Triassic to Early Cretaceous stratigraphic and structural development of the northeastern Møre Basin margin, off Mid-Norway

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The oldest sedimentary rocks penetrated by exploration wells on the northeastern Møre Basin margin are of Early Triassic age. These sediments were deposited in a continental, arid climate. A large hiatus separates these sedimentary rocks from the overlying Jurassic strata of Bathonian age, which were deposited in a humid continental environment. Marginal marine conditions were first established in early Callovian times, and late Middle Jurassic to earliest Cretaceous sediments were deposited in a fully marine anoxic to suboxic environment. Early Cretaceous sediments were deposited in a dominantly oxic, marine environment. Extensional tectonic movements were probably initiated during Early to Middle Triassic times. This caused erosion of local highs, while basinal areas underwent subsidence and sediment accumulation. A phase of uplift and erosion took place between late Early Jurassic and early Middle Jurassic times. In Bathonian times rift movements resumed, but fault block rotation was relatively gentle and gradual until the end of the Kimmeridgian. Extension and fault block rotation accelerated in early Volgian times, and climaxed in middle Volgian times, resulting in present day dips of up to 50°. The area went into a thermal relaxation phase in earliest Cretaceous times with relatively uniform subsidence, although some of the major faults remained active until Turonian times.

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Exploration history and introduction

In March 1989, two production licences covering parts of the northeastern Møre Basin margin were awarded in the second phase of the 12th licencing concession round. Production Licence 154 (blocks 6205/3 and 6305/12) was awarded to a group with Norsk Hydro a.s as the operator, while Production Licence 155 (block 6306/10) was awarded to a group with A/S Norske Shell as the operator. Jurassic strata within rotated fault blocks were important objectives, as similar structures are very efficient hydrocarbon traps in the North Sea and in the Haltenbanken area (Spencer et al. 1986). To date, four wells have been drilled; three within PL 154 and one within PL 155. All wells penetrated hydrocarbon-bearing strata, but failed to prove commercial accumulations. Due to these disappointing results, both licences have been relinquished.

In this paper, the Mesozoic stratigraphy, sedimentology and structural features of the northeastern margin of the Møre Basin are described and interpreted, and some comparisons with adjacent areas are made.

Regional geology

The geographical location and the main structural elements of the study area are shown in Fig. 1. This paper focuses on the northeastern part of the Møre Basin, which is located off Mid-Norway, about mid-way between the Måløy Terrace in the northern North Sea to

the south and the Haltenbanken area to the north. Towards the southwest, the offshore areas west of Shetland are aligned with the northeastern part of the Møre Basin along the strike of the Møre-Trøndelag Fault Complex.

A detailed map of the study area highlighting well locations, IKU shallow boreholes in block 6206/2, a key seismic line and a geoseismic section is shown as an inset in Fig. 1. The main structural elements in this area are the Fennoscandian Shield, a narrow platform area, the northeastern part of the Slørebotn Subbasin and the Gossa High. These structural elements are separated from each other by segments of the NE–SW striking Møre-Trøndelag Fault Complex. In addition to the Møre-Trøndelag Fault Complex, three other lineament directions join up in this area: the N–S striking Klakken Fault Complex, the NW–SE striking Jan Mayen Lineament, and a less prominent, E–W striking fault system. This configuration has resulted in a complex terrain with rotated fault blocks on the narrow platform and within the Slørebotn Subbasin, and the relatively complex Gossa High (see also Hamar & Hjelle 1984; Brekke & Riis 1987; Graue 1992). For a more comprehensive description of the structural elements on the mid-Norwegian shelf, see Blystad et al. (1995).

Structural setting and stratigraphy

Fig. 2 shows the WNW–ESE striking seismic line GGW-91-418 (see Fig. 1 for location). This line runs in a dip
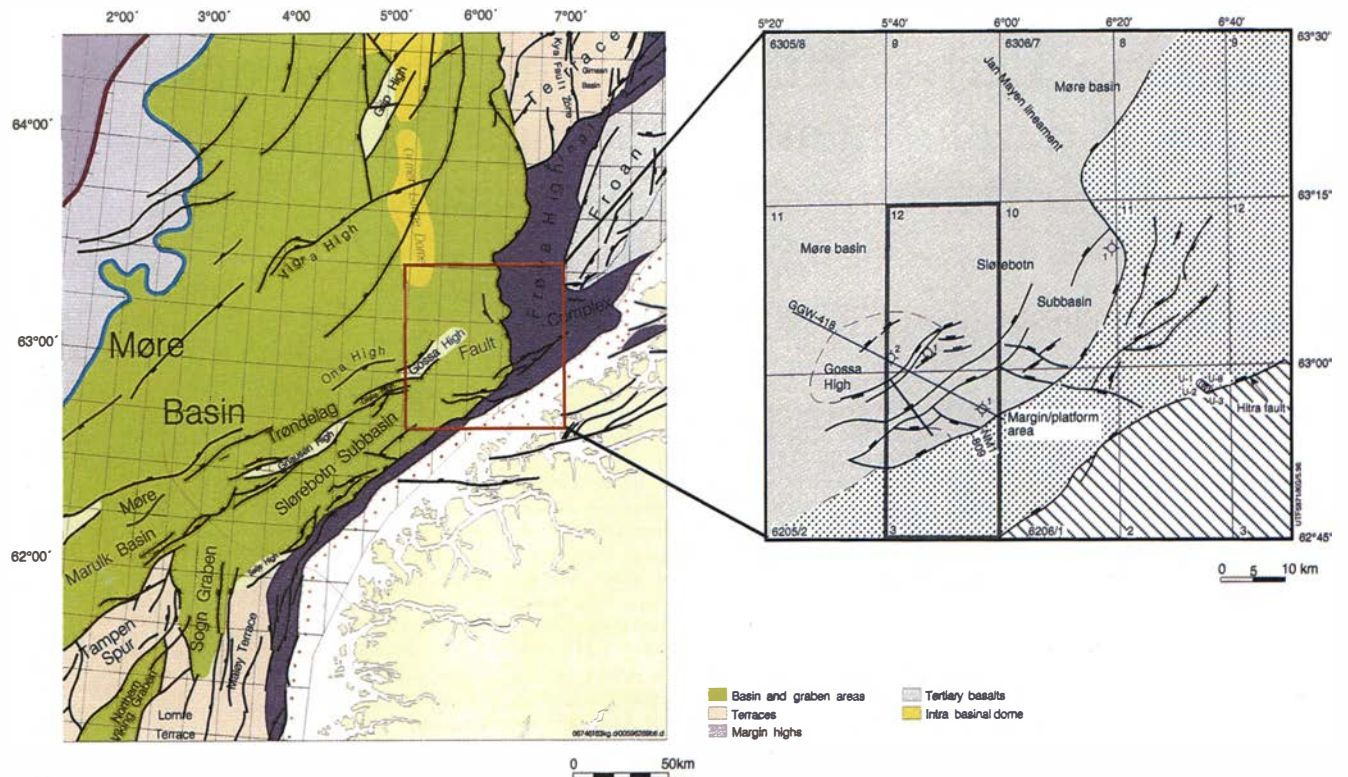
Fig. 1. Location map of the northeastern Møre Basin margin (after Blystad et al. 1995). Inset: Detailed map of the study area with main structural elements, location of wells and location of seismic line GGW-91-418 and geological dip section. *Note added in proof:* The location of the dip section is incorrect. The correct location is through well 6205/3-1.

direction through the position of well 6205/3-1,1R and very close to the position of well 6305/12-2. In addition, the approximate position of well 6305/12-1 is projected approximately 4 km from the NNE. This seismic line shows the typical structural configuration of the area at base Cretaceous level. The area is subdivided into the following structural elements: a shallow platform, two steeply rotated fault blocks (in the Slørebotn Subbasin) and a complex high (the Gossa High). Fig. 2 also shows the large fault throw between the platform area and the Slørebotn Subbasin, the steep dip of the pre-Cretaceous horizons within the fault blocks (up to 50°), and the near flat-lying or gently dipping deep reflectors within basement rocks, thought to be Caledonian thrust surfaces of early Paleozoic origin.

A general litho- and chronostratigraphy chart for the pre-Tertiary stratigraphy is shown in Fig. 3. As shown on this chart, the oldest sedimentary rocks are assigned an Early to early Late Triassic age, no younger than Carnian. The Triassic rocks consist mainly of conglomerates, sandstones, siltstones and mudstones, and attain a stratigraphic thickness of at least 600 m. A large stratigraphic gap separates these rocks from the overlying Jurassic strata. In the Slørebotn Subbasin, the oldest Jurassic rocks have been confidently dated as middle Bathonian. These rocks are very heterolithic, and composed of alternating sandstones, siltstones, claystones, coal beds and subordinate conglomerates. The stratigraphic thickness varies from 150 m to more than 350 m. The Jurassic rocks found in the IKU shallow boreholes

adjacent to the Fennoscandian Shield consist of conglomerates and sandstones. They have been subdivided into three units (A, B and C) by Smelror et al. (1994). Unit A is assigned a latest Triassic to earliest Jurassic age, probably Hettangian, although it may range into the Late Triassic (Rhaetian), which is in accordance with our interpretation. However, Smelror et al. (1994) have assigned Units B and C a Pliensbachian–Toarcian and Late Toarcian–Aalenian age, respectively. The evidence for these ages is relatively weak, as age diagnostic taxa are very sparse and the palynoflora is dominated by continentally derived spores and pollen. The main palynomorph events are summarized in Table 1, and indicate a general Middle Jurassic age. Based on the close resemblance with miospore assemblages found in the Bathonian sections of the Slørebotn Subbasin wells, a Bathonian age is also preferred for units B and C in the 6206/2 shallow boreholes.

