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THE UPPER CARBONIFEROUS-PERMIAN OSLO RIFT; BASIN FILL IN RELATION TO TECTONIC DEVELOPMENT

SNORRE OLAUSSEN
Saga Petroleum a.s.
P.O. Box 490
1301 Sandvika, Norway

BJØRN T. LARSEN
Norsk Hydro a.s.
P.O. Box 200
1321 Stabekk, Norway

RON STEEL
Geologisk Institutt avd. A
University of Bergen
Alle gt. 41
5007 Bergen, Norway

ABSTRACT

The Permo-Carboniferous Oslo Rift, an *en echelon* graben system, was created by east-west extension partly caused by dextral movement along the Sorgenfrei-Tornquist-Teissure Zone. This zone was most likely activated by a late compressional event in the Variscan segment of the Hercynian Orogenic cycle. The Oslo Rift is thus an example of local suturation during the creation of the Pangea super-continent.

The north-south trending Oslo Rift system consists of the onshore Oslo Graben and the offshore Skagerrak Graben. The basin-fill of the onshore Oslo Graben is characterised by large volumes of volcanics and only minor sedimentary rocks, for which a six phase development model from pre-rift to the termination phase has been derived. The pre-rift and initial rift phases (Late Carboniferous) coincided with the late Variscan stage of the Hercynian Orogeny. The basin fill which accumulated prior to the rift basin formation, the pre-rift phase, consists of a thin alluvial and deltaic succession with a marine limestone of (?) Moscovian age. The initial rift phase is recorded in the Vestfold Graben with more than 1500 m of alkali basalt lavas, while in the north, close to the transfer zone in the initial Oslo Graben, the basin fill comprises Gzelian lacustrine delta and volcaniclastic alluvial fan deposits capped by a single tholeiitic basalt. The syn-rift phase (Early Permian) is divided into two sub-phases that were characterized by plateau lavas, fissure eruption and normal faulting as well as formation of central volcanos and caldera collapse. The basin fill in the syn-rift phase, besides volcanics and thin but widespread continental deposits that are intercalated with the plateau lavas, developed as thick alluvial fan deposits along the master fault or locally inside the rift valley along escarpments bounding a volcanic accommodation zone, and as thick eolian and wadi deposits in the northern part of the Oslo Graben. The two last recorded phases (late Early and Late Permian) of graben development were the emplacement of young syenitic and granitic batholiths.

The highly volcanic Oslo Rift is comparable with the Kenya Rift of the East African rifts and has some similarities to the Rio Grande Rift. In many periods the high production rate of extrusives in the Oslo Graben was enough to fill the relief created by extension, thus explaining the small amount of syn-rift sediments.

Although only known from seismic and geophysical data, the basin-fill development of the offshore Skagerrak Graben is similar to the Oslo Graben, but probably with less volcanism.

A post-rift sedimentary cover as a response to thermal cooling has probably been developed in the offshore Skagerrak Graben. A previous existence of post-rift basin fill in the onshore Oslo Graben is unclear. Post-rift sediments may also have been developed there, but at different scale and time in comparison to the Skagerrak Graben due to variations in duration and activity of the magmatism. The assumed post-rift infill is dated as Late Permian (offshore graben) and Triassic/ Early Jurassic (onshore graben) by onshore age determination and by seismic/well correlation between neighbouring basins. Subsequent uplift and erosion of the Oslo Rift and surrounding areas are suggested to have occurred in Early Triassic and "mid" Jurassic, with stripping of the post-rift basin fill in the offshore Skagerrak Graben taking place in Early Triassic, whereas "mid" Jurassic uplift removed the possible post-rift basin fill and much of the syn-rift basin fill of the onshore Oslo Graben.

Potential source rocks are burned out in the Oslo Graben. However the Skagerrak Graben may yet prove to be hydrocarbon bearing.

RÉSUMÉ

Le rift Oslo permo-carbonifère, un système de grabens en échelons, fut créé par une extension est-ouest causée en partie par un mouvement dextre le long de la zone Sorgenfrei-Tornquist-Teissure. Cette zone fut tout probablement activée par une événement de compression tardif dans le segment varisque du cycle orogénique hercynien. Le rift Oslo est donc un exemple de suture locale qui résulta de la création du supercontinent de Pangea.

Le système de rift Oslo orienté nord-sud est composé du graben Oslo à terre et du graben Skagerrak dans la région extra-côtière. Le remblai de bassin du graben Oslo à terre est caractérisé par de grandes quantités de roches volcaniques et seulement une petite accumulation de roches sédimentaires. Un modèle de développement en six phases, du pré-rift à la phase terminale, fut dérivé pour le graben Oslo. Les phases pré-rift et initiale (Carbonifère supérieur) coïncident avec l'étage varisque tardif de l'orogénèse hercynienne. Le remblai de bassin qui s'accumula avant la formation du bassin de rift, la phase pré-rift, consiste en une mince succession alluviale et deltaïque avec un calcaire marin d'âge moscovien. La phase initiale est représentée dans le graben Vestfold par plus de 1 500 m de laves basaltiques alcalines, tandis que dans le nord, près de la zone de transfert dans le graben Oslo initial, le remblai de bassin consiste en dépôts deltaïques lacustres gzéliens et en épais sédiments clastiques de cône de déjection d'origine volcanique recouverts d'un seul basalte tholéiitique. La phase syn-rift (Permien inférieur) est divisée en deux sous-phases qui furent caractérisées par des laves des plateaux, des éruptions de fissures et la formation de failles normales ainsi que la formation de volcans centraux et l'effondrement de caldeiras. Le remblai de bassin de la phase syn-rift, en plus des roches volcaniques et des dépôts continentaux minces mais étendus intercalés avec les laves des plateaux, se développa sous forme d'épais dépôts de cône de déjection le long de la faille maîtresse ou localement à l'intérieur du fossé du rift le long d'escarpements bornant une zone accommodant les roches volcaniques, et sous forme d'épais dépôts éoliens et d'oueds dans la partie nord du graben Oslo. Les deux dernières phases (Permien inférieur le plus tardif et Permien supérieur) de formation de graben observées furent la mise en place de jeunes batholites syénitiques et granitiques.

Le rift Oslo, très volcanique, est comparable au rift Kenya du système de rifts de l'Afrique orientale et montre certaines similarités avec le rift Rio Grande. Durant plusieurs des périodes le taux élevé de production de roches extrusives dans le graben Oslo fut suffisant pour combler le relief créé par l'extension, expliquant ainsi la petite quantité de sédiments syn-rift.

Bien que connu seulement à partir de données sismiques et géophysiques, le développement du remblai de bassin du graben extra-côtier Skagerrak est semblable à celui du graben Oslo, mais comporte probablement moins de volcanisme.

Un revêtement sédimentaire post-rift, en réponse au refroidissement thermique, à probablement été formé dans le graben extra-côtier Skagerrak. L'existence dans le passé d'un remblai de bassin post-rift dans le graben à terre Oslo n'est pas certaine. Des sédiments post-rift pourraient aussi avoir été déposés à cet endroit, mais à une échelle et une époque différentes en comparaison avec le graben Skagerrak à cause de différences dans la durée et l'activité du magmatisme. Le présumé remblai post-rift est attribué au Permien supérieur (graben extra-côtier) et au Trias/Jurassique inférieur (graben à terre), par des méthodes de datation à terre et de corrélation sismique/puits entre les bassins voisins. Par conséquent, il est suggéré que le soulèvement et l'érosion du rift Oslo et des régions avoisinantes se produisirent durant le Trias inférieur et le Jurassique "moyen", avec l'enlèvement du remblai de bassin post-rift dans le graben extra-côtier Skagerrak durant le Trias inférieur, tandis que le soulèvement du Jurassique "moyen" enleva le remblai de bassin post-rift possible et une bonne partie du remblai de bassin syn-rift du graben à terre Oslo.

Les roches mères potentielles sont usées dans le graben Oslo. Par contre, le graben Skagerrak pourrait bien un jour être prouvé porteur d'hydrocarbures.

Introduction

The north-south trending Oslo Rift (Fig. 1) (Dons, 1978), a 520 km long, down-faulted crystalline segment in southern Norway, is of Permo-Carboniferous age and includes both the highly volcanic onshore Oslo Graben and the offshore Skagerrak Graben (Ramberg, 1976; Ramberg and Larsen, 1978). The Oslo Graben, well known for its tectonomagmatic evolution, is subdivided into a southern segment, the Vestfold Graben and the northern Akershus Graben (Fig. 2) (Ramberg and Larsen, 1978). The less well known Skagerrak Graben is connected with the Oslo Graben through a poorly known structural high south of the Vestfold Graben. The graben segments of the rift propagated north-northeastwards as *en echelon* half graben systems. The graben polarity in the system shifts in polarity from the Vestfold Graben segment in the south to the Akershus Graben segment in the north, across a northwest striking accommodation zone and a transfer fault around the city of Oslo. The Oslo Rift developed coevally with late Hercynian compression and wrench tectonics and the early collapse of the Variscan Fold Belt (Glennie, 1984), features which marked the closure of the proto-Tethys Ocean and creation of the super-continent Pangea. Compression within this mega-tectonic structure (Fig. 2) caused wrench deformation and dextral movement along the Sorgenfrei-Tornquist-Teissure Zone (Ziegler, 1978, 1990; Pegrum, 1984), and also established the approximate east-west tensional stress regime responsible for the formation of the Oslo Rift (Larsen and Sundvoll, 1983).

The aim of this study is to emphasise the character of the basin-fill strata (Fig. 3) and particularly the relationship of the infill to the structural development of the onshore Oslo Graben and partly to the offshore Skagerrak Graben. In addition we comment on the development of the Oslo Rift in relation to the Hercynian Orogeny. Burial history and post-rift development of the rift will be discussed. Finally we remark on the rift as a former and possible potential hydrocarbon province.

Development and Timing of the Oslo Graben

Ramberg and Larsen (1978) proposed a 6-step tectonomagmatic evolution of the Oslo Graben, a scheme which was later refined by Larsen and Sundvoll (1983, 1984). The latter authors discussed the magmatic evolution and stress develop-

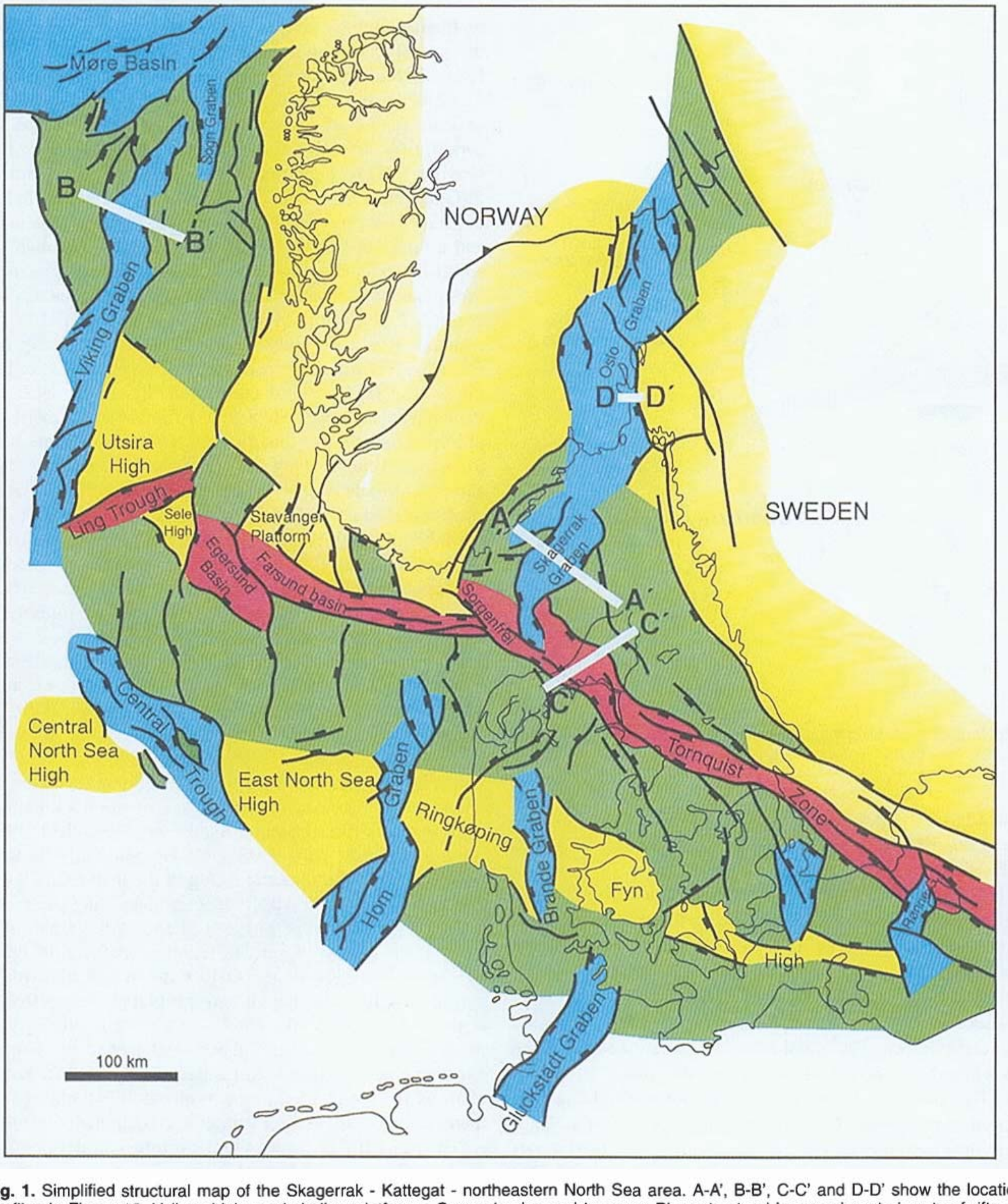

Fig. 1. Simplified structural map of the Skagerrak - Kattegat - northeastern North Sea area. A-A', B-B', C-C' and D-D' show the location of geoprofiles in Figure 16. Yellow: highs and shallow platforms; Green: basins and terraces; Blue: structural lows and central parts of rifts; Red: basins and structural lows along the Sorgenfrei-Tornquist Zone/Fennoscandian Border Zone.

ment coupled with detailed radiometric dating and sparse biostratigraphic data. The 6-stage evolution (Larsen and Sundvoll, 1983) is defined as; 1) proto-rift stage 2) initial basalt stage, 3) main plateau lava and rift-valley stage, 4) central volcano and cauldron stage, 5) syenitic batholith intrusion stage and, finally 6) termination stage. In this study we emphasise the infill of the Oslo Graben in relation to the six tectonomagmatic stages (though we use the term phase instead of stage), but simplify them as follows: 1) pre-rift, 2) initial rift, 3) syn-rift I, 4) syn-rift II, 5) batholith emplacement and, finally 6) termination. This is summarized in Figure 18. These phases developed from Late Carboniferous through Permian times. Due to later erosion of the graben only the infill of the three first phases has been preserved in some scattered outcrops (Fig. 3).

