

Differential subsidence in the Ness Formation (Bajocian), Oseberg area, northern North Sea: facies variation, accommodation space development and sequence stratigraphy in a deltaic distributary system

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The Ness Formation (Bajocian) consists of the alluvial distributary plain deposits of the Middle Jurassic Brent delta. The formation comprises fluvial channel sandstones intercalated with fine-grained floodplain deposits. The sandstone bodies are significant hydrocarbon reservoirs in the Oseberg field and surrounding smaller structures in the Norwegian North Sea, to which the present study pertains. The alluvial succession shows significant thickening across normal faults, reflecting syndepositional differential subsidence. The thickness proportion of fluvial sandstones varies with the succession thickness. Where the succession is relatively thin, it is characterized by a large variation in the content of fluvial sandstones. Where thicker, the succession shows less variation in the proportion of fluvial sandstones. The proportion of fluvial sandstones tends to stabilize or even decrease in the thickest profiles of the formation. These findings are in contrast to theoretical alluvial stratigraphy models, which predict greater sandstone body proportions in areas of greater subsidence. The stacking pattern of fluvial sandbodies shows widespread temporal changes that can be correlated throughout the study area, and are independent of variations in thickness of the formation. These facies changes are approximately chronostratigraphic and allow for the definition of two sequences, each comprising a low-accommodation systems tract, succeeded by a high-accommodation systems tract.

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Introduction

The Middle Jurassic (Bajocian) Ness Formation represents the delta-plain part of the large deltaic Brent Group (e.g. Eynon 1981; Livera 1987; Ryseth 1989; Morton et al. 1992), which is the main petroleum reservoir in the northern North Sea region (e.g. Spencer & Larsen 1990). In the Horda Platform area of the Norwegian North Sea sector (Fig. 1), significant hydrocarbon resources occur in the Ness Formation in the giant Oseberg field, and production from the Ness Formation is also economically vital to the development of several smaller fields in the surroundings of the Oseberg installation.

Sedimentological studies in the Oseberg field (Ryseth 1989; Ryseth & Fjellbirkeland 1995; Ryseth et al. 1998) have demonstrated that the deposition of the Ness Formation occurred in a fluvially dominated delta-plain environment, and that its reservoir potential is controlled by the vertical and lateral distribution of fluvial channel sandstones encased within contemporaneous, fine-grained floodplain deposits.

The formation thickness (approx. 40–310 m) varies significantly between neighbouring fault-bounded blocks, apparently attributable to syndepositional differential subsidence. This study relates the reservoir potential of the Ness Formation, in terms of its total sandstone content and sandstone proportion, to the local thickness of the sedimentary succession. Furthermore, the variation in the

stacking density of fluvial sandstone bodies (depositional architecture) is addressed from the point of view of sequence stratigraphy, on which two possible stratigraphic sequences are distinguished in the Ness Formation.

Database and methods

The database for this study includes cores and wireline logs from 30 exploration wells and 56 production wells penetrating the Ness Formation in and around the Oseberg field (Fig. 1). Additional data from a number of wells with truncated Ness Formation have also been used. Environmental interpretations and definitions of sandstone body types (single-storey vs. multistorey bodies) are based on examination of slabbed cores, and form the principal basis for interpreting depositional environments from wireline logs, including gamma ray, bulk density, neutron porosity and velocity curves.

The analysis of alluvial architecture follows two main lines. First, the role of differential subsidence is assessed by considering the relationships between the formation's gross thickness and the cumulative thickness/proportion of channel sandstones and between the gross thickness and the number of coal beds. For this purpose only wells with complete Ness Formation profiles have been used. Secondly, the sandstone body geometry and stacking

