Jurassic sandstone provenance and basement erosion in the Møre margin – Froan Basin area

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Upper Triassic, Jurassic and Lower Cretaceous sandstones and conglomerates from different settings around the Møre-Trøndelag Fault Complex have been studied for interpretation of sediment provenance and basement erosion history. Mineralogical and petrographic data provide evidence of erosion of local sources in different geological provinces, probably connected to tectonic activity at various times. The continental and paralic Triassic and Lower Jurassic sediments off Møre were sourced from erosion of retrograde, high-grade metamorphic, eclogite-bearing rocks from the Western Gneiss Region, and the sedimentation in the northwestern part of the Slørebotn Sub-basin was sourced from outboard structural highs of lower grade, metamorphic igneous rocks. Middle Jurassic shallow-marine sandstones have mixed compositions of local basement provenance and longer transported metamorphic components. Middle Jurassic sandstones from Frohavet (Froøyane erratics) were sourced from medium- and low-grade, metamorphic pelitic and mafic rocks, most likely from the Trondheim Nappe Complex. Upper Jurassic and Lower Cretaceous marine mass-flow deposits in the Froan Basin are dominantly sourced from felsic plutonic rocks which may represent outboard extensions or analogues to the Hitra-Frøya igneous complex. The main provenance development with time in the study area is from a local provenance of varied metamorphic and igneous rocks in the Triassic – Lower Jurassic sediments to a mixed provenance in the Middle Jurassic and an increasing contribution from erosion of Palaeozoic plutonic rocks in Upper Jurassic and Lower Cretaceous, mass-flow sediments. The main diagenetic influences on sandstone porosity in the studied areas include carbonate cementation in the shallow-buried locations, and feldspar dissolution, clay mineral growth and quartz cementation in the deeper wells in the Slørebotn Sub-basin (> 2.7 km overburden).

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Introduction

Jurassic sandstones are the main petroleum reservoirs on Haltenbanken and in the North Sea. In the Møre Basin, these sandstones have been less extensively explored due to deep subsidence and thick covers of younger sediments. Information on the sediment compositions in adjacent areas is, however, available from exploration drilling at structural highs and from shallow stratigraphic coring in more marginal areas. Jurassic sediments are interpreted to occur also in inner parts of the shelf from Frohavet to inner Trondheimsfjorden (Beistadfjorden). This interpretation is based on occurrences of erratic blocks (Nordhagen 1921, Manum 1964, Vigran 1970, Oftedahl 1972, 1975) and seismic mapping (Askvik & Rokoengen 1985, Bøe & Bjerkli 1989, Bøe 1991, Bøe & Skilbrei 1998, Sommaruga & Bøe 2002).

The present study describes and compares the compositional variation of sandstones and conglomerates from the Jurassic and Lower Cretaceous successions in the eastern and marginal areas to the Møre Basin (Fig. 1). The aim has been to interpret sandstone provenance and basement erosion in the related source areas. The principal questions have been: - do the eroded areas have distinct provenance signatures and, if so, can these signatures help in constraining provenance models also in wider petroleum exploration areas offshore? Published models of Jurassic sandstone provenance suggest both eastern and western source areas in the Haltenbanken area (Gjelberg et al. 1987, Brekke et al. 1999) and only very local provenance in the Gossa High area (Jongepier et al. 1996). The bedrock composition of the sediment source areas has not been described or characterised in the literature, and this is discussed in more detail in the present study.

In this study, sandstone compositions are analysed on the basis of core samples from exploration wells in the Gossa High – Slørebotn Sub-basin and shallow stratigraphic cores off Møre-Trøndelag. Also included are samples from erratic blocks from Froøyane collected on an expedition conducted by NTNU, IKU and Statoil in 1987. Stratigraphic relationships of the studied sedimentary units are shown in Figure 2. The stratigraphic ages ascribed to the units are reported by Smelror et al. (1994) for the shallow cores 6206/02-U-01, -02, -03 and -08, Skarbø et al. (1988) and Smelror et al. (in prep.) for 6307/07-U-02 and –03, and Skarbø et al. (1988) for 6408/12-U-01. Stratigraphic ages for exploration wells 6205/3-1, -1R, 6305/12-1 and -2, and 6306/10-1 refer to Jongepier et al. (1996). The samples from Froøyane represent erratic blocks that were probably transported by glaciers from the Frohavet Basin in Quaternary time (Oftedahl 1975). A Middle Jurassic age for erratics from Froøyane was inferred already by Nordhagen (1921). This has later been confirmed by S. Kelly (pers. comm. 1988, unpublished report to NTH), who described a palaeofauna of bivalves, ammonites and molluscs, the ammonites suggesting a possible Bathonian to Early Callovian age.

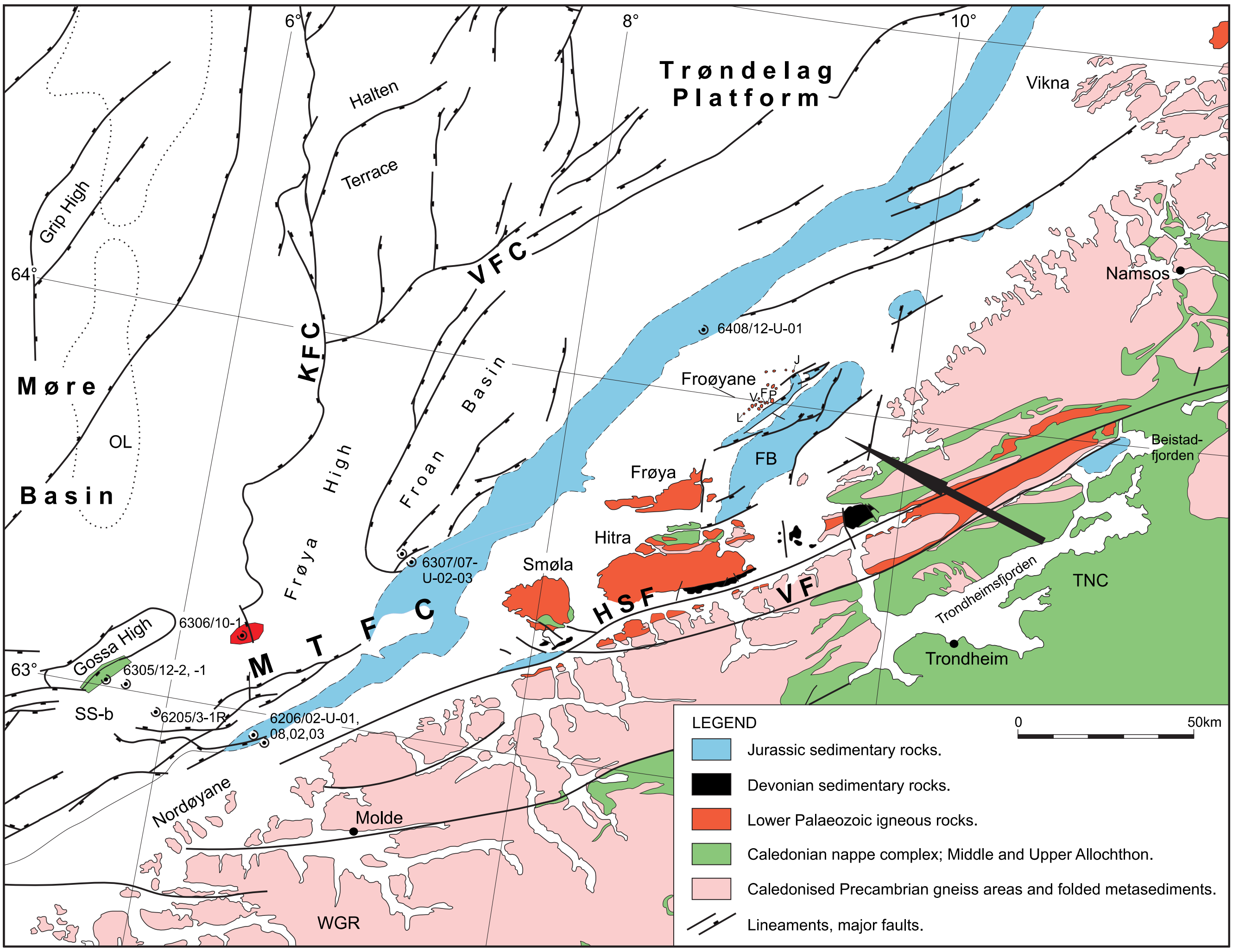

Fig. 1. Well and sample locations in relation to main geological provinces. Structural elements and faults refer to Blystad et al. (1995) and Roberts (1998). MTFC = Møre-Trøndelag Fault Complex, FB = Frohavet Basin, SS-b = Slørebotn Sub-basin, WGR = Western Gneiss Region, KFC=Klakk Fault Complex, VFC=Vingleia Fault Complex, HSF=Hitra-Snåsa Fault, VF=Vingleia Fault, TNC = Trondheim Nappe Complex. The offshore sub-crop of Jurassic beds (Lundqvist et al. 1996) is also shown. OL = Ormen Lange Dome for reference. Erratic block sample locations from Froøyane: J = Jamtøya, P = Prestøya, F = Futøya, V = Vassøya, L = Lyngøyan. Black arrow refers to possible sediment transport direction into the Frohavet Basin in Mid Jurassic time (see later discussion and Figure 8). Basement shown at the Gossa High–Frøya High is overlain by Mesozoic sediments (see text).

