentation of Miocene sand derived from the Shetland Platform. Gregersen et al. (1998) ascribed clay diapirs in upper Oligocene sequences in the northern North Sea to overpressure and density inversion, where some diapirism is interpreted to have occurred

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0191-8141/99/$ - see front matter
PII: S0191-8141(99)00083-8

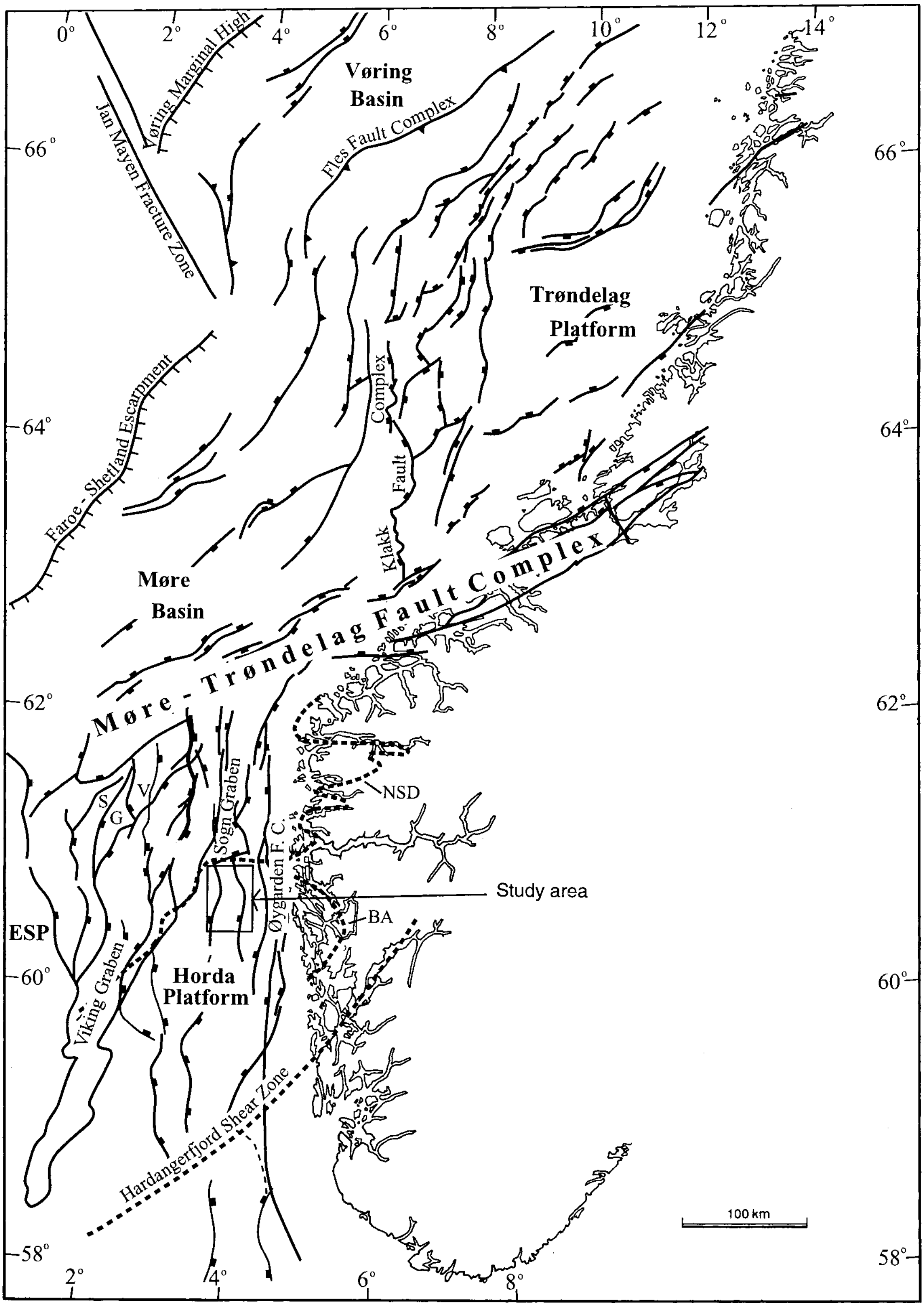

Fig. 1. Study area. The Troll Field (study area) is situated on the Horda Platform at the eastern margin of the Viking Graben, northern North Sea. NSD = Nordfjord–Sogn-Detachment, BA = Bergen area, ESP = East Shetland Platform, S = Statfjord Fault-block, G = Gullfaks Fault-block and V = Visund Fault-block. After Gabrielsen et al. (1999).

during the deposition of local major sand bodies of the Utsira Formation. Faults within late Cretaceous rocks in the Barents Sea region have been connected with regional uplift during the late Cretaceous–Cenozoic. It has been proposed (Lippard and Fanavoll, 1992; Lippard, personal communication, 1997) that fluid overpressure and gravity sliding contributed to the initiation of these faults.

Intraformational faults in Oligocene mudstone-dominated sediments in the Moray Firth area were described by Higgs and McClay (1993), who supported their study by the use of analogue experiments. They argued that the faults resulted from downslope gravity sliding, triggered by tilting in the middle Miocene. Clausen and Korstgård (1993) analysed faults in Tertiary mudstone units in the northern Danish Central Trough. Developments of these faults have been connected with differential subsidence along older fault trends. Also, Tertiary extensional intra-deformational fault systems on the western margin of the North Sea Basin have been described by Stewart (1996), who argued that fault development was controlled by several factors, including thermal subsidence, gravity instability generated by inversion tectonics, and by active basement faults (see also Galloway et al., 1993). Henriet et al. (1991) described small-scale intra-deformational extensional faults from the Eocene of Belgium, both from outcrop studies and from offshore data. Finally, Cartwright (1994a, b), Cartwright and Lonergan (1996) and Lonergan et al. (1998a, b) analysed faults in Palaeocene–Miocene mudstone-dominated sequences in the central and southern North Sea basin from high-resolution seismic data. These authors concluded that the faults formed in response to repeated events of overpressure build-up with associated density inversions between overpressured units and overlying seal. Cartwright and Lonergan (1996) suggested that volumetric contraction during the compaction of the mudstones also contributed to the faulting.

In the Troll West area of the northern North Sea (block 31) (Fig. 1) faults of this type are particularly common in the Oligocene sequence. Because intraformational faults in this unit occur above the Troll Field reservoir, which is the second largest gas field discovered offshore from Europe (Bolle, 1990), a very good reflection seismic data base exists. The aims of this paper are to describe the general characteristics of intraformational faults in the late Oligocene sequence in the Troll West area and to evaluate the potential influence from fluid pressure build-up. The study is supported by one-dimensional forward t, p (time, pressure) modelling. Based on the various structural and stratigraphic observations and the modelling results, different deformation mechanisms for the evolution of the faults and other implications for fault development are discussed. The paper concludes with an evolutionary model suggesting that anomalously high fluid pressure, downslope gravity sliding, gravity collapse and regional tectonic stresses all contributed to the faulting. It seems that reactivation of some Mesozoic master faults and influence of lithology/mineralogy and differential compaction related to thickness variations may also have influenced the deformation of the late Oligocene sequence.

2. Geological framework

The giant Troll oil and gas field (Block 31 in the Norwegian sector of the northern North Sea) is situated about 80 km northwest of Bergen, on the Horda Platform of the eastern margin of the Viking Graben (Fig. 1). The most prominent structural elements within this area are N–S-, NW–SE- and NNW–SSE-striking faults (Rønnevik and Johansen, 1984; Birtles, 1986; Hellem et al., 1986; Gabrielsen and Koestler, 1987; Gray, 1987; Badley et al., 1988; Bolle, 1990; Gabrielsen et al., 1990; Horstad and Larter, 1997). The structural evolution of the northern North Sea is generally considered to have been a multistage process, including prominent Permo-Triassic and Jurassic active stretching phases each followed by concomitant thermal cooling and subsidence (Gabrielsen et al., 1990; Færseth et al., 1995; Færseth, 1996).