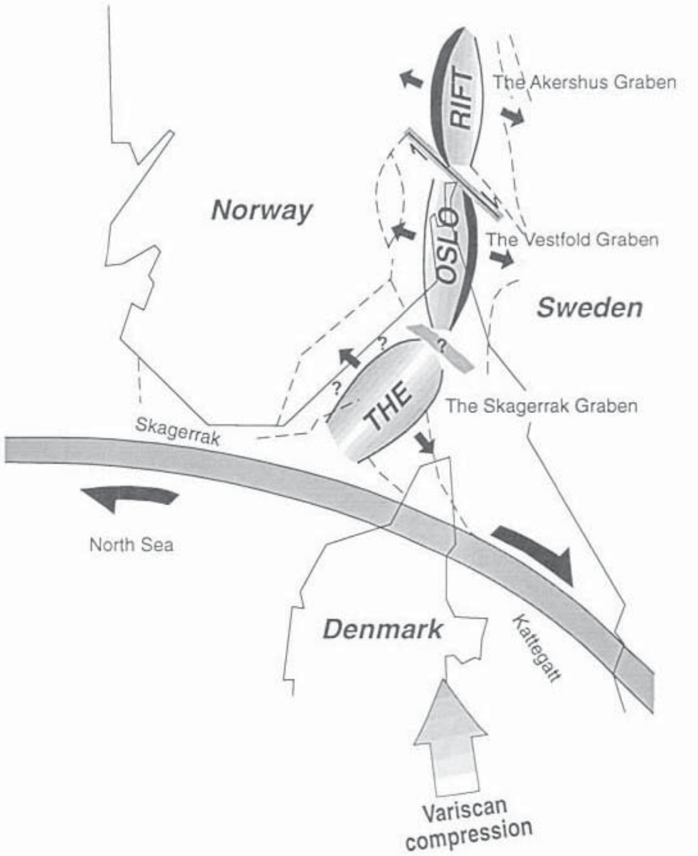

Fig. 2. Sketch showing the main components of the Oslo Rift in relation to Variscan dextral wrench movements.

Phase 4 has only minor remnants of the infill preserved inside caldera remnants. Basin fills as a response to later rift phases are absent.

The pre-rift (Fig 4) is here defined as the earliest phase, prior to the rift-basin formation and when the relative principal stress was compressive at a shallow level in the crust (Sundvoll et al., 1992). Felsic sills dated between 305 to 295 m.yr. (Sundvoll et al., 1990) are interpreted as compressive stress indicators of this phase. No pre-rift doming is recorded in the Oslo Graben. The initial rift phase is defined here as the time when the principal stress became dominated by extension. The first important volcanism and normal faulting occurred in this phase. The syn-rift phase represents the major extensional period of rift development. The initial rift and syn-rift phases define the rift and the post-rift flexural phases respectively, as established by the theory of lithospheric stretching and subsequent cooling given by McKenzie (1978).

Recent radiometric dating (Sundvoll et al., 1990, 1992; Sundvoll and Larsen, 1990, in press) has given detailed age determinations (Rb-Sr ages) for each of the magmatic phases of the Oslo Graben. These data, together with stratigraphy of the lava/sedimentary succession, tectonic analysis and the sparse biostratigraphic record are used to date the infill of the Oslo Graben.

Biostratigraphy can be used with confidence only within the pre-rift and initial rift basin-fill. Poorly preserved plant fossils in the lowermost formation, the Kolsås Formation (Fig. 5), of the basin fill of the Oslo Graben (Henningsmoen, 1978), indicate Late Carboniferous to Early Permian age. A sparse foraminifer assemblage suggests a Moscovian age for the marine limestone beds in the Tanum Formation (Fig. 5)(Olaussen, 1981). The upper part of the Tanum Formation in the Asker area has a common flora assemblage (Høeg, 1936) and a fauna of freshwater mussels (Dix and Trueman, 1935) and fishes (Heintz, 1934). These fossils suggest ages from the Westphalian/Stephanian boundary to the Stephanian C (written comm., E. Paproth, 1983; A.C. Scott, 1985; H.W.J. van Ameron, 1987). Recently, Eager (1994) has reinvestigated the fresh water mussels from the upper part of the Tanum Formation (Fig. 5) and correlated this fauna with Upper Pennsylvanian (upper Stephanian) from North America. It is of importance to note that the marine fossils correlate with the Russian marine stages of Moscovian and the freshwater fauna and plant fossils relate to West European and North American continental stages. Although the exact interrelation of the marine and continental stages is uncertain, local correlation indicates a hiatus is likely between the marine carbonate and the upper part of the Tanum Formation in the Asker area. This intra-Stephanian unconformity can be linked roughly to an upper Variscan unconformity in NW Europe. The rest of the basin fill has been radiometrically dated on lavas, given absolute age of the lavas and comparable volcaniclastics (Sundvoll, 1978; Sundvoll and Larsen, 1990; Sundvoll et al., 1990, 1992). The first capping basalt above the fossil-bearing strata in the Kolsås/Asker area gives a Rb/Sr age of 291 +/-8 Ma (Fig. 5), which is close to the Carboniferous - Permian transition. Great uncertainty exists concerning the age of the thick eolian and wadi deposits (the Brumund Sandstone; Rosendahl, 1929) in the northernmost part of the Oslo Graben. Only its tectonic position and the radiometric dating of the underlying lava suggest an Early Permian syn-rift depositional setting (see p. 187).

Based on biostratigraphy, Rb-Sr age, stratigraphic succession, magmatic evolution and tectonic analysis of the basin fill, the succession of the Oslo Graben can be informally assigned to the following chronostratigraphic stages (using the scale of Harland et al., 1989): The pre-rift phase is dated Moscovian, the initial rift phase Gzelian and the composite syn-rift phase Asselian and Sakmarian. The last recorded phase is the termination phase, with small batholith emplacements dating close to the Permian-Triassic transition (Fig 18).

The basin fill, in relation to the timing and development of the Oslo Graben, is described below.

The Pre-Rift Phase, Moscovian

The pre-rift phase was characterized by sedimentation, minor faulting, sill intrusions and, probably, towards its late stage minor volcanism (Fig. 4) (Sundvoll et al., 1992, Sundvoll and Larsen, in press). The basin fill consists of up to 80 m of widespread siliciclastics, with minor carbonates and rare evaporites in the Vestfold Graben as well as in the accommodation zone between the two onshore graben segments. (Figs. 3, 11b) The pre-rift succession thins northwards in the Akershus Graben and only weathered Cambro-Silurian

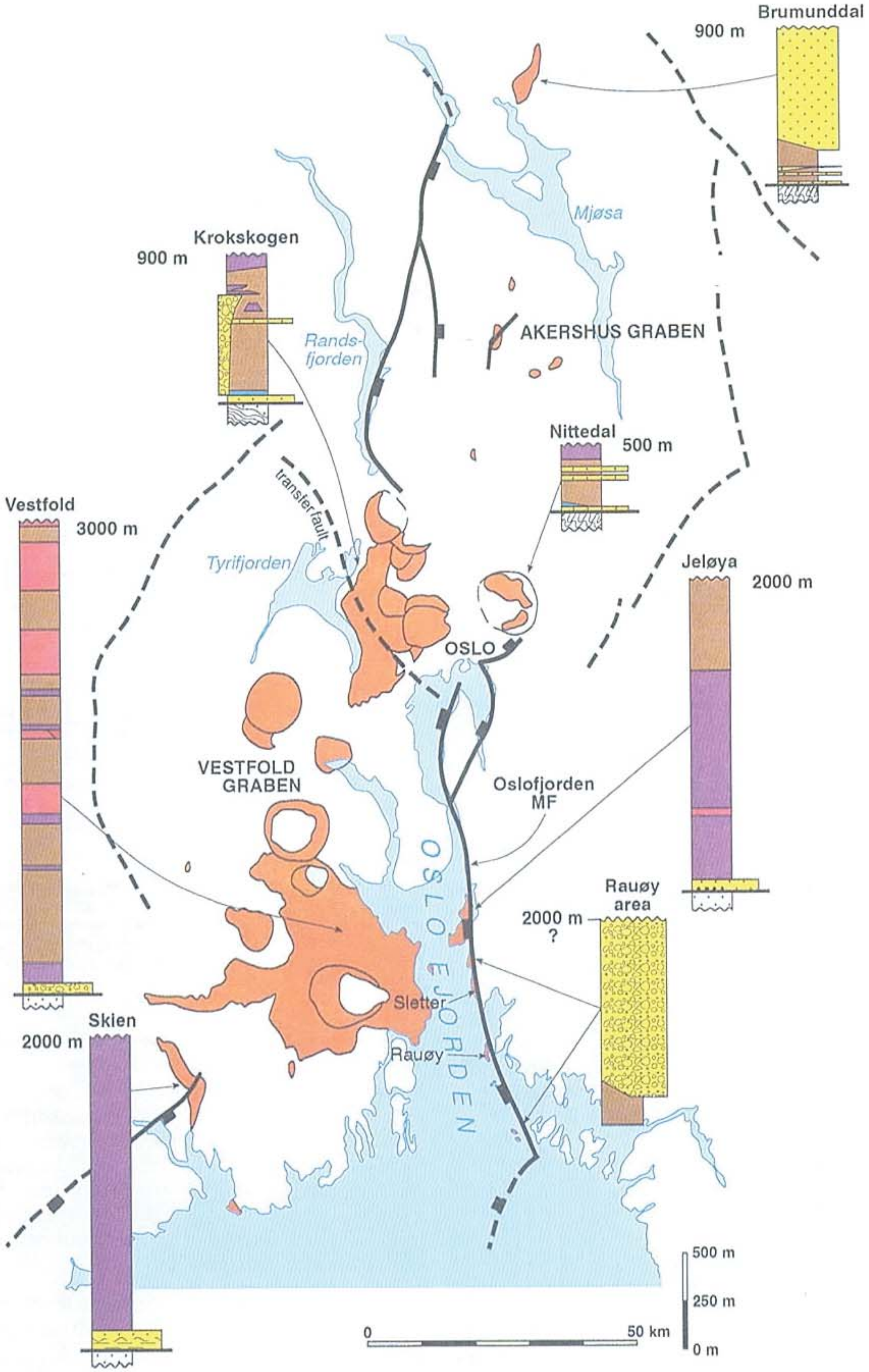

Fig. 3. Outcrop map and some representative measured vertical sections of Upper Carboniferous - Permian basin fill of the Oslo Graben. Yellow: sedimentary rocks; Purple: basalts; Brown: rhomb-porphyry and Red: trachytes. Orange shows the distribution of the remnants of the basin fill. MF: master fault.

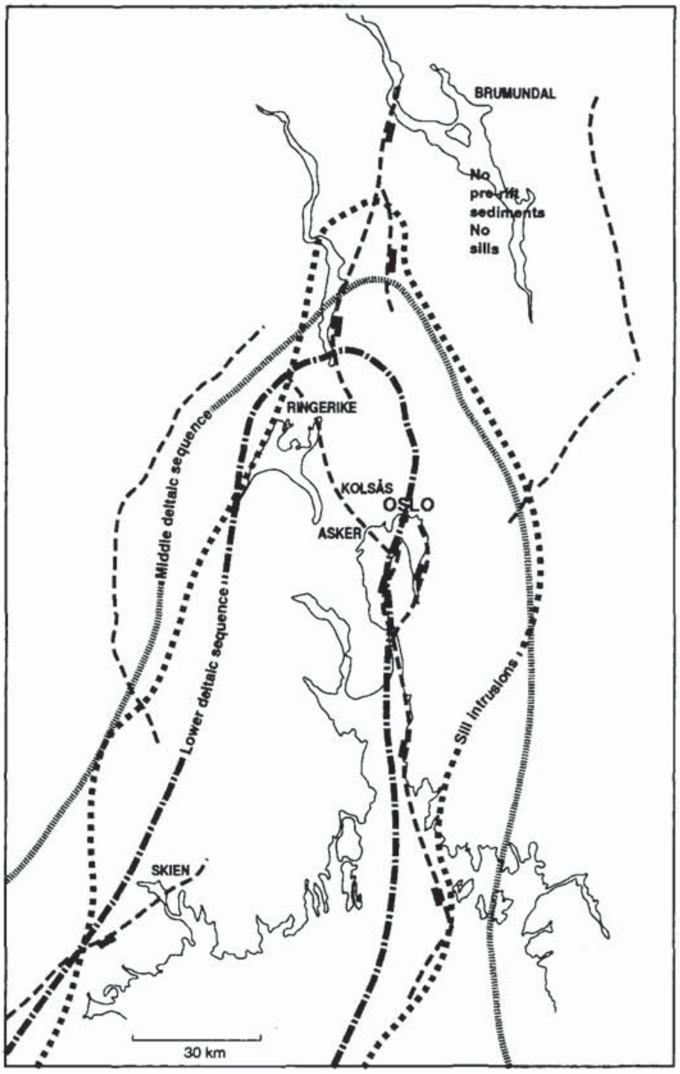

Fig. 4. Pre-rift phase in the Oslo Graben with basin fill in a broad proto-rift depression, sill intrusions and insignificant volcanism.