Sandstone provenance is interpreted on the basis of diagnostic sediment components at each location and the geographic variation in sandstone composition combined with sedimentological information. The petrographic and mineralogical data are based on optical microscopy, and supplemented by SEM heavy-mineral fraction analyses.

The oldest cored units in the study area are of Triassic – Lower Jurassic age. These deposits are, in part, conglomeratic and the up to boulder-sized fragments within the conglomerates provide valuable information on the type of paleo-basement that was exposed to erosion. Mudstone and claystone compositions based on stratigraphic cores have been discussed elsewhere (Mørk et al. 2003).

The coastal areas of crystalline basement rocks have been strongly eroded into numerous islets and fjords, and these areas acted as sources for westward sediment transport at several times in the past. This study provides evidence of erosion of high pressure metamorphic rocks like those that are exposed at the present Møre coast, as well as of igneous and low-grade, metamorphic Palaeozoic rocks from the Trøndelag area already in Early Mesozoic time. Drillcores retrieved from basement offshore also allow an interpretation of the offshore extension of the different basement provinces beneath the younger sedimentary cover.

Onshore and offshore crystalline basement provinces

The study area is located offshore within and adjacent to the Møre Trøndelag Fault Complex (MTFC) (Fig. 1). This is part of a major regional NE-SW lineament zone recognised both offshore and onshore (Blystad et al. 1995, Gabrielsen et al. 2002), including extensive regional faults such as the Hitra-Snåsa Fault and the Verran Fault (Grønlie & Roberts 1989).

Faults within this major lineament zone have been reactivated during several periods in Late Palaeozoic to Cenozoic time (e.g. Grønlie et al. 1991, Braathen et al. 2000). Isolated Jurassic fault basins are identified from the inner fjords (Beistadfjorden) to the outer island areas of Møre-Trøndelag and westwards to the Gossa High - Slørebotn Sub-basin area (Askvik & Rokoengen 1985, Bøe & Bjerkli 1989, Bøe 1991, Bøe & Skilbrei 1998, Sommaruga & Bøe 2002) (Fig. 1).

The geology of the Møre-Trøndelag Fault Complex and bordering areas may be of importance to our understanding of Mesozoic provenance in the adjacent offshore areas, and this major lineament zone may also be a divide between different basement provinces (see below). The fault complex comprises Precambrian gneisses, Palaeozoic plutonic, metavolcanic and sedimentary rocks, Devonian sedimentary rocks and the down-faulted Jurassic sedimentary succession (Fig. 1). Early Palaeozoic plutonic rocks dominate north of the Hitra-Snåsa Fault on the islands of Hitra, Frøya, Smøla and Froøyane and they include granite, granodiorite, monzonite, diorite and gabbro (Gautneb & Roberts 1989, Nordgulen et al. 1995). The Palaeozoic sedimentary and volcanic rocks on the islands north of the Hitra-Snåsa Fault are typically of low metamorphic grade (Bøe et al. 1989). In contrast, rocks in the Western Gneiss Region (WGR) south of this fault experienced the highest pressure and temperature conditions during the Caledonian (Scandian) continent–continent collision (Griffin et al. 1985, Mørk 1985, Mørk & Mearns 1986, Dobrzhinetskaya et al. 1995, Terry et al. 2000a,b). One of the questions raised in this study is if these contrasting geological provinces can be recognised by different mineralogical and petrographic signatures in the Mesozoic sediments offshore.

Exploration drilling into crystalline basement has provided increased knowledge of the extension of various basement provinces offshore Mid Norway, and some of the observations are mentioned briefly below as a basis for the provenance framework:

Gossa High: Crystalline basement drilled below Jurassic sediments at the Gossa High (well 6305/12-2, Fig. 1) consists of low-grade metamorphic greenstone.

Frøya High (south): Retrograde quartz diorite to monzonite is documented offshore on the west side of the Frøya High (6306/10-1). The feldspar is variably sericitized, and the presence of green hornblende, chlorite and epidote is similar to retrograde minerals observed in Palaeozoic batholiths onshore (e.g., Nordgulen et al. 1993). The crystalline basement is overlain by the Middle Jurassic (Bathonian) Garn Formation, including a zone of red-brown paleosols at the base (Jongepier et al. 1996).

Froan Basin: Granitic basement underlying Middle Jurassic sandstone in the northeastern part of the Froan Basin (6408/12-U-01) is strongly weathered, producing a kaolinite. The accessory heavy-mineral composition consists of zircon, biotite and some Ti-oxides and tourmaline. Occurrences of greenstone and quartz dioritic to monzonitic plutonic rocks in the crystalline basement offshore in the Gossa High–Frøya High area resemble the onshore Palaeozoic rocks of Hitra-Frøya-Smøla. This suggests that there is a southwestward offshore continuation of the low-grade metamorphic Palaeozoic province of the MTFC and the adjacent islands, and that the WGR may have a relatively limited western offshore extension (a few kilometres off the present coastline). The basement boundary may be within the faulted Slørebotn Sub-basin, which is located at the SW extension of the regional extensive Hitra-Snåsa Fault.

Mesozoic deposits – provenance components

The Mesozoic sandstone deposits studied here are shown schematically with respect to stratigraphy and location in Figure 2. The oldest cored deposits consist of Triassic continental, alluvial and debris-flow conglomerate, sandstone and mudstone from the Gossa High, and Upper Triassic – Lower Jurassic conglomerates off Møre (Smelror et al. 1994, Jongepier et al. 1996). Upper Lower - Middle Jurassic transgressive, shallow- marine sandstones are represented in all the locations, except in the southern part of the Froan Basin where the oldest cored sediments are Upper Jurassic. Samples from Froøyane give evidence of sediment compositions from eastern parts of the area. Upper Jurassic – Lower Cretaceous deposits were cored at the Gossa High and in the Froan Basin. These are interpreted as marine mass flows (Jongepier et al 1996, Smelror et al. in prep.).

For each area, the main detrital components and compositional variation is discussed below, and provenance is thereafter compared and discussed in a regional geological framework.

Triassic and Jurassic conglomerate and sandstone deposits off Møre

Upper Triassic – Lower Jurassic conglomerates

The oldest cored sediments in block 6206 near the present Møre coast consist of Upper Triassic - Lower Jurassic debris-flow and alluvial-fan, polymict conglomerates (6206/02- U-03; -U-02), separated from basement by a steep fault contact (Smelror et al. 1994, Fig. 3a). The biostratigraphic range of the older deposits may be extended to include the Late Triassic (J.O. Vigran, pers. comm. 1996). The conglomerate clasts (including granules, pebbles, cobbles and boulders) display great lithological variation and they also show a compositional change with stratigraphy as mafic lithologies are more common in the lower part (6206/03-U-03), and felsic gneiss is the main boulder lithology in the coarser-grained upper part (6206/03-U-03, -02).

The lower conglomerates include a great variety of mafic rocks such as amphibolite, variably retrograded eclogite, epidote-skarn and metavolcanite as well as ultramafics, granitic augen-gneiss and various gneisses of tonalitic, granitic, amphibolitic, and quartz-mica-rich compositions (Fig. 3b). SEM analysis of a mafic symplectitic rock verifies the pres-

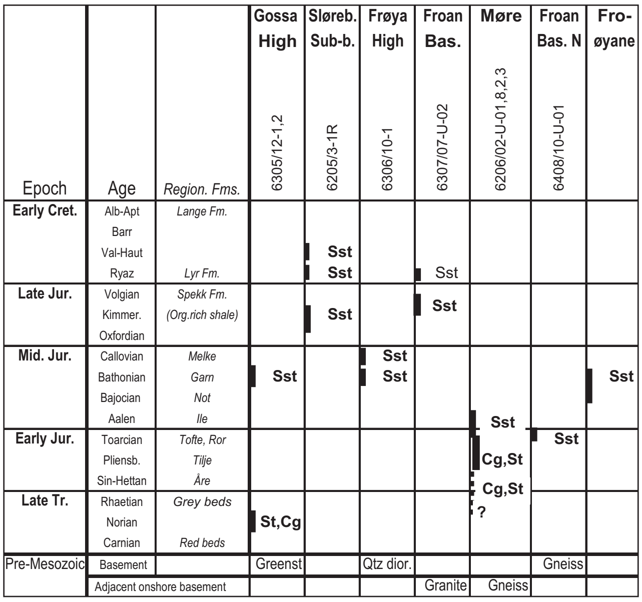

Fig. 2. Stratigraphic overview of studied sandstone (Sst) and conglomerate (Cg) units. Bar marks range in stratigraphic age of the sandstones and conglomerates. St = sandstone alternating with conglomerate. Stratigraphic formations are shown in detail elsewhere (e.g., figure 2 in Rokoengen et al., this volume).

ence of omphacitic pyroxene inclusions in garnet, which provide evidence of high-pressure metamorphism. The eclogites are variably altered by retrograde metamorphism to epidote- and titanite-bearing assemblages. The lithologies of the clasts in the overlying conglomerates are dominated by felsic gneisses including augen-gneiss and migmatite gneiss (Fig. 3).