Lower Callovian rocks found in Shell well 6306/10-1 apparently overlie the Bathonian section conformably, and consist mainly of claystones and siltstones with some sandstones. There is limited control on the stratigraphic thickness, but based on seismic, the total thickness of Callovian rocks is probably not more than 150 m. Middle Callovian to early Kimmeridgian rocks have not been penetrated in the area. Seismic data suggest that this stratigraphic interval may attain a thickness of 200–400 m in the area. Well 6205/3-1R penetrated very thick Kimmeridgian, Volgian and Ryazanian strata. These rocks consist mainly of mud- and siltstones with a rela-
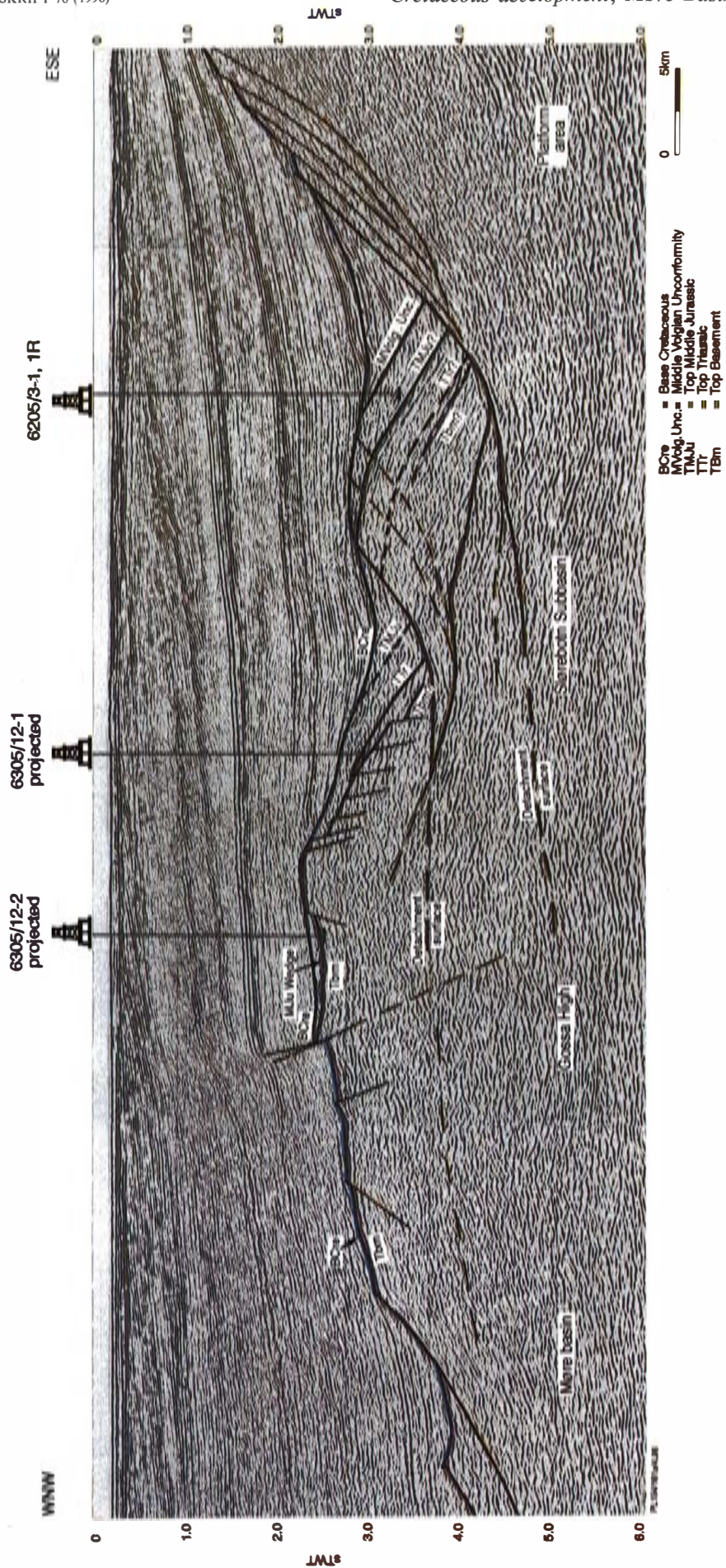
Fig. 2. Seismic section GGW-91-418 across the northeastern Møre Basin margin (Data courtesy of Geco-Prakla). The location of the section is shown in Fig. 1.
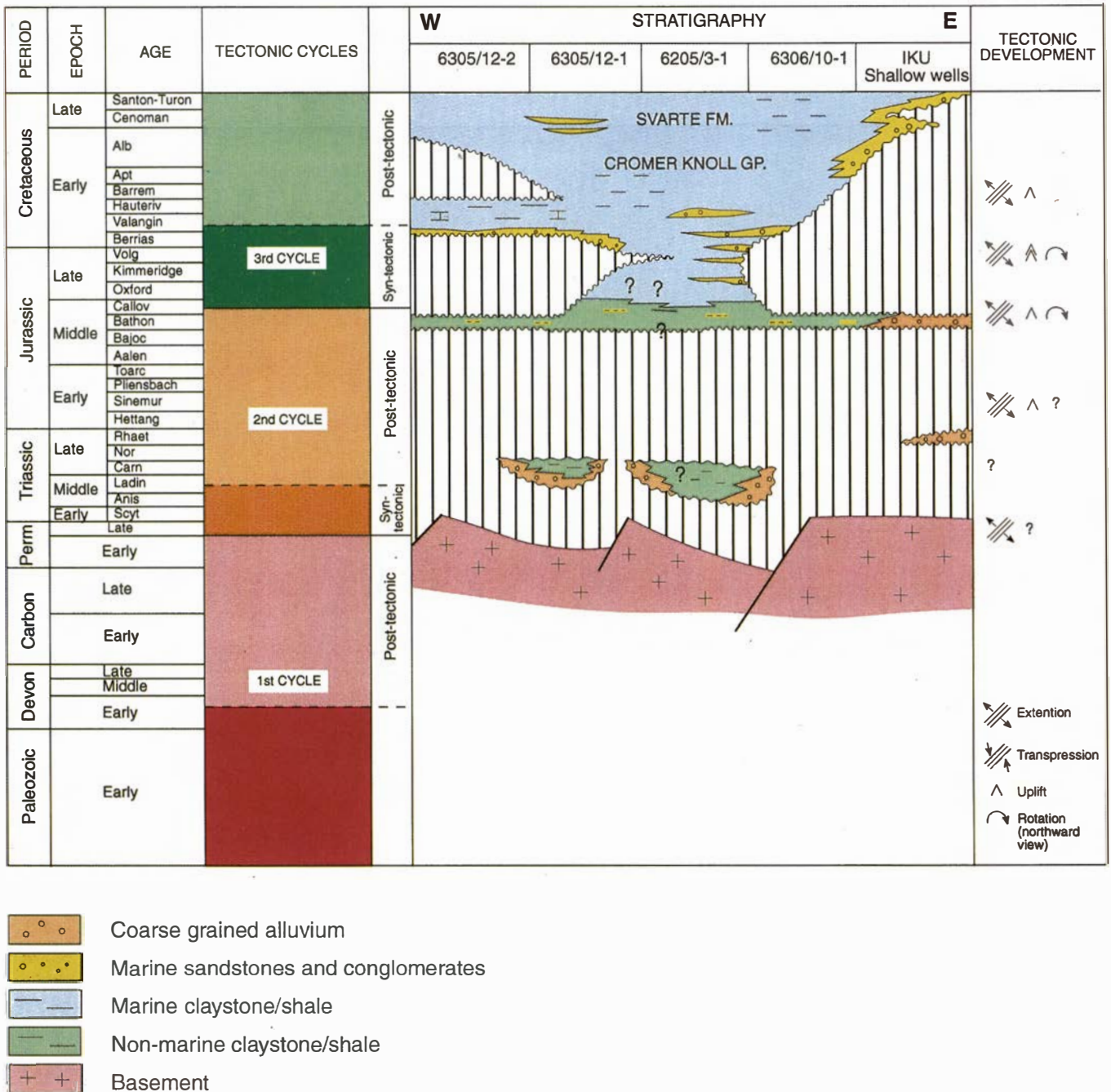
Fig. 3. Stratigraphic and tectonic summary, northeastern Møre Basin margin.

tively high organic carbon content, although sandstones of considerable thickness occur in the upper Kimmeridgian and lower Volgian. The stratigraphic thickness of the Upper Jurassic rocks varies considerably because of contemporaneous fault block rotation during deposition. In well 6205/3-1R, the penetrated section exceeds 800 m, while adjacent to the fault scarp, the stratigraphic thickness of Upper Jurassic sediments is more than 1500 m. Post-early Callovian Jurassic rocks have not been found in any of the other wells, due to Late Jurassic structuring related to fault block rotation. In these wells, Middle Jurassic strata are unconformably overlain by Lower Cretaceous strata (Fig. 3).

The Lower Cretaceous strata are dominated by mudstones and siltstones, but Hauterivian to lower Barremian sediments in the eastern part of the Slørebotn Subbasin are relatively sand-prone.