In general, the Cretaceous–early Cenozoic evolution of the North Sea Basin was characterised by thermal subsidence and sediment loading, accompanied by uplift of Fennoscandia and the Shetland Platform, as well as by regional subsidence and infill from the uplifted areas to the west and east (Rundberg, 1989; Gabrielsen et al., 1990; Rohrman, 1995; Jordt, 1996). It is assumed that tectonic movements in northwest Europe may have overprinted the effect of global sea-level changes (Cloetingh et al., 1985; Cloetingh, 1986; Cloetingh and Kooi, 1989). Still, the base of the transgressive late Oligocene sequence (i.e. the intra-Oligocene unconformity) probably corresponds to the mid Oligocene global sea-level fall, which was accompanied by uplift of the Fennoscandian Shield. The top of the Oligocene sequence is an erosional unconformity caused by subaerial exposure of the area in Miocene time (e.g. Berg et al., 1993). The sequence represents the upper part of the Hordaland Group, and the sediments consist of light-grey to light-brown silty claystones interbedded with local sands in the eastern part of the study area (Berg et al., 1993). Rundberg (1989) and Jordt (1996) state that smectitic clays are dominant, and according to Rundberg (1989) the smectite content is 50–80%, whereas the remaining part consists of illite, kaolinite and chlorite. The con-

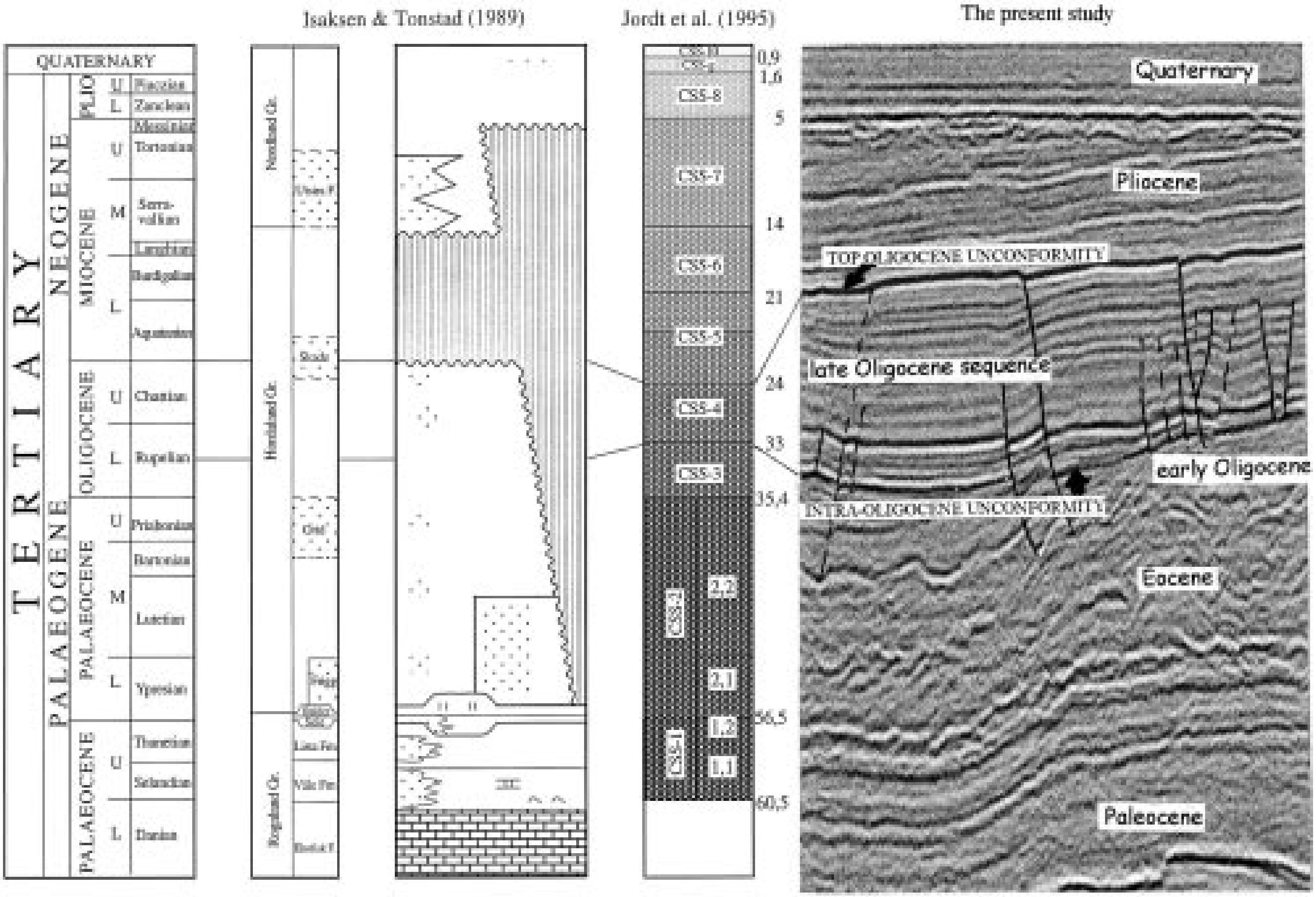

Fig. 2. Stratigraphic position of the late Oligocene sequence, correlated to unit CSS-4 defined by Jordt et al. (1995) and to the lithostratigraphy in the northern North Sea according to Isaksen and Tonstad (1989).

tent of organic carbon is high (4–6%) and the water content is of the order of 30% (Sejrup et al., 1995).

The stratigraphic nomenclature used in the present work is in accordance with Deegan and Schull (1977) and Isaksen and Tonstad (1989). Except for the Palaeocene, a standard lithostratigraphic subdivision is poorly developed for the Cenozoic. Still, Rundberg (1989), Galloway et al. (1993), Jordt et al. (1995), Veeken (1997), Gregersen (1998) and Gregersen et al. (1998) have subdivided the Cenozoic into different units based on seismic stratigraphy. For the present correlation to reflection seismic data, the subdivision of Jordt et al. (1995) has been preferred. The tie between the lithostratigraphic units and the reflection seismic data are illustrated in Fig. 2.

3. Data and methods used in the three-dimensional seismic interpretation

The intraformational faults of the late Oligocene sequence in the Troll West area are too closely spaced for two-dimensional seismic data to be useful in the mapping, since line spacing in these data is greater than the average length of the faults, making correlation of the faults impossible. Hence, a three-dimensional set (survey NH9101 provided by Norsk Hydro ASA) has been utilised to obtain the necessary geometrical and kinematic data. Using this dataset, manual horizon interpretation on a line-by-line basis, where the line spacing is 18.75 m, was performed using a Charisma workstation. The data quality is excellent, and seismic resolution is such that dip-slip offset resolution across faults is approximately 10 m.

Seismic attribute maps and time (horizontal) slice images were applied in map-plane fault correlation. Structural maps outlined by this method gave the same image of the fault pattern as that obtained by line-by-line interpretation. Finally, depth-conversion of maps and seismic cross-sections based on interval velocities derived from well velocities (wells—located in the Troll Field: 31/2-1, 31/2-2, 31/2-3, 31/2-4, 31/2-6, 31/2-10, 31/2-12, 31/2-15, 31/2-18, 31/3-1, 31/3-2, 31/5-2, 31/5-3, 31/5-5) and calibration to seismic velocities was performed.

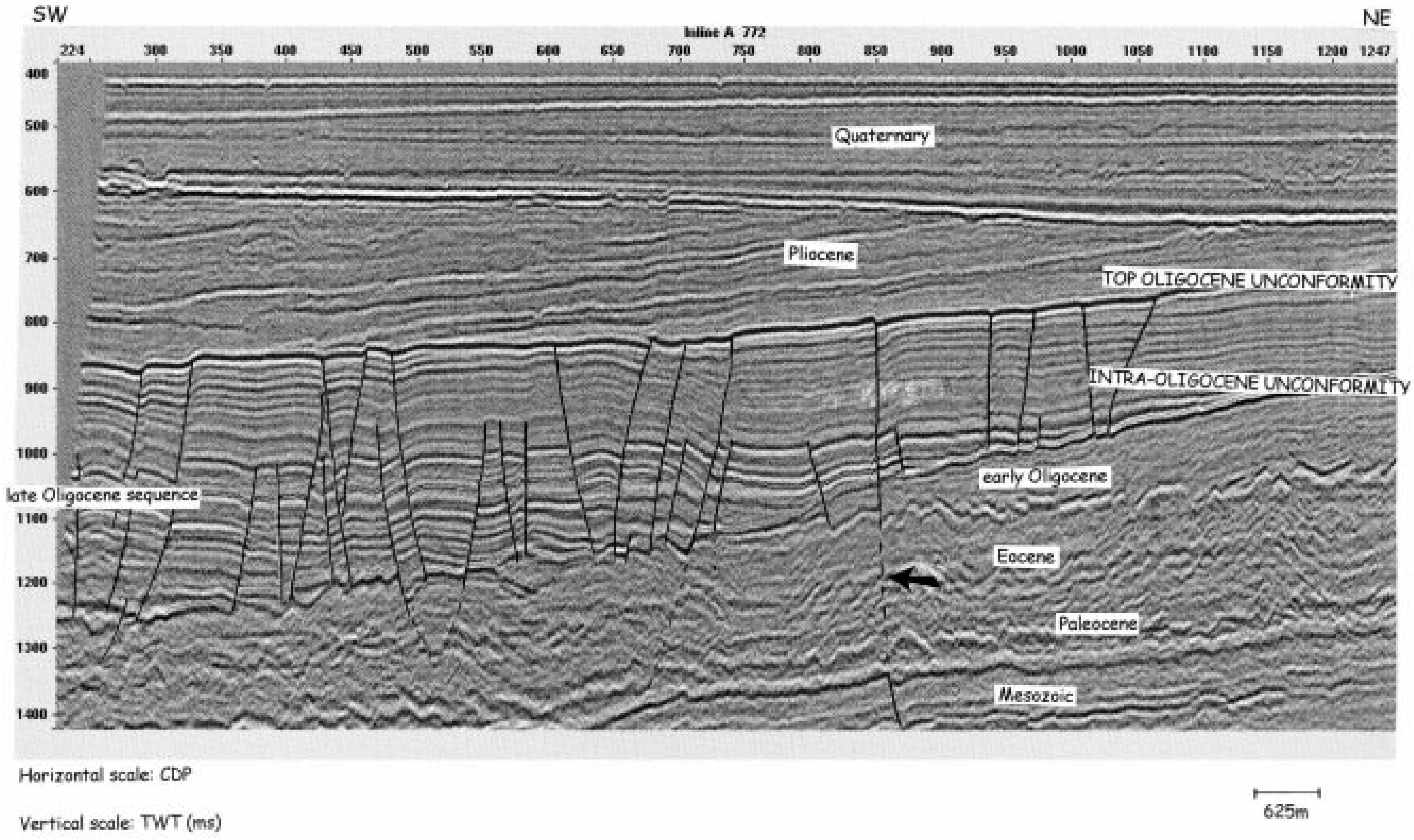

Fig. 3. The fault population of the late Oligocene sequence is entirely dominated by intraformational faults, where the faults are all extensional. In some exceptional cases, fault planes can be traced as continuous structures through the underlying early Oligocene sequence and further down to the Mesozoic where they link up with the large extensional fault sets which compartmentalise the Horda Platform. See Fig. 5 for approximate location.