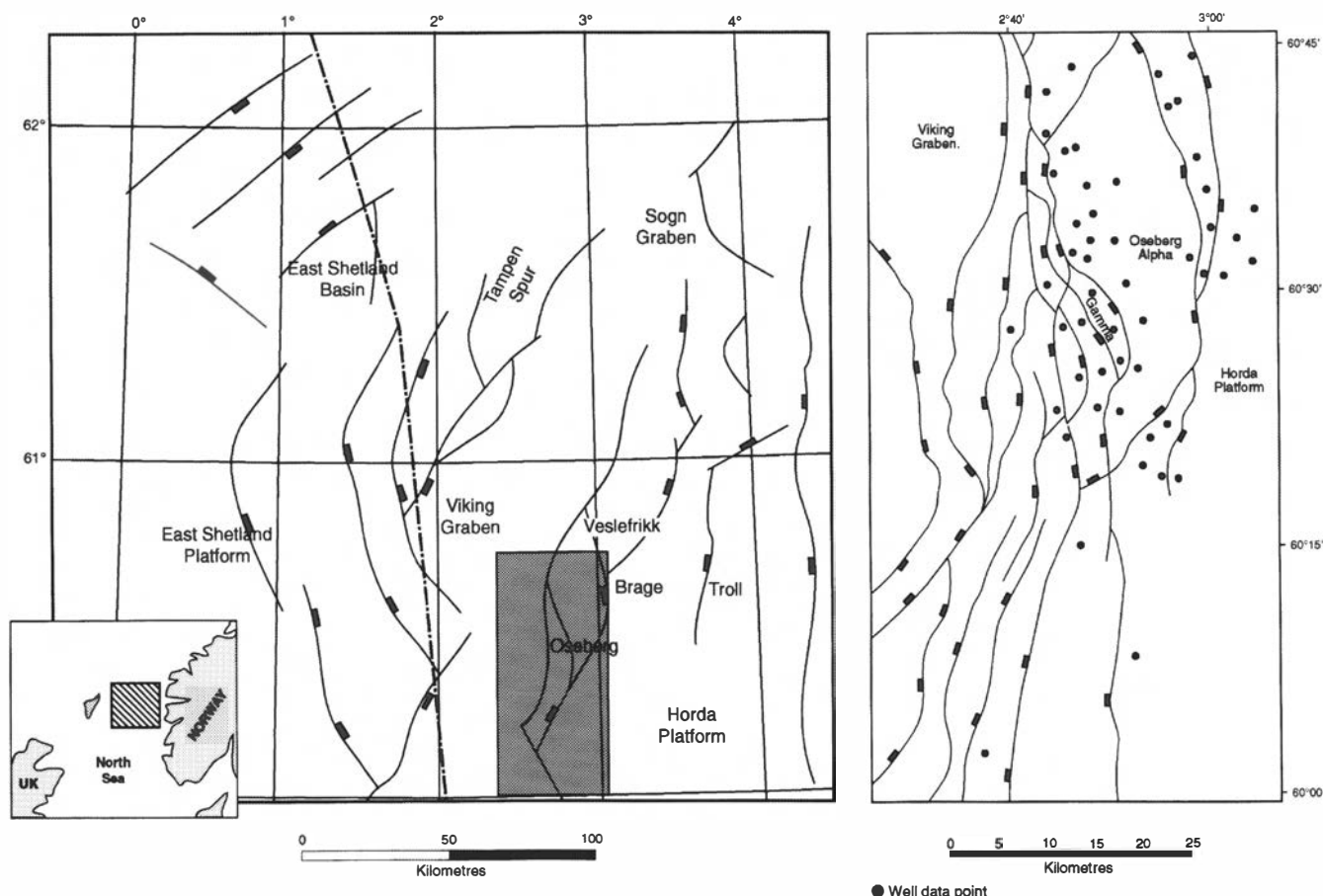


Fig. 1. Locality map showing the structural elements, main faults and the regional well database. The study area is located at the western margin of the Horda Platform, where north- and northwest-trending normal faults demarcate the main structural elements. The database comprises exploration and production wells (not shown) from the Oseberg field and surrounding areas.

pattern for various formation thicknesses are investigated, and discussed in terms of sequence stratigraphy.

The gross stratigraphic thickness (T) of the alluvial succession and the cumulative thickness of channel sandstones (SB) within each profile have been obtained from wireline logs or cores. The ratio SB/T, reflecting the proportion of channel deposits (CDP) in the alluvial succession, is the most important parameter for the prediction of sandstone body interconnectedness (Bridge & Mackey 1993) and is correlated with the variation in gross formation thickness (T). Table 1 shows a list of parameters and units used in the analysis.