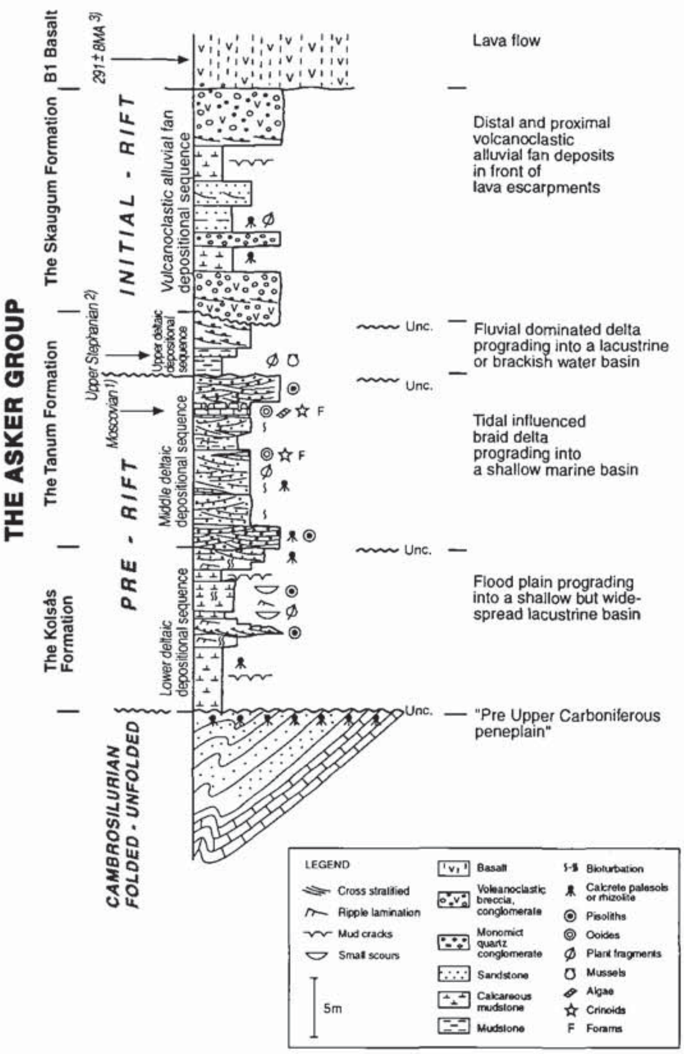

Fig. 5. Composite stratigraphic column from the central area of the Oslo Graben (close to the transfer zone between the two onshore graben segments). Unc=Unconformity. 1) forams suggesting Moscovian age (Olaussen, 1981), 2) fresh water mussels suggesting late Stephanian age (Eager, 1994), 3) radiometric age (Rb/Sr age) from basalt (Sundvoll and Larsen, 1990).

bedrock and a thin cover up to 1 m thick of basal quartz conglomerate occur in the northernmost part of the graben. This basal carpet of sedimentary rocks reflects proto-rift subsidence (Late Carboniferous) and records the onset of Oslo Graben infill. The basal bounding surface (Upper Carboniferous peneplain, Fig. 5), which is flatlying or has a gentle dip on underlying folded Cambro-Silurian rocks is only rarely exposed; the few exposures show a paleosol profile characterized either by carbonate-filled root structures, calcrete development or simply red weathered Cambro-Silurian rocks. The pre-rift basin fill is best exposed and defined close to the transfer zone between the two half-graben segments in the Oslo Graben (Figs. 4 and 5). There the basal sedimentary succession is subdivided into the Kolsås, Tanum and Skaugum Formations of the Asker Group (Fig 5) (Dons and Gyøry, 1967; Henningsmoen, 1978). These formations make up three deltaic depositional sequences and a volcaniclastic alluvial fan sequence. In the present study we use the terms depositional sequence or sequence to refer to a succession of genetically related strata bounded below and above by major unconformities. There is no further implication in our use of the terms to the particular internal ordering of the strata; we simply lay weight on the presence of the unconformities bounding the stratal packages. The first deltaic depositional sequence corresponds to the Kolsås Formation, the second to the Tanum Formation, while the third is best developed in the Asker area, where it belongs to the upper part of the Tanum Formation. The Skaugum Formation comprises an alluvial fan depositional sequence (Fig. 5). Only the two lower deltaic depositional sequences are assigned to the pre-rift basin fill.

The lower deltaic depositional sequence, the Kolsås Formation (Fig. 5) consists of 20 m of red mudstones and very fine grained sandstones, with occasional green to grey, coarser grained sandstones, conglomerates, limestones and scattered occurrences of anhydrite (Henningsmoen, 1978), as well as pseudomorphs after evaporites. Minor occurrences of plant fragments and burrows have been recorded. The lower deltaic depositional sequence in the Kolsås/Asker area (Fig. 5) is normally developed in its lower part as a red mudstone unit capped by a thin coarsening upward unit and then by a thick fining upward channel-fill unit capped by thin calcrete paleosols. The upper part of the depositional sequence comprises cut-and-fill channels and horizontally laminated sandstone beds in a general coarsening upward trend. Occasionally a calcrete paleosol (up to 1 m thick) caps the upper part. Red mudstones or fine grained sandstones contain raindrop imprints, desiccation cracks, wave and current ripple-lamination, lenticular and flaser bedding and small scours with lags of calcrete pisoliths. The sedimentary structures, together with the evaporites and distinct beds with burrows, calcrete nodules and rhizoliths suggest a shallow lake environment (Dons and Gyøry, 1967) with periodic emergence during arid to semi-arid conditions. Minor coarsening upward sub-units, together with fining upward channel fills (1-2 m thick) or massive, thick calcretes suggest fluvial deposits prograding into lake/flood plain environments. The massive calcretes suggest prolonged emergence. Lack of lateral accretion surfaces in the channel fills, as well as the laminated, well sorted, thinly bedded, coarse grained sandstones interpreted as sheet flood deposits, suggest an environment dominated by ephemeral streams and flash floods.

To the north of the transfer zone, at Ringerike, the coarse grained parts of the sequence are missing and red mudstones with bedded limestones containing pseudomorphs after anhydrite laths and micritic clasts are seen. This outcrop probably represents a more distal facies of lake deposits. In the southernmost part of the Oslo Graben, in the Skien area (Fig. 3), the depositional sequence thickens to 30 metres and exhibits two coarsening upward to fining upward (CU-FU) units, each with red mudstones passing upward to very fine grained sandstones overlain by fining upward, channelized sandstones which again are capped by calcrete paleosols. The second CU-FU unit passes from mudstones to burrowed, medium grained, lenticular bedded sandstones to fining upward, cross-stratified, massive sandstones interbedded with finer grained burrowed sandstones. This reflects pro-delta and delta-front deposits within a lacustrine basin, terminated by distributary channel and mouth bar deposits. The lower deltaic depositional sequence is thus interpreted as representing fluvial dominated deltas which prograded into a shallow lacustrine basin.

The middle deltaic depositional sequence, the Tanum Formation in the Kolsås area consists of 15 to 20 m of thick grey to light blue sandstones and conglomerates, sandy limestones and minor shales which together show a coarsening upward trend (Fig. 5) The lower boundary of the middle deltaic depositional sequence is erosional with a common basal conglomerate lag and shows an abrupt colour change from red to light blue/grey. This basal conglomerate lag, which overlies the erosional surface above the lower deltaic depositional sequence, contains vertical burrows and clasts of calcrete and pisoliths, the latter derived from the underlying sequence. It is interpreted as a ravinement deposit overlying a transgressive surface. Broadly, the sequence can be subdivided into a lower 5 to 15 m thick sandstone part and an overlying 0-10 m thick conglomeratic part.

The lower part is often channelized and consists of medium grained, carbonate-cemented sandstones. The latter show hummocky cross-stratification and wave ripples as well as planar to trough cross-strata with bi-directional paleocurrents and beds with double mud drapes and rare burrows, all of which suggest tidally influenced, shallow marine conditions. Massive, poorly sorted pebbly sandstone beds are interpreted as sediment gravity flows. Minor grey shales, occasionally with plant fragments are also present. The upper beds of the lower part consist of sandy oobiosparites and marine (?) Moscovian fossils, the Knabberud Limestone Member. This unit was discussed in detail by Olaussen (1981) and is likely to represent beach deposits (Fig. 6). Thin calcrete layers and karst surfaces in the the limestone member testify to several periods of temporary emergence.

The upper part of the middle depositional sequence consists of cross-stratified conglomerate up to 10 m in thickness, composed mainly of well rounded, monomict quartz grains with a clast-supported framework. In the Kolsås area there is an erosional contact to the underlying karstified marine limestone beds, causing limestone clasts to occur in the basal part of the conglomerates. Cut-and-fill units with planar and trough cross-stratified imbricated conglomerates, and minor lenses of medium to very coarse grained sandstone suggest braided stream channel fills. Paleosol and calcrete deposits occur within the conglomeratic beds. However, rare occurence of thin, intercalated marine limestone beds within the conglomerates in the Kolsås area suggests marine flooding on the braidplain. Above the conglomerate beds, in the upper part of this depositional sequence and below the first capping basalt flow, B-1 (Fig. 5) there occur, in some places, up to 2 m thick eolian dunes, probably dome dunes, resting on a deflation surface of the conglomerate bed (Nedkvitne, pers. comm., 1993).

It is notable that Dons and Gyøry (1967), though without any direct recorded evidence of marine indicators, considered the possibility that the middle depositional sequence represented by the Tanum Formation in the Kolsås area represents deltaic

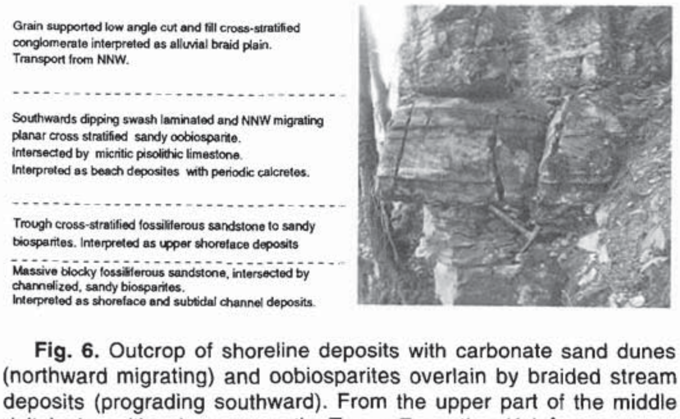

Fig. 6. Outcrop of shoreline deposits with carbonate sand dunes (northward migrating) and oobiosparites overlain by braided stream deposits (prograding southward). From the upper part of the middle deltaic depositional sequence, the Tanum Formation. Kolsås area.

deposits which prograded into a marine basin. This is also the main conclusion of the present authors. Furthermore, we interpret the delta to have been a tidally influenced braid delta. Abrupt changes in the hinterland relief, probably caused by increased fault activity (Dons and Gyøry, 1967), arid climate, restricted basin floor subsidence and a regional relative rise in sea level were the main controlling factors for sediment influx, sedimentation and delta progradation.

North of the transfer fault between the Vestfold and Akerhus Graben segments the middle depositional sequence comprises conglomeratic beds with red-coated quartz pebbles and medium to coarse grained, cross-stratified sandstones. It was here deposited as stream channel fills. Thick (up to 2 m), interbedded, massive calcretes show supermature paleosols.

In the southern part of the Oslo Graben the middle sequence consists of 50 m of interbedded red mudstones, sandstones and conglomerates with calcrete horizons. The sedimentary succession consists of alternating coarsening and fining upward units. Sedimentary and biogenic structures and stacking pattern suggest fluvial/deltaic progradation into a lacustrine basin, followed by retrogradation. Only the upper 3 m show evidence of marine influence.

THE INITIAL RIFT PHASE. GZELIAN

In the Vestfold Graben the basin fill comprises numerous basalt flows with thin associated extrusive and volcaniclastic beds. Debris deposits occur below the first lava flow on Jeløya. In the Skien area this "basin fill" is more than 1500 m thick (Figs. 3, 7) (Segalstad, 1979). In the lower succession of the basalt flows in the Vestfold Graben burrowed grey sandstones, with cross- to horizontal stratification and with clasts of basalt and marine (?) Moscovian limestone (Fig. 8), suggest deposition in a standing body of water. A marine environment is not excluded. It is suggested that the first basalt flows in the Vestfold Graben are older than the first basalt flow in the Krogskogen area (Fig. 3) (Sundvoll and Larsen, in press).

The infill of the initial rift basin in the Kolsås/Asker area consists generally of lacustrine deltaic and alluvial fan deposits and a single tholeiitic basalt flow (Fig. 5).

In contrast to the underlying sequences, volcaniclastic grains and volcanic ash are common in the sedimentary strata in this basin fill.

The upper deltaic depositional sequence, the upper part of the Tanum Formation, is exposed in the Asker area. This sequence is organised as an overall coarsening upward sequence. The lower boundary, representing a hiatus, is seen where shales overlie conglomeratic delta-plain deposits of the uppermost part of the middle depositional sequence, suggesting that the boundary represents a flooding surface (Fig. 5). The upper alluvial fan boundary is a scoured surface, overlain by the volcaniclastic depositional sequence. From the base, green to red and grey fossiliferous laminated shales (3 m thick) pass upwards into 2 m thick interbedded sandstones and shales, and finally to a 4 m thick grey, coarse grained, cross-stratified, pebbly sandstone. The shales and interbedded sandstones (the lower 5 m of the 9 m thick sequence) are organised in 20 m wide stacked, channelized cut (and coarsening upward) fill structures which suggest prograding events (e.g., bay fills) due to minor shifts in a deltaic environment. Macrofauna and flora (Holtedahl, 1931) of Westphalian/Stephanian age occur in the finer grained part of the sequence. The fossil fish remnants (Heintz, 1934) resemble species found in fresh to brackish

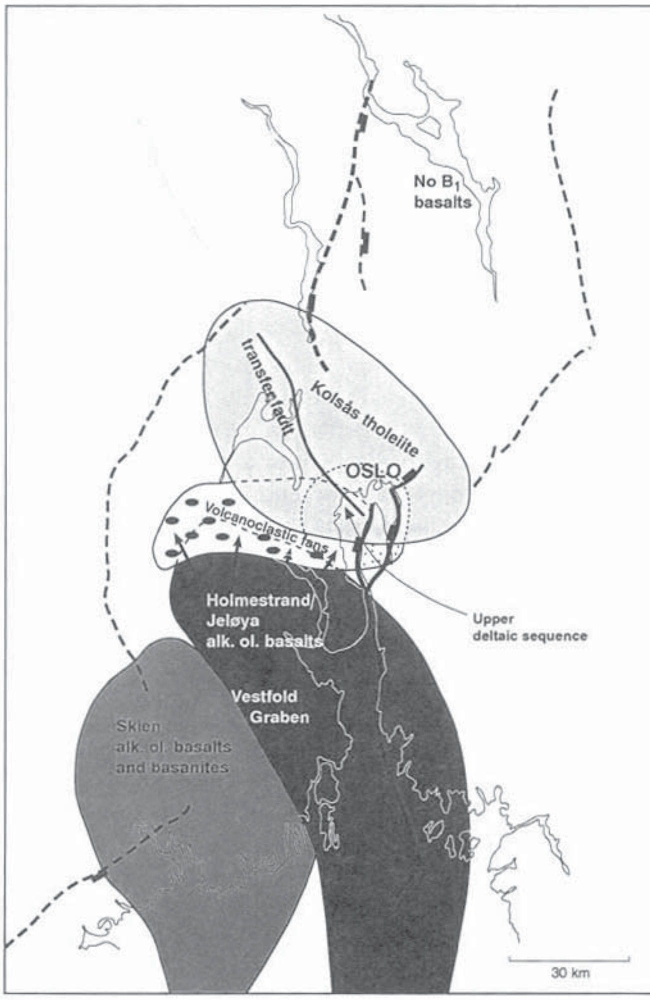

Fig. 7. Initial rift phase with basaltic volcanism, lacustrine deltaic deposits and volcaniclastic alluvial fans.