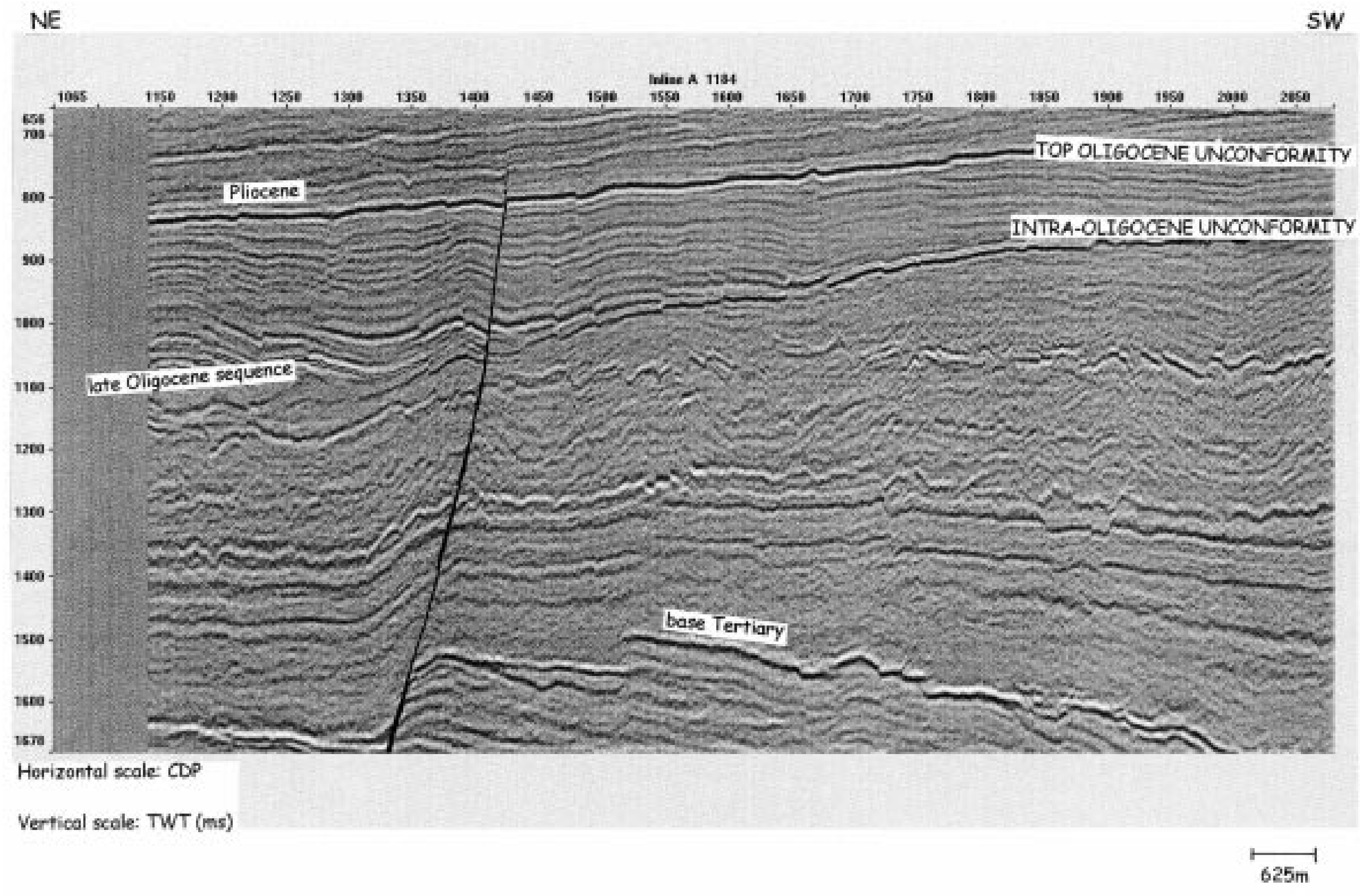

Fig. 4. Reactivations of Mesozoic faults have mainly taken place before the establishment of the intra-Oligocene unconformity (base of the sequence). However, some of these faults were active in Pliocene time. See Fig. 5 for approximate location.

4. Three-dimensional seismic interpretation of faults in the late Oligocene sequence

The base of the Oligocene sequence in the study area is represented by an angular intra-Oligocene unconformity, which presently has a westerly mean slope angle of 4.8° (measured in depth-converted cross-sections). When the post-Oligocene rotation of the Horda Platform is subtracted, as determined by Horstad and Larter (1997) and Fossen et al. (1997), a primary westerly mean slope angle of 1.8° is obtained. The upper sequence boundary also representing an angular unconformity, is characterised by a reduced fault density as compared to the intra-Oligocene unconformity.

The late Oligocene unit is characterised by an anomalously low interval velocity (~1850 m/s) and a calculated log porosity of up to 40%. The late Oligocene sequence has a thickness from 0 m in the eastern part of the study area to approximately 475 m in the western part of the study area. Presently the sequence has a burial depth of approximately 500 mBSL (metres below sea level) in the eastern part of the study area and down to about 1150 mBSL in the western part. A late Oligocene age of this sequence is supported from strontium-isotope data, giving an age of 30.5 Ma (Rundberg, 1989) and is also confirmed by biostratigraphic investigations (Sejrup et al., 1995). The late Oligocene sequence laps on to the intra-Oligocene unconformity in the east, gradually increasing in thickness westwards to 475 m in the Troll West area. Within the transgressive sequence it is possible to differentiate a set of system tracts onlapping the intra-Oligocene unconformity. The overlying sequence is dated to Pliocene and the underlying sequences, which are truncated by the intra-Oligocene unconformity, are of early Oligocene, Eocene and Paleocene ages (Figs. 2 and 3).

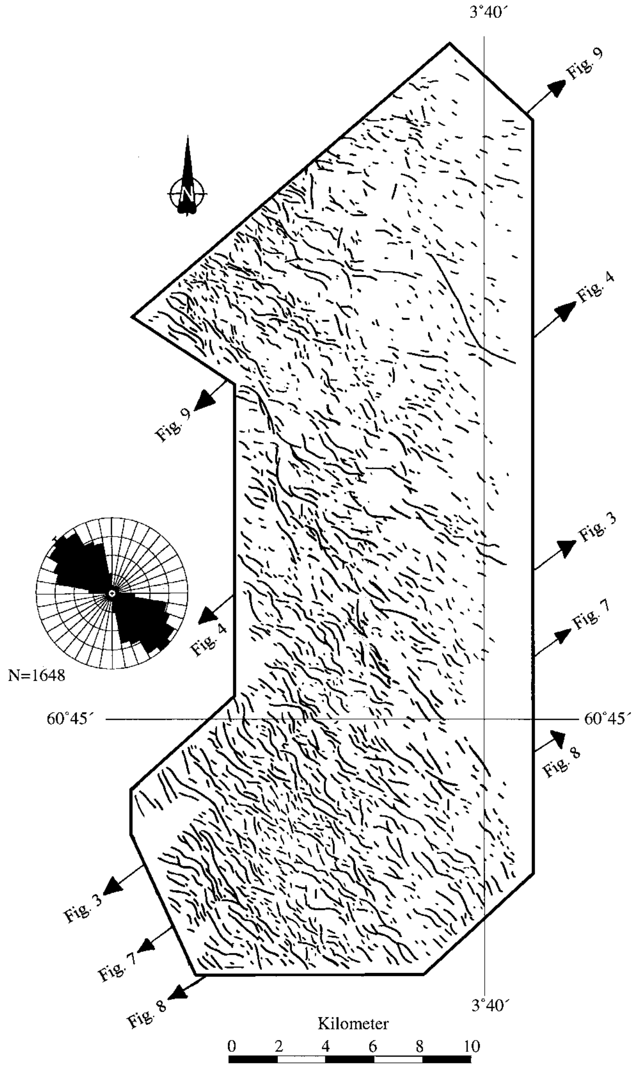

Fig. 5. Fault map at the intra-Oligocene unconformity (i.e. the base of the sequence). The dominant fault trend is NW–SE with additional, subordinate fault populations striking NNW–SSE, WNW–ESE and N–S. The faults have linear to curvilinear traces. Some faults can be followed as continuous structures, where others are strongly splayed or form arrays of isolated fault branches.