Structural setting

The Horda Platform area (Fig. 1) is part of the economic-

ally important Brent province (e.g. Yielding et al. 1992), and constitutes the eastern margin of the Viking Graben (Fig. 1). The platform contains important hydrocarbon fields, such as the giant Troll and Oseberg fields and a number of smaller hydrocarbon accumulations like Brage, Huldra, Veslefrikk and several smaller structures around Oseberg (Oseberg satellites). The play hydrocarbon characterizing the province involves rotated Mesozoic fault blocks capped with Cretaceous and Tertiary mudrocks (for a review, see Spencer & Larsen 1990).

Rifting and crustal extension in the Viking Graben commenced in Late Permian/Early Triassic time (Giltner 1987; Badley et al. 1988; Steel & Ryseth 1990; Færseth 1996) and was followed by post-rift thermal subsidence throughout Triassic to Middle Jurassic time. A second phase of rifting occurred in the Late Jurassic and earliest Cretaceous, forming the present-day fault block structure, and was followed by renewed crustal contraction and thermal subsidence throughout Cretaceous and Tertiary time (e.g. Badley et al. 1988). Most faults in the study area strike N-S and NNW-SSE, fairly parallel to the Viking Graben (Fig. 1). The majority of faults show substantial thickening (up to 100%) of Early and Middle Jurassic strata, implying that they were established prior to the Late Jurassic rift phase (Færseth 1996; Frisstad et al. 1997).

Table 1. List of quantitative characteristics.

T	Total thickness (m) of the alluvial succession in a well profile
#SB	No. of fluvial sandstone bodies in a well profile
SB	Total cumulative thickness (m) of fluvial sandstones in a well profile
SBT	Average sandstone body thickness (m) in a well profile
CDP	Thickness proportion of fluvial sandstones (= SB/T) in a well profile
CB	No. of coal beds in a well profile

Incipient fault-block rotation heralding the Late Jurassic–Early Cretaceous rifting commenced in the Oseberg area in the Late Bajocian, after deposition of the Ness Formation (Færseth & Ravnås 1998).

The study area, comprising the Brage field and the Oseberg field with smaller ‘satellite’ structures to the southwest, is located on the western flank of the Horda Platform (Fig. 1). Here, a number of fault blocks separate the moderately faulted platform to the east from the deeply down-thrown graben floor to the west. Detailed seismic investigation of the western boundary fault in the Oseberg field has shown that this fault accommodated considerable differential subsidence during the deposition of the Brent Group, and that faulting at this stage was normal and planar (Badley et al. 1984; Fristad et al. 1997). Accordingly, formation thicknesses within each fault-bounded block are fairly constant, but vary significantly from block to block. Differential subsidence across steep, planar faults is typical for the Brent Group throughout the North Sea, but the amount of crustal extension related to this faulting is small (Yielding et al. 1992).

Brent Group

The Middle Jurassic deltaic deposits of the Brent Group (Aalenian–Bathonian; Fig. 2) are the principal reservoirs in the area. This regressive/transgressive cycle of sedimentation (e.g. Eynon 1981; Graue et al. 1987, Helland-Hansen et al. 1992; Johannessen et al. 1995) occurred during the late phase of post-rift subsidence following the Late Permian/Early Triassic rifting. The thickness distribution of the deposits is consequently controlled by both the thermally driven subsidence, and incipient faulting of the Late Jurassic–Early Cretaceous episode of rifting (Yielding et al. 1992).

The nature of the Brent Group in the Oseberg field area is summarized in Fig. 2 (for a detailed account of the reservoir geology in the Oseberg field, see Ryseth et al. 1998). Deposition commenced with a phase of lateral progradation and sand emplacement (Oseberg Fm.), followed by the northward advance and retreat of the giant deltaic system (Rannoch, Etive, Ness and Tarbert fms.). The vertical transition from shelfal mudrocks (Drake Fm; Fig. 2) into shallow marine sandstones (Oseberg Fm.) can be related to a Late Aalenian regression caused by ‘mid-Cimmerian’ thermal activity and tectonic uplift of the basin margins (Mitchener et al. 1992; Steel 1993). The base of the Oseberg Formation is regarded as a sequence-bounding unconformity.

