Sedimentological Development of the Fangst Group, Halten Terrace, Mid-Norway

by

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Abstract

Cores from well 6506/12-1 of the Smørbukk Field (Halten Terrace, Mid-Norway) show a nearly complete 175 meter thick section comprising the Middle Jurassic Fangst Group and the upper part of the underlying Ror Formation of the Båt Group. The Fangst Group comprises three formations: The Ile Formation, the Not Formation and the Garn Formation. The Ile-and Garn formations are sand-dominated and constitute some of the most important reservoir units in the prolific hydrocarbon province of the Norwegian Sea. The aim of the present study was to thoroughly describe the Fangst Group of well 6506/12-1 and from this interpret its sedimentological development. Correlation with well 6506/11-6 and 6506/11-8 was carried out based on wireline logs and core photos, and this correlation led to increased understanding of sand body development in the study area and formed the basis for paleogeographic reconstruction.

Rifting between Norway and Greenland initiated in the Late Carboniferous and occurred in pulses until the two landmasses finally separated in Early Cenozoic times. The Mid-Jurassic has been described as a period of nearly total tectonic quiescence on the Halten Terrace, but some faulting may have occurred which influenced sedimentation when the Fangst Group was formed. A total number of 18 facies or subfacies was recognized in well 6506/12-1, and have been grouped into five facies associations (FAs).

FA1 represents a prograding low-energy offshore to prodelta succession (the Ror Formation) conformably overlain by prograding, tidally reworked mouth bar deposits. These mouth bars are interpreted as the delta front of the progradational/aggradational tide-dominated delta which was responsible for deposition of the Ile Formation. FA2 represents the lower delta plain, consisting of tidally-dominated facies comprising tidal flats and channel sandstones, with minor fluvial dominance toward the top of the interval. FA3 records the backstepping of the delta plain towards the end of Ile Formation deposition, and the delta plain was eventually flooded. This transgression left a wave ravinement surface and a significant transgressive lag. The overlying FA4 defines the Not Formation, with a maximum flooding surface defined within offshore black shales and marking the change from transgression to regression. Regression in the Not Formation is characterized by normal shoreface progradation. FA5 defines the Garn Formation, and unconformably overlies FA4. A significant hiatus has been interpreted at this sequence boundary in well 6506/12-1. The medium- to coarse-grained sands are interpreted as a progradational to aggradational stack of amalgamated braided river deposits, deposited in a braid delta. A transgression in mid-Garn flooded the braid delta and created shallow embayments on the former delta top, before renewed progradation brought the braided rivers closer to the location of well 6506/12-1 again.

Correlation with wells 6506/11-8 and 6506/11-6 west of 6506/12-1 confirms the continuance of sand bodies of the Fangst Group. However, there are differences between the wells which aid the paleogeographic reconstruction. A roughly N-S oriented shoreline and seaway is interpreted for the Fangst Group. The Ile Formation is interpreted as a tide-dominated delta which prograded from the east into a basin experiencing low wave-energy. The delta may have had several distributaries where some were dominated by ebb-tidal- and fluvial currents whereas some were dominated by flood-tidal currents. This led to development of an asymmetric delta front with extensive, tidally modulated mouth bars only developing outside ebb-dominated distributaries. The Garn Formation is interpreted to be facies- and time-diachronous along the transect. Faulting, possibly combined with eustatic sea-level fall and uplift of a major source area to the west led to increase in coarse sediment influx to the Halten Terrace. It is interpreted that footwall uplift led to erosion at the location of well 6506/12-1, which was concomitant with deposition of shallow-marine sandstones in the hanging wall (at the location of well 6506/11-6). Backstepping of the shallow marine sands onto the footwalls of faults may have occurred. The Garn Formation of well 6506/12-1 formed as erosion ended and braid deltas were able to build out across this area, continuously feeding the shallow seaway where sediments were distributed and reworked by a combination of longshore currents and tides.

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1 Introduction

1.1 *Aim of study*

The Halten Terrace is the type area of the Middle Jurassic Fangst Group, which is the focus of this study. The Fangst Group comprises the Ile, Not and Garn formations, and along with these formations the upper part of the Ror Fm. of the Båt Group is included in this study. The investigated interval is Late Toarcian to Early Bathonian in age (Dalland et al., 1988), approximately 169 – 182 Ma. Although a lot of work has been done on both the study area in general and on the Fangst Group formations in particular (see next section), it is often valuable to conduct re-examinations in order to confirm or contest earlier interpretations. The aim of the study was to:

- Describe the sedimentology of the above mentioned formations in a 175 m core section from well 6506/12-1 of the Smørbukk Field on the Halten Terrace.

- Build a detailed facies- and facies association scheme for the entire cored section based on the sedimentological description and the variations seen vertically in the core.

- Incorporate wireline logs (Gamma Ray, Neutron/Density,) from both the studied well 6506/12-1 and from two additional wells, 6506/11-6 and 6506/11-8, in order to correlate the interpreted depositional environments and further assess sand body geometries and the validity of the existing interpretation.

- Use all of the above to comment on sequence stratigraphy of the studied interval, and to create paleogeographic maps for the area at different stages through the development of the Ror Formation and the Fangst Group.

1.2 *Previous work*

As mentioned the Halten Terrace has been the focus of many studies, which initiated early in the 1970s with the area being recognized as part of a large sedimentary basin offshore Mid-Norway. This realization came from geophysical studies (Eldholm, 1970; Grønlie & Ramberg, 1970; Talwani & Eldholm, 1972; Åm, 1970), motivated by the recent success in hydrocarbon exploration in the North Sea.

The main structural elements of the mid-Norwegian shelf were named and defined by Gabrielsen et al. (1984), but these were later revised and the nomenclature was formalized by Blystad et al. (1995). Both older and more recent studies have dealt with the tectonic history and structural development of the Halten Terrace area (e.g. Bukovics et al., 1984; Corfield & Sharp, 2000; Gabrielsen & Robinson, 1984; Marsh et al., 2010; Ziegler, 1988).

The lithostratigraphy of the Mesozoic succession was formalized by Dalland et al. (1988), and this publication established the nomenclature used to this day. Prior to the paper by Dalland et al. (1988) the Ror, Ile, Not and Garn formations were often referred to as the Leka Siltstone and the Lower-, Middle- and Upper Tomma Sandstone, respectively (e.g. Gjelberg et al., 1987; Heum et al., 1986). The formations contain large proportions of the hydrocarbons discovered on the Halten Terrace, and hydrocarbon exploration has therefore motivated many studies on the geology of the Fangst Group and the Norwegian Shelf in general (e.g. Brekke et al., 2001; Chuhan et al., 2001; Corfield et al., 2001; Dreyer, 1992; Ehrenberg, 1990; Ehrenberg et al., 1992; Ehrenberg & Nadeau, 1989; Gjelberg et al., 1987; Harris, 1989; Heum et al., 1986; Karlsson, 1984; Martinius et al., 2005; McIlroy, 2004a).

1.3 Methodology

This study is based on the following data:

- Sedimentological description of the upper Ror Fm. and Fangst Group in core from well 6506/12-1
- Gamma Ray and Neutron/Density wireline logs from well 6506/12-1, 11-6 and 11/8
- Core photos from the Norwegian Petroleum Directorate web pages
- Published papers

1.3.1 Core Analysis

The core description took place at the core storage facility at Weatherford Laboratories in Sandnes in February 2010. The 175 m long core from well 6506/12-1 is complete and shows the entire interval from the upper Ror Formation through to near the top of the Garn Formation of the Fangst Group. The core was described with as great care and detail as possible, as this is crucial for later interpretation. Along with description of sedimentary structures, textures and bed contacts, some emphasis was put on noting the trace fossils. Trace fossils can aid in the correct identification of sedimentary environments, as some environments may produce rocks with grossly similar sedimentary structures. The concept of tiering was used to retrieve additional information about possible hiatuses in sedimentation not discernible as a distinct change in grain size or as a surface. Tiering is a concept dealing with the distribution of organisms and their traces in the sediment body (McIlroy, 2004b).

Data from the core description are presented in the chapters on facies and facies associations, where core photos from the NPD web pages and personal footage taken with a Nikon D50 digital camera are used to illustrate the interpreted facies and environments. The computer-redrawn 1:50 vertical scale graphic logs are presented in the appendix. The grain size profile and much of the sedimentary characteristics have been transferred to a summary panel (Fig.6.2) where they are shown in 1:200 vertical scale, alongside the wireline logs and checker plots of the interpreted facies and facies associations. Also included in this panel are transgressive/regressive trends and important sequence stratigraphical surfaces.

1.3.2 Correlation

In order to successfully correlate the interpreted facies of the 6506/12-1 well, a core shift was needed as the depths registered when coring often are dissimilar to the ones registered from wireline logs. This core shift was carried out by comparing the 1:50 scale graphic log created from core description with the wireline logs, by matching mud-dominated sections of the core with high gamma-ray values and positive separation in the neutron/density log, and by matching sand-dominated intervals with low gamma-ray values and none or negative separation on the neutron/density log. In addition these wireline log panels showed the location of plugs drilled in the core for porosity- and permeability measurements. This made it possible to further constrain the depth of the core by comparing the depth of plugs on the log panel with the position of the holes seen in NPD core photos. The cores were on average shifted 2 meters down relative to the logs as shown in the 1:200 summary panel (Fig.6.2). This was also implemented in the correlation panel (Fig.5.2).

1.4 Outline of chapters

The contents of the chapters in this thesis are as follows:

- Chapter 2 – *Geological framework*; presents the geological setting of the study area and its development through geological time, with emphasis on the Mesozoic.
- Chapter 3 – *Facies description and interpretation*; presents details on every facies and subfacies including photographs illustrating important features. A summary table is shown at the start of the chapter.
- Chapter 4 – *Facies associations*; the grouping of facies into associations based on their stacking.

- Chapter 5 – *Sand body geometries*; assessed by correlation of well 6506/12-1 with the two other wells, and by information from the literature on typical geometries of the interpreted depositional environments.
- Chapter 6 – *Sequence stratigraphy*; comments on some of the most important sequence stratigraphical features expressed in well 6506/12-1.
- Chapter 7 – *Paleogeography of the Halten Terrace*; maps of the study area at different stages in the Middle Jurassic.
- Chapter 8 – *Conclusions*

2 Geological Framework

2.1 Study Area

The study area is situated on the passive continental margin offshore mid-Norway, and is commonly referred to as the Halten Terrace (Fig.2.1). This prolific hydrocarbon province is situated between 64° and 65°30'N, and between 6° and 8°E, and it constitutes a rhomboidal-shaped and highly block-faulted terrace that is separated from the largely unfaulted Trøndelag Platform to the east by the Bremstein- and Vingleia Fault Zones, and from the deep Vøring- and Møre Basins to the west and south by the Klakk Fault Zone (Fig.2.2). The Halten Terrace constitutes an area of approximately 10 400 km^2 in total (Marsh et al., 2010). It constituted a part of the Trøndelag Platform until a rifting episode lasting from late Mid-Jurassic to Cretaceous established it as a separate structural element. More than 3000 meters of Cretaceous- to Cenozoic strata cover the Halten Terrace, and most of the terrace also has a complete Jurassic succession. The exception is the Sklinna Ridge on the western margin of the terrace (see Fig.2.2), where the Jurassic has been eroded (Blystad et al., 1995).

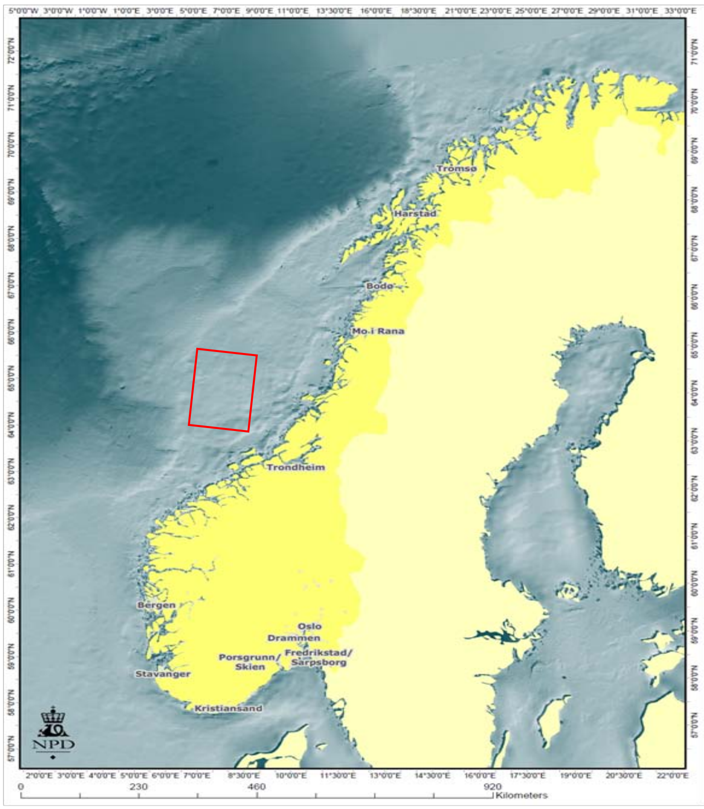

Figure 2.1: Rough outline of the study area, the Halten Terrace, located on the passive continental margin of the coast of mid-Norway (modified from Norwegian Petroleum Directorate web pages, 2010).

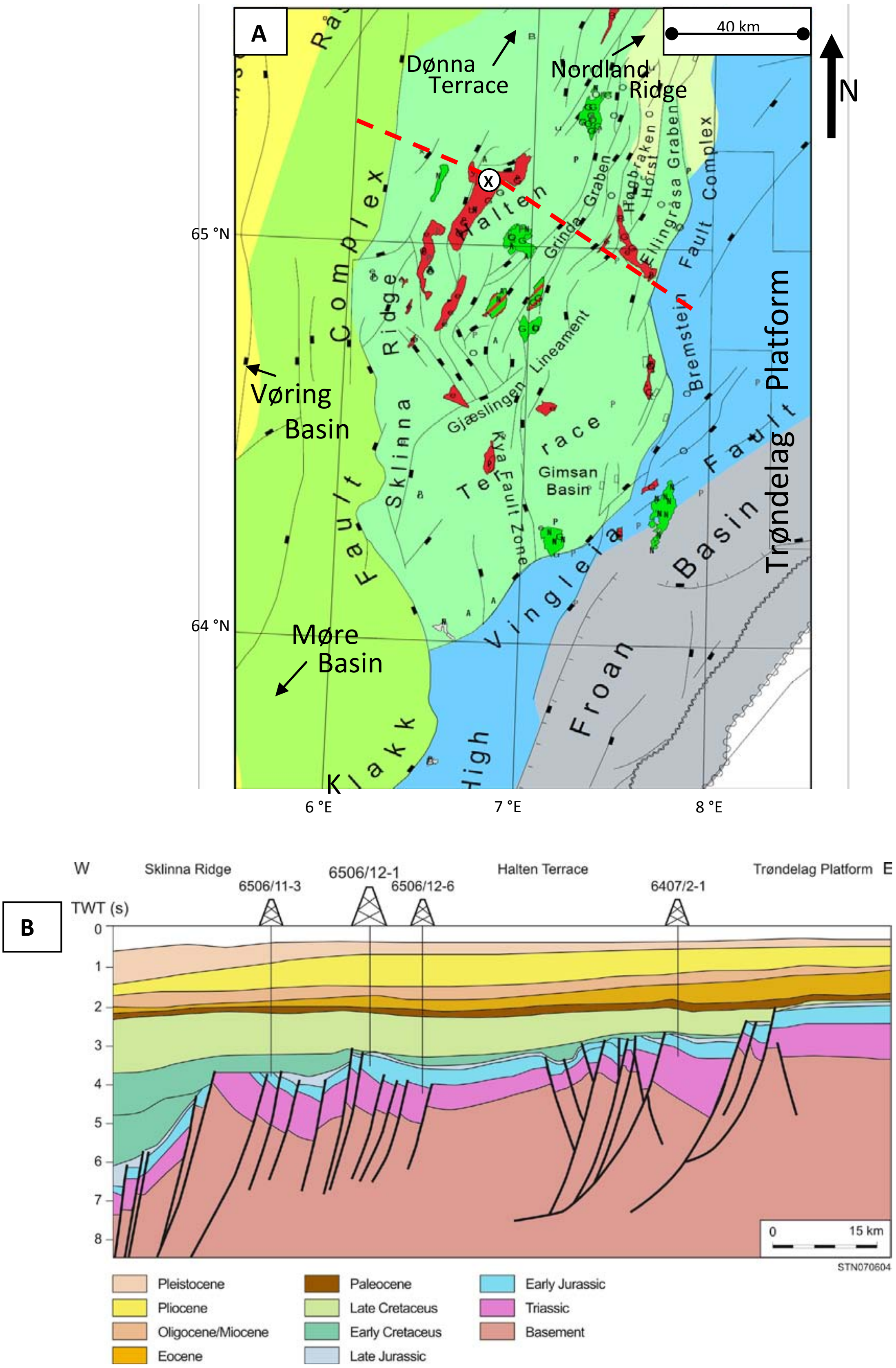

Figure 2.2: The structural elements of the Halten Terrace and surrounding area (modified from figure made by Ryseth (Statoil), 2010). *B*: W-E cross section across the Halten Terrace, showing the studied well 6506/12-1 drilled into Jurassic sediments on the crest of a rotated fault block. Location of cross section shown by red stippled line in A, location of well 6506/12-1 by the circled X (original from Nysæther, 2006; modified by Ryseth (Statoil), 2010, and author).

A preliminary nomenclature for the structural elements of the mid-Norwegian shelf was published in 1984 (Gabrielsen et al.), but these definitions were revised and formalized in 1995 (Blystad et al.). Based on these works, some prominent structural features in the vicinity of the Halten Terrace should be mentioned.

The Dønna Terrace is the northward continuance of the Halten Terrace, west of the Nordland Ridge. It formed together with the Halten Terrace, but was further downfaulted relative to the Nordland Ridge in Late Cretaceous. The Nordland Ridge is regarded as part of the Trøndelag Platform, and is defined relative to the basal Cretaceous unconformity (BCU) which represents several events of nondeposition and erosion on the ridge. The hiatus varies as rocks truncated by the unconformity range from Early Permian to Jurassic in age, while rocks above are from the Early Cretaceous to Pliocene. Uplift of the ridge initiated in late Middle Jurassic to Early Cretaceous, and this also defines the creation of the Trøndelag Platform. This large platform contains several subsidiary elements along with the Nordland Ridge, and has been largely stable since the Jurassic. Its western boundary is the Bremstein Fault Zone which leads down to the Halten Terrace. On the western margin the Sklinna Ridge forms the outer structural element of the Halten Terrace. The ridge formed as a flank uplift in Late Jurassic along the Klakk Fault Zone, at the same time as the Nordland Ridge and Frøya High was uplifted. The deep basins outside the Halten Terrace are the western Vøring Basin, a large sedimentary basin comprising several highs and sub-basins, and the southwestern Møre Basin. Both basins have a complex subsidence history initiated by Late Jurassic-Early Cretaceous rifting and continued by later rifting and thermal subsidence, and they both contain large thicknesses of post-rift sediments (Blystad et al., 1995).

The studied well 6506/12-1 (65° 10` 07.58`` N, 6° 43` 44.07`` E; see Fig.2.2) was drilled as a wildcat and became the discovery well for the Smørbukk field in the western part of the Halten Terrace back in 1984; four years after the government opened the area for exploration. The well was plugged and abandoned in 1985 after having proved gas condensate in five zones contained within the Middle Jurassic Fangst group and the Early Jurassic Båt Group (Ehrenberg et al., 1992; Norwegian Petroleum Directorate web pages, 2010). As seen in Fig.2.2B, the well was drilled at the crest of a dipping fault block. The field is bounded to the west by a major normal fault, and to the north by an east-west trending graben structure that crosses the crest of the rotated fault block (Ehrenberg et al., 1992). The oldest penetrated formation is the Early Jurassic Åre Formation (see Fig.2.3) (Norwegian Petroleum Directorate web pages, 2010).

The following section will attempt to provide a brief overview of the geological history of the Halten Terrace. Please consult Figure 2.3 for the stratigraphic units of the region. The stratigraphic nomenclature shown in this figure was established and formalized in 1988 (Dalland et al.).

2.2 Geological History

2.2.1 Paleozoic – from wrench movements to crustal extension

The first stages in the development of the Halten Terrace can be traced as far back as the earliest Devonian Era, when the Iapetus Ocean closed as Norway was sutured to Greenland in the Caledonian orogeny. The collision was not head-on, which led to complex sinistral fault movements along the axis of the Arctic North Atlantic Caledonides during the Middle Devonian to Early Carboniferous. These movements weakened a broad zone of the crust in the orogen, and created deep fractures that were reactivated when wrenching ceased and was replaced by crustal extension in the major Norwegian-Greenland Sea Rift System in the Late Carboniferous (Bukovics et al., 1984; Ziegler, 1988). These first extensional forces would eventually lead to the opening of the Norwegian Sea by Early Cenozoic times (Gjelberg et al., 1987).

Evidence for the initiation of rifting is abundant in Central East Greenland, where large thicknesses of sediment including the Early Permian red conglomerates, fluvial sands and lacustrine black shales accumulated in large half-grabens (Surlyk et al., 1984). The shelf of Mid-Norway do not contain the same compelling evidence for initiated rifting, but interpretation of seismic data from the Trøndelag Platform may indicate the presence of Upper Paleozoic clastics (Ziegler, 1988). The initial rifting is recorded outside Mid-Norway by N-NW trending basement fault blocks that are onlapped by Triassic seismic reflectors (Ehrenberg et al., 1992). Late Permian times saw the start of thermal subsidence which continued into the Triassic. This subsidence, combined with eustatic sea-level rise possibly related to retreating ice-caps in Gondwana, led to transgression of the Arctic Sea into the Norwegian-Greenland Sea Rift. Upper Permian Carbonates have been confirmed in a well on the Mid-Norwegian Shelf (Ziegler, 1988).

2.2.2 Mesozoic to present –rifting phases and varied sedimentation on the road to crustal separation

2.2.2.1 Triassic

Thermal subsidence and accelerated crustal extension affected the Norwegian-Greenland Sea Rift in the first part of the Triassic Era, producing large rotational fault blocks. The increased extension caused the rift system to propagate southward and into the North Sea area, where the Viking- and Central Graben were formed (Ziegler, 1988). An elongated arm of marine waters extended into the rift system from the Boreal Sea in the north (Nøttvedt et al., 2008). Wells that have reached Triassic deposits on the Halten Terrace confirm that deposits from Middle Triassic time is dominated by restricted marine evaporites and claystones. Later in the Triassic these were followed by continental sedimentation and deposition of fluvial and lacustrine grey- and red beds (Fig.2.3). The

Sklinna Ridge on the southwestern margin of the Halten Terrace may have been an emergent structural element as early as the Triassic, offering a possible boundary separating the Early Triassic salt basin from normal marine waters to the west (Heum et al., 1986; Jacobsen & van Veen, 1984).

Relative tectonic quiescence prevailed during the Late Triassic, except for some minor uplift and faulting along the Nordland Ridge and Frøya High (Ehrenberg et al., 1992). It has been suggested that uplift of highs like these in the rift zone led to increased erosion and clastic influx into the basins, and thereby dominantly continental sedimentation (Ziegler, 1988). A few major faults may have already been active in the Halten Terrace area, a sign that its bounding fault zones had started developing (Gabrielsen & Robinson, 1984). Syndepositional faulting of Triassic strata is also documented on the Trøndelag Platform (Bukovics et al., 1984).

2.2.2.2 Early Jurassic

Sea-level rise through the Jurassic led to development of a permanent seaway between Greenland and Norway, connecting the Boreal Sea with the Tethys Ocean (Nøttvedt et al., 2008). The early stages of the Jurassic Era saw little rifting, and gradual subsidence of the uplifted flanks of the rift system may have led to a lower clastic input into the basin (Ziegler, 1988). The Late Rhaetian to Sinnemurian Åre Fm. (Fig.2.3) constitutes a thick deltaic sequence of various lithologies and substantial amounts of coal that transitionally overlies the continental sediments of the Triassic (Jacobsen & van Veen, 1984). Several lines of evidence point to an eastern sourcing of this prograding deltaic sequence (referred to as the Hitra Formation in Gjelberg et al., 1987), that is thought to have occurred in a period of continued tectonic quiescence (Ehrenberg et al., 1992). Contrary to most authors, Marsh et al. (2010) suggest that the subsequent tectonic phase started already in the Hettangian-Pliensbachian, and that a few large basement faults affected the deposition of the upper coal-rich intervals of the Åre Formation. Nevertheless, this minor tectonic phase involved the formation of N-NE trending growth faults detaching in Triassic evaporites (Ehrenberg et al., 1992). It was during this rifting phase that the lower part of the Tilje Formation (Aldra Formation in Gjelberg et al., 1987) was deposited, representing the initial retreat of the deltaic system and a generally transgressive trend. This is a temporary trend however, as the upper part of the Tilje Formation is characterized by an increase in clastic input, probably due to uplift and erosion of a tectonically active element in the west, which led to an eastward deltaic progradation (Bukovics et al., 1984; Gjelberg et al., 1987). The dominance of tidal features over those generated by wave action is thought to reflect the physiography of the basin, which may have been quite narrow as both a western and an eastern source of clastics have been proven both for the Pliensbachian and later times (Gjelberg et al., 1987).

The transition from the deltaic Tilje Formation into the marine mudstones of the Ror Formation in the Late Pliensbachian is sharp and reflects a regional transgression that flooded the delta. Locally on the Halten Terrace the deposition of mudstone is interrupted by the coarse sands and conglomerates of the Tofte Fm., interpreted to result from local uplift and erosion near the Sklinna Ridge on the western Halten Terrace. The deposits themselves are commonly interpreted as fan-delta sediments (Ehrenberg et al., 1992; Gjelberg et al., 1987).

2.2.2.3 Late Toarcian to Early Bathonian – the Fangst Group

Concomitant with break-up Pangaea drifted northwards, and by Mid-Jurassic times the study area was situated between 45° and 60° N in a warm and humid climate (Nøttvedt et al., 2008). The Fangst Group, the main focus of this thesis, was deposited in this setting along with the upper Ror Formation. Thus, a detailed description of their sedimentology and environmental setting will be presented in following chapters. To give a brief overview, the Fangst Group is a sand-dominated and largely regressive sequence consisting of the Ile, Not and Garn formations (Fig.2.3), and the group is regarded as largely equivalent to the Brent Group of the northern North Sea. The Late Toarcian to Early Bathonian is regarded as a time of nearly total tectonic quiescence (Ehrenberg et al., 1992). There is compelling evidence from $^{143}Nd/^{144}Nd$ data presented by Ehrenberg et al. (1998) that a large landmass existed west of the Halten Terrace and was contributing sediment to the basin for most of the Jurassic (Brekke et al., 2001; Martinius et al., 2005).

The Ile Formation conformably overlies the Ror Formation on the Halten Terrace, and it shares many of the characteristics of the Tilje Formation. Gjelberg et al. (1987) suggests that it was deposited in a narrow and roughly N-S orientated seaway that like during Tilje deposition received sediment from both its eastern and western margin, and was affected by strong tidal currents. Some wells in the northern, eastern and southern parts of the Halten Terrace show an increase in wave influence at the top of the formation, maybe reflecting a transgression that drowned significant parts of the area.

The transition from the Ile Formation to the Not Formation is sharp and is often marked by a significant ravinement surface, related to a transgression that affected the whole of the Halten Terrace. The Not Formation resembles the Ror Formation, with largely offshore to shoreface deposition of mud- and sandstone organized in a coarsening-upward succession.

The Garn Formation is separated from the Not Formation by a very sharp surface. This upper formation of the Fangst Group has a blocky gamma-log pattern and consists of very prospective reservoir sandstones that cover the entire Halten Terrace, though with somewhat varying thickness (Gjelberg et al., 1987).

2.2.2.4 Late Jurassic

The transition from Middle- to Late Jurassic is marked by a major transgression, which lasted into the Early Cretaceous. At first this transgression resulted in deposition of the

Melke Formation, a shale with a moderate organic content, but this is in turn unconformably overlain by the rich source rocks of the Spekk Formation. This formation corresponds to the Draupne Formation of the North Sea (Ehrenberg et al., 1992). The transgression that caused deposition of the Melke- and Spekk formations can be related to large-scale regional extension that began in Late Bathonian and continued through the Early Cretaceous. The maximum of this rifting episode is often referred to as the "Late Kimmerian rifting pulse". The Møre- and Vøring basins subsided rapidly in the Late Jurassic while the Trøndelag Platform only experienced minor faulting, which shows that the rifting was now focused in the axial area of the rift zone (Bukovics et al., 1984; Ziegler, 1988). The Halten and Dønna Terraces were in this axial area and began separating from the Trøndelag Platform (Blystad et al., 1995). Most of the large faulting of this episode was related to detachment in the Triassic evaporites, but some are considered to be high-angle basement faults. The tilted fault blocks seen on the Halten Terrace (Fig.2.2B) were created during the late Kimmerian rifting pulse, giving the horsts and half-grabens that delineate many of today's fields (Ehrenberg et al., 1992). Another characteristic of this Late Jurassic rifting was the uplift and deep erosion of the Sklinna Ridge, Frøya High and Nordland Ridge (Blystad et al., 1995).

2.2.2.5 Cretaceous to Pliocene

The Base Cretaceous Unconformity (BCU) separates Jurassic from Cretaceous deposits on the Halten Terrace. The area experienced deposition of thick marine shales along with thin carbonate- and sand beds through the Cretaceous. As seen in Fig.2.2B the Late Cretaceous section thins significantly on the Trøndelag Platform to the east. Relative uplift of the Nordland Ridge and the Trøndelag Platform explain turbiditic sand-deposition on the Halten Terrace, and the fact that marine deposits only started draping these positive features in the Late Cretaceous (Heum et al., 1986). Only minor syndepositional faulting affected the Trøndelag Platform in this time (Ziegler, 1988). The Late Cretaceous show several signs of decreasing rift activity. The regional subsidence at this time is largely attributed to gradual cooling of a thermal anomaly created during the large Late Kimmerian rifting pulse (Bukovics et al., 1984).

Through the Cenozoic Era up until the Pliocene Epoch the accumulation of marine shales continued, and these units were more continuous across the whole region (Ehrenberg et al., 1992). Rifting increased again in the first part of the Cenozoic, mostly concentrated in the western part of the Møre- and Vøring basins (Bukovics et al., 1984). The Paleocene Tang and Tare formations contain ash layers that probably are related to the Thulean Volcanism, the extrusion of large plateau basalts associated with the final rifting phase that separated Greenland from Norway in Early Eocene (Ziegler, 1988). It was only now that the study area became a passive continental margin, after withstanding several rifting pulses in the prior 270 Ma.

2.2.2.6 Late Pliocene through Quaternary

Starting at approximately 3.0 Ma in the Pliocene, the depositional style changed with the deposition of the Naust Formation and the overlying Quaternary deposits. The Halten Terrace and Trøndelag Platform experienced rapid subsidence and was overlain by glaciomarine clastics prograding from the southeast. This caused accelerated hydrocarbon generation and -migration on the Halten Terrace. An additional effect was generation of overpressures in the faulted Jurassic reservoirs on the western part of the Halten Terrace. The eastern part of the reservoirs did not become overpressured, as they were able to relive the pressure via connections with sandy units to the east. The overlying Cretaceous shales had no way to relive the overpressure, and thus became an effective seal of the normally pressured sandstones in this part of the Halten Terrace. The Smørbukk field lies at the borderline to the overpressured region, but its reservoirs are of normal pressure (Ehrenberg et al., 1992).

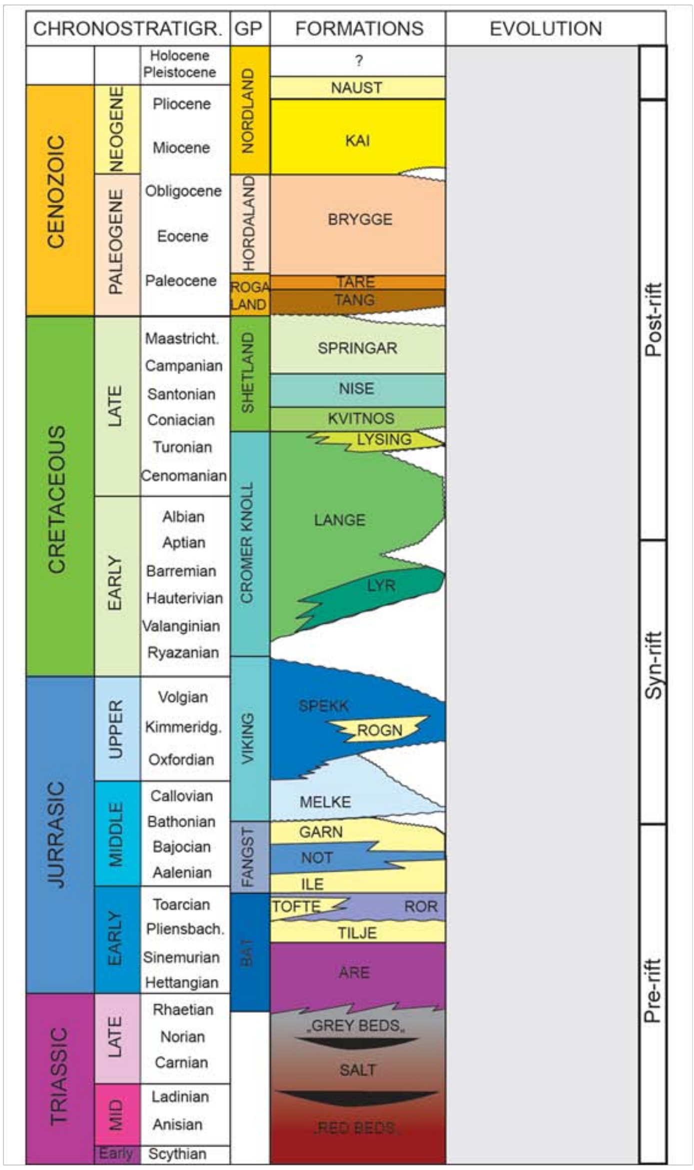

Figure 2.3: Stratigraphic column for the Halten Terrace. The Pre-, Syn- and Post-rift refer to the main rifting that created the Halten Terrace (Dalland et al., 1988; modified by Ryseth (Statoil), 2010).

3 Facies Description and Interpretation

3.1 Introduction

The term “facies” has been a part of geological terminology since it was first introduced by Nicholas Steno in 1669, but it was only in 1838 that the word got its present meaning, when the Swiss geologist Amanz Gressly defined a facies as the “*sum total of the lithological and paleontological aspects of a stratigraphic unit”* (Walker, 2006). There has been much debate over the definition of the term, but a good working definition was stated by Middleton (1978):

> “… The facies may be given informal designations (“Facies A” etc.) or brief descriptive designations (“laminated siltstone facies”) and it is understood that they are units that will ultimately be given an environmental interpretation; but the facies definition is itself quite objective and based on the total field aspect of the rocks themselves… . The key to the interpretation of facies is to combine observations made on their spatial relations and internal characteristics (lithology and sedimentary structures) with comparative information from other well-studied stratigraphic units, and particularly from studies of modern sedimentary environments”.

“Facies” is a term that can be used in both a descriptive and an interpretive sense (Walker, 2006), as the naming may highlight either a specific distinguishing feature of the deposits of a given facies, or may include an interpretation as to the depositional environment from which the deposits originate. In this chapter the facies are given interpretative names, in the belief that this makes it easier for the reader. Although the names assigned to facies describe a certain element within a depositional system, e.g. “Tidal Channel Fill”, a very clear distinction is made between the description of the deposits and the interpretation of them. As this study is based on a single length of core 175 meters long and ten centimeters wide, a successful division into facies relies on a very accurate description of the deposits and their relationships in a vertical sense. Much effort has been put into the description of lithologies, sedimentary structures, bed contacts, textures and trace fossil assemblages, and from there a subdivision of the core into facies has been established.

Table 1 provides a brief description of the different facies that constitutes the Ror Formation and the Fangst Group, roughly arranged in order distal to proximal. The table is followed by a detailed description and interpretation of each facies. Subfacies are included when the depositional environment is largely the same but the deposits have one or more features that indicate a minor difference in processes acting on that environment. Please consult the appendix and Figures 4.1-4.3 and 6.2 when core depths are referred to, and to get a better understanding of the stacking of facies.