4.1. Fault geometry, orientation and distribution

The fault population of the late Oligocene sequence is dominated by intraformational faults, all of which are extensional (Fig. 3). However, in some places, the faults are seen to transect the Eocene sequence, and in some exceptional cases, fault planes can be traced as continuous structures through the underlying early Oligocene sequence, and further down to the Mesozoic units. Here, they link up with the large extensional fault set which compartmentalise the Horda Platform. This indicates that the Oligocene deformation also involved a mild reactivation of Mesozoic or even older faults. It is also evident from the reflection seismic data that some of these master faults were active in Pliocene time (Fig. 4).

The dominant fault trend is NW–SE with three additional subordinate fault populations striking NNW–SSE, WNW–ESE and N–S (Fig. 5). In map view the faults have linear to curvilinear traces. Some fault segments can be followed as continuous features along strike for up to 4–5 km, whereas others are strongly bifurcated, or form arrays of isolated fault branches. It is particularly noted that the faults have a dominant strike deviating 45° from the present N–S-striking slope, and that the NNW–SSE- to WNW–ESE-striking fault swarms are all parallel to the dominant fault trends of the Paleozoic–Mesozoic units (Fig. 6).

The bulk of the faults in the late Oligocene sequence are planar (Fig. 3), although some faults display gentle listric geometry at depth (Fig. 7). The true present dips of the faults range from 48° to 85° with a mean dip

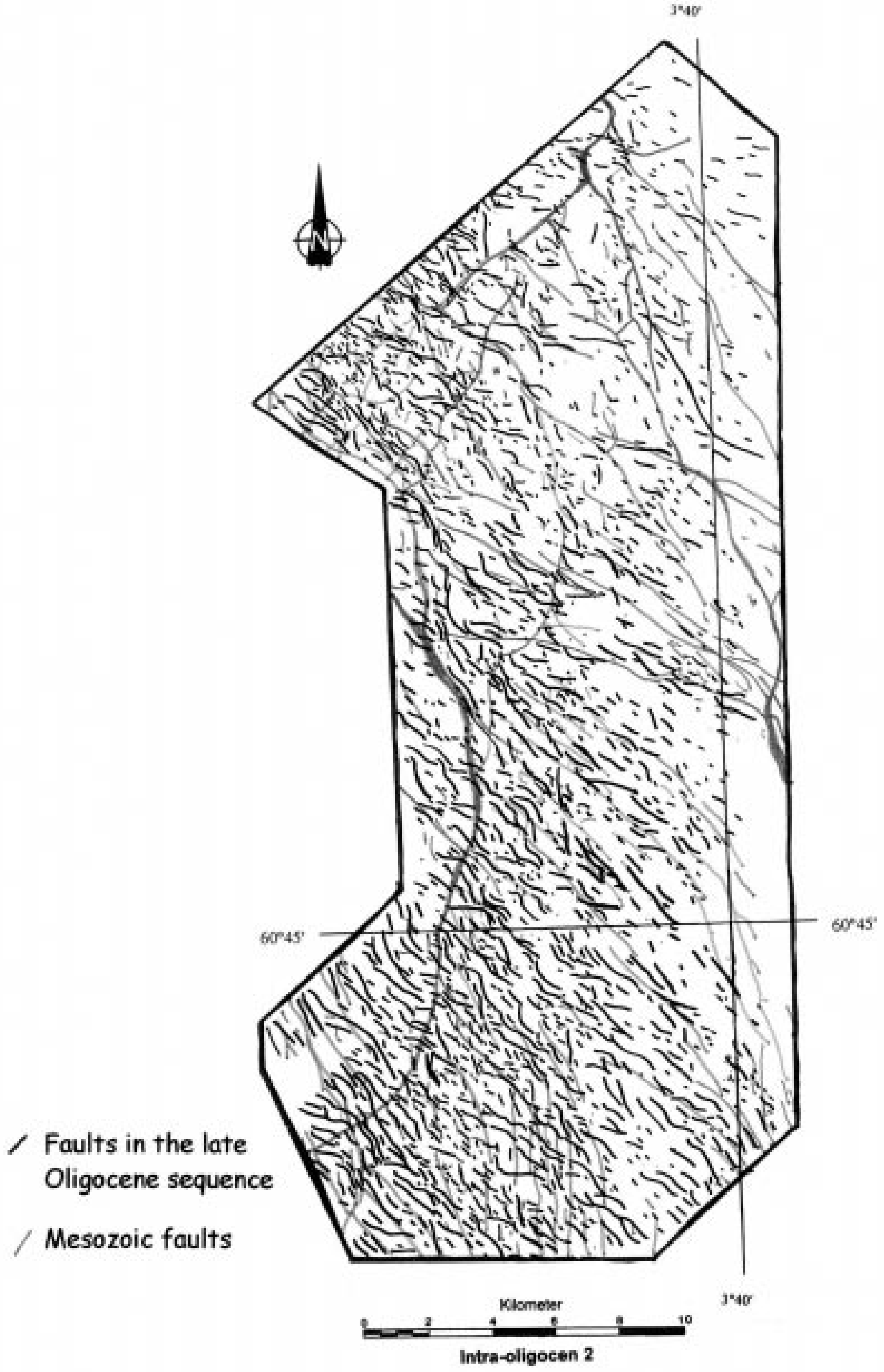

Fig. 6. The NNW–SSE- to WNW–ESE-striking fault swarms are all parallel to the dominant fault trends of the Paleozoic–Mesozoic.

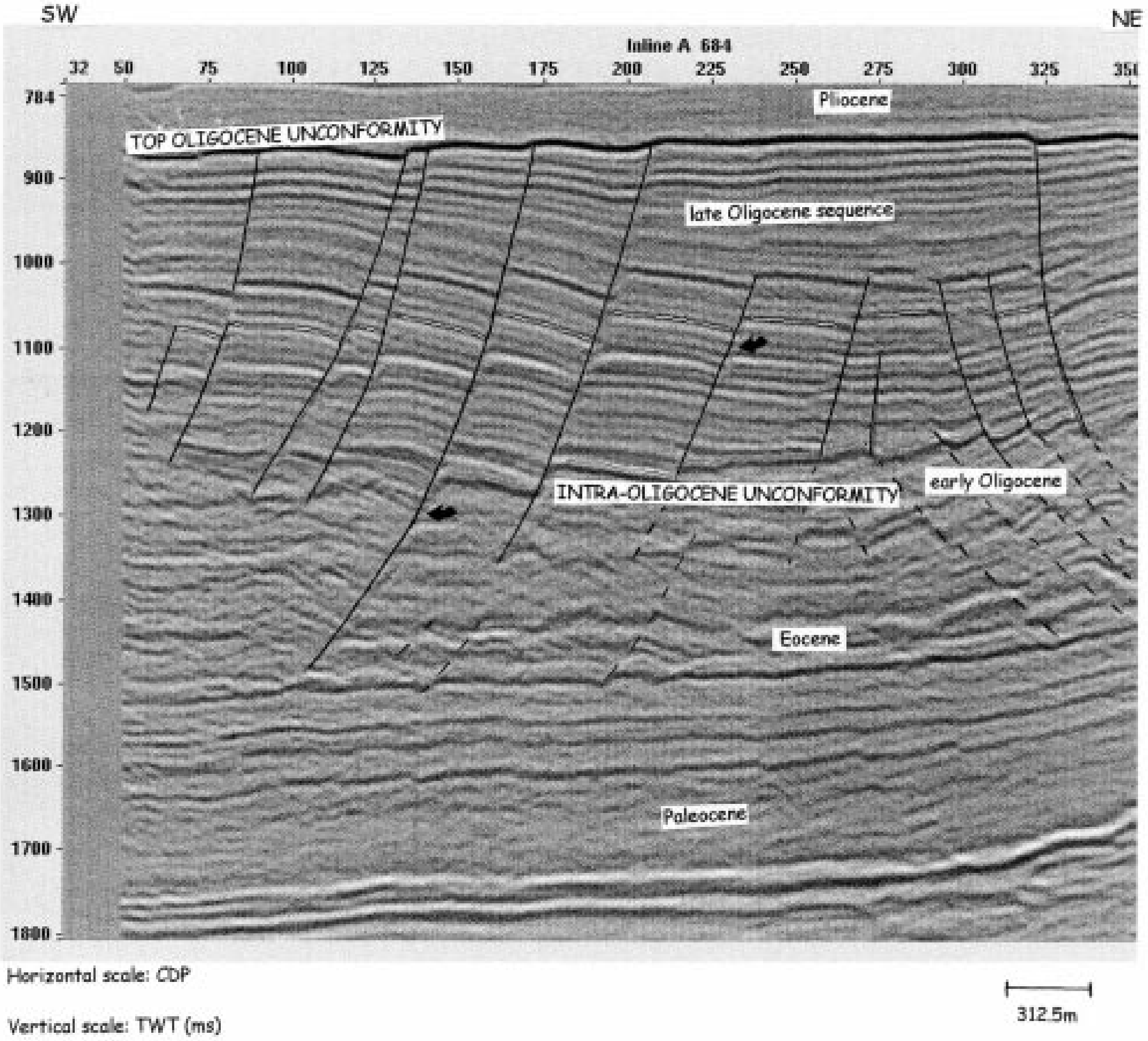

Fig. 7. Some faults display gentle listric geometry at depth, this particularly applies to fault planes that can be traced as continuous structures into the underlying early Oligocene sequence. See Fig. 5 for approximate location.