Altogether, the sedimentary facies and conglomerate clast compositions provide evidence of a dominant provenance from the nearby WGR, including high-pressure mafic metamorphic rocks and felsic migmatite gneisses as well as retrograde and weathered ultramafic rocks. Metavolcanic rock fragments may reflect erosion of lower –grade metamorphic units from elsewhere within the MTFC.

Upper Lower Jurassic and Middle Jurassic sandstones

Upper Toarcian – Aalenian, deltaic marine sandstones unconformably overlie the Lower Jurassic conglomerate above a transgressive surface (-U-02; -08; -01, fig. 4 in Smelror et al. 1994, simplified in Fig. 3). The sandstones are mineralogically immature, classifying as lithic greywacke in the lower part of the succession (core -02) and lithic arenite and greywacke in the upper part (cores -08, -01). Modal analyses

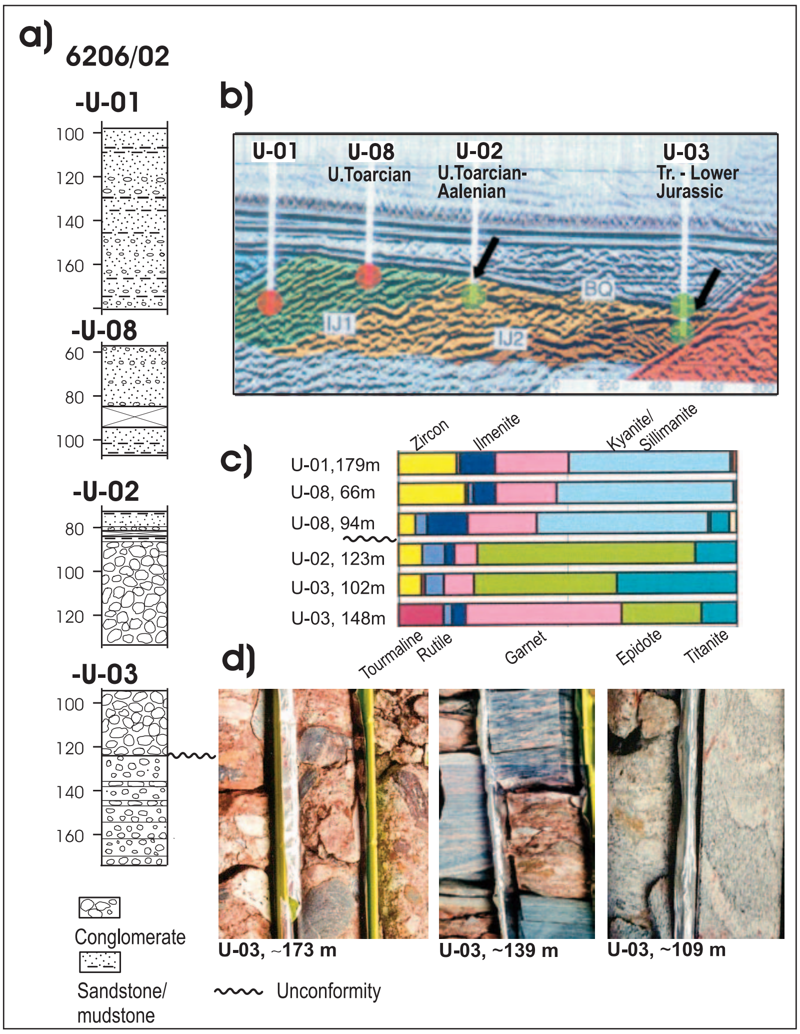

Fig. 3. (a) Lithostratigraphy of Mesozoic sediments off Møre (left, simplified from Smelror et al. 1994). Scale refers to metres below seabed for each core. (b) Relative core positions are shown on an interpreted seismic profile (modified from Smelror et al. 1994). BQ = Base Quaternary reflection, BC = base Cretaceous reflection, IJ1 = intra-Jurassic reflection 1, IJ2 = intra-Jurassic reflection 2. Green and red dots refer to difference in heavy-mineral characteristics as exemplified in Fig. c. Compositional boundaries are marked by arrows at unconformities (Figs. b and c). (c) Heavy-mineral analyses of sandstone beds in cores 6306/03-U-03, -02, -08 and 01, numbers refer to core depth. Note abundance of garnet, epidote and titanite in the lower part and kyanite/sillimanite and garnet in the upper part. (d) Details of core photos from lower and upper parts of the debris flow/conglomerates of 6306/03-U-03 (core diameter ~7 cm). Depths refer to core log. Left (~173 m) and central (~139 m): varied mafic and felsic gneiss pebble and boulder lithologies in the matrix-supported lower conglomerates. Right (~109 m): example of migmatite gneiss boulder within the upper conglomerate.

(Fig. 4a, Table 1) show large variations in the proportions of mica and rock fragments. Microcline is the dominant feldspar; plagioclase, which is present in small amounts in core –08, is nearly absent in the upper core (-01). The rock fragments consist of polygranular quartz, quartz-feldspar gneiss and mica schist.

Heavy-mineral analyses of sandstone beds within the conglomerate units (cores -03 and -02) show abundant epidote, titanite, garnet, biotite and rutile (Fig. 3b). Samples from the overlying sandstone units (cores -08 and -01) show an unusual enrichment of kyanite and sillimanite in the heavy-mineral fraction (garnet, zircon, rutile and Fe-Ti oxides are also present), suggesting a very local provenance (see also Fig. 4a).

Summary of provenance implications based on cored sediments off Møre

In the lower part of the sandstone succession, the heavy-mineral variation is compatible with a main contribution from mafic source rocks. The abundant epidote and titanite in the sandstones is also in agreement with the occurrence of retrograde eclogite clasts in the conglomerate in core -03. The characteristic garnet + kyanite association higher up in the stratigraphy, however, suggests a change in provenance to a more dominant erosion of pelitic rocks. Such garnet-kyanite gneisses are very common in the nearby present-day exposures extending to the southwest and including the outer skerries of Nordøyane (Fig. 1) where they are interfolded with meta-eclogites and amphibolites (e.g., Mørk 1988). This zone may have a wider extension offshore.

Gossa High – Slørebotn Sub-basin – Frøya High

Exploration wells penetrate Triassic and Middle Jurassic sediments at the Gossa High, Middle Jurassic at the Frøya High, and Upper Jurassic-Lower Cretaceous in the Slørebotn Sub-basin (Figs. 1 and 2). Lithologs and sedimentological facies interpretations are presented elsewhere (Jongepier et al. 1996).

Triassic sandstones and conglomerates

Conglomerates, sandstones, siltstones and mudstones of Early Triassic to early Late Triassic age overlie greenstone basement at the Gossa High. These are the oldest, cored, Mesozoic sediments in the study area, interpreted to have been deposited in arid alluvial environments (Jongepier et al. 1996).

The examined Triassic samples in well 6305/12-1 comprise fine-grained, red wacke and siltstone in the lower part and very coarse-grained sandstone in the upper part of the cored interval. The detrital grains are dominated by quartz, plagioclase and mica. Very coarse-grained rock fragments consist of quartzite, chert and volcanic rocks with flow- oriented feldspar laths. The main accessory heavy minerals are epidote, chlorite and opaques. These compositions indicate a sediment source area proximal to volcanic felsic to intermediate rocks and greenstones. The provenance area may have been very local Palaeozoic basement, as recorded at the Gossa High and onshore northwest of the MTFC.

Middle Jurassic sandstones

Bathonian sandstones from near the Gossa High (6305/12-1 and 2) and Bathonian – Callovian sandstones from the Slørebotn Sub-basin near the Frøya High (6306/10-1) are interpreted to represent alluvial-fan, coastal-plain and shallow-marine environments (Jongepier et al. 1996). The studied samples include poorly sorted, fine- to very coarse-grained sandstone, as well as moderately sorted fine-, medium- or coarse-grained sandstones. The sandstones from the Gossa High classify as arkosic-lithic arenite and wacke. Sandstones at the Frøya High have arkosic and subarkosic arenite and wacke compositions (Fig. 5), and are slightly richer in quartz. K-feldspar and plagioclase are abundant in all three wells (Figs. 4c,d, Table 1).

Rock fragments comprise quartzite, gneiss, mica schist, chert and some slate, and with sporadic evidence of recycled sediments. Chert is detected in several samples in 6306/10-1. Heavy minerals observed in petrographic thin-sections are garnet, rutile, opaques, zircon and less commonly titanite, epidote, Cr-spinel, tourmaline and monazite. Garnet appears to be more common in 6305/12-1 and -2 than in 6306/10-1.