Sedimentology

A geoseismic section derived from line GGW-91-418 is shown in Fig. 4 (see Fig. 1 for location). It shows the general Triassic, Jurassic and lowermost Cretaceous stratigraphy and lithology. Fig. 4 also shows the gamma ray wire-line response in the three wells, cored intervals
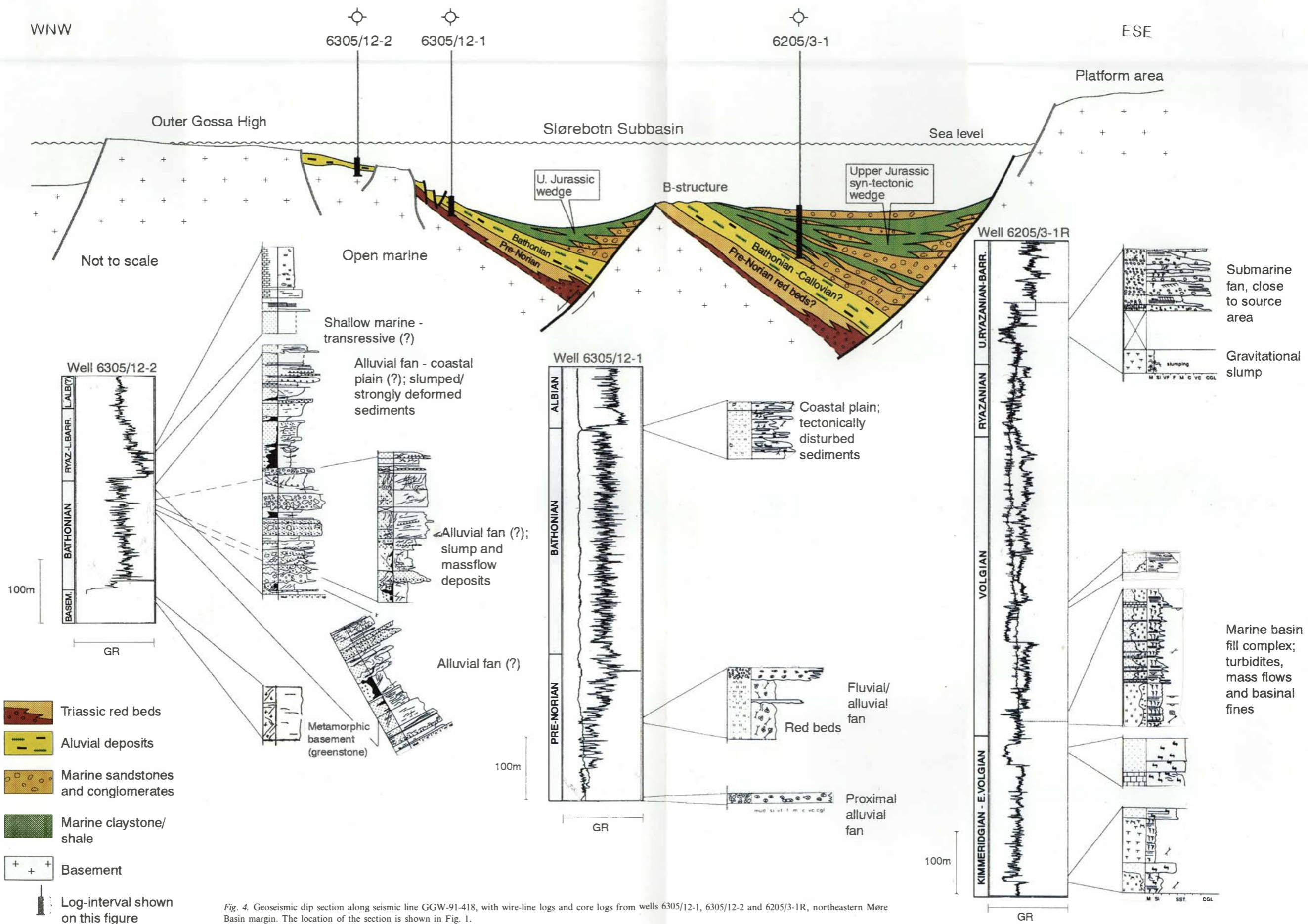
Fig. 4. Geoseismic dip section along seismic line GGW-91-418, with wire-line logs and core logs from wells 6305/12-1, 6305/12-2 and 6205/3-1R, northeastern Møre Basin margin. The location of the section is shown in Fig. 1.

Table 1. Palynological events in the Jurassic sections of the IKU shallow boreholes in block 6206/2.

	Present	Few	Common	Abundant	Superabundant
			(Depth in meters below seabed)		
Well 6206/2-U-1					
Eurydinium saxoniensis	98.3				
Chomotriletes spp.		99.2	117.5/145.0	135.0	
Deltoidospora spp.					99.2 (t)/179.8 (b)
Cerebropollenites mesozoicus			135.0 (b)	108.0	
Baculatisporites/Osmundacites gr.			108.0 (t)	179.8 (b)	131.5/155.5
Vitreisporites pallidus			131.5	114.5	
Cycadopites nitidus			117.5		
Eucommiidites troedssonii	117.5 (t)				
Klukisporites variegatus (small)					123.8
Neoraistrickia gristhorpensis	135.0 (t)				
Marattisporites scabratus			159.0		
Polycingulatisporites triangularis	168.5/179.8				
Callialasporites minus	170.0				
Parvisaccites enigmatus	176.0				
Well 6206/2-U-2					
Chomotriletes spp.	74.5 (t)/85.0 (b)				
Cerebropollenites mesozoicus	98.0 (b)				
Botryococcus spp.	76.5/110.0 (b)				
Todisporites minor	76.5 (t)				
Duplexisporites gyratus	76.5 (t)				
Stereisporites spp.	76.5 (t)				
Chasmasporites spp. (in situ?)	76.5 (t)/98.0 (b)				
Bisaccate pollen			85.0 (b)		
Lycopodiumsporites spp.	110.0 (b)				
Well 6206/2-U-3					
Cerebropollenites mesozoicus	102.5				
Parvisaccites enigmatus	122.5				
Uvaesporites argenteaeformis	102.5				
Well 6206-2-U-8					
Chomotriletes spp.	74.5/106.0				
Deltoidospora spp.				74.5	106.0 (b)
Cerebropollenites mesozoicus	73.0 (t)				
Baculatisporites/Osmundacites gr.	65.0 (t)			74.5	93.5
Cycadopites nitidus		106.0 (b)			
Botryococcus spp.	61.5 (t)/101.5 (b)				
Todisporites minor	73.0 (t)				
Stereisporites spp.		101.5			
Chasmasporites spp. (in situ?)	61.5 (t)				
Callialasporites trilobatus	61.5				
Staplinisporites caminus	77.5 (t)				
Leptolepidites spp.	77.5 (t)/93.5 (b)				
Duplexisporites problematicus				93.5	
Lycopodiumsporites austroclavatidites		93.5			
Pterospermella helios	101.5				

t = top
b = base

and an interpretation of these cored intervals. Triassic sediments were only penetrated and cored in well 6305/12-1; Middle Jurassic rocks were extensively cored in wells 6305/12-1 and 6305/12-2, while Upper Jurassic and Lowermost Cretaceous rocks were cored in well 6205/3-1R.

Triassic

The cored Triassic rocks in well 6305/12-1 consist of conglomerates, pebbly sandstones, siltstones and some mudstones. The deepest part of the section is composed of a thick sequence of stacked conglomerates with up to cobble-size clasts, while siltstones and mudstones become more and more common higher in the section, resulting in a large-scale fining-upwards character, clearly seen on wireline logs (Fig. 4). Fig. 5a shows core photographs from a representative Triassic section. The conglomerates are dominantly matrix-supported, but occasionally clast-supported, and are texturally immature. The coarse-grained sediment is generally green-coloured, whereas the fine-grained material is usually red-coloured. Both conglomerates and the coarse-grained sandstones are typically arranged in 30 cm to 50 cm fining-upwards units with sharp bases. These coarser-grained sediments alternate with siltstone and mudstone bedsets which are usually several meters in thickness.