Graue et al. (1987) recognized a marine flooding event at the base shoreface deposits of the Rannoch Formation, and a maximum flooding surface is placed at this stratigraphic level. Notably, the Rannoch and Etive formations, which jointly attain a thickness of more than 100 m in other parts of the province (Graue et al. 1987; Johannessen et al. 1995), are consistently thin (5–15 m) above the Oseberg Formation. This indicates that the

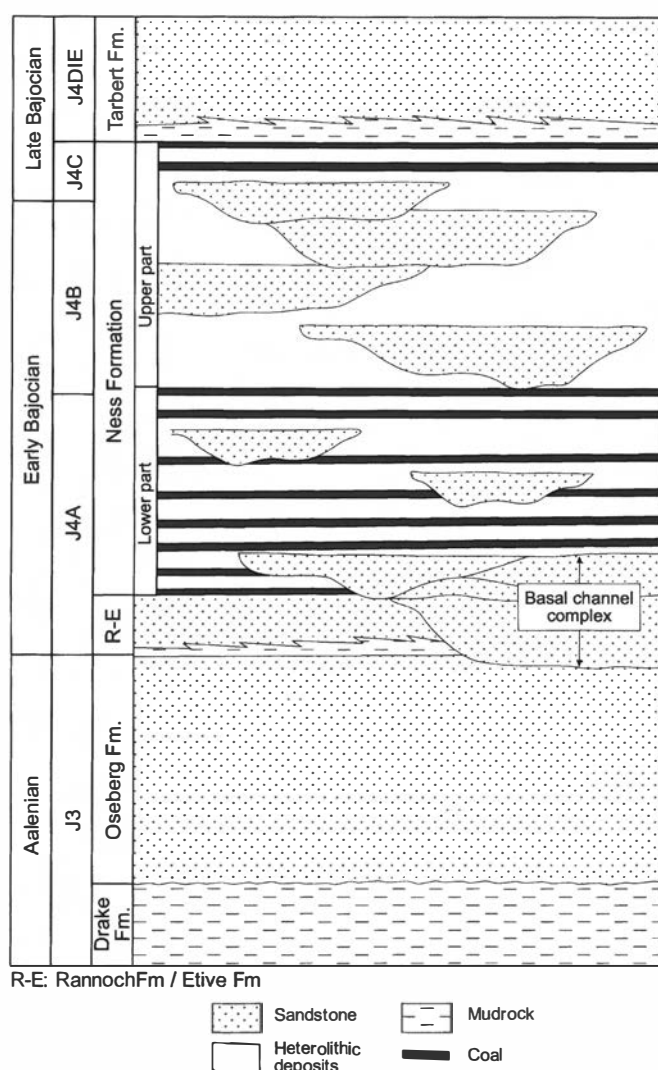


Fig. 2. The stratigraphy and main facies of the Brent Group in the Oseberg field. The Ness Formation is an alluvial succession of mudrocks, coal beds and fluvial sandstones, sandwiched between laterally persistent shallow marine sandstones (Oseberg Fm, Rannoch/Etive fms. below, and Tarbert Fm. above). Biozones (J3, J4A, J4B; J4C, J4D/E) are after Helland-Hansen et al. (1992) and Hauger et al. (1994).

shoreline progradation across the Horda Platform took place in relatively shallow water (Graue et al. 1987).

The Ness Formation (Early Bajocian) in the Oseberg field comprises sandstones, mudrocks and coal beds deposited in an upper delta-plain environment (Ryseth 1989). Consequently, the formation is less affected by marine processes than further to the north, where lower delta plain lagoonal deposits are common (e.g. Livera 1989). As shown in Fig. 2, the Ness Formation can be divided into a lower and upper unit owing to differences in coal content and sandstone distribution. The lower part comprises a basal fluvial channel complex, locally incised into the subjacent Rannoch, Etive and Oseberg formations, covered by coal-bearing, fine-grained deposits with only sporadic fluvial sandstones. The upper part of the Ness Formation is relatively sandy, but is capped with coal-bearing, fine-grained deposits. The Tarbert Formation (Late Bajocian), deposited during the transgressive retreat