Upper Jurassic- Ryazanian sandstones

Upper Jurassic – Lower Cretaceous sandstones ranging in age from Late Oxfordian - Kimmeridgian to Ryazanian (Jongepier et al. 1996) have been examined in well 6205/3-1R in the Slørebotn Sub-basin (Fig. 1). These sediments were interpreted by Jongepier et al. (1996) to represent marine environments, deposited by turbidites and mass flows. The studied samples are fine-grained ranging to medium- and coarse-grained, subarkosic – arkosic arenites, including a few wackes. K-feldspar is more common than plagioclase. Polygranular rock fragments of quartzite, biotite gneiss and recycled sandstone, and heavy minerals such as rutile, zircon, ilmenite, opaques, epidote and, in places, Cr-spinel, apatite and amphibole are present.

Valanginian sandstones

The Upper Jurassic – Ryazanian sandstones in well 6205/3-1R are succeeded by a unit of open marine, mass-flow sandstones of Valanginian – Hauterivian age (Jongepier et al. 1996). This sandstone unit is generally of coarser grain size (medium- to very coarse-grained). It differs from the underlying sandstones by the content of plutonic and volcanic rock fragments such as monzonite and feldspar-rich lava. Metamorphic rock fragments (biotite gneiss/schist, quartzite) and recycled sedimentary rock fragments (chert, mudstone) are also observed. The detrital heavy minerals differ from the underlying Upper Jurassic – Lower Cretaceous units by presence of garnet. The heavy minerals recorded are rutile, zircon, opaques, garnet, tourmaline, epidote and possibly titanite.

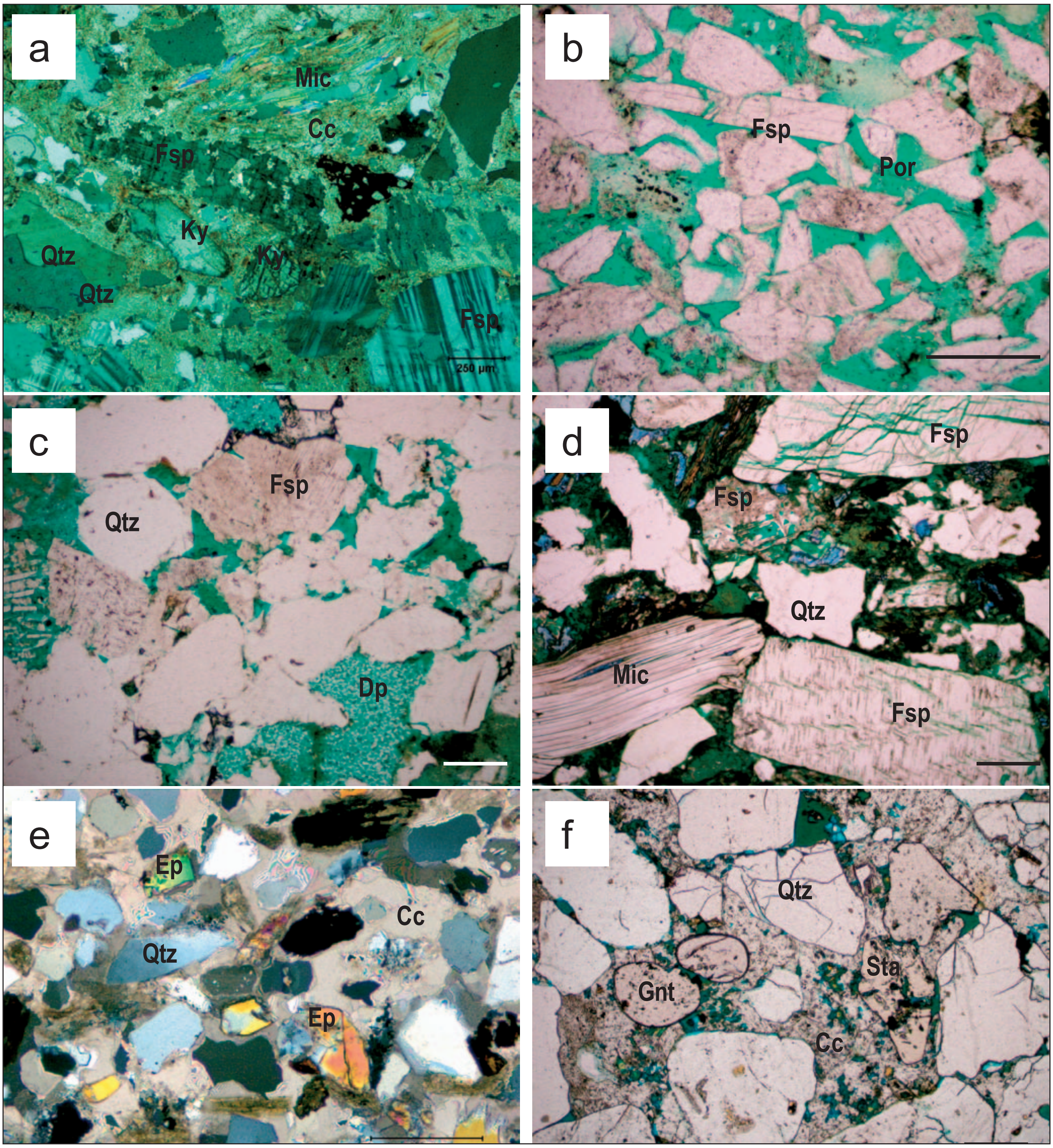

Fig. 4. Optical micrographs of selected sandstones. Scale bar = 0.25 mm. (a) Kyanite (Ky), mica (Mic) and microcline feldspar (Fsp) in calcite cemented, upper Lower Jurassic sandstone off Møre, 6206/02-U-08, 98.00 m (crossed polars). (b) Fine-grained, Upper Jurassic feldspar (Fsp)-rich sandstone (arkosic arenite) from the Froan Basin, 6307/07-U-02, 139.43 m. Bluish-green colour shows porosity. (c) Middle Jurassic sandstone from the Frøya High, 6306/10-1, 2756.6 m. Note diagenetic quartz overgrowths on quartz (Qtz) grains and pseudomorphic clay aggregates and dissolution porosity (Dp). (d)Very coarse-grained, feldspar-rich, Middle Jurassic sandstone from the Gossa High, 6305/12-2, 3008.50 m. (e) Calcite (Cc)-cemented, epidote (Ep)-rich, fine-grained sandstone from Froøyane, FR7208; crossed polars. (f) Staurolite (Sta) and rounded garnet (Gnt) in calcite-cemented, coarse-grained sandstone from Froøyane, 82/87.

Provenance variation with time

The mineralogical data provide evidence of variation in the proportion of metamorphic and igneous rocks in the eroded source areas with time. Garnet-bearing, higher-grade metamorphic components are most prominent in the Middle Jurassic sandstones, whereas the Valanginian – Hauterivian

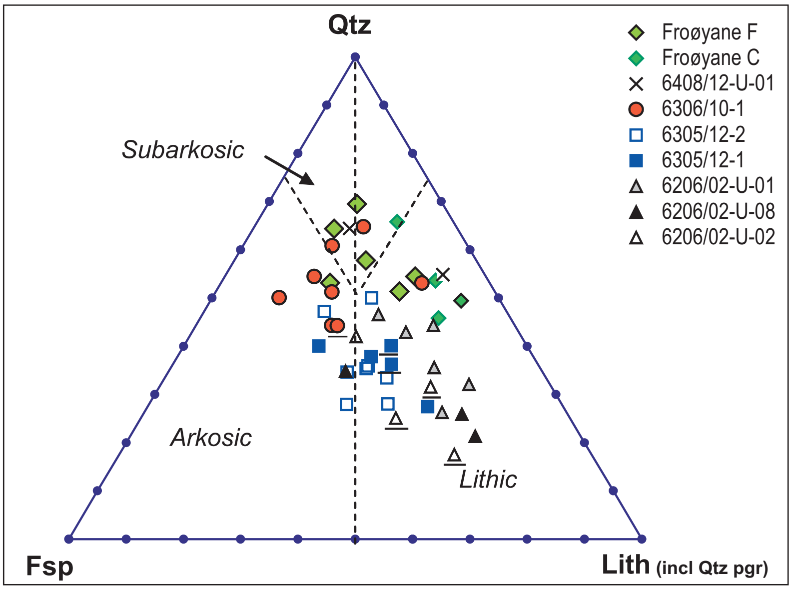

Fig. 5. Upper Lower and Middle Jurassic sandstones compared in a detrital quartz-feldspar-lithics diagram using dividing lines after Pettijohn et al. (1972). Polygranular rock fragments (including quartz), mica and heavy minerals are grouped as lithics. Underlined symbols show samples with >15% total clay (wackes).

sandstone compositions signify erosion of relatively unaltered feldspathic igneous rocks of both plutonic and volcanic origin.