The Triassic sediments were probably deposited in an arid alluvial environment and represent coalescing allu-
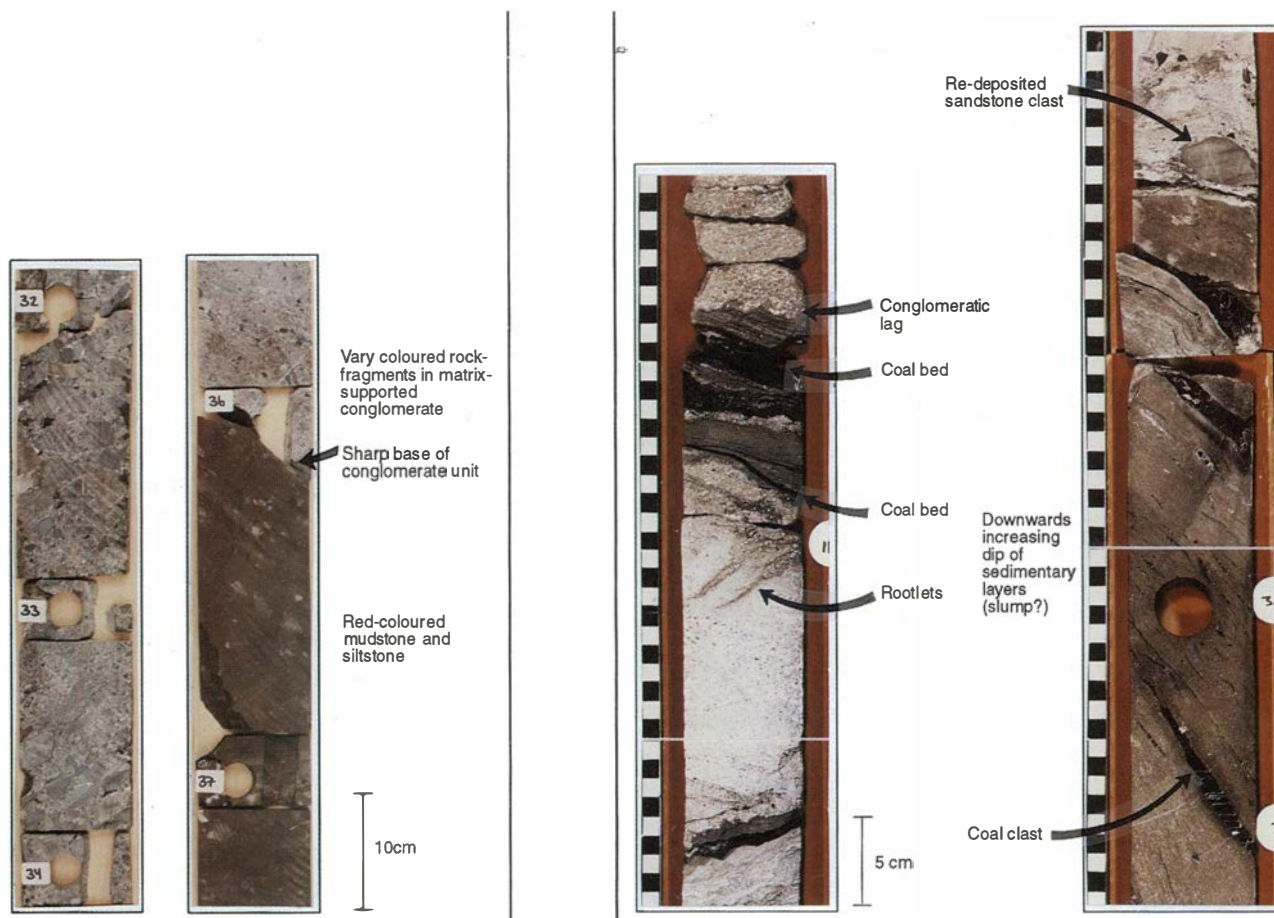
Fig. 5. Core photographs of cored Triassic and Middle Jurassic (Bathonian) rocks, northeastern Møre Basin margin. (a) Triassic mudstones and conglomerates (well 6305/12-1). (b) Bathonian sandstones, mudstones and coals (well 6305/12-2).

vial fan and alluvial plain sediments. The alternation between coarse- and fine-grained material reflects the variation in depositional energy, either due to autocyclicity or tectonic pulses (allocyclicity). The conglomerates are interpreted as debris-flow deposits and high-density gravity flows, while sandstones, siltstones and mudstones were dominantly laid down by lower density gravity flow processes. Some of the fine-grained material was probably deposited by stream-flow processes.

The Triassic sandstones and conglomerates have no reservoir potential due to their immature texture and mineralogy. The initial porosity and permeability was probably low, and was further reduced by extensive mechanical and chemical compaction after burial. In addition, carbonate, kaolinite and illite cementation is common, and has led to additional deterioration of reservoir properties.

Bathonian

The cored Middle Jurassic rocks consist of alternating sandstones, siltstones, claystones, coal beds and subordinate conglomerates. Fig. 5b shows core photographs of

typical Middle Jurassic lithofacies. Sandstone beds and bedsets are typically 30 to 50 cm thick and are often capped by mudstones and/or coal beds. The *in situ* character of the coals is demonstrated by the occurrence of rootlets (Fig. 5b). The sandstone beds are dominantly coarse- to very coarse-grained (occasionally pebbly), texturally and mineralogically immature, and often form fining-upwards units. In the western part of the Sløribotn Subbasin (well 6305/12-1), the depositional environment for these sediments is interpreted as a coastal plain with a humid climate. The palynoflora has a distinct continental character and is dominated by spores and pollen, but some marine palynomorphs are recorded and indicate occasional marginal marine conditions.

On the Gossa High (well 6305/12-2), the sedimentary rocks are coarser-grained. In addition to this, resedimentation and syn-sedimentary deformation is common. Fig. 5b from well 6305/12-2 shows redeposited sandstone clasts and a steeply inclined limb of a fold. Hence, the Bathonian depositional environment to the west was of a more proximal character than in well 6305/12-1, and is interpreted as a distal alluvial fan/flood plain environ-

ment dominated by gravity flow processes. The contorted nature of the sediments and the rapid lateral change of sediment character from well 6305/12-1 to well 6305/12-2 indicates that the Gossa High was tectonically active during the Bathonian.

The lithofacies of units B and C (interpreted in this paper to be of Bathonian age) in the IKU shallow boreholes in block 6206/2 are described in detail by Smelror et al. (1994). The lithofacies indicate an alluvial fan depositional environment changing upwards from dominantly subaerial to subaqueous. Hence, the general Bathonian paleogeography was dominated by coastal plain deposition within the Slørebotn Subbasin (well 6305/12-1), with alluvial fan deposition on the easternmost margin of the Møre Basin (block 6206/2), and possibly also on the western margin (well 6305/12-2).

The reservoir quality of the Middle Jurassic sandstones is generally poor due to immature texture and mineralogy, considerable amounts of interstitial clay and, in places, extensive carbonate cement.

Callovian

Callovian sediments have not been penetrated by any of the wells in blocks 6205/3 and 6305/12. However, a thin interval of Callovian sedimentary rocks was penetrated by Shell well 6306/10-1. The lithological data from this well suggest that the Bathonian–Callovian boundary represents a transgressive event, and a change from dominantly continental to marginal marine conditions. Middle Callovian to lower Kimmeridgian stratigraphy has not been penetrated in the area, and the nature of these rocks therefore remains unknown. However, based on the general increasingly marine trend from the Middle to the Late Jurassic, it is assumed that the depositional environment became increasingly marine during middle Callovian to early Kimmeridgian times.

Middle Kimmeridgian to lower Volgian

Since well 6205/3-1R is located relatively far downdip on the easternmost fault block in the Slørebotn Subbasin, this well provides unique data on the syn-rift development of the area. A number of cores were taken in the Upper Jurassic section, and provide good control on sedimentary facies and depositional environment. Fig. 6a shows typical facies in the Kimmeridgian section. The sediments are composed of alternating siltstones and mudstones and some thin fine-grained sandstones. The sedimentary rocks are variably bioturbated; some sections are laminated with no or very limited bioturbation, while other sections are intensively bioturbated; see Fig. 6a. The ichnofacies indicate a relatively deep marine depositional environment. The average total organic carbon content (TOC) is fairly high (approximately 5%) despite the relatively high thermal maturity of these rocks. The laminated parts and bioturbated parts of the

sections, represent deposition in anoxic and suboxic environments, respectively. In addition to the dominant lithofacies described above, some thick sandstone intervals occur. These sandstones typically have sharp bases and contain mudstone rip-up clasts in their basal sections. These sandstones are dominantly coarse-grained, in part pebbly, and are often massive. Sedimentary structures are rare, but water escape structures are relatively common and some ripple marks occur. The sandstone intervals become more fine-grained upwards, and occasionally contain Bouma sequences in their upper parts.

The sedimentary facies are indicative of gravity flow processes as the dominant depositional process. The coarse-grained sandstones are interpreted as deep marine fan deposits, where the coarsest grained sediments were laid down by grain flows and high-density gravity flows, while the finer grained sediments were deposited by turbidity currents with decreasing density. The finest grained sedimentary rocks most likely represent background pelagic deposition. Apart from some minor compaction related faults (Fig. 6a), the section is almost undisturbed by tectonics. The thick sandstone intervals have very poor reservoir quality due to extensive quartz cementation related to severe mechanical and chemical compaction. Locally, carbonate cementation, kaolinitization and illitization contribute to the reservoir quality deterioration.
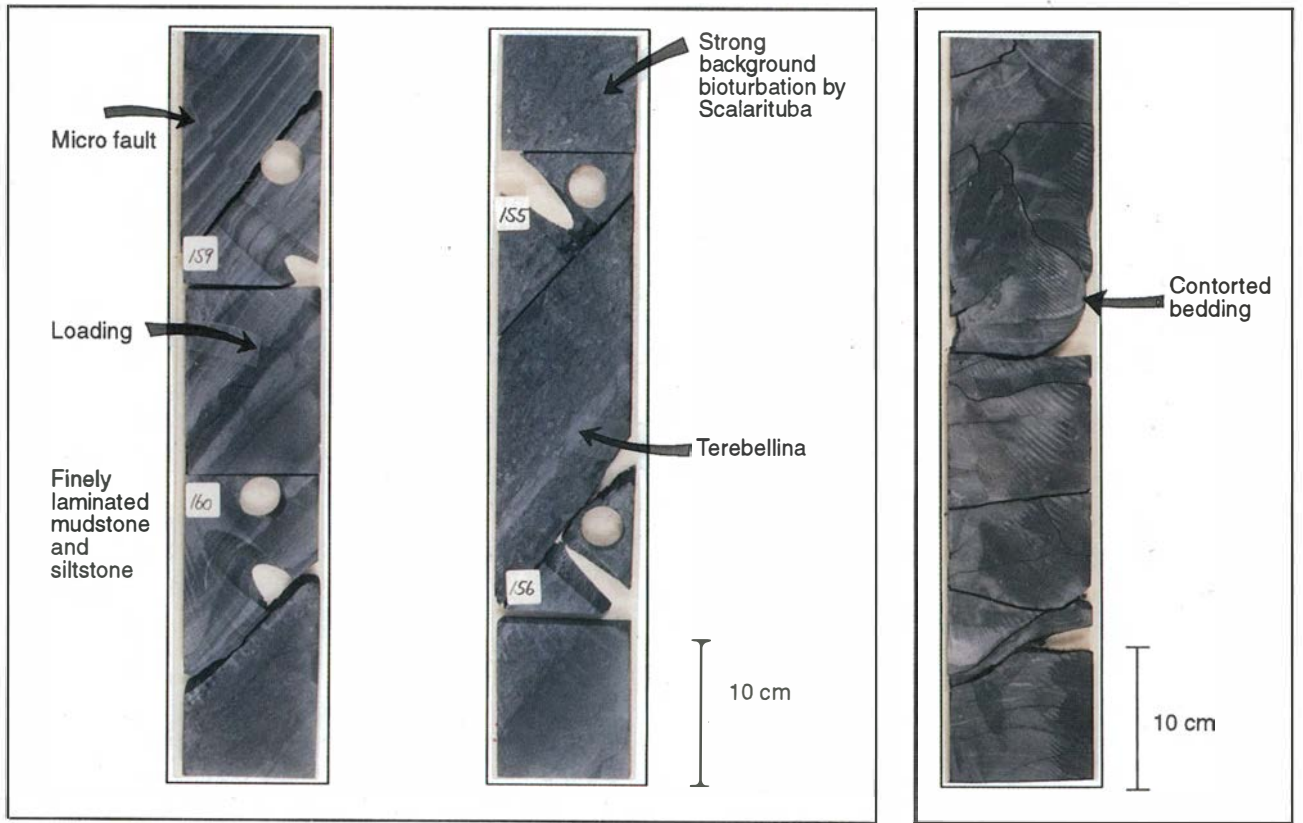
Middle Volgian to Ryazanian