Table 3-1: Summary of the facies interpreted in the Ror Formation and the Fangst Group, 4151.73 – 3975 m core depth, well 6506/12-1, Smørbukk Field

Facies	Subfacies	Lithology	Thickness information	Grain size and trends	Boundaries	Sand/shale -ratio	Sedimentary structures	Bioturbation (Degree + type)	Interpretation	Pictures
A	-	Shale, vf sandstone	5.7 m	Clay, some silt and vf sand in lowermost part	Transitional fining-up (FU) in base, gradual coarsening-up (CU) in top	0-0.1	Planar parallel lamination (ppl) in shale, ripple cross-laminated vf sand. Synsedimentary pyrite nodule	Generally none, but lowermost two meters show degree 1. *Phycosiphon*, *Chondrites*, *Planolites*	**Offshore Black Shale**	*3.1A,B*
B	-	Muddy siltstone	14.1 m	Silt, clay, minor amounts of vf sand	Base not cored, upper boundary is gradual and CU	0-0.3	None. Synsedimentary nodules of pyrite/siderite	Generally 6. *Phycosiphon*, *Schaubcylindrichnus*, *Zoophycos*, *Asterosoma*, *Teichichnus*. Possibly a few *Chondrites* and *Rhizocorallium*	**Open Shelf**	*3.2A,B*
C	C1	Muddy siltstone, silty- to very fine sandstone	21.7 m, w/ CU units 35 cm-2 m thick	Clay, silt, vf sand. Several meter-scale CU units contained within one larger CU trend	Gradual CU in base and sharp, erosive top. Internal CU unit boundaries vary between gradual to sharp and slightly erosive	0.1-0.8	Hummocky cross-stratification (HCS), low-angle ppl, wave-ripple cross-lamination (WRCL)	4-5. *Phycosiphon*, *Schaubcylindrichnus*, *Zoophycos*, *Asterosoma*, *Teichichnus*, *Chondrites*, *Rhizocorallium*, *Paleophycus*, *Planolites*, *Skolithos*, *Teichichnus*, *Phoebichnus* and *Thalassinoides*	**Offshore Transition Zone/Prodelta**	*3.3A-D*
	C2	Muddy siltstone, silty- to fine sandstone	19.7 m CU, event beds 1-30 cm thick	CU trend from clay and silt to fine sand	Gradual CU in base, transitional top boundary. Event beds with erosive bases and sharp- to gradual tops	0.1-1	HCS and SCS (swaley CS), ppl, WRCL, CRCL (current ripples).	3-5 in regular sedimentation; *Phycosiphon*, *Zoophycos*, *Schaubcylindrichnus*, *Planolites*, *Teichichnus*, *Asterosoma*, *Thalassinoides*, *Paleophycus*, *Taenidium*, *Ophiomorpha*, *Skolithos* and *Chondrites* 0-1 in event beds; *Skolithos*, *Ophiomorpha*, *Cylindrichnus*	**Offshore Transition Zone w/ Distal Tempestites**	*3.4A-D*
D	-	Very fine- to fine sandstone.	7.5 m	Mostly fine sand with some finer laminae. Stacked blocky- to slightly FU units	Transitional base, sharp erosive boundary in top	0.8-1	HCS and SCS, low-angle ppl, WRCL, CRCL. Mud clasts	0-6. *Asterosoma*, *Paleophycus*, *Planolites*, *Skolithos*, *Arenicolites*, *Trichichnus*, *Schaubcylindrichnus*, *Teichichnus*, *Rosselia* and *Ophiomorpha*	**Lower Shoreface**	*3.5A-C*
E	-	Siltstone, vf sandstone. Partly siderite/pyrite cemented	1.5 m	Slight FU from vf sand to silty sand. Few angular pebbles	Gradual base, sharp planar top	0.2-0.5	Some low-angle ppl. Nodules of siderite, granules of chamosite	4. *Phycosiphon*, *Asterosoma*, *Thalassinoides*, *Chondrites* and *Paleophycus*	**Condensed Section**	*3.6A,B*

F	-	Interbeds of vf sandstone and mudstone	6.3 m, interbedding on cm- to dm-scale	Vf sand, silt, clay	Sharp and erosional boundaries of the facies, sharp interbed boundaries	0.5-0.8	Current ripples, wave ripples, herringbone cross-lamination, double drapes, climbing ripples, load casts, synaeresis cracks	0-3 in sands, 1-3 in muds. *Planolites*, *Paleophycus*, *Thalassinoides*, *Rosselia* and *Skolithos*	**Distal Distributary Mouth Bar**	*3.7A,B*
G	-	Vf-f sandstone	5.8 m	Vf sand, minor amounts of fine sand and mud	Sharp erosive base, gradual in top	0.8-1.0	Wave ripple cross-lamination w/ reactivation surfaces, climbing ripples, double draped current ripples, herringbones, organic fragments and roots	1-4. *Schaubcylindrichnus*, *Asterosoma*, *Ophiomorpha*, *Diplocraterion*, *Planolites*, *Paleophycus*, *Rosselia*, *Trichichnus* and *Skolithos*	**Middle Distributary Mouth Bar**	*3.7C-E*
H	-	F-m sandstone. Partly carbonate cemented and micaceous	12 m combined thickness. Fining-up units on dm- to m-scale	Sand, some silt. FU to non-graded bedsets	Sharp, commonly erosional bases, sharp planar to erosive tops boundary	0.7-1.0	Horizontal/low-angle ppl, trough cb, current ripples, herringbones, double drapes, climbing ripples, wave-rippled beds w/ reactivation surfaces, fluid muds, rip-up clasts of siderite, mud and organic fragments.	0-1. *Trichichnus*, *Ophiomorpha*, *Planolites*, *Rosselia*, *Schaubcylindrichnus* and *Paleophycus*	**Proximal Distributary Mouth Bar**	*3.8A,B*
I	-	M sandstone, occasional coarser sand beds	10.2 m. Set of trough-cross bedding typically a few dm thick.	Dominantly medium sands. Several coarse – gravelly lags. Blocky- to FU bedsets generally a few dm thick, within large slight FU trend	Sharp erosive base, sharp planar top	1.0	Dominated by trough CS, but also low-angle planar- and tabular CS. Some foresets are normal graded. Sigmoidal CS, WRCL, CRCL. Double mud drapes on foresets, few coal chips.	0	**Braid Delta Bar Complex**	*3.9A-D*
J	-	F sandstone, thin silty interbeds and some very coarse lags	15.9 m	Fine sand. Some muds and medium/coarse sands	Sharp base, top not cored	0.8-1.0	Low-angle- and trough CS, herringbone-, current- and wave ripple cross-lamination, double mud drapes	0-5. *Paleophycus*, *Trichichnus*, *Cylindrichnus*, *Asterosoma*, *Skolithos* and *Ophiomorpha.*	**Flooded Braid Delta**	*3.10A-C*
K	K1	Vf-f sandstone, siltstone	Up to 1 m intervals within a 3 m core section; bedding on dm-scale	Sand, silt, minor clay. Blocky to slight FU	Gradual to sharp bases, sharp planar to erosive top boundary	0.5-1.0	Wavy lamination in silts; in sands: low-angle cross-bedding, erosional base, double draped herringbone- and current ripple cross-lamination, wave ripples and reactivation surfaces.	2-4. *Paleophycus*, *Planolites*, *Trichichnus*, *Skolithos*, *Monocraterion*, *Cylindrichnus*, *Psilonichnus*, *Asterosoma* and *Ophiomorpha.*	**Subtidal Flat**	*3.11A,B*
	K2	Vf-f sandstone, mudstone interbeds	Up to 3.75 m thick successions, interbedded muds appear every 0.5-1 m	Sand, minor amounts of silt and clay. Blocky to slight FU bedsets	Gradual to sharp boundaries, commonly eroded by J1 deposits in top	0.7-1.0	WRCL, CRCL, ppl, trough CS and reactivation surfaces, herringbone cross-lamination, single- and double mud drapes, climbing ripples, mud chips.	0-1. *Trichichnus*, *Skolithos*, *Planolites*, *Paleophycus* and *Cylindrichnus*. *Escape burrows*	**Intertidal Flat**	*3.11C,D*
	K3	Vf-f sandstone, interbeds of siltstone. Few vc lags	7.8 m	Fine sand, interbeds of silt up to ten cm thick. Few coarse lags	Sharp erosive boundaries of facies	0.5-0.9	WRCL, CRCL, occasional herringbone cross-lamination, double mud drapes, ppl. Silty interbeds show ppl or wavy lamination	0-4. Dominated by *Diplocraterion.* Minor amounts of *Paleophycus*, *Planolites*, *Skolithos*, *Ophiomorpha* and *Teichichnus*	**Shallowing Intertidal Flat**	*3.12A-C*

L	-	Interbeds of mud to gravel. Pyrite, mica and quartz abundant.	1 m	Gravel, sand, silt, clay. Transitional FU form base to top of facies	Sharp erosive base, gradual top boundary	0.1-0.5	Wavy top surface of coarse beds. Lenticular- to wavy bedding in shales.	0	**Transgressive lag deposits**	*3.13*
M	M1	Vf-c sandstone, occ. mudstone	Occurs within a 44 m interval. FU-units in lower half on dm-m scale, in upper half they reach several meters. Cross-bedded unit typically few dm thick.	Dominated by m-c sand, with less amounts of finer sand, silt and mud	Sharp erosive base, sharp to gradual top	0.8-1.0	Low-angle-, trough- and tabular cross bedding, WRCL, CRCL (commonly bidirectional), double mud drapes, ppl, wavy interbeds of fluid muds. Mud-, organic or sideritic fragments common.	Generally low, 0-2. *Ophiomorpha, Skolithos, Paleophycus, Trichichnus.* In finer channel fill also *Chondrites*.	**Tidal channel fill**	*3.14A-E*
	M2	Vf-m sandstone, mudstone, interbedded	Occur on top of M1 deposits, 1 dm to 1.5 m thick intervals	Vf-m sand, silt, clay	Gradual- and sharp boundaries	0.5-0.9	Low-angle-, planar parallel- and current ripple cross-lamination. Wavy- to ppl siltstones	3-5. *Asterosoma, Paleophycus, Planolites, Thalassinoides, Siphonichnus, Chondrites, Rosselia, Diplocraterion* and *Ophiomorpha*	**Channel Abandonment Fill**	*3.15A,B*
	M3	F-m sandstone	Constitutes 5.9 successive meters of core. Largest complete FU sequence 2.5 m	F-m sand, minor amount of fine material	Sharp and erosive boundaries of FU sequences	0.9-1.0	Trough- and tabular cross-stratification, mud- and coal chips, some planar- to wavy- lamination in finer beds.	0	**Fluvial-dominated channel fill**	*3.15C*

3.2 Facies A: Offshore Black Shale

3.2.1.1 Description

Facies A starts at 4044 m depth where it overlies transgressive reworked deposits of facies L (Fig.3.1B). Except for an influx of thin beds of ripple cross-laminated very fine sandstones between the depths of 4042.6 and 4043 m, the facies consists of a 5.7 m long succession of very finely laminated, fissile to massive shales lasting until 4038.3 m core depth, where it passes conformably into subfacies C2. The shales are black to dark grey in color and generally show no bioturbation or sedimentary structures of any kind, but in the lowermost meters of the facies where interfingering of shale and thin, rippled sand beds occur, some small, flattened burrows are identified. These are mostly *Phycosiphon* and *Chondrites*, but a few *Planolites* are also recognized. In addition the facies contains micronodular pyrite, as well as a bigger nodule, approximately 8 cm in diameter. This appears in the middle of the black, laminated section (see Fig.3.1A), with laminae draping around it.

3.2.1.2 Interpretation

The shales of facies A are interpreted to have been deposited in calm water below the reach of waves or currents, where very fine material was allowed to rain out quietly from the water column. The dark color of the shales indicates that the sediments contain organic material (Arthur & Sageman, 1994). The abundance of this organic material and the deposition of black shales are thought to be controlled by enhanced supply of organic material to the basin and/or increased preservation potential of organic material following deposition. Factors included in these controls are for example high plankton productivity, intense oxygen-minima, accumulation of organic-rich anoxic sediments, and salinity stratification in a largely anoxic body of water where surface water productivity is low and degradation of organic carbon is incomplete (Stow et al., 1996, p. 403). The shale passes conformably into a 27 m thick coarsening-upward sequence of offshore transition- and shoreface deposits of facies C2 and D leads to the interpretation of facies A as an *offshore, low-oxygen black shale.* The shale may have been deposited in a local depression experiencing very restricted circulation during transgression.

There has been significant debate around the origin of the black shales, with authors advocating possible depositional settings ranging from restricted lagoons and bays (e.g. Grabau, 1913) to open marine areas with poor circulation and a stratified water column (e.g. Twenhofel, 1939). Anoxic black shales have been cored from Mesozoic strata in many basins, and deposition of these and similar facies seem to have been coeval in many areas of the world (Jenkyns, 1980). This fact led Schlanger and Jenkyns (1976) to take these time intervals to represent what they called “Oceanic Anoxic Events”. Through geological history the correlation between these “anoxic events” and significant marine transgressions is quite good (Stow et al., 1996, p. 404). No such global anoxic event has been recorded for the Aalenian-Bajocian, but this should not exclude the possibility that the black shales were deposited during a significant transgression in the Halten Terrace area. The uncompacted thickness of the shale would be significantly larger than the five meters seen in core, which makes a lagoonal setting for deposition less likely. A lagoonal setting for these sediments would suggest unrealistically deep with a significant proportion of the water-column having low-oxygen conditions, and a stability of this setting through time.

The rippled thin beds of sand are anomalies, probably representing distal storm deposits. The sands indicate both wave- and current influence, which can be explained by a short period of strong storm activity where waves were large enough to affect this restricted depression offshore. Storm-generated rip currents are strong enough to transport sands far into the offshore environment (Gruszczynski et al., 1993) and may have transported sands into the basin.

The transition from a low-diversity assemblage of *Phycosiphon, Chondrites* and *Planolites* to a completely unbioturbated shale may indicate a change from dysaerobic bottom-water conditions to anaerobic conditions (Arthur & Sageman, 1994; Ekdale & Mason, 1988; Martin, 2004). Pyrite nodules are abundant in organic-rich marine shales, as seawater is a rich source of sulphate which can be reduced to sulphide by bacteria. Evidence points to a pre-compactional origin of the large nodule, and further differential compaction have led to the draping of the laminae around the nodule (Tucker, 2003).

3.3 Facies B: Open Shelf

3.3.1.1 Description

Facies B consists of an intensely bioturbated muddy siltstone, constituting the interval from 4137.6 to 4151.73 m. Grain size fluctuates regularly between silt-dominated and mud-dominated without distinct boundaries, and the succession passes conformably into subfacies C1 above. The dark grey rocks of this facies are intensely bioturbated, and original lamination is only vaguely visible in the uppermost meters. *Phycosiphon* burrows are dominant, but are also accompanied by burrows of *Zoophycos*, *Schaubcylindrichnus*, *Asterosoma* and *Teichichnus*. In places the *Phycosiphon* cross-cut earlier burrows. A few pyrite nodules appear in the facies, where the largest has a diameter of 6 cm and demonstrate curving of laminae around it (Fig.3.2A).

3.3.1.2 Interpretation

Facies B constitutes the lowermost interval of the core. The complete bioturbation of the fine-grained sediments by a diverse ichnofauna that are typical of a marine setting, along with the fact that there hardly are any physical sedimentary structures visible in the section, leads to the interpretation that we are dealing with an *open marine, shelfal* *setting* well below storm wave base and distal from a terrigenous sediment source. The very fine sediments could have arrived at this distal location by transportation by winds, by suspension in plumes (e.g. distal of river mouths) or in a near-bottom nepheloid layer (Baldwin & Johnson, 1996, pp. 253-256). Waves and currents may have combined to resuspend and disperse this sediment (McCave, 1984), and some of it settled in the low-energy setting interpreted for facies B.

Grain size fluctuates quite regularly between being dominated by clay and silt, respectively. Such changes seem to take place more or less every five meters, and may be interpreted as the distal manifestation of parasequence stacking. This indicates that facies B is formed too far from the coastline to record a real change in depositional environment through a single parasequence, and too far to have a distinct surface demarcating the flooding that separate the parasequences. The quite large siderite/pyrite nodule in the core with laminae draping around is of pre-compactional origin (Tucker, 2003).

The trace fossils of the facies show a complex tiering style. Through continuous sedimentation the normal trend is that deep-tier burrows like *Zoophycos* overprint shallow-tier burrows like *Phycosiphon.* This is normally the case for facies B as well, but in places the opposite occurs. At 4149.4 m an example of this is seen where *Phycosiphon* clearly overprints an earlier *Zoophycos* burrow (see Fig.3.2B). It can also be demonstrated at 4145.2 m where *Phycosiphon* are overprinting the top of an *Asterosoma* trace. This may be an indication hiatuses at these levels, not necessarily visible as a surface or change in grain size (McIlroy, 2004b). In this case these observations correlate well with the grain size fluctuations from silt to clay at these levels, strengthening the interpretation of these levels as hiatuses, flooding surfaces and parasequence boundaries.

The facies in all indicate quiet deposition in a marine environment well below storm wave base, where communities of organisms had plenty of time to thoroughly bioturbate the substrate.

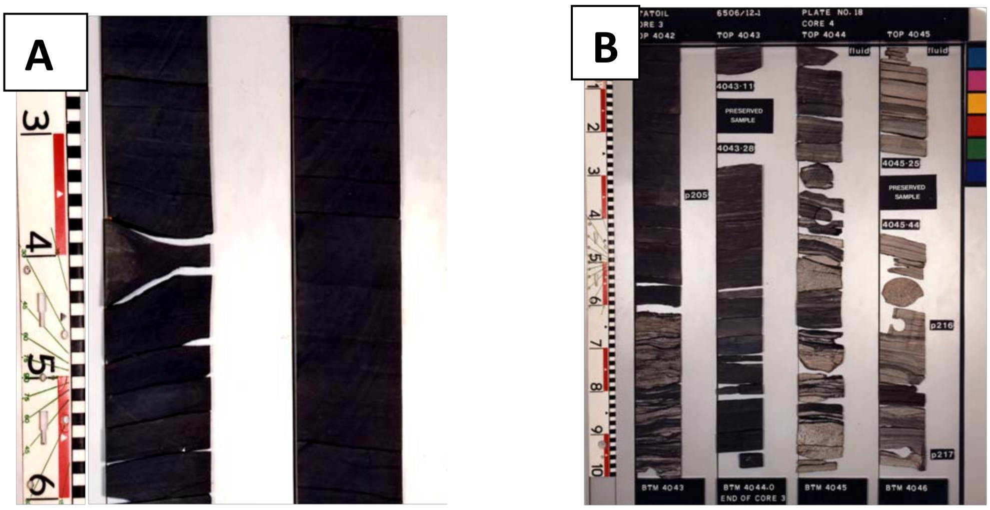

Figure 3.1 (Facies A). ***3.1A*****; Black laminated shale with pre-compactional pyrite nodule, depth intervals 4040.2-4040.6 m and 4041.2-4041.6 m.** ***3.1B*****; The transition from facies L below to facies A above, interval 4042-4046 m. Lower right is deepest (modified from Norwegian Petroleum Directorate web pages, 2010).**

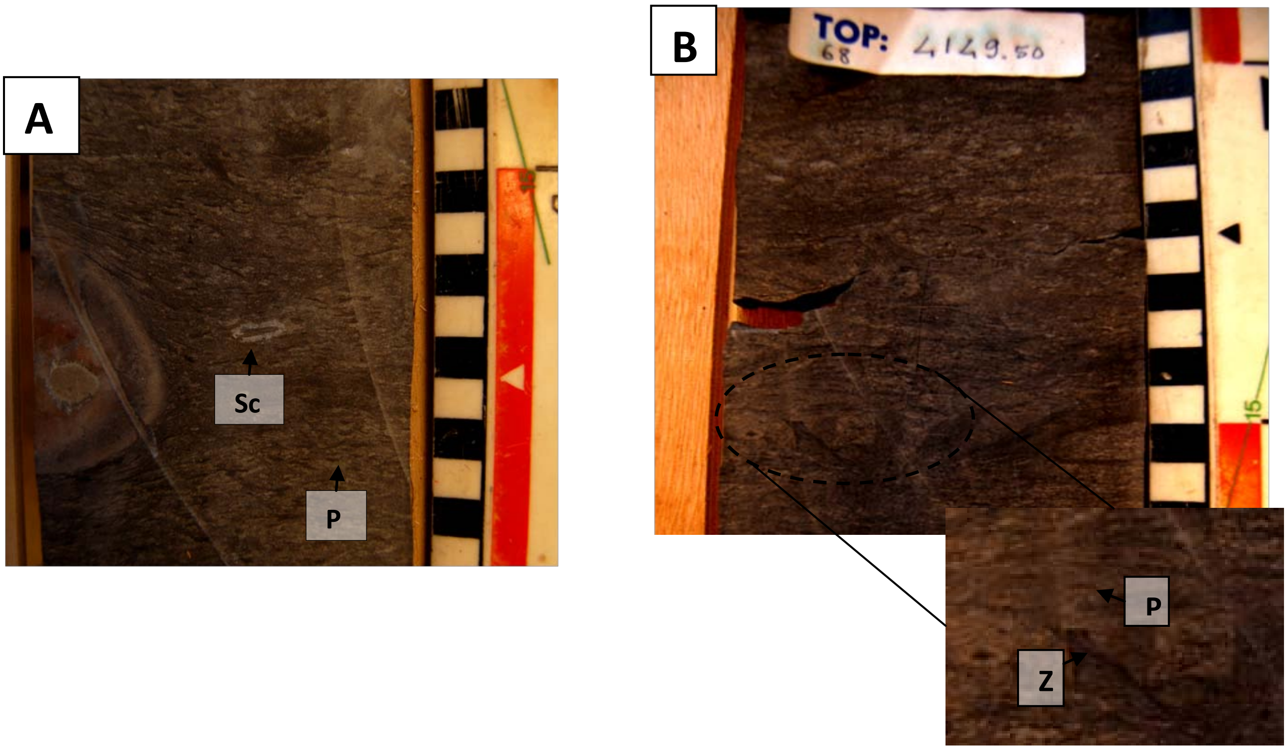

Figure 3.2 (Facies B). ***3.2A***; **Syndepositional nodule of pyrite and siderite, with visible draping of laminae around it (4146.6 m). The white elliptic shape is a** ***Schaubcylindrichnus*** **(Sc), the tiny black dots with a white lining are** ***Phycosiphon*** **(P).** ***3.2B***; **Possible hiatus recognized by the shallow tier** ***Phycosiphon*** **(P) overprinting the deeper tier** ***Zoophycos*** **(Z), depth 4149.6 m.**

3.4 Facies C: Offshore Transition Zone

3.4.1 Subfacies C1: Offshore Transition Zone/Prodelta

3.4.1.1 Description

Subfacies C1 appears in the interval 4114.4-4137.6 m, and is an overall coarsening-upwards succession from dominantly muddy siltstone to dominantly silty- to very fine sandstone (Fig.3.3A), but where sandstones and siltstones are alternating. In the lower half of the 21.7 m thick interval this alternation occurs more or less every couple of meters, but no distinct surfaces can be detected. Further up-section the subfacies has several smaller coarsening-upward cycles within it, with thicknesses varying from 35 cm to more than a meter. Most of these cycles are separated by surfaces showing signs of minor erosion and/or non-deposition. Subfacies C1 is interrupted by a cemented- and shell-rich section (facies E) at 4118.5-4120 m, and reaches its top at 4114.4 m where an erosion surface separates it from the overlying facies F.

The whole subfacies is dominated by bioturbation which has removed almost all evidence of physical sedimentary processes. Exceptions exist, as in the interval 4136-4137.6 m where one can see the outline of low-angle planar parallel lamination with alternating dip directions; this is particularly visible above 4137.6 m (Fig.3.3C, D). Remains of low-angle planar parallel lamina are present throughout the subfacies, but are commonly obscured by bioturbation. Symmetrical ripple cross-lamination is scarce but present toward the top of the interval, and at 4120.8 m such ripples follow directly from bidirectional cross-lamination below (Fig.3.3B). Trace fossil variety is large. *Phycosiphon* burrowing is not as dominant as in facies B, and becomes less frequent as the deposits coarsen upward. *Schaubcylindrichnus* and *Zoophycos* traces are also less abundant upward, the latter being limited to some finer grained intervals. Instead, subfacies C1 contains more of the trace fossils *Rhizocorallium*, *Teichichnus*, and *Chondrites*. *Chondrites* preferably appear in the more silty interbeds, and some large *Teichichnus* burrows show evidence of having been re-burrowed by *Phycosiphon*. Other trace fossils include *Asterosoma, Planolites*, *Paleophycus*, *Skolithos*, *Thalassinoides* and *Phoebichnus.*

3.4.1.2 Interpretation

The thick interval of subfacies C1 passes conformably from facies B deposits below, and is interpreted to start at the first sign of sedimentary structures. This change occurs at 4137.6 m (see Fig.3.3C, -D), and the vaguely visible laminated units with opposing dip directions seen here are interpreted as hummocky cross-stratified siltstones. Hummocky cross-stratification is likely a result of a combination of the strong and complex wave action and unidirectional currents produced by storm events, at water depths between fairweather- and storm wave base (Baldwin & Johnson, 1996; J. D. Collinson et al., 2006; Dumas & Arnott, 2006). The fact that these structures are not associated with distinctly coarser beds in this well suggests that the storms lacked the energy to transport coarser sediment to this location. The hummocky structures are also extensively bioturbated, suggesting that the sedimentation rate following a storm event was slow enough for organisms to thoroughly rework the event deposits and obscure its structures. The passing from hummocky cross-lamination to wave-ripple cross-lamination seen in Figure 3.3B is an evidence of oscillatory flow, and represents a sequence likely to have been produced by a waning flow (Baldwin & Johnson, 1996).

The ichnofauna is quite diverse and traces reflect a deposit-feeding and grazing behavior indicating marine conditions below fairweather wave base. The slight change seen in ichnofauna from facies B below can be attributed to the shallowing and increase in energy levels. The introduction of *Skolithos* may be due to the sporadic deposition of sands during storm events (Bann et al., 2004), and the lesser amount of *Zoophycos*-burrows are suggested by modern day studies to reflect increased sedimentation rates (Lowemark et al., 2006).

The structures present combined with the ichnofauna and the interchanging sand- and silt deposition within a coarsening-upward trend from open shelf deposits leads to subfacies C1 being interpreted as *offshore transition zone/prodelta* deposits, as they pass into delta front sediments further up-section. Deposition took place between storm- and fairweather wave base.

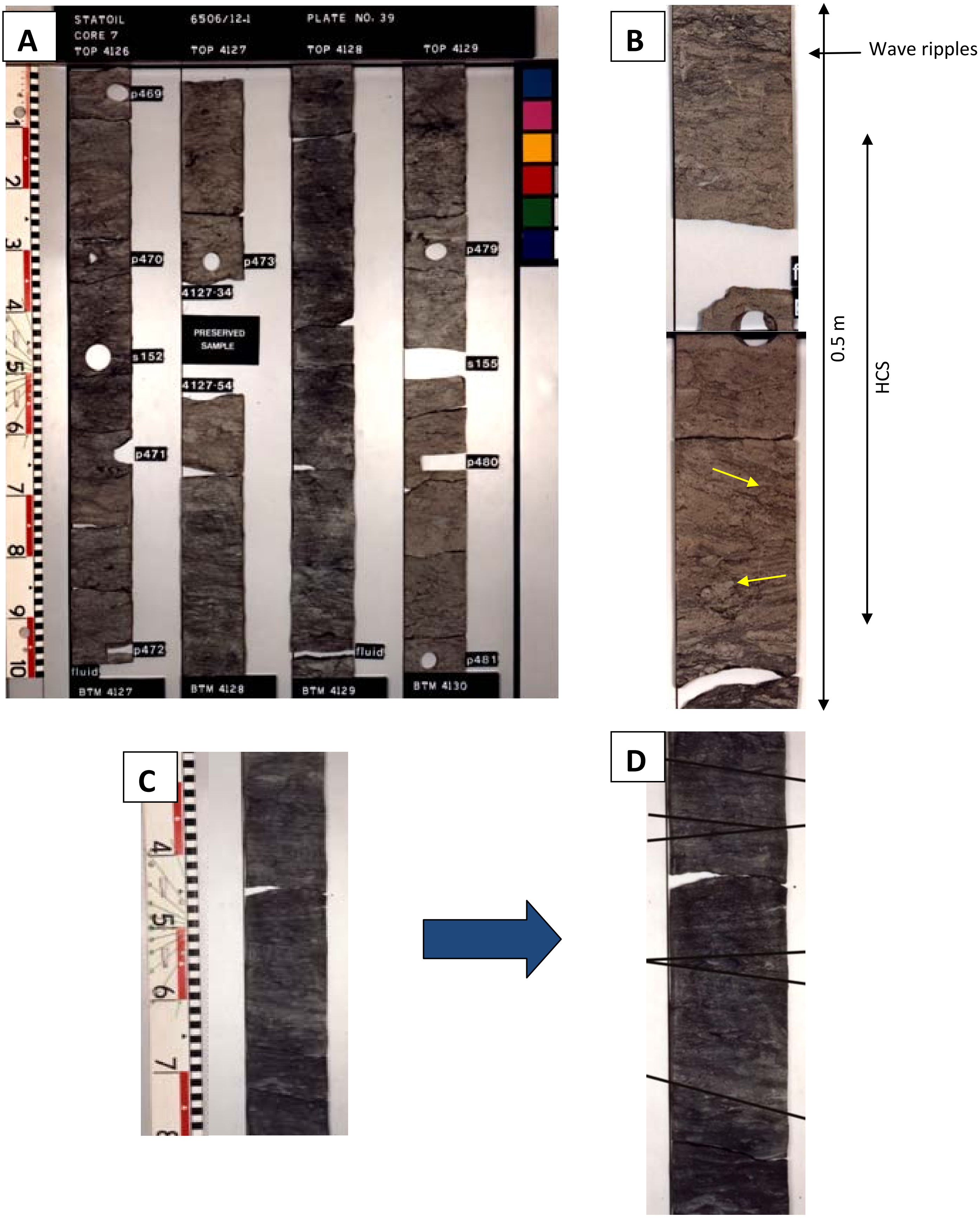

Figure 3.3 (Subfacies C1). *3.3A*; Ex. of subfacies C1 offshore transition zone/prodelta, 4126-4130 m. *3.3B*; Indication of waning flow, with wave ripples following HCS, 3120.8-3121.3 m. *3.3C, 3.3D*; Bioturbated silts w/ planar parallel lamination showing opposing dip directions, interpreted as hummocky cross-stratification (4137.2-4137.6 m) (modified from Norwegian Petroleum Directorate web pages, 2010).

3.4.2 Subfacies C2: Offshore Transition Zone w/ Distal Tempestites

3.4.2.1 Description

The base of subfacies C2 is interpreted at 4038.3 m where it passes conformably from facies A black shales below into a 20 m thick coarsening-upward sequence ranging from dark grey siltstone into fine sandstone. Characteristic for the whole sequence is the generally high degree of bioturbation with a diverse ichnofauna, only interrupted by unbioturbated sandy beds of varying thickness (Fig. 3.4A, -B).

The ichnofauna changes as deposits become coarser. The lowermost meters of dark grey siltstone occasionally have planar lamination preserved, but bioturbation dominates with *Phycosiphon* as the dominant trace fossil. Other trace fossils that are abundant include *Zoophycos, Teichichnus* and *Planolites*, with less common *Schaubcylindrichnus*, *Asterosoma, Thalassinoides* and *Paleophycus.* Except for the interval 4034-4035 m, where very fine-, thoroughly bioturbated sand interrupts the siltstone sequence, the dominance of sand initiates at 4031.5 m. Above this depth the facies becomes increasingly sand-dominated, consisting of 80-90 % sand. Trace fossils of *Zoophycos* are no longer present, and there are much less of the trace fossil *Phycosiphon.* Additional traces to the ones in the lower part of the coarsening-upward interval are *Taenidium, Ophiomorpha, Skolithos* and *Chondrites.* Physical sedimentary structures in the bioturbated sands are scarce, but some thin intervals of low-angle planar parallel lamination have been identified, along with some tentatively interpreted current ripples. In addition definite wave ripple cross-lamination has been identified.

Along the full length of the sandy interval of this facies there is a regular occurrence of virtually unbioturbated beds of fine sand, varying in thickness from one cm to 20-30 cm at the most (Fig.3.4C). In the lower part of the coarsening-upwards succession these beds are usually a few cm thick and have a recurrence interval of 20-40 cm, but the trend when moving up-section is that the individual sands become thicker and farther separated. The beds typically have a planar and slightly erosive base containing sole marks, and a planar-to rippled top surface. The thicker beds commonly contain hummocky/swaley cross-stratified sand (see Fig.3.4D), or planar parallel-laminated sandstone overlain by this type of stratification. The thinnest sand beds are usually ripple cross-laminated. A few *Skolithos, Ophiomorpha, Cylindrichnus* and escape burrows have been observed in the sand beds.

The facies is interpreted to end at 4018.6 m where the deposits change from bioturbated, muddy sand to a less bioturbated, lighter colored sand. The boundary is transitional but defined at the top of the last significant muddy bed.

3.4.2.2 Interpretation

Subfacies C2 is related to subfacies C1 as they contain many of the same trace fossils and generally exhibit a high degree of bioturbation. The base of the subfacies is interpreted where trace fossils starts to appear above the black shales of facies A, which indicates re-oxygenation at the sediment/water interface (Ekdale et al., 1984). The increasing sand content and described changes in ichnofauna upward through the subfacies is interpreted as a shallowing trend from offshore- toward shoreface conditions, and thus C2 also belongs to the *offshore transition zone*.

The feature separating subfacies C2 from subfacies C1 are the thin, virtually unbioturbated sand beds, where the thicker beds show an idealized storm sequence. This sequence starts with a basal erosion surface with sole marks, cut by a combination of oscillatory and unidirectional flow. The erosion is followed by the main storm deposition, represented mainly by hummocks deposited under oscillatory flow conditions but occasionally by planar parallel-lamination due to sustained combined flow. In the waning stage of the storm ripple cross-lamination may be created towards the top of the bed, before returning to fairweather conditions and deposition of more muddy sediments (Baldwin & Johnson, 1996, p. 265). The beds are interpreted as distal tempestites, storm beds. Their preservation potential is thought to be limited in a setting with the diverse ichnofauna seen in subfacies C2. According to Wiberg (2000), preservation potential increases with increased thickness of the storm beds. He further suggests that sufficient thickness for preservation may be achieved by a combination of storms and flood events on shelves that received considerable amounts of fluvial sediment.

Alongside the coarsening-upward trend of the entire subfacies, the change upward into thicker event beds containing predominantly hummocky/swaley-cross-stratification point to subfacies C2 being part of a regressive succession.

3.5 Facies D: Lower Shoreface

3.5.1.1 Description

Facies D follows conformably from subfacies C2 below starting at 4018.6 m, and is a 7.5 m thick succession of very fine- and fine sand containing occasional and wavy laminae of finer material. A few cm-scale zones of increased mud content are present, as are a few rounded mud clasts. The facies reaches its top at an erosion surface at 4011.1 m depth. The interval consists of blocky- to slightly fining-upward bedsets, sometimes separated by surfaces of minor erosion. The sandstones show a very variable amount of trace fossil reworking, from completely unbioturbated to degree six of bioturbation (Fig.3.5B). Trace fossils include *Asterosoma, Paleophycus, Planolites, Skolithos, Arenicolites, Trichichnus, Schaubcylindrichnus, Teichichnus, Rosselia* and *Ophiomorpha.* The less bioturbated zones where primary structures are still visible contain horizontal- to low-angle planar parallel lamination, abundant wave ripple- and some current ripple cross-lamination, and possibly hummocky-swaley cross-lamination.

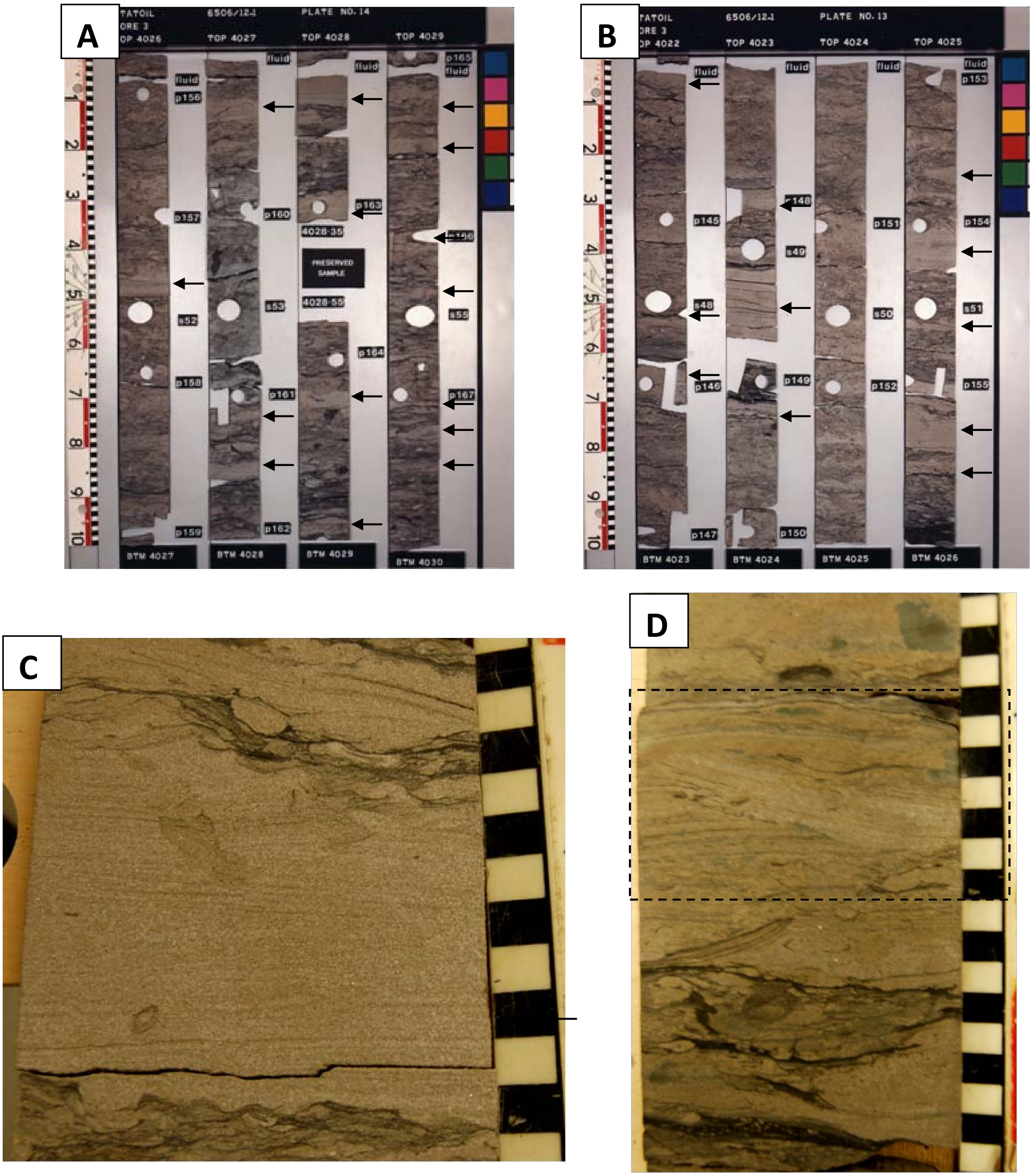

Figure 3.4 (Subfacies C2) *3.4A*; Muddy sandstone containing thin, unbioturbated event beds (black arrows), 4026-4030 m. *3.4B*; Further up the sands become cleaner and the event beds become thicker, 4022-4026 m (Norwegian Petroleum Directorate web pages, 2010). *3.4C*; Event bed with erosive base, sub-horizontal laminae, ripple structures and minor bioturbation, 4025.8 m. *3.4D;* Bioturbated sand bed showing hummocky/swaley structures, 4020.8 m.

At 4018.15 m a rounded mud clasts rests on a surface separating low-angle, planar parallel-laminated sandstone above from a bioturbated zone containing several trace fossils of *Skolithos* and *Arenicolites* (Fig.3.5A). A similar surface also appears at 4015.15 m, where a bioturbated zone is cut and overlain by mud draped low-angle laminated sandstone. Worth noting is that the sands in the top two meters of facies D are dark grey in color (see Fig.3.5C).

3.5.1.2 Interpretation

The sands of facies D rests conformably on subfacies C2 deposits below, have a higher sand/mud-ratio and are mostly composed of very fine- to fine sand. This trend indicates a more proximal setting compared to the offshore transition zone of subfacies C2. The fact that some bedsets are dominated by bioturbation while others are virtually without it suggests quite variable energy conditions. It is interpreted that planar-parallel lamination indicate upper flow-regime conditions, and both wave- and current action can play a part in their formation (J. D. Collinson et al., 2006, p. 130). The beds where these structures are preserved, along with the ones where remnants of hummocky/swaley cross-stratification are interpreted, are thought to indicate rapid deposition by storm processes. The absence of cross-bedding, and dominance of planar lamination and wave ripples where not obscured by bioturbation, supports a lower shoreface interpretation (Reineck & Singh, 1980, pp. 368-370).

The surface at 4018.15 m depth with several vertical to sub-vertical trace fossils in a zone below it can be characterized as an omission surface, and the assemblage of traces as an omission suite (Ekdale et al., 1984). In Pemberton et al. (2004) this is referred to as a "Glossifungites ichnofacies", thought to represent traces made by animals that colonized a firmground after an erosional event. The post-depositional origin of the traces, in this case *Skolithos* and *Arenicolites*, is confirmed by their cross-cutting relationships with earlier burrows, here of *Asterosoma* and *Paleophycus*. The surface represents a hiatus in the stratigraphic record, and several of them may be present within the facies D interval. The darker color of the upper two meters of the core is thought to reflect a heavy mineral enrichment.

The fact that the facies contains zones of very intense bioturbation and increased mud content in the sands is thought to reflect very calm conditions, below fairweather wave base. It is therefore interpreted that the facies formed in a *lower shoreface* setting, close to the fairweather wave base.

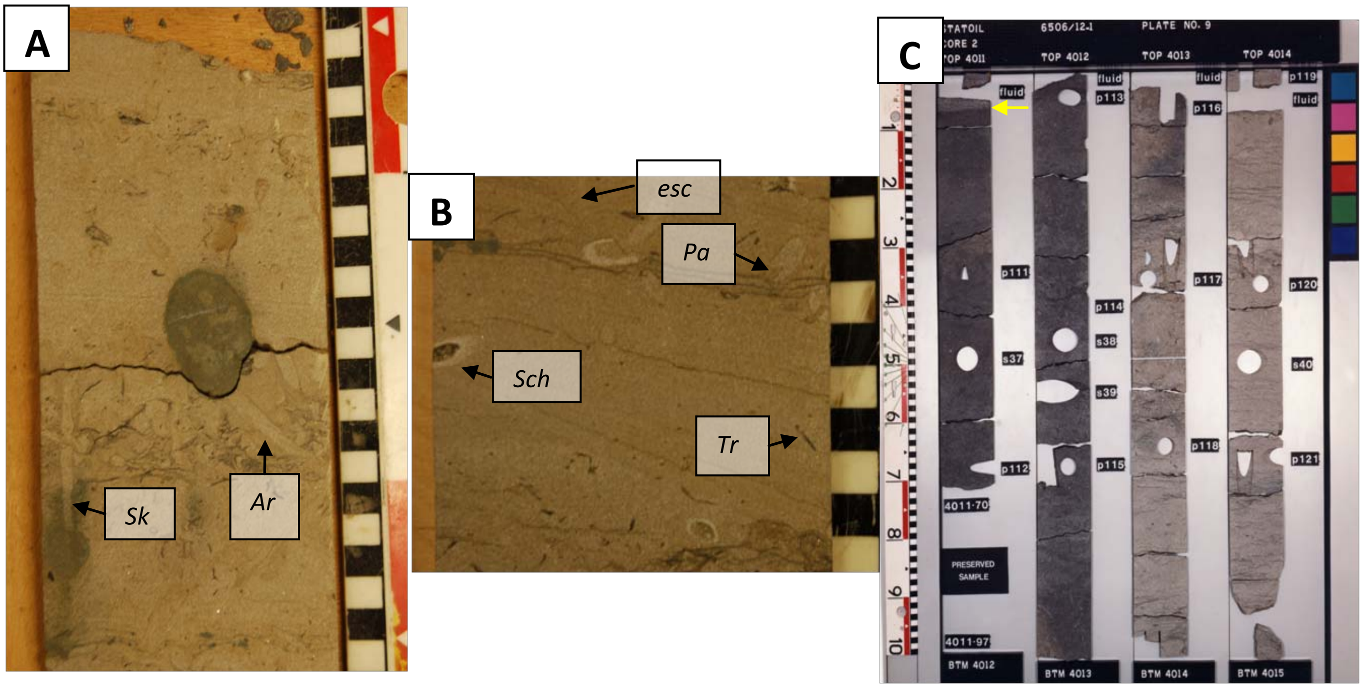

Figure 3.5 (Facies D). ***3.5A;*** **Omission surface at 4018.15 m, with omission suite of trace fossils** ***Skolithos (Sk)*** **and** ***Arenicolites (Ar)*** **cross-cutting earlier burrows. Big mud clast rests on the surface.** ***3.5B;*** **Lamination with shallowing dip angle upwards above truncation surface, interpreted as remains of hummocky cross-stratification. Trace fossils of** ***Schaubcylindrichnus (Sch), Paleophycus (Pa)*** **and** ***Trichichnus (Tr)*****, and escape burrow (esc).** ***3.5C;*** **A color change is seen in the upper part of the facies. Erosive boundary toward facies I in top left (yellow arrow). 4011-4015 m depth (Norwegian Petroleum Directorate web pages, 2010).**

3.6 *Facies E: Condensed Section*

3.6.1.1 *Description*

Facies E is found in the interval 4118.5-4120 m (see Fig.3.6A), and shows a slight fining-upwards trend from very fine sandstone into siltstone. The facies has several characteristic features. In the lowermost half meter it contains a considerable amount of small greenish nodules and carbonaceous material. This section also contains lots of broken and a few complete fossil shells (Fig.3.6B), along with some small pebbles with angular, nearly quadrilateral shapes. A few large *Thalassinoides* are observed through the interval. The top meter of the facies consists of sands bioturbated by *Phycosiphon*, *Chondrites* and *Paleophycus*, and a zone of darker silty sediments containing *Asterosoma* and *Chondrites* trace fossils and some visible low-angle planar parallel lamination. This upper interval has a reddish color and contains some large red nodules.

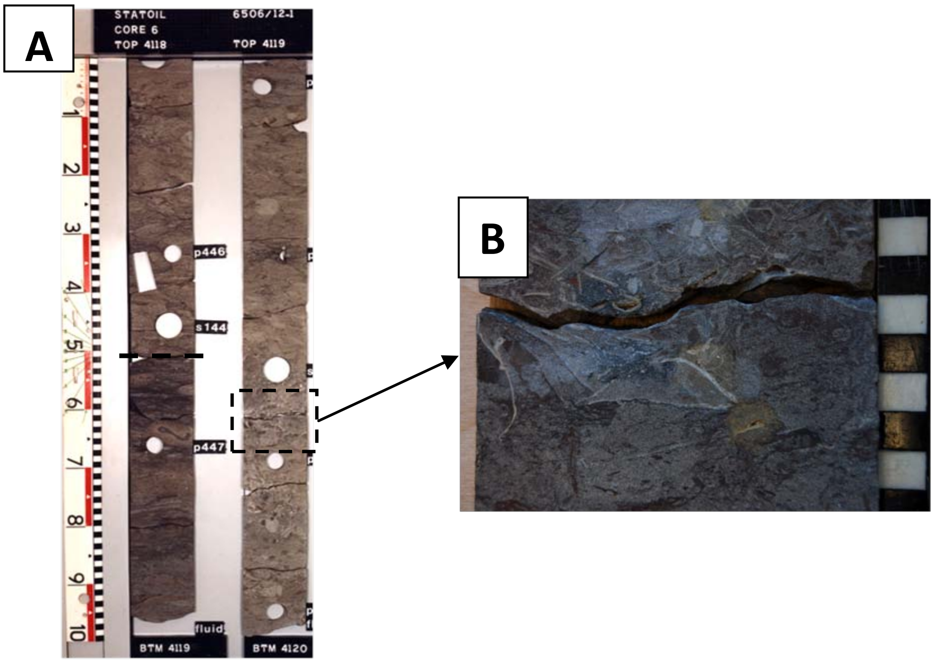

Figure 3.6 (Facies E) *3.6A;* the condensed section from 4118.5-4120 m (modified from Norwegian Petroleum Directorate web pages, 2010). *3.6B*; Broken and more complete shells from the shell gravel in the lower part of facies E. Also note angular white pebbles and green chamosite granules.

3.6.1.2 Interpretation

The lower half of this facies is interpreted as a shell lag, where carbonate cementation has occurred. The green, circular nodules seen near the base of the interval are possibly chamosite granules, and further up the red color indicates extensive siderite- or pyrite cementation. This may indicate very low sediment input (Van Houten & Purucker, 1984). The shell lag together with this cementation leads to an interpretation of the facies as a *condensed section* representing a significant hiatus. This cemented interval is recognized across most of the Halten Terrace (Karlsson, 1984), and is considered by some to mark the base of the Fangst Group and the Ile Formation (Harris, 1989).

3.7 Facies F: Distal Distributary Mouth Bars

3.7.1.1 Description

Facies F is a heterolithic facies consisting of thinly bedded very fine sandstones with interbeds of mudstone (Fig.3.7A), and appear in core between the depths of 4108.05 m and 4114.4 m. The base of the interval is an erosion surface overlain by a two centimeter thick, normal graded bed with medium sand at the base along with a few coarse grains. This thin bed separates facies F from prodelta sediments of subfacies C1 (Fig.3.7B). The facies contains 50 – 80 % sand; thickness of individual beds of sandstone range between cm-scale lenses to beds of a few tens of centimeters at the most. No grain size increase can be observed in the sands when moving up-section, but the frequency of mudstone interbeds diminishes. The deposits are partly micaceous.

Sandstones of facies F are dominated by ripple cross-lamination which also appears interbedded with planar parallel lamination. Near the bottom of the interval the ripples are suggested to have been formed by waves; however bidirectional current ripples seem to be dominant throughout the succession. These create what is also known as herringbone cross-lamination. The sands contain streaks of mud on ripple tops and -foresets and throughout the interval one can find examples of double mud drapes. Layers with climbing ripples, dominated by one direction of ripple migration, and reactivation surfaces increase in abundance upward through the facies.

The mudstones are generally cm-scale beds, and are frequently wavy in appearance as they drape the rippled sand beneath. The top surface of some of the thin mudstones has features resembling load casts and shrinkage cracks. Internally, the mudstones have lenses and thin beds of sand.

Bioturbation of the subfacies as a whole is intermediate in degree. It is not affecting the sands in the lowermost meters of this subfacies very much but becomes more pervasive moving up. The trace fossils found in the sands are mostly *Paleophycus*, along with a few *Planolites, Skolithos* and *Rosselia.* Also worth noting are v-shaped escape burrows. The mudstones have a higher degree of bioturbation and contain traces of mostly *Planolites*, but also *Thalassinoides* and *Paleophycus*.

3.7.1.2 Interpretation

The general impression of the deposits of this heterolithic facies is that they have been affected by tidal processes. The cm-scale rhythmicity in interbeds of mud, the herringbone cross-lamination, reactivation surfaces and double mud drapes are strong evidence for shifting current directions with intermediate periods of low energy conditions (Visser, 1980). This is also reflected in the differences in bioturbation between sands and muds. Double mud drapes within the rippled sandstones reflect the ebb-flood tidal cycle, with a dominant current stage followed by a slack water stage, a second subordinate current stage and a final slack water stage. The mud drapes are formed during the slack water stage from suspension fallout. Together with the flat-lying mudstone interbeds, these rippled sandstones make up what is called tidal rhythmites, and their frequency variation seen through facies F may record past spring-neap cyclicity (Boyd et al., 2006). Formation of climbing ripples is favored by high suspended sediment load and rapidly decelerating flow velocity, such that deposition from suspension outpaces that of the bedload (Lanier & Tessier, 1998). Mostly the angle of climb must have been less than the inclination of the stoss slope, as this stoss slope generally is not preserved. This is referred to as subcritical climb, and indicates low rates of aggradation (J. D. Collinson et al., 2006, pp. 82-83).

Load casts on the interface between mudstone interbeds and sandstones indicate that sands were rapidly emplaced on the less dense mud and sank into it (J. D. Collinson et al., 2006, pp. 183-185). The shrinkage cracks seen in the top of some of the mudstone interbeds are probably synaeresis cracks, formed as clays contracted due to salinity changes (Plummer & Gostin, 1981). Such salinity variations may undoubtedly arise as a consequence of the competition between fluvial flow out through distributaries and the standing marine waters of the basin. Deposition of muddy interbeds in facies F is probably due to flocculation of clays as fluvial waters entered the saline water body (Brettle et al., 2002).

The decrease in mudstone interbed frequency upwards is taken to reflect shallowing toward a more proximal setting. The facies may resemble subtidal flats in many ways, but its position on top of prodelta fines and at the base of a coarsening-upward sequence into facies G and H leads to an interpretation of facies F as the distal part of tidally reworked *distributary mouth bars.* A similar heterolithic mouth bar facies consisting of sands with mud couplets separated by thin bioturbated muds has been noted in the modern tidal-fluvial Mahakam delta in Indonesia (Gastaldo et al., 1995), and bioturbated heteroliths in a delta front setting are also described in the study of the modern Fly River delta in Papua New Guinea (Dalrymple et al., 2003).

3.8 Facies G: Middle Distributary Mouth Bars

3.8.1.1 Description

This facies (Fig.3.7C) is present between two erosive surfaces at 4101.3 m and 4108.05 m, only interrupted by a deposit of facies H between 4103.45 m and 4104.4 m. The facies is sand-dominated with grain size ranging from very fine- to fine sandstone, and the facies shows a slight coarsening-upward trend continued from facies F below. Mud is only present as thin beds and mud drapes in certain parts of the interval.

The appearance of this facies is quite variable, as the degree of bioturbation varies between one and four. In intervals where sedimentary structures are visible the sands contain double draped ripple cross-lamination, climbing ripples and reactivation surfaces (Fig.3.7D), planar parallel lamination and herringbone cross-lamination. There are also organic remains showing a sub-vertical and dendritic pattern ten cm long at 4105.3 m (Fig.3.7E).

The sands are generally reworked by organisms, and the ichnodiversity is large. The deposits contain several v-shaped escape burrows; trace fossils identified comprise *Schaubcylindrichnus, Ophiomorpha, Asterosoma, Diplocraterion, Planolites*, *Paleophycus, Rosselia* and *Skolithos*. When moving up toward the top of the facies the deposits starts to coarsen toward fine sandstone, and contain a few traces of *Trichichnus* and *Planolites*.

3.8.1.2 Interpretation

The increase in sand content relative to facies F below indicates a more proximal setting for facies G. The abundance of different trace fossils indicates marine conditions, while the intervals of little bioturbation and better preserved sedimentary structures like climbing ripple-lamination and planar parallel-lamination point to periods of higher energy conditions. Double mud drapes and herringbone cross-lamination are indicative of tidal influence. Facies G is interpreted as deposits from a *middle distributary mouth bar* setting, where water depth was quite shallow and deposition was episodic and generally quite slow, allowing for abundant bioturbation. A reason for this may be that this middle section of the mouth bar in places was eroded where tidal currents focused their energy. The middle areas of the mouth bars were elevated relative to these areas and protected from the highest energy, except during particularly high discharge events (Elliott, 1989) or during spring tide. Shallow crested mouth bars may develop when basinal energy is low (H. G. Reading & Collinson, 1996, p. 185), and low energy was also suggested by the prodelta deposits of subfacies C1. The organic fragments at 4105.3 m resemble roots and may indicate that the crest of the bar may even have been vegetated in periods. Vegetation stabilizes the mouth bar and leads to initiation of new mouth bars seaward as the delta progrades (Fielding et al., 2005).

Both modern and ancient analogs of tide-dominated delta front facies exist. The "*tidal sand ridge*" facies interpreted in the Eocene tide-dominated deltaics of the Lagunillas Field in Venezuela (Maguregui & Tyler, 1991) and the tide-dominated delta front facies association interpreted in the Mid-Jurassic Lajas Formation in Argentina (McIlroy et al., 2005) share many of the features of the tidally reworked mouth bar facies of well 6506/12-1. They exhibit the same coarsening-upward trend with bioturbated heteroliths in the lower part which are replaced up-section by bioturbated sands (facies G) and trough cross-bedded sands (see facies H below).

3.9 Facies H: Proximal Distributary Mouth Bars

3.9.1.1 Description

This facies (Figure 3.8A and B) is interpreted in several intervals between 4090.1 m and 4104.4 m depth, and comprises a variety of grain sizes and sedimentary structures. Facies H usually consists of blocky- to slightly fining-upward bedsets of fine sand, occasionally with medium sand in the base. The characteristics of the coarser beds of the facies are usually an erosive base, overlain by low-angle planar- to trough cross-bedded sandstone. The lower part of these sands commonly contains rip-up clasts of mud and siderite and occasionally thin, structureless beds of mud or organic material. The finer-grained deposits of facies H commonly show planar parallel lamination followed by ripple cross-lamination, both wave-and current generated. In places this cross-lamination creates herringbone cross-lamination. The fine sands contain significant amounts of mica, and horizons of micaceous siltstone several centimeters thick do occur, especially in the planar parallel laminated units. Double mud drapes and climbing ripples are present but uncommon.

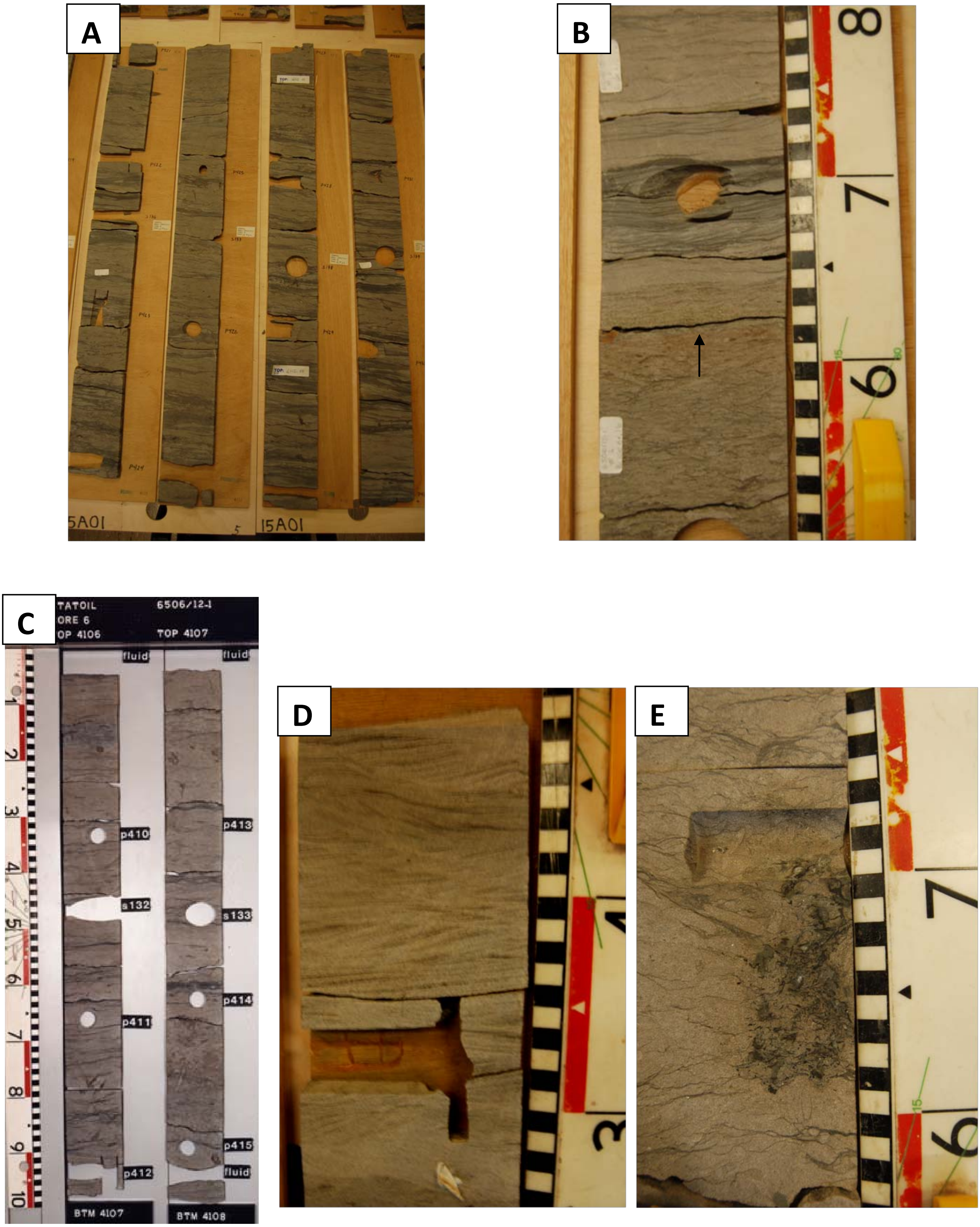

Figure 3.7: *3.7A;* Facies F distal distributary mouth bar heteroliths, 4110-4114 m (bottom right is deepest). *3.7B;* Erosive boundary (black arrow) separating facies C1 prodelta deposits from facies F distal mouth bars with mud draped current ripples above, 4114.4 m. *3.7C;* Facies G middle distributary bar, 4106-4108 m (modified from Norwegian Petroleum Directorate web pages, 2010). *3.7D;* Facies G, climbing ripples with dominantly leftward progradation of ripples, 4103.6 m. *3.7E;* Facies G, root traces, 4105.3 m.

The interval of the facies between 4097.2 and 4099.7 m is a bit different than the rest due to its massive appearance. The structures are vague in this interval, and sands are light gray. Two vertical veins of carbonate have been identified. Bioturbation is of low degree, with tiny burrows of *Trichichnus* as the most common. In addition a few burrows of *Ophiomorpha*, *Planolites*, *Rosselia*, *Schaubcylindrichnus* and *Paleophycus* have been identified.

3.9.1.2 Interpretation

Facies H is present towards the top of the coarsening-upward sequence that started with shelf sediments of facies B. Sedimentary structures are generally larger here than in facies F and G, and bioturbation is not prominent. This may indicate higher energy conditions that together with salinity variations made it difficult for organisms to colonize the substrate. The facies shows a complex set of structures, with wave ripples suggesting wave action, herringbone cross-strata and double mud drapes indicative of tidal flow, and planar parallel lamination and climbing ripples that were deposited in times of high sediment supply and energy conditions during for example river floods (H. G. Reading & Collinson, 1996, p. 191).

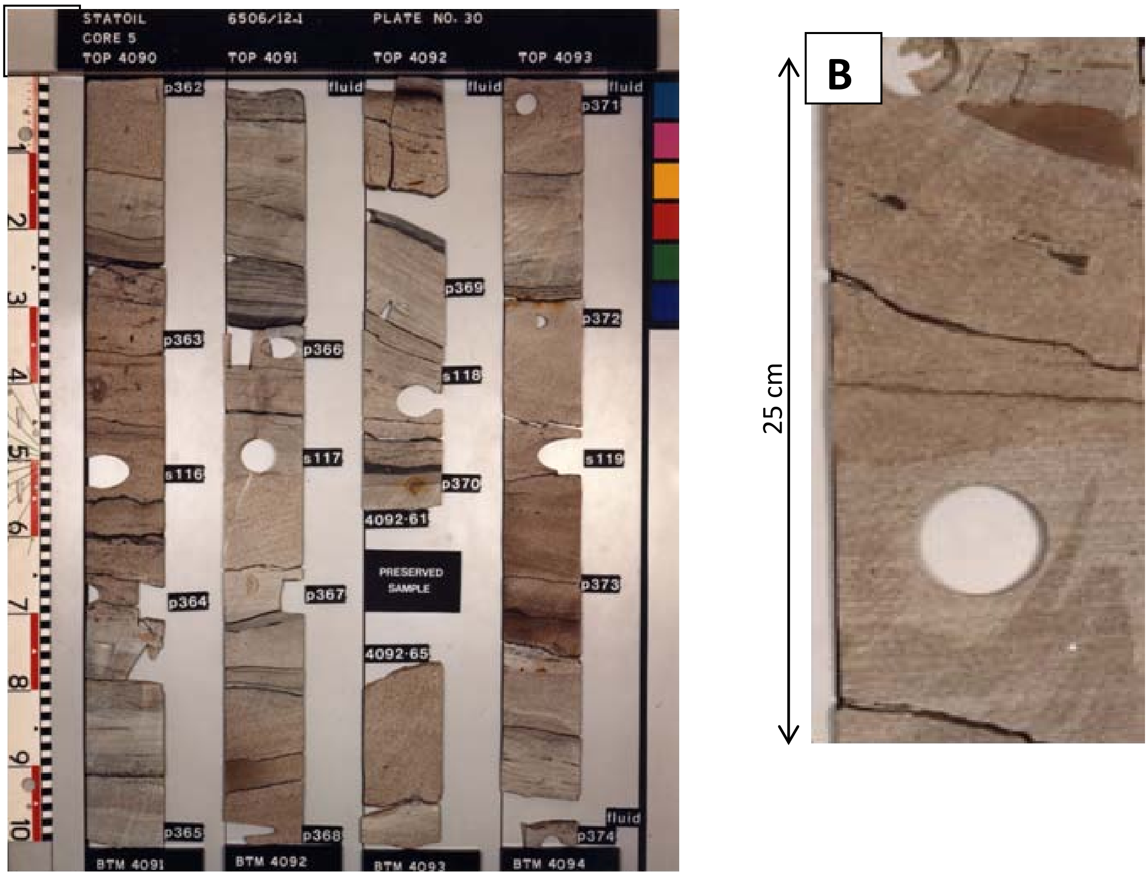

Figure 3.8: Facies H, proximal mouth bar deposits. 3.*8A;* Core interval containing several stacked fining-upward proximal mouth bar deposits. Erosive bases overlain by trough cross-bedded sands with rip-up clasts of mud or organic material near the base, grading into finer sandstone with planar parallel lamination and ripple cross-lamination, 4090-4094 m. Note examples of fluid muds (F). *3.8B;* Planar parallel laminated sands eroded by a trough cross-stratified bed with mud- and siderite clasts along foreset, 4100.3-4100.6 m (modified from Norwegian Petroleum Directorate web pages, 2010).

The thin interbeds of mud in the lower part of fining-upwards sequences are fluid mud deposits, which according to Ichaso and Dalrymple (2009) may be widespread in the base of tidal channels and in the coarsest and least bioturbated parts of mouth bars. They are associated with the zone of maximum turbidity, which is where tidal salt water and fluvial fresh water interacts and the mixing causes flocculation of the suspended sediment of the river.

The erosive scours overlain by fining-up sequences from trough cross-beds containing rip-up clasts of mud and coal, into wave- and current ripple- and planar parallel lamination, with frequent signs of tidal processes, brings on an interpretation of stacks of the proximal areas of *tidally modified distributary mouth bars* (H. G. Reading & Collinson, 1996, p. 207).

3.10 Facies I: Braid Delta Bar Complex

3.10.1.1 Description

Above a sharp erosive surface separating facies I from facies D below (Fig.3.9A), this subfacies constitutes the interval 4011.1 – 3990.9 m. The thick succession is built up of beds and bedsets that are either blocky or slightly fining-up from individual erosion surfaces, commonly associated with lags of very coarse sand or granules. A single set of cross-beds is typically a few tens of decimeters thick, but thinner and thicker sets occur as there is a high degree of amalgamation of beds in this facies. Overall the facies interval is slightly fining-upwards from just above- to just below medium-grained sand.

In the first half meter above the basal erosion surface the deposits are planar parallel laminated, before a new erosion surface leads into a four meter thick interval where low-angle planar cross-bedding is subtle and the coarse sediments have a massive appearance (Fig.3.9B). These deposits contain a lot of quartz and a few coal lenses.

Very coarse quartz grains and -pebbles occur throughout the facies. Low-angle planar cross-bedding is a common structure, but dominating are thick successions of trough cross-stratified and tabular cross-stratified sandstone (Fig.3.9C), often with mud drapes on foresets. A few observations have been made where cross-bedded sandstone has normal graded foresets. Sigmoidal cross-bedding has been observed as well (Fig.3.9D), along with both wave- and current-generated ripple cross-lamination.

3.10.1.2 Interpretation

The general medium grain size of the deposits with associated coarse grains indicates high energy conditions of this facies. Trough cross-bedding are produced by migrating three-dimensional dunes, whilst tabular sets are formed by straight-crested dunes (J. D. Collinson, 1996, p. 65). Indications that we are dealing with fluvial sands rather than upper shoreface sands or offshore sandwave fields are the abrupt grain size variations in parts of the succession, the dominance of trough cross-beds over other sedimentary structures and the complete absence of any marine trace fossils. A braided river system is suggested due to the lack of any overbank facies and distinct fining-upward sequences (Harris, 1989). The term braid delta was introduced by McPherson et al (1987), who defined it as a coarse-grained delta formed by progradation of a braided river system into a standing body of water. Small base level fluctuations may have led to some intervals being reworked by waves and showing planar parallel lamination and wave-ripple cross-lamination. Paired mud drapes on foresets may indicate that tidal currents protruded into the fluvial distributaries at times. The predominantly trough cross-bedded sands are interpreted as stacked and amalgamated *braid delta bars*, deposited in braided river channels in a deltaic setting.

The half meter just above the basal erosion surface of the facies, where deposits are planar-laminated, may be interpreted to reflect deposition from high energy currents of the upper flow regime (McKee et al., 1967), and may thus represent sheetfloods. Sheetfloods are regarded as a minor depositional process in braid deltas (McPherson et al., 1987). The low-angle planar cross-bedded and somewhat massive sands that erode into these planar-laminated sands reflect deposition from rapidly decelerating flow, which dumped a large amount of sediments at this location. Why these should be deposited on top of braidplain sheetsands is hard to imagine, and another interpretation may be needed. The high amount of rounded quartz grains in the deposits may indicate a nearshore depositional environment. The combined features of the lower four meters of the facies are here interpreted to represent the bottom- and foresets deposited where the braided river system prograded into a shallow water body. It is likely that sediments have been reworked by wave processes in this subaqueous part of the braid delta (McPherson et al., 1987).

3.11 Facies J: Flooded Braid Delta

3.11.1.1 Description

Facies J starts at 3990.9 m, where eight cm of very fine sandstone containing four mud layers separate it from facies I. Facies J ends at 3975 m, which is the top of the core. The lower part of this facies is generally fine-grained sandstones which contain some erosive beds of medium-grained sands, sometimes with associated coarser lags. Deposits vary between being thoroughly bioturbated (Fig.3.10A) and completely without bioturbation. Some of the coarser beds are low-angle planar- to herringbone cross-bedded (Fig.3.10B), while the fine-grained sands either are trough- or low-angle planar cross bedded, or contain double draped ripple cross-lamination and possibly herringbone cross-lamination. Trace fossils found in the facies include *Ophiomorpha, Paleophycus, Trichichnus, Cylindrichnus, Asterosoma* and *Skolithos.*

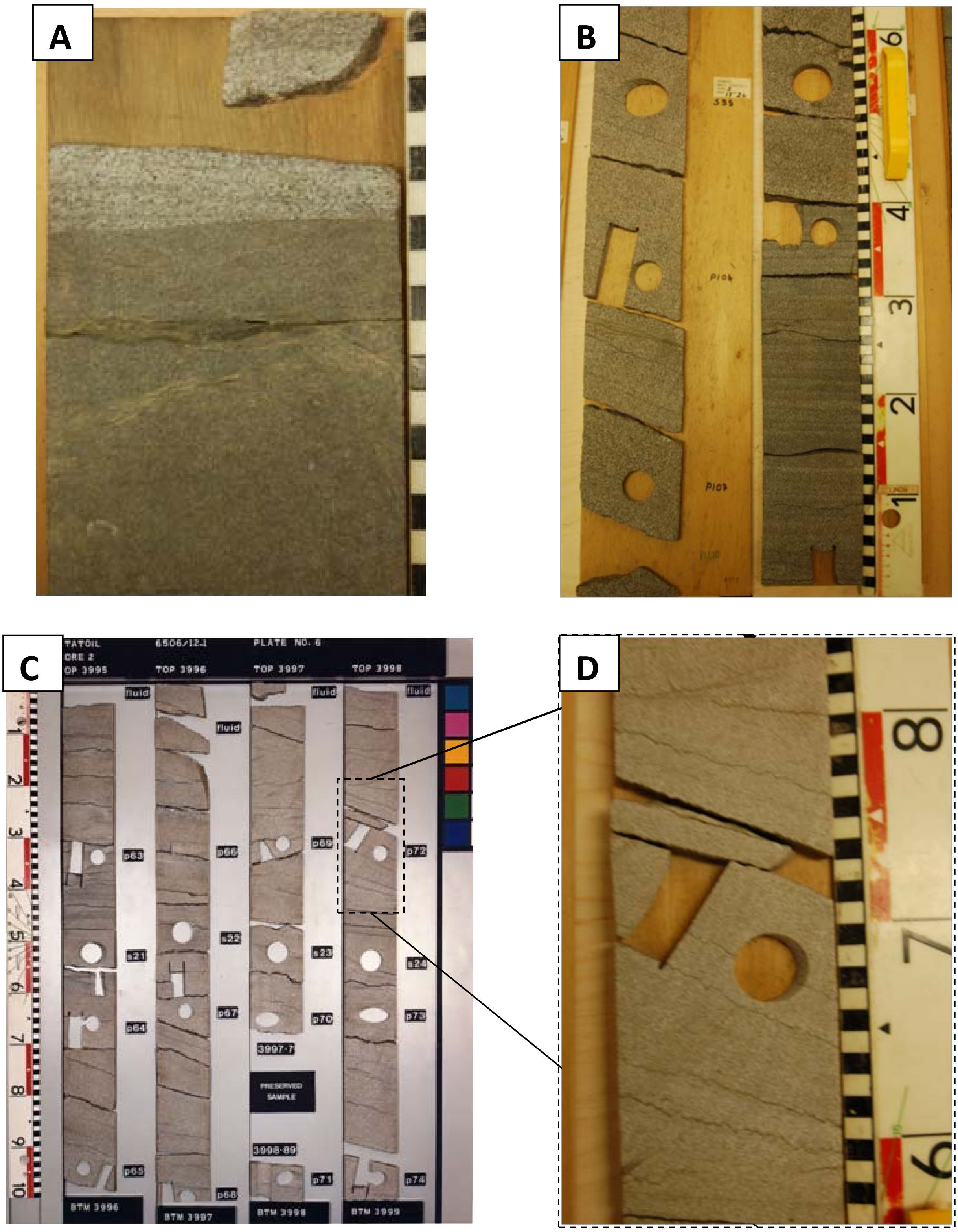

Figure 3.9 (Facies I). ***3.9A:*** **Erosional sharp surface separating facies I from facies D below, at 4011.1 m.** ***3.9B:*** **Planar-parallel laminated- to massive sandstones, deposited in a wave-influenced upper shoreface/braid delta mouth setting. Lower right from 4011 m depth, lower left from 4010 m depth.** ***3.9C:*** **Typical interval of facies I, amalgamated cross-bedded sands deposited in braid delta bars, 3995-3999 m (from Norwegian Petroleum Directorate web pages, 2010).** ***3.9D:*** **25 cm thick sigmoidal cross-bedded sand, see location in 3.9C.**

Above an erosion surface at 3983.4 m the subfacies changes character a bit, as the amount of bioturbation decreases. This uppermost part of the facies J consists of generally fine sands stacked in blocky- or slightly fining-up intervals. Structures are of smaller scale than the ones found in facies I, and upward through the entire interval there seems to be a systematic alternation between low-angle planar lamination and herringbone- or current ripple cross-lamination, occasionally with double mud draped structures (Fig.3.10C). The alternation occurs once or twice in every meter section of core. Wave ripple and climbing ripples are also found within the subfacies, but not to the same extent. A few *Skolithos* and *Ophiomorpha* burrows are observed.

3.11.1.2 Interpretation

Facies J is generally finer grained than facies I braid delta bar complex below, and the texture of the deposits is much more varied as parts are thoroughly bioturbated. This development is interpreted as a response to marine transgression, which may have created shallow water conditions on the former delta plain, and possible shallow embayments. The dominance of sand in the facies is probably due to winnowing of the sediments by tidal currents, suggested by the herringbone- and draped ripple cross-lamination, and wave activity, suggested by low-angle planar cross-bedding and wave ripples. The coarser beds are thought to reflect specific river flood events which released coarser sediments than usual from the river mouths and into the delta front area. *Trichichnus* is a type of trace fossil which is commonly found in brackish estuarine conditions (Hubbard et al., 2004), which easily may have prevailed in this shallow water due to competition of fluvial and marine processes.

Above the erosion surface at 3983.4 m the slight increase in grain size and low degree of bioturbation suggests that progradation have brought the braided rivers closer. The almost cyclic alternation of low-angle planar- and herringbone cross-lamination may indicate that the process of reworking switched between waves and tides. This situation may arise if for example the tides are only strong enough to overcome wave action during spring tide.

The interpretation of facies J is a *flooded braid delta*, deposited in a shallow inshore area where braided river deposits are influenced by basinal processes (McPherson et al., 1987). The changes vertically are thought to reflect renewed progradation of the braid delta following the transgression of the former braid delta top.

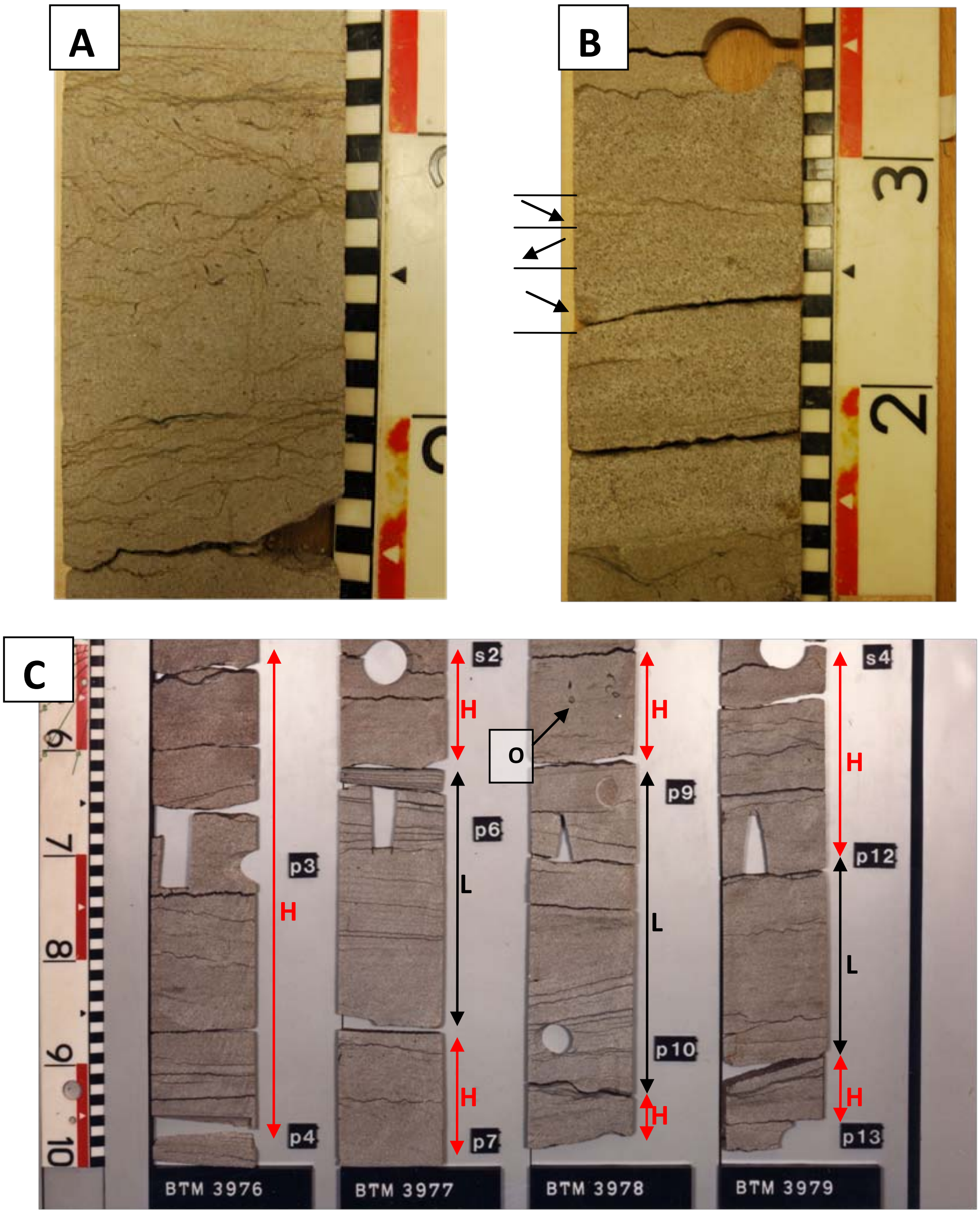

Figure 3.10 (Facies J) *3.10A:* Typical bioturbated fine sands of facies J, 3983.65-3983.85 m. Tiny black lines are *Trichichnus* traces. *3.10B:* 20 cm thick erosive based event bed, planar laminated in the lower half and vaguely herringbone cross-laminated (arrows) in the upper half. The bed is thought to reflect river flood deposits. *3.10C:* The lower half of four core-meters of this facies, showing the two most typical stratification styles; low-angle planar- (L) and herringbone cross-lamination (H). Also note a few *Ophiomorpha* burrows (O). (modified from Norwegian Petroleum Directorate web pages, 2010)

3.12 Facies K: Tidal Flats

3.12.1 Subfacies K1: Subtidal Flat

3.12.1.1 Description

Subfacies K1 (Fig.3.11A, B) occurs in fining-upward intervals of up to a meter thickness, between 4086.4 and 4089.4 m. The facies is characterized by thinly bedded sandstones of very fine to medium grain size, in sets up to one dm thick, interbedded with cm-scale beds of wavy laminated mudstone. The overall sand/mud-ratio is around 80 % for this subfacies. The sands show evidence of both low-angle planar parallel lamination, wave ripple cross-lamination and bidirectional current ripples. Both single and double mud drapes are observed on ripple foresets.

Bioturbation is relatively high, most of it being concentrated in the mudstones and in the upper part of sands below these muddy interbeds. Escape burrows are present, and ichnodiversity is high. Trace fossils are dominated by *Planolites,* accompanied by less common traces of *Paleophycus, Ophiomorpha*, *Chondrites*, *Teichichnus, Cylindrichnus, Asterosoma, Rosselia, Siphonichnus* and *Arenicolites.*

3.12.1.2 Interpretation

Mud couplets in the sandstones indicate tidal current action and that the deposits were always submerged in order to record both slackwater stages in the tidal cycle (Visser, 1980). The relatively high degree of bioturbation is a sign that marine conditions prevailed that were suitable for a diverse ichnofauna. The deposits of subfacies K1 are therefore interpreted as subtidal flat deposits, deposited in the part of the tidal flat that normally lies below low tide levels and also commonly experience some wave activity (Boggs, 2006, pp. 326-332).

3.12.2 Subfacies K2: Intertidal Flat

3.12.2.1 Description

Subfacies K2 appears as up to 3.75 m thick successions within the core interval 4078.4 to 4086.3 m. The successions typically contain several sets of fine sand that show a very slight fining-upwards trend usually less than a meter thick. Some of these sets have increased mud content relative to other sets, and there are a few thin interbeds of wavy laminated mudstone contained in the subfacies. Mud chips occur within the subfacies.

The fine sands of subfacies K2 contain a wide range of sedimentary structures. Wave- and current ripple cross-lamination is common, along with planar parallel lamination (Fig.3.11C) and sets of thin trough cross-stratified beds. In some intervals the current ripples create true herringbone cross-lamination. Ripples and foresets of trough cross-beds are commonly mud draped, mostly by single drapes. Climbing ripples appear several times in the subfacies; the interval 4082.1-4082.4 m show a particularly beautiful example of these along with abundant reactivation surfaces and ripples both wave- and current generated (Fig.3.11D).

Mostly this facies is completely without trace fossils, but a low diversity ichnofauna is present, represented by a few burrows of *Trichichnus, Skolithos, Planolites, Paleophycus* and *Cylindrichnus*. Escape burrows are more common.

3.12.2.2 Interpretation

The intertidal realm lies between the mean high and low tide levels, and therefore experiences subaerial exposure through the tidal cycle. The intertidal flats are environments of both bedload and suspension sedimentation. The current velocities acting on a tidal flat are strong enough for sand to be transported and create ripples, dunes, cross-bedding and plane bedding (Klein, 1998). The abundant reactivation surfaces seen in the sands in Fig.3.11D are thought to reflect tidal activity. As can be seen, the ripple foresets are dominated by a single dip-direction, pointing to an asymmetrical tidal cycle. The ripples and dunes migrate downstream during the dominant tidal phase, when current velocities are high enough to entrain and deposit sediment. During the subordinate tidal phase the effect of currents are limited to reshaping of the ripples, a process that creates the reactivation surface, over which the bedform will migrate during the next dominant tidal phase (Boggs, 2006, pp. 326-332). The predominance of single mud drapes over couplets also suggests subaerial exposure during low tide, meaning that no mud couplet could be deposited at this stage (Visser, 1980). Near the low-tide mark on an intertidal flat the wave activity is the strongest and of longest duration, which may account for the planar parallel lamination and ripple cross-lamination seen in the subfacies. In addition, the wave activity has probably winnowed the deposits so that they contain very little mud (Reineck & Singh, 1980, p. 432). The low degree of bioturbation is also typical of intertidal flat formed near the low-tide mark, due to the high degree of instability of the sandy substrate (Klein, 1998). Subfacies K2 is in all interpreted as sandy intertidal flat deposits.

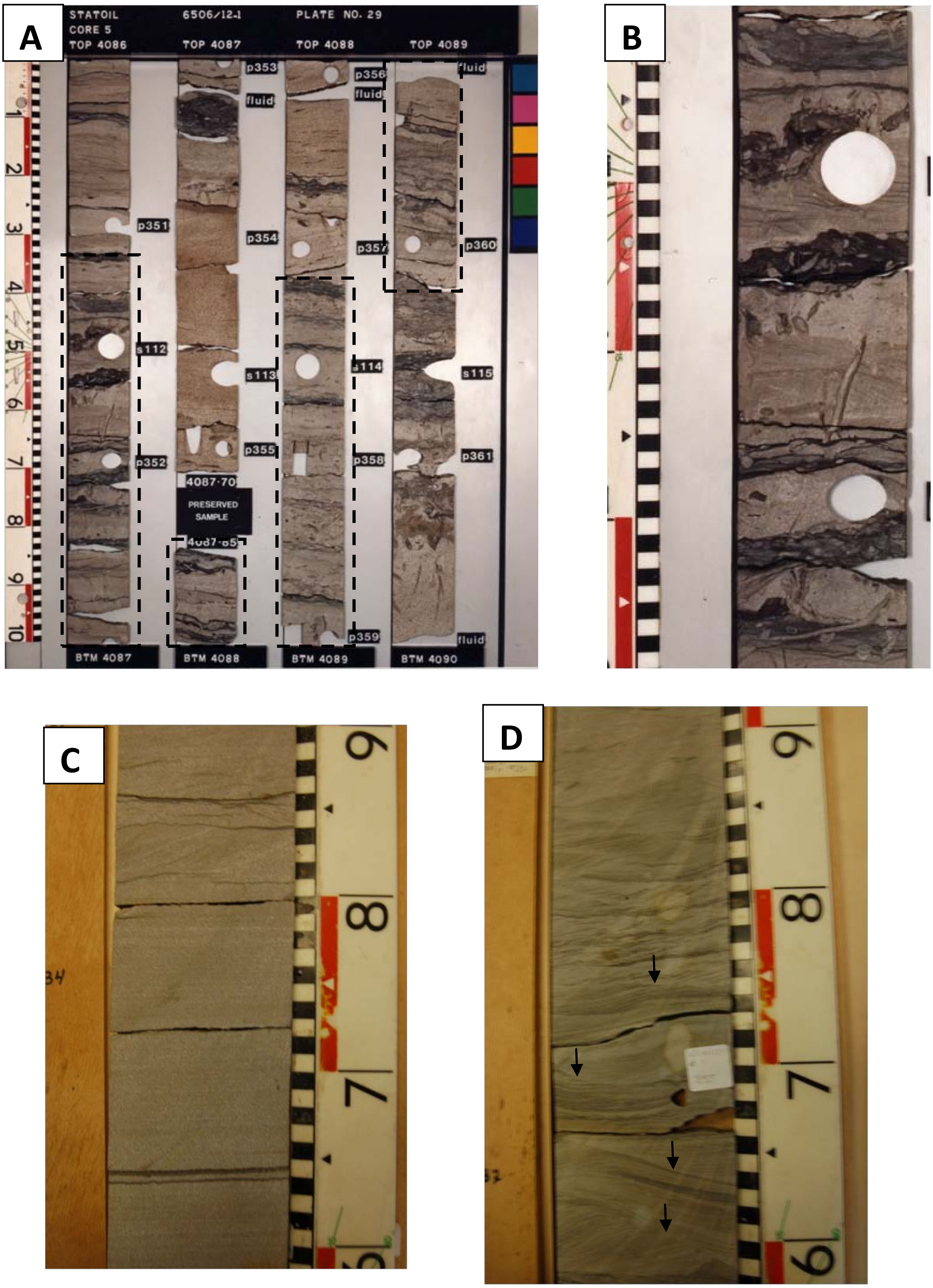

Figure 3.11: ***3.11A;*** **The stippled squares delineate deposits interpreted as subfacies K1 subtidal flat deposits.** ***3.11B;*** **Close-up of typical subfacies K1 heteroliths with mud draped current ripples in sand interbedded with bioturbated muds, 4086.35-4086.8 m (modified from Norwegian Petroleum Directorate web pages, 2010).** ***3.11C,D;*** **Deposits from the K2 subfacies, intertidal flat.** ***C;*** **Planar-parallel laminated sands and mud draped current ripples. Note double mud drape in lower part of planar parallel laminated sands (4081.1-4081.4 m).** ***D;*** **Abundant reactivation surfaces (examples indicated with arrows) in wave- and current influenced sands (4082.1-4082.4 m).**

3.12.3 Subfacies K3: Shallowing Intertidal Flat

3.12.3.1 Description

Subfacies K3 extends from a planar surface at 4052.8 m (Fig.3.12A) and up to a sharp and erosional boundary to facies L at 4045 m. The subfacies K3 interval shows an overall fining-upwards trend from fine sandstone to very fine sandstone, but a regular interbedding with silt and clay leads to a sand/shale ratio varying between 0.5 and 0.9 through the subfacies interval. Along with the decrease in grain size as one move up the core there is a marked change in style of bioturbation.

The lowermost four meters of this subfacies is characterized by very large burrows of *Diplocraterion* (Fig.3.12B), with some burrows as long as 30 cm. The burrows mottle the deposits as they redistribute mud from the interlayers, which makes identification of original sedimentary structures difficult. Some ripple cross-lamination has been identified, mostly of which are formed by waves. The subfacies as a whole contain some other trace fossils besides *Diplocraterion*, namely a few *Paleophycus*, *Ophiomorpha, Teichichnus, Planolites* and *Skolithos.*

From 4049 m and up the bioturbation becomes less dominant and the true heterolithic character of the facies is more evident (Fig.3.12C). The long *Diplocraterion* burrows decrease both in number and in length from here, and towards the boundary with facies L there is no bioturbation. Sedimentary structures in the sand include wave ripples, bidirectional and occasionally double draped current ripples, and both the sand and muddy interbeds contain wavy- to planar lamina. From 4046 m and up the deposits are planar parallel laminated and micaceous.

3.12.3.2 Interpretation

The structures present indicate a tidal flat setting influenced by both tidal and wave activity. The general fining-upwards trend seen is believed to indicate progressively shallower water. Low ichnodiversity may indicate hostile, brackish-water conditions. *Diplocraterion* is a diagnostic marine trace fossil that can be used as an indicator of tidal activity when it occurs in successions reflecting rapid deposition. The U-shaped burrow acts as a dwelling tube for the animal. In subfacies K3 both protrusive and retrusive behavior is tentatively identified in these burrows, meaning, respectively, that the organisms burrowed deeper due to erosion at the surface or followed the rising surface due to deposition. (Cornish, 1986). The reduction in burrow dimensions registered cannot be used as definite marker of environmental changes, because it can reflect the size of the animal and varying amounts of erosion (Fürsich, 1974). It is tempting though to interpret it as a response of shallowing, as weaker tidal currents and less erosion would reduce the animal's need to make long tubes to re-equilibrate with the surface. The subfacies is interpreted as an intertidal flat which shows a shallowing-upwards trend, becoming muddier and less bioturbated upwards.

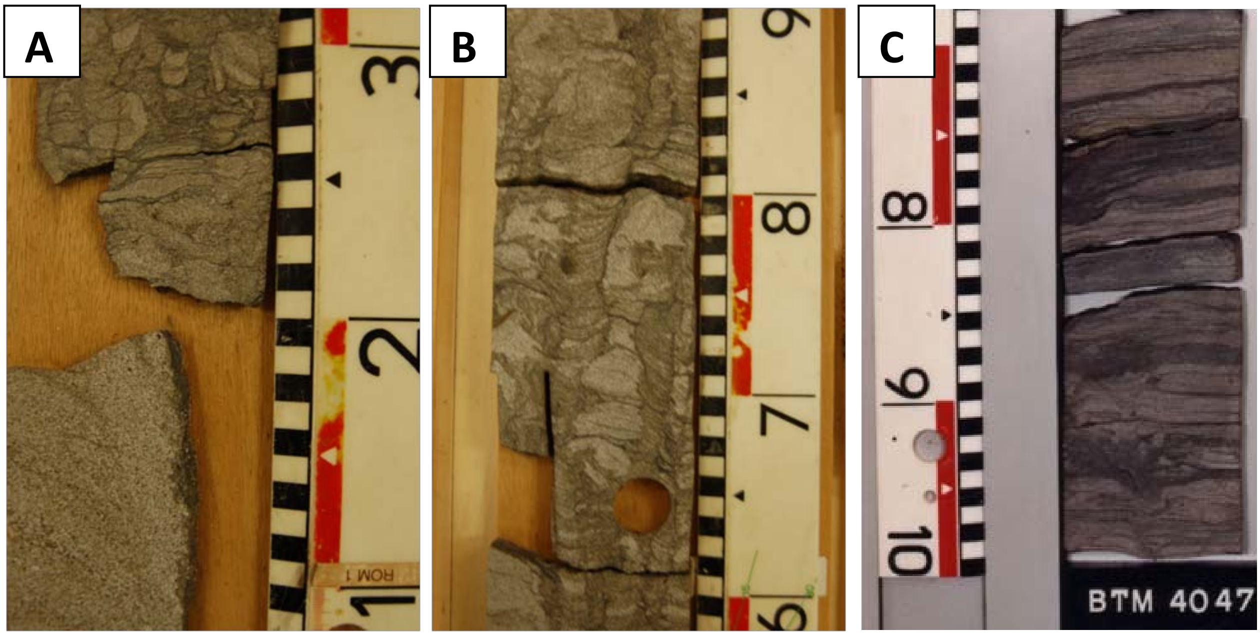

Figure 3.12 (Subfacies K3). ***3.12A:*** **The sharp boundary between tidal channel sands of subfacies M1 below and transgressive intertidal flat sands above, at 4052.8 m. Boundary is interpreted as a flooding surface.** ***3.12B:*** **The lower part of the subfacies is dominated by long** ***Diplocraterion*** **trace fossils that redistribute mud in the sand-dominated deposits, 4052.2 m.** ***3.12C:*** **Further up-section deposits of subfacies K3 have less and smaller burrows, and the true heterolithic character is revealed, here by wave interlaminated muds and current rippled sands, 4046.7-4047 m (modified from Norwegian Petroleum Directorate web pages, 2010).**

3.13 Facies L: Transgressive lag deposits

3.13.1.1 Description

Facies L (Fig.3.13) starts at 4045 m where an erosion surface is overlain by a ten cm thick bed of very coarse sand containing granule-sized clasts. The material is moderately sorted but well rounded, and contains grains of pyrite, quartz and mica. The top of the bed is wavy. For the next half meter there is a distinct interbedding of cm-scale beds of fine- to coarse-grained sandstones and thin shales. The shales in this part commonly have a lenticular style of bedding, containing streaks of sand. Toward the top of this thin facies at 4044 m the deposits become increasingly mud-dominated.

3.13.1.2 Interpretation

The lower surface separating these heteroliths from the intertidal flat deposits of subfacies K3 is interpreted as a transgressive surface. The interfingering of thin, wavy beds of coarse sand and lenticular bedded shales in the basal part of this facies are interpreted as transgressive lag deposits, deposited in a shallow marine setting as the wave base created a ravinement surface when it migrated landwards.

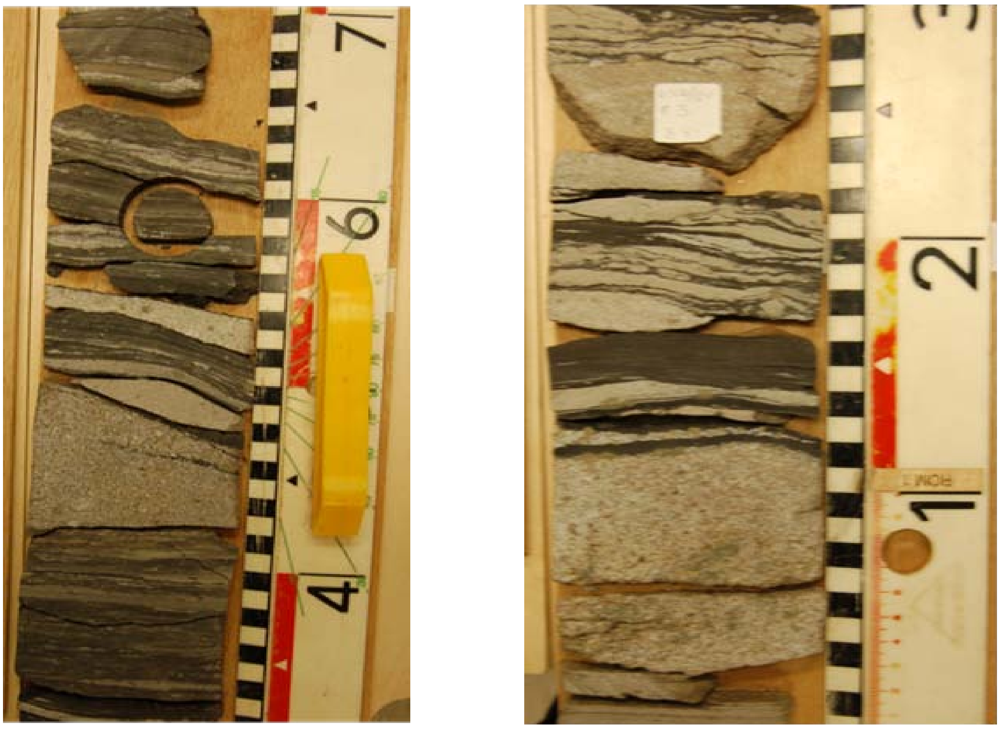

Figure 3.13: Facies L transgressive lag deposits, from 4045 m in the lower right up to 4044.3 m in top left. The rippled fine-coarse sand beds and lenses decrease in thickness and abundance upward.

3.14 Facies M: Channel fills

3.14.1 Subfacies M1: Tidal Channel Fill

3.14.1.1 Description

Subfacies M1 can be demonstrated in several intervals between 4052.8 m and 4096.8 m, above the coarsening-upward delta front succession constituted by subfacies C1 and facies F, G and H. The subfacies is in general characterized by sands having an erosive base toward the underlying facies, and which are fining-upwards from a base of medium- to coarse sands up into fine- to very fine sands (Fig.3.14B). The thickness of fining-upward sequences is typically 1-5 dm in the lower part of the interval containing this subfacies, where it alternates with subfacies K1 and K2. Up-section thicknesses increase and sets of trough cross bedded sandstone can approach several meters in thickness.

The coarser grained lower part of M1 sands typically consists of sets of dm-thick trough cross-beds, in places separated by low-angle planar bedding. Some bedsets have mud-, organic- or siderite clasts near the base; mud- or organic drapes on cross-bed foresets are also common. These can occasionally be demonstrated to thicken toward the toe of the foreset (Fig.3.14D). Some of the fining-up sequences contain interbeds of wavy mudstone several centimeters thick, as seen in Figure 3.14B. The first encounter with this subfacies when moving up through the core is at 4096.5 to 4096.8 m. Here there are two stacked 15 cm thick tabular cross-bedded units of medium-grained sandstone (Fig.3.14A).

The bedset has an erosive base and a planar top; bottom- and foresets of the beds contain sub-rounded coarse sand- to granule-sized grains, with quartz as the dominating constituent. Foresets in the two beds dip in opposite directions.

The upper, finer grained part of the subfacies is not always present due to erosion and stacking of the coarser lower parts. This is a situation especially common in the upper part of the interval where this subfacies has been identified and the fining-upwards sequences are thicker. Where present, the finer intervals usually contain interbeds of very fine- to fine sandstone and siltstone, with occasional thin beds of coarser sand. Sedimentary structures present in these fine sands include double draped bidirectional current ripples (Fig.3.14E), wave ripples and planar parallel lamination. Silts are typically planar parallel laminated to wavy- or lenticular-laminated.

Bioturbation is generally absent in the coarser lower part of bedsets of this subfacies, but a few trace fossils of *Ophiomorpha, Skolithos, Planolites, Paleophycus* and *Trichichnus* have been identified. The finer grained upper part is also characterized by low degrees of bioturbation, comprising several escape burrows, and traces of *Chondrites, Skolithos* and *Planolites.*

3.14.1.2 Interpretation

The generally erosive based, fining-upwards cross-bedded and rippled sandstones are interpreted as channel sandstones. The coarse basal part of fining-upward units is probably related to migration of dunes or sand waves along the channel floor. When interpreting cross-bedded sandstones in core one should be careful in interpreting if there exist a bidirectional component in the currents depositing them, especially when dealing with trough cross-bedding (J. D. Collinson et al., 2006, p. 101). As seen in the coarse sandstone in Fig.3.14A and C, tabular cross-strata with different dip direction from one bed to the next may be related to two-dimensional dunes migrating in opposite directions in a tidal channel, but it may also be apparent due to the cut of the core. Tabular cross-bedding are created by two-dimensional bedforms, and the angular and coarse-grained foresets in Fig.3.14A indicate weak flow and grainfall-dominated deposition (J. D. Collinson et al., 2006, p. 103). The cm-scale wavy mud beds seen usually near the base of fining-up channel sands are interpreted as fluid mud deposits (Ichaso & Dalrymple, 2009).

The foresets of trough-cross bedded sands shown in Figure 3.14D contain paired mud drapes, separating a foreset increment a few cm thick from a larger increment of foresets. This is indicative of a tidal environment, and if traced along the set it might have been possible to distinguish tidal bundles by the systematic increase and decrease in mud drape spacing (J. D. Collinson et al., 2006, p. 102).

The facies also contains additional clues to the tidal origin of this subfacies. The presence of vertical burrows like *Skolithos* and *Ophiomorpha* in the sands may reflect opportunistic behavior in the shifting current conditions of a tidal environment, and escape traces may be a response to sudden sediment influxes (Ekdale et al., 1984). The fact that the finer upper parts of the channels contain bidirectional current ripples that are double draped is a very strong indication of the fining-upward sequences being tidal channels. The finer upper intervals resemble the tidal flat facies that appear associated with the channel deposits in the Ile Formation, and were deposited as channels filled and migrated laterally. Both wave- and tidal-processes are thought to have affected the shallow parts of channels. The close spacing in pairs of mud drapes seen in Fig.3.14E may point to one current direction being dominant within the channel (Allen, 1982). The thin coarse sand lenses found in some of the finer intervals may be a result of deposition in small tidal creeks that eroded into the fill of the larger channel.

3.14.2 Subfacies M2: Channel Abandonment Fill

3.14.2.1 Description

This subfacies is uncommon but occurs a few times in the core, in the intervals 4089.4-4089.8 m, 4087.05-4087.15 m and 4072.2-4073.55 m. In all these subfacies M2 conformably overlies subfacies M1. In the lowermost intervals it passes upward into subfacies K1 subtidal flats whilst in the upper interval it passes into an erosion surface overlain by new subfacies M1 deposits.

M2-deposits are characterized by having larger mud content and much higher degree of bioturbation than surrounding facies (Fig.3.15A,-B). Clean, fine- to medium-grained sands and more muddy deposits are commonly organized in interbeds, where the sands have preserved a varying degree of their original depositional structures. These structures comprise low-angle-, planar parallel- and current ripple cross-lamination. A few laminated siltstones also exist in this subfacies, but generally these finer deposits are thoroughly bioturbated. Trace fossils identified in this subfacies include *Asterosoma, Paleophycus, Planolites, Thalassinoides, Siphonichnus, Chondrites, Rosselia, Diplocraterion* and *Ophiomorpha*.

3.14.2.2 Interpretation

This subfacies was also recognized and described by McIllroy (2004a) in his study of the Ile Formation on the Kristin Field. As he noted, the sudden diversification of ichnofauna and a higher content of finer grained sediments point towards abandonment of the tidal channel, probably due to avulsion. The stressed conditions in terms of energy and salinity associated with tidal channels is thought to have been replaced by less hostile marine conditions similar to those found in subtidal flat areas. The presence of *Siphonichnus* in these subfacies intervals is also thought to indicate tidal channel abandonment, and therefore a reduction in sediment supply. Surfaces associated with this particular trace fossil may be hiatal (McIlroy, 2004a).

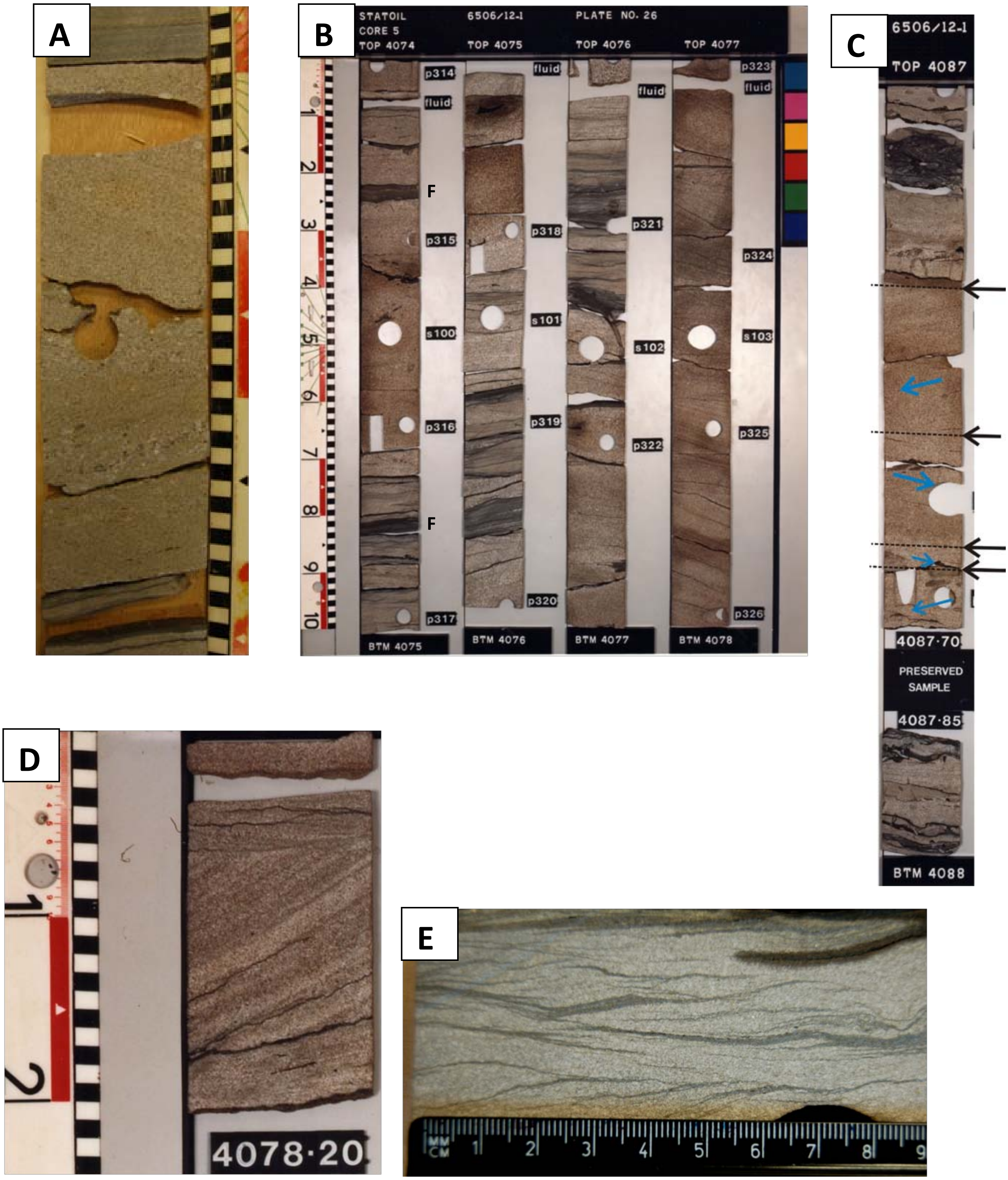

Figure 3.14 (Subfacies M1 tidal channel fills) *3.14A;* Erosive based bedset containing two tabular cross-bedded coarse sand beds, with foresets dipping in opposite directions, 4096.5-4096.8 m. These sediments are interpreted as basal deposits of a tidal channel/inlet, as they are found within proximal mouth bar deposits of facies H. *3.14B;* Typical succession of tidal channel fill, both trough- and tabular cross-bedded basal part and rippled- to laminated upper part with abundant tidal features. Note fluid muds (F). *3.14C;* Possible herringbone cross-strata in tabular cross-bedded bedset. Black arrows and dotted line indicate roughly parallel bedding planes, while blue arrows indicate foreset dip. *3.14D;* Trough-cross bedded sand with mud laminae of foreset (possible tidal bundling), deposited in a tidal channel by migrating 3D dunes. *3.14E*; The upper part of a tidal channel fill, showing mud draped current ripples, 4075 m depth. Double mud drapes can be recognized, but they are closely spaced, and current ripples are mostly unidirectional. This is taken to indicate that one direction of flow was dominant in this channel (modified from Norwegian Petroleum Directorate web pages, 2010).

3.14.3 Subfacies M3: Fluvial-Dominated Channel Fill

3.14.3.1 Description

Subfacies M3 is characterized by stacks of medium-grained sandstone that have a blocky appearance but eventually become finer upwards into fine sandstone. The individual fining-upward sequences commonly have an erosive base containing grains of very coarse sand. The facies constitutes the whole core between 4056 and 4061.9 m, and the most complete fining-upwards sequence is 2.6 m thick.

The medium-grained sandstones are trough- and tabular cross-stratified and contain rare coarse grains on foresets along with transported chips of coal and mud. Fine, planar-laminated sandstones are present above some of the medium-grained sandstones. A few observations have been made of paired mud drapes in the finer sandstones of the subfacies. The deposits are completely unbioturbated.

3.14.3.2 Interpretation

The fining-upward sequences of this facies are also interpreted as channel sandstones, but they contain less signs of tidal influence relative to subfacies M1 and M2, and no signs of any marine trace fossils. The paired mud drapes mean that tidal currents partly affected the channels when these sands were deposited, possibly only during spring tide when the currents grew stronger and could protrude further up the channel system. The fact that there are no fluid mud deposits point to conditions closer to fresh water, as muds did not flocculate and get deposited in the channel. Freshwater conditions are also indicated by the complete absence of marine trace fossils. The tabular- and through cross-bedding are formed by migration of two- and three-dimensional dunes along the channel floor, respectively.

According to Gjelberg et al. (1987), well 6506/12-1 is the only well on the Halten Terrace where fluvial dominance has been noted in the Ile Formation. It is interpreted that tidal activity increased after some time and the fluvial processes were no longer dominant (Fig.3.15C).

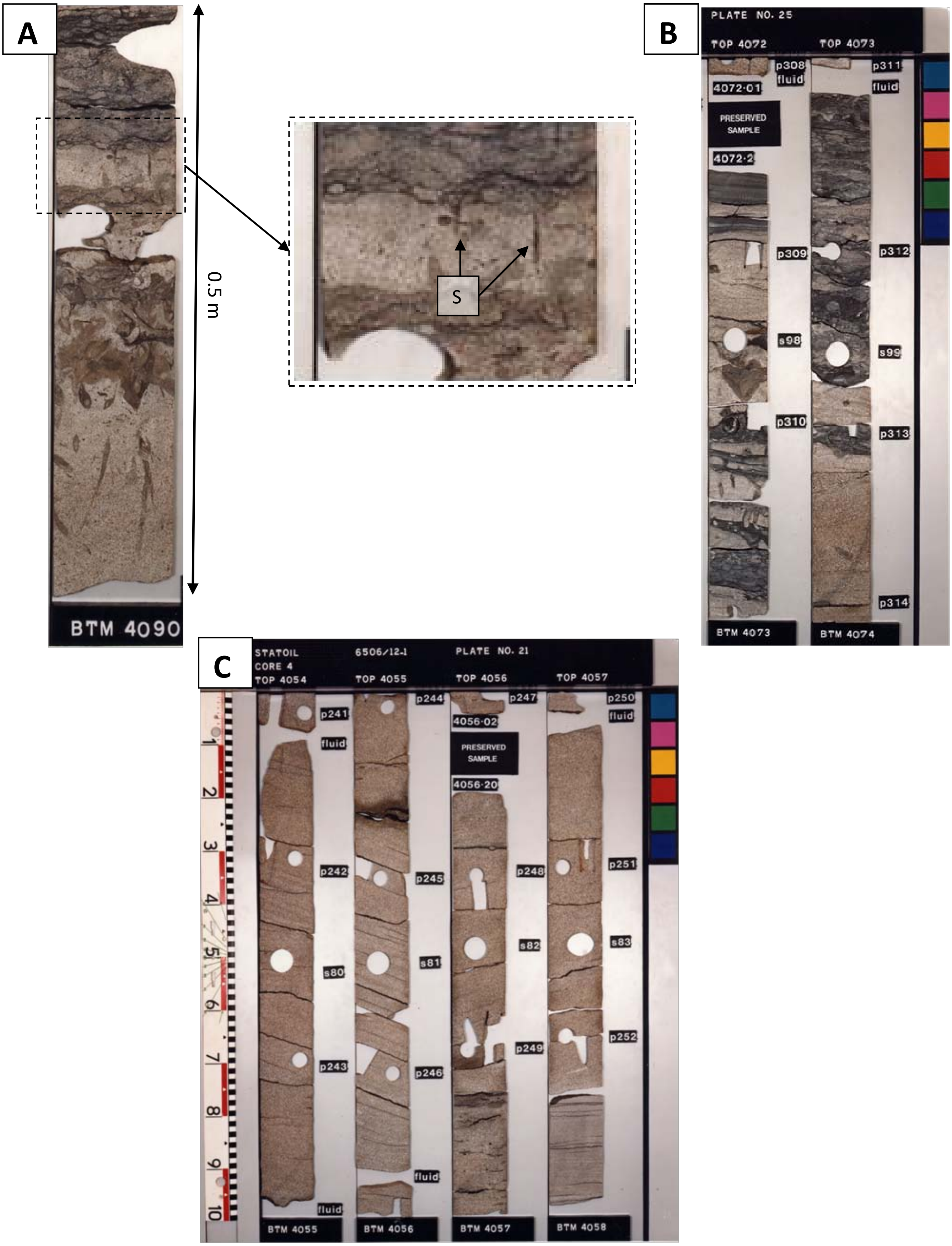

Figure 3.15: *3.15A and B;* Highly bioturbated subfacies M2 channel abandonment facies above clean tidal channel sandstones. Note *Siphonichnus* (S) coming down from a mud-rich horizon into a thin rippled sand bed. *3.15C;* The upper portion of subfacies M3 deposits, showing a discrete change from purely fluvial sands in the two columns on the right, back into some tidal influence shown by the reappearance of mud drapes (dark bands) on foresets in the two columns on the left (modified from Norwegian Petroleum Directorate web pages, 2010).

4 Facies Associations

4.1 Introduction

In order to go from interpreting facies in core to building a paleogeographic- and sequence stratigraphical model it is useful to start with recognizing that facies do not stack randomly together, and that changes occurring vertically in a conformable succession should also take place laterally. This fundamental principle in stratigraphy was first formulated in Walther's Law:

> *"The various deposits of the same facies areas and similarly the sum of rocks of different facies areas are formed beside each other in space, though in cross-section we see them lying on top of each other….it is a basic statement of far-reaching significance that only those facies and facies areas can be superimposed primarily which can be observed beside each other at the present time"* (Walther, 1894), translated by Middleton (1973).

Based on this basic principle it is possible to group the interpreted facies into facies associations, where each association contain facies that are genetically linked and have some environmental significance (John D. Collinson, 1969). The construction of facies associations is in fact a construction of depositional systems, and therefore permits reconstruction of paleogeographic changes through time and the recognition of key surfaces in a sequence stratigraphic framework (Catuneanu, 2006). For detailed description and interpretation of the individual facies please consult chapter 3.

Each facies association recognized in well 6506/12-1 occurs only once, and is thus presented from the base of the cored interval and upwards (Table 4-1).

Table 4-1: Facies associations in well 6506/12-1

Facies Associations	Facies
FA1 – Prograding offshore to delta front	B, C1, E, F, G, H, M1
FA2 – Lower delta plain	K1, K2, M1, M2, M3
FA3 – Backstepping delta plain	K3, L, M1
FA4 – Prograding offshore to lower shoreface	A, C2, D
FA5 – Braid delta complex	I, J

4.2 Facies Associations of well 6506/12-1

4.2.1 Facies Association 1 – Prograding offshore to delta front

4.2.1.1 Description

Facies Association 1 (Fig.4.1A) consists of in all seven facies and subfacies, namely open shelf (B), offshore transition/prodelta (C1), condensed section (E), distal-, middle- and proximal distributary mouth bars (F, G and H, respectively) and tidal channel fill (M1). The combined thickness of the facies association in well 6506/12-1 is 61.6 m. As demonstrated in Fig.6.2 this long interval comprises two separate large-scale coarsening-upward sequences of approximately equal thickness. The two sequences are both indicated in the wireline logs by a decrease in gamma ray values and a general converging of the density and neutron logs from a positive shale separation at the base of each sequence.

The lower of the two large-scale coarsening-upward sequences initiates at the base of the described core at 4151.73 m depth. The lowermost deposits of the core are 14 meters of completely bioturbated open shelf mudstones of facies B which in turn are conformably overlain by subfacies C1 offshore transition zone/prodelta sediments. Both B and C1 contain several small coarsening-upward cycles on a 2-3 meter scale. The total thickness of subfacies C1 is 21.7 m, occurring in two sections as it is interrupted in the upper part by a 1.5 m thick interval of cemented and shell-rich sediments belonging to facies E and interpreted as a condensed section.

The second of the two large-scale coarsening-upward sequences of FA1 initiates at 4114.4 m depth, where an erosion surface separates subfacies C1 from overlying deposits. The heteroliths above this surface belong to facies F, and are interpreted as distal distributary mouth bars that have been significantly modified by tidal activity. The total thickness of facies F is 6.3 meters. Facies F pass upward across an erosion surface into sandier facies G middle mouth bar deposits. Facies G comprises 5.7 m of core, only interrupted by a thin medium-grained sand deposit belonging to facies H, proximal distributary mouth bars. Facies H deposits are the most proximal deposits of this facies association, constituting 12 meters of core. In the middle of the thick proximal mouth bar succession a 30 cm thick bed with coarse-grained M1 tidal channel deposits are interpreted (4096.5 – 4096.8 m). The FA1 interval ends at 4090.1 m depth.

4.2.1.2 Interpretation

The lower of the two large-scale coarsening-upward sequences of FA1 is interpreted to reflect progradation which results in shelfal sediments being overlain by offshore transition zone/prodelta deposits. The smaller, 2-3 m scale coarsening-upward sequences seen in both these facies may be interpreted as stacked parasequences (J. Van Wagoner et al., 1988). The dominance of bioturbation in both facies, with the corresponding lack of preserved sedimentary structures, may indicate that the progradation took place in a basin where wave energy was low, as strong currents are needed to generate sedimentary structures in the water depth of the offshore transition zone (Clifton, 2006).

The interpretation of the entire FA1 as a prograding delta front succession is built on the interpretation of the upper of the two coarsening-upward sequences. The facies constituting this sequence have been interpreted as prograding, tidally modulated distributary mouth bars. The distal bar facies (F) is interpreted in an interval where the wireline logs demonstrate a very clear shale-separation on the density/neutron logs in addition to high gamma ray values (see Fig.6.2). This reflects a combination of the heterolithic nature of the facies and its mica content, as high gamma ray values may also be triggered by high concentrations of mica and other radioactive minerals in sandstone (H.G. Reading & Levell, 1996). It is believed that the erosional surface separating the distal mouth bar facies from the prodelta sediments was created by current scour as the mouth bar prograded (Boyd et al., 2006).

The uppermost part of FA1 is characterized by the coarser proximal part of the mouth bars, which is also incised by a tidal channel fill. This is expected as the distributaries reaching the shoreline diverge around their mouth bars, and thus the delta front will in places be dissected by channels where tidal currents may protrude into the delta plain. The interpretation of the upper coarsening-upward sequence of FA1 as tidally modified mouth bars may also explain a few features down-section, such as transported mud clasts in prodelta sediments. In addition, the condensed section occurring within the prodelta deposits may be related to delta lobe shifting. Such a shift may have significantly reduced sediment input in this area, and the condensed section may therefore correspond to a significant amount of time.

4.2.2 Facies Association 2: Lower Delta Plain

4.2.2.1 Description

Facies Association 2 (Fig.4.1B) is built up of tidal flat facies, comprising subtidal flats (K1) and intertidal flats (K2), and of channel facies comprising tidal channel fills (M1), abandonment fills (M2) and fluvial-dominated channel fills (M3). FA2 overlies FA1, with the transition defined at a tidal channel incision that brings an end to proximal mouth bar deposition in this well. The total thickness of FA2 is 34.1 m, between 4056 and 4090.1 m depth. It can be demonstrated both in the Fig.5.2 and Fig.6.2 that FA2 exhibits a serrated gamma ray pattern that moves toward less serration and, on average, lower values upwards. A change upward is also indicated by the density/neutron logs, where a transition from overlapping curves in the lower parts to a clear negative separation of the curves is seen.

The responses in the wireline logs are caused by changes seen in the facies stacking within this facies association. In the lower 12 m of FA2 the dominant feature are thick successions of tidal flat facies with the tidal channel- and abandonment fills occurring as sets of seldom more than a half meters thickness. Near the base of FA2 the tidal channel sands scour bioturbated subtidal heteroliths, with the thickest succession of heteroliths preserved being around one meter. The tidal flats change character up-section, with more sandy and less bioturbated intertidal flats replacing the subtidal flats. The thickest succession of intertidal sands between two tidal channel sands is 3.5 m thick.

The sandier upper 32 m of FA2 are dominated by thick successions of erosive based, fining-upwards and dominantly trough-cross bedded channel fills. Mostly these are tidally influenced channels, as several indicators of tidal processes are present both in the coarser parts and in the upper channel fines. In the uppermost 4.5 m of FA2 none of these indicators are present, which leads to this interval being interpreted as dominated by fluvial deposition. It should also be mentioned that a muddier, bioturbated interval 1.5 m thick interpreted as a channel abandonment fill occurs within the tidal channel deposits of FA2.

4.2.2.2 Interpretation

The association of tidal flats, small scale channel units and larger distributary channel sequences is likely in a lower delta plain setting (H. G. Reading & Collinson, 1996, p. 206). The lower delta plain is a depositional environment sloping very gently seaward proximal of the delta front. A distinct vertical development is demonstrated in FA2 and is visible in Fig.4.1B. As mentioned, domination of subtidal flats is replaced by domination of intertidal flats, before thick successions of channel sands follow. This is the natural development for a prograding lower delta plain.

As deltas by definition are protuberances into a standing body of water, the delta plain is at its widest along strike near the delta front. A subtidal environment with large subtidal flats is likely to have existed proximal to the delta front where the tidally reworked mouth bars were deposited. The subtidal flats were locally scoured by tidal channels. The main tidal inlets in a tide-dominated delta can remain quite stationary through time, and may have been located elsewhere on the delta plain relative to where this well penetrates the succession, as the channel sands are thin here. The more heavily bioturbated abandonment facies were deposited in depressions left behind when a channel was abandoned, and finer-grained sediments were able to accumulate until the surface equilibrated with the rest of the subtidal flat. Progradation of the lower delta plain causes intertidal sediments to overlie the subtidal. The thin tidal channel sands seen in this environment are possibly related only to ebb-currents as the flat was drained subsequent to high tide conditions. The total dominance of channel facies in the upper interval of FA2 reflects that this part of the lower delta plain either was dominated by stable distributaries or that it did not include significant tidal flats or interdistributary facies. As the delta plain progrades it is also a natural development that tidal influence in the channels weaken, and that deposits take on a purely fluvial character.

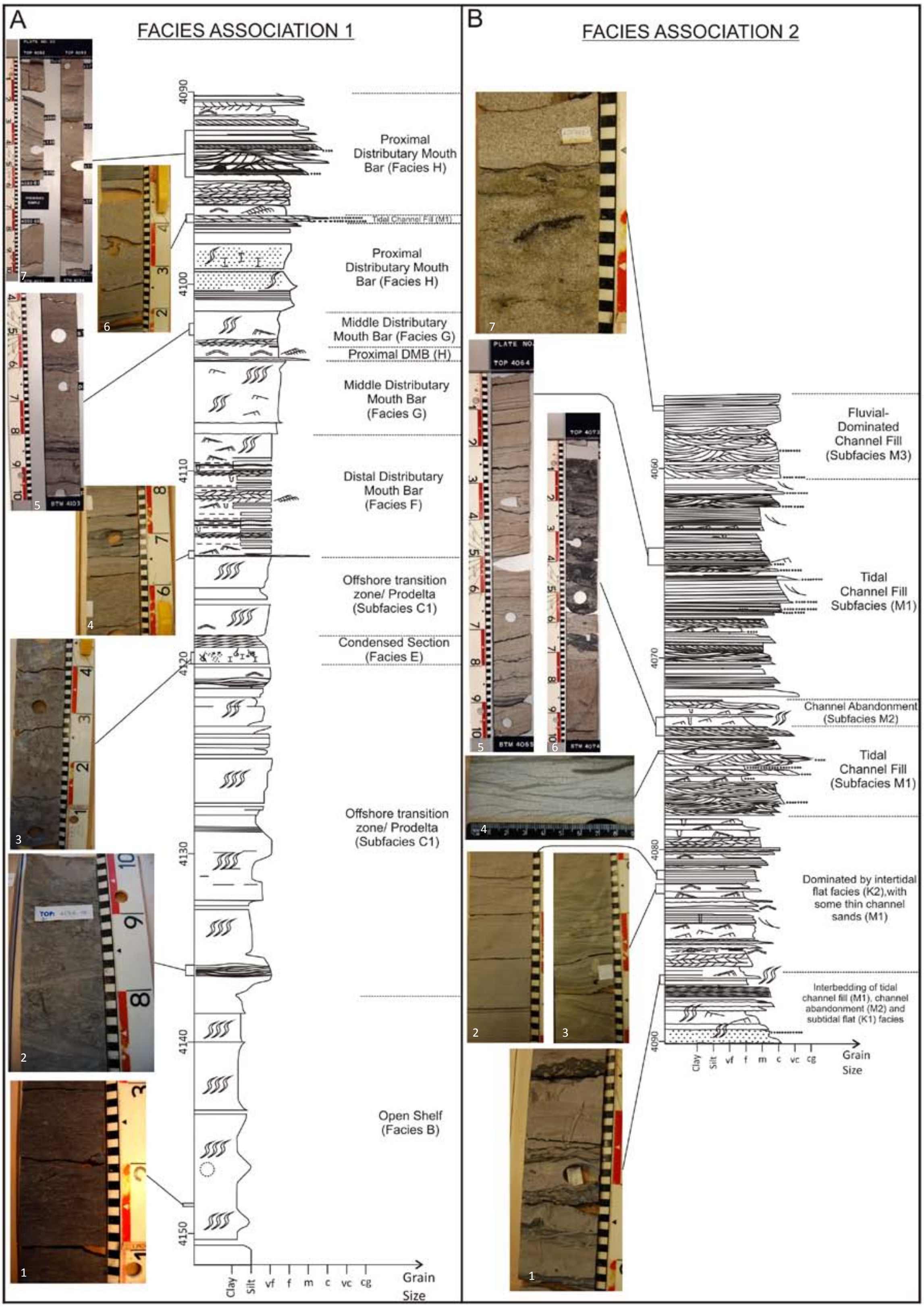

Figure 4.1*A*: FA1, prograding offshore to delta front. *Pictures:* 1: Bioturbated mudstones of the shelf (facies B). 2: Remains of HCS in bioturbated offshore transition zone (subfacies C1). 3: Part of the condensed section; carbonate cemented, shell-rich and with chamositic nodules (facies E). 4: Distal mouth bar heteroliths (facies F) sharply overlying bioturbated prodelta (subfacies C1). 6: Bioturbated fine sands and muds of the middle mouth bars (facies G). 7: Bidirectional cross-bedding of a tidal channel (subfacies M1) within a proximal mouth bar succession (facies H). 8: Sharp-based FU proximal mouth bar (facies H).
Figure 4.1*B*: FA2, lower delta plain. *Pictures:* 1: Subtidal flat deposits (subfacies K1). 2/3: Sand-dominated planar-laminated and ripple cross-laminated deposits from an intertidal flat setting (subfacies K2). 4: Double draped bidirectional current ripples from fine-grained upper-channel fill (subfacies M1). 5: Mud-draped cross-beds in a tidal channel (subfacies M1). 6: Bioturbated and mud-enriched channel abandonment facies (Subfacies M2). 7: Transported organic material in a fluvial-dominated channel sand (subfacies M3) (partly modified from Norwegian Petroleum Directorate web pages, 2010).

4.2.3 Facies Association 3: Backstepping Delta Plain

4.2.3.1 Description

FA3 (Fig.4.2A) conformably overlies FA2 at 4056 m depth, where the channel sands go from being fluvial-dominated to again showing signs of tidal current activity. Along with the three meters of tidal channel fill (M1) at the base, this 12 m facies association consists of around eight meters of intertidal flat deposits (K3) and a meter of transgressive reworked deposits toward the top at 4044 m depth.

Towards their upper boundary the tidal channel sands become coarser and contain several coarse lags, before they are sharply overlain by the distinctly finer grained sands of the intertidal flat. This subfacies show a fining-upwards trend together with a clear decrease in burrow size. At 4045 m depth a sharp erosion surface is overlain by a meter showing interbedding of coarse grained thin beds and lenses of sand together with dark, fine-grained sediments similar to those seen in facies A which overlies FA3.

From Fig.5.2 and Fig.6.2 it seems that FA3 is characterized by increasing gamma ray values and a decrease in the negative separation of the density and neutron curves upwards.

4.2.3.2 Interpretation

The opposite development to the one seen in FA2 is interpreted for FA3. The changes observed in core are interpreted as a response to initial transgression. This would allow for tidal currents to protrude further up the distributaries than before, and fluvial dominance would be suppressed. After a time of tidal channel deposition the delta plain was further flooded, leading to extensive tidal flats covering the area again. Based on the general fining-upwards trend with decreasing burrow length seen in the intertidal flat deposits at this level it is suggested that although there was an overall transgression, normal regression occurred intermittently. At a certain point in time the final transgression of the delta plain occurred, and a sharp erosion surface was cut by wave ravinement and overlain by a meter thick zone of transgressive lags.

4.2.4 Facies Association 4: Prograding Offshore to Lower Shoreface

4.2.4.1 Description

FA4 (Fig.4.2B) passes conformably from FA3 below and consists of three facies/subfacies, which from the base and upwards are conformably stacked in the order offshore black shales (A), offshore transition zone with distal tempestites (C2) and lower shoreface (D). The FA4-interval is around 33 m thick, starting at 4044 m depth and ending abruptly at a sharp erosion surface at 4011.05 m, and the core displays several stacked coarsening-upward cycles (Fig.6.2).

The wireline logs of this facies association show a varied pattern, see Fig.5.2 and Fig.6.2. An average decrease in gamma ray values upwards is seen, noting also that there are two peaks of high values within the offshore transition zone subfacies. In terms of density/neutron trends, the three facies constituting FA4 each have characteristic appearances in well 6506/12-1. The offshore black shales show very high neutron and corresponding low density readings. The overlying offshore transition zone sediments show a general decrease in positive separation of the two logs when moving up, and the lower shoreface continues this trend by having largely overlapping log values. From both wireline logs and the deposits themselves five smaller scale coarsening-upwards sequences are possibly discernible.

4.2.4.2 Interpretation

Following the backstepping and final transgression of the delta plain recorded in FA3, FA4 records a progradational trend which is visible both as stacked coarsening-upwards bedsets in core and from the wireline logs. It is evident from the nature of the facies present in FA4 that the transgression was significant and that true offshore conditions prevailed in the times that followed. The succession in FA4 is interpreted as normal shoreface progradation. Deposition of offshore black shales of facies A in a oxygen-poor environment ended when waters again became re-oxygenated, and shoreline progradation lead to a thick succession of offshore transition zone sands and silts being deposited. As discussed in chapter 3, the degree of bioturbation compared to the relatively thin storm beds suggests that storms where not a dominant factor in the basin. The offshore transition zone is conformably overlain by sandier lower shoreface deposits (facies D) by continued progradation of the system.

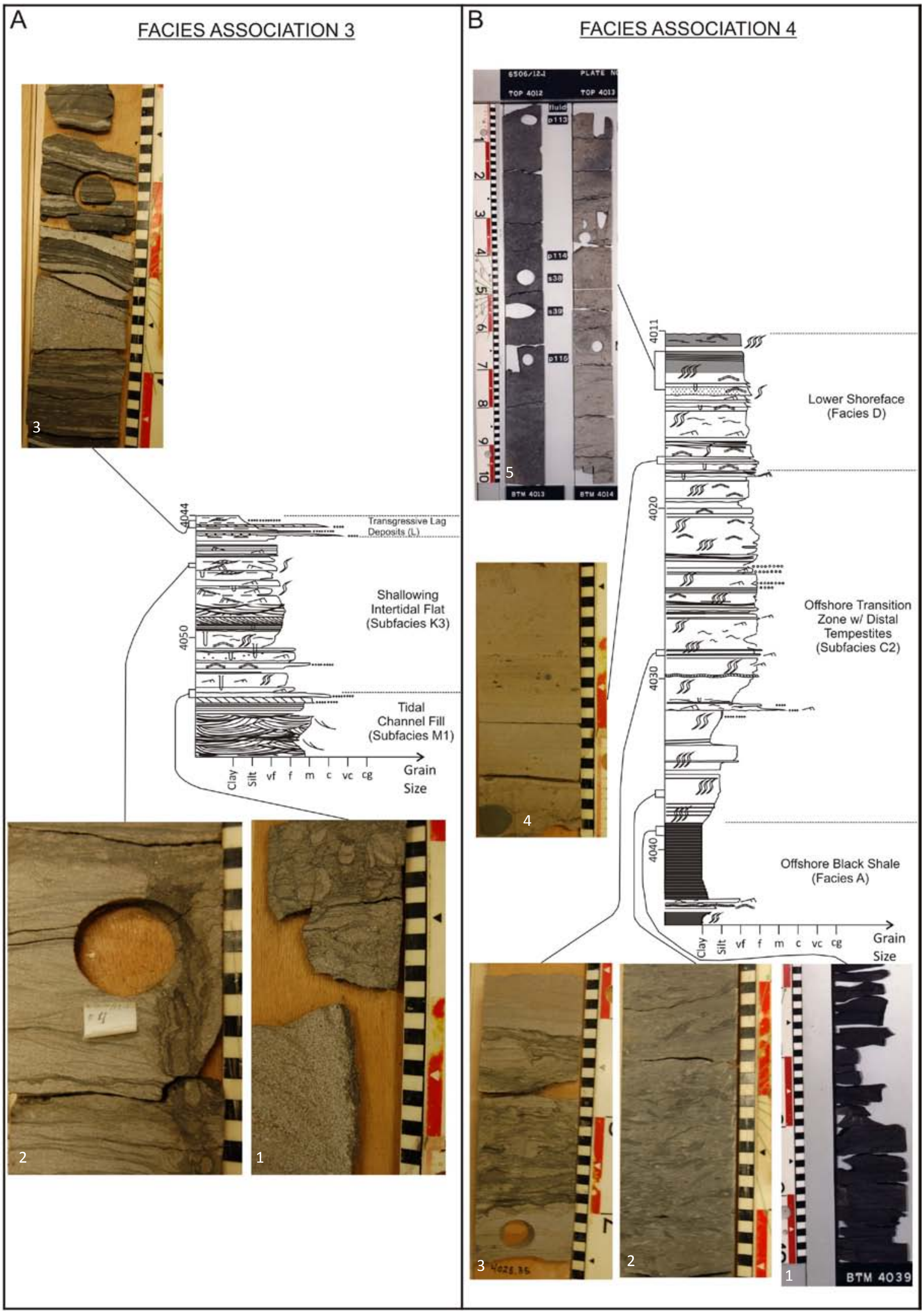

Figure 4.2*A*: FA3, backstepping delta plain. *Pictures:* 1: The sharp surface separating underlying tidal channel fill (subfacies M1) from overlying shallowing intertidal flat deposits (subfacies K3). 2: Example of the bidirectional mud draped current ripples and the characteristic *Diplocraterion* traces of the intertidal flats (subfacies K3). 3: Coarse beds and lenses in muddy matrix in the transgressive lag deposits (facies L). Figure 4.2*B*: FA4, prograding offshore to lower shoreface. *Pictures:* 1: Offshore black shales (facies A). 2: Bioturbated offshore transition zone deposits (subfacies C2). 3: Example of the thin event beds interrupting the bioturbated sequence (subfacies C2). 4: Planar laminated and bioturbated lower shoreface (facies D). 5: Upper part of the lower shoreface interval (facies D), where deposits change color due to heavy mineral accumulation (partly modified from Norwegian Petroleum Directorate web pages, 2010).

4.2.5 Facies Association 5: Braid Delta Complex

4.2.5.1 Description

FA5 (Fig.4.3) is the uppermost facies association of well 6506/12-1, and constitutes a total thickness of 36 m from 4011.05 m to 3975 m depth. The interval is built from two facies, which in order from the base upwards are the braid delta bar complex (I) and flooded braid delta (J). FA5 shows a characteristic signal in the wireline logs, see Fig.5.2 and Fig.6.2. The gamma ray generally looks blocky and has low values, but some subtle trends are visible. The gamma ray values for facies I shows a very slight increase upward, whilst some high value peaks appear when entering facies J deposits. Further up this flooded braid delta in fact shows a clear decrease in gamma ray values, with a low value peak just at the top. The density/neutron shows a clear negative separation, except for a more varied signal in the lower part of facies J.

From a sharp and erosional base at 4011.05 m, the generally medium-grained and trough cross-bedded sands of the braid delta bar complex fine slightly upward to a sharp surface 20 m up-section. Here, at 3990.9 m, a flooding is marked by a few thin mud beds. The flooded braid delta facies continues for almost 16 m, and exhibits a varied character as described in chapter 3.

4.2.5.2 Interpretation

FA5 unconformably overlies FA4, as the facies transition seen from lower shoreface sands to a braid delta bar complex records a significant shallowing in water depth. The thick succession of trough cross-bedded sands in facies I seem to suggest that the braided fluvial system was deposited in a braid delta that partly prograded and partly aggraded. The interpretation of a significant aggradational component is further strengthened by the facies change that divides FA5 into two almost equally thick units. A transgression of the delta at this level led to the development of more marine conditions, possibly with embayments existing on the flooded delta top as a consequence of the transgression reworking some of the fluvial sands into barriers. The braided river system would backstep and still deposit bars in a more proximal location, whereas renewed progradation of the braid delta explains the shallowing- and coarsening-up seen in facies J in the upper half of FA5.

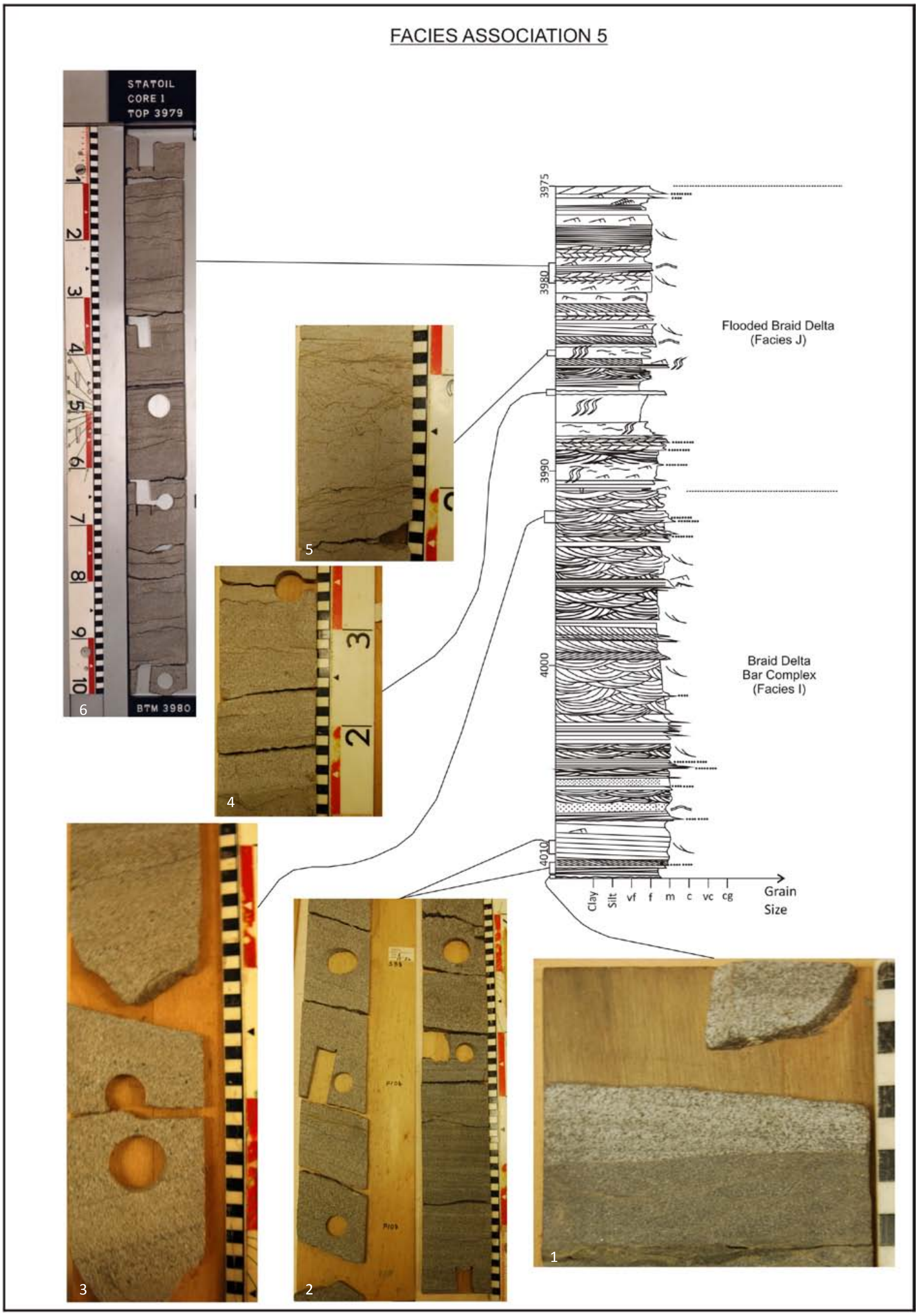

Figure 4.3: FA5, braid delta complex. *Pictures:* 1: The sharp, erosive surface separating FA5 from lower shoreface sediments of FA4 below. 2: The lowermost part of the braid delta bar complex (facies I), with planar- to low-angle cross-stratification. 3: Trough cross-bedded sands of the braid delta bars, here with normal graded foresets (facies I). 4: 20 cm thick erosional medium-grained sand within fine-grained, bioturbated delta front sands (facies J). 5: *Trichichnus* bioturbation in the flooded braid delta (facies J). 6: Mud draped herringbone cross-lamination and planar parallel stratification developed on the flooded braid delta (facies J) (partly modified from Norwegian Petroleum Directorate web pages, 2010).

5 Sand body Geometry

5.1 Introduction

The interpreted facies and facies associations of well 6506/12-1 has shown a wide range of depositional environments in which sand has accumulated on the Halten Terrace in Mid-Jurassic times. For regional understanding it is useful to investigate the geometries of these sand bodies. This chapter comments on possible geometries and lateral extents of depositional environments. A correlation of the investigated well with two additional wells is performed; these are 6506/11-6 of the Kristin Field and 6506/11-8 of the Morvin Field (Fig.5.1). The correlation panel is presented in Fig.5.2. The correlation is based on similarities in wireline log signals and on core photos in the case of well 6506/11-6, but regrettably no core photos are available of well 6506/11-8. The quality of core photos available on the web pages of the Norwegian Petroleum Directorate is generally quite good, but facies recognition based solely on photographs and wireline logs will always increase uncertainty and the risk of misinterpretation.

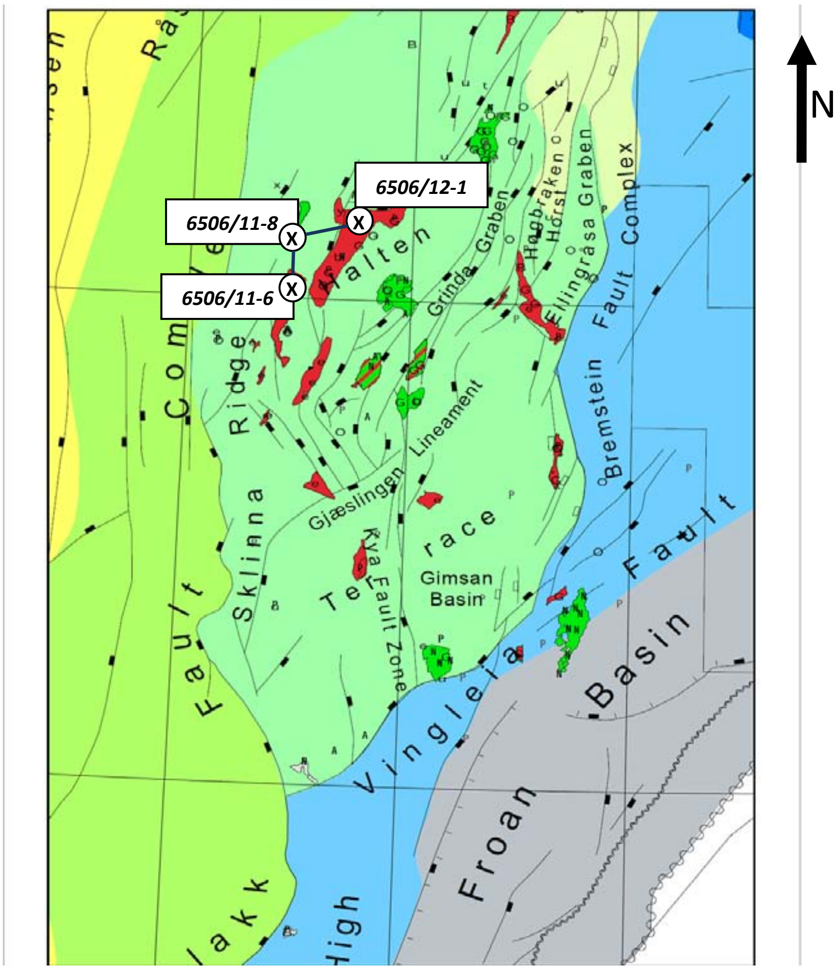

Figure 5.1: Map of the Halten Terrace showing the location of the location of the correlated section from the north-eastern well 6506/12-1 to the south-western well 6506/11-6 (modified from a figure made by Ryseth (Statoil), 2010).

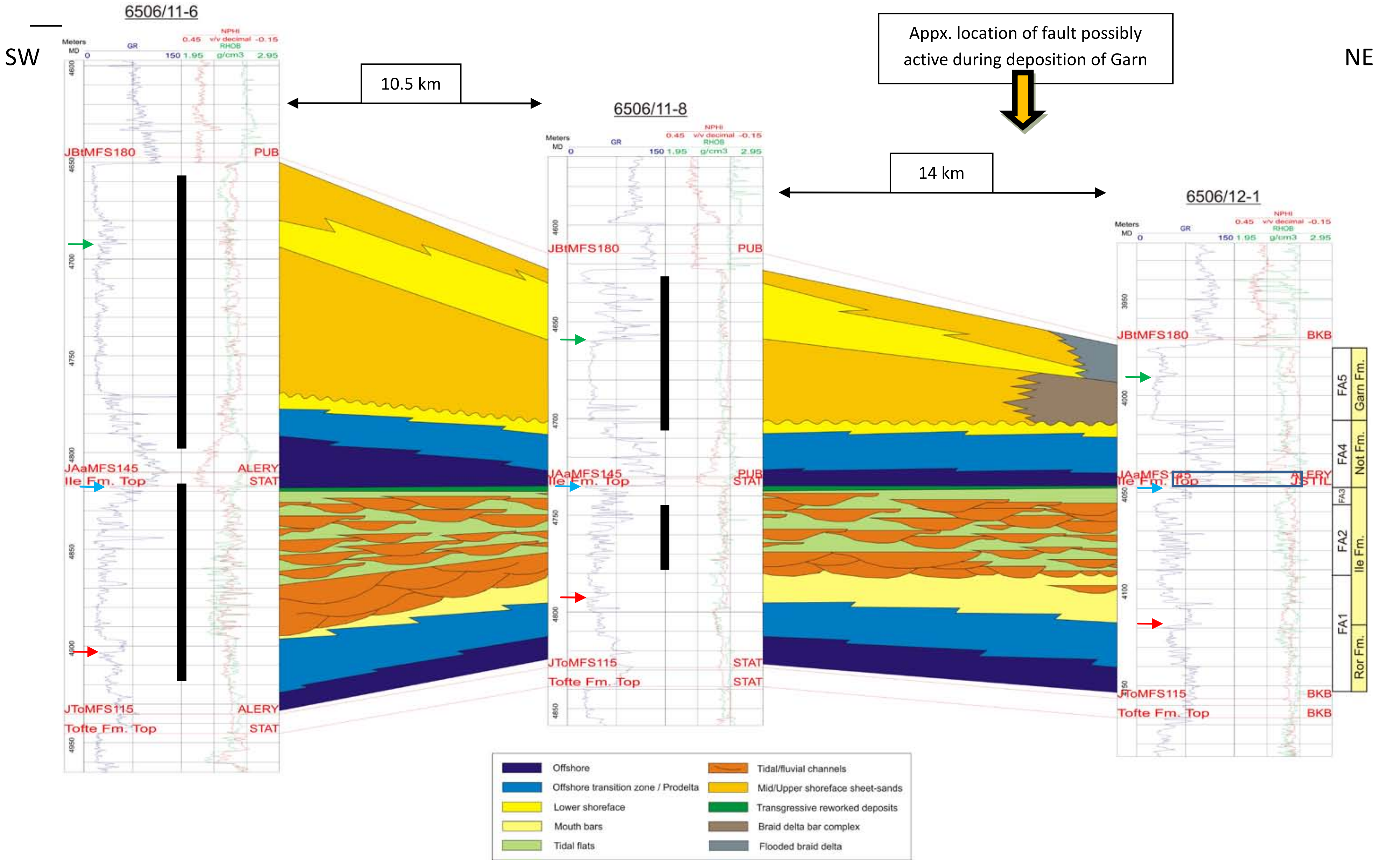

Figure 5.2: Correlation panel showing the lateral facies trends in a 25 km NE-SW transect on the Halten Terrace, flattened at Top Ile level. Well 6506/12-1 is the basis for the interpretation of facies and facies associations in this thesis, and to the right of its wireline logs the facies associations and the different formations of the cored interval are indicated. The cored intervals in the two other wells are indicated black bars along the centerline of their respective wireline panels (approximation for 6506/11-8, from Norwegian Petroleum Directorate web pages, 2010).

5.2 Correlation

5.2.1 Observations and description

FA1, at the base of the interpreted succession, displays a similar succession of facies in 6506/11-6 as in the 6506/12-1, with offshore mudstones approximately 14 m thick gradually coarsening-upward into offshore transition zone or prodelta silts and sands which attain a thickness of almost 22 m. The condensed section of shells and cement observed in well 6506/12-1 is not seen in well 6506/11-6. At one point the gamma log shows an abrupt increase in the radioactive signal in all three wells (red arrows on gamma logs in Fig.5.2), corresponding to an increase in fine-material in the prodelta interval just beneath the mouth bar sands in well 6506/11-6 (see black arrow in Fig.5.3) and the mouth bar heteroliths in well 6506/12-1. This sudden fining may represent a timeline along the transect. Mouth bars are much less developed in well 6506/11-6 compared to 6506/12-1, as only a few meters of proximal mouth bar facies separates the prodelta fines from thick channel sandstones above. Well 6506/11-8 on the other hand seems to have some development of mouth bars indicated by a similar coarsening-upward gamma-ray pattern as seen in well 6506/12-1.

Figure 5.3: Prodelta fines abruptly overlain by mouth bar sands (boundary not seen, but the two core meters on the left are interpreted as mouth bar sands). Black arrow indicates base of sudden fining of prodelta sediments in well 6506/11-6, core depth 4888-4893m (Norwegian Petroleum Directorate web pages, 2010).

FA2, the lower delta plain facies association, seems to be well developed in all wells. This is confirmed both in core photos and by similar serrated gamma ray patterns. A relative thickening of the facies association in well 6506/11-6 is observed, as it is roughly 60 m thick here compared to the 34 m seen in well 6506/12-1. The lower part of the interval in well 6506/11-6 is entirely dominated by channel sandstones (Fig.5.4A), a trend which seems to diminish moving northeastward. As is indicated in the correlation in Fig.5.2, 6506/11-6 contains an increasing amount of tidal flat deposits upward through the facies association, contrasting the development in 6506/12-1 where channel sands are increasingly dominant upward. The middle 6506/11-8 well displays a higher amplitude serration of the gamma ray curve than the other two wells, suggesting more dominant successions of heterolithic tidal flat deposits in this well. In all three wells a fining-upwards trend approximately ten meters thick indicates the presence of FA3, capped by a distinct low-gamma peak (blue arrow in Fig.5.2) representing the transgressive reworked deposits (Fig 5.4B).

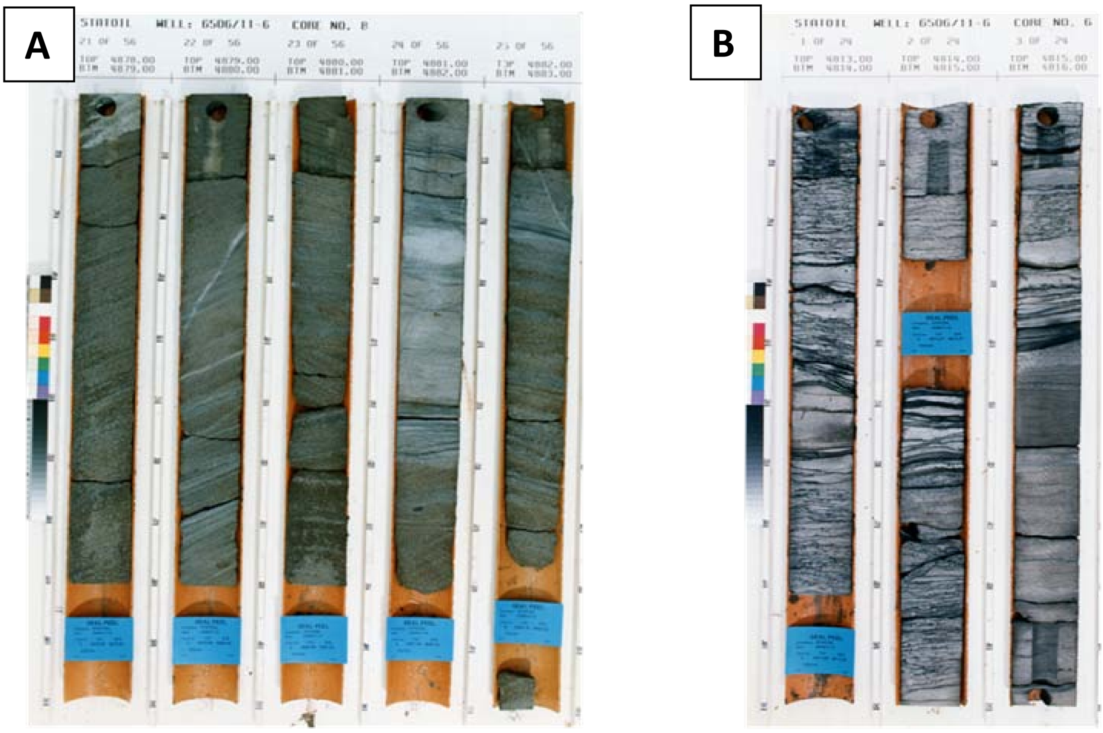

Figure 5.4*A;* Thick accumulations of channel sandstones in the lower part of FA2 in well 6506/11-6, 4878-4883 m. *5.4B;* 2.5 meters of transgressive reworked deposits in well 6506/11-6, 4813-4816 m depth (Norwegian Petroleum Directorate web pages, 2010).

FA4 shows the same prograding development from offshore to lower shoreface conditions in all three wells. The black shales in well 6506/12-1, indicated by very low density and correspondingly high neutron readings (blue square in Fig.5.2), are probably not present in the two other wells as the basal interval of FA4 in these wells are indicated by more usual positive shale separation on the wireline logs in question. The logs also indicate a thicker interval of offshore mudstones in the southwestern 6506/11-6 well, roughly 25 m thick compared to the 6 m in 6506/12-1.

FA4 is in all three wells abruptly overlain by FA5 sandstones, displaying a easily recognizable blocky gamma-ray pattern. The gamma-ray jump when going from FA4 into

FA5 is much less pronounced in well 6506/11-6 than in 6506/12-1, with 6506/11-8 as an intermediate. FA5 thickens quite distinctly moving southwestward. In all wells a tripartite division of the facies association is visible. The lower blocky interval is correlatable across the section, but in terms of facies there seems to be a difference. From examination of core photos (Fig.5.5A) from well 6506/11-6 the interval may be characterized by finer grain size and a much higher degree of grain size sorting than in well 6506/12-1, which is also reflected in the less pronounced negative density/neutron separation. The wireline patterns for well 6506/11-8 are similar to the ones in 6506/11-6, so similar deposits are inferred in that location.

In well 6506/12-1 a transgressive event that flooded the braid delta plain was interpreted half way through FA5 (green arrows in Fig.5.2). This flooding is much less pronounced in 6506/11-6 to the southwest; in core it is only seen as a minor fining in overall grain size and the occurrence of a few burrows, possibly of *Ophiomorpha*-type (Fig.5.5B). In contrast, this transgressive event seems to have resulted in a much finer-grained deposits in well 6506/11-8, evident from the thick interval of interchanging high and low gamma ray values and overlapping density/neutron curves. The uppermost interval of FA5 in well 6506/11-6 s characterized by a new blocky gamma ray signal, which seem to correlate with a thinner but similar interval in well 6506/11-8. The corresponding interval in well 6506/12-1 has a less blocky and more coarsening-upward type of motif, and as for the lowermost interval of FA5 this difference corresponds to facies changes along the transect.

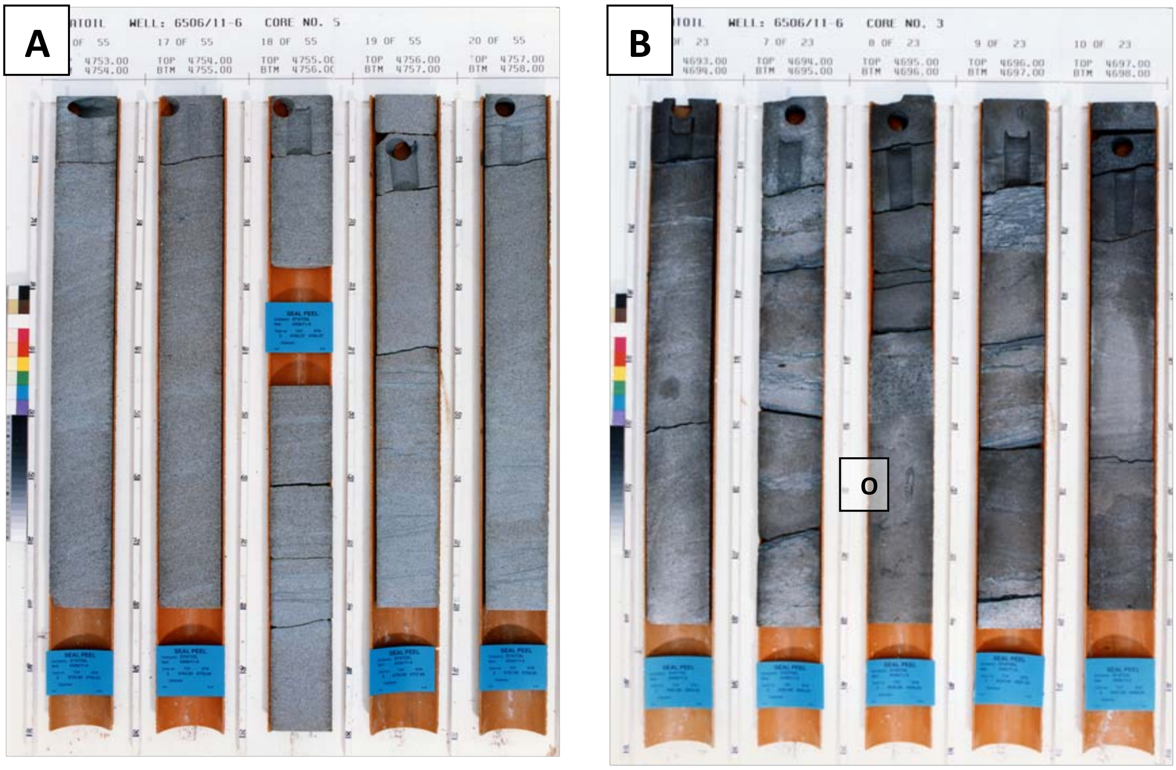

Figure 5.5*A;* Section of the thick well-sorted cross-bedded sands observed in the lower interval of FA5 in well 6506/11-6, core depth 4753-4758 m. *5.5B;* The only effect of transgression seen in well 6506/11-6 is a slight fining in overall grain size and the appearance of a few burrows, as the *Ophiomorpha* trace fossil (O). 4693-4698 m (Norwegian Petroleum Directorate web pages, 2010).

5.2.2 Interpretation

What is evident from the observations above is that sand bodies are largely correlatable along this transect. However, this is not always the case for the depositional environments responsible for deposition of the sand. This affects the sand body geometries within the Fangst Group. Based on the facies associations and the observations made when correlating their development along the cross section it is interpreted that for most of the time during deposition of the Fangst Group this transect is oriented roughly along shoreline strike, with well 6506/11-8 situated somewhat distal to the other two wells. The following sections will attempt to explain this interpretation, and the lateral variations seen along the transect.

5.2.2.1 The sands of the Ile Formation

According to Dalland et al. (1988), the boundary separating the Fangst Group from the underlying Ror Formation is differently expressed in different wells, but is either defined at the base of a generally coarsening-upward cycle, where lithology changes from dominantly siltstone to sandstone, and/or in a transitional interval containing one or more carbonate-rich beds. As the condensed section (facies E) observed in well 6506/12-1 is not developed in well 6506/11-6, the ambiguity of defining the base of the Ile Formation based on this is demonstrated. Karlsson (1984) advocates that this condensed interval is recognized across most of the Halten Terrace and thus should represent the base of the Fangst Group. This view is not supported in this thesis as it seems more natural to pick the transition from prodelta fines into mouth bar deposits as the transition from the Ror Formation into the Ile Formation, and thus the base of the Fangst Group. In well 6506/12-1 the base is defined at 4114.4 m depth, just above the red arrow in Fig.5.2 and at the base of a distinct coarsening-upward trend interpreted as mouth bar progradation. In well 6506/11-6 the base of the formation may be picked at the sharp decrease in gamma ray values, interpreted as the transition from prodelta sediments to mouth bar sands. As mentioned above, the mouth bar facies in this well are rather poorly developed compared to the main study well, and the mouth bar sands are sharply overlain by thick channel sands. The explanation for this difference may lie in the interpretation of the Ile Formation as a tidal delta prograding over shelfal and prodelta sediments of the Ror Formation. Much like in a tide-dominated estuary, a partitioning of the delta may occur where one or more channels in a certain part of the delta acts as the main flood tidal channels, whereas a different area on the delta is dominated by ebb tidal channels. In the area dominated by flood tidal currents, mouth bar deposits are poorly developed due to the suppression or complete absence of river discharge and the constant reworking by inflowing flood tidal currents. The much better developed mouth bars in well 6506/12-1 may reflect a dominance of ebb tidal- and fluvial currents in this location, with large amounts of sediment being fed to the basin. A described modern analog possibly showing similar behavior is the Fly River delta in Papua New Guinea (Dalrymple et al., 2003). In this tide-dominated delta it has been noted that since the main distributary shifted to the southern margin of the delta in 1990, the abandoned and now purely tide-dominated channel to the far north (Fig.5.6) has developed a low-relief channel form which extends tens of km seaward of the delta front. The erosion required to develop such a feature may have completely removed formerly deposited mouth bars. McIlroy et al. (2005) noted that the depth of erosion at the contact between mouth bars and their feeder channels control the preservation potential of mouth bars in the Mid-Jurassic Lajas Formation of Argentina. In addition, McIlroy (2004a) suggests that low preservation potential of mouth bar facies may be related to progradation of the delta into a low-accommodation basin, as this leads to increased tidal channel cannibalization of their own mouth bars.

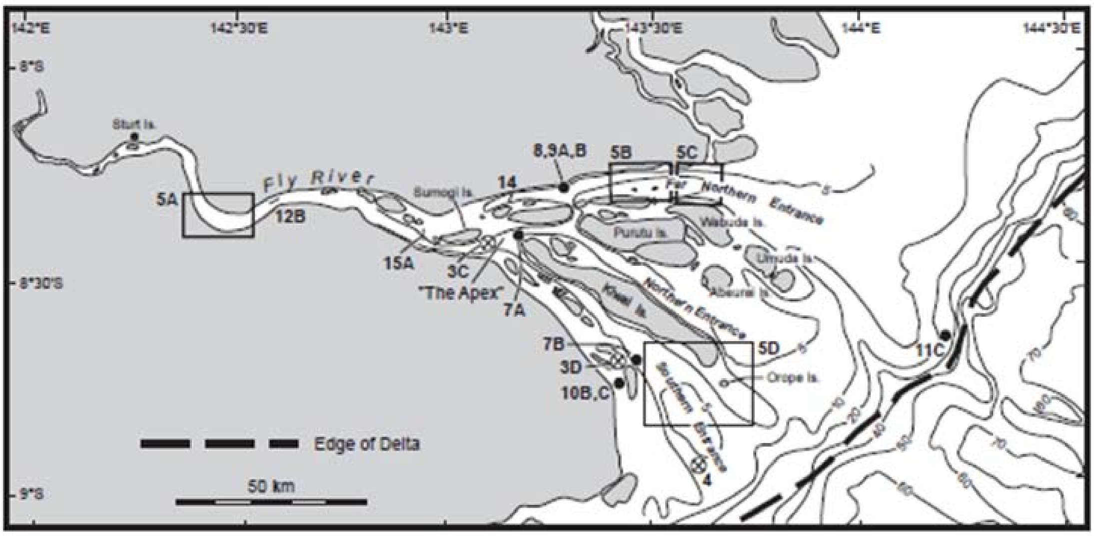

Figure 5.6: The Fly River delta in Papua New Guinea (from Dalrymple et al., 2003). The main distributary has since 1990 been through the "Southern Entrance", leaving the "Far Northern Entrance" blind to the fluvial system and purely dominated by tides. In this tidal entrance a channel feature extending far out from the delta front, its margin indicated by the line marking 5 m water depth at the northern termination of the delta.

Tidal processes commonly dissect distributary mouth bars, and may elongate them perpendicular to the shoreline. They also result in greater winnowing of distributary channels, and may stabilize them for considerably longer periods than typical for terminal distributary channels in river-dominated deltas. This may lead to significantly more elongated bars and bar assemblages than in non-tidal settings (Bhattacharya, 2006). If the partitioning of ebb- and flood dominated channels on the delta plain is the case, a result will be an asymmetric delta front where the strongest progradation occurs where mixed fluvial- and ebb-dominated tidal channels fill the basin with mouth bar deposits. An indication of such a development is the fact that channel sandstones increase in abundance through time in well 6506/12-1, and are even interpreted as dominantly fluvial for a significant time interval, whereas in the two other wells channel sands decrease in abundance through time. The development of thick tidal flat successions in all wells may indicate that the delta development in the Ile Formation was in large parts aggradational to keep pace with rising sea level. The preservation of tidal flat succession may also indicate that tidal- and fluvial channel meander belts did not migrate across the whole width of the delta plain (McIlroy et al., 2005). Backstepping of the delta is likely to have occurred in the uppermost Ile Formation, where FA3 is similarly expressed in all wells.

The interpretation of the Ile Formation as a prograding tidal delta is advocated by other authors (e.g. Martinius et al., 2005). Analogs of such tide-dominated deltas are found both in modern environments and in ancient successions. Examples of the former are the Mahakam River delta on the eastern margin of the island of Borneo, Indonesia, and the already mentioned Fly River delta. The Mahakam is a prograding delta with a combined size of delta plain wetlands, subaqueous delta front to prodelta environments of approximately 4000 km^2. It contains a high number of channels and largely the same facies as interpreted in the Ile Formation (Gastaldo et al., 1995; Gastaldo & Huc, 1992). As imagined for the Mid-Jurassic delta on the Halten Terrace, the Mahakam also shows different channel development in different parts of the delta. A few channels are dominated by fluvial discharge whereas some are only hosting tidal current activity and are largely blind to the fluvial system (Fig.5.7). In their study of the Fly River delta, Dalrymple et al. (2003) describes a prograding prodelta to distributary mouth bar succession which exhibits very similar characteristics as the prograding delta front seen in the cores of the Ile Formation in 6506/12-1. Their description includes bioturbated muds and sands of the prodelta which pass upward into bioturbated heteroliths of the delta front and finally into cleaner mouth bar sands with decreasing amount of mud layers upward.

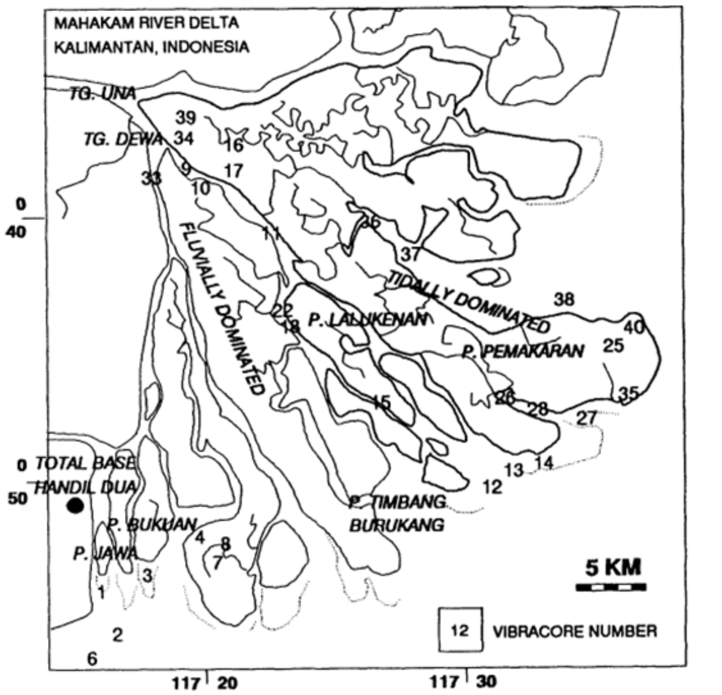

Figure 5.7: The Mahakam fluvial-tidal delta of Borneo, Indonesia, gives an idea of what the Ile delta system may have looked like.. A few large distributaries are dominated by fluvial discharge while the rest of the channels are dominated by tidal processes and are largely blind to the fluvial system. The stippled lines indicate tidal flats. As envisioned for the Ile Formation, the different processes dominating different parts of the delta leads to asymmetric delta development. (figure from Gastaldo & Huc, 1992)

5.2.2.2 The sands of the Not and Garn Formation

Transgression across the Ile tidal delta initiated deposition of offshore sediments across the study area, deposits belonging to the Not Formation. From wireline logs is seems that the thickest offshore shales accumulated in the southwestern 6506/11-6 well, perhaps due to larger subsidence here. It is therefore interpreted that the shoreline progradation seen within the Not Fm. is directed from the two other wells toward well 6506/11-6. The sands in the lower shoreface constitute long, shoreface-parallel sand bodies.

Entering the Bathonian a change must have taken place which caused the normal regressive shoreface of the Not Formation to be overlain by varying thicknesses of Garn Formation sands. The blocky gamma-ray signal of these sands can be recognized across the whole of the Halten Terrace. In well 6506/12-1 the lowermost interval in the Garn Formation is interpreted as amalgamated fluvial channel sands deposited in a braid delta. From the appearance of the sands in well 6506/11-6 it is suggested that this braid delta is not responsible for deposition of the entire Garn Formation. In 6506/11-6 and 11-8, the generally finer-grained and better sorted sands bear resemblance to sands deposited in shallow water, reworked by a combination of tides and waves. It is therefore suggested that the sands in these two wells originate from the fronts of braid- and fan deltas along the basin margin that were picked up by longshore currents and tides and reworked and deposited in a mid/upper shoreface type of setting.

Several lines of evidence support this interpretation. One of the explanations for thickness increase west and southwest of well 6506/12-1 is that more accommodation space was available for thick successions of these shallow-marine sheet sands to accumulate, while the braid delta was characterized by channel amalgamation and slower accumulation. However, a fact that maybe offers a more satisfactory explanation to the thickness- and facies differences in the Garn Formation is diachroneity. An integrated study of seismic, seismic attribute, core and biostratigraphic data in the Smørbukk-Smørbukk South area suggests a strong time- and facies-diachroneity for the Garn Formation, even over short distances of 5-10 km. It is also demonstrated that sediment dispersal and the stratigraphic architecture were influenced by faulting, and that fault-created basin physiography in Early-Mid Jurassic in the area of the Smørbukk Field may have been significant (Corfield et al., 2001). Due to active faulting prior to- and during Garn deposition there may have existed narrow, shallow seaways in the hanging walls and grabens throughout the Halten Terrace where material eroded from uplifted blocks were deposited and reworked by tides, waves and longshore currents. As the gamma-ray signal for well 6506/11-6 in Fig.5.2 shows a gradual decrease toward the Garn Formation it may indicate that the transition from the Not Formation was, if not completely, at least close to conformable. If this is true it may indicate that the Garn Formation initially was deposited in the central part of the elongated shallow sea and then started backstepping onto the horsts and footwalls of the area. This backstepping may have involved reworking of the fans and braided rivers that fed sediment to the initial basins, and explain that these are no preserved. Corfield et al. (2001) indicate that the lower sands of the Garn Formation onlap the structural highs such as the Smørbukk fault block, and therefore are limited to down-dip depocenters.

The faulting of the Halten Terrace probably led to footwall uplift of the Smørbukk area, which if it lead to subaerial exposure and erosion of this area concomitant with Garn deposition in well 6506/11-6 offers an explanation to why the gamma-ray log indicates a much more distinct break between the Not- and the Garn Formation in 6506/12-1, with the 6506/12-8 as an intermediate between the two. The Garn Formation simply did not accumulate in the Smørbukk area until later in the Bathonian. Gjelberg et al. (1987) concluded that Garn represents a series of “backstepping progradational clastic wedges” deposited in a shallow marine environment, and by this advocated the view that the Garn Formation is diachronous. Accumulation of what has been interpreted as braid delta deposits in 6506/12-1 may only have occurred in a time interval just before the mid-Garn transgression.

The mid-Garn transgression is demonstrated in both the deposits and in the wireline logs of all the wells. It is interpreted that the ocean protruded from the north-northwest, as well 6506/11-8 demonstrates a more serrated- and higher value gamma-ray curve than the other two wells. This may indicate a lower shoreface setting for 6506/11-8 at this time. The transgression led to flooding of the braid delta, and deposition of finer grained sand in a protected embayment setting evidenced by typical estuarine ichnogenera. Large amounts of sand were probably still fed to the basin, explaining the very subtle response to transgression seen in well 6506/11-6. The upper shoreface sheet sands must have prograded again following the transgression, reaching the distal 6506/11-8 well just before the area was flooded in what terminated deposition of the Fangst Group.

5.2.2.3 Discussion

The facies constituting the Ile Formation shows several features which seem to strongly indicate a progradational tide-delta environment. However, as the present study is mainly based on description and interpretation of the facies in one single well, 6506/12-1, a large scale environment assessment will be uncertain. The facies interpreted in the Ile Formation, which show many strong indications of tidal activity, could of course develop in a more estuarine type of setting. In fact, the development seen in 6506/11-6 (Fig.5.2) with thick channel sands more or less directly on top of marine deposits and an increasing amount of interdistributary facies upwards through the Ile Formation may resemble the creation of an incised valley which gradually fills and evolves into a tide-dominated estuary, as described by Boyd et al. (2006). If this was the case, the dissimilarity in facies stacking in 6506/12-1 might suggest that this well was not located within the initial estuary, but as the estuary filled it may have developed into a prograding tidal-delta that reached 6506/12-1. An argument against an estuarine interpretation of the Ile Formation, besides the arguments already presented for a tidal delta, is the fact that thick successions of tidal flat deposits have low preservation potential in estuarine systems due to the constant migration of tidal channels across the width of the estuary (McIlroy et al., 2005).

As can be imagined, an estuarine interpretation would lead to a very different model of the depositional setting and paleogeography of the Halten Terrace at the time of deposition of the Ile Formation. The interpretation of the Ile Formation as an estuarine system is an alternative and cannot be confirmed or ruled out in the present study. Based on the deposits in the Ile Formation in well 6506/12-1 and the correlation the interpretation of the formation as a tide-dominated delta is a sound interpretation. In structurally confined seaways as what may have existed on the Halten Terrace, tidal sediments are not restricted to incised valleys as the shape of the basin may allow for strong tidal activity, irrespective of what the base level is (McIlroy et al., 1999; McIlroy et al., 2005). This may have resulted in the large tidal influence of the delta in the Ile Formation.

The tidal delta in the Ile Formation seems to prograde out of the east or southeast due to the nature of the facies stacking in well 6506/12-1 combined the fact that 6506/12-8 seems to contain more fine-grained facies relative to channel sands based on the gamma-ray serration. In other words it is indicated that the shoreline during delta progradation at this stage was directed roughly N-S. This trend was preserved throughout deposition of the Fangst Group, as the 6506/11-8 seems to have remained the most distal of the three wells due to the interpreted lower shoreface deposition in this well location following mid-Garn transgression. A roughly N-S oriented seaway is also supported by the orientation of the Smørbukk Fault, which is NNE-SSW. This fault may have been active during Garn Formation deposition and could have confined the shallow seaway. In this shallow seaway backstepping of marine sandstones may onto the footwalls and horts of the area may have occurred.

6 Sequence Stratigraphy

6.1 Introduction

Sequence stratigraphy is a field of geology which by Van Wagoner's (1995) definition is *"the study of rock relationships in a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or non-deposition, or their correlative conformities"*. The grouping of facies interpreted in well 6506/12-1 into facies associations facilitates definition of important bounding surfaces in the well, and thereby the framework of the sequence stratigraphical development of the Fangst Group. An attempt is made to recognize the important bounding surfaces and the stacking patterns of bedsets or parasequences, as these are the fundamental building blocks of sequences of rocks and will delineate the transgressive and regressive trends of the Fangst Group. These transgressive/regressive trends are related to the balance between accommodation space and sediment supply, which in turn control relative sea-level changes. Sequence stratigraphy is a field of science with a large variety of interpretations and nomenclatures, and a thorough review of nomenclature is out of scope for this thesis. Also, the construction of systems tracts is seen as unnecessary as a study based on only one thoroughly described well will not contain enough information to confirm the systems tracts. It is deemed more fruitful to describe the development in terms of important surfaces and the transgressive and regressive trends that separate them. In any case, the definition of the bounding surfaces mentioned are briefly defined below (sensu "Depositional Sequence IV" in Catuneanu, 2006). The relative sea-level curve in Fig.6.1 illustrates where some of the different surfaces will develop.

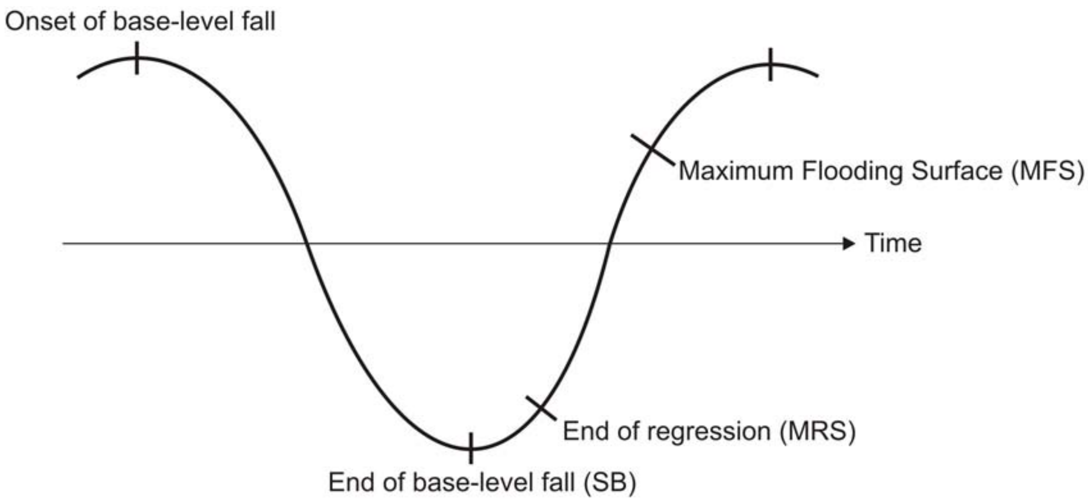

Figure 6.1: Important surfaces indicated on a relative sea-level curve (Based on "depositional Sequence IV" in Catuneanu, 2006, p. 7)

- *The Sequence Boundary (SB):* Taken at the top of forced regressive deposits; includes the subaerial unconformity, the correlative conformity (Sensu Hunt & Tucker, 1992, which is the youngest clinoform associated with offlap) and the distal portion of the regressive surface of marine erosion that is overlain by normal regressive deposits of the LST.
- *Maximum Regressive Surface (MRS):* The surface which marks the boundary between a regressive stacking pattern and a transgressive stacking pattern. The change takes place during the base-level rise at the shoreline, as the rise starts to outpace sediment input.
- *Maximum Flooding Surface (MFS):* Is usually conformable except for in distal reaches, and forms as a retrogradational stacking pattern is replaced by a progradational one when base-level rise is no longer fast enough to overcome sediment input.

6.2 The sequence stratigraphy of the Fangst Group

6.2.1 Summary panel

Fig.6.2 on the following page is a summary panel in 1:200-scale which highlight all the features of well 6506/12-1 for this study. It presents the wireline logs of the well, along with the formation names, the core log and checker plots of facies and facies associations. Added to this panel are the interpreted flooding surfaces in the core, and other important sequence stratigraphic surfaces which aid in the delineation of transgressive/regressive trends. These trends are also indicated in the panel. In the following sections the surfaces and trends will be discussed.

6.2.2 Surfaces and trends of well 6506/12-1

As mentioned in earlier chapters, the Ror Formation in the base of the core shows a regressive trend. It can be demonstrated based on the core log and on wireline logs that this regressive trend is built of at least eight coarsening-upward sequences capped by surfaces or zones where deepening is recorded. These may be true flooding surfaces separating stacked parasequences, but it may be better to call them stacked coarsening-upward bedsets (Charvin et al., 2009) as all eight may not represent true parasequences. Condensed sections like facies E, occurring within the coarsening-upward trend of the Ror Formation, are commonly related to maximum flooding surfaces (Catuneanu, 2006, pp. 143-144; Coe & Church, 2005, p. 80). The reason for this is that at maximum flooding the distal areas will receive the most limited supply of terrigenous material of the cycle.

Figure 6.2: Summary panel of well 6506/12-1, in scale 1:200

The condensed section in well 6506/12-1 is however not interpreted as a related to a maximum flooding surface since the deposits below and above it are both interpreted to have formed in a prodelta setting. The condensed section may merely be a result of delta lobe switching.

The coarsening-upwards trend continues with what has been interpreted as delta front mouth bars overlying the prodelta deposits, in this transition defines the base of the Ile Formation and the Fangst Group. The contact is sharp and slightly erosive, but no sequence stratigraphic significance is attributed to it. It is interpreted rather as a result of rapid progradation of the delta front, resulting in erosion at the base of the mouth bar complex. Such a facies contact may be sharp and mappable (Catuneanu, 2006, p. 156). In the "*progradational estuarine system*" of Meyer et al. (1998) this surface is referred to as *"tide-cut source diastem"*, which is a low-angle surface created as tidal bars prograde and build a subtidal platform above, in our case, prodelta sediments. The term estuary, however, does not apply as estuaries are transgressive in nature (Boyd et al., 2006). In Fig.6.2 the erosive surface is referred to as a within-trend normal regressive surface (wtNRS).

The dominant feature of the Ile Formation is the thick stack of aggrading to prograding delta plain facies. A few flooding surfaces and candidates for parasequences have been identified in this formation. Close to the top of the Ile Formation there is a change from fluvial channel sands to tidal channel sands which is interpreted as the change from a prograding lower delta plain to a backstepping lower delta plain. The change is subtle but marks the onset of transgression in the location of well 6506/12-1, and is probably an expression of the maximum regressive surface (MRS), which indeed may be quite subtle (Catuneanu, 2006, pp. 135-142). This maximum regressive surface marks the end of the regressive trend which has been interpreted to last all the way from the base of the core in the Ror Formation and almost to the top of the Ile Formation.

The backstepping seen in the top of the Ile Formation, with tidal channel sands sharply overlain by extensive and intermittently progradational tidal flat deposits, records the initial transgression of the lower delta plain. The tidal flats are then cut by a sharp surface, which is interpreted as a transgressive ravinement surface (TRS) overlain by a transgressive lag deposit. This ravinement surface was cut by the wave base as the sea flooded the delta, and ended the deposition of the Ile Formation. The dark shales of facies A which overlie the transgressive lag are the first deposits belonging to the Not Formation, and contains the maximum flooding surface (MFS). It has been interpreted at the point where the density reading on the wireline logs has its lowest value. The maximum flooding surface marks the end of the transgressive trend.

Above the maximum flooding surface a regressive shoreface progradation defines the rest of the Not Formation. The sharp erosive boundary separating the Not Formation and the Garn Formation separates deposits characterized by very different grain sizes and structures and very different wireline log signals. Increased sediment supply which initiated the deposition of the Garn Formation may have resulted from uplift to the west of the Halten Terrace which provided a lot of sediments to the basin. In addition, Fig.6.3 demonstrates that a eustatic sea level fall is indicated to have occurred in the Bathonian (Haq et al., 1988; Sahagian et al., 1996), which may also have played a part in the formation of the coarse-grained deposits. Lowering of the sea-level combined with tectonic activity may have elevated significant areas and exposed them to erosion, and by this increased the amount of coarse sediments fed to the basin. The erosive contact between the Garn Formation and the underlying Not Formation is thus interpreted as a subaerial unconformity and a sequence boundary (SB). As discussed in chapter 5, it is possible that the braid delta deposits in well 6506/12-1 were deposited long after initiation of Garn Formation deposition elsewhere on the Halten Terrace. Thus, the sequence boundary separating the Garn Formation and the Not Formation in well 6506/12-1 may represent a significant hiatus. The quite thick succession of braid delta deposits, overlain by a flooding surface at 3990.9 m core depth and deposits interpreted as laid down in a flooded braid-plain setting, may suggest a largely aggradational to retrogradational Garn Formation development.

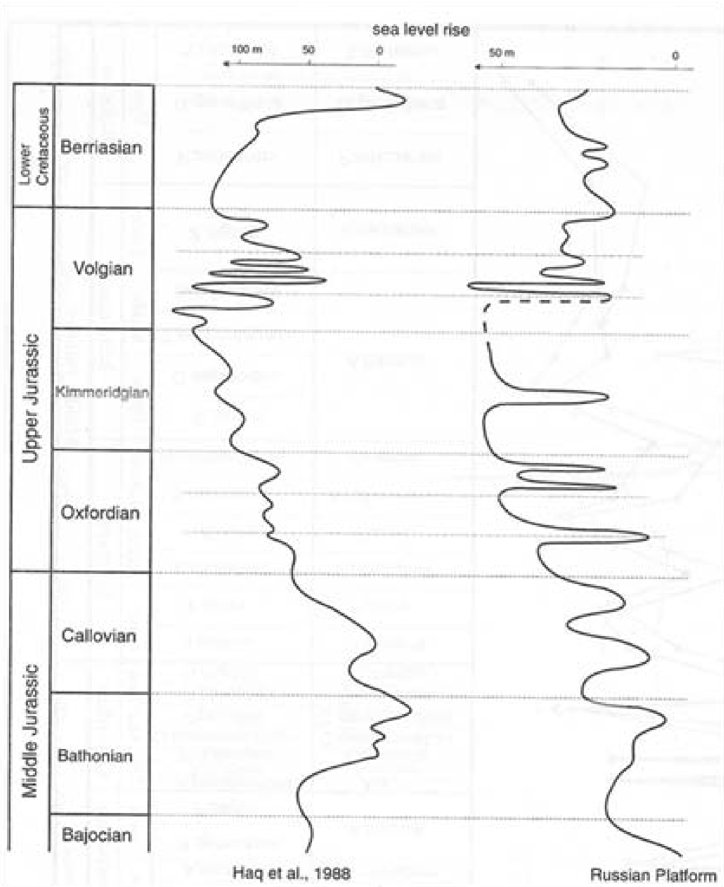

Figure 6.3: Eustatic sea level curves from separate studies of Haq et al. (1988) and Sahagian et al. (1996) both indicating a fall in eustatic sea level in the Bathonian (from Sahagian et al., 1996).

7 Paleogeography

7.1 Introduction

The paleogeography of the Mid-Jurassic on the Halten Terrace has been interpreted by several authors (Corfield et al., 2001; Gjelberg et al., 1987; Karlsson, 1984). A crucial matter in reconstructing the paleogeography of a region is the provenance of sediments and the orientation of the shoreline through time. Shoreline orientation and migration path based on only a few wells is of course highly uncertain, but it is possible to make an educated guess based on the facies development through the Fangst Group. The issue of source areas for the Fangst Group on the Halten Terrace has been debated for many years, but little has been published on the topic of provenance. Ehrenberg (1998) published a study of Sm-Nd data that indicated that at least two separate areas were supplying sediment to the Halten Terrace when the Garn Formation was deposited. A recent study published by Morton et al. (2009) has implemented data from provenance-sensitive heavy minerals, mineral chemistry and U/Pb-dating of detrital zircons to reveal the changes in provenance through the Early-Mid Jurassic in the Heidrun Field approximately 30 km NE of Smørbukk. This study indicates that there was an interplay between a source area on the Norwegian landmass and one in East-Greenland through this interval of time. The Ror and Ile Formations seem to have received most of their sediments from Norway, contrasting the pattern in the Early Jurassic Åre Formation. This may possibly be related to rising sea-level after Åre deposition which may have cut off the supply from East-Greenland (Morton et al., 2009). The Garn Formation represents a regional regressive event (Corfield et al., 2001), and the data suggests that the event enabled sediments from East-Greenland to reach the Halten Terrace area. The mechanism behind this return to dominantly westerly sourcing is dubious, as the Garn Fm. have been interpreted to host fluvial, delta top and shallow marine facies (Dalland et al., 1988; Morton et al., 2009).

7.2 Paleogeographic maps

Based on the sedimentological interpretations presented in the previous chapters and the published literature on the topic, the following pages presents several maps aimed at reconstructing the paleogeographic evolution of the Halten Terrace, focused on the area of study. These maps are of course only educated guesswork of what the area might have looked like, as a complete reconstruction of paleogeography would require a larger number of wells spread across the entire Halten Terrace. The first map (Fig.7.1) shows the map from NPD of the study area which has been used as the base map for drawing the paleogeographic reconstructions.

The map in Fig.7.2 shows the development of the tidal-fluvial delta which was the environment for deposition of the Ile Formation. It has been interpreted to prograde roughly from east to west. A fluvial system of one or more rivers is thought to have supplied the sediment. The tidal limit is indicated; this is the point at which channels downstream are tidally-influenced or –dominated. The reconstruction demonstrates how some channels are dominated by ebb-tidal and fluvial currents, while some are dominated by inflow of water from the sea during rising tide. The delta develops an asymmetric front due to this separation. The mouth bar sands develop outside ebb-channels while the flood-dominated channel has no mouth bars developed. Interchannel areas are dominated by quite extensive sub- and intertidal flats. Supratidal and perhaps marshy islands may have occupied areas between distributaries as well.

The map in Fig.7.3 shows the setting for deposition of the Not Formation. It is interpreted that a roughly north-south oriented seaway developed after a severe transgression, and that shoreline progradation following the maximum flooding occurred both from the east and the west, as a precursor of what was to come when the Garn Formation was deposited. It is also interpreted that the southernmost well, which is 6506/11-6, stayed in an offshore environment longer than the two wells further north.

The final map shows a stage in Garn Formation development (Fig.7.4). As has been discussed in previous chapters, the development may have been quite complex if Garn is diachronous across the Halten Terrace. The map of the Garn Formation shows the area at a stage where coastal braid deltas had started to develop in the area of Smørbukk 6506/12-1 well, after backstepping of shallow-marine sands onto footwalls of faults may have already been going one for quite some time. The other two wells are located in this shallow seaway experiencing high-energy conditions. It is interpreted a dual provenance of the sediment, from both the Norwegian margin and the Greenland margin. Later during deposition of the Garn Formation it is interpreted that the braid deltas were flooded and that larger areas experienced shoreface-like deposition. It is possible that the flooding and reworking in a shallow marine environment is the reason for low preservation of fluvial deposits in the Garn Formation (Gjelberg et al., 1987).

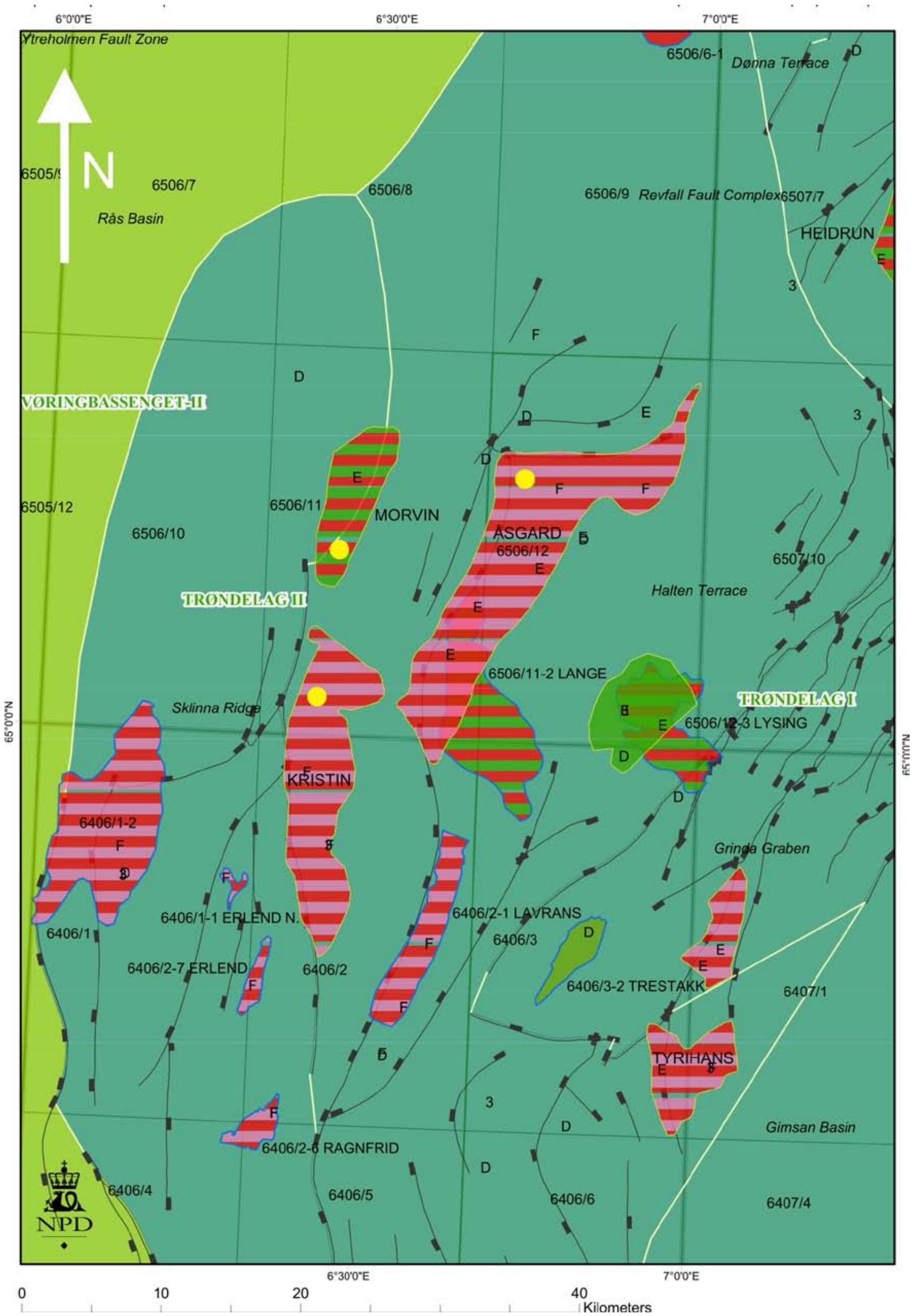

Figure 7.1: The map of the Halten Terrace study area which forms the background for all the paleogeographic maps (from Norwegian Petroleum Directorate web pages, 2010). Yellow dots are the three well locations.

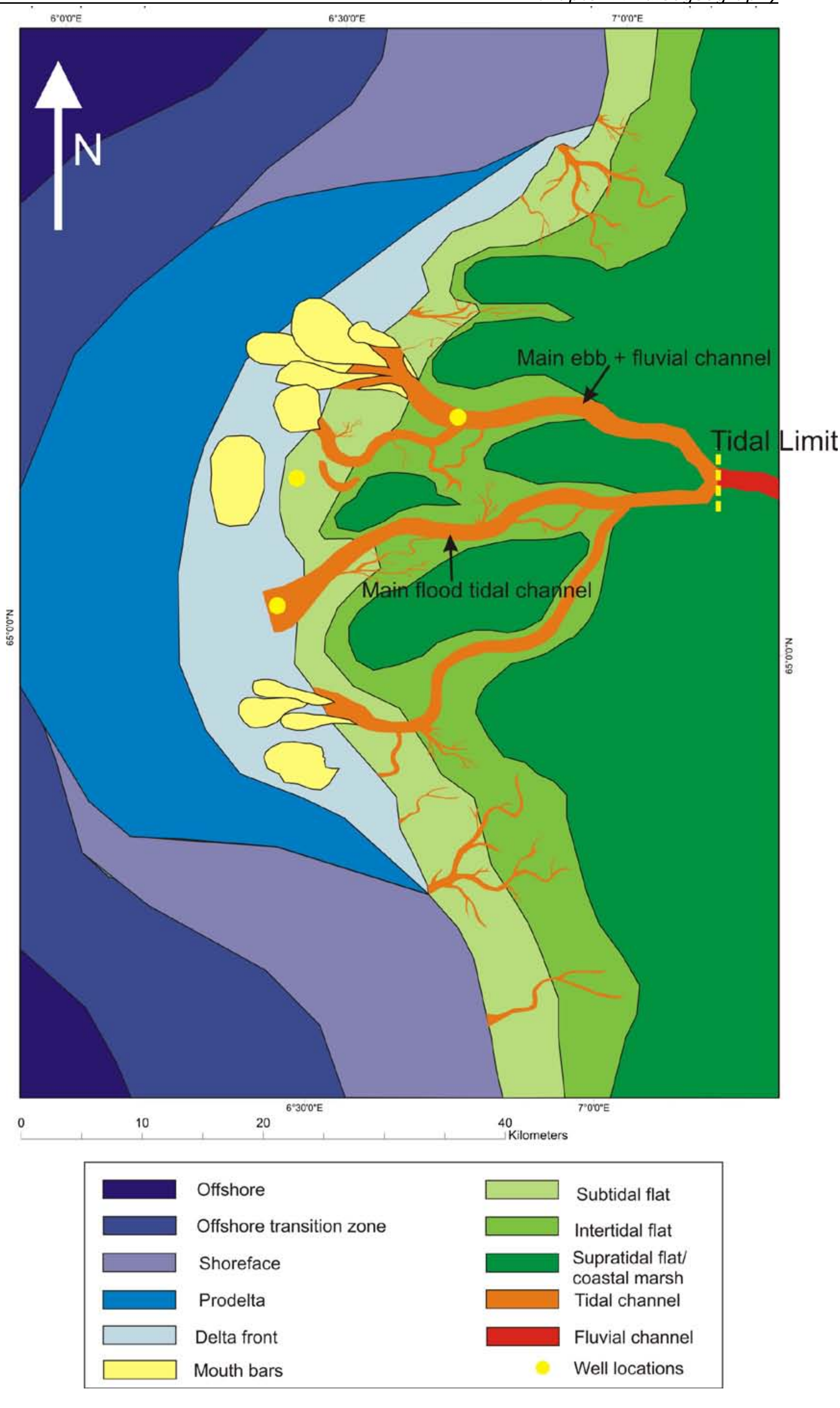

Figure 7.2: Paleogeographic reconstruction for the Ile Formation.

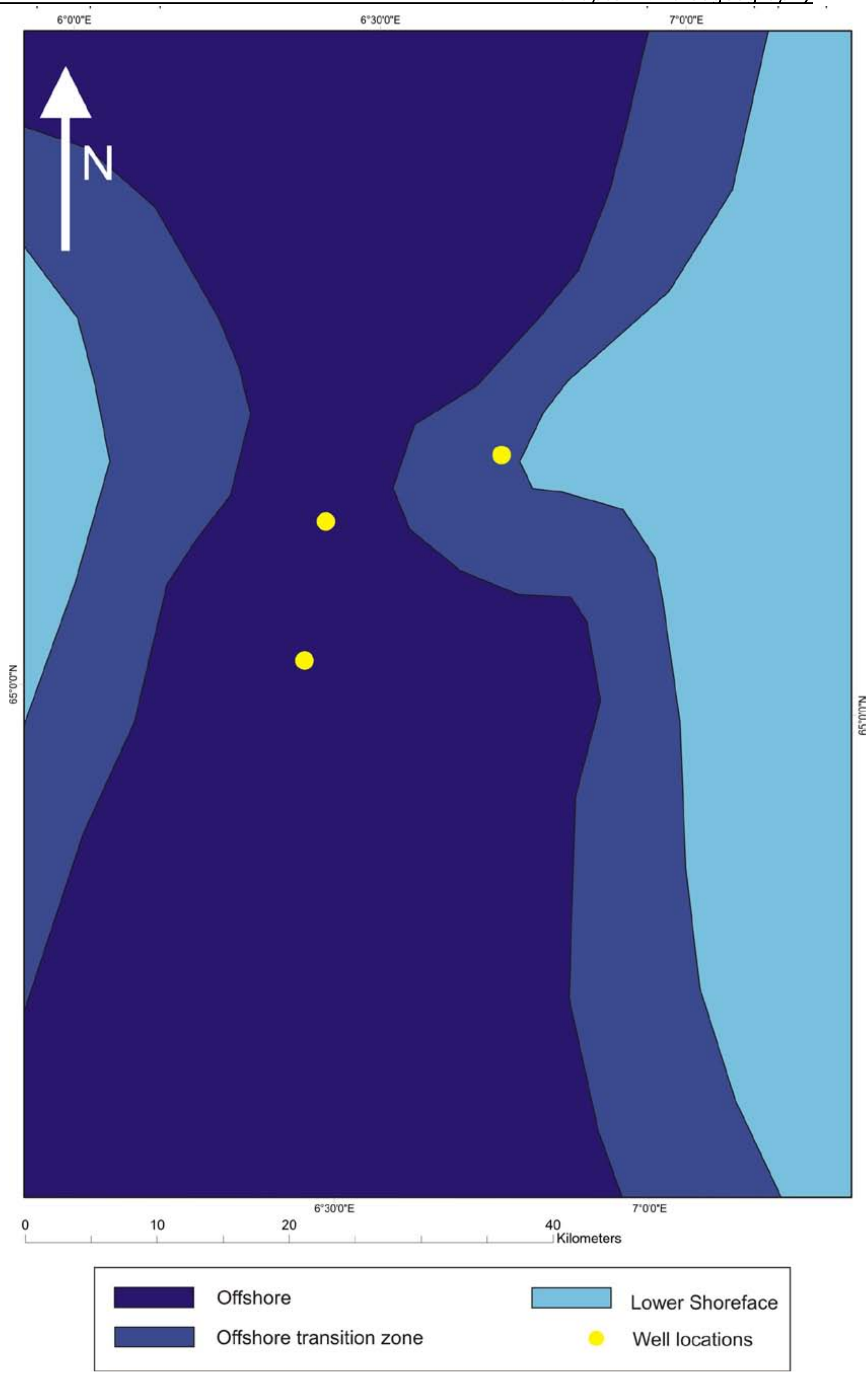

Figure 7.3: Paleogeographic reconstruction for the Not Formation.

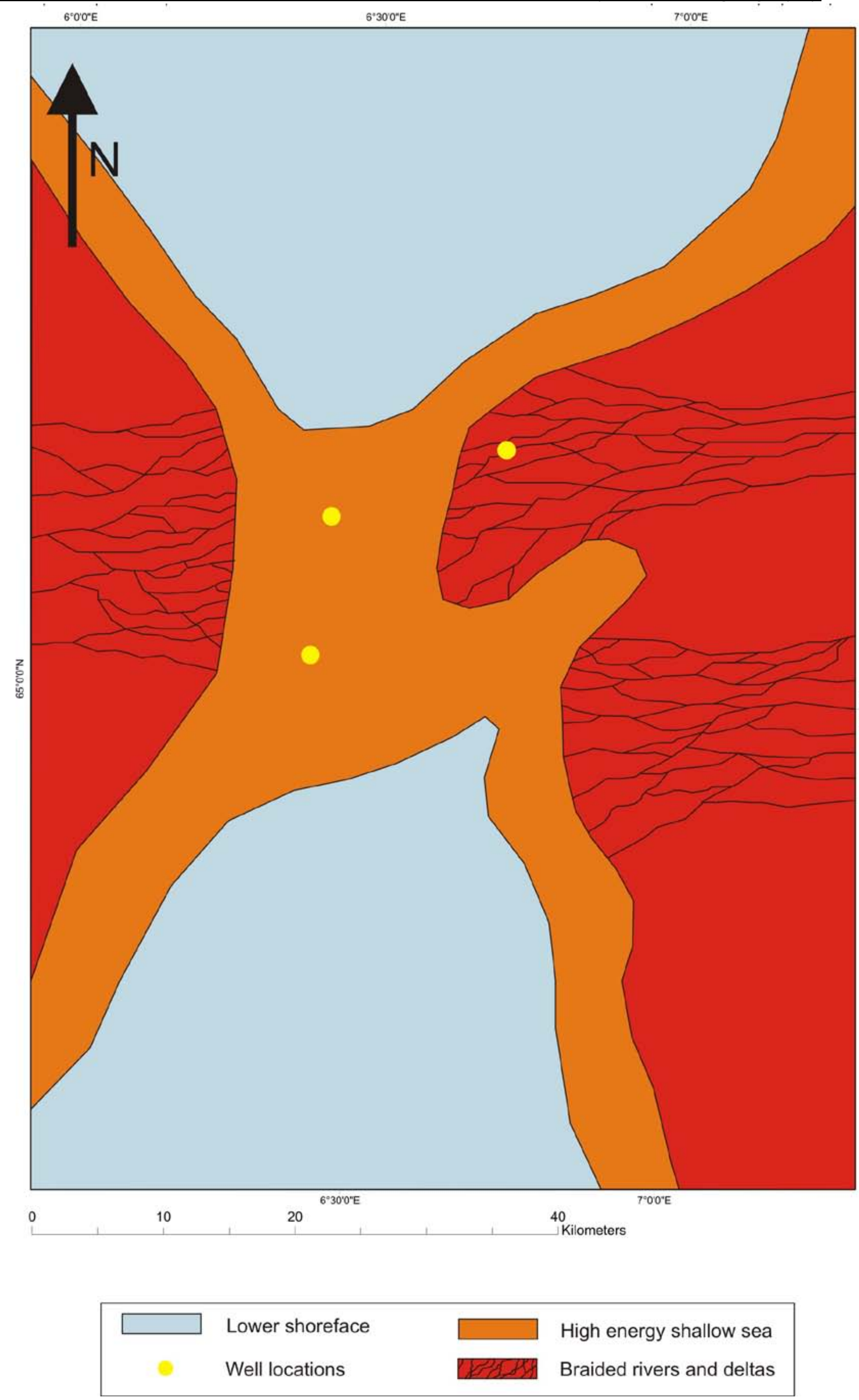

Figure 7.4: Paleogeographic reconstruction for the Garn Formation.

8 Conclusions

The core description of well 6506/12-1 of the Smørbukk Field on the Halten Terrace, and the subsequent interpretation of its features, has resulted in the following conclusions about the sedimentological development of the Fangst Group:

- The Ror Formation of the Båt Group and the overlying Fangst Group contains a wide range of facies. The Fangst Group comprises the sandstone-dominated Ile- and Garn Formations separated by the finer-grained and partly shaly Not Formation.
- The facies recognized in well 6506/12-1 may be grouped into five facies associations:
  - FA1 (prograding offshore to delta front) is built from the coarsening-upward succession of low-energy offshore mudstones and prodelta sediments of the Ror Formation, and a second coarsening-upward succession representing prograding tidally reworked mouth bars. The mouth bars form the lowermost deposits of the Ile Formation, separated from the Ror Formation prodelta fines by a surface of minor erosion created by the mouth bar progradation.
  - FA2 (lower delta plain) defines the main environment of Ile Formation deposition, and represents a thick progradational/aggradational succession of tidally-dominated deltaic facies comprising tidal flats and channel sandstones, with minor fluvial dominance toward the top of the interval.
  - FA3 (backstepping delta plain) contains retrogradational delta plain deposits which are finally cut by wave ravinement and overlain by a transgressive lag during transgression.
  - FA4 (prograding offshore to lower shoreface) defines the Not Formation, with a maximum flooding surface formed within offshore black shales and defining the change from transgression to regression. Regression in the Not Formation is characterized by normal shoreface progradation.
  - FA5 (braid delta complex) defines the Garn Formation, and unconformably overlies FA4. A significant hiatus has been interpreted at this sequence boundary. The medium- to coarse-grained sands are interpreted to represent a progradational to aggradational stack of amalgamated braided river deposits, deposited in a braid delta. A transgression in mid-Garn flooded the braid delta and created shallow embayments on the former delta top, before renewed progradation brought the braided rivers closer to the location of well 6506/12-1 again.

- Correlation of well 6506/12-1 with 6506/11-8 to the west and 6506/11-6 to the southwest confirms the continuance of sand bodies of the Fangst Group. However, there are differences between the wells which aid the paleogeographic reconstruction. A roughly N-S oriented shoreline or seaway is interpreted for the Fangst Group and the provenance studies of Morton et al. (2009) indicate an eastern sourcing for the Ile Formation and a combination of an eastern and a western source for the Garn Formation..
- The Ile Formation is interpreted as a tide-dominated delta which prograded from the east into a basin experiencing low wave-energy. The delta may have had several distributaries where some were dominated by ebb-tidal- and fluvial currents whereas some were dominated by flood-tidal currents. This led to development of an asymmetric delta front with extensive, tidally modulated mouth bars only developing outside ebb-dominated distributaries.
- The Garn Formation is interpreted to be facies- and time-diachronous along the transect. Initiation of faulting in the area, possibly combined with eustatic sea-level fall and uplift of a major source area to the west led to increase in coarse sediment influx to the Halten Terrace. It is interpreted that footwall uplift led to erosion at the location of well 6506/12-1, which was concomitant with deposition of shallow-marine sandstones in the hanging wall (at the location of well 6506/11-6). Backstepping of the shallow marine sands onto the footwalls of faults may have occurred. The Garn Formation of well 6506/12-1 formed as erosion ended at this location and braid deltas were able to build out across the area, continuously feeding the shallow seaway where sediments were distributed and reworked by a combination of longshore currents and tides.

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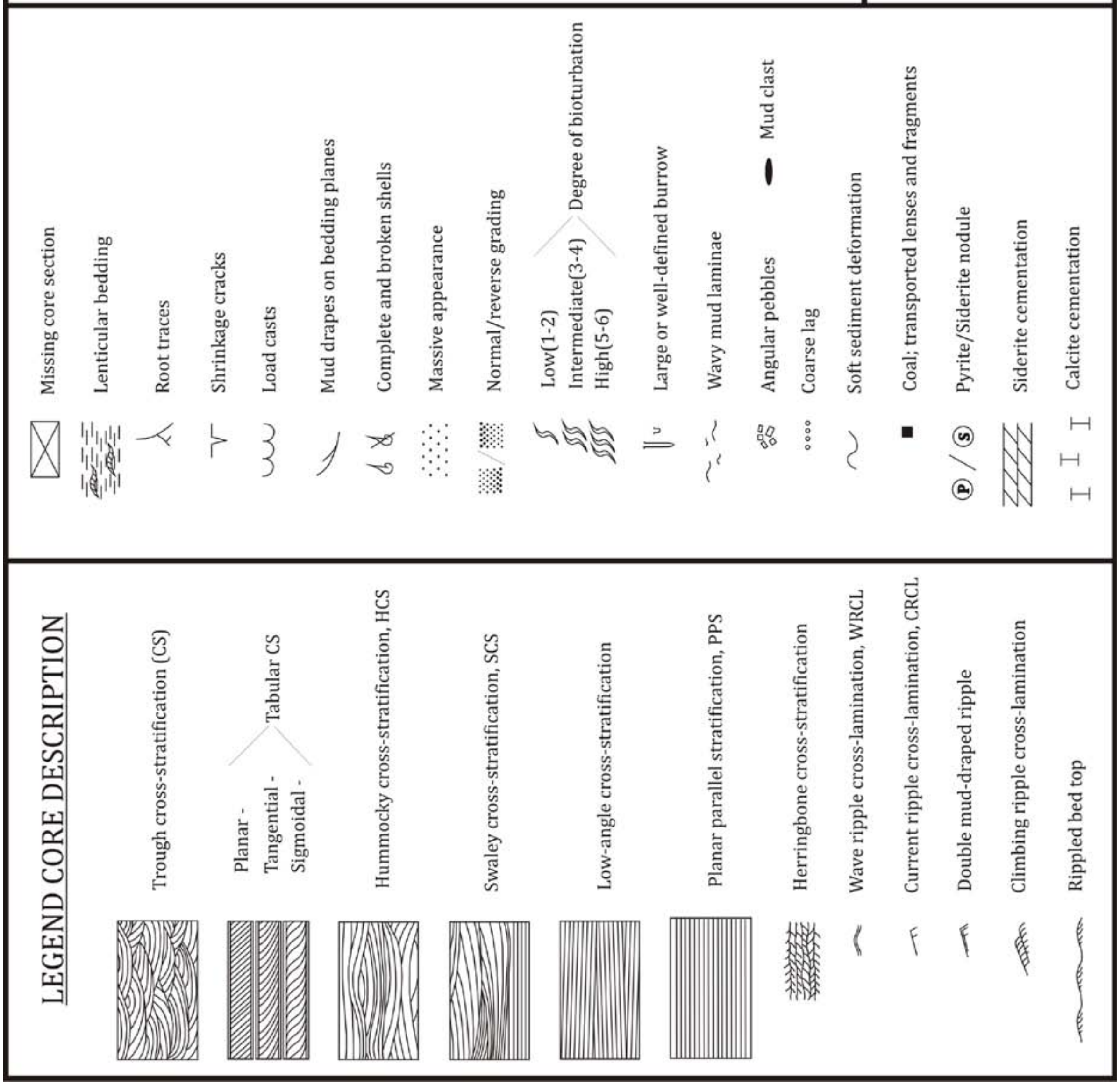
Appendix: 1:50 core logs with legend



Grain size scale

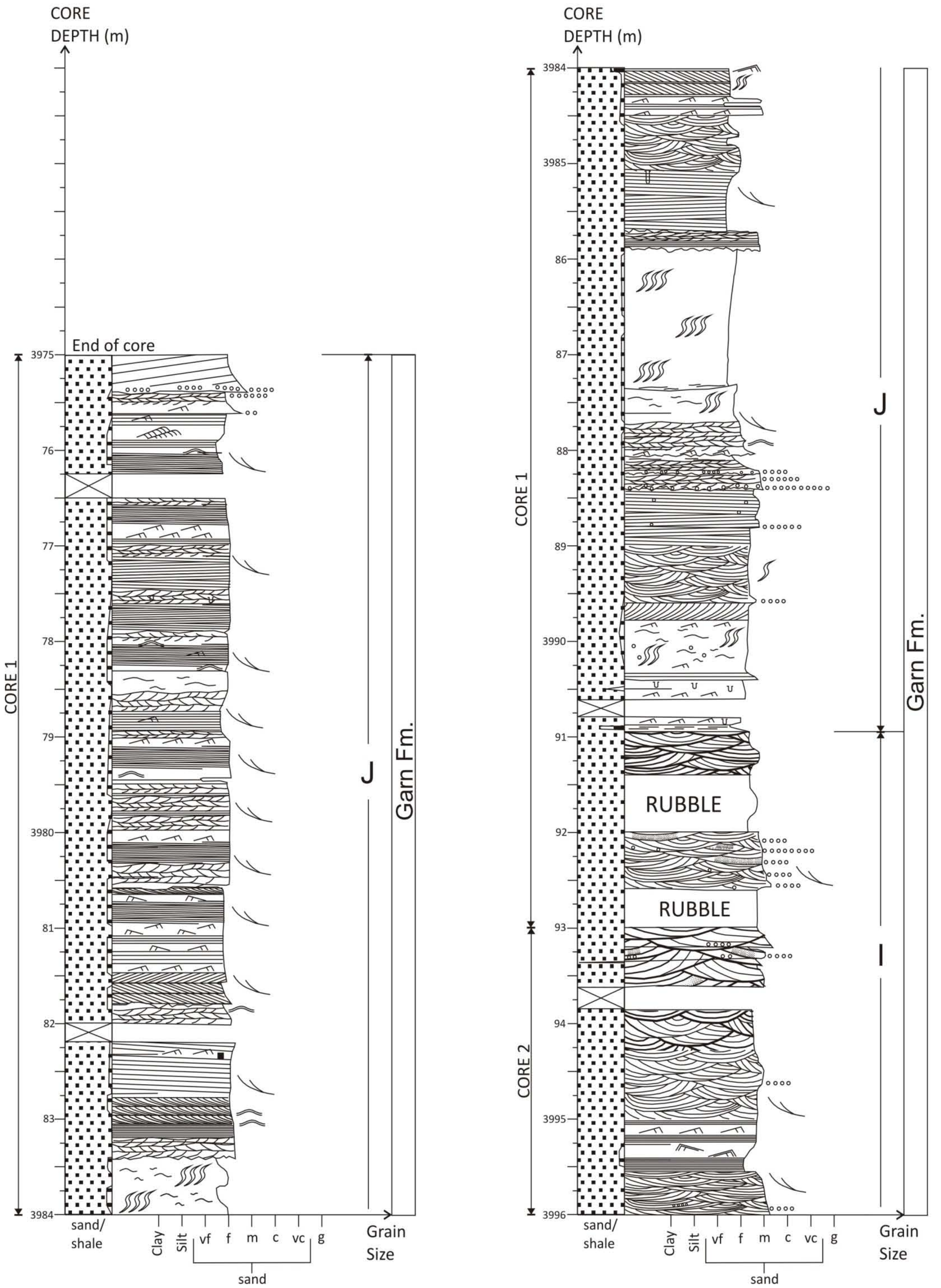
Clay	< 16 microns
Silt	16-63 microns
Very fine (vf) sandstone	63-125 microns
Fine (f) sandstone	125-250 microns
Medium (m) sandstone	250-500 microns
Coarse (c) sandstone	0.5-1.0 mm
Very coarse (vc) sandstone	1.0-2.0 mm
Granules (g)	2.0-4.0 mm

Bioturbation Index

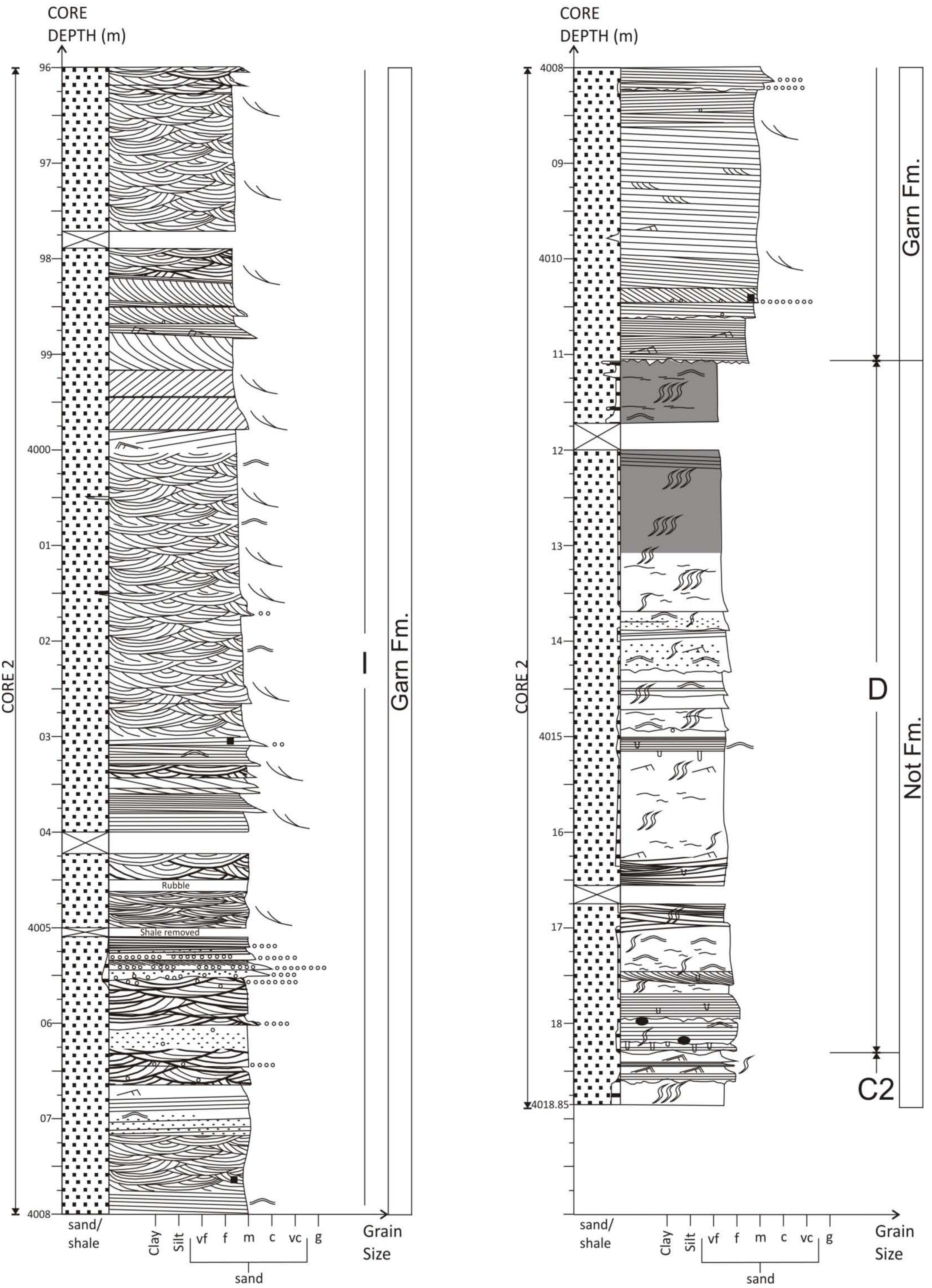
Grade	Percent	Classification
1	1-5	Sparse bioturbation, bedding distinct, few discrete trace fossils and/or escape structures
2	5-20	Little bioturbation, bedding distinct, low trace fossil density
3	20-50	Moderate bioturbation, bedding still visible, trace fossils discrete, overlap rare
4	50-80	Abundant bioturbation, bedding indistinct, high trace fossil densitywith overlap common
5	80-95	Intense bioturbation, bedding completely disturbed (just visible), later burrows discrete
6	95-100	Complete bioturbation, sediment reworking due to repeated overprinting

Legend for symbols used in core logs. Above: Explaination of abbreviations used in the grain size scales of core logs. Bioturbation index after Tucker (2003)

1:50-scale

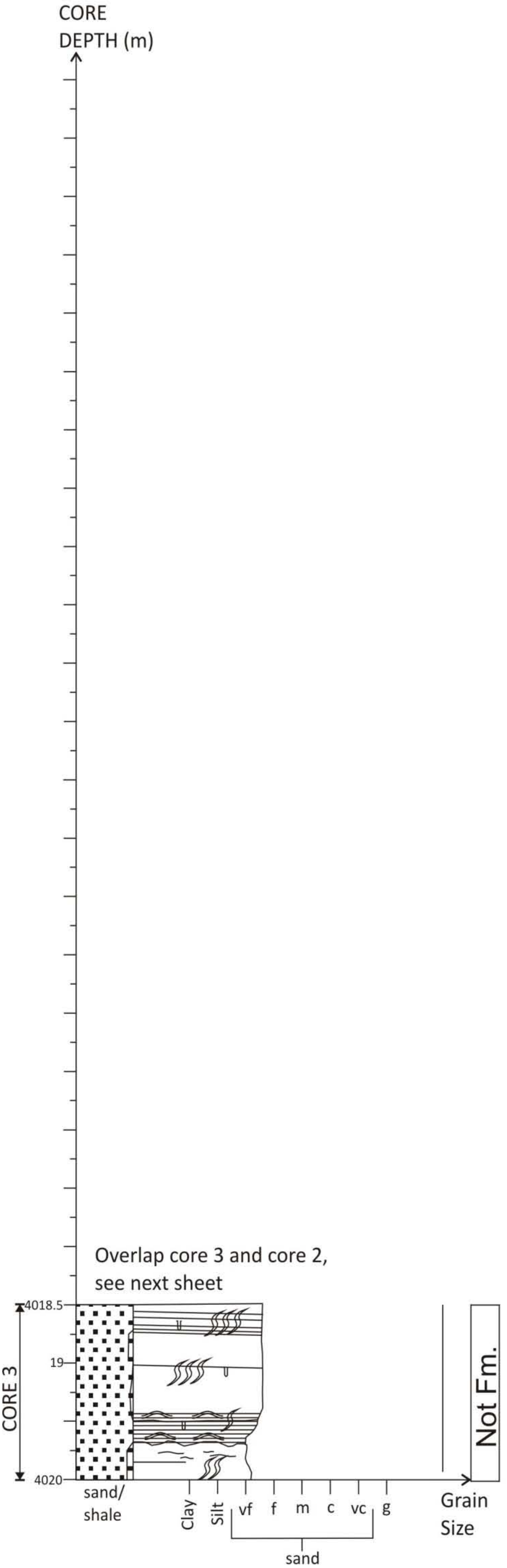

CORE
DEPTH (m)
End of core
3975
76
77
78
79
3980
81
82
83
3984
CORE 1
J
Garn Fm.
sand/
shale
Clay
Silt
vf
f
m
c
vc
g
sand
Grain
Size
CORE
DEPTH (m)
3984
3985
86
87
88
89
3990
91
92
93
94
3995
3996
CORE 1
CORE 2
RUBBLE
RUBBLE
J
I
Garn Fm.
sand/
shale
Clay
Silt
vf
f
m
c
vc
g
sand
Grain
Size

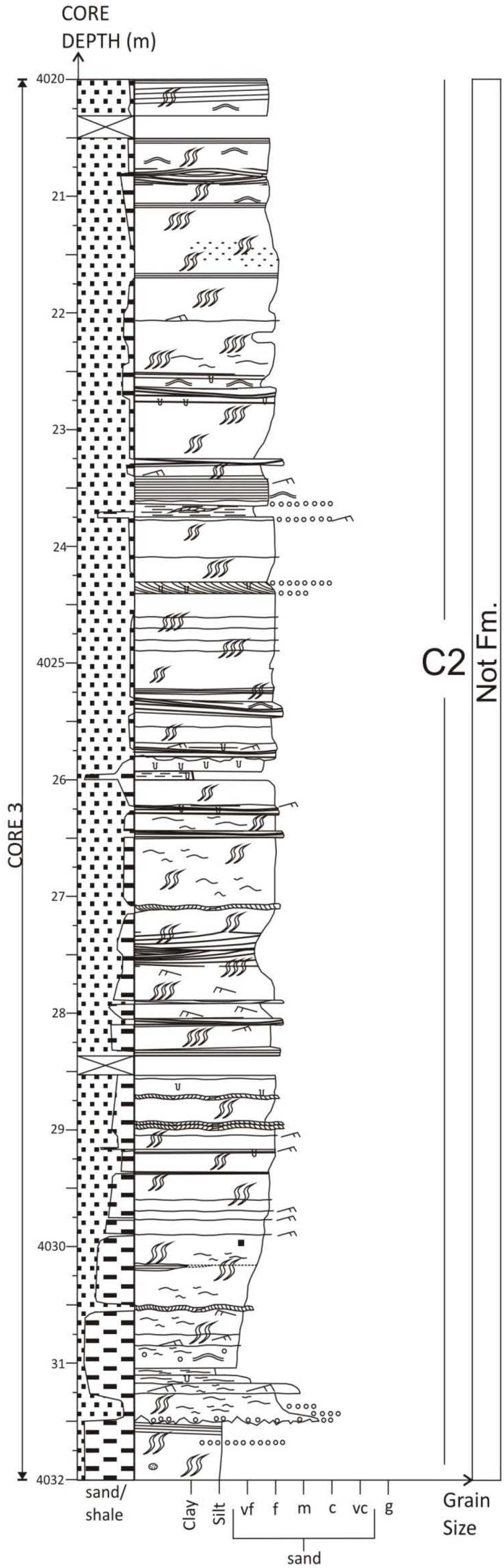
1:50-scale



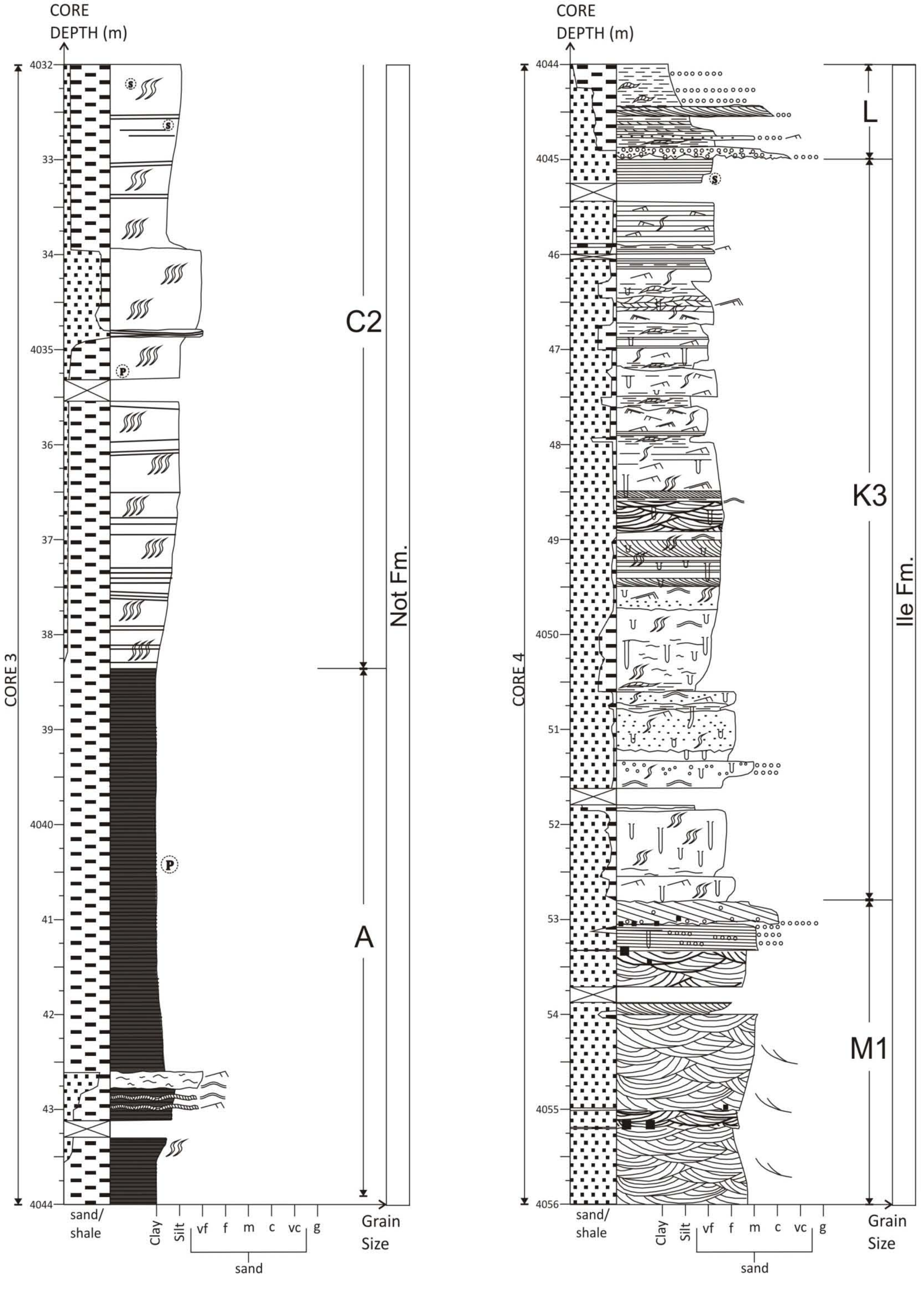
CORE DEPTH (m)
96
97
98
99
4000
01
02
03
04
4005
06
07
4008
CORE 2
Rubble
Shale removed
I
Garn Fm.
sand/shale
Clay
Silt
vf
f
m
c
vc
g
sand
Grain Size
CORE DEPTH (m)
4008
09
4010
11
12
13
14
4015
16
17
18
4018.85
CORE 2
Garn Fm.
D
Not Fm.
C2
sand/shale
Clay
Silt
vf
f
m
c
vc
g
sand
Grain Size

1:50-scale


CORE
DEPTH (m)
4018.5
19
4020
CORE 3
Overlap core 3 and core 2,
see next sheet
Not Fm.
sand/
shale
Clay
Silt
vf
f
m
c
vc
g
sand
Grain
Size

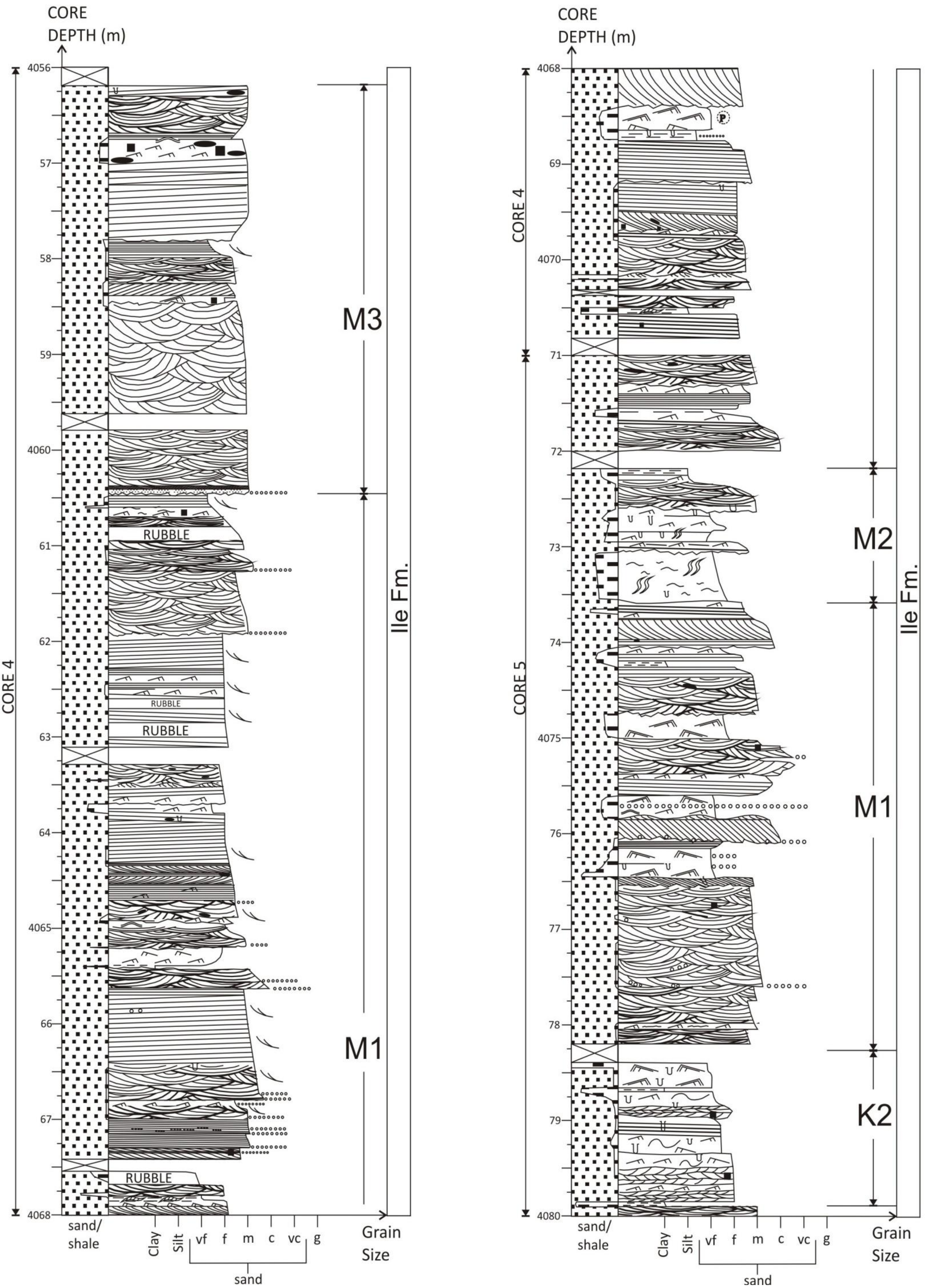

CORE
DEPTH (m)
4020
21
22
23
24
4025
26
27
28
29
4030
31
4032
CORE 3
C2
Not Fm.
sand/
shale
Clay
Silt
vf
f
m
c
vc
g
sand
Grain
Size

1:50-scale

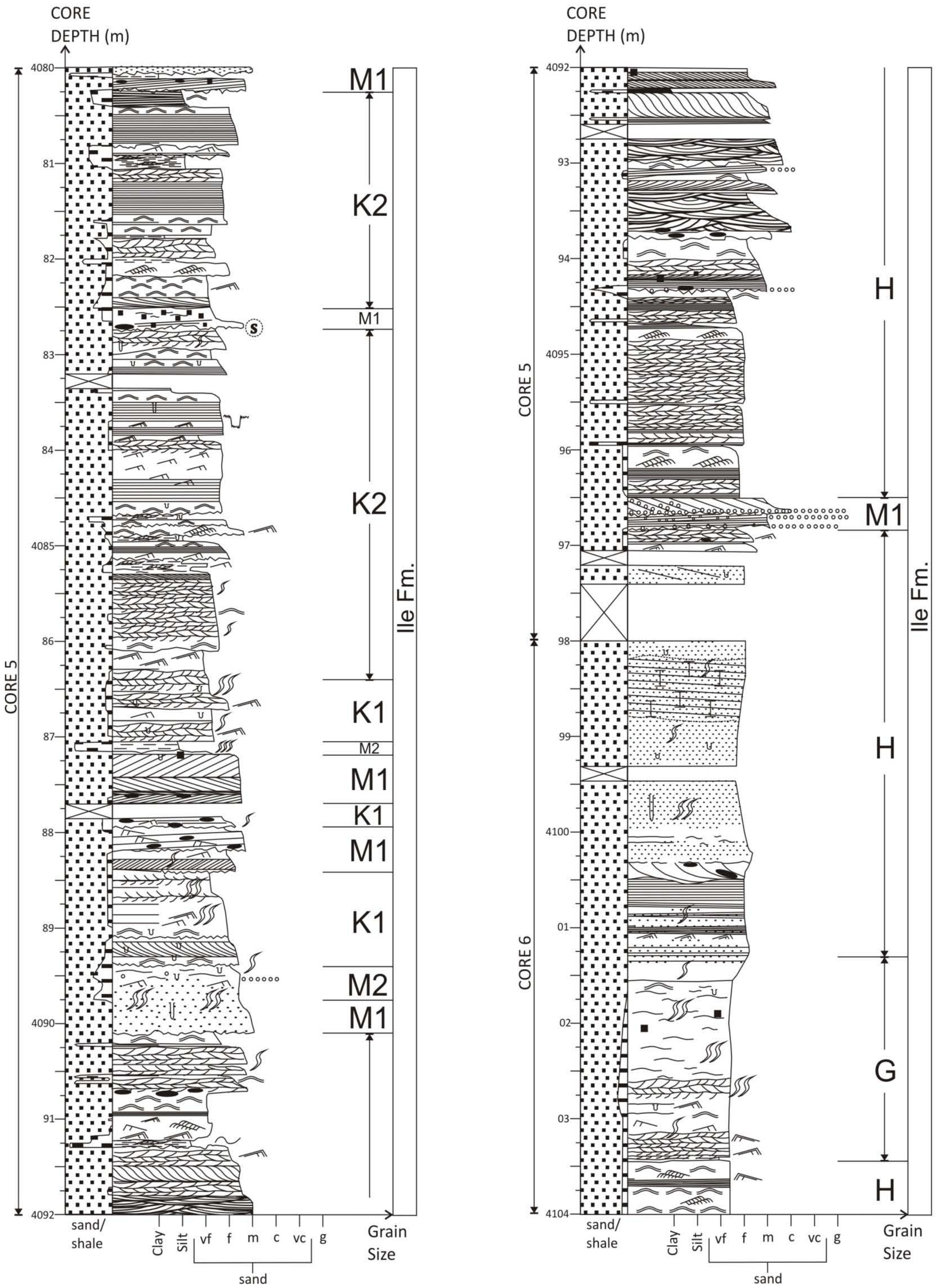


CORE DEPTH (m)
4032
33
34
4035
36
37
38
39
4040
41
42
43
4044
CORE 3
C2
A
Not Fm.
sand/ shale
Clay
Silt
vf
f
m
c
vc
g
sand
Grain Size
CORE DEPTH (m)
4044
4045
46
47
48
49
4050
51
52
53
54
4055
4056
CORE 4
L
K3
M1
Ile Fm.
sand/ shale
Clay
Silt
vf
f
m
c
vc
g
sand
Grain Size

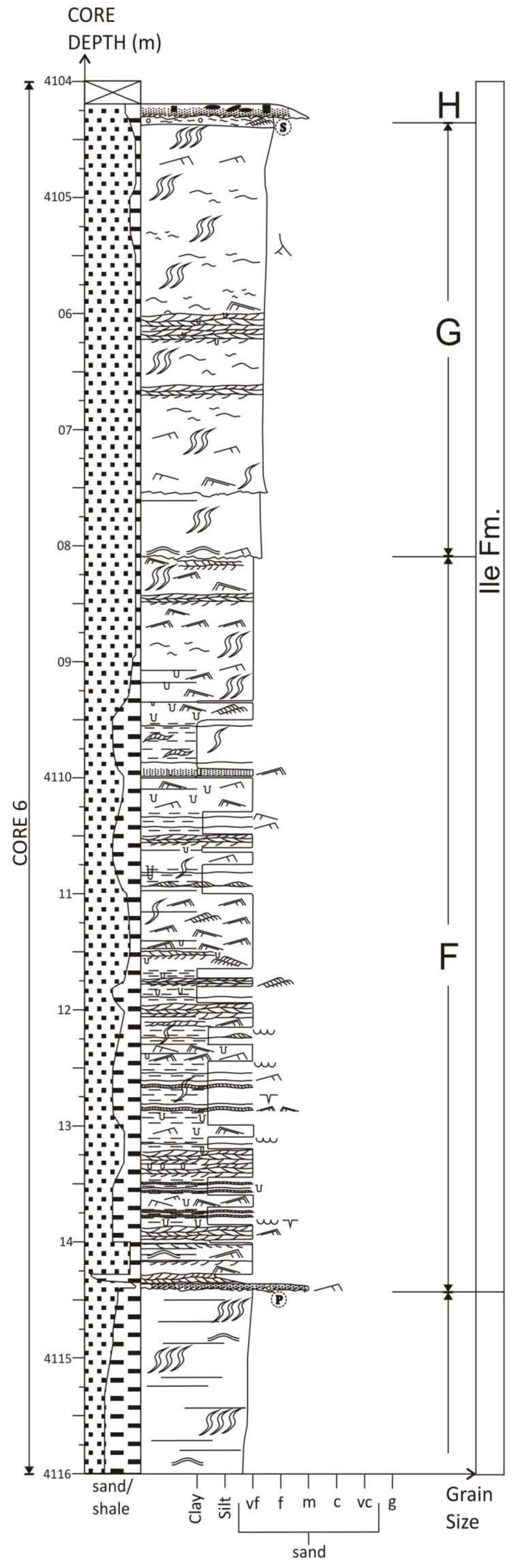
1:50-scale

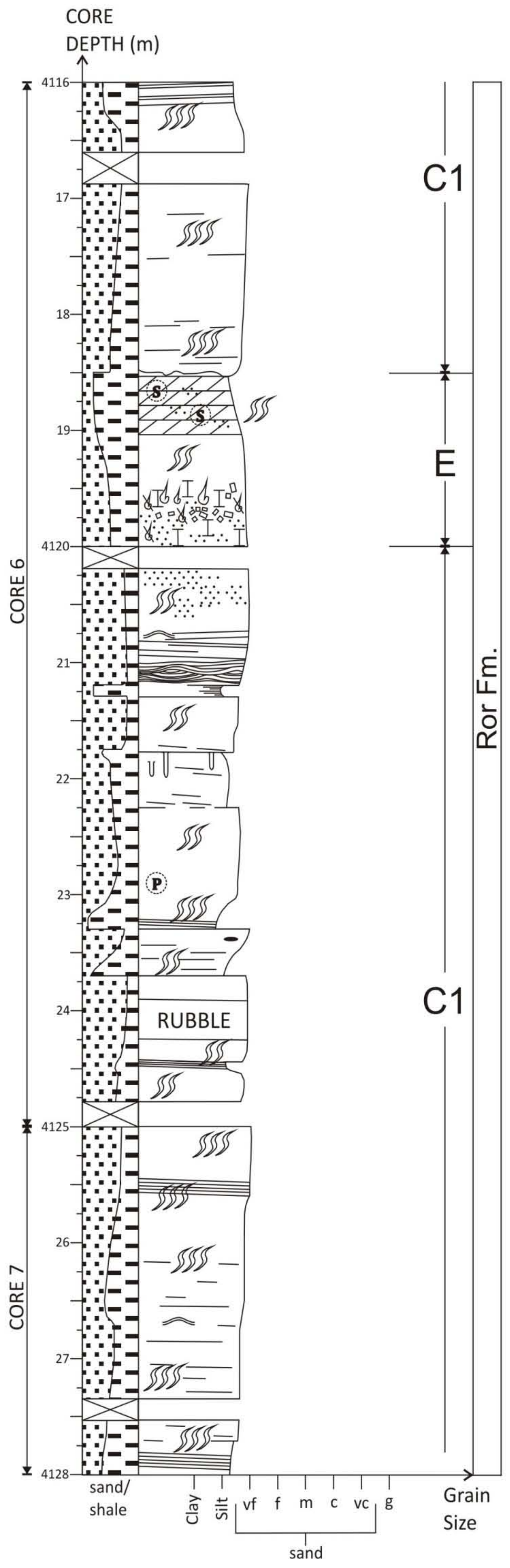

CORE
DEPTH (m)
4056
57
58
59
4060
61
62
63
64
4065
66
67
4068
CORE 4
RUBBLE
RUBBLE
RUBBLE
RUBBLE
M3
M1
Ile Fm.
sand/
shale
Clay
Silt
vf
f
m
c
vc
g
sand
Grain
Size
CORE
DEPTH (m)
4068
69
4070
71
72
73
74
4075
76
77
78
79
4080
CORE 4
CORE 5
M2
M1
K2
Ile Fm.
sand/
shale
Clay
Silt
vf
f
m
c
vc
g
sand
Grain
Size

1:50-scale

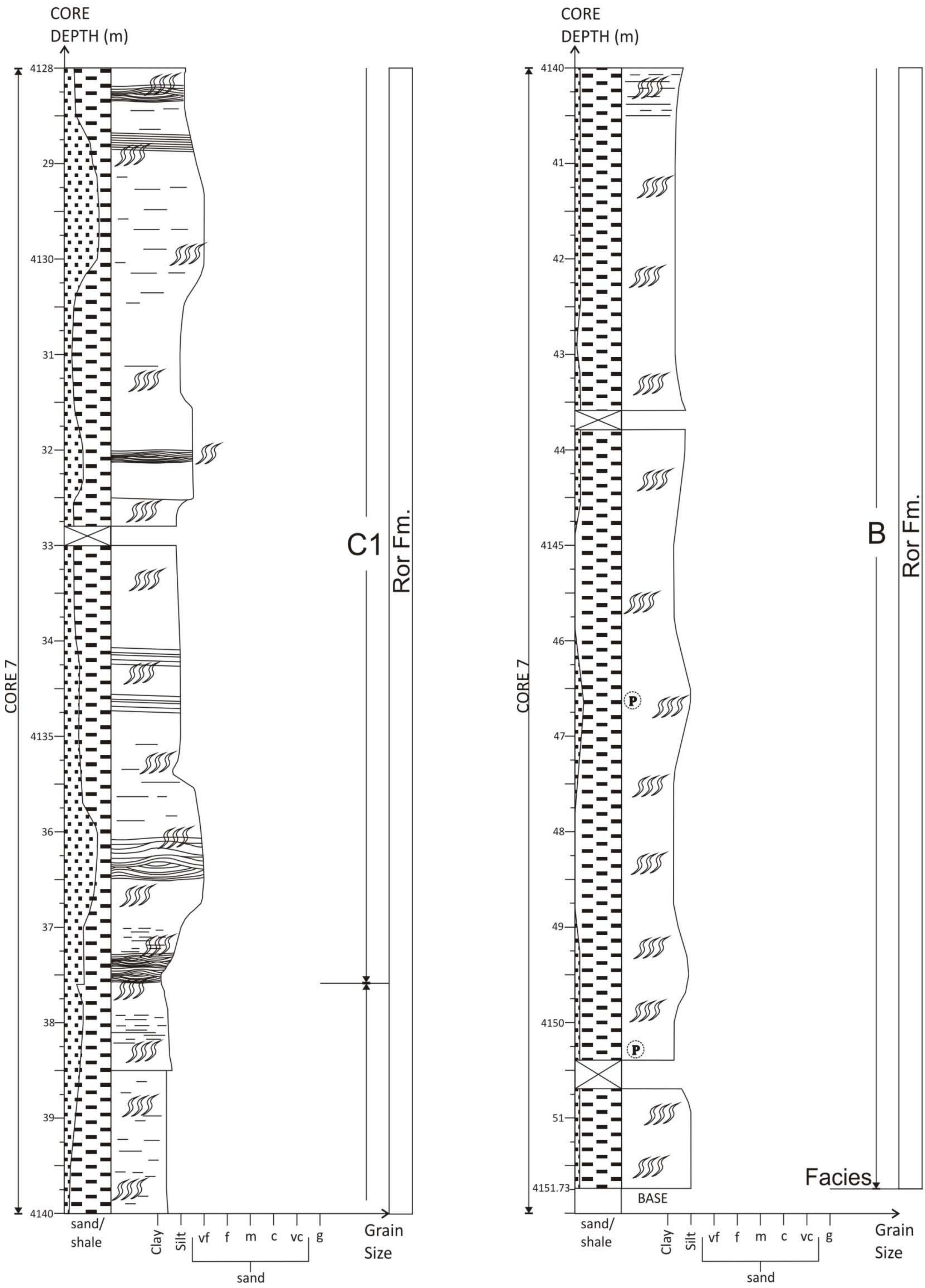

CORE DEPTH (m)
4080
81
82
83
84
4085
86
87
88
89
4090
91
4092
CORE 5
M1
K2
M1
K2
K1
M2
M1
K1
M1
K1
M2
M1
Ile Fm.
sand/shale
Clay
Silt
vf
f
m
c
vc
g
sand
Grain Size
CORE DEPTH (m)
4092
93
94
4095
96
97
98
99
4100
01
02
03
4104
CORE 5
CORE 6
H
M1
H
G
H
Ile Fm.
sand/shale
Clay
Silt
vf
f
m
c
vc
g
sand
Grain Size

1:50-scale


CORE
DEPTH (m)
4104
4105
06
07
08
09
4110
11
12
13
14
4115
4116
CORE 6
H
G
F
Ile Fm.
sand/
shale
Clay
Silt
vf
f
m
c
vc
g
sand
Grain
Size


CORE
DEPTH (m)
4116
17
18
19
4120
21
22
23
24
4125
26
27
4128
CORE 6
CORE 7
C1
E
C1
Ror Fm.
RUBBLE
sand/
shale
Clay
Silt
vf
f
m
c
vc
g
sand
Grain
Size

1:50-scale


CORE DEPTH (m)
4128
29
4130
31
32
33
34
4135
36
37
38
39
4140
CORE 7
C1
Ror Fm.
sand/ shale
Clay
Silt
vf
f
m
c
vc
g
sand
Grain Size
CORE DEPTH (m)
4140
41
42
43
44
4145
46
47
48
49
4150
51
4151.73
CORE 7
BASE
B
Ror Fm.
Facies
sand/ shale
Clay
Silt
vf
f
m
c
vc
g
sand
Grain Size