angle of 73° ($n = 1684$). Dip-slip displacements range from 10 to 75 m, as measured on depth-converted sections. Most of the faults (~61%) dip towards the soutwest, and hence are facing down-slope. Fault density is generally high (average fault spacing of 450 m), with the highest fault density found in the western part of the study area where the sequence is thickest, and in the lowermost part of the sequence (Fig. 8). The lowermost part of the late Oligocene sequence rests on a unit that has a particularly transparent and partly chaotic signature in the reflection seismic data, suggesting instability. Structures that have been interpreted as incipient clay pillows and diapirs have been identified within this unit (Fig. 9). Extensional faults dipping toward the W, SW, E and NE are associated with these features. Dip-slip displacement on these faults is very small. Detailed displacement analysis suggests that the faults were nucleated at the top of the diapirs, growing up-section.

Dating the exact timing for fault activity is restricted to observations in the reflection seismic sections and to results from the one-dimensional forward modelling (see Section 5). The top Oligocene unconformity is affected by the faults, proving that fault activity lasted beyond the latest Oligocene (Fig. 3). Furthermore, synsedimentary movement along the faults does not seem to have occurred, because geometries that are typical for growth faults have not been observed. This indi-

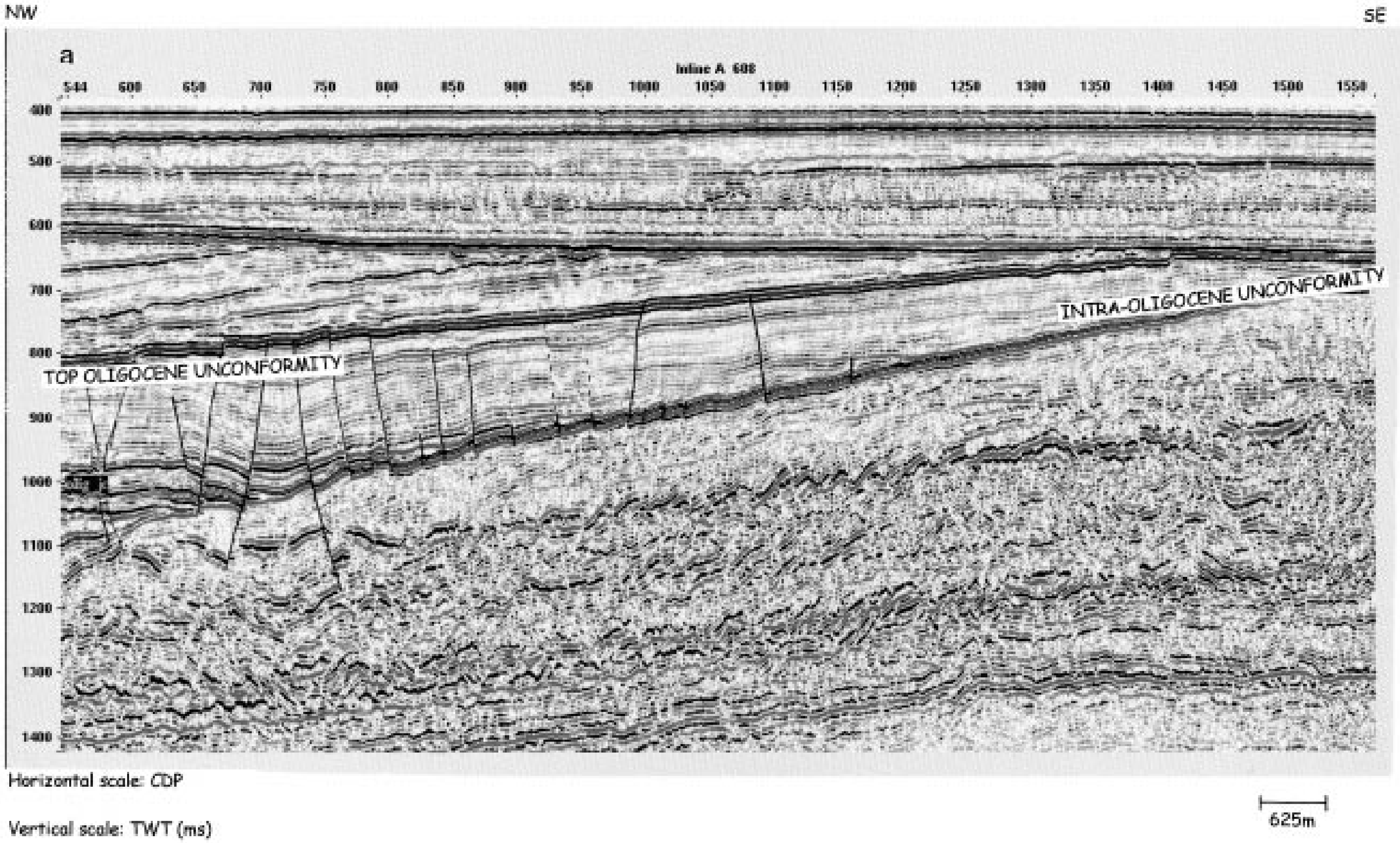

Fig. 8. Fault density is higher in the western part of the study area where the late Oligocene sequence is thickest, than in the eastern part of the study area. (a) The western part of line 608; (b) the eastern part of the same section. See Fig. 5 for approximate location.

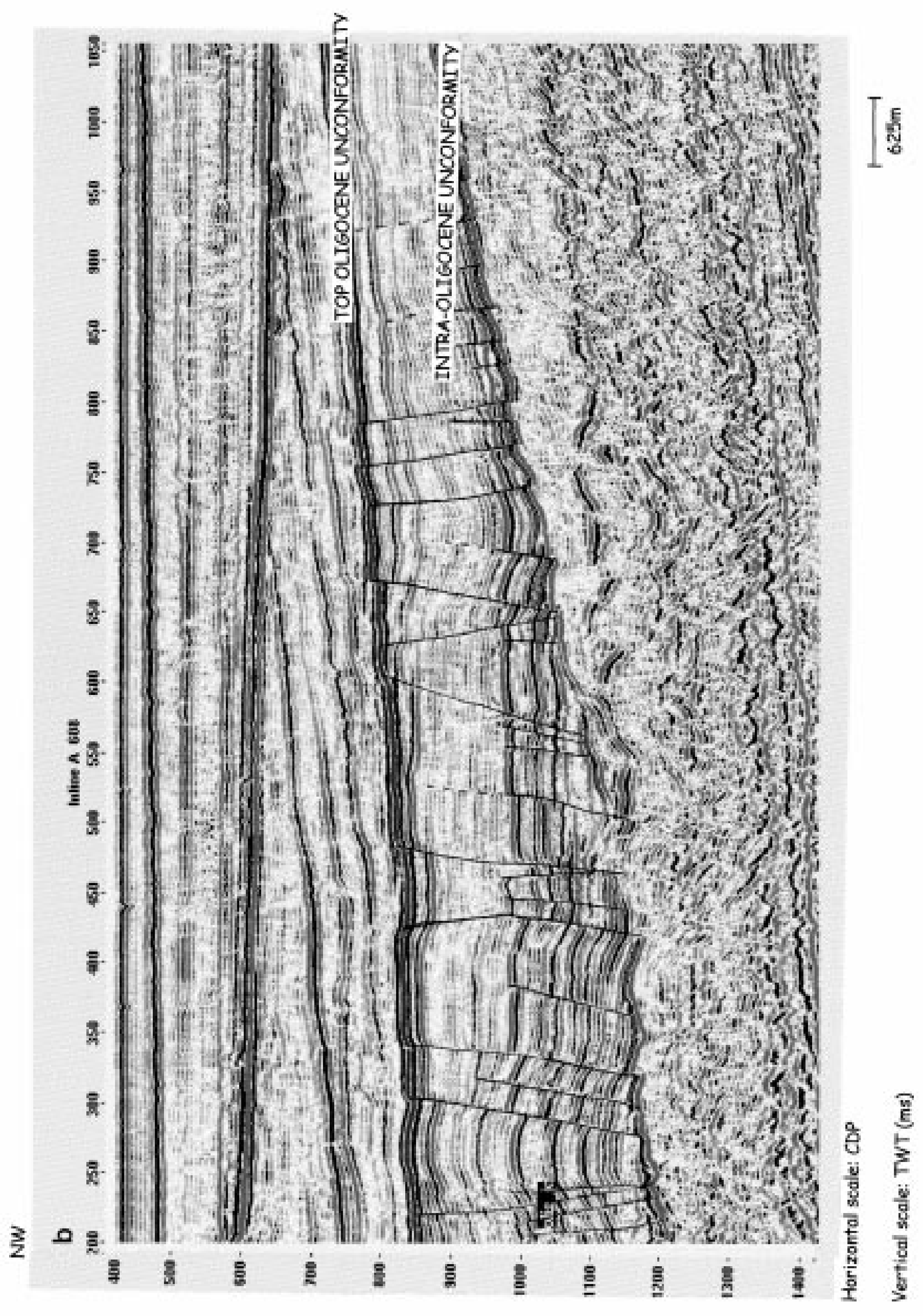

Fig. 8. (*continued*).