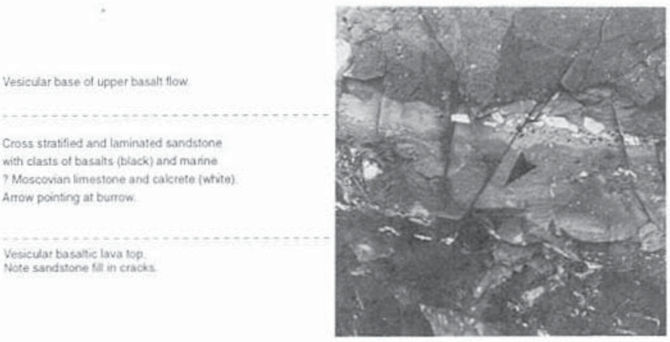

Fig. 8. Thin volcaniclastic sedimentary rocks interbedded between two basaltic lava flows. Close to the Oslofjord Master Fault, Jeløya. See figure 3 for location. Height of section 0.5 m.

water environments from Upper Carboniferous and Lower Permian. Recent dating of freshwater mussels (Eager, 1994) gives a late Stephanian age for this deltaic depositional sequence and thereby suggests an important time break between the middle and upper deltaic depositional sequences, i.e., between the pre-rift and initial rift infill. Lack of calcretes and the presence of minor coaly fragments (in contrast to the overlying and underlying depositional sequences), together with a flora partly comparable to Carboniferous swamp deposits in Northern Europe suggest more humid conditions during deposition of this sequence.

The depositional environment for the upper deltaic depositional sequence is suggested to have been a fluvial-dominated delta which prograded into a lacustrine or brackish water basin.

Thin shales and up to 1 m thick, dark grey sandstone below the first lava flow elsewhere in the central part of the Oslo Graben may represent remnants of the upper deltaic depositional sequence.

Volcaniclastic alluvial fan depositional sequence (Skaugum Formation) and/or thin basalt flows occur in the northernmost part of the Vestfold Graben (Figs. 5 and 7). The lower boundary of the Skaugum Formation (Henningsmoen, 1978) is erosive. The formation consists of red debris flow and water laid conglomerates, calcrete beds, paleosols and laminated limestones with ripple laminae and teepee structures suggesting playa-lake deposits. Coarse grained stream and debris flow facies dominate the lower and upper parts of the up to 20 m thick sequence and fine grained lake deposits with minor plant fragments occur in the middle part. Deposition from alluvial fans is suggested for this formation. The clasts consist of basalt fragments with a clear affinity to the alkali olivine basalt flows of the Vestfold Graben. This, together with northeastward directed paleocurrents, shows that the alluvial fans were derived from local lava highs in the south. These highs could have been developed either by tectonism or by accumulation of the lava flows themselves, as volcanic ridges or plateaus.

Calcretes, teepee structures in the playa-lake deposits, together with sparse flora, suggest an arid to semi-arid climate in contrast to more humid conditions of the underlying upper deltaic depositional sequence.

The basin fill of the initial rift phase was controlled by basin floor subsidence, climate, volcanism and increasing topographic differences caused by lava flows and minor faulting.

The Skaugum Formation does not occur north of the transfer faults in the accommodation zone between the two graben segments; only a single tholeiitic lava flow caps the pre-rift basin fill. The eruption of this lava flow ended the initial rifting phase (Fig 7). To the north, in the Akerhus Graben only weathered lower Paleozoic rocks or a thin conglomerate bed underlie lavas of the syn-rift phase (see below).

THE SYN-RIFT PHASE I (RIFT CLIMAX) ?ASSELIAN-SAKMARIAN

This is the main lava eruption and graben-forming phase of the Oslo Rift (Figs. 9 and 10). Generally the basin fill in this phase comprises large volumes of mildly alkaline intermediate lava flows (rhomb-porphyry, RP) and some alkaline basalt flows. The rhomb-porphyry flows erupted from north-south striking monogenetic fissures. Some of these lava flows covered several thousand square kilometres and a much larger area than the present outline of the Oslo Graben. The lava units become thinner and are more locally developed upwards in the stratigraphic column. The fault activity increased towards the end of this phase and local highs and lows were well developed. A rift valley was formed at the close of this phase. In addition to the lavas and associated extrusives, the sedimentary infill also reflects the syn-rift character of this phase. The deposits (Figs. 9 and 10), which are of continental origin, can be subdivided into the following depositional settings: 1) thin but widespread alluvial, eolian and lacustrine deposits between the lavas, 2) local volcaniclastic alluvial fans associated with structural highs of the rift segments, 3) thick volcaniclastic alluvial fans banked against the Vestfold Graben master fault, and finally 4) some 700 m of dune and wadi deposits, the Brumund Sandstone, in the northernmost part of the Oslo Rift. The deposits of the first three settings are well dated, based on lava stratigraphy and thereby clearly related to the syn-rift phase.

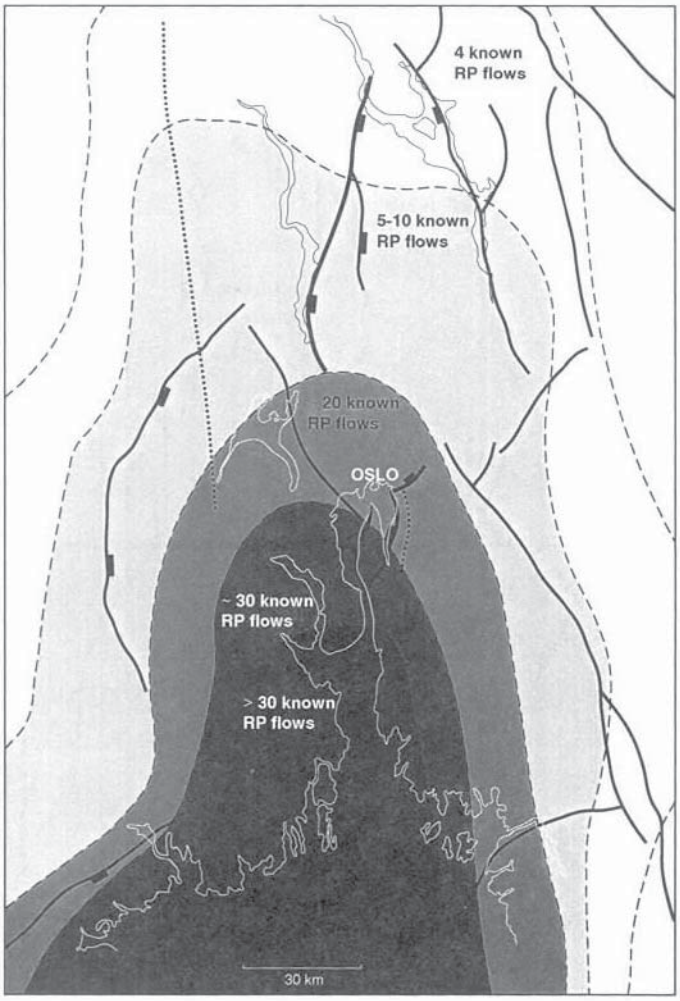

Fig. 9. Early syn-rift I phase with rhomb-porphyry lavas and thin continental sediments between lavas. Stippled line: Rhomb-porphyry dykes.

The thin, widespread alluvial/eolian/lacustrine deposits are intercalated with the lavas and can be mapped for several

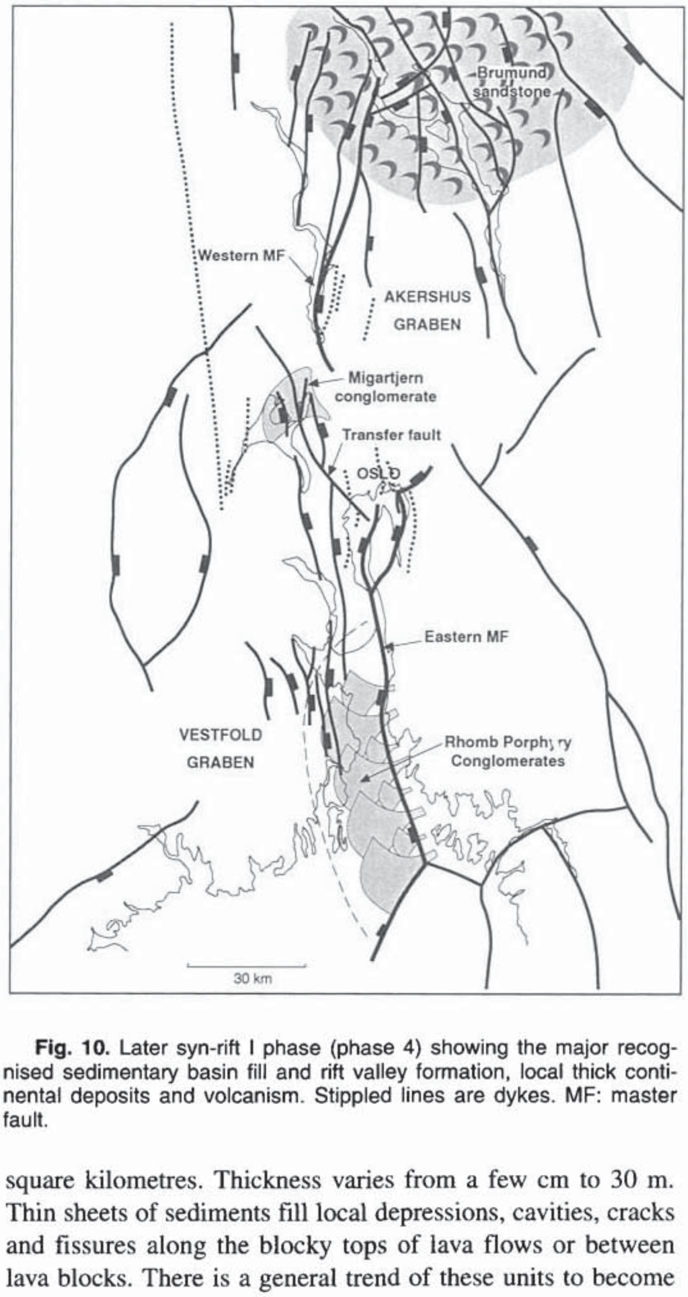

Fig. 10. Later syn-rift I phase (phase 4) showing the major recognised sedimentary basin fill and rift valley formation, local thick continental deposits and volcanism. Stippled lines are dykes. MF: master fault.

square kilometres. Thickness varies from a few cm to 30 m. Thin sheets of sediments fill local depressions, cavities, cracks and fissures along the blocky tops of lava flows or between lava blocks. There is a general trend of these units to become thicker upwards and northwards in the Akershus Graben, reflecting both increasing topography and a decrease of volcanic activity (Henningsmoen, 1978). Fine to very fine grained, large scale cross-stratified sandstones consisting of very well sorted and rounded sand grains suggest eolian deposits, while planar and trough cross-stratified conglomerate and cross-stratified coarser grained sandstones represent stream flood deposits. Mudstones with minor carbonate nodules suggest flood plain or minor pond deposits.

The thickest units occur in the northernmost outcrop of the Oslo Graben. No fossils have been found. Of particular interest is a 10 m thick succession between the uppermost rhomb-porphyry lava flows in the northernmost outcrop area at Brumunddal. This succession can be subdivided into two shallowing upward units. Both consist of ripple laminated, fine grained sandstone and calcareous mudstones which become increasingly calcareous upwards. Both units are capped by fining upward stream channel-fill deposits. Within the upper unit the calcareous mudstone passes upwards into 5 to 10 cm laminated limestone beds which show undulating surfaces and in one case form two mound-like structures. Faint tubes of algal affinity are seen in thin section, suggesting a fresh water stromatolitic origin for the limestone and mounds. The two units are interpreted in terms of lacustrine basin fill. Calcareous nodules elsewhere in the Oslo Graben within this thin, widespread, intercalated sedimentary basin fill represent calcrete palesols.

Alluvial fans associated with structural highs of the accommodation zone occur between the Akershus and Vestfold Graben segments. Two volcaniclastic conglomerates outcrop in the Krokskogen Lava Plateau. The stratigraphic succession of the thin, widespread deposits in the lower pile of the lava flows and the occurrence of these two alluvial fans higher up in the volcanic strata reflect the evolving topography in the Oslo Graben during syn-rift phase I.

The first unit consists of up to 30 m of monomict conglomerate, rare sandstones and mudstones (Fjellstadhytta conglomerate; Larsen, 1978). The pebbles derive from the underlying 5th rhomb-porphyry (RP) lava flow, with a few clasts of the laterally outcropping 6th RP lava flow on the top of the unit. Some of the conglomeratic beds are well sorted, rounded and cross-stratified, and this, together with sandstones with current ripple laminae suggests stream deposits. Unlike the thin, widespread deposits intercalated with the underlying rhomb-porphyry lavas, these deposits can be traced only for 2.5 km and are laterally replaced by a lava flow (6th RP flow). This unit thins southwestwards and abuts against a fault in the northeast. It was probably deposited as small fans with drainage towards the west or north during episodes of faulting and catastrophic flooding associated with the eruption and outpouring of the laterally equivalent lava flow.

The second unit is younger than the first unit and is called the Migartjern conglomerate (Fig. 10) (Larsen, 1978). The Migartjern conglomerate has a thickness of up to 400 m, with blocks reaching 4 m in diameter (Fig. 11a). Conglomerates with fragments of the nine underlying rhomb-porphyry and basalt lavas are the dominant rock facies. Minor occurrences of sandstones and mudstones are also seen. The dominating facies are interpreted as debris flows, with minor sheet floods, stream channel and sieve deposits. The conglomerate covers an area less than 5 km^{2}, but cuts erosively down through a stratigraphic succession of up to 700 m of the lava pile, including most of the basal basalt flow, suggesting that the conglomerate represents a canyon fill. The sequence is capped to the north by a local basalt flow and by a rhomb-porphyry flow, both of which also appear to be a part of the canyon fill. Fragments of basalt flows occur in the upper part of the depositional sequence, suggesting contemporary events of lava flows and deposition further south of the lava plateau. Mapping, coupled with depositional facies and scattered paleocurrent measurements suggests that the paleocurrent direction was to the north-northwest. The deposition presumably terminated in an alluvial fan that spread out onto lowlands and