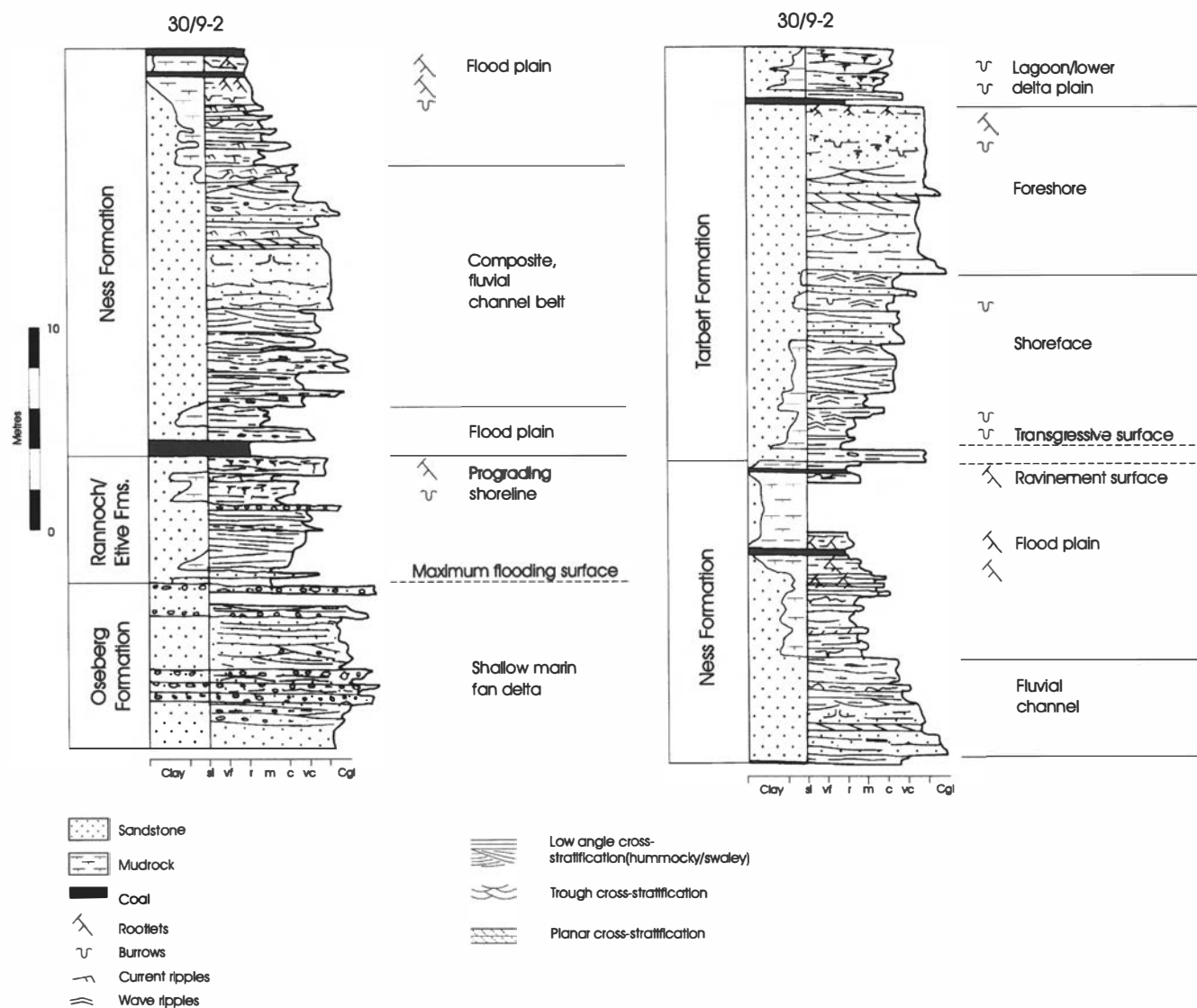


Fig. 3. Detailed facies definition of the Ness Formation boundaries; examples from well 30/9-2. The base is marked by an *in situ* coal bed resting on shallow marine sandstones (Rannoch-Etve fms.), except where overlying channel deposits (Ness Formation) incise the subjacent units. The top is an upward transition from coal-bearing, floodplain deposits to lenticularly bedded mudrocks and wave-ripple laminated sandstones of the overlying Tarbert Formation.

of the Brent delta, comprises shallow-marine sandstones and associated coal-bearing sediments representing successive transgressive/regressive events (e.g. Rønning & Steel 1987; Richards 1992).

Examination of the lithostratigraphic boundaries, particularly the basal and top surfaces of the Ness Formation in cored sections (Fig. 3), gives further insight as to their stratigraphic significance. The maximum flooding surface near the base of the Rannoch/Etve shoreline deposits represents an important correlative event that may approximate a timeline at the base of the prograding shoreline succession. The base of the Ