Dunlin Group Sequence Stratigraphy in the Northern North Sea: A Model for Cook Sandstone Deposition[1]

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ABSTRACT

The Dunlin Group in the northern North Sea, consisting of the Johansen, Amundsen, Burton, Cook, and Drake formations of late Sinemurian–Toarcian age, hosts important hydrocarbon reservoirs in the Cook Formation sandstones. The Johansen Formation is associated with a relative fall of sea level and is interpreted to be a large sandstone delta confined within a broad incised valley at the base of the group. During a later stage of relative sea level rise, the finer grained Amundsen and Burton formations were deposited. The overlying Cook Formation consists of four sandstone tongues, each of which is characterized by a lower zone of sharp-based, upward-coarsening, thinly bedded shoreface sandstones and siltstones (reflecting forced regression during falling relative sea level) and an erosively based upper zone of thin tidal flat and thick deltaic/estuarine sandstones (reflecting lowstand incision, as well as initial progradation and subsequent transgressive backfill of estuaries during relative sea level rise). The Drake Formation shales were deposited during continued relative sea level rise. Several types of erosional surfaces are recognized within the studied succession: (1) sequence boundaries occur at the base of the Johansen Formation and within the Cook Formation, and represent the bottoms of incised valleys that truncate the underlying shoreface deposits; (2) regressive surfaces of marine erosion occur at the base of Cook Formation units and truncate the underlying Burton and Drake shales, siltstones, and mudstones; (3) transgressive tidal channel (tidal ravinement) surfaces within the Cook Formation underlie the estuarine sandstones of the incised valley fills; (4) wave ravinement surfaces truncate the tops of estuarine sandstones and are overlain by thin transgressive lags that grade upward into the overlying black shales. Three-dimensional (3-D) models, based on structure-contour maps of sequence boundaries, unveil a paleotopography that controls the characteristics and distribution of the Dunlin Group reservoir sandstones.

INTRODUCTION

The Lower Jurassic Dunlin Group (Hettangian–Bajocian, Doré et al., 1984; latest Sinemurian–latest Toarcian, Partington et al., 1993) ranges in thickness from 204 m in the Statfjord field area (Doré et al., 1984) to 627 m in the northeast Frigg field area. The succession is known only from the subsurface, and was subdivided by Vollset and Doré (1984) (Figure 1) into the Amundsen, Johansen, Burton, Cook, and Drake formations. Except for the Johansen Formation, which is restricted to the Horda Platform, all of these formations occur on the western (United Kingdom) and eastern (Norway) sides of the embryonic North Viking Graben. The Dunlin Group boundaries to the underlying Statfjord Formation and overlying Brent Group are marked by sharp breaks in the well-log curves, as are the boundaries of the component formations (though with breaks of smaller magnitude).

The Cook Formation sandstones are important as secondary hydrocarbon reservoirs in the Statfjord field (Buza and Unneberg, 1987; Gradijan and Wiik, 1987; Roberts et al., 1987), Gullfaks field (Erichsen et al., 1987; Dreyer and Wiig, 1995), Oseberg field (Livbjerg and Mjos, 1989), and Veslefrikk field. The Cook sandstones on and around the Horda Platform are usually informally referred to as the "intra-Dunlin" and "intra-Drake"

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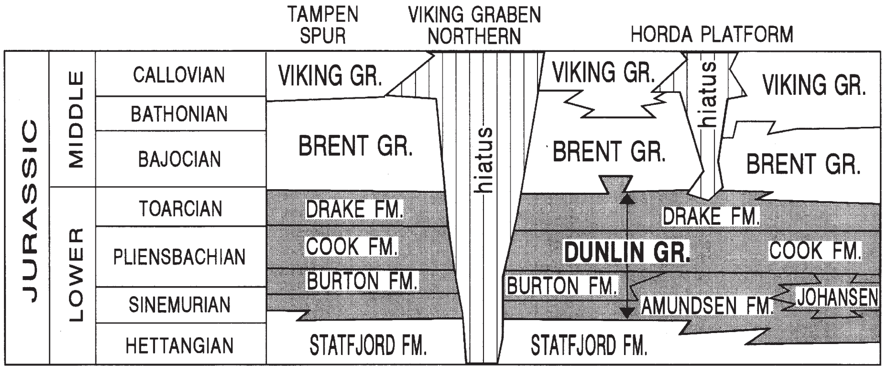

Figure 1—Stratigraphic position of the Dunlin Group, simplified after Vollset and Doré (1984). Compare this with the revised stratigraphic scheme, resulting from this paper, in Figure 2. The Amundsen, Cook, and Drake formations are heterolithic in nature with a varying sandstone content in the United Kingdom and Norwegian sectors. The most shaly level in the succession is the Burton Formation and the lowest part of the Drake Formation. Thick sandstones occur only in the Johansen and Cook formations.

sandstones because of the uncertain correlation with the Cook Formation in the Gullfaks field area. In a suggested revision of the lithostratigraphy of the Dunlin Group, Marjanac (1995) recommended that all thick Lower Jurassic sandstones (above the Johansen Formation) be assigned to the Cook Formation, including these informal units (see Figure 2).

We studied the Dunlin Group because of the need for a stratigraphic model that could both explain the apparent long-distance transport of the Dunlin Group shelf sands and provide a predictive map to account for the apparently irregular distribution (in time and space) of the good-quality Cook (reservoir) sandstones across the northern North Sea. We also tried to address the question as to whether all of the Dunlin Group sandstones really are shelf deposits, or if a more dynamic view of Early Jurassic changes in sea level could better explain the shape and distribution of the Dunlin Group sandstone tongues.

The main aims of the present work are to (1) draw attention to regionally extensive incision surfaces associated with each of the Cook Formation sandstone bodies, and to the great significance of these surfaces in controlling the emplacement and distribution of large volumes of the Cook sandstone more than 100 km from their contemporary hinterlands; (2) present a new Cook Formation sequence stratigraphic model that integrates and explains the relationships between the clean and the heterolithic Cook lithosomes, as well as the occurrence and succession of four different types of regressive and transgressive erosion surfaces within the component tongues of the formation.

This paper is based on the study of more than 100 well logs from the northern North Sea, as well as the available cored horizons. We correlated well logs and constructed about 1000 km of regional (intersecting) cross sections with selected examples from the Horda Platform area illustrated (Figure 3). The well logs are illustrated with the gamma-ray (GR) (natural radioactivity) and sonic (Δt) curves because of their good response to lithology. Correlation of the well logs is based on the assumption that maximum flooding surfaces (MFS) and other major flooding surfaces [referred to as extensive flooding surfaces by Marjanac (1995)] were more or less horizontal surfaces, justifiable particularly in such low-gradient, epicontinental basins. These are manifested in the well logs as gamma-ray maxima, and as peaks with no more than 10–15% deviation from the maximum extensive flooding surfaces (EFS). For correlation purposes, the higher MFS and EFS are taken as horizontal datums. Typically, these occur just above the sandstones of the Cook Formation and within the Drake Formation. Even where the MFS and EFS above the Cook 1 sandstones are diverging (for example, between wells 30/3-1 and 30/3-2, Figure 4), the higher MFS and EFS correlate well as horizontal surfaces.

Partington et al. (1993) constructed a regional stratigraphic template based on biostratigraphically calibrated MFS of basinwide extent. Although they did not provide data on the locations of the dated surfaces, it is possible to recognize some of these surfaces (Figure 2) and to suggest best candidates for the others. This template has been applied to the succession studied here (Figure 2).

Systematic ties between intersecting regional cross sections (Figure 3) provided means for accurate correlation of sandstones and major erosional surfaces. To visualize the topography of the major erosional surfaces, corresponding isopach maps (based on horizontal datums, MFS) and 3-D block diagrams were constructed. Prominent paleotopographic features (valleys and highs) on the resultant maps are informally named after the nearest field or structural unit.

PREVIOUS INTERPRETATIONS

The oldest accounts of depositional models for the Dunlin Group were general paleogeographic

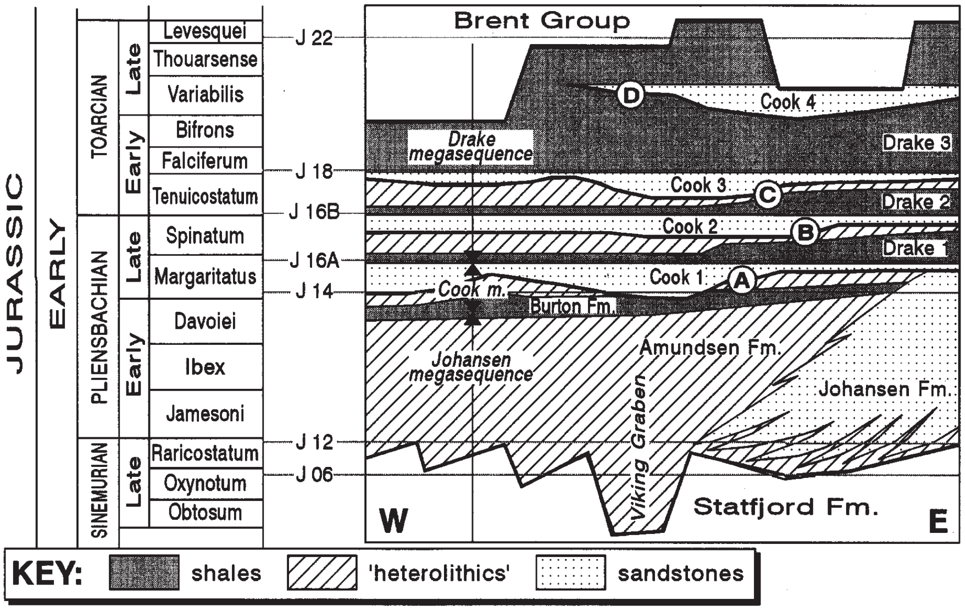

Figure 2—Revised stratigraphic architecture of the Dunlin Group across the northern North Sea showing megasequences of Steel (1993) and the biozones (J06 to J22) (and maximum flooding surface) of Partington et al. (1993). Major erosional surfaces A, B, C, and D are labeled as in the text. Surface D is of subregional extent, is restricted to the Horda Platform, and was not modeled or discussed in detail. These surfaces represent the bases of the Cook Formation sandstones; their topographies are illustrated in Figure 12.

reconstructions that covered the whole of the North Sea, usually presented as a part of a wider paleogeographic/stratigraphic discussion (e.g., Ager, 1975; Gage and Doré, 1986). According to these models, the Early Jurassic North Sea was a narrow seaway open between Laurentia in the west and Baltica in the east, and with communication of the Boreal Ocean and the Tethyan Ocean already established. Skarpnes et al. (1980) suggested that the northern North Sea was a wide epicontinental embayment open toward the north during the Hettangian–early Pliensbachian, and that this expanded during the middle Sinemurian–middle Pliensbachian when the terrigenous depositional systems retreated landward. During the Sinemurian–late Pliensbachian, the North Sea embayment was narrower, and terrigenous depositional systems had spread across both the Shetland and Horda platforms (Richards, 1990). Skarpnes et al. (1980) related the deposition of the Cook Formation to a middle Pleinsbachian regression and to structural movements within the basin. The Pliensbachian–Toarcian saw the maximum widening of this Early Jurassic embayment, resulting in flooding of coastal lowlands and extension of the seaway to the south (Skarpnes et al., 1980). These early models were based on the assumption that the Dunlin Group is composed of discrete formations with chronostratigraphic validity, and they failed to recognize multiple-flooding and shoreline-retreat events. Livbjerg and Mjos (1989), in work restricted to the Horda Platform area, interpreted the Cook sandstones of the Oseberg field as sand ridges formed by tidal currents on a structurally high area, but disconnected from the paleoshoreline.