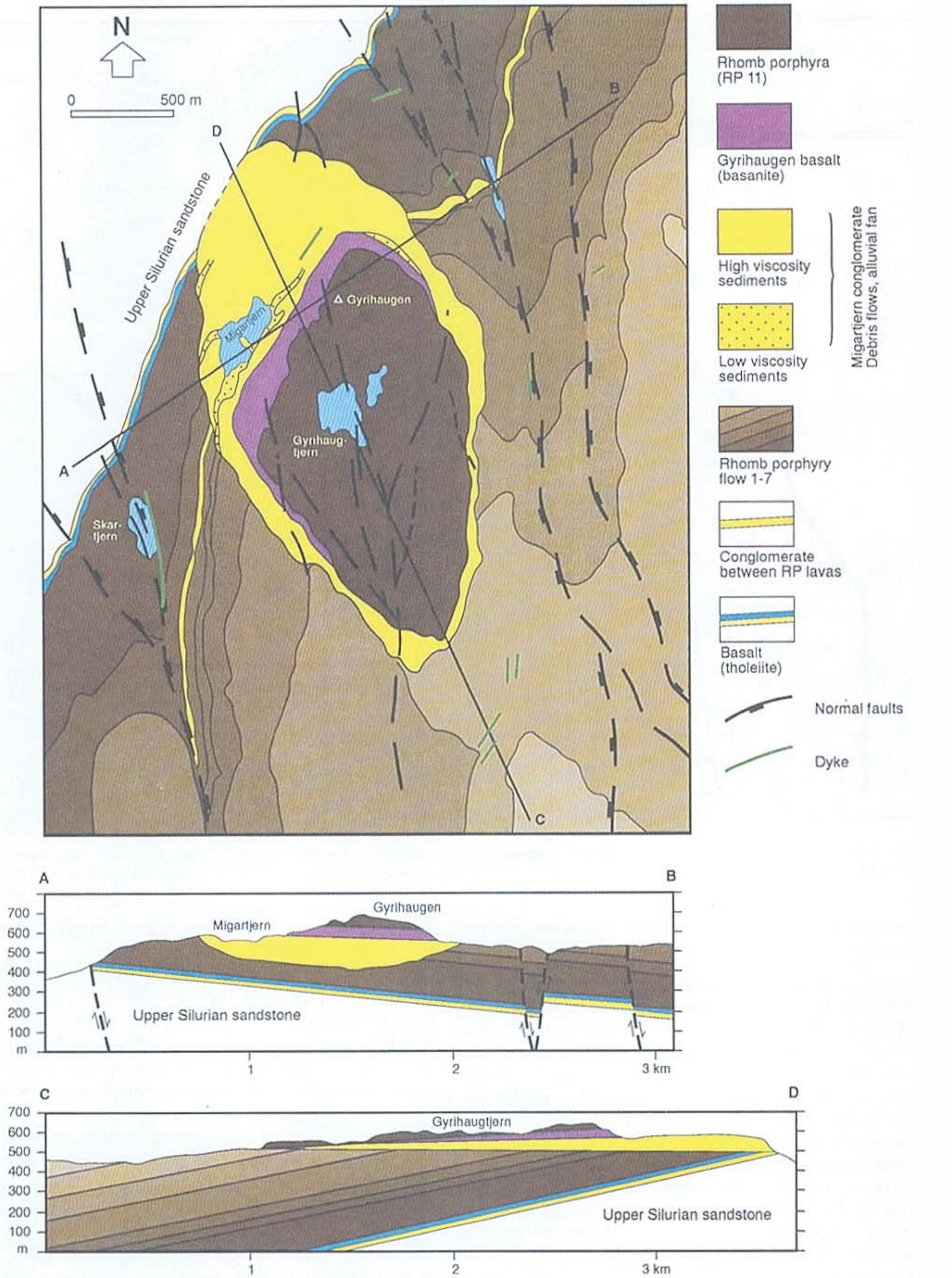

Fig. 11. Map sections and model showing alluvial fans associated with structural highs in the accomodation zone between the Vestfold and Akerhus Graben. a) Geological map and cross-sections of the canyon fill.

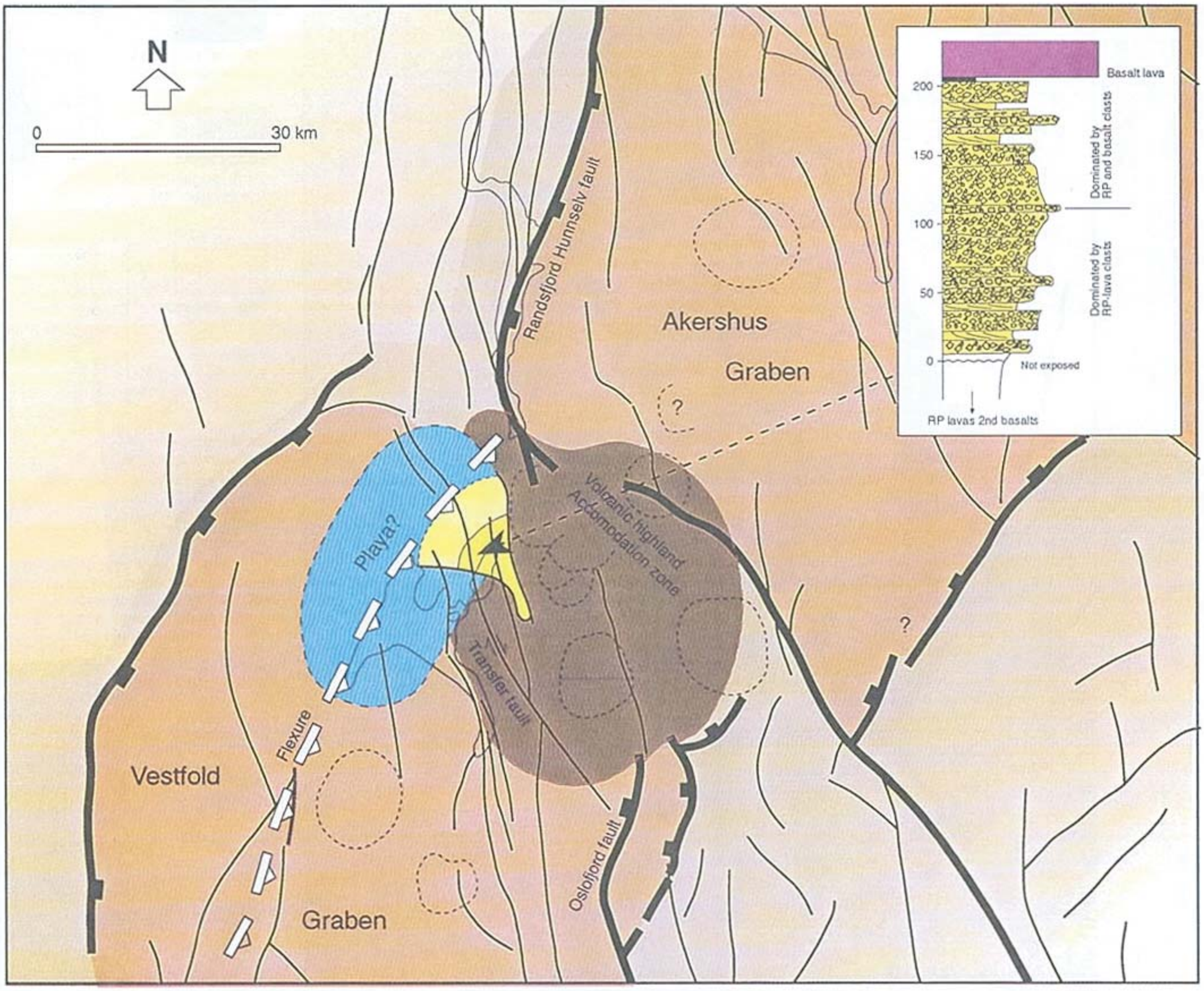

Fig. 11. b) Conceptual model of the volcaniclastic fan spread out onto lowlands in northern part of the Vestfold Graben. Stippled circles are outline of calderas. Legend as in figures 3, 5 and 18. Inset shows a stratigraphic column of the canyon fill at the arrow. Vertical scale in metres.

probably across the area of the northern part of the Vestfold Graben (Fig. 11b).

Alluvial fans banked against the master fault occur in the Vestfold Graben. The conglomerates formed along the Oslofjord Master Fault (Fig. 10), known as the Rhomb Porphyry Conglomerates (Brøgger, *1900*; Størmer, *1935*; Larsen et al., 1978; Midtkandall, 1981), outcrop along a 40 km stretch of islands. The succession has apparently a great stratigraphic thickness, and a minimum thickness of 1000 m can be measured on Rauøy (Fig. 3). The coarseness of the conglomerates (blocks up to 3-6 m in diameter), their textural immaturity, the rapid changes in grain size vertically and laterally, the stratigraphic thickness of the succession and its overall disposition flanking the graben master-fault all suggest that the deposits are fanglomerates built out from the marginal fault during basin subsidence. A measurable westwards decrease in coarseness of the conglomerates on some of the islands (e.g., the Sletter islands) supports this notion and suggests a minimum fan radius of 2 km in places.

The fanglomerates are of a variety of types, ranging from deposits of viscous debris flows to those resulting from stream flow. The debris flows are usually the most poorly sorted, though they occur in often well defined beds, with clasts sometimes matrix-supported. Signs of laminar flow in these beds include inverse or inverse-normal grading, outsize clasts protruding above bed tops and lack of obvious basal erosion. The most common types of fanglomerate are those deposited, or at least influenced in their latest phases by stream processes. These beds are usually better sorted than the debris flows, always clast-supported (sometimes openwork), associated with rapid grain size changes above and below and sometimes stratified internally. The finest grained conglomerates, commonly on the west side of the islands, are of sheet flood origin. These are extensively laminated and originated by sheetflows or laterally extensive, shallow braided channels on the lower reaches of the alluvial fans. Scattered outsize blocks in these deposits arose by dumping at the mouths of channels with the sudden reductions of flow depth. As a whole the fanglomerate beds are dominated by stream and sheetflood deposits, characterizing the fans as "wet" or fluvial-dominated. This is relatively unusual in an arid or semi-arid climate (as testified by caliche here and in neighbouring deposits farther north) and may be a result of repeated rainstorms caused by the ongoing volcanic activity.

In the fanglomerate successions there occur relatively well defined, coarsening upward (CU), fining upward (FU) and symmetrical (CUFU) units of some 2 - 8 m and 20 - 30 m thick (Fig. 12a). The thinner sequences are likely to reflect fan lobe progradation, abandonment and lateral shifting, while the thicker sequences may be major progradational wedges initiated by phases of repeated basin floor sinking and/or tilting against the master fault. Vertical grain size trends of 100-200 m thick units, usually coarsening upwards or near symmetrical in character, have also been defined. Their origin is as yet unknown, but they appear to be developed on individual blocks and may be related to syn-sedimentary fault block movement (Fig. 12b).

The composition of the fanglomerate clasts is monotonously volcanic-dominated by different rhomb-porphyry lavas (65%) and a number of different basalt (30%) types. Additional clast types (usually less than 5%) are conglomerates, sandstones and calcrete from the Upper Carboniferous Tanum Formation, and sandstones from the Upper Silurian (Fig. 12a). Precambrian rocks and clasts of marine lower Paleozoic rocks have not been found. The reason for the incoming of greater than normal concentrations of older sedimentary clasts at certain levels in the succession is also uncertain, but presumably is related to the development of specific dispersal shadows tapping older sources. This may have been achieved by syn-sedimentary block faulting and erosional downcutting into the substrate of the volcanic pile through canyons on the footwall to the east of the Oslofjord Master Fault. Some northerly paleocurrents (in addition to those from the east) support this idea. There is some evidence of an overall change to older clasts in the conglomerates along the master fault northward as far as the Sletter Islands. This may indicate a northwards migration of the depocentre and fault movement with time, as well as a northerly onlap of sediments (Fig. 12b).

Dune and wadi deposits, the Brumund Sandstone. Lack of biostratigraphic data, as well as lack of preserved lateral or overlying rock units in the thick eolian and wadi deposits, the Brumund Sandstone (Fig. 10), make the age speculative. A suggested Triassic age (Spjeldnæs, 1971; Ramberg and Spjeldnæs, 1978) would relate the sandstone to the post-rift phase. However, based on the following geological observations and interpretations, we suggest an Early Permian age for the Brumund Sandstone: a) the sandstones are petrologically and with respect of facies association very similar to the underlying sandstones, which are intercalated with four rhomb-porphyry lavas, b) the uppermost of these lavas is dated to 279 +/-9 Ma (Sundvoll and Larsen, 1990), c) the sandstones are preserved within a down-faulted block and have progressively less dip angle upward in the strata (Rosendahl, 1929), which is interpreted to be coeval with the major syn-rift extensional phase. The Brumund Sandstone, which is reported to be up to 700 m thick (Rosendahl, 1929), consists of very well sorted sandstone with well rounded grains (Fig. 13b) with minor mudstone intercalations. The formation has been interpreted by Rosendahl (1929) in terms of aeolian, fluvial and lacustrine conditions. The textural data from the permeable and porous (18-20%) fresh water, reservoir sandstones are consistent with an aeolian origin (Englund and Jørgensen, 1975). Outcrops along the river Brumunda (Fig. 13 a) have revealed large scale dunes with clear grain size separation between laminae in the foreset beds, cut by channel structures, some 1-2 m deep, where the fill of the latter consists of more poorly sorted sandstone with a yellowish colour. This facies association suggests an aeolian dune deposits and ephemeral stream deposits, i.e., similar to the wadi deposits of the Rotliegendes in northern Europe (Glennie, 1984).

Radiometric dating of batholithic intrusions (Sundvoll and Larsen, 1990; Sundvoll et al., 1990) indicates that during the latest part of this syn-rift phase large larvikitic and granitic batholiths were intruded at deeper levels and reached locally the earliest lava flows. At the present erosion level syn-rift batholiths are particularly well exposed in the southern part of the Vestfold Graben.

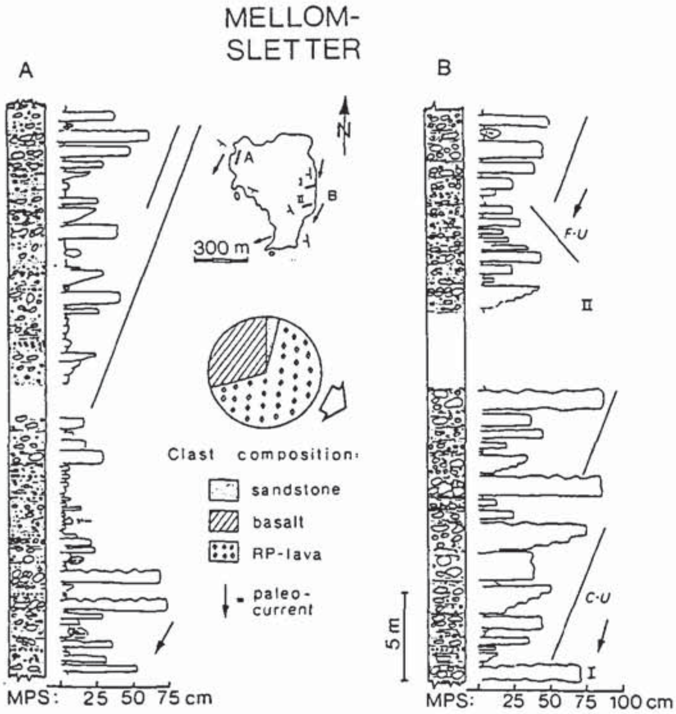

Fig. 12. Thick alluvial fans banked against and derived from the Oslofjord Master Fault. **a)** Stratigraphic profiles from Mellom Sletter island which illustrates the coarsening upward (C-U) and fining upwards (F-U) trends. MPS: Maximum Particle Size. After Midtkandal (1981).