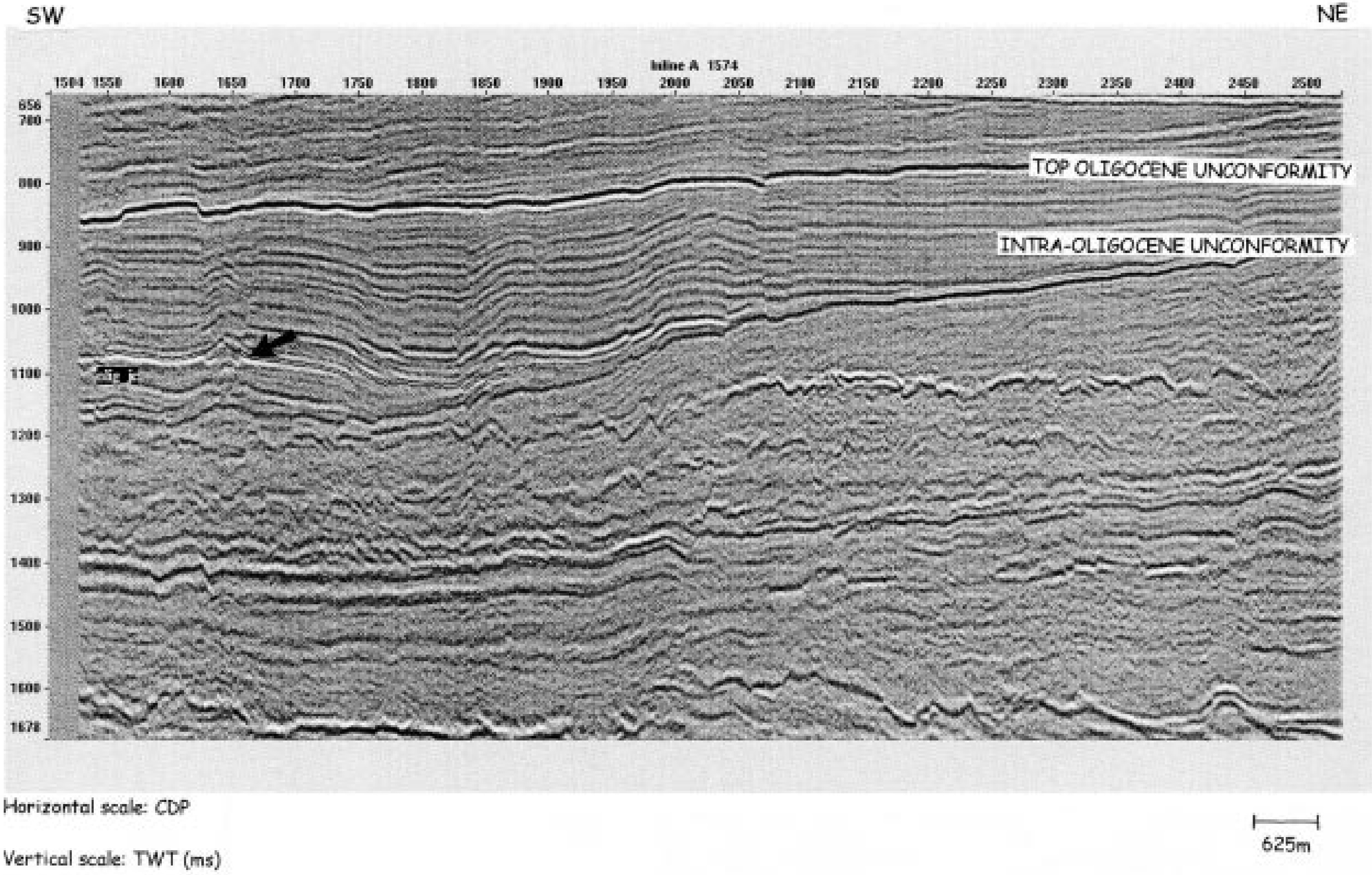

Fig. 9. The late Oligocene sequence rests on a unit that is considered to be unstable. Structures interpreted as incipient clay pillows and diapirs have been identified within this unit, and are here indicated by arrows. See Fig. 5 for approximate location.

cates that bulk deformation was restricted to the Miocene, since the base Pliocene reflection generally is not affected by the faults. There are some exceptions to this, but post-earliest-Pliocene reactivation is restricted to faults that obviously are connected to deeper structures (see above; Fig. 4). Hence, it can be concluded that faulting took place after establishment of the top Oligocene unconformity, but prior to deposition of the Pliocene sequence. This gives a time interval of ca. 17 Ma for faulting to have occurred.

4.2. Extensional strain of the late Oligocene sequence

The strongly dominant NW–SE-trend of the faults in the study area (Fig. 5) indicates a SW–NE extension. To assess a minimum value for the extensional strain, the horizontal fault separation was measured in profiles oriented transverse to the strike direction, and the finite bed length extension was calculated [$e = (L_1 - L_0)/L_0$, where L_1 is bed length after extension and L_0 is bed length before extension]. The normalised horizontal separation is rather constant within the study area, and the total extension was estimated to ~2.5%. It is realised that this is a minimum figure, since a ductile component is common in deformation of poorly consolidated sediments (Ziegler, 1983; Fossen and Gabrielsen, 1996) and because subseismic faults (e.g. Childs et al., 1990) are assumed to be present.

5. Fault initiation

Intraformational faults are commonly observed in fine-grained sediments that are characterised by high fluid pressure and small to intermediate depths of burial (Rundberg, 1989; Henriet et al., 1991; Lippard and Fanavoll, 1992; Clausen and Korstgård, 1993; Higgs and McClay, 1993; Cartwright, 1994a, b; Collinson, 1994; Maltman, 1994; Cartwright and Lonergan, 1996; Jordt, 1996; Stewart, 1996; Gregersen et al., 1998; Lonergan et al., 1998a). Such faults may be genetically related to several deformational conditions, as gravity sliding triggered by seismic activity (Rundberg, 1989), differential subsidence along older fault trends (Clausen and Korstgård, 1993), downslope gravity sliding related to uplift and tilting (Lippard and Fanavoll, 1992; Higgs and McClay, 1993) and fluid overpressure and associated density inversion (Henriet et al., 1991; Cartwright, 1994a, b; Cartwright and Lonergan, 1996; Gregersen et al., 1998; Lonergan et al., 1998a). Different geometries have been reported for intraformational faults in soft rocks, varying from complex arrays of small extensional faults organised into cellular networks of polygonal prismatic and pyramidal forms (Cartwright, 1994a, b; Cartwright and Lonergan, 1996; Lonergan et al., 1998a, b) to extensional fault swarms with prevailing trends (Lippard and Fanavoll, 1992; Higgs and McClay, 1993). It is reasonable to assume that these geometrical differences reflect contrasting genesis.

Cartwright (1994a, b) concluded that the faults in Palaeocene–Miocene mudstones of the central and southern North Sea, which form cellular networks, had been initiated in response to repeated events of fluid overpressure build-up with associated density inversions, and eventually supported by volumetric contraction during the compaction of the mudstones (Cartwright and Lonergan, 1996). Higgs and McClay (1993) argued that faults with a preferred down-slope dip in Oligocene mudstones in the Moray Firth area resulted from gravity sliding triggered by tilting in the middle Miocene. Fault development in late Cretaceous mudstones in the Barents Sea has been related to regional uplift followed by gravity sliding during late Cretaceous–Cenozoic, where overpressure contributed to the initiation of the faults (Lippard and Fanavoll, 1992; Lippard, personal communication, 1997).

The fault systems in the late Oligocene sequence of the Horda Platform as reported here, are characterised by a strongly dominant NW–SE-trend. Faults mainly occur as extensional intraformational structures and commonly terminate in the lowermost seismically transparent part of the formation. In some exceptional cases, however, fault traces can be followed as continuous structures through the underlying early Oligocene sequence and further down to the Mesozoic, where they link up with the large extensional faults which compartmentalise the Horda Platform.

Fault density is generally very high, particularly in the western part of the study area, where the sequence is thickest. Depth-conversion and correction for post-depositional regional structural rotation (extracted from Fossen et al., 1997; Horstad and Larter, 1997), demonstrate that the base of the sequence (i.e. the intra-Oligocene unconformity) had a mean depositional slope angle of 1.8° toward the west during deposition. Furthermore, fault analysis shows that 61% of the faults dip toward the southwest, hence facing down-slope. It is particularly noted that the seismically transparent layer in which the faults terminate down-section, is characterised by incipient mud pillows and diapirs.