The lithofacies of this section are fairly similar to the underlying lower-middle Volgian section, but are generally finer-grained. The dominant lithofacies is mudstone with thin siltstone beds and fine-grained sandstone laminae. Depositional processes are dominated by low-density turbidity currents and pelagic deposition from suspension. A characteristic feature in this section is the contorted nature of the sediments, reflecting deposition on an unstable slope and/or contemporaneous tectonic movements (Fig. 6b). High TOC levels prevail and little bioturbation is seen. The depositional environment is interpreted as marine anoxic. The generally low content of coarse clastics compared to the underlying lower–middle Volgian section probably reflects ponding of the coarser clastics closer to the fault scarp, although a general decrease in coarse-grained input into the basin also may be the cause.

Lower Cretaceous

In well 6205/3-1R, the Jurassic–Cretaceous boundary is conformable, whereas on the fault block crests and on the Gossa High, the Upper Jurassic and large parts of the Lower Cretaceous stratigraphy is missing. Subaerial and subaqueous erosion was, however, most likely confined to the Late Jurassic, as Ryazanian sediments are

Micro fault

Loading

Finely
laminated
mudstone
and
siltstone

Strong
background
bioturbation by
Scalarituba

Terebellina

10 cm

a)

Contorted
bedding

10 cm

b)

Basal
grain-supported
conglomerate with
rock fragments

Fining
upwards
unit

Organic rich
layers

10 cm

Stylolite

Rock fragments

Matrix-
supported
conglomeratic base

Stylolite
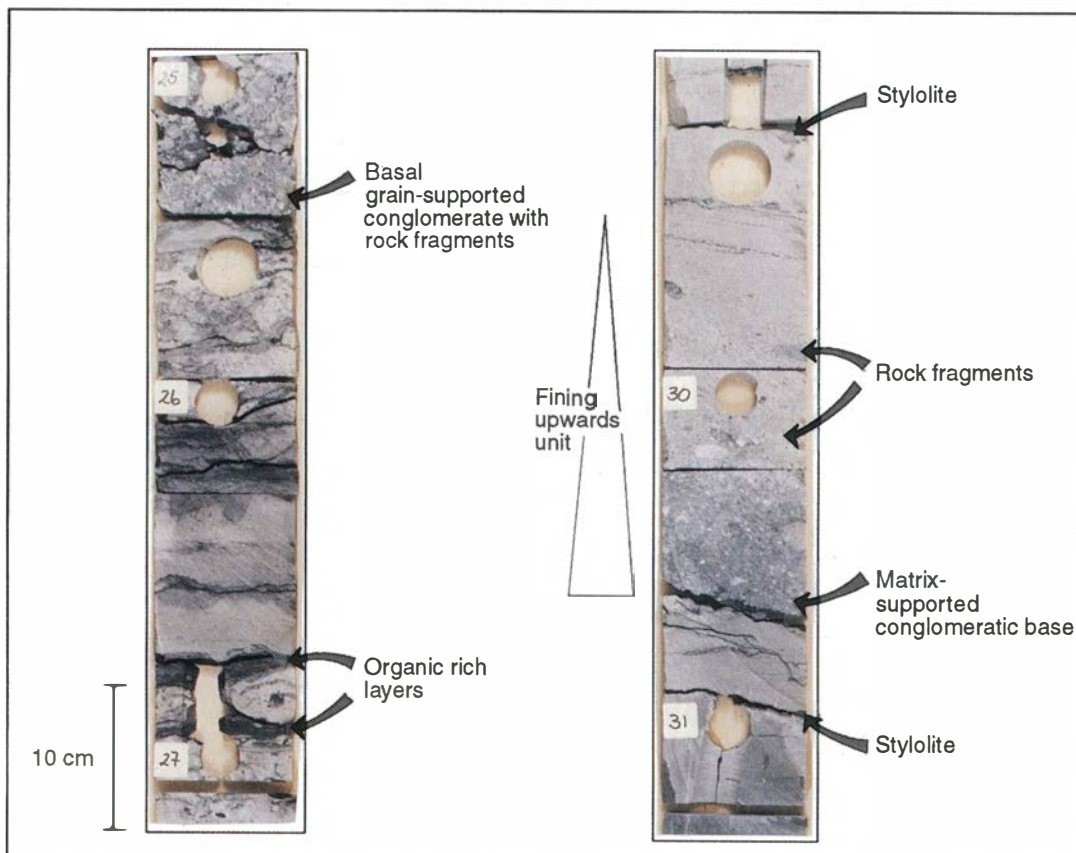
c)

present in well 6305/12-2 on the elevated Gossa High. Hence, the large Cretaceous stratigraphic breaks seen in some of the wells in the Slørebotn Subbasin are probably the result of minor intra-Cretaceous erosion events or extreme condensation.

The lithology of the Lower Cretaceous section in the area is relatively monotonous, and is composed of mudstones and siltstones. These sediments are interpreted as low density turbidites and some pelagic background deposits from suspension fall-out. Deposition occurred in a fully marine basin, and oxic bottom conditions prevailed. Slightly elevated TOC values in thin beds of Aptian age indicate occasional suboxic conditions.

A notable exception from the fine-grained lithology is represented by a relatively thick unit of conglomerates and sandstones of Hauterivian to early Barremian age; see Fig. 6c. Very poorly sorted conglomerates with abundant rock fragments alternate with sandstone beds and thin mud- and siltstone beds. The conglomerates are dominantly matrix-supported, and show fining-upwards trends, typically 10–30 cm in thickness. The sandstones are generally massive, but show some ripple marks. Stylolitization along thin mudstones and organic laminae is common. The conglomerates are interpreted as debris flow deposits, while the sandstones most likely were laid down by high-density turbidity currents. More fine-grained sediments reflect background sedimentation by low-density turbidity currents and suspension fall-out.

The overall facies association is interpreted as a phase of deep marine fan sedimentation, in response to a relative sea-level drop and/or tectonic movements. The conglomerates have no reservoir quality, while the sandstones have poor to very poor reservoir properties, due to immature texture and mineralogy, and extensive cementation.

Structural geology

As outlined briefly above, the structural setting of the area at pre-Cretaceous level is complex, but may be subdivided into a shallow platform area, the Slørebotn Subbasin with steeply rotated fault blocks, and the Gossa High. The first three wells in the area targeted the rotated fault blocks, while the fourth well targeted the Gossa High. As previously mentioned, only minor amounts of hydrocarbons were found, but the well data provided detailed geometrical information, and also enabled relatively accurate dating of tectonic movements. Wells 6305/12-1 and 6305/12-2 both shed light on the Triassic–Middle Jurassic tectonic development of the area, while well 6205/3-1R provided excellent data for the Late Jurassic–Early Cretaceous tectonic development. Based on these new data, the structural develop-

ment of the area has been subdivided into a number of tectonic phases, described below.

Triassic tectonic phase

Triassic sedimentary rocks have only been penetrated in well 6305/12-1 in the western part of the Slørebotn Subbasin and in the shallow boreholes in block 6206/2 (Smelror et al. 1994), but may also be present beneath the penetrated section of well 6205/3-1R in the eastern part of the Slørebotn Subbasin. In well 6305/12-2 on the Gossa High, Bathonian sedimentary rocks rest directly on metamorphic greenstones. Although the evidence for the Triassic development is limited, well and seismic data indicate that the area developed into a system of structural highs and lows during Early Triassic times. The absence of Triassic rocks on the Gossa High (well 6305/ 12-2) indicate that this high was exposed and eroded, while at least parts of the Slørebotn Subbasin developed as one or several low-lying structural elements where large thicknesses of sediments accumulated. The thick section of stacked conglomerates at the base of well 6305/12-1 indicates very close proximity to a source area, most likely the Gossa High, as the basal part of this conglomerate contains cobble-size clasts of greenstone and jasper. The coarse-grained rocks in this well are dated late Early Triassic to early Middle Triassic, and give an approximate timing for this tectonic phase. The general mega fining-upwards character of the Triassic section is interpreted as the waning of tectonic activity through Middle Triassic times.

Pre-Bathonian Jurassic development

As previously mentioned, a large stratigraphic gap separates the Bathonian sediments from pre-Jurassic rocks in the Slørebotn Subbasin and on the Gossa High. On the eastern basin margin, however, lowermost Jurassic rocks of Hettangian age are probably present in the shallow borehole 6206/2-U-3 drilled by IKU (Smelror et al. 1994). In addition to these data, a few reworked palynomorphs of Pliensbachian age have been found in the Bathonian section in Shell well 6306/10-1 in the Slørebotn Subbasin. Hence, Lower Jurassic strata were probably present in most of the area, but were removed by erosion some time between end Pliensbachian and the onset of the Bathonian. The adjacent Viking Graben to the south and the Halten Terrace to the north experienced flank uplift and erosion in Toarcian to earliest Aalenian times (Gjelberg et al. 1987; Helland-Hansen et al. 1992). A contemporary development may have occurred in the Møre area, and uplift may have started in the Toarcian.

Fig. 6. Core photographs of Upper Jurassic and Lower Cretaceous rocks, well 6205/3-1R, northeastern Møre Basin margin. (a) Steeply inclined Upper Kimmeridgian mudstones and siltstones. (b) Upper Volgian contorted mudstones. (c) Hauterivian sandstones and conglomerates.

Bathonian early rifting phase

In early to middle Bathonian times the area underwent a major transgression and started to accumulate sediments on a coastal plain which may have been confined to the Slørebotn Subbasin. Towards the west, on the Gossa High, the proximity to a western source is indicated by sedimentological data (Fig. 5b), and deposition was dominantly in a distal alluvial fan/flood plain environment. Deposition on a steep slope, or contemporary tectonic movements, caused severe deformation of the sediments during and shortly after deposition. This has resulted in large steep folds, liquefaction structures and redeposition resulting in conglomerates with sandstone clasts (Fig. 5b). Major differential subsidence and significant thickness variations are evident from both seismic and well data. The Slørebotn Subbasin was probably separated from the Gossa High by faults and subsided more rapidly.

On the eastern margin, in block 6206/2, the Bathonian depositional environment is interpreted as a proximal alluvial fan setting. The deposition of very coarse-grained material adjacent to a major fault scarp (the Hitra Fault) suggests contemporary movement on this fault.

Callovian to early Kimmeridgian development

Due to limited well control, the tectonic development during this time span is largely unknown, but it is assumed that the area underwent relatively gentle extension and fault block rotation in an increasingly marine environment.

Middle Kimmeridgian to Ryazanian rifting

As mentioned above, well 6205/3-1R provides excellent data for the reconstruction of the major fault block rotation in the area. This well reached a total depth of more than 5200 m in rocks of middle Kimmeridgian age.

Fig. 7 shows a simplified geological section through this well in a dip direction together with a schematic dipmeter log in the well position (see Fig. 1 for location). The penetrated Upper Jurassic section is subdivided into three tectonic units. The lowermost section of Kimmeridgian age displays gently upwards decreasing dip magnitudes, while the middle section, of early Volgian age, clearly displays upwards decreasing dip magnitudes. A marked break occurs at approximately the early–middle Volgian boundary. Below this boundary, all the dips have a consistent SSE direction. Above this boundary, the dips have scattered directions and have a much lower magnitude. Fig. 8 shows the dipmeter log in more detail together with a gamma ray log and core examples. Measured dips in cores generally support the downhole measurements and the trend described above, but dip magnitudes in the cores are slightly lower. This may be
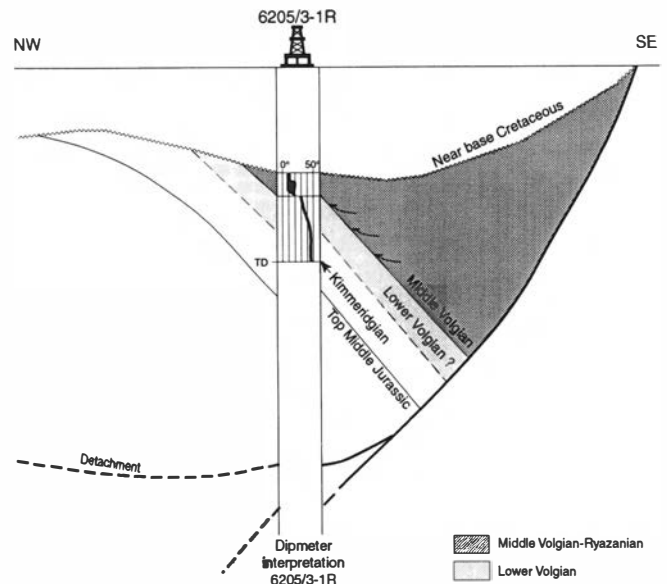

Fig. 7. Geological dip section through well 6205/3-1R with summary of dipmeter interpretation. The location of the section is shown in Fig. 1.

due to core-slabbing in a direction slightly different from the true dip direction, which will give lower and only apparent dips.

The above data suggest a three-fold division in the Late Jurassic rifting history of the fault blocks in the Slørebotn Subbasin:

(1) Kimmeridgian very gentle and gradual fault block rotation, in the order of 5°.
(2) Early Volgian accelerated fault block rotation, in the order of 15–20°.
(3) Middle Volgian fault block collapse, with rapid fault block rotation in the order of 20°.

The late Volgian and Ryazanian development was dominated by relatively passive sediment infill of relief created in middle Volgian times.

The stepwise fault block rotation described above may also be reflected in the vertical arrangement of the sediments. As described above, the pre-middle Volgian rocks are dominated by siltstones and mudstones, some thin sandstones and a few sandstone bodies of considerable thickness. The distribution of these lithofacies does not appear to be arbitrary, however. Fig. 8 shows an interpretation with division of the lithofacies into three complete and possibly a fourth incomplete mega fining-upwards unit (MFU). Each of the MFUs are roughly 150 m to 200 m thick. The base of each MFU is defined by a sharply based, often pebbly sandstone. This sandstone is in turn overlain by thinner and more fine-grained sandstones, which in turn are overlain by siltstones and mudstones. This vertical arrangement of lithofacies into MFUs may reflect tectonic pulses with initial hinterland uplift and development of sandy submarine fan systems followed by a decrease in coarse clastic input due to the waning of the tectonic activity.
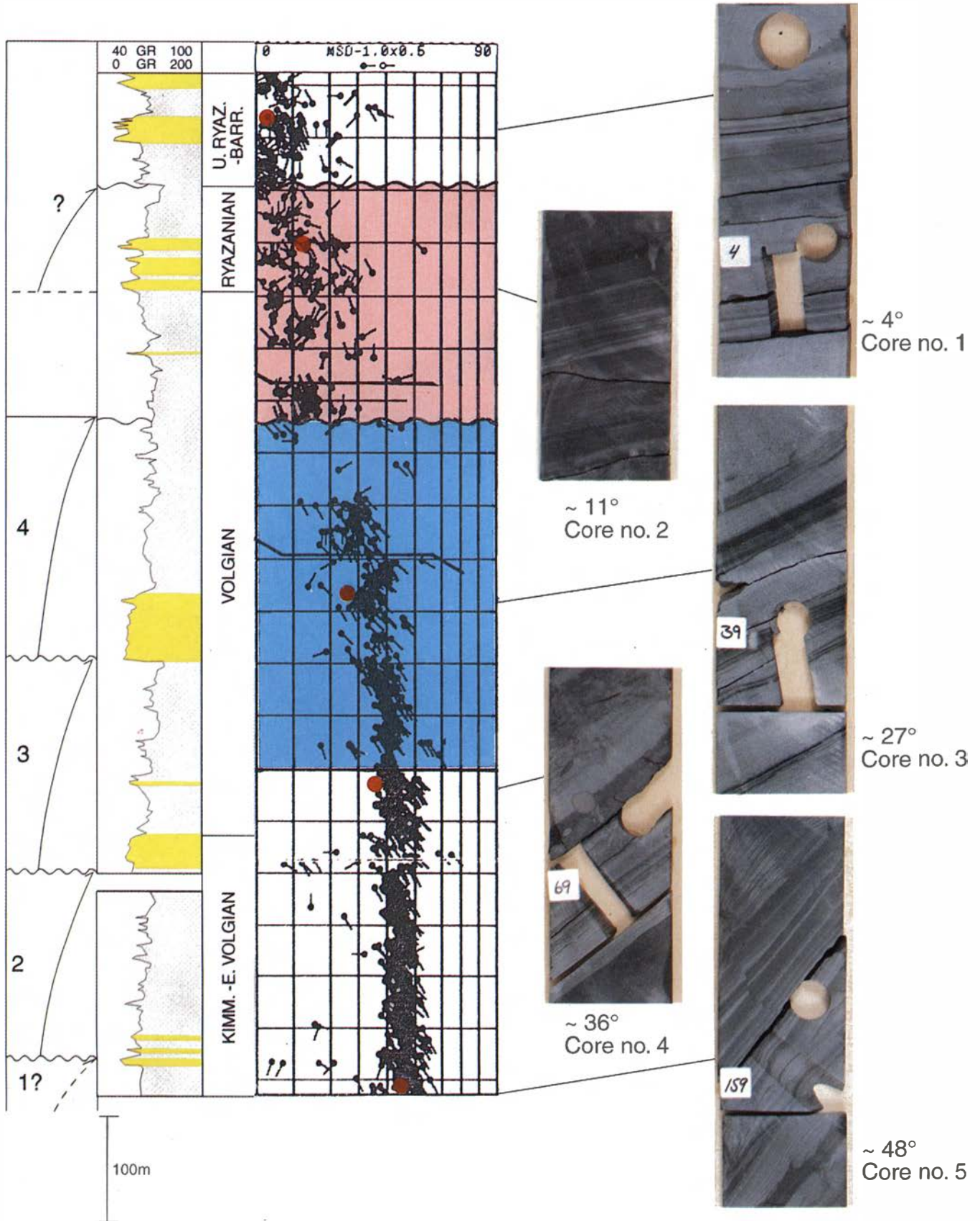
Fig. 8. Gamma ray log, dipmeter log and core measured dips in the Upper Jurassic section of well 6205/3-1R. Mega fining-upwards units (MFUs) are characterized by upwards gamma ray increase within each unit.

Gossa High   Platform

① Lower Volgian

② (Middle ?) - Upper Volgian

③ Upper Volgian

6305/12-2   6305/12-1   6205/3-1R

0   5   10km

④ Upper Volgian -Ryazanian (Post tectonic)

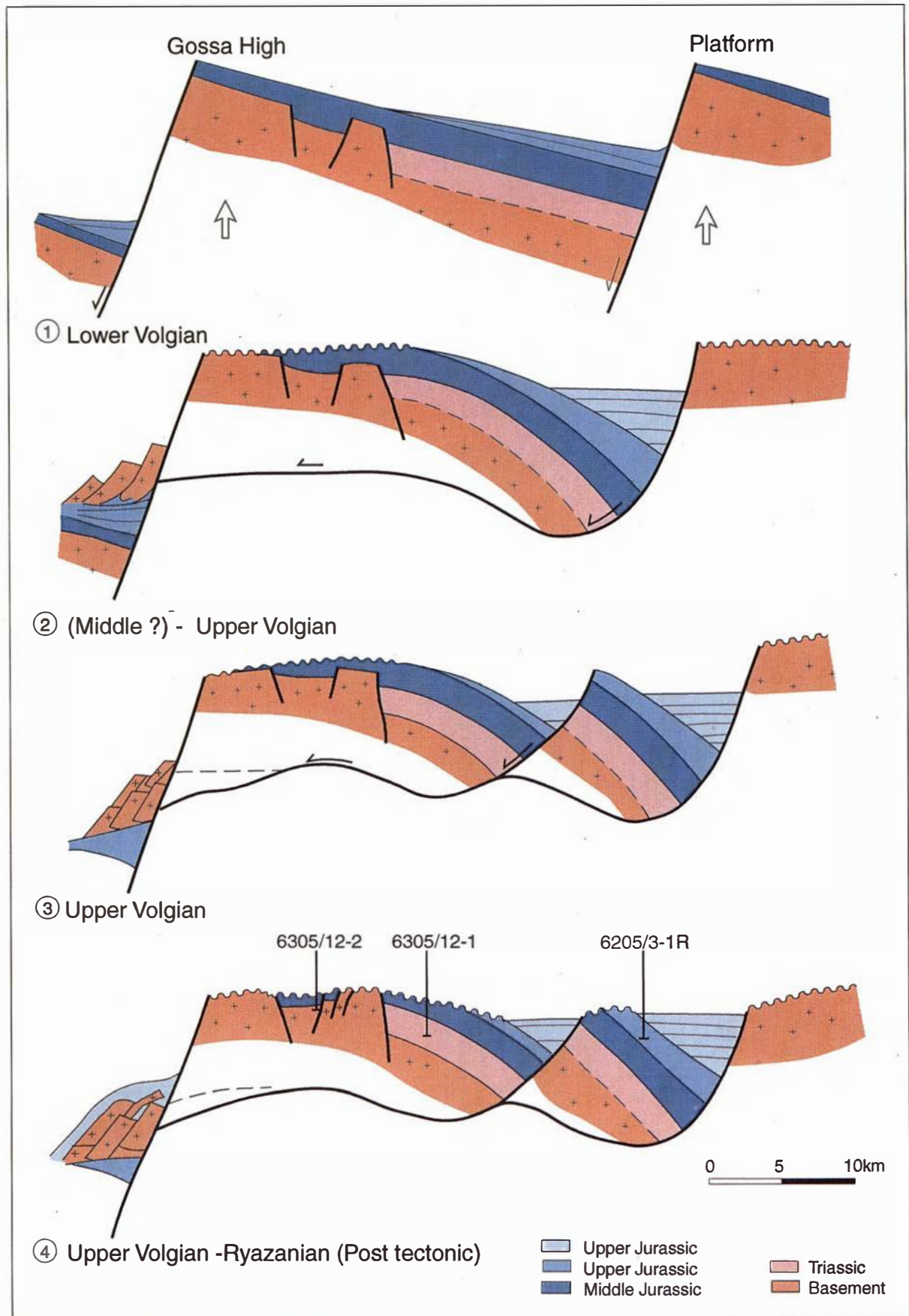|	
☐ Upper Jurassic	
☐ Upper Jurassic	☐ Triassic
■ Middle Jurassic	■ Basement

Fig. 9. Simplified sketch of Volgian structural development, northeastern Møre Basin margin.

The collapse type of rotation in middle Volgian times is associated with a general decrease in sediment grain size, indicating the limited uplift of the adjacent footwall to the southeast in the late syn-rift stages. This relationship and the presence of low-angle detachment surfaces (see Fig. 2) beneath the rotated fault blocks is interpreted such that the early phases of block rotation occurred along relatively steep, planar faults, whereas the middle Volgian rotation occurred along low-angle faults. The low-angle faults within basement rocks probably represent reactivated thrust surfaces (so-called extensional inversion) within the Caledonian basement. The lack of compressional features between the Slørebotn Subbasin and the Gossa High may be explained by a linked development in the late rotation phase, i.e. gravitational collapse involving both the fault blocks in the Slørebotn Subbasin and the Gossa High. Seismic data also suggest that parts of the platform east of the Slørebotn Subbasin participated in this collapse. Our work supports the gravitational collapse mechanism for the Gossa High suggested by Graue (1992).

Fig. 9 shows a simplified sketch of the tectonic development during the Volgian.

Post-rift development – early Cretaceous

From late Ryazanian time, fault block rotation ceased, and the geometry of the Lower Cretaceous sediment package reflects relatively passive early post-rift infill of the Slørebotn Subbasin, which was probably mainly governed by isostatic loading, thermal subsidence and a rapidly rising sea level. On the eastern shallow platform and on the Gossa High, the Lower Cretaceous section is very thin, and is stratigraphically incomplete. Hence, subsidence rates differed significantly laterally, and were controlled by underlying structural elements. Submarine and occasionally subaerial erosion probably occurred on the eastern shallow platform, while in the Slørebotn Subbasin and on the Gossa High, submarine conditions probably prevailed from Ryazanian times as sediments of this age are preserved in well 6305/12-2. However, some periodic (submarine) erosion probably also occurred in these structurally lower-lying areas.

The fault (zone) constituting the boundary between the Slørebotn Subbasin and the eastern shallow platform (Figs. 1, 2) may have remained active until Turonian times when more uniform passive subsidence developed. The geometry of the sedimentary package in the Slørebotn Subbasin, however, shows no or very little rotation. The movement on the fault complex thus was mainly vertical, with little extension of the lithosphere. The fault action is hence interpreted to reflect a phase of thermal subsidence rather than active extension and rifting. Alternatively, most of the fault movement may have occurred in the latest Jurassic–earliest Cretaceous, creating a significant submarine relief, which was subsequently filled in with sediment. Isostatic loading by the

water column and the sediment may have led to some additional fault displacement.

A phase of footwall uplift along this fault zone may have caused deposition of the Hauterivian–Barremian conglomerates and sandstones. It may, however, also be due to a regional relative sea-level fall as coarse-grained deposits of the same age are found in the North Sea, West of Shetland and on the Halten Terrace.

The post-Barremian development was tectonically quiet but is characterized by increased subsidence rates, especially during the Albian.

Geological synthesis

The structural and stratigraphic development on the northeastern Møre Basin margin from Triassic to Early Cretaceous times is summarized in Fig. 10 and briefly discussed below.

Triassic tectonic phase (rifting?). – This tectonic phase is not very well-constrained in time and space, but appears to have resulted in a segmentation of the area, with the Gossa High acting as a prominent feature, while the Slørebotn Subbasin was a structurally low-lying area. The timing of this event is probably (late?) Early–Middle Triassic. Late Triassic sedimentation was of a post-tectonic character with passive infill of the relief created during the rifting phase. Sedimentation occurred in an arid continental environment, mainly by gravity-flow processes but also with some stream-flow deposition. The post-tectonic development may have encompassed the Early Jurassic, although this must be regarded as speculative because of the almost entire absence of Lower Jurassic rocks in the area (only found in shallow well 6206/2-U-3).

Late Early Jurassic to early Middle Jurassic uplift and erosion. – Sediments of Early Jurassic age are largely absent in the area, and were probably eroded during this phase. The age of this episode is poorly constrained due to the large stratigraphic gap between Bathonian and underlying rocks. However, correlation with the northern North Sea (Helland-Hansen et al. 1992) and the Haltenbanken area (Gjelberg et al. 1987), together with the presence of rocks of Hettangian age in block 6206/2 (Smelror et al. 1994), and reworked Pliensbachian palynomorphs in the Middle Jurassic section of Shell well 6306/10-1, suggest that uplift most likely occurred during Toarcian to earliest Aalenian times.

Bathonian early rifting phase. – Deposition in the area resumed in Bathonian times in a continental to marginal marine, humid environment. Soft sediment deformation, sedimentary facies variations and thickness variations are all evidence of an early tectonic phase with mild extension. Relatively moderate extension probably continued during the Callovian and Oxfordian.
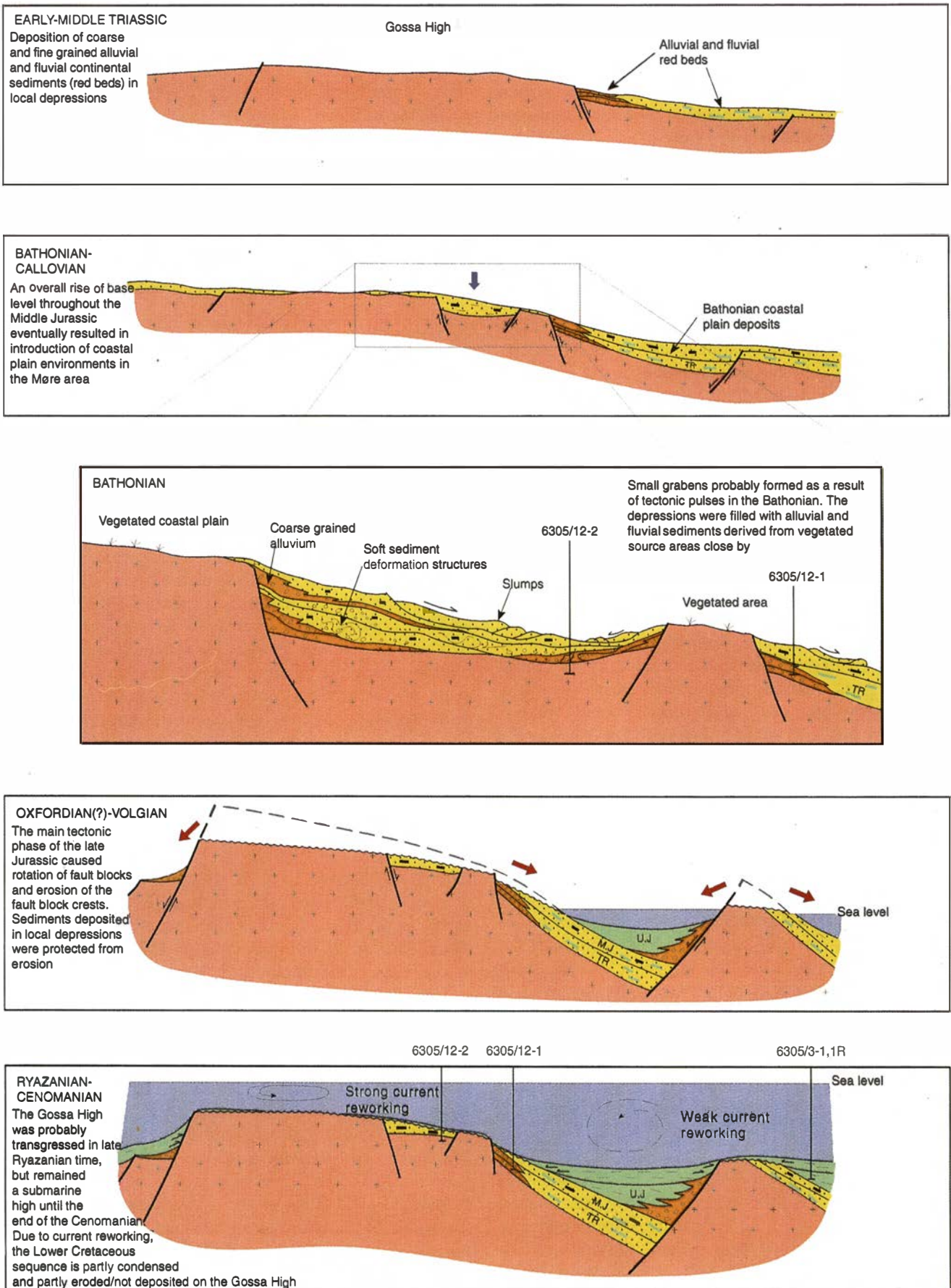
EARLY-MIDDLE TRIASSIC
Deposition of coarse and fine grained alluvial and fluvial continental sediments (red beds) in local depressions

Gossa High

Alluvial and fluvial red beds

BATHONIAN-CALLOVIAN
An overall rise of base level throughout the Middle Jurassic eventually resulted in introduction of coastal plain environments in the Møre area

Bathonian coastal plain deposits

BATHONIAN

Vegetated coastal plain

Coarse grained alluvium

Soft sediment deformation structures

Slumps

6305/12-2

Small grabens probably formed as a result of tectonic pulses in the Bathonian. The depressions were filled with alluvial and fluvial sediments derived from vegetated source areas close by

6305/12-1

Vegetated area

TR

OXFORDIAN(?)-VOLGIAN
The main tectonic phase of the late Jurassic caused rotation of fault blocks and erosion of the fault block crests. Sediments deposited in local depressions were protected from erosion

M.J
U.J
TR

Sea level

6305/12-2   6305/12-1

6305/3-1,1R

Sea level

RYAZANIAN-CENOMANIAN
The Gossa High was probably transgressed in late Ryazanian time, but remained a submarine high until the end of the Cenomanian. Due to current reworking, the Lower Cretaceous sequence is partly condensed and partly eroded/not deposited on the Gossa High

Strong current reworking

Weak current reworking

M.J
U.J
TR

Fig. 10. Triassic–Early Cretaceous structural and depositional history, northeastern Møre Basin margin.

Kimmeridgian–Volgian main rifting phase. – During this time-span, the area underwent major extensional deformation, beginning gradually during the Kimmeridgian, accelerating during the early Volgian, and climaxing with very rapid and severe fault block rotation in middle Volgian times. The latter movement was governed by dip-slip along relatively flat-lying detachment surfaces, probably reactivated Caledonian thrust surfaces. The middle Volgian fault block rotation is interpreted (in part) to be due to gravitational collapse. From seismic data it seems likely that both the eastern platform and the Gossa High participated in the gravitational collapse. Sedimentation took place in a fully marine, anoxic to suboxic environment dominated by gravity-flow processes. Large fining-upwards sequences within the Kimmeridgian to middle Volgian interval may be a response to tectonic pulses. The crests of the fault blocks were probably subject to subaerial erosion in early Volgian and middle Volgian times.

Early Cretaceous thermal subsidence phase. – During the Early Cretaceous, the rotational movement almost entirely stopped and the area went into a thermal relaxation phase. The fault complex between the eastern shallow platform and the Slørebotn Subbasin remained active, resulting in large thickness variations between these structural elements. However, fault movement was mainly vertical and extension was minor. Alternatively, most of the fault movement may have occurred during the latest Jurassic–earliest Cretaceous and created a significant submarine relief which was subsequently passively infilled with sediment. The depositional environment remained marine, but now with oxic bottom conditions. The sediment deposited during this time-span is dominated by claystone, although relatively thick sandstones and conglomerates of Hauterivian and early Barremian age are evidence of a phase of footwall uplift or a regional relative sea-level drop.

Regional correlation

The Jurassic lithostratigraphy of the area shows some important differences from both the Haltenbanken area to the north (Dalland, Worsley & Ofstad 1988) and the northern North Sea to the south (Vollset & Doré 1984; Isaksen & Tonstad 1989).

However, the timing and general style of tectonic events resembles the development in both reference areas, even though the magnitude of tectonic movement/ intensity differs. This is particularly well-expressed by the tectonic phase occurring in all three areas from late Early Jurassic and into early Middle Jurassic times. In the Haltenbanken area and the northern North Sea, relatively gentle flank uplift and erosion occurred, and sedimentation was almost continuous. Shallow marine conditions prevailed from as early as Aalenian times, and both the northern North Sea and the Haltenbanken area

experienced a major transgression and deep water conditions in Bathonian times (Gjelberg et al. 1987; Helland-Hansen et al. 1992). On the northeastern Møre Basin margin, however, a pre-Bathonian tectonic phase was associated with major uplift and erosion of almost the entire Lower Jurassic and in places also older rock sections. The area also experienced a significant transgression in Bathonian times, but shallow marine conditions were probably not established until middle–late Callovian times. All three areas (the northern North Sea, Haltenbanken and northeastern Møre Basin margin) underwent renewed rifting, starting in middle–late Bathonian times and lasting with varying intensity into Callovian and Late Jurassic times. In all areas, the early–middle Volgian was a time of intense faulting activity, although the highest intensity again is seen in the Møre area. All areas went into a thermal relaxation phase almost contemporaneously, in latest Volgian-Ryazanian times. Hence, although the Jurassic lithostratigraphy and sedimentary facies differ between the mentioned areas, the tectonic events and marked facies' shifts are apparently broadly synchronous.

The Jurassic section of the Slørebotn Subbasin and Gossa High resembles the Jurassic outliers in the Trondheimsfjord area (Oftedahl 1972, 1975; Bøe & Bjerkli 1989; Bøe 1991) and also the development reported from West of Shetland (Hitchen & Ritchie 1987; Morton et al. 1987; Nelson & Lamy 1987; Stoker, Hitchen & Graham 1993). Both areas lack sedimentary rocks of Early Jurassic age, and both have a major transgressional event in Bathonian times (possibly Bajocian times West of Shetland). These areas are all aligned within the Møre–Trøndelag Fault Complex and its westernmost extension, the Shetland Spine Fault, which shows the importance of this fault complex as a controlling structural element.

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