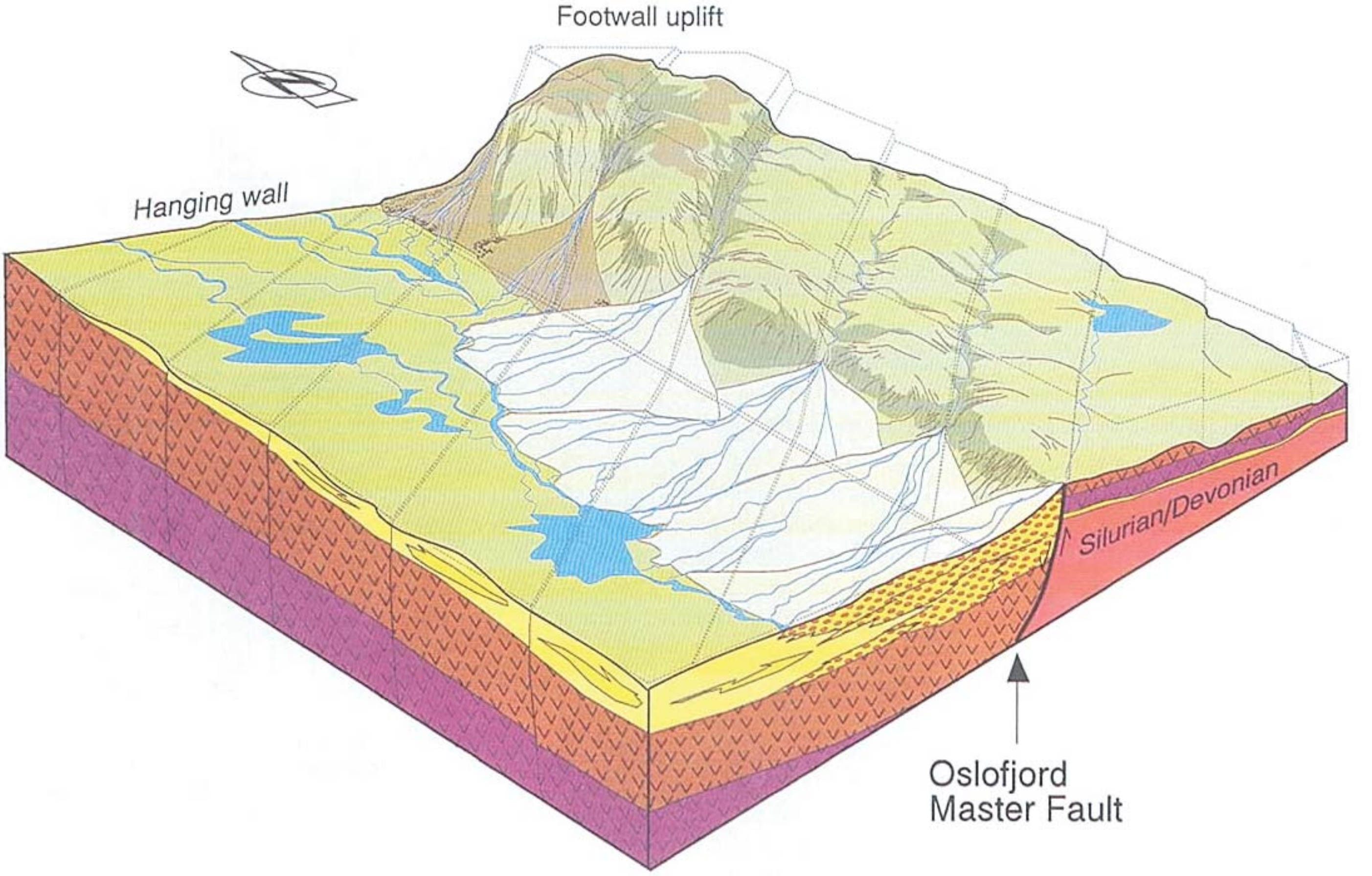

Fig 12. b) Conceptual model of the fanglomerates along the Oslofjord Master Fault. Radius of fans: 2-5 km.

The Syn-Rift Phase II (Early Permian Rift Relaxation)

This phase was characterized by the building up of large, polygenetic, mostly alkali basaltic, central volcanos which formed along prominent tectonic lineaments on the rift valley floor (Fig. 14) (Ramberg and Larsen, 1978). Later the basaltic melts differentiated in the magma chambers, with explosive felsitic volcanism resulting in caldera collapse (Larsen, 1984). Small local syenitic and alkali granitic intrusions are present as ring dyke intrusions and central intrusions inside the calderas. Radiometric dating, mostly on ring dykes, suggests an Early Permian age (Sundvoll and Larsen, 1990; Sundvoll et al., 1990).

Besides lava flows and agglomeratic deposits, alluvial and lacustrine deposits inside the calderas are recorded. Though the basin fill must have been prominent in this phase, none of these fillings are preserved today. The volcaniclastic rocks inside the caldera consist of conglomerates with dominance of basaltic and felsic fragments, sandstones and red mudstones (Sæther, 1962; Naterstad, 1978). The volcaniclastics are intercalated with ignimbrites, tuffs and lavas which are locally developed and can seldom be followed laterally more than a few hundred metres. Interfingering of poorly sorted and slumped conglomerates and cross-stratified sandstones and mudstones suggest an origin as talus breccias, alluvial fans and lacustrine deposits. This phase records the last preserved basin fill within the two onshore graben segments.

The Batholith Emplacement and Termination Phase (Early Permian-Earliest Triassic)

The two last phases have, at the present erosion level, no sedimentary or extrusive rocks preserved. The 5th phase of development was characterized by intrusions of large batholiths, whereas the termination phase, phase 6, saw the emplacement of some few and small granitic intrusions (Fig. 15) (Ramberg and Larsen, 1978; Larsen and Sundvoll, 1983). These phases, which end the recorded development of the onshore graben segments, are suggested to have taken place from the Early Permian through to the earliest Triassic (Sundvoll et al., 1990).

Summary of the Preserved Basin Fill of the Oslo Graben

The basin fill of the Oslo Graben has been described from the pre-rift, via initial rift to the syn-rift, and finally to the magmatic termination phases of the Oslo Graben (Fig 18). The Oslo Graben is a high-volcanicity, intracontinental rift system comparable to the recent Kenya Rift of the East Africa rifts (Larsen and Sundvoll, 1984). It is therefore important to stress that the major volume of the basin fill in the extensional rift phase (initial rift, syn-rift I and syn-rift II) comprises lavas and

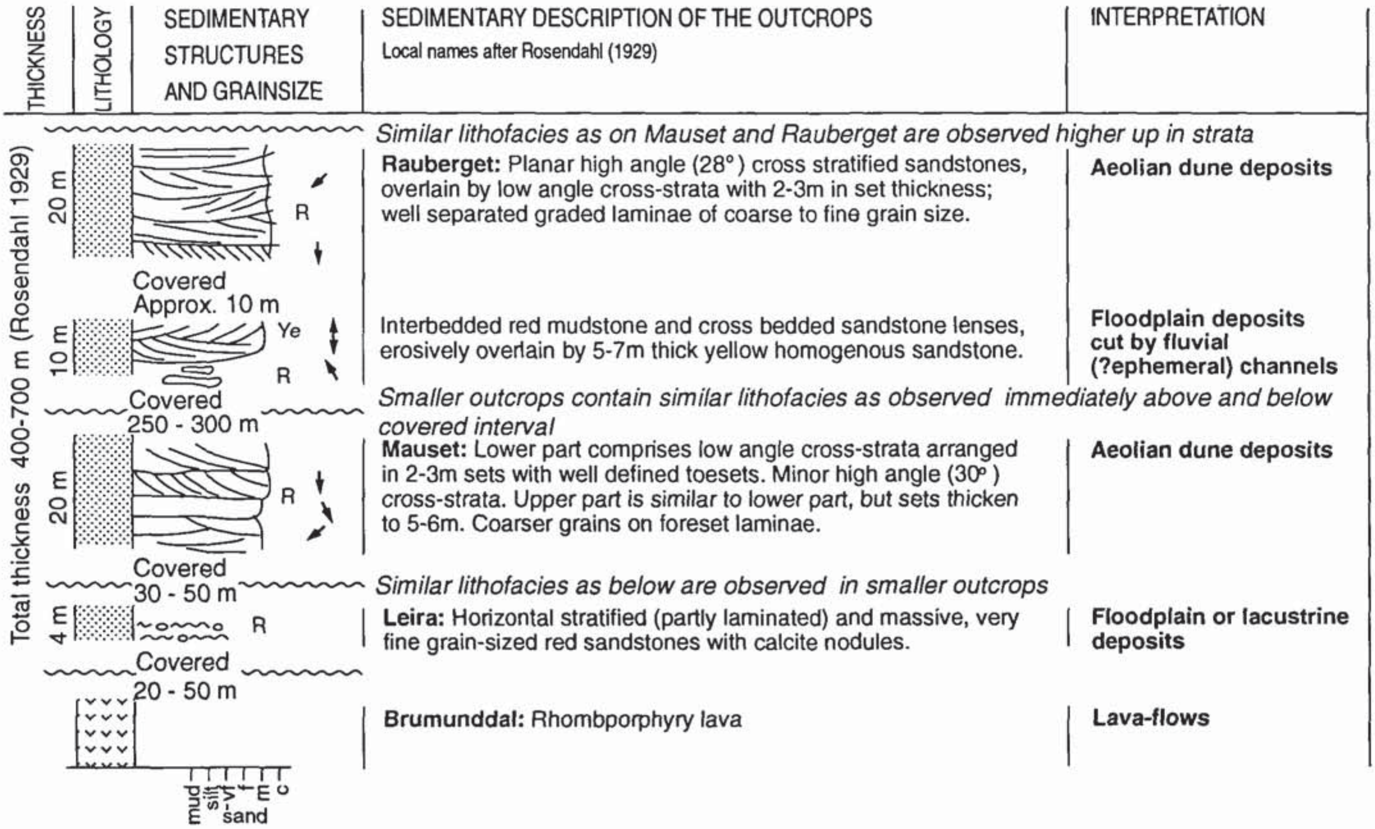

Fig. 13. Thick aeolian and wadi deposits in the northernmost part of the Akershus Graben segment. The Brumund Sandstone. **a)** Compiled profile from scattered and poor outcrops along the river Brumunda.

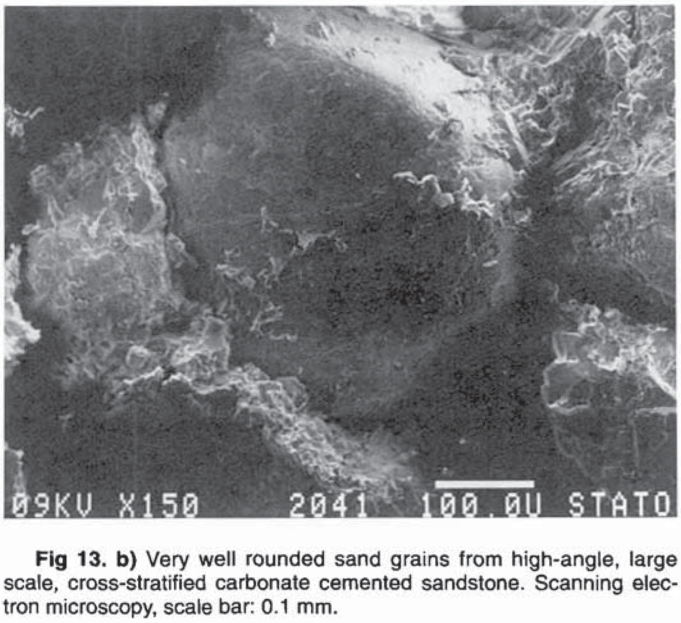

Fig 13. b) Very well rounded sand grains from high-angle, large scale, cross-stratified carbonate cemented sandstone. Scanning electron microscopy, scale bar: 0.1 mm.

other associated extrusive rocks. Indeed, volcanicity in the Oslo Graben was strong enough for extrusives to fill in most of the relief produced by rifting (Oftedahl, 1980), thus explaining the small amount of extensional rift sediments.

The two graben segments in the Oslo Graben express an excellent example of polarity changes and offsets, including an accommodation zone and associated transfer fault in the graben architecture (Figs. 2, 3 and 10 and 11b), as derived from the East African rifts (Rosendahl, 1987).

The thickness variations of the sediments and lavas, the compositional variations of the lavas and the facies variations of the sedimentary rocks can be associated with specific locations and the graben architecture in the Oslo Graben (Fig 3). The Vestfold Graben and Akershus Graben segments were, in most situations, developed differently.

From the sparse sedimentary rock record and the documented magmatic and tectonic evolution the development of the Oslo Graben has been subdivided into six phases, in which only the first four have a preserved stratigraphic record of the basin fill (Fig 18):

1) On the Late Carboniferous peneplain in the Oslo Region a lacustrine alluvial plain and fluvial-dominated delta and a overlying Moscovian tidal-influenced braid-delta developed, reflecting the basin fill prior to the rift basin formation. This is the pre-rift phase.

2) The basin fill of the first extensional rift phase, the initial rift phase, was dominated in the south (Vestfold Graben) by thick alkali basalts and associated extrusives and volcaniclastics. To the north, a Gzelian (late Stephanian) lacustrine delta and volcaniclastic alluvial fan and a thin tholeiitic, basaltic lava flow were deposited and extruded close to the accommodation zone between the two graben segments.

Fig. 14. Syn-rift II phase, central volcanos and caldera collapse. Dark mm sized spots: mafic plugs. Light grey mm sized dots: volcanic vent breccia. Small cm sized circles: cauldrons as observed in field. Larger, stippled, cm sized circles: possible extent of central volcanos.

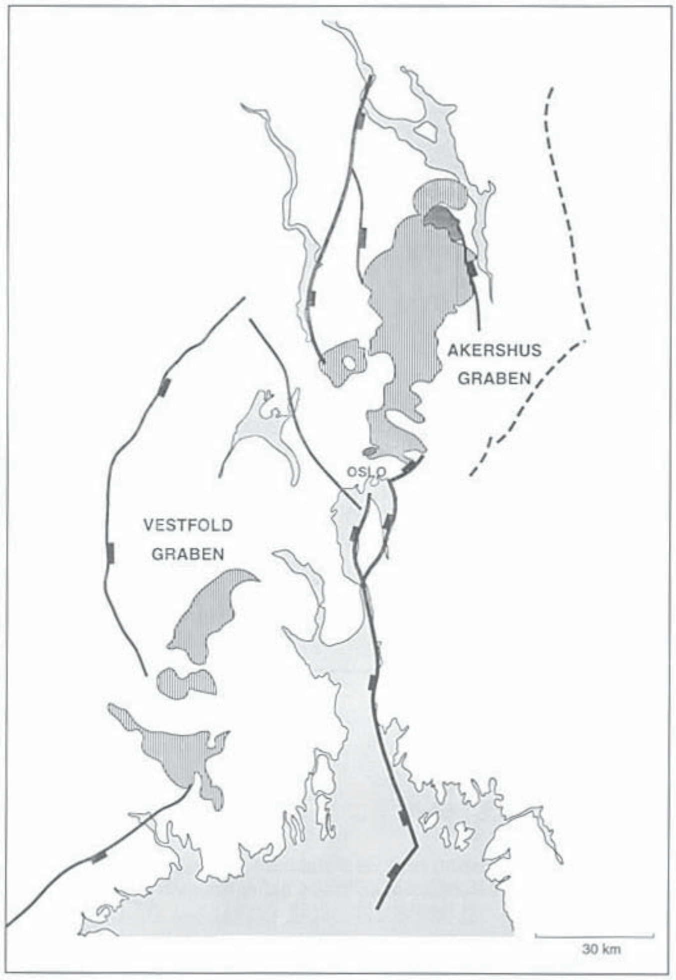

Fig. 15. The batholith emplacement and termination phase (phases 5 and 6). Areas with vertical lines represent large batholiths, while dark dotted areas represent small granitic intrusions.