Froan Basin, South

Upper Jurassic sandstones cored in the southern part of the Froan Basin (6307/07-U-02, -U-03) form a c. 80 m-thick unit within the dark shales of the Spekk Formation. The lower, main part of the sandstone is dated to Kimmeridgian - earliest Volgian, and the uppermost 10 m to more definite early Volgian (Smelror et al. in prep.). This division also coincides with a compositional change from arkosic to subarkosic (Fig. 6, Table 1). The sandstones are interpreted as marine mass-flow units as in the Slørebotn Sub-basin.

Sandstones in the lower unit are fine to medium grained, and include dark laminae of very fine-grained sandstone in the lower part. The detrital composition is rich in microcline (Fig. 4b, Table 1), commonly associated with authigenic K-feldspar overgrowths. The rock fragments are of quartzite, feldspar/gneiss and, in some cases, recycled sedimentary rocks (including chert) and possibly volcanic rocks (e.g., at 135.15 m core depth, see log in Smelror et al. 2005). Common accessory heavy minerals are zircon, rutile, tourmaline, opaques, garnet and apatite. A dominance of the stable heavy minerals could reflect an origin from plutonic source rocks. This is also supported by an apparent lack of rounding: the zircons are short prismatic to tabulate euhedral and subhedral, and with no distinct evidence of mechanical abrasion. The rutile grains are elongate anhedral - subhedral and the tourmaline grains elongate subhedral and subangular.

The upper sandstone unit consists of bimodal fine-medium grained and fine-coarse-grained sandstone. The composition differs from the underlying unit by its lower microcline content and higher mica content. Rock fragments of quartzite, and of recycled sandstone and chert are present. Sediment reworking is shown also by the presence of reworked Middle Jurassic fossils in the core (M. Smelror, pers. comm. 2004). Accessory heavy minerals include zircon, rutile, epidote, tourmaline, garnet, opaques and, in places, amphibole, staurolite and kyanite.

Comparison with basement compositions

The feldspar-rich compositions and euhedral to subhedral zircons in the sandstones from the Froan Basin point to igneous source rocks. In combination with the abundant microcline, this indicates a granitic plutonic source rock. However, the presence of garnet shows that sediment was derived also from metamorphic rocks. The microcline-rich compositions in the older unit differ from the cored plagioclase-rich basement in core 6306/10-1 from the southern part of the Frøya High. However, microcline-rich plutonic rocks are extensively represented to the east in the Hitra-Smøla-Froøyane batholiths (e.g., Gautneb & Roberts 1989, Nordgulen et al. 1995).

The combined enrichment of mica and diagnostic metamorphic heavy minerals in the upper part of the stratigraphic cores suggests a provenance change from igneous to dominantly metamorphic rocks in the Volgian. Mafic metamorphic components such as epidote and amphibole may occur as retrograde minerals in the nearby igneous

Table 2. Main heavy minerals in the Mesozoic sandstones in wells from each studied locations.

Location Age interval	Gossa H Sløreb Sb*	Frøya H	Møre	Froan B	Froøyane
E. Cretaceous	Zir, Ru, Opq				
Late Jurassic	Zir, Ru (Opq, Ep)			Ru, Zir Amf, Ep, Gnt	
L.Toarcian-M.Jurassic	Gnt, Ru, Zir	Ru, Opq, Gnt (Ep, Cr, Zir)	Ky, Gnt, Ilm Ep, Gnt, Tit		Ep, Amf, Opq Gnt, Staur, Ky
L.Tr.-E-Jur.			Gnt, Ep, Tit		
Triassic	Ep, Opq				

Abbreviations: Zir=zircon, Ru=rutile, Opq=opaques, Ep=epidote, Gnt=garnet, Cr=Cr-spinel, Ky=kyanite, Ilm=ilmenite, Tit=titanite, Amf=amphibole, Staur=staurolite.

complexes (Nordgulen et al. 1995). However, erosion of metamorphic schist is supported by the occurrence of garnet and staurolite in the Upper Jurassic sandstone of the Froan Basin.

Froan Basin, North

Upper Toarcian mudstones and sandstones overlying kaolinite-weathered basement gneiss have been cored in the northern part of the Froan Basin (6408/12-U-01, Skarbø et al. 1988, Mørk et al. 2003). These are time-analogous to sandstones described offshore from Møre, and represent shallow-marine, transgressive sediments. The detrital minerals comprise quartz, microcline, plagioclase and micas. Quartzite and chert occur as polygranular rock fragments in the coarse sandstone. The heavy-mineral assemblage includes rutile, garnet, tourmaline, Cr-spinel, zircon and ilmenite.

Provenance implication

The dominance of quartz in the coarse-grained sandstones associated with kaolinite-rich mudstone compositions (Mørk et al. 2003) suggests a strong influence from the local weathered basement. However, the varied heavy-mineral composition shows that sediments have been supplied also from less weathered metamorphic rocks and igneous mafic rocks.

Froøyane/Frohavet Basin

A selection of 10 sandstone samples from erratic blocks of Jurassic rocks occurring along the shore of the Froøyane islands was included in the study for petrographic comparison with the offshore locations. The samples discussed below are from the small islets of Jamtøya (59/87 and FR7208), Prestøya (4/87), Futøya (3/87), Vassøya (82/87) and Store Lyngøy (2/87) (Fig.1). Based on petrography, the samples are divided into fine-grained, well-sorted sandstones and coarse-grained poorly sorted sandstones.

The sandstones are relatively quartz-rich (lithic to subarkosic) and with much less K-feldspar than in other sandstone units of this study (Table 1, Fig. 6). The fine-grained samples (2/87, 3/87, 4/87) and fine-medium-grained sample FR7208 are rich in mafic heavy minerals such as epidote, amphibole and chlorite (Fig. 4e) (8% epidote, FR7208).

The coarse-grained sandstones have a notable content of mica schist and quartzite rock fragments and include the diagnostic metamorphic minerals garnet, staurolite and kyanite (samples 59/87, 82/87, Fig. 4f). The garnet grains are well rounded (Fig. 4f).

Provenance implication

The high concentration of epidote, amphibole and chlorite in the heavy-mineral fraction of the fine-grained samples supports an origin from mafic, low-grade to lower medium-grade metamorphic rocks (e.g., greenstone). The garnet-staurolite-bearing assemblages in the coarse-grained samples record an origin from medium-grade metamorphic pelitic schists. This implies a provenance from the erosion of greenstone as well as medium-grade schists.

Discussion of compositional variation and provenance

In the previous chapter, various sandstone provenance signatures have been described for each area. Modal and heavy-mineral data from the different locations are here compared to examine possible geographic variation in the compositions. The same modal data also allow a comparison of certain reservoir properties such as porosity, and also assist in identifying the main porosity-reducing minerals. Although some of the exploration well samples are from considerable burial depths (2-5 km), relatively unstable mafic grains are still present, as described above. This may, in part, reflect the relatively coarse grain size of the samples. Diagenetic feldspar dissolution is accounted for in the regional comparisons described below.

The sandstone modal compositions, as compared in Figures 5 and 6, show a wide compositional range. The most lithic compositions are from the shallow cores off Møre and

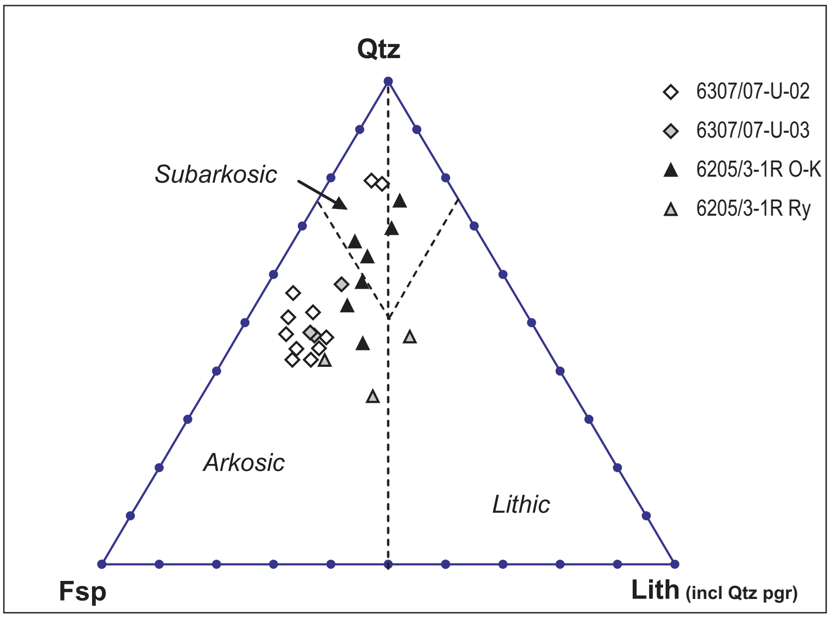

Fig. 6. Quartz-feldspar-lithics plot of Upper Jurassic sandstones from the Froan Basin and Upper Jurassic – Ryazanian sandstones from the Slørebotn Sub-basin. See Fig. 5 for explanations.

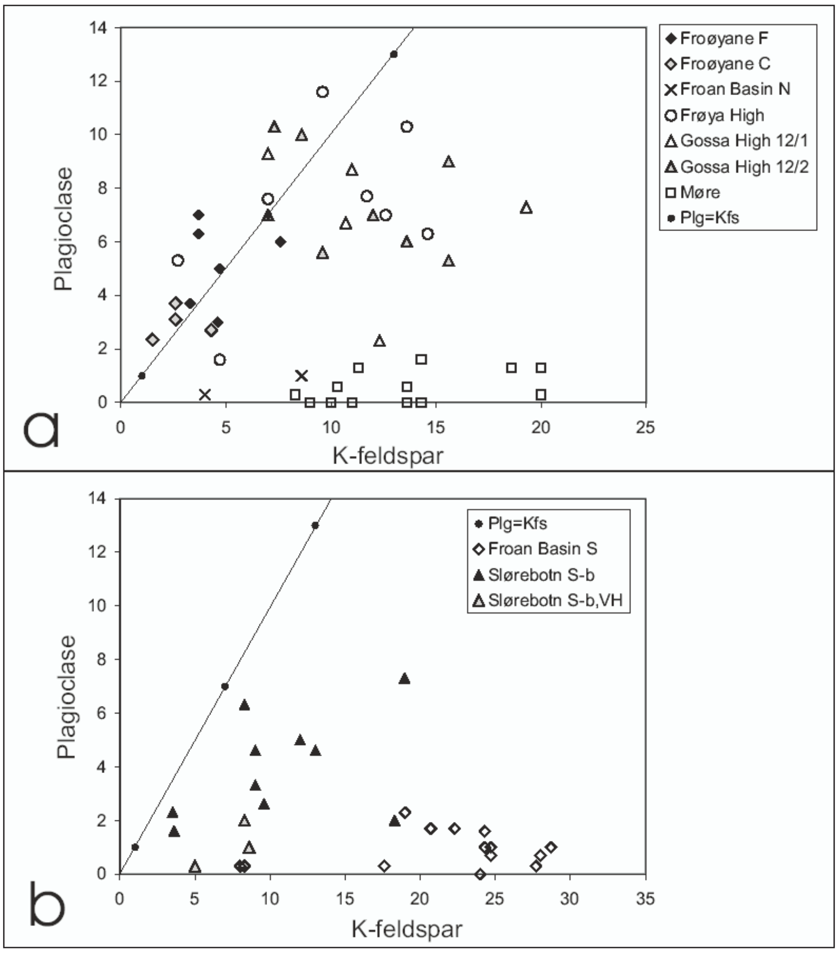

Fig. 7. K-feldspar vs. plagioclase (modal data) for a) Upper Lower Middle Jurassic sandstones and b) Upper Jurassic-lowermost Cretaceous sandstones. Note K-feldspar dominance in samples (off Møre (a) and in the Froan Basin S (b). Plagioclase/K-feldspar ratios are higher and more variable in samples from the Gossa High, Slørebotn Sub-basin and Froøyane.

the most feldspar-rich compositions are detected in the outboard areas. In each area, polygranular grains appear to be more frequent in the coarser-grained sandstones, whereas mica, which is also grouped with the lithics in the FQL plots, is more common in the finer-grained sandstones. Another uncertainty with respect to quantitative mineral comparison is that the feldspar content is variably reduced by secondary dissolution in the deeper wells (Fig. 4c). However, samples with both extensive and minor feldspar dissolution show a compositional overlap in the FQL diagrams, and preserve the geographic trends. Scatter in K-feldspar/plagioclase and quartz/feldspar ratios is observed in both the unaltered and the altered samples.

The common heavy-mineral distributions are compared in Table 2, and provenance interpretations are summarised in Figure 8.

Upper Lower – Middle Jurassic sandstones

The main regional trends in the Upper Toarcian - Middle Jurassic sandstone compositions are:

1) An increase in the sandstone mineralogical maturity of sandstones northeastward from the Møre and Gossa High locations to the Frøya High location (Fig. 5).
2) Sandstones from Møre, Gossa High and Frøya High are richer in feldspar than those from Froøyane and the Froan Basin (Fig. 5).
3) Gossa High and Frøya High sandstones differ from those in more eastern locations in having higher plagioclase contents (Fig. 7a). However, note that the Froøyane samples have unusually low K-feldspar contents.
4) Coarse-grained sandstones from Froøyane are mineralogically more mature than the fine-grained samples. The heavy minerals also suggest differences in provenance lithologies.
5) Differences in sandstone compositions with respect to the major components (FQL) and some of the accessory heavy minerals may be due to different local provenance and source area heterogeneities.
6) In spite of local variations in provenance, garnet-bearing metamorphic source rocks (or recycled sediments from such rocks) are present in all locations of cored Toarcian-Callovian sandstones.

The feldspar distribution in the above-described sandstones mirrors the mineralogy of the adjacent crystalline basement provinces. At the Frøya High, plagioclase-rich basement (quartzdiorite) was exposed to erosion prior to Middle Jurassic deposition. A similar local provenance may explain the plagioclase enrichment in the overlying sediments there, suggesting continued erosion of the plutonic province west of the present exposures. High feldspar contents are preserved in spite of variable secondary dissolution, and as plagioclase is commonly more easily dissolved than K-feldspar during diagenesis (e.g., Ehrenberg & Jacobsen 2001) the sandstones from the Gossa High – Frøya High wells may have been even more plagioclase rich originally.

The presence of metamorphic components suggests that the feldspar-rich sandstones in the Gossa High – Slørebotn Sub-basin area may have received sediments not only from the Gossa High, but also from higher-grade metamorphic provenance areas. As the local basement is probably composed of lower-grade metamorphic rocks, the higher-grade minerals such as garnet may have been transported from the Western Gneiss Region or higher-level Caledonian nappes (e.g., north of Trondheimsfjorden).

Table 1, Range and average sandstone compositions based on modal analyses (300 points) of selected samples.

Area/Well/Age	Grain size	n	Detrital Qtz	Q pgr	Kfs	Plg	Rfr	HM	Mica	Diagenetic minerals & porosity Cly	Qcem	Carb	OpCem	Por
Størebotn Sub-basin, E. Cretaceous														
6205/3-1R	M	2	**42**	**10**	**7**	**1**	**3**	**<1**	**3**	**16**	**10**	**1**	**4**	**2**
			(38-47)	(9-10)	(5-9	(<1-1)	(2-5)		(1-5)	(3-29)	(4-16)	(1-2)	(2-7)	(1-4)
	C	1	**17**	**14**	**8**	**2**	**9**	**1**	**2**	**13**	**<1**	**29**	**3**	**<1**
L.jur,E.Cret														
6205/3-1R	F-M	7	**30**	**3**	**12**	**4**	**2**	**<1**	**7**	**11**	**7**	**16**	**6**	**2**
Late Jurassic			(20-42)	(1-3)	(4-19)	(2-7)	(0-10)	(0-1)	(3-15)	(8-15)	(2-19)	(4-25)	(5-8)	(0-4)
6205/3-1R	M-C	3	**31**	**5**	**7**	**4**	**2**	**<1**	**1**	**7**	**1**	**34**	**5**	**3**
			(25-36)	(3-8)	(4-10)	(2-6)	(1-2)		(0-2)	(6-9)	(0-2)	(22-55)	(3-7)	(<1-5)
Froan Basin S, Late Jurassic														
63078/07-U-02	F,M	2	**54**	**1**	**8**	**<1**	**2**	**<1**	**3**	**12**	**0**	**8**	**2**	**11**
			(50-58)	(0-1)						(9-14)		(0-15)		
6307/07-U-02,-03	F-M	12	**30**	**3**	**24**	**1**	**3**	**<1**	**1**	**11**	**0**	**9**	**1**	**17**
			(26-36)	(1-5)	(18-29)	(0-2)	(<1-6)	(0-1)	(<1-2)	(5-17)		(5-20)	(0-4)	(11-21)
Area/Well/Age	Gr.s.	n	**Qtz**	**Q pgr**	**Kfs**	**Plg**	**Rfr**	**HM**	**Mica**	**Cly**	**Qcem**	**Carb**	**OpCem**	**Por**
Møre, Late Early, Jurassic														
6206/02-U-	F-M	5	**22**	**8**	**12**	**<1**	**1**	**1**	**14**	**21**	**0**	**10**	**1**	**8**
			(20-28)	(2-17)	(8-20)	(0-<1)	(0-4)	(<1-2)	(5-28)	(8-33)		(0-43)	(0-2)	(0-14)
6206/02-U-	M-VC	8	**19**	**16**	**14**	**1**	**5**	**1**	**10**	**15**	**0**	**17**	**<1**	**2**
			(12-30)	(7-22)	(10-20)	(0-2)	(0-16)	(<1-2)	(1-18)	(2-32)		(0-38)	(0-1)	(0-9)
Gossa High, Mid Jurassic														
6305/12-1	M-VC	5	**25**	**9**	**12**	**7**	**8**	**2**	**6**	**13**	**1**	**12**	**5**	**<1**
			(17-29)	(5-13)	(7-19)	(2-9)	(5-12)	(1-3)	(3-11)	(5-19)	(1-3)	(3-26)	(3-7)	(<1-2)
6305/12-2	F-M	3	**26**	**4**	**9**	**8**	**2**	**<1**	**9**	**5**	**3**	**23**	**5**	**5**
			(19-32)	(3-5)	(7-12)	(7-10)	(1-3)		(5-11)	(3-9)	(<1-7)	(9-31)	(3-8)	(<1-9)
6305/12-2	M-VC	5	**20**	**9**	**12**	**7**	**6**	**<1**	**7**	**7**	**2**	**16**	**7**	**5**
			(16-24)	(6-12)	(7-16)	(5-10)	(2-11)		(3-13)	(1-12)	(<1-8)	(2-30)	(2-18)	(2-9)
Frøya High, Mid Jurassic														
6306/10-1	F-M	6	**34**	**6**	**10**	**8**	**1**	**<1**	**3**	**8**	**10**	**8**	**3**	**8**
			(29-38)	(4-7)	(3-15)	(5-10)	(1-2)	(0-1)	(1-8)	(1-12)	(1-16)	(0-26)	(<1-5)	(<1-10)
6306/10-1	M-VC	2	**29**	**11**	**7**	**7**	**2**	**<1**	**4**	**16**	**5**	**6**	**4**	**8**
			(28-30)	(8-15)	(5-10)	(2-12)	(1-3)	(0-1)	(2-5)	(14-17)	(2-9)	(1-10)	(3-6)	(5-12)
Froøyane, Mid Jurassic														
Froøyane	F(-M)	6	**31**	**2**	**5**	**5**	**<1**	**7**	**4**	**2**	**1**	**39**	**4**	**1**
			(26-35)	(<1-5)	(4-8)	(3-7)		(0-16)	(<1-8)	(<1-4)	(0-3)	(35-45)	(<1-9)	(0-4)
Froøyane	M-VC	4	**32**	**17**	**3**	**3**	**2**	**1**	**2**	**<1**	**2**	**29**	**5**	**4**
			(26-42)	(13-22)	(2-4)	(2-4)	(<1-6)	(0-3)	(0-3)	(<1-1)	(1-3)	(24-35)	(3-8)	(<1-7)
Froan Basin N, Late Early Jurassic														
6408/12-U-01	C	1	**32**	**22**	**4**	**<1**	**0**	**<1**	**0**	**1**	**<1**	**1**	**39**	**0**
6408/12-U-01	VF	1	**33**	**2**	**9**	**1**	**0**	**0**	**6**	**12**	**0**	**1**	**0**	**36**