In comparison with the polygonal fault system reported by Cartwright (1994a, b) and Cartwright and Lonergan (1996), the faults in the Oligocene of the Troll Field differ particularly in that faults have a strongly dominant (NW–SE) trend. Polygonal prismatic and pyramidal geometries, which are believed to be characteristic of repeated pressure build-up and density inversions and in situations where $\sigma_{\text{hmin}} \sim \sigma_{\text{Hmax}}$ (Henriet et al., 1991; Cartwright, 1994a, b; Cartwright and Lonergan, 1996), are not seen in the present study area. The strong parallelism of the faults suggests that a homogeneous stress field where σ_{hmin} was significantly less than σ_{Hmax} was prevalent during the deformation in the late Oligocene sequence in the Horda Platform. It is also tempting to assume, from the reconstructed slope of the base of the sequence, that a downslope gravity sliding mechanism contributed to the fault initiation and progress. However, the present slope is to the west, and N–S-trending faults should have been expected in response to down-dip movement. Thus, the observed dominant fault strike (NW–SE) deviates approximately 45° from the fault strike predicted to be associated with the present slope. It is also noted that the dominant fault trend (NW–SE) is parallel to the Oligocene–Miocene remote stress related to ridge-push (i.e. Vågnes et al., 1998). This may be taken as an indicator that initiation of NW–SE-trending normal faults might have been supported by the far-field stress.

The far-field plate-tectonic stress on the NW-European shelf in the Cenozoic probably were composed of several components. These include the Alpine (approximately N–S-directed) compression and its secondary stresses (Letouzey, 1986; Bergerat, 1987; Le Pichon et al., 1988; Kooi et al., 1989; Vågnes et al., 1998) and NW–SE- to NNW–SSE-directed ridge-push associated with the North-Atlantic mid-oceanic ridge-system (Kooi et al., 1989; Dorè et al., 1997; Vågnes et al., 1998). In addition, it is now well documented that doming of south-central Norway (e.g. Rohrman and van der Beek, 1996; Rohrman et al., 1996) and differential subsidence of the North Sea Basin (thermal subsidence and differential subsidence ascribed to other mechanisms) contributed to the total stress field (Hall and White, 1994; Jordt et al., 1995; Nadin and Kusznir, 1995). Within this framework, and taking the dominant NW–SE trend of the faults in the late Oligocene sequence into account, the resultant stress vector ($\vec{\sigma}_{\text{total}} = \vec{\sigma}_{\text{Alpine}} + \vec{\sigma}_{\text{ridge-push}} + \vec{\sigma}_{\text{doming}} + \vec{\sigma}_{\text{differential subsidence}} + \vec{\sigma}_{\text{reference stress}} + P_{H_2O}$) was obviously oriented NE–SW. Furthermore, the preference of faults to face SW supports the view that this was most probably the slope direction. In this situation, the body force associated with the observed thickening of the Oligocene sequence would contribute to its destabilisation.

The occurrence of incipient clay pillows and diapirs in the lowermost part of the late Oligocene sequence, the fact that the faults mainly occur as intraformational structures within the unit, the high fault density in the western part of the area where the sequence is thickest and the anomalously low interval velocity and the high log porosity, strongly indicate that fluid overpressure and perhaps gravity inversion may have contributed to the destabilisation which was followed by down-slope movement and faulting. This conclusion is supported by results from one-dimensional fluid pressure modelling performed in the study area. Nyland et al. (1992), Skagen (1992) and Gaillet (1993) have previously conducted simulation of fluid pressure for the offshore Norway areas. However, no such studies have hitherto been performed in the Horda Platform. In the present study, one-dimensional forward modelling has been used to analyse the fluid pressure development through time in the late Oligocene sequence.

The development of fluid pressure was modelled using the program Hydrobas (Nøttvedt et al., 1996). Hydrobas simulates the fluid pressure development as a function of mechanical compaction of the sediments and the thermal expansion/contraction of water. In this model, sediments are successively and incrementally loaded by adding stratigraphical units until the entire sequence is deposited. Erosion can also be handled in the model. In the present one-dimensional forward modelling, permeability was set to 10^{-5} mD with little variation from the base to the top of the sequence.

The modelling encompassed two model cases in order to explore the range of pressure build-up. In the minimum case 500 m of Miocene sediments and similar subsequent erosion were used, whereas the maximum case utilised 1500 m of Miocene sediments and subsequent erosion (Fig. 10). These values are consistent with previous estimates. Dorè (1992) suggested that 1000 m of erosion were associated with Neogene tilting in the study area. This estimate of erosion is supported by Fossen et al. (1997) who showed that late Jurassic sediments of the Bjorøy Formation (Bergen area; Fig. 1), which is found east of the Øygarden Fault, cannot have been buried at depths of more than approximately 1000 m. From 400 to 600 m of Miocene sedimentation and erosion was also suggested by Riis (1992) and by Dahl (personal communication, 1997) for the study area, and by Ghazi (1992) for the Stord Basin which is situated southwest of the Troll Field.

The results of the modelling obtained by applying the minimum case conditions suggests an overpressure of 27 bar (2.7 MPa) at 15 Ma (Fig. 10), followed by subsequent fluid pressure release at 5 Ma. From 5 Ma the pressure again built up, reaching an overpressure of 29 bar (2.9 MPa) at Present. For the maximum case (erosion of 1500 m), an overpressure of 160 bar (16.0 MPa) was generated at 15 Ma, again followed by subsequent fluid pressure release from this time to 5 Ma (Fig. 10). Following a similar pattern as for the minimum case, an overpressure of 40 bar (4.0 MPa) is calculated for the Present conditions.

The existence of an anomalously high fluid pressure is consistent with observations made by previous workers in the area, including rapid sedimentation in the Neogene (e.g. Rohrman, 1995), which probably

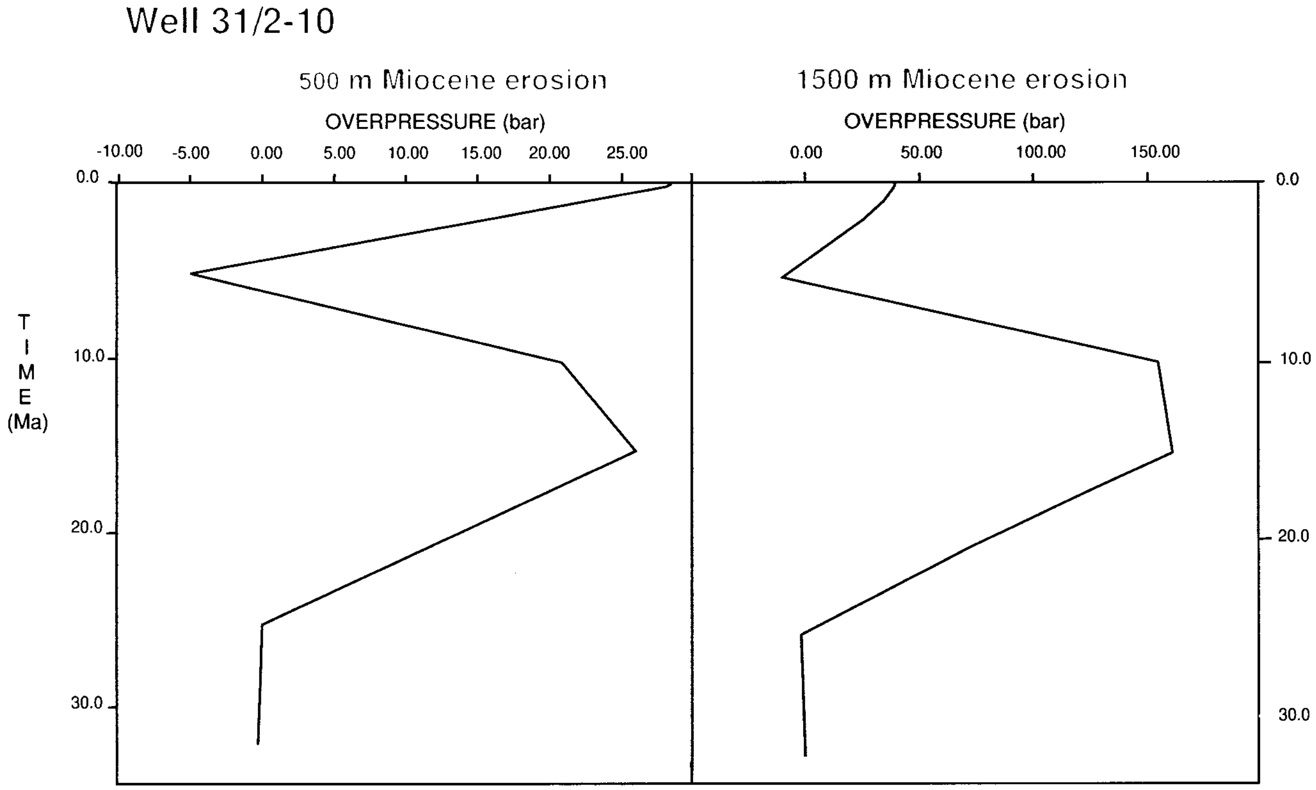

Fig. 10. Overpressure build-up with time in the late Oligocene sequence. (a) Minimum case using 500 m Miocene sedimentation and erosion and (b) maximum case using 1500 m Miocene sedimentation and erosion. Note that horizontal scale is different in (a) and (b).

generated additional disequilibrium compaction due to prevention of the escape of pore fluids through the cap rocks, resulting in the development of an anomalously high fluid pressure. Dehydration of smectite might have contributed in the development of this since the sequence consists of smectitic clay/claystone (e.g. Rundberg, 1989). The latter effect is, however, considered to be of minor importance.