3) Large volumes of lava flows (rhomb-porphyry and basalt), interbedded with thin but widespread eolian, lacustrine and fluvial deposits introduce the syn-rift phase. Major normal fault displacements, local but thick alluvial fan deposits within the accommodation zone, fanglomerates banked against the Oslofjord Master Fault and thick aeolian and wadi deposits in the northern part of the Akershus Graben reflect the major extensional event in the Oslo Graben and the rift valley formation and architecture in the syn-rift I phase (rift climax). Normal faulting, coupled with a high production rate of extrusives and rapid basin floor subsidence controlled deposition in the syn-rift I phase, which occurred in the Asselian and Sakmarian.

4) The syn-rift II phase was a phase of central volcano collapse and caldera infill in connection with felsic explosive volcanicity. Only local lacustrine and fanglomerate deposits, together with extrusives, are preserved inside the calderas as basin fill in this phase.

Today the Oslo Graben is expressed as an erosional feature (Fig. 16d), a large volume of its original basin fill having been by erosion in post-Permian time.

The Skagerrak Graben and Post-Rift Development of the Oslo Rift

We have described the recorded development of the Oslo Graben; from pre-rift in Late Carboniferous through the syn-rift and to the termination phases at the Permian to Triassic transition (Fig. 18). Thermal sag and sediment infill as seen in relation to the subsequent cooling of the lithosphere after rifting (McKenzie, 1978) is not recorded in the Oslo Graben. Lack of typical post-rift sedimentary fill has been used as an argument that the onshore Oslo Graben is an abnormal rift basin (Pallesen, 1993), or that the post-rift phase might have been developed but later eroded (Bjørlykke, 1983). Several kilometres of erosion of the Oslo Graben has long been recognised in the literature (Fig. 16d) (Brøgger, 1886)). Due to the present erosion profile no stratigraphic record is present to determine the post-Permian burial history.

Investigation of the offshore graben segment, coupled with regional geological knowledge, fission track analysis (Rohrman et al., 1993) and geophysical investigation can provide some insight into the post-rift development of the Oslo Rift.

Ramberg and Smithson (1975) suggested that the onshore Oslo Graben continued offshore towards the Sorgenfrei - Tornquist Zone. Seismic interpretation of the Skagerrak Graben and regional seismic studies in adjacent areas, together with well data from analogous half grabens along the Sorgenfrei-Tornquist Zone, suggest that the Skagerrak Graben developed in a similar manner to the onshore Oslo Graben, but with probably less magmatism (Ro et al., 1990; Ro and Faleide, 1992; Vejbæk, 1990; Michelsen and Nielsen, 1991). Geophysical studies (gravity, magnetic and deep seismic) and seismic interpretation suggest that the Skagerrak Graben is a sedimentary basin with lower Paleozoic deposits and probably upper Paleozoic pre-rift and syn-rift deposits. This basin fill is capped by Mesozoic to Cenozoic platform deposits as illustrated in Figure 16a (Ro and Faleide, 1992; Vejbæk, 1990; Husebye et al., 1988; Pedersen et al., 1991; Lie et al., 1993). Vejbæk (1990) suggested that the eastern part of the Skagerrak Graben consists of a 2 km thick lower Paleozoic sequence overlain by a 2 km thick succession of Upper Carboniferous/Lower Permian volcaniclastics. The borehole Sæby 1, north of the Børglum Fault in the Danish Kattegat area, encountered 200 m of volcaniclastics in a setting similar to that of the east boundary fault in the Skagerrak Graben (Michelsen and Nielsen, 1991). A thin marine Upper Permian clastic unit overlies an unconformity above the volcaniclastics in the east of the Skagerrak Kattegat Platform. However, as illustrated in Figs. 16a and c, Triassic and younger strata generally onlap either Rotliegendes or older strata in the eastern part of the Sorgenfrei-Tornquist Zone (Vejbæk, 1990). From the above observations and interpretation we conclude that the Skagerrak Graben infill probably consists of lower Paleozoic shales, limestones and sandstones and upper Paleozoic sandstones, shales and volcaniclastic and extrusive rocks.

In contrast to, for example, the Viking Graben (Fig. 16b), we suggest that the typical post-rift basin fill, as a response to flexural subsidence, is missing in the Skagerrak Graben (Fig. 16a). In the Skagerrak Graben a regionally correlative Triassic reflector truncates not only most of the interpreted upper Paleozoic basin fill but also the basal Cambro - Silurian rocks on the "highs" (Fig. 16a). This unconformity can be correlated

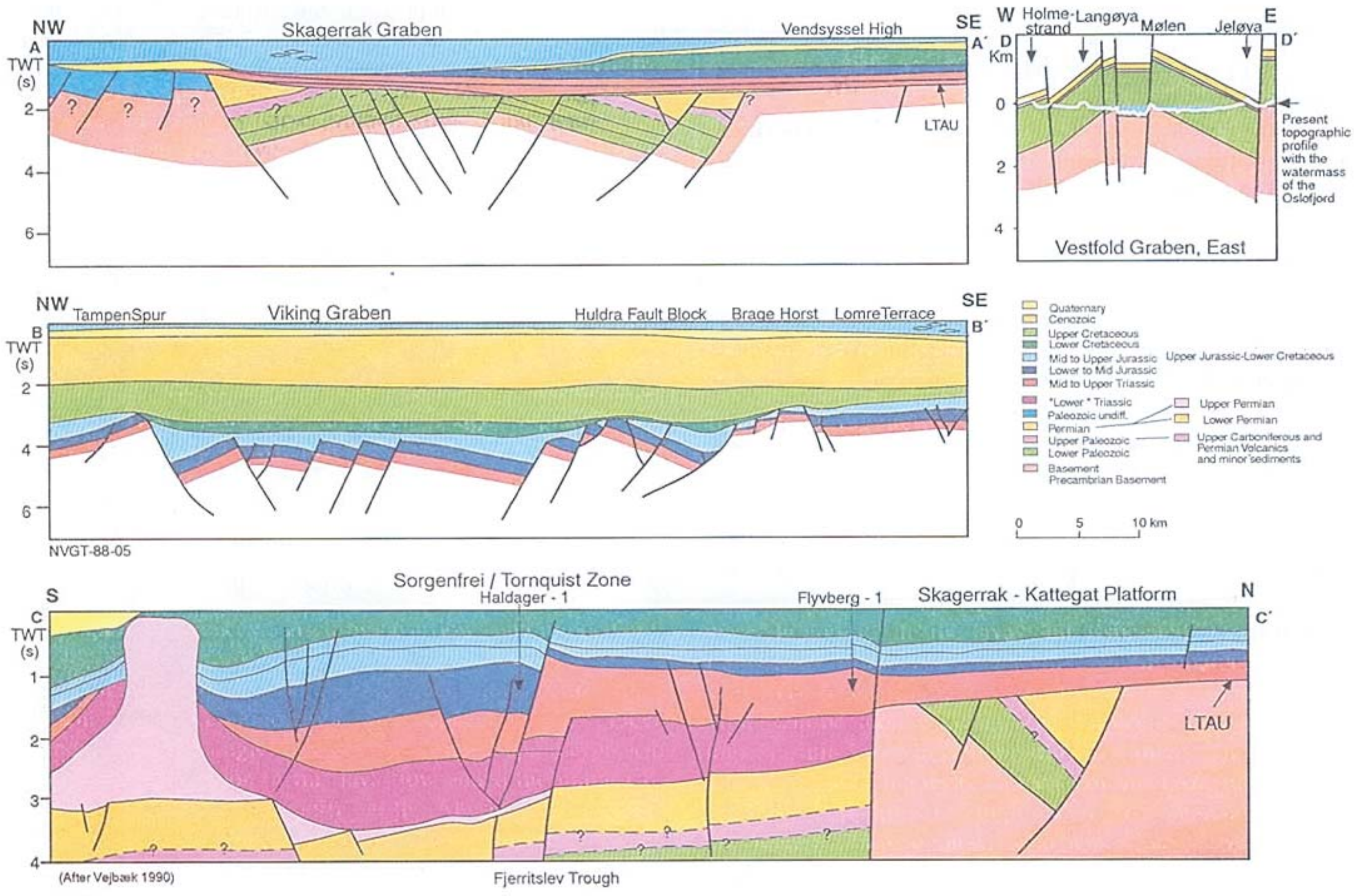

Fig. 16. Geoprofiles. See Figure 1 for location. All profiles close to horizontal scale. a) Skagerrak Graben, note the erosive character of the near base Triassic reflector. A-A' section in figure 1. Based on seismic line OG-7 (University of Oslo/Geoteam). b) Viking Graben, note the post rift sag, green on the figure. B-B' section in figure 1. LTAU: Lower Triassic angular unconformity. Based on seismic line NVGT-88-05 (Nopec). c) Geoprofile from Skagerrak-Kattegat Platform to the Danish basin. Note the erosive character of the Paleozoic half graben capped by Upper Triassic. C-C' section in figure 1. LTAU: Lower Triassic angular unconformity. Modified from Vejbæk (1990). d) E-W section (D-D' section in Fig. 1) across the middle part of the Oslofjord, Vestfold Graben. Modified geoprofile from Brøgger (1886).

with the Lower Triassic angular unconformity (LTAU Fig. 16a,c) as reported in the Skagerrak and Kattegat area, (Jensen and Schmidt, 1993; Vejbæk, 1990; Michelsen and Nielsen, 1991). Lie et al. (1993) investigated the less known and problematic transitional zone between the Skagerrak Graben and the Oslo Graben (Figs. 1, 2). They interpreted it as a graben remnant with most of its basin fill removed through uplift and erosion. Zeck et al. (1988) suggested a 3 to 4 km uplift of Southern Sweden in the Early Triassic.

A possible post-rift basin fill of the offshore graben segment, the Skagerrak Graben, should be younger than the Early Permian syn-rift phase of the Oslo Rift, but older than the regionally correlative LTAU reflector, i.e., Late Permian to earliest Triassic in age. The thin Upper Permian marine clastic sequence seen in the Skagerrak/Kattegat area (Michelsen and Nielsen, 1991) could be a remnant of the post-rift basin fill. The nearby offshore basins to the south of the Skagerrak Graben (Fig. 16c) have preserved Upper Permian and Lower Triassic units. The post-rift development is then coeval with subsidence of the Northern Permian Basin in northern Europe (Glennie, 1984). We conclude that uplift and erosion may explain the lack of recorded post-rift basin fill in the offshore Skagerrak Graben. The "mid" to Upper Triassic basin fill in the Skagerrak Graben and surrounding areas overlying the LTAU reflector (Fig 16a) is interpreted as a response to large scale regional subsidence.

Drainage of the post-rift sediments of the Skagerrak Graben and strata from surrounding areas was probably towards the Farsund and Danish Basins (Fig. 17). Lervik et al. (1989) suggested that uplift of mainland Norway during the Triassic is reflected by deposition of thick coarse clastics within north-south fault-bounded basins. Steel and Ryseth (1992) refined this model further by suggesting a Scythian syn-rift sequence followed by Triassic post-rift sequences, implying erosion of mainland Southern Norway and deposition in rift basins close to the present coastline. This series of events is in accordance with the observed feature of the Skagerrak Graben.

As the Oslo Rift has the character of a normal continental rift (Ramberg and Larsen, 1978; Sundvoll et al., 1990; Neumann et al., 1992), we might also expect that post-rift basin fill occurred in the onshore Oslo Graben. However, there may have been a difference between the offshore Skagerrak Graben and the onshore Oslo Graben in the sense that the Oslo Graben was a more magmatic and "hotter" graben and may have been uplifted 2 km above sea level during the late syn-rift phase, as the Kenya Rift and Rio Grand Rift are today. Consequently, a broad post-rift fill may have been only sparsely developed late during the post-rift thermal subsidence. The termination of magmatism in the onshore graben segments is dated close to the Permian to Triassic transition. This, together with fission track analyses in northern part of the onshore Akerhus Graben segment (Rohrman et al., 1993) which suggest a "mid" Jurassic uplift, limits the possible post-rift basin fill to Triassic to Early Jurassic age in the Oslo Graben. An important period of regional uplift in the "mid" Jurassic in southeastern Norway is then suggested.

In this connection the development of some 7 major clastic wedges (time scale 5-16 m.yr) which built out from the West Norwegian mainland into basins in the northern North Sea during the mid Triassic to mid Jurassic intervals (between Early Triassic and Late Jurassic rift phases)(Steel, 1993) may well be of significance. These clastic wedges are believed to have been a response to large scale variations in Mesozoic subsidence rates. It is likely that basinal subsidence changes are closely related to hinterland uplift rates, in this case periodically from Scythian to Bathonian time.