The fine-grained sandstones from Froøyane are characterised by a low feldspar content and a distinct epidote, amphibole and chlorite content. This may be interpreted in terms of provenance from mafic, relatively low-grade metamorphic rocks similar to those that are widespread in upper parts of the Trondheim Nappe Complex, and in units within the MTFC, including areas north of Trondheimsfjorden.

The coarser-grained sandstones from Froøyane differ from the finer-grained with respect to provenance, as the association of garnet, staurolite, biotite and kyanite suggests an origin from medium-grade pelitic schists. Such rocks are known to be present elsewhere locally in the Trondheim Nappe Complex, e.g., in the Gula Complex and Støren/Fundsjø groups east of Trondheimsfjorden (Wolff 1979, Lagerblad 1984, Lundqvist et al. 1997). Medium-grade metamorphic parageneses are also recorded north of Trondheimsfjorden (Lundqvist et al. 1997), e.g., along the Høybakken detachment zone (Braathen et al. 2000). The presence of garnet has also been described from metamorphic rocks in the northern part of Hitra (Kollung 1963), close to Frohavet; but there is no mention of staurolite in these coastal areas.

In summary, different crystalline basement provinces acted as sediment sources to the upper Lower and Middle Jurassic sandstone deposition off Møre and Trøndelag. Source areas for deposition in the Slørebotn Sub-basin were both high-P/T metamorphic rocks of the WGR (Møre coast) and Palaeozoic igneous and sedimentary rocks which were exposed between the Frøya High and Gossa High. Contemporaneous sedimentation in the Frohavet Basin may

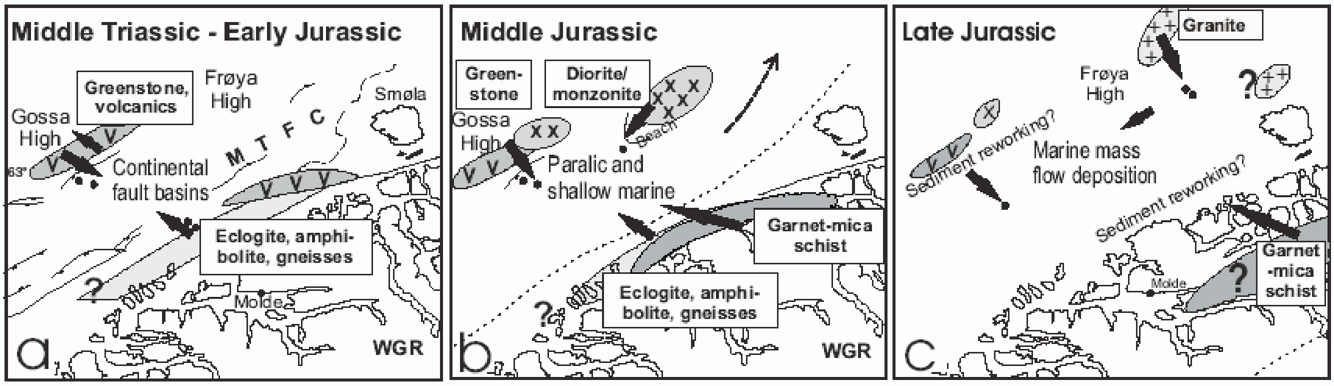

Fig. 8. Cartoon illustrating location and characteristic rock types of the local basement (coloured areas) as interpreted from sediment compositions combined with regional geological knowledge. Arrows show sediment transport to the Slørebotn Sub-basin and southern Froan Basin (see structural lineaments in Fig. 1). Stippled line in Figs. b and c shows limit of exposure inferred by Swiecicki et al. (1998), for comparison. The thin arrow in Figure b gives a possible sea connection to Haltenbanken. MTFC = Møre-Trøndelag Fault Complex, WGR = Western Gneiss Region. See Fig 1 for provenance interpretation for the Frohavet Basin area. Two alternative locations of the granitic source area are shown on both sides of the Froan Basin in c. The western area is the most likely based on other studies (Smelror et al. 2005), implying the presence of granitic basement on parts of the Frøya High.

have been sourced from areas of medium-grade pelitic rocks east or north of Trondheimsfjorden, or possibly nearby from the outer Trondheimsfjorden - Frohavet area.

Upper Jurassic – Lower Cretaceous sandstones

Upper Jurassic arkosic sandstones from the southern part of the Froan Basin (core 6307/07-U-02) represent the most feldspar-rich compositions in all the studied wells, dominantly microcline. The time-analogous deposits in the Slørebotn Sub-basin have lower feldspar/lithic ratios, and with a higher proportion of plagioclase and metamorphic components than in the Froan Basin. However, the heavy-mineral composition resembles that of the micaceous sandstone unit in the upper part of the Froan Basin cores.

In conclusion, the Upper Jurassic sandstones in the Froan Basin may have been derived from granitic plutonic rocks. Compared to the Middle Jurassic deposits, these younger sandstones show an increase in the K-feldspar/plagioclase ratio. This may reflect a provenance change from erosion of dioritic basement in Middle Jurassic time (e.g., 6306/10-1 south Frøya High basement) to erosion of granite in the Late Jurassic. These compositions are all represented by different plutons in nearby areas (e.g., north of the MTFC at Froøyane, Nordgulen et al. 1995).

The distinct increase in the mica/feldspar ratio in the upper unit in core 6307/07-U-02 suggests a stronger metamorphic input with time in the Volgian. However, the possible effects of sediment reworking on this change have not yet been evaluated. The similarity of this unit to the Upper Jurassic sandstones in the Slørebotn Sub-basin suggests a common provenance for these areas.

Hauterivian – Lower Barremian deposits

The Hauterivian – Lower Barremian conglomerates and sandstone beds in the Slørebotn Sub-basin have been interpreted as deep-marine fan sedimentation in response to relative sea-level drop and/or tectonic movements (Jongepier et al. 1996). The sediment compositions give evidence of erosion from diverse lithologies such as plutonic, volcanic and sedimentary rocks. Clast compositions and the coarse grain size suggest a new phase of erosion of plutonic rocks either from within the MTFC or from the areas to the north.