More recent models have attempted to provide a sequence stratigraphic framework for the Dunlin Group. Steel (1993) recognized three regressive-transgressive megasequences (defined as large-scale depositional units bounded by maximum flooding levels) within the Dunlin Group. This model did not take into account the multiple occurrence of the Cook Formation, and some of these megasequences can now be subdivided into several higher frequency depositional sequences.

Parkinson and Hines (1995) subdivided the Dunlin Group into four regressive-transgressive cycles, and showed the Dunlin Group as comprising the J12/14 to J18 BP cycles on the scheme of Partington et al. (1993). Parkinson and Hines (1995) interpreted the Johansen Formation as a shoreline/middle shelf deposit emplaced during an interval of maximum regression. The Cook Formation was also interpreted in terms of a shoreline/middle shelf deposit, whereas the Amundsen, Burton, and Drake formations were attributed to the outer shelf. Also, Parkinson and Hines failed to recognize the incised nature of the base of the Cook sand bodies.

Sequence stratigraphic concepts were applied more rigorously by Dreyer and Wiig (1995) in a study of reservoir architecture of the Cook Formation sandstones on the Gullfaks field. These authors realized the incised nature of some of the sand bodies and recognized the same major bounding surfaces as in the present work, although their study was more local. Their paleogeographic reconstruction illustrates sediment supply from the east, and two depocenters located to the north and south of the Gullfaks field area. The major Cook

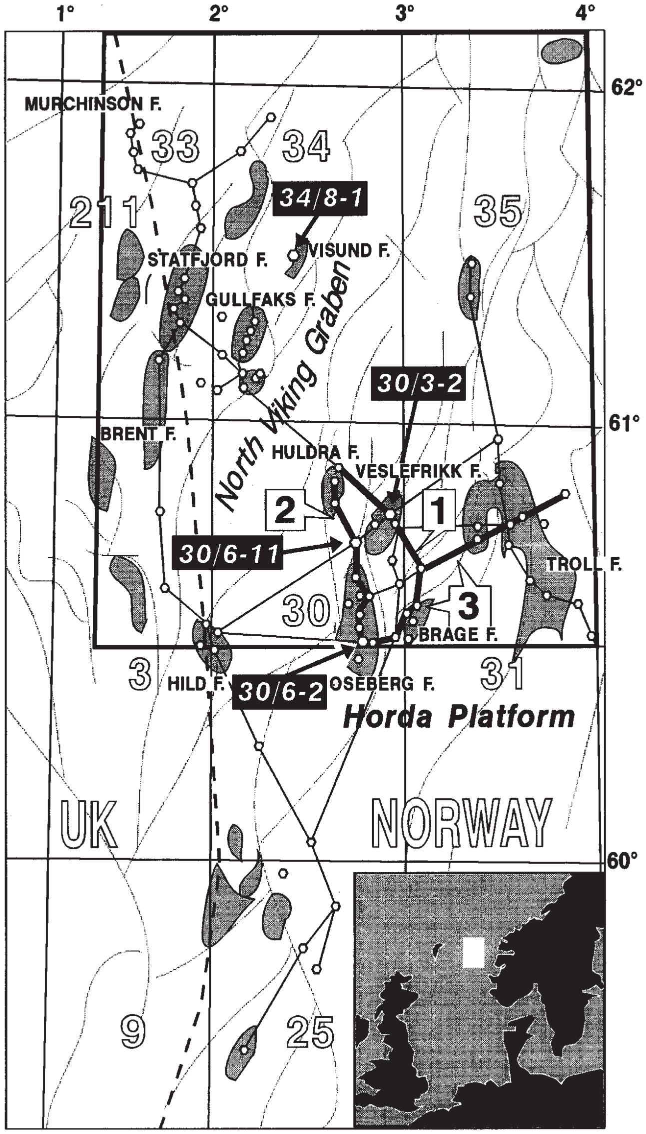

Figure 3—Map of the northern North Sea showing major faults, oil fields, correlation panels (sections), and wells illustrated in Figures 5, 6, 8, and 9. Sections 1, 2, and 3 (boxed numbers) are illustrated in Figures 4, 10, and 11, respectively; the framed area is the region covered by the three-dimensional block diagrams in Figure 12.

sandstone body was correlated with the uppermost intra-Drake sandstone on the Horda Platform, as in our interpretation.

FACIES AND DEPOSITIONAL ENVIRONMENTS

Dunlin Group shales and heterolithic facies (interbedded thin sandstones, siltstones, and shales) have generally been interpreted as shelf deposits (Vollset and Doré, 1984). Dunlin Group sandstones, which achieve great thicknesses in the Johansen and Cook formations, have also been interpreted as shelf deposits, albeit tidally influenced in some cases (e.g., Livbjerg and Mjos, 1989). In this paper, we distinguish between a true shelf depositional setting and shallow-water deposits merely resident within a shelfal location due to sea level changes. In true shelf deposits, the sediments were transported onto the shelf by shelf processes and reworked, whereas in shallow-water deposits, the sandstones could have been deposited in a coastal or nearshore setting immediately after a relative fall of sea level (thereby located above offshore/shelf deposits), but were later abandoned in an apparent shelf setting after a relative rise of sea level (therefore overlain by shelf deposits). Genuine shelf sands form extensive sheets and isolated sand banks with generally good lateral continuity and isotropy of facies. However, incised valley fills commonly reside on the shelf because of a preceding relative fall and a subsequent relative rise of sea level. The resultant sand bodies have a restricted lateral distribution, and their lateral isotropy is poor. Shelf sands such as offshore sand ridges typically occur as shore-parallel or shore-oblique bodies (Houbolt, 1968), unlike estuarine sand-wave fields that are oriented normally or at high angles to the shoreline (Dalrymple et al., 1990). These two models have significantly different predictive implications as regards sand distribution, geometry, and reservoir properties. In a succession where such sand bodies alternate vertically, it is important to distinguish them precisely because of their contrasting reservoir architecture and properties.

Johansen Formation

The Johansen Formation is composed of fine-grained sandstones and siltstones that built a large, generally westward- and northward-prograding and wedging sandstone body interpreted as a large delta (Marjanac, 1995). This interpretation is based on its external geometry, internal architecture as read from well logs, and relationship with adjacent deposits. The sand body, composed of large basinward-dipping clinoforms that indicate direction and mode of progradation (see also Parkinson and Hines, 1995), is dominated by its progradational phase and has only a thin retrogradational top. At the base and near the western margin of the body, Johansen sandstones interfinger with shales and heterolithic facies of the Amundsen Formation. The Johansen Formation sandstones are partly overlain by Burton Formation shales, but also in some areas by the Cook sandstones (e.g., in the eastern reaches of the Troll field area).

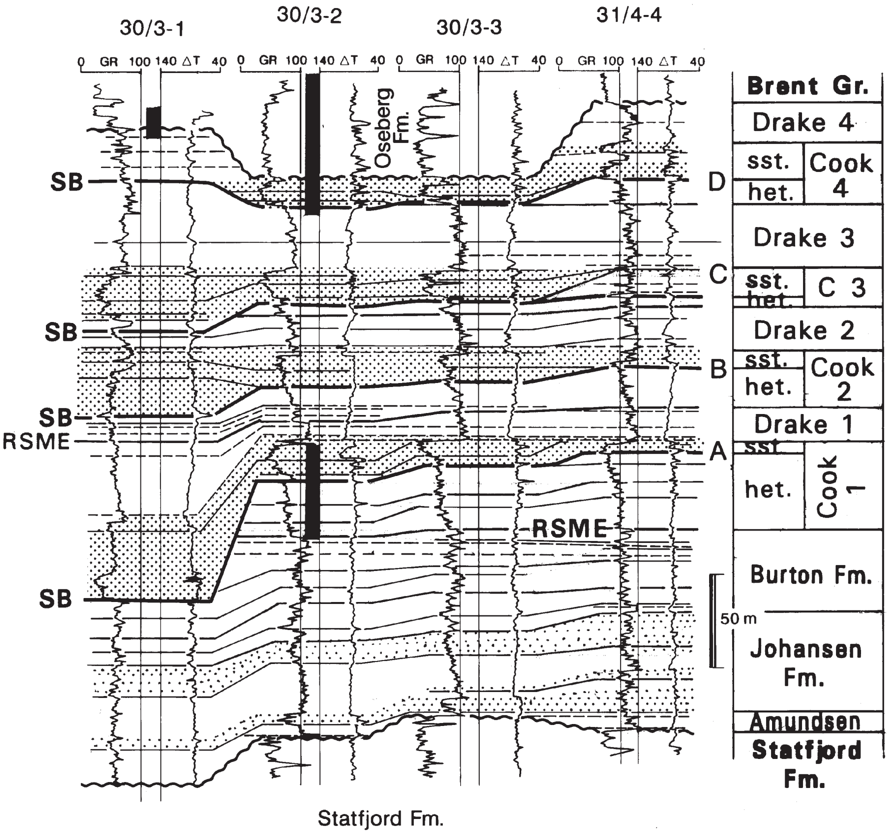

Figure 4—Cross section of the Huldra-north Brage field (location number 1 in Figure 3), a dip section approximately 36 km long. Cored intervals are shown by black rectangles.

Cook Formation

The Cook Formation is typically composed, from bottom to top, of (1) strongly bioturbated interbedded centimeter-to-decimeter–thick sandstones and shales (referred to as the Cook heterolithic facies), (2) unbioturbated interbedded millimeter-to-centimeter–thick sandstones and shales or laminites, and (3) relatively clean sandstones (referred to as the Cook sandstones). This pattern of facies distribution is typical for all four of the Cook Formation tongues, although the thicknesses of the individual facies vary locally.

Units of Cook heterolithic facies are generally sharp based (Figure 5A, B) and marked by a fall in natural radioactivity, indicating a rapid increase in sand supply to the depositional system. The cores show this facies to be marine and pervasively bioturbated (Figures 5A, C; 6C), but wave-generated ripple lamination in a few of the less bioturbated sandstone interbeds suggests that the thin sands were emplaced by storm processes. Bioturbation typically decreases upward, and on the gamma-ray log this facies shows a coarsening-upward pattern (Figures 5B, 7). These sandstones and shales are interpreted as lower to middle shoreface deposits and almost always occur in a progradational motif.

On a larger scale the heterolithic facies tends to dip gently basinward and downlaps onto the underlying, semihorizontal shaly strata of the Burton and Drake formations. The facies is also typically truncated from above by the base of the cleaner Cook sandstones. Because of its progradational character and location above the outer shelf/offshore shales (Burton and Drake formations) and below the erosionally based, tidally influenced Cook sandstones, this heterolithic facies could be interpreted in terms of a late highstand sequence tract. However, the sharp base of this lithosome indicates abrupt downlap and probable erosion, as well as a basinward shift of facies with respect to the underlying shales. In a late highstand systems tract setting, this scenario can imply deposition after the initiation of relative sea level fall. The submarine erosion surface generated during such regression has been referred to as a regressive surface of marine erosion (RSME) by Nummedal (1992), and the deposits generated above it as a product of forced regression (Posamentier et al., 1992) or as falling-stage deposits (Nummedal, 1992).

Unbioturbated interbedded millimeter-to-centimeter–thick sandstones and shales, and bituminous laminites, occur locally just above pedogenic horizons (see following sections) and below

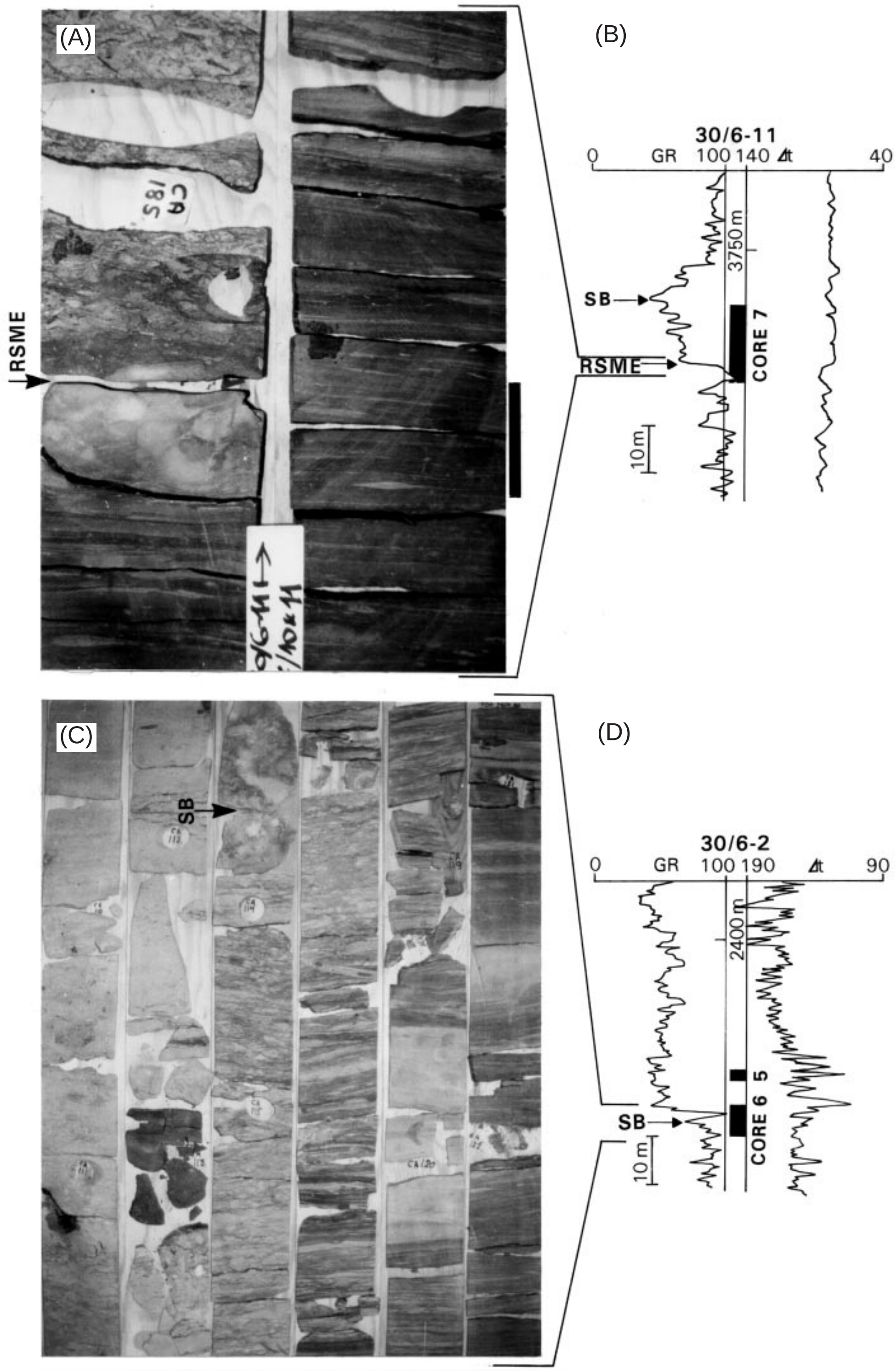

Figure 5—(A) Well 30/6-11, core 7 at 3776 m. Top of the Burton Formation shales overlain by the Cook Formation bioturbated shoreface heterolithic facies. The contact is cemented and interpreted in terms of a regressive surface of marine erosion (RSME). Scale bar is 5 cm. (B) Well log 30/6-11 showing the cored interval. Note sharp base of the shoreface deposits (RSME) and the coarsening-upward pattern in the shoreface heterolithic deposits (above RSME and below sequence boundary SB). (C) Well 30/6-2, core 6 at 2433.7–2439.7 m. The Burton Formation shales (at lower right) are overlain by thin shoreface heterolithics of the Cook Formation. The top of the Cook is marked is marked by siderite-cemented sandstone that is interpreted to be of pedogenic origin and to mark a sequence boundary (SB). This is overlain by very thin bituminous silty shale and thick Cook Formation clean sandstones with their characteristic sharp base. The cores are each 1 m long. (D) Well log 30/6-2 showing the cored intervals. Note high natural radioactivity of the bituminous silty shale.

the Cook sandstones. The sandstones are characterized by form-discordant ripple-lamination (Figure 8A); we interpret these as wave-generated beds deposited on a muddy tidal flat. At the same stratigraphic level with respect to the underlying shoreface deposits and the overlying sandstones are local, thin, unbioturbated bituminous laminites (Figure 8C) and unbioturbated black silty shales (Figure 6C). The bituminous laminites are made of millimeter-thin sandstone stripes

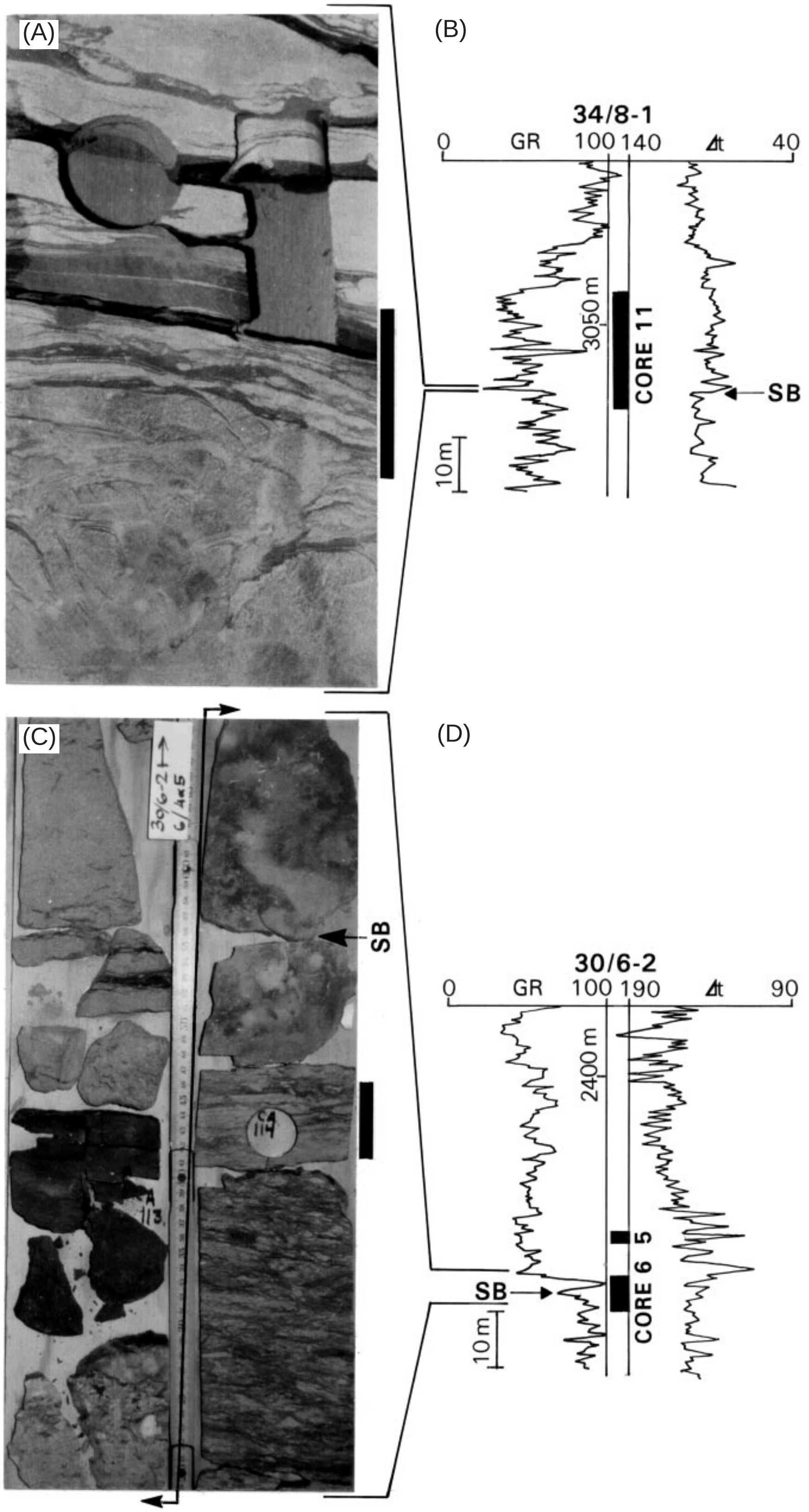

Figure 6—Core- and well-log expression of the pedogenic layers and sequence boundaries. (A) Well 34/8-1, core 11 at 3061.6 m. Close-up of the early diagenetically cemented sandstone with characteristic microfaults at the top of a Cook heterolithic unit. This microfractured, cemented sandstone is interpreted to be a pedogenic layer and sequence boundary that is overlain by thin tidal-flat deposits. Scale bar is 5 cm. (B) Well log 34/8-1 showing the cored interval. The pedogenic horizon (SB) is characterized by a sharp break in the gamma-ray (GR) and sonic (Δt) logs. (C) Well 30/6-2, core 6 at 2438 m. The Cook heterolithic facies in the lower part (bottom right) are overlain by siderite-cemented sandstone (SB) and bituminous silty shale. The siderite-cemented sandstone is interpreted to be a pedogenic horizon and a sequence boundary, whereas the silty shale is interpreted to be a remnant of marsh deposit. Note sharp base of the Cook clean sandstones. Scale bar is 5 cm. (D) Well log 30/6-2 showing the cored interval. The sequence boundary (SB) and the base of the Cook Formation sandstone are sharp and marked by characteristic breaks in gamma-ray log.

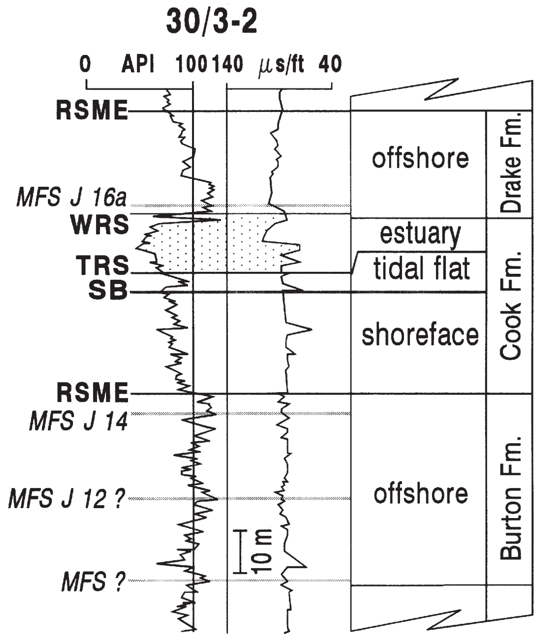

Figure 7—Interpreted well log 30/3-2 and the key surfaces recognized. Interpretation of facies is based on the core study. Maximum flooding surfaces (MFS) are labeled as proposed by Partington et al. (1993). Note coarsening-upward pattern in the Cook Formation shoreface deposits and Drake Formation offshore shales, as well as the blocky-to-fining-upward trend of the Cook Formation estuarine sandstones. RSME = regressive surface of marine erosion, WRS = wave ravinement surface, TRS = tidal ravinement surface, SB = sequence boundary.

interbedded with siltstones and shales that we interpret as marsh deposits.

The Cook sandstones occur typically as units of clean, fine- to coarse-grained, massive or cross-stratified sandstones (Figures 5C; 9A, C) characterized by a sharp, erosive base (Figures 5C, 6C), indicated in the well logs by a decrease in natural radioactivity and an increase in sonic velocity as a result of preferential cementation (Figures 5B, D; 6D; 7; 8B, D). The Cook sandstones themselves are characterized by a blocky or abruptly coarsening-upward log pattern commonly followed by a fining-upward pattern. In some cores, just below the sharp-based Cook sandstones, are pedogenic horizons or sandstones impregnated with early diagenetic carbonate (Figure 6A) or sideritic (Figure 6C) cements.

Some of the Cook sandstones were deposited by tidal currents, as strongly suggested by tidal bundles, double mud drapes (Figure 9A), cross-stratification reversals, and a general abundance of cross strata; other sandstones were probably deposited in fluvial channels (Figure 9C), as suggested by a total lack of burrows, coarser and well-segregated grain sizes, fining-upward motifs, and larger scale cross-bedding. The tidal influence, the coarseness, the amalgamated cross-stratified character of the Cook sandstone, their great basinward extent (Figures 4, 10) and strike-discontinuous character (Figure 11) strongly suggest an origin as tidal sandbar complexes and tidal distributaries. The stratigraphic position of the sandstone bodies and the relative scarceness of fluvial deposits favor a tide-dominated deltaic to outer estuarine setting (cf. Aliotta and Perillo, 1987; Dalrymple et al., 1990). Nevertheless, locally common, millimeter-to-centimeter–thick coal seams in some of the sandstones (originating from carbonization of drifted plant debris) indicate a proximity to land. These seams certainly suggest a distance much less than the present 100 km or so between these deposits and the hinterlands. In the few cases where tidal flat deposits have been identified below the Cook tidal sandstones, the tidal flat deposits are separated from the tidal sandstones by an erosional surface interpreted as a tidal ravinement surface (TRS, Figure 7) within the estuary (see also Allen and Posamentier, 1993). Another erosional surface commonly occurs near the top of the Cook sandstones, just below the fining-upward transition to the offshore shales of the Drake Formation (Figures 2, 9E), and is interpreted as a wave ravinement surface (WRS, Figure 7).

Cook sandstones normally lie with marked erosion above forced regressive shoreface units (Cook heterolithics) or Burton Formation shales (where there has been deeper erosion; for example, in well 30/3-1 in Figure 4 and wells 30/6-2 and 30/6-7 in Figure 10). Pedogenic horizons or tidal/fluvial sediments above strongly suggest that these surfaces are associated with subaerial erosion, represent significant basinward facies shifts, and can be referred to as sequence boundaries (SB in Figure 4). The incised topography illustrated in Figures 4 and 10–12 thus was probably created largely by fluvial processes during periods of significant fall in relative sea level, and was later infilled by fluvio-estuarine systems.

The dominantly estuarine system of the Cook sandstones was characterized by landward migration of distributary systems and sand-bar complexes. Fluctuations in sea level caused new incisions and created new estuaries, whose sandstones locally became amalgamated with the older sandstones. Polyphase infill is a characteristic feature of the Cook valley infills.

Drake Formation

The Drake Formation forms predominantly shaly intervals with high, natural radioactivity (Figure 2), but is commonly characterized by

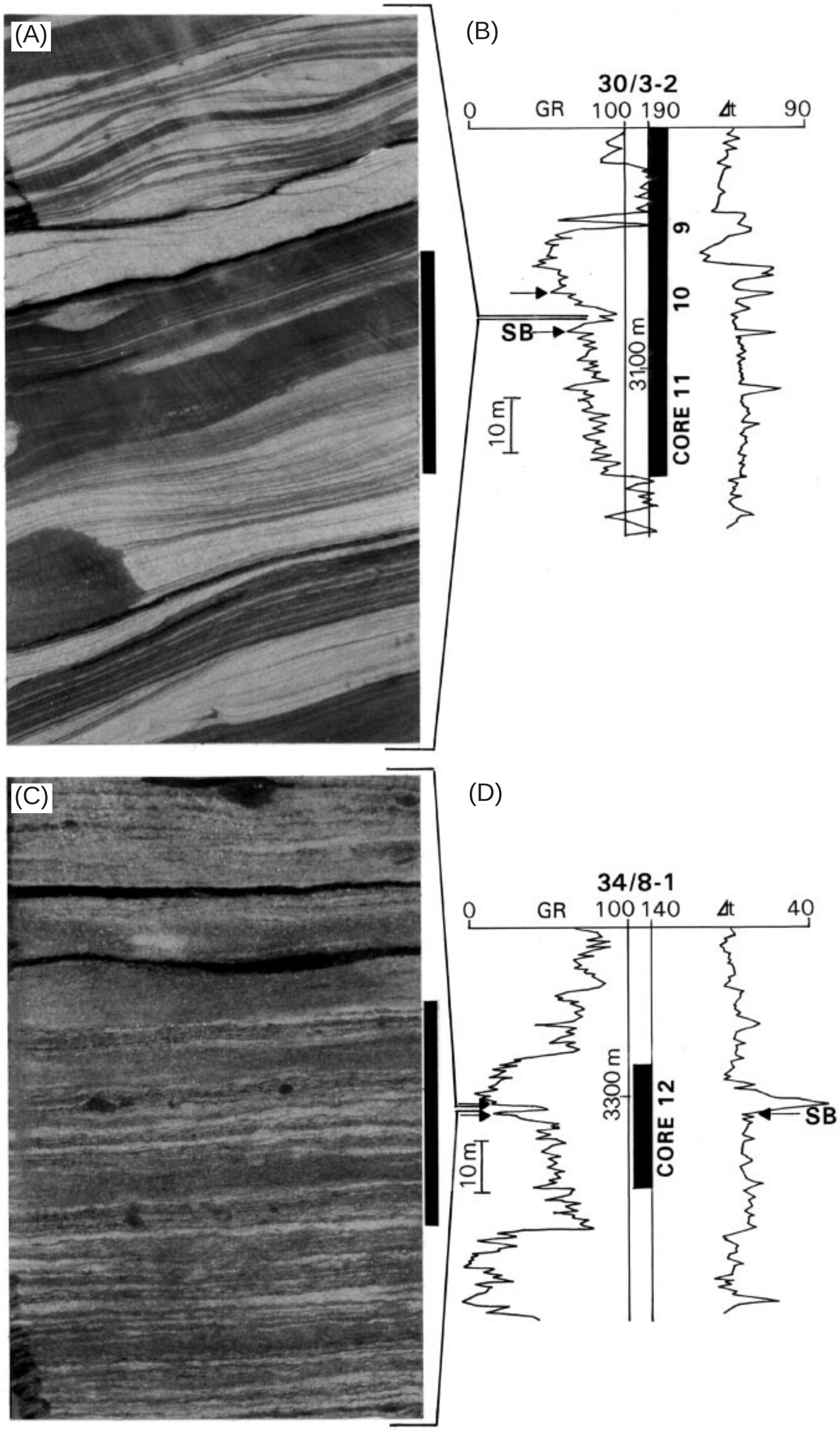

Figure 8—(A) Well 30/3-2, core 10 at 3090.6 m. These wave-generated sandstones and associated shales and siltstones, commonly unbioturbated to poorly bioturbated, are interpreted to be tidal-flat deposits. The form-discordant ripples and microhummocky cross-strata are very common. Scale bar is 5 cm. (B) Well log 30/3-2 showing the cored interval. Note the high radioactivity of the tidal-flat deposit and the sharp base of the overlying Cook Formation sandstones (arrow). (C) Well 34/8-1, core 12 at 3302 m. These unbioturbated, bituminous laminites (developed above the sequence boundary in the base of the Cook 1 unit) are interpreted as marsh deposits. Scale bar is 5 cm. (D) Well log 34/8-1 showing the cored interval. The base of the overlying Cook Formation sandstones (arrow) is very sharp.

coarsening-upward trends (Figure 7) caused by an increase in the number of siltstone and very fine rained sandstone interbeds. Only the lowermost part of the Drake Formation fines upward, with a decreasing number of sandstone laminae in dark-gray sandy and silty shales (Figure 9E). These basal intervals contain *Planolites* and occasional *Thalassinoides* traces, but the bioturbation

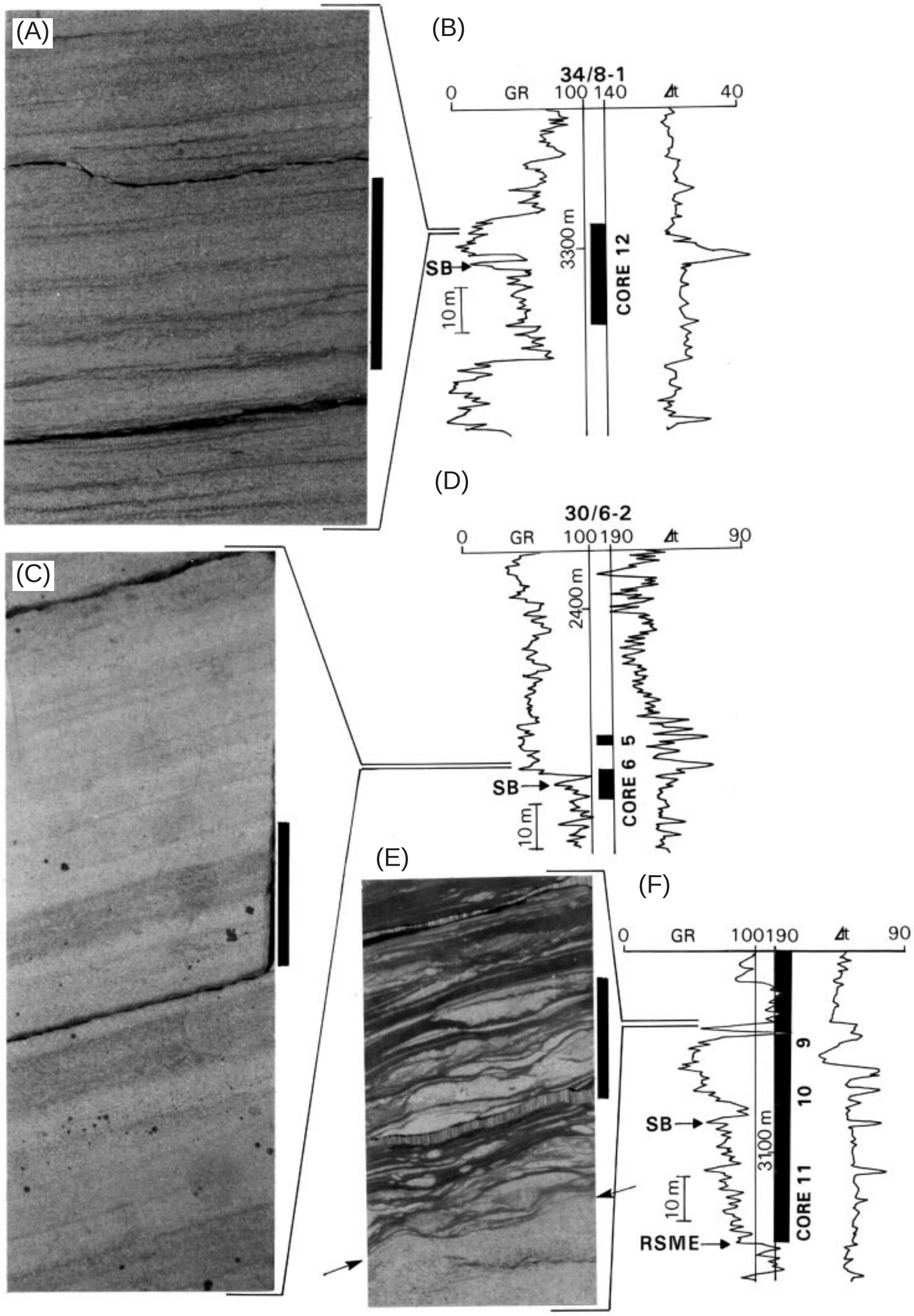

Figure 9—The Cook Formation sandstones. (A) Well 34/8-1, core 12 at 3295.6 m. The Cook Formation clean sandstones occasionally display well-developed large-scale cross-strata with double mud drapes along the lower parts of the foresets. The cross-strata with double mud drapes along the lower parts of the foresets are interpreted as parts of tidally constructed sand waves. Scale bar is 5 cm. (B) Well log 34/8-1 showing the cored interval. (C) Well 30/6-2, core 6 at 2434 m. The Cook Formation clean sandstones with no traces of ichnofauna, well-sorted sand, and well-developed large-scale cross-bedding are interpreted as fluvial sandstones. Scale bar is 5 cm. (D) Well log 30/6-2 showing the cored interval. (E) Well 30/3-2, core 9 at 3071 m. The top of the Cook Formation sandstone (arrows) is truncated by the wave ravinement surface. The erosional products form thin lenses of ripple-laminated sandstone that decrease in their number and thickness upward. Scale bar is 5 cm. (F) Well log 30/3-2 showing the cored interval. SB = sequence boundary, RSME = regressive surface of marine erosion.

commonly diminishes upward into silty shales with small *Chondrites*. Most of the Drake Formation is composed of laminated silty shale, and bioturbation disappears and reappears in intervals of a few meters to tens of meters. Several layers with exceptionally high natural radioactivity are developed, and these are interpreted as clean shales that are candidates for MFS. We have labeled as such only the maximum GR peaks, whereas lesser GR peaks are understood in terms of abortion of silt supply, and are labeled as EFS, and probably were caused by increased rates of sea level rise. The intervals with poor (only *Chondrites*) to absent bioturbation suggest deposition in a poorly oxygenated environment because of the apparent lack of bottom dwellers, and because the *Chondrites* trace is thought to indicate sea-bottom anoxia (Bromley and Ekdale, 1984; Savrda and Bottjer, 1986, 1987). The Drake Formation shales

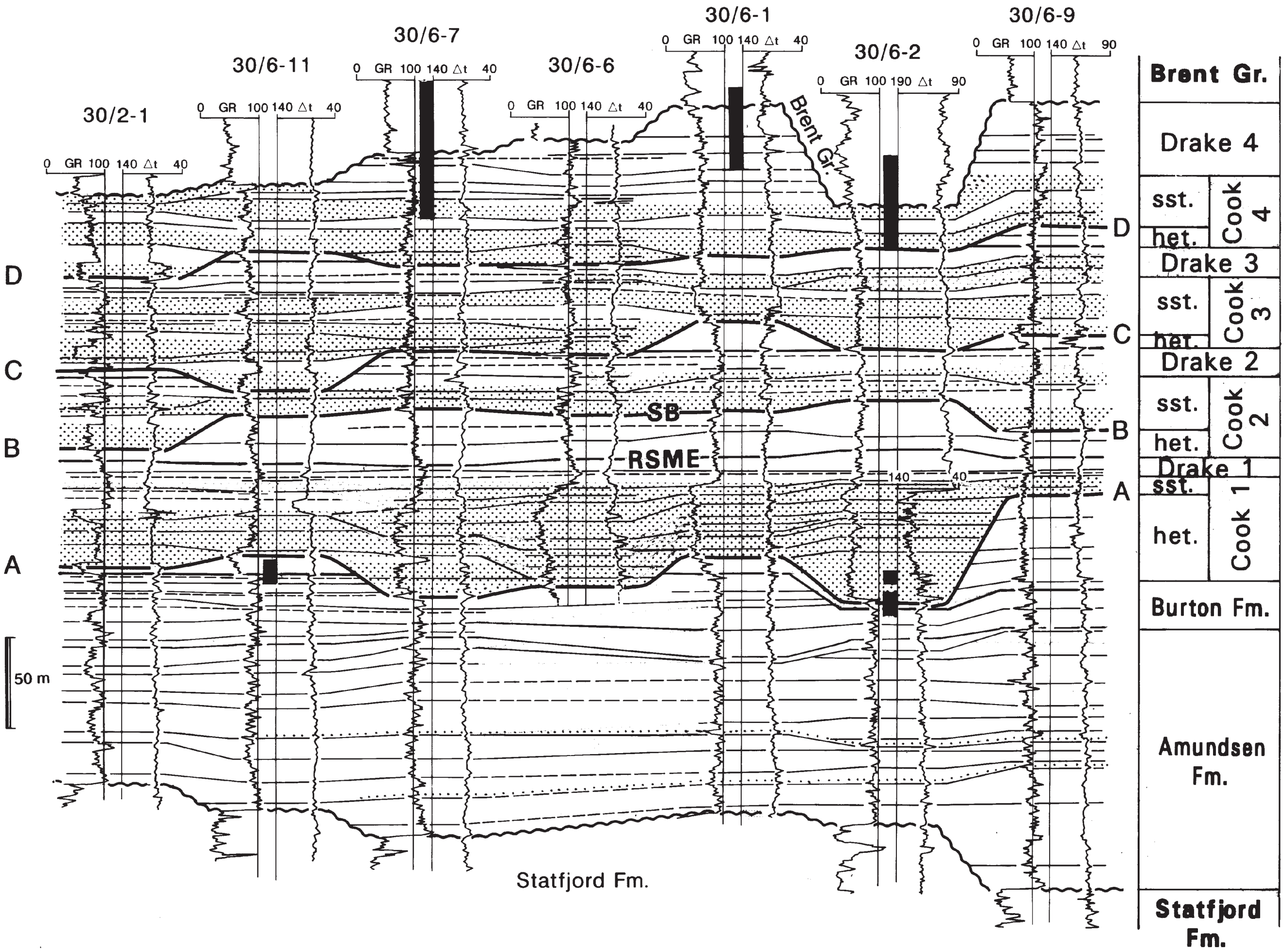

Figure 10—Cross section Huldra-south Oseberg field (location number 2 in Figure 3), approximately oblique-dip section, 44.4 km long. Cored intervals are shown by black rectangles. Note the deep incision of surface A into the underlying Burton and Amundsen formations and the complex infill of this incised topography.

(as well as lithologically identical Burton Formation shales) are interpreted as offshore/shelf deposits.

The Drake Formation is extensively developed on both sides of the northern North Sea. On the Horda Platform it interfingers with the Cook Formation, but its youngest part extends widely across the northern North Sea toward the basin margins (Figure 2). Where Drake Formation overlies Cook sandstones, the contact is abrupt (Figure 9E) and is interpreted in terms of a wave ravinement surface (WRS, Figure 7). The Drake Formation units are commonly truncated from above by deep incision at the base of younger Cook Formation units, as well as by the base of the Brent Group.

EROSIONAL SURFACES

A series of important erosional surfaces are found within the Dunlin Group: (1) surfaces associated with indications of some subaerial exposure and across which is a major basinward shift of facies, interpreted as sequence boundaries (SB), (2) surfaces that show a lesser basinward shift of facies, but that have marine facies both above and below, interpreted as regressive surfaces of marine erosion (RSME), and (3) surfaces across which is a landward shift of environments with successively deeper facies developed above them, and which are interpreted as ravinement surfaces created by accelerated sea level rise. The latter include tidal ravinement (TRS) and wave ravinement (WRS) surfaces, depending on whether the landward migration of the system was associated with the tidal prism or by shoreface erosion. All three types of surfaces truncate the underlying sediments to some degree.

Sequence boundaries are regionally developed erosional surfaces characterized in places by pedogenic horizons and (early) cementation (Figures 5C; 6A, C). They are sometimes overlain by tidal-flat

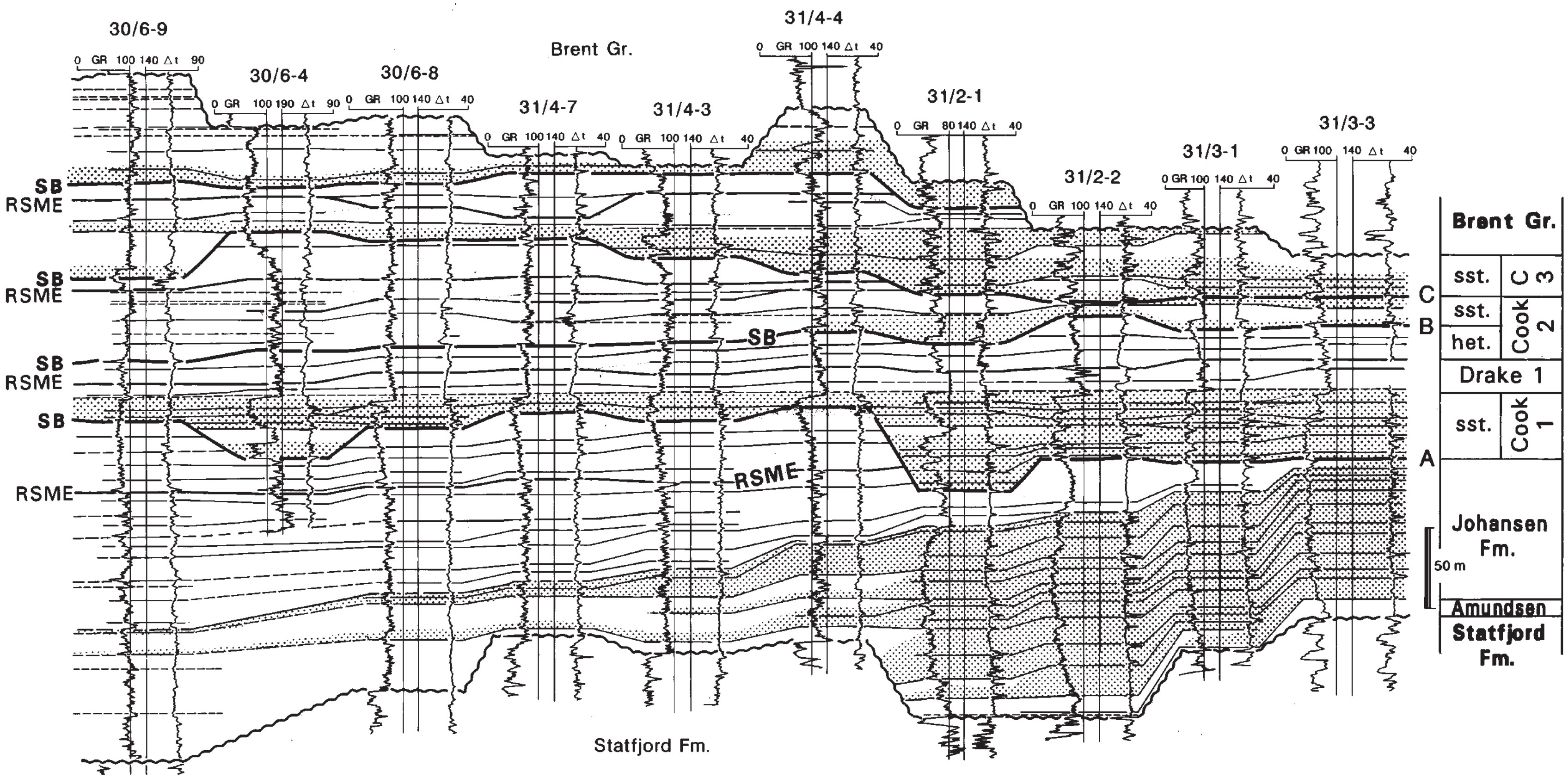

Figure 11—Cross section Oseberg-Brage-Troll field (location number 3 in Figure 3) is a 74.2-km-long strike section. Note wedging of the Johansen deltaic sandstones toward the west and a very thin backstepping unit marking the top of this body. Surface A shows deep incision in the south Oseberg (well 30/6-4) and Troll field areas (well 31/2-1).

(Figures 6A, 7, 8A) and marsh deposits (Figures 6C, 8C) or, more often, directly by estuarine sandstones (the main reservoir levels). In the well logs, these surfaces are sometimes characterized by sharp breaks in the GR log and a peak on the sonic curves, suggesting cleaner and better cemented sandstone. The sequence boundaries generally occur at the base of units of the Cook clean sandstones, and can be mapped to have a regional erosional development, as discussed further in the following paragraphs. Pedogenic features (Figure 6) recognized below some of these surfaces suggest a partly subaerial origin during times of low relative sea level. The initial progradational nature of many of the cleaner sandstone units above the sequence boundaries is taken as an indication of high sediment supply despite the likelihood that sea level had begun to rise. The lower parts of some of these sandstone units thus are considered to be tide-influenced deltas developed as lowstand systems tracts (lowstand prograding wedges, sensu Helland-Hansen and Gjelberg, 1994), whereas others are likely to be entirely transgressive, estuarine units that accumulated during backfilling of the incised topography.

The regressive surfaces of marine erosion at the base of the Cook heterolithic units are expressed by a rapid reduction in natural radioactivity and a peak in the sonic curve (Figures 5B, 7). These surfaces dip gently basinward (Figures 4, 10), and therefore are overlain by a shoreface lithosome (Figure 5A) that not only progrades basinward, but sometimes can be seen to have a slight downward trajectory (e.g., in the Cook 1 unit, Figure 4). The latter geometry is diagnostic of shoreface growth during a falling phase of relative sea level, and thus is consistent with the erosive nature of the basal shoreface and its associated truncation into the offshore shales below. These erosion surfaces are interpreted in terms of a response to relative sea level falls and mark the reestablished sand supply to the shelf. The regressive surfaces of marine erosion and their associated heterolithic shoreface deposits are therefore analogous to the falling-stage deposits of Nummedal (1992) and to the forced regressive systems tract of Hunt and Tucker (1992) and of Helland-Hansen and Gjelberg (1994). Note that these surfaces are not sequence boundaries because they form during falling sea level (see also Mellere and Steel, 1995) and underlie fully marine (shoreface) deposits. The sequence boundaries in the Dunlin Group, in contrast, always lie above the heterolithic shoreface lithosomes, are marked by significantly deeper and more widespread erosion than is the case for regressive surfaces of marine erosion, and are generally overlain by the best reservoir sandstones (Figures 4, 7, 10, 11).

Marine transgressive or ravinement surfaces (sensu Swift, 1968) are typically associated with the tops of the Cook sandstones (wave ravinement surfaces) (WRS in Figure 7, and Figure 9E). The wave ravinement surfaces are recognized in cores as small-scale but distinct erosion surfaces, fairly abruptly overlain by increasingly finer grained facies, and are interpreted in terms of abrupt deepening of the water column. The shales contain centimeter-thick sandstone interbeds that decrease in number upward. There is also commonly a marked erosion surface at the base of the Cook Sandstone units (estuarine sands). This is a surface of tidal erosion developed by the landward migration of estuarine channels back across the muddier zones of the estuarine system, and is referred to here as a surface of tidal ravinement to also convey the transgressive nature of this type of surface (TRS in Figure 7) (see also Allen and Posamentier, 1993). The tidal ravinement amalgamates with and is indistinguishable from the sequence boundary in places, but it is quite distinct and occurs above the sequence boundary where there is an intervening unit of tidal-flat deposits (Figures 7, 8).

Table 1. Relief and Average Depth on the Major Erosional Surfaces and Incised Valleys

	Maximum Relief (m)	Average Depth (m)
Base	327	169
A	157	97
B	75	45
C	75	39
D	37	24

TOPOGRAPHY OF SEQUENCE BOUNDARIES

The geometry of the major erosion surfaces (sequence boundaries) is revealed by regional cross sections (Figures 4, 10, 11), as well as by isopach maps and 3-D block diagrams (Figure 12). The greatest topography is developed on the Dunlin Group base (referred to as the base surface in Figure 12) with an amplitude of up to several hundreds of meters in places. The younger surfaces (A, B, C, and D, Figure 2) have smaller amplitudes, but still have well-developed topography (Figure 12). Surfaces A–D have maximum known depths of incision of less than 100 m, but the associated relative sea level falls probably exceed these values. A brief summary of incision depths is given in Table 1.

The topography associated with the sequence boundaries in Figure 12 shows several valley-like features bordered by highs developed at various stratigraphic levels. The deepest incised areas are overlain by the thickest sandstones, suggesting that these acted as conduits and sand traps. These lows are interpreted as the incised valleys, whereas the intervening highs are interpreted as interfluves. For purposes of easier reference, the lows (valleys) and highs are informally labeled, usually after the closest field or structural unit.

In this setting, deltaic and estuarine systems provided and accumulated sands that originated from the erosion of exposed shelf areas, as well as from the hinterlands beyond. The hinterlands at this time were sited more than 100 km landward from the contemporary shorelines. Fluvial systems transported sands farthest basinward during the lowstand periods. During subsequent sea level rise, tidal currents became amplified in embayments and incised valleys from the mouth headward (as in the modern Gironde estuary; Bern et al., 1993), building large sand-wave fields that eventually filled most of the valleys. Tidal channels cut deeply into the underlying tidal-estuarine muds and heterolithic deposits (see also Allen and Posamentier, 1993); thus, the preservation of the heterolithic deposits is only patchy. The outer reaches of the early subaerial relief may have been erosively modified by transgression during continued sea level rise, creating flat-bottomed wide valleys with blunt-shaped heads. The upper reaches of these valleys locally extend into narrow tributaries with steeper slopes (Figure 12).

Base Surface

The main topographic feature developed at this level is the steep-sided north-south–trending Sogn base-valley (Figure 12). This valley is approximately 40 to 50 km wide, more than 70 km long, and about 150 to 200 m deep. It was open toward the north and its upslope extensions are the relatively narrow Troll and Southern base-valley. The Southern base-valley is about 20 km wide, more than 60 km long, and approximately 50 m deep. The Gullfaks base-valley seems to be a western tributary of the Southern base-valley, although it appears somewhat deeper. We suspect that the deep part of the Gullfaks base-valley extended along the southern flank of the Visund base-high and drained into the Sogn base-valley, although this extension is not clear due to the lack of wells in that area.

The most prominent high developed at this level is the Murchinson base-high. Other lesser, but still well defined, highs are the Visund, Brage, and Agat base-highs.

Surface A

The main topographic feature at this level (Figure 12) is the broad Sogn A-valley, widely open toward the north and matching the position of the earlier Sogn base-valley. The Sogn A-valley is about 50 km wide, more than 70 km long, and approximately 30 to 50 m deep. Its head is blunt, and extends updip as the Troll A-valley, matching the position of the earlier Troll base-valley. The Southern A-valley also seems to have been an "inherited" feature; it is approximately 10 km wide, more than 50 km long, and approximately 30 m deep. Its lowest area is on the margin of the later Viking Graben, and it is very likely that the graben drained into the Sogn A-valley through a narrow strait that provided ideal conditions for amplification of tidal currents.

Prominent highs at this level are the Murchinson A-high and the somewhat lower Visund and Brage A-highs, which match the positions of equivalent highs developed at the base level. Erosional surface A (Figure 12) gives the impression of a mature relief created by subaerial erosional processes.

Surface B

The main topographic feature here is the broad Northern B-valley, open toward the north (Figure 12). This valley is about 60 km wide in its central part, more than 60 km long, and approximately 35 to 50 m deep. Diagonally across the study area are several shallow depressions that are probably linked in the form of the shallow, broad Diagonal B-valley, connecting the Southwestern and Eastern B-valleys.

The prominent highs were Murchinson B-high and Visund B-high. A broad, low high was developed also in the Horda platform area (Horda B-high). The embayment-like Northern and Eastern B-valleys are also likely to have amplified tidal currents, particularly during the sea level rise, with flooding of the Diagonal B-valley that looks more like a narrow seaway or a strait. The topography of erosional surface B also resembles a mature relief created by subaerial erosional processes, subsequently modified by ravinement processes during the sea level rise.

Surface C

Surface C is generally smoother, compared to surfaces A and B (Figure 12). The northward drainage was still open through the Northern C-valley, which is about 20 to 30 km wide, more than 40 km long, and approximately 20 m deep. This valley appears to have shifted toward the west with respect to the position of the earlier Northern B-valley. The Eastern C-valley is on the margin of the study area, and its dimensions are not known. The Southeastern C-valley opens toward the southeast.

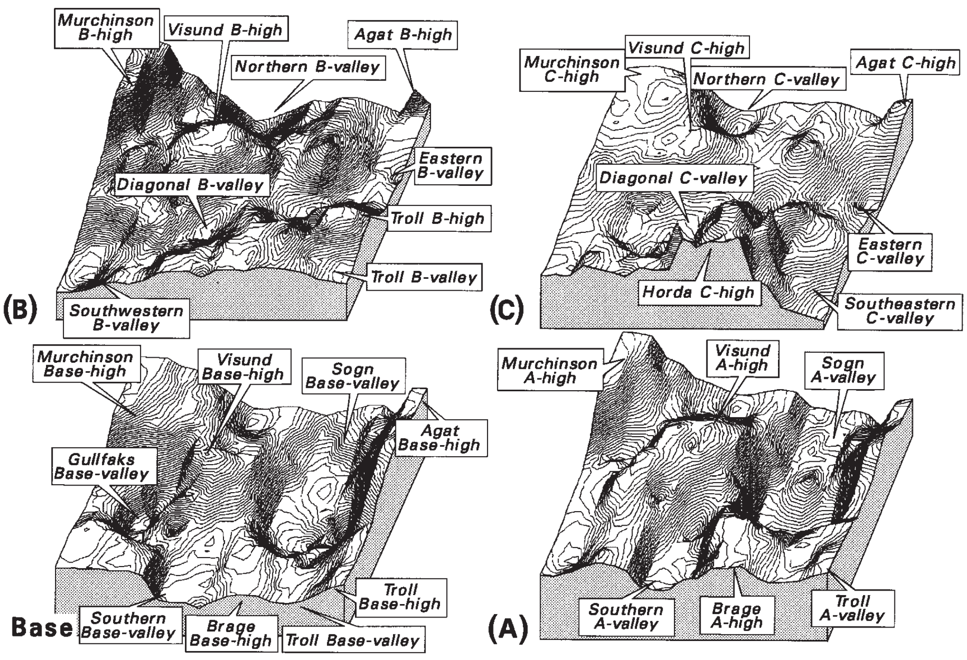

Figure 12—Three-dimensional reconstruction of topography at the Dunlin Group base (base surface) and on erosional surfaces A, B, and C. Paleotopographic features are named informally. Some inherited topographic features, such as the Sogn base-valley and Sogn A-valley, as well as the Visund Base-high, Visund A-high, and Visund B-high, were most likely structurally controlled.

The central part of the study area is characterized by a few shallow depressions that appear isolated because of the lack of well data in that area. However, a regional gradient toward the northeast suggests that they represent parts of the larger Diagonal C-valley, which was draining into the Eastern C-valley.

The prominent highs at this level are Murchinson C-high and Visund C-high in the northwest and Horda C-high in the south. Regional gradients of slope suggest possible southeastward drainage from the Murchinson C-high, as well as northward and southeastward drainage from the Horda C-high. The Diagonal C-valley probably allowed drainage toward the Eastern C-valley. Thus, the sandstones associated with surface C in the Gullfaks field area may have originated from sources on the northwest (Murchinson-Visund highs), though possibly also from some sources in the south and east, as reconstructed by Dreyer and Wiig (1995).

A NEW STRATIGRAPHIC MODEL FOR COOK SANDSTONE TONGUES

We suggest two main scenarios for the emplacement of nearshore sands (Cook Sandstone units) far out into shelf locations: (1) times of falling sea level that tended to stretch wave-influenced shorelines basinward, far beyond their former highstand positions (see also Plint et al., 1993), and (2) times of initial rising sea level that allowed the development of tide-dominated lowstand-to-transgressive wedges (see also Mellere and Steel, 1995), the most basinward sandy lithosomes, to develop in such low-gradient epicontinental basins. The false impression of a shelf location for these sandy shoreline lithosomes is then further exaggerated by the subsequent sea level rise and transgression, causing true shelf mudstones to both overlie as well as underlie the sandstone tongues.

The sequence stratigraphic model suggested for each of the Cook Formation sandstone tongues in the northern North Sea, summarized in a simplified one-dimensional profile in Figure 7, is one composed of three systems tracts with a series of regressive and transgressive surfaces of erosion. The important subregional aspects of the model are illustrated in Figures 4, 10–12.

The Cook heterolithic facies were deposited during a falling stage of sea level and represent a forced regressive systems tract (latest highstand tract in some interpretations). Their bases are interpreted as regressive surfaces of marine erosion. Their tops are erosion surfaces of even greater relief, usually the lower boundaries of each of the four Cook Formation sandstone units, and these can be mapped subregionally as four major surfaces of incision that controlled the distribution and the nature of the Cook Formation reservoir units. The base, A, B, and C surfaces, formed largely by subaerial erosion, are recognized as sequence boundaries. This conclusion is strongly supported by the magnitude of the incised relief and the clear basinward shift of facies across these surfaces, as well as the occasional presence of pedogenically altered sandstones associated with the erosion surfaces. Local developments of tidal-flat deposits (with markedly different ichnofabrics from the underlying middle shoreface deposits) lie immediately above the sequence boundary, but below the tidal ravinement surface (e.g., in well 30/3-2, Figure 7). Over most of the region, however, the sequence boundary and the surface of tidal erosion are amalgamated into a single surface (Figures 4, 10–12).

The Cook sandstones and the underlying tidal-flat remnants were deposited partly during initial sea level rise (prograding lowstand wedges) and partly during the subsequent accelerated rise in sea level (estuarine backfilling during the development of a transgressive systems tract). Note that the transgressive systems tract consists of both the main reservoir sandstone unit (below the wave ravinement surface, but above the tidal ravinement surface) and the overlying thin upward-fining unit (between the wave ravinement surface and the maximum flooding surface).

In the overlying Drake Formation interval, a surface of maximum flooding was developed during the period of highest rate of sea level rise. The bulk of the Drake Formation was thus deposited mainly as late transgressive and highstand deposits in an offshore setting.

CONCLUSIONS

The Johansen Formation sandstones are interpreted in terms of a northward-prograding delta confined to topographic lows developed at the base level of the Dunlin Group. This topography was created during a significant sea level fall, but was presumably modified during subsequent sea level rise. The greater part of the Johansen delta can be seen as a lowstand prograding systems tract with only a thin, upper transgressive layer. The delta was probably aborted by higher rates of sea level rise that both drowned the delta and initiated deposition of the shaly Amundsen and Burton formations.

The Cook Formation sandstone tongues within the Dunlin Group occur at four distinct stratigraphic levels. Each tongue consists of a lower heterolithic part and an upper sandstone part. The lower heterolithic parts are reinterpreted as shoreface deposits created during falling relative sea level and are characterized by gentle basinward progradation and downlap/offlap onto the underlying offshore shales of the Burton and Drake formations. The Cook sandstones have sharp erosive bases (sequence boundaries), are laterally more restricted, and are interpreted as largely estuarine deposits. Thus, they form combined lowstand and transgressive systems tracts, whereas the overlying Drake Formation shales are highstand deposits. Structure-contour maps of the Cook sandstone bases reveal the considerable paleotopography that controls the character and distribution of the Cook Formation reservoirs.

REFERENCES CITED

Ager, D. V., 1975, The Jurassic world ocean (with reference to the North Atlantic): Jurassic Northern North Sea Symposium, Stavanger, p. 1–43.

Aliotta, S., and G. M. E. Perillo, 1987, A sand wave field in the entrance to Bah¡a Blanca estuary, Argentina: Marine Geology, v. 76, p. 1–14.

Allen, G. P., and H. W. Posamentier, 1993, Sequence stratigraphy and facies model of an incised valley fill: the Gironde estuary, France: Journal of Sedimentary Petrology, v. 63, no. 3, p. 378–391.

Bern, S., P. Castaing, E. Le Drezen, and G. Lericolais, 1993, Morphology, internal structure, and reversal of asymmetry of large subtidal dunes in the entrance to Gironde estuary (France): Journal of Sedimentary Petrology, v. 63, no. 5, p. 780–793.

Bromley, R. G., and A. A. Ekdale, 1984, Chondrites: a trace fossil indicator of anoxia in sediments: Science, v. 224, p. 872–874.

Buza, J. W., and A. Unneberg, 1987, Geological and reservoir engineering aspects of the Statfjord field, *in* J. Kleppe, E. W. Berg, A. T. Buller, O. Hjelmeland, and O. Torsaeter, eds., North Sea oil and gas reservoirs: London, Graham and Trotman, p. 23–38.

Dalrymple, R. W., R. J. Knight, B. A. Zaitlin, and G. V. Middleton, 1990, Dynamics and facies model of a microtidal sand-bar complex, Cobequid Bay–Salmon River estuary (Bay of Fundy): Sedimentology, v. 37, p. 577–612.

Doré, A. G., G. P. Hamar, T. Lilleng, N. D. Shaw, O. Skarpnes, and J. Vollset, 1984, Revised Jurassic lithostratigraphy of the Norwegian North Sea, northern area, *in* J. Vollset and A. G. Doré, eds., A revised Triassic and Jurassic lithostratigraphic nomenclature for the Norwegian North Sea: Norwegian Petroleum Directorate Bulletin, v. 3, p. 2–53.

Dreyer, T., and M. Wiig, 1995, Reservoir architecture of the Cook Formation on the Gullfaks field based on sequence stratigraphic concepts, *in* R. J. Steel, V. L. Felt, E. P. Johannessen, and C. Mathieu, eds., Sequence stratigraphy on the northwest European margin: Norwegian Petroleum Society Special Publication 5, p. 109–141.

Erichsen, T., M. Helle, J. Henden, and A. Rognebakke, 1987, Gullfaks, *in* A. M. Spencer, C. J. Campbell, S. H. Hanslien, E. Holter, P. H. H. Nelson, E. Nysæther, and E. G. Ormaasen, eds., Geology of the Norwegian oil and gas fields: London, Graham and Trotman, p. 273–286.

Gage, M. S., and A. G. Doré, 1986, A regional geological perspective of the Norwegian offshore exploration provinces, *in* A. M. Spencer, C. J. Campbell, S. H. Hanslien, E. Holter, P. H. H. Nelson, E. Nysæther, and E. G. Ormaasen, eds., Habitat of hydrocarbons on the Norwegian continental shelf: London, Graham and Trotman, p. 21-38.

Gradijan, S. J., and M. Wiik, 1987, Statfjord Nord, , *in* A. M. Spencer, C. J. Campbell, S. H. Hanslien, E. Holter, P. H. H. Nelson, E. Nysæther, and E. G. Ormaasen, eds., Geology of the Norwegian oil and gas fields: London, Graham and Trotman, p. 341–350.

Helland-Hansen, W., and J. G. Gjelberg, 1994, Conceptual basis and variability in sequence stratigraphy: a different perspective: Sedimentary Geology, v. 92, p. 31–52.

Houbolt, J. J. H. C., 1968, Recent sediments in the Southern Bight of the North Sea: Geologie en Mijnbouw, v. 47, p. 245–273.

Hunt, D., and M. E. Tucker, 1992, Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall: Sedimentary Geology, v. 81, p. 1–9.

Livbjerg, F., and R. Mjos, 1989, The Cook Formation, an offshore sand ridge in the Oseberg area, northern North Sea, *in* J. D. Collinson, ed., Correlation in hydrocarbon exploration: London, Graham and Trotman, p. 299–312.

Marjanac, T., 1995, Architecture and sequence stratigraphic perspectives of the Dunlin Group formations and proposal for new type- and reference-wells, *in* R. J. Steel, V. L. Felt, E. P. Johannessen, and C. Mathieu, eds., Sequence stratigraphy on the northwest European margin: Norwegian Petroleum Society Special Publication 5, p. 143–165.

Mellere, D., and R. J. Steel, 1995, Facies architecture and sequentiality of nearshore/shelf sand bodies, Haystack Mountain Formation, Wyoming, USA: Sedimentology, v. 42, p. 551–574.

Nummedal, D., 1992, The falling sea level systems tract in ramp settings (abs): Proceedings of the Mesozoic of the Western Interior Abstracts, SEPM Theme Meeting, p. 50.

Parkinson, D. N., and F. M. Hines, 1995, The Lower Jurassic of the North Viking Graben in the context of western European Lower Jurassic stratigraphy, *in* R. J. Steel, V. L. Felt, E. P. Johannessen, and C. Mathieu, eds., Sequence stratigraphy on the northwest European margin: Norwegian Petroleum Society Special Publication 5, p. 97–107.

Partington, M. A., P. Copestake, B. C. Mitchener, and J. R. Underhill, 1993, Biostratigraphic calibration of genetic stratigraphic sequences in the Jurassic–lowermost Cretaceous (Hettangian to Ryazanian) of the North Sea and adjacent areas, *in* J. R. Parker, ed., Petroleum geology of northwest Europe: Proceedings 4th Conference London (1992), 1, Geological Society of London, p. 371–386.

Plint, A. G., B. S. Hart, and W. S. Donaldson, 1993, Lithospheric flexure as a control on stratal geometry and facies distribution in Upper Cretaceous rocks of the Alberta foreland basin: Basin Research, v. 5, p. 69–77.

Posamentier, H. W., G. P. Allen, D. P. James, and M. Tesson, 1992, Forced regressions in a sequence stratigraphic framework: concepts, examples, and exploration significance: AAPG Bulletin, v. 76, p. 1687–1709

Richards, P. C., 1990, The early to mid-Jurassic evolution on the northern North Sea, *in* R. F. P. Hardman and J. Brooks, eds., Tectonic events responsible for Britain's oil and gas reserves: Geological Society of London Special Publication 55, p. 191–205.

Roberts, J. D., A. S. Matheison, and J. M. Hampson, 1987, Statfjord, *in* A. M. Spencer, C. J. Campbell, S. H. Hanslien, E. Holter, P. H. H. Nelson, E. Nysæther, and E. G. Ormaasen, eds., Geology of the Norwegian oil and gas fields: London, Graham and Trotman, p. 319–340.

Savrda, C. E., and D. J. Bottjer, 1986, Trace-fossil model reconstruction of paleo-oxygenation in bottom waters: Geology, v. 14, p. 3–6.

Savrda, C. E., and D. J. Bottjer, 1987, The exaerobic zone, a new oxygen-deficient marine biofacies: Nature, v. 327, p. 54–56.

Skarpnes, O., G. P. Hamar, K. H. Jakobsson, and D. E. Ormaasen, 1980, Regional Jurassic setting on the north sea north of the central highs, *in* The sedimentation of the North Sea reservoir rocks: Norwegian Petroleum Society, Geilo Paper XIII, p. 1–8.

Steel, R. J., 1993, Triassic–Jurassic megasequence stratigraphy in the northern North Sea: rift to post-rift evolution, *in* J. R. Parker, ed., Petroleum geology of northwest Europe: Proceedings 4th Conference London (1992), 1, Geological Society of London, p. 299–315.

Swift, D. J. P., 1968, Coastal erosion and transgressive stratigraphy: Journal of Geology, v. 76, p. 444–456.

Vollset, J., and A. G. Doré, 1984, A revised Triassic and Jurassic lithostratigraphic nomenclature for the Norwegian North Sea: Norwegian Petroleum Directorate Bulletin 3, p. 2–53.

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