The Oslo Rift in Relation to the Hercynian Orogeny

As summarised by Ziegler (1990), the Hercynian Orogenic cycle spans Devonian to Early Permian times, and thus represents both the final formation and internal suturing of the Pangea super-continent. The Variscan segment of the Hercynian Orogeny is referred to as the Western and Central European deformation part of this orogenic megasuture, and the formation of it lasted well into the late Westphalian (Ziegler, 1990; Glennie, 1984). From south to north in Western Europe we observe during Westphalian/Stephanian time a situation of collision, compression and formation of a thick foreland basin in the Rhenohercynian Basin. This basin had shal-

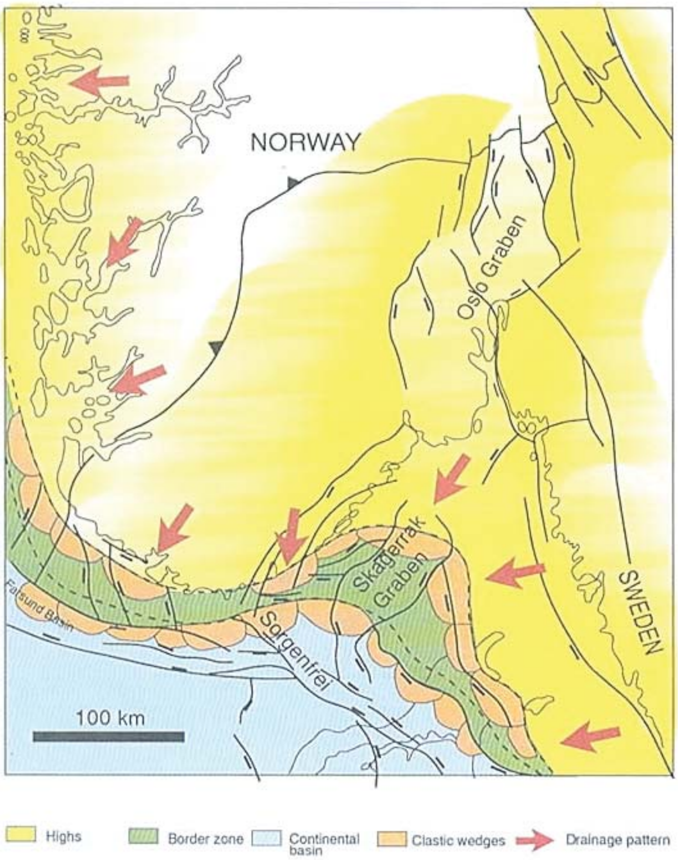

Fig. 17. A palinspastic reconstruction for the Early Triassic denudation of Southern Norway and subsequent basin fill in Kattegat and Skagerrak.

lowed out in the early Westphalian and a "molasse" stage of the foreland basin was introduced with deposition of paralic coal measures (Ziegler, 1990). Sediments were supplied from the Variscan Orogeny in the south and possibly from highs in the north. Ahrendt et al. (1983) reported from radiometric dating that the Variscan deformation front advanced northwards at a minimum rate of 0.5 cm/yr during the Namurian and Westphalian. This compressional stress reached as far north as the Oslo Region. The roughly east-west striking Variscan deformation front is today about 700 km south of the Oslo Graben. North of the Variscan front the WNW-ESE striking Sorgenfrei - Tornquist Zone (Fig. 1) was activated or reactivated by dextral strike slip movements along the location of the Fennoscandian Border Zone in its western segment (Pegrum, 1974). After the slip along the Sorgenfrei-Tornquist Zone, the stress was transformed into extensional stress north of the wrench fault and gave rise to formation of the Oslo Rift (Fig. 2).

The Oslo Rift was introduced by a weak, compressional pre-rift sag and deep magmatism during the Westphalian. This further resulted in formation of the northward propagating Oslo Rift as a mature rift structure consisting of several grabens with reversed polarities during the Early Permian. Another factor was the creation of a hot mantle under the Oslo Region which was able to produce large volumes of melted material and the high volcanicity of the rift.

We suggest an analogous setting between the tectonism and dynamic formation of the Oslo Rift in relation to the Variscan compression and the Baikal Rift formed from the Himalayan collision (Molnar and Tapponnier, 1975, 1977)

Early stages in the development of the Oslo Rift reflect minor extension and depression and are coeval with the late Variscan orogenic phase in the Westphalian (Fig. 18). The pre-rift deposits and its fauna and flora in the Oslo Graben are partly comparable with the Westphalian to Stephanian in Northern Europe, the so called barren red measures, and partly to Moscovian carbonates in the Barents Sea, Norwegian Sea and the Russian platform farther north, west and east of the Oslo Graben.

The initial and early syn-rift sedimentary basin fill shows similarities to the Lower Rotliegendes in the Northern Permian basins of the North Sea. The major extension of the Oslo Graben was succedeed by Variscan compression and was coeval with the onset of dyke swarms and lavas in the Mid North Sea area, Scania and northern British Isles (Glennie, 1984), together with the onset of subsidence of the Northern and Southern Permian basins in the North Sea.

The basin fill in the syn-rift stage is highly comparable to the Rotliegendes deposits in the Northern Permian Basin; particulary analogous are the 700 m thick dune and wadi deposits, the Brumund Sandstone, seen in the northernmost part of the Oslo Graben, which must have originally covered a wide area inside and outside the northern Akershus Graben.

The large scale pattern and tectonic setting and the timing of events are arguments favouring an influence of Variscan compression for the Oslo Rift forming as an extensional feature during the late Variscan. These structural relationships are thus examples of internal suturation during the formation of the Pangean super-continent.

Hydrocarbons in the Oslo Rift

Very little information exists concerning the history of hydrocarbon generation in the Oslo Rift. The occurrence of organic residues in some Cambrian, Ordovician and Silurian shales, limestones and sandstones (Dons, 1956; Hanken, 1974) suggests that the Oslo Region has been a former hydrocarbon generating basin (Dons, 1978). Indeed, oil stained Upper Ordovician inter-reef limestone which shows mature and biodegraded oil occurs in the north western corner of the Vestfold Graben. The Upper Cambrian and Lower Ordovician radioactive alum shales, which are rich in organic matter (average TOC 10%, Bjørlykke, 1974; Nyland and Teigland, 1984), are today post mature (Bharati, 1988) and overcooked. However, the alum shales are believed to have been oil generating source rocks in the Oslo Rift. Outcropping equivalent Cambrian/Lower Ordovician alum shales in Southern Sweden, approximately 200 km east of southern part of the Oslo Rift, are immature to late mature (Bharati, 1988).

Source rocks in the Oslo Region may have expelled hydrocarbons as early as Late Silurian and Devonian, during the development of the foreland basin fill of the Caledonian Orogeny. This foreland basin fill probably buried Cambrian/Lower Ordovician shales to several kilometres in depth (3-4 km) and was later removed by erosion (Ramberg and Spjeldnæs, 1978; Bjørlykke, 1983). High temperatures during Permian magmatism finally overcooked the Cambrian/Lower Ordovician source rocks in the Oslo Graben.

Gas chromatography analysis of oil in Permian diabase in the Arendal district (Dons, 1956; Carstens, 1959) shows dominance of n-C28,32 above n-C20,22 (Dons, 1975). In the Tvedestrand area (Fig 1) inclusions of light oil are also found in a Permian dyke (Kihle, written comm., 1993) (Fig. 19). Both of these localities are situated northwest of the Skagerrak Graben. Hovland (1991) suggested that gas seeps with methane and heavier hydrocarbons related to upper Paleozoic faults in the Skagerrak Graben were of combined thermogenetic and biogenetic origin. These observations suggest that secondary migration has taken place in the Skagerrak Graben or in the vicinity of the graben. Hydrocarbon discovery in the Skagerrak Graben is a possibility, though at very high risk. A speculative alternative to the Cambrian/Ordovician alum shale as source rock is the marine and/or lacustrine shales of Silurian or late Palaeozoic age.

Conclusions

i. The Permo-Carboniferous Oslo Rift was formed as an extensional response to dextral wrench movements along the Sorgenfrei - Tornquist Zone during late Variscan compression. Thus the Oslo Graben represents a local event of the formation and suturing of the Pangea super-continent.

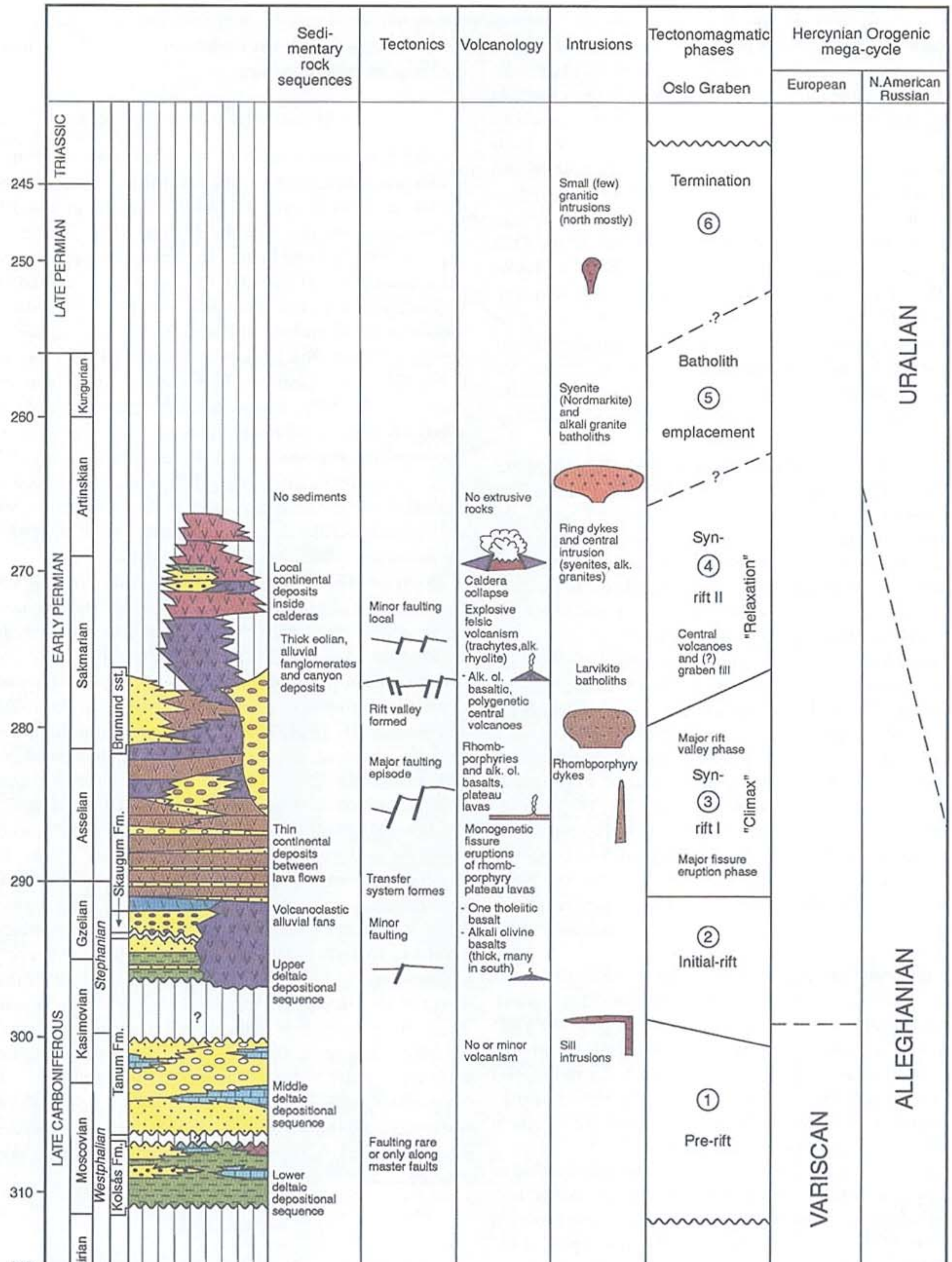

Fig. 18. Summary of the geological development of the Oslo Graben. Yellow: Sandstones and conglomerates; Green: shales; Blue: limestone; Red: evaporites or beds with pseudomorphs after evaporites; Purple: basalts; Dark blue: tholeiitic basalt; Brown: rhomb-porphyry and Red: trachytes.

ii. The Oslo Rift shows "normal" rift dynamics as seen, for example, in the East African rifts and the Rio Grande Rift. The Oslo Rift is comparable to the Kenya Rift of the East African rifts, and partly to the Rio Grande Rift in its high volcanicity and magmatism. The Oslo Rift is also comparable with classical continental rifts in its tectonic setting, length and breadth and graben offsets (rift architecture), and in its time span of tectonic activity.

iii. The concept of pre-, syn- and post-rift phases is applicable to the Oslo Rift in the development of the volcanic and sedimentary infill and erosion. In detail it has comparable similarities to, but also differences from other continental rifts.

iv. The stratigraphy and architecture of the basin fill, coupled with geophysical and petrological data, modelling results, the occurrence of a limited fossil record and detailed radiometric dating indicate a dynamic, six phase evolution of the Oslo Graben, from (?) Moscovian to the Permian - Triassic transition.

v. Apart from a short lived marine incursion in the Late Carboniferous, the mainly continental red coloured sediment fill of the pre- to syn-rift phases of the Oslo Graben was controlled by the rate of basin floor subsidence, faulting, volcanism and an arid to semi arid climate. The offshore Skagerrak Graben has probably undergone similar development, timing and basin fill, but probably with less magmatism.

vi. Post-rift sediments may have covered the entire Oslo Rift. The post-rift basin fill in the onshore graben segments is suggested to have been of Triassic and Lower Jurassic age. In the offshore graben segment an older, post-rift basin fill of Late Permian to earliest Triassic is suggested. This implies regional uplift and erosion north of the Sorgenfrei- Tornquist Zone in the Skagerrak/Kattegat area in earliest Triassic and "mid" Jurassic time.

vii. Potential hydrocarbon source rocks have been burned out in the onshore Oslo Graben. In the offshore Skagerrak Graben accumulation of hydrocarbons is possible, but the exploration risk is very high.

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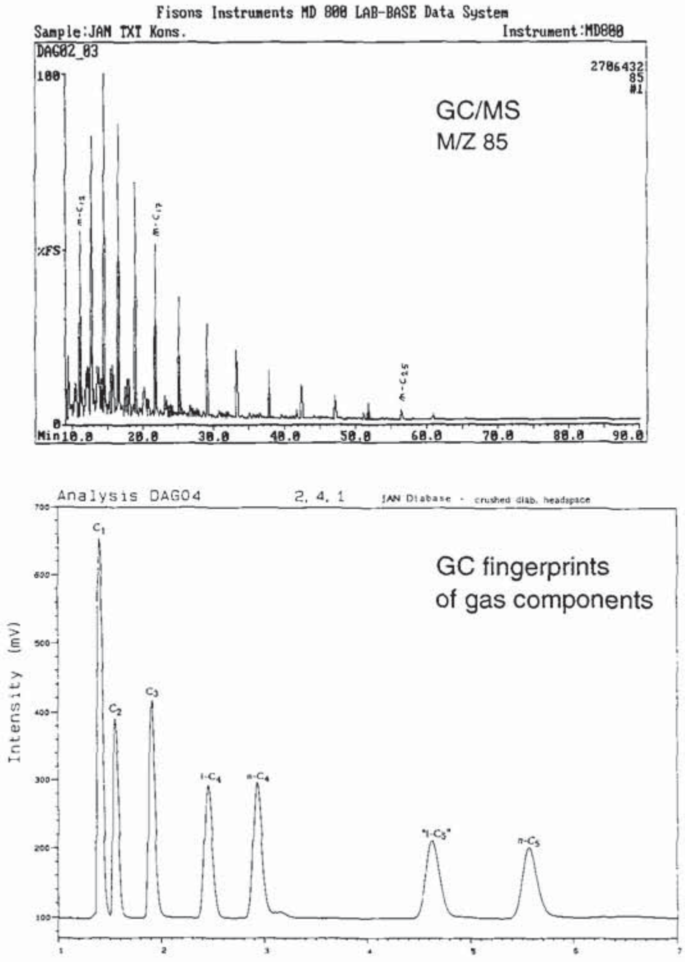

Fig. 19. Chemical characteristics of gas and liquids shows from a Permian dyke, onshore Southeastern Norway (Tvedestrand, localized at the capital letter A in Figure 1 and east of geoprofile A-A' in figure 16.) From D. Karlsen and J. Kihle, written comm. (1993)

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