Comparison of sandstone reservoir properties from modal data

Reconnaissance information on porosity and the main diagenetic minerals can be obtained from the modal analyses (Table 1). Note that modal porosity is a minimum value for porosity in cases of prominent clay contents. The modal porosity of the studied sandstones is highest in the Upper Jurassic sandstones from the Froan Basin that show an average of 16% porosity (Table 1). This is mainly primary porosity as diagenetic alteration is relatively limited (e.g., minor K-feldspar overgrowths and carbonate cementation). These sandstones may have experienced as much as 2 km of burial in the past (Mørk & Stiberg, in prep.).

The Upper Jurassic – Lower Cretaceous sandstones from the Slørebotn Sub-basin from much greater burial depths (4.3-5.2 km) display porosities below 5%. These sandstones show evidence of considerable quartz cementation, but on average, carbonate and clay minerals are volumetrically the main porosity-reducing minerals (Table 1). Due to considerable feldspar dissolution, much of this porosity is secondary and associated with clay minerals.

The upper Lower and Middle Jurassic sandstones have low to moderate modal porosity values due to both carbonate cements and clay minerals (Table 1). The average porosity is somewhat higher in the samples from the Frøya High, where carbonate cementation is less extensive. However, much of this porosity may be secondary dissolution porosity. The average quartz cement content is highest in this location (Table 1), including values up to 16%. The lower quartz cement content in the slightly deeper buried sandstones of the Gossa High partly reflects primary compositional differences, e.g., higher feldspar, lithics or clay content, which reduce the available quartz surface areas for cement precipitation (e.g., Walderhaug 1996, Oelkers et al. 1996). In the shallow cores off Møre, the main porosity-reducing factors are the high clay contents and the carbonate cement. The erratic block sandstones from Froøyane are all carbonate cemented.

In total, it appears that carbonate cement is the most important porosity-reducing mineral in the shallow cores and exposed samples. Quartz cementation is more important in the deeper wells (Table 1), but in these feldspar-rich sandstones the potential reservoir properties tend to have been strongly influenced by secondary dissolution and clay mineral growth.

Summary and discussion

This chapter summarises the conclusions on erosion and provenance based on the sediment compositions and basement geology. Results of the studies on provenance and reservoir quality also have some implications for sediments in the offshore exploration areas, and these are discussed towards the end of this chapter.

Paleo-exposures and erosion

Comparison of offshore basement with the overlying Mesozoic sedimentary succession and detailed provenance interpretations provide evidence of exposure and erosion of different geological basement provinces (and tectonic units) in Møre and Trøndelag and adjacent offshore areas in Triassic – Jurassic time.

Data from the 6206/02 cores off Møre confirm that high pressure metamorphic rocks/eclogites and granitic migmatite gneisses of the Western Gneiss Region were exposed to erosion already in the Late Triassic-Early Jurassic. The mineral compositions and sedimentary facies support the hypothesis that it was the westernmost parts, i.e. the site of the present islets and skerries, that were eroded at that time (Fig. 8). This is also supported by the apatite fission-track data from the Nordøyane islands (Mørk & Stiberg 2003).

Basement underlying Jurassic strata at the Gossa High and Frøya High shows a strong resemblance to the Palaeozoic igneous rocks northwest of Trondheimsfjorden on Hitra, Smøla, Frøya and Froøyane, suggesting that there is an offshore southwestward extension of this province. Mesozoic erosion in these offshore basement areas has earlier been inferred from seismic interpretations (Koch & Heum 1995, Jongepier et al. 1996) and is here supported by the mineralogical data acquired from the studied exploration wells. Low-grade metamorphic rocks including greenstone were eroded at the Gossa High in the Triassic, and minerals derived from greenstone were deposited also in overlying Jurassic sediments. Feldspar-rich plutonic rocks were exposed at the Frøya High prior to the Middle Jurassic deposition. This means that outboard extensions of the Hitra-Frøya-Froøyane batholiths were exposed to erosion in Middle and Late Jurassic as well as in Early Cretaceous time.

Jurassic exposure and erosion may have also taken place in some areas to the southeast or northwest of Trondheimsfjorden. This is indicated by the mineralogy of the Frohavet sandstones (Froøyane erratics), which were sourced from diagnostic medium-grade metamorphic rocks similar to some units within the Trondheim Nappe Complex (Fig. 1).

Phases of uplift and erosion are inferred also from the occurrence of unconformities in the lithostratigraphy, showing that erosion took place not only in crystalline basement areas, but also in the sediment sub-basins at various times. In the offshore Møre region, a large stratigraphic break is identified between Middle Jurassic and Upper Cretaceous strata (Smelror et al. 1994), whereas Pliensbachian – Callovian erosion is indicated by the break at the Gossa High (Jongepier et al. 1996). Martinius et al. (2001, fig. 3) show extensive areas of erosion both at the Gossa High and the Frøya High at the time when the Pliensbachian Tilje Formation was being deposited at the Halten Terrace.

Late Middle Jurassic and Early Cretaceous tectonic activity is inferred from a structural interpretation of seismic data (Blystad et al. 1995, Jongepier et al. 1996). The repeated Mesozoic erosion and deposition at the flanks of the Slørebotn Sub-basin suggest that there was episodic tectonic activity along the Møre–Trøndelag Fault Complex. The NNE-SSW-trending Vingleia and Klakk Fault Complexes (Fig. 1) may have had a major influence on uplift and erosion of the Frøya High (e.g., Koch & Heum 1995, Smelror et al. in prep.).

Sediment provenance implications

The oldest sediments (Triassic – Lower Jurassic) were deposited in continental settings (Fig. 8), and they are typically mineralogically immature and display different local basement provenance signatures (Møre and Gossa High). Following periods of local tectonic movements and erosion, transgressive sediments were deposited in shallow-marine and coastal-plain environments in late Early – Middle Jurassic time. These sediments show evidence of both local provenance influence and of mixing (e.g. by the presence of garnet in all locations). The local influences off Møre are from a gneissic terrane and at the outboard locations (Gossa High, Frøya High) more from a feldspar-rich plutonic rock source. The distribution of metamorphic minerals suggests that the Slørebotn Sub-basin received sediments from both the Møre margin and the paleo-highs within the MTFC (Fig. 8).

As noted earlier, Upper Jurassic and Lower Cretaceous sandstone deposits preserved in the more basinal areas have been interpreted as marine mass-flow deposits (Jongepier et al. 1996, Smelror et al. 2004). However, transport distances may not have been very long as the sandstone petrography and mineral compositions suggest a main provenance of granitic plutonic rocks as in the Hitra-Frøya-Froøyane province, i.e. close to y the MTFC, or alternatively, related to movements on the Klakk Fault to the west (Fig. 8). Additional seismic information, however, would be necessary for a better localization of this outboard part of the igneous complex in Early Jurassic time. Farther to the north in the Draugen area, Van der Zwaan (1990) noted reworked Early and Middle Jurassic sediments in sand bars of the time-equivalent Rogn Formation. This may have been related to fault uplift along the western margin of the Trøndelag Platform, suggesting that both crystalline basement rocks and Mesozoic sedimentary deposits were involved in the erosion.

One of the aims of the study was to constrain provenance signatures from the south-eastern margin of the Norwegian Sea as a basis for interpreting sandstone provenance in the offshore exploration areas. However, due to the variety of geological provinces that were available to erosion in this part in the Mesozoic, it is not possible to identify a unique 'southeastern' provenance signature from this margin. The sediment components from these areas are derived both from feldspathic plutonic rocks typically associated with stable heavy minerals as well as from heterogeneous metamorphic rock complexes. The sediments originated from outboard areas northwest of the MTFC, western coastal areas of the WGR and possibly also from eastern areas (Trondheim Nappe Complex). Complicated and very local variations in detrital mineral signatures, even through limited intervals of stratigraphic time, have been demonstrated in the cores off Møre. However, a very rough generalisation is suggested, namely that varied metasedimentary and metavolcanic rocks contributed more to sedimentation in the Triassic – Lower Jurassic, and that erosion of Palaeozoic plutonic rocks from present-day outboard areas was more important in Late Jurassic–Early Cretaceous time.

The basin configuration and the possibility of sediment transport from these marginal areas to more western and northwestern sites (Møre Basin area) cannot be interpreted from compositional data alone. It is also uncertain exactly how extensive the outboard exposures of the igneous provinces actually were, and if these areas acted as barriers to westward sediment transport from the WGR. Jongepier et al. (1996) correlated coastal- plain environments in the Slørebotn Sub-basin with proximal areas at the Gossa High and more marine facies towards the Frøya High. Brekke et al. (1999) postulated a restricted marine inlet from the Slørebotn Sub-basin northwards into the Jurassic basin of the Trøndelag Platform and an exposed paleoland to the northwest. Mineralogical signatures of sediments and Jongepier et al.'s (1996) inferred northward deepening indicate that a northwest-directed sediment transport from these marginal areas may have been possible.

Note on diagenesis

The petrographic study of these feldspar- and lithic-rich marginal sandstone occurrences suggests that the main diagenetic influences on porositiy are carbonate cementation in the relatively shallow buried sandstones (including the Froøyane erratic block samples), and quartz cementation, feldspar dissolution and clay mineral growth in the deeper wells.

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