According to Sejrup et al. (1995) the present shear strength of the upper part of the late Oligocene sequence is 0.0085–0.01 MPa/m (8.5–10 kN/m^3), which is compatible with the unit having a high water content even today. Comparing shear strength with measured overpressure, we see that the calculated overpressure is sufficient to promote fracturing.

The NW–SE-striking faults in the late Oligocene sequence are also parallel to, and sometimes connected with the underlying Mesozoic or older faults, some of which bear the characteristics of a mild reactivation in Tertiary time (e.g. the Øygarden Fault Complex; Fossen, 1998). These observations indicate that the Oligocene structuring to some extent may have involved the deep faults that are parallel to the strike of the palaeoslope, and hence, which were oriented favourably to the total stress in the Oligocene.

Fault density is highest in the western part of the area where the late Oligocene sequence is thickest. The western part of the area mainly consists of smectitic clay/claystone, whereas sand is locally present in the eastern part of the study area. This indicates that fault development was influenced by thickness variations in sediment distribution compaction. It is also probable that dominance of clay/claystone and the smectite content have been prerequisites for deformation (see also Henriet et al., 1991; Lippard and Fanavoll, 1992; Clausen and Korstgård, 1993; Higgs and McClay, 1993; Cartwright, 1994a, b; Cartwright and Lonergan, 1996; Stewart, 1996).

6. Conclusions

Based on the observations and modelling results, we propose the following sequence of events for development of the late Oligocene sequence in the Troll Field area (Fig. 11):

1. Mid Oligocene time (Rupelian, ca. 28 Ma): The intra-Oligocene unconformity (i.e. the base of the sequence) was established due to uplift of Fennoscandia and a sea-level fall.
2. Late Oligocene time (Chattian, ca. 28.5–23.8 Ma): Quick deposition of the late Oligocene sequence (mainly smectitic clay). The high smectite content

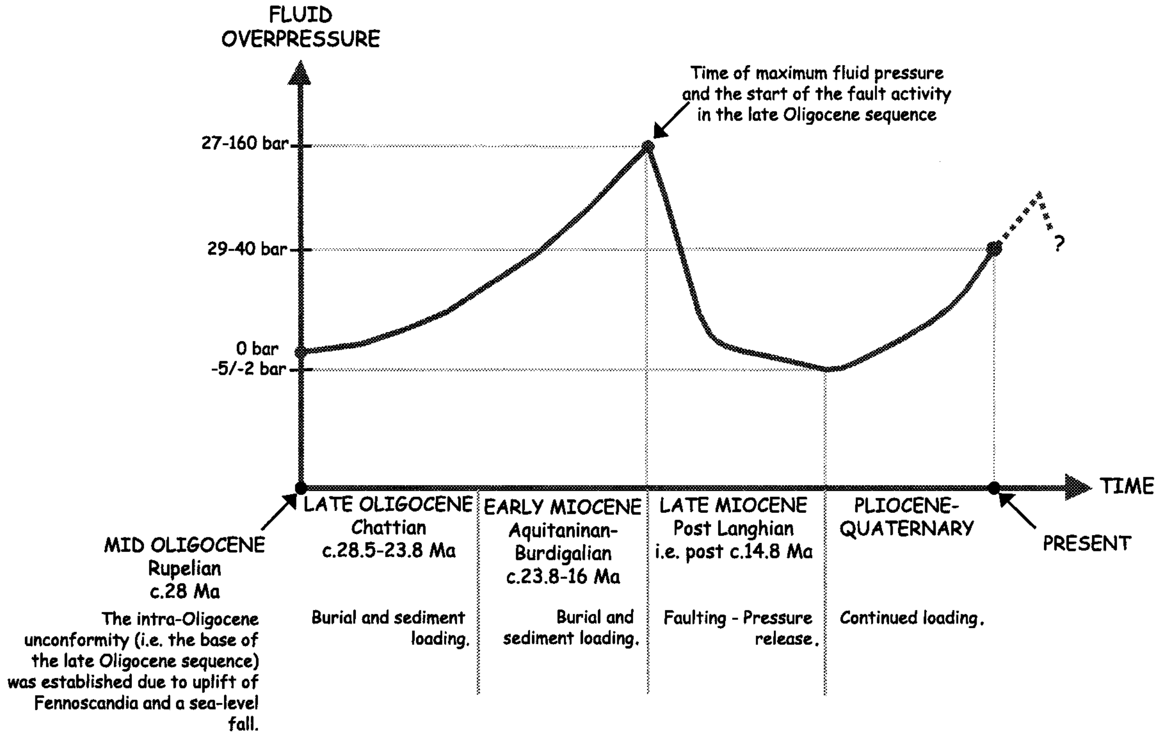

Fig. 11. Fluid overpressure vs time for the late Oligocene sequence. Development and deformation history for the sequence. See text for explanation. Absolute datings after Gradstein and Ogg (1996).

and hence, low permeability of the clays, caused intraformational entrapment of water and anomalously high fluid pressure. The base of the sequence had presumably a southwesterly mean slope angle of 1.8°, contributing to the general instability of the sequence.

3. Early Miocene time (Aquitanian–Burdigalian, ca. 23.8–16 Ma): Burial of the late Oligocene sequence. Miocene deposition caused further build-up of anomalously high fluid pressure. Incipient clay pillows developed, and minor diapirism and incipient faulting probably occurred. The faults associated with this stage of deformation did not transect the late Oligocene sequence.
4. Late Miocene time (post Langhian, i.e. post ca. 14.8 Ma): Continued uplift of south-central Norway promoted further tilting of the Horda Platform area, and hence, erosion of Miocene sediments. The maximum fluid overpressure was reached at the late/early Miocene boundary, and the sequence was destabilised. Deformation of the sequence took place, and was related to downslope gravity sliding (possibly triggered by rejuvenation and seismic activity along main Mesozoic faults), density inversion and collapse. Also, remote tectonic stresses related to ridge-push, differential subsidence of the North Sea Basin and doming of Fennoscandia contributed. The fault activity resulted in fluid pressure release in the late Oligocene sequence.
5. Pliocene–Quaternary time: Deposition of Pliocene and Quaternary sediments. Again build-up of a high fluid pressure in the late Oligocene sequence occurred. Further doming of Fennoscandia.

Fluid pressure release from 15 to 5 Ma, as indicated from the one-dimensional forward modelling, is considered to be a result of faulting in addition to Miocene erosion, hence is consistent with fault development taking place in Miocene time. This observation suggests that the dome of the south Norwegian mainland, which had been developing since the Triassic (Rohrman and van der Beek, 1996; Rohrman et al., 1996) probably had an outline different from the present one with a NW–SE-trending western flank in the Miocene. It also supports the growing awareness that the Cenozoic–Present stress history of the Norwegian mainland and its continental shelf is much more complicated than hitherto assumed, and that the stress system, which was responsible for the Miocene intraformational faulting in the Troll area of the Horda Platform, was composed by far-field tectonic stresses related to ridge-push, doming of Fennoscandia and differential subsidence of the North Sea Basin, downslope gravity sliding, anomalously high fluid pressure, gravity collapse and reactivation of Mesozoic faults. This means that further investigations of stress systems, like sub-critical asthenospheric diapirism (Rohrman and van der Beek, 1996), thermal influence

(Skogseid et al., 1992) and other effects (Torske, 1972; Sales, 1992) from the North-Atlantic break-up, migration of lithospheric phase boundaries (Riis and Fjeldskaar, 1992) and finally the post-glacial rebound (Nansen, 1922, 1927; Dorè, 1992; Jensen and Scmidt, 1992; Riis, 1992) are necessary for understanding the vertical movements of the Norwegian Continental shelf.

Acknowledgements

The authors would like to thank Norsk Hydro ASA for financial support, for making the dataset used in this work available, for all the help during the work at Vækerø, Oslo, and finally for permission to publish this work. Special thanks go to Elisabeth Skoglund, Peter Swanberg and Eivind S. Aarseth for all help given during the stay at Vækerø, and to Bjørn T. Larsen who initiated the study. Haakon Fossen (Geological Institute, University of Bergen), Walter Wheeler (Geological Institute, University of Bergen), Roald B. Færseth (Norsk Hydro ASA), John Korstgård (Department of Earth Sciences, University of Aarhus), Yngve Rundberg (Saga Petroleum), Chris Elders (Royal Holloway, University of London) and one anonymous reviewer are thanked for useful comments on earlier versions of the paper. Jane Ellingsen (Geological Institute, University of Bergen) prepared several of the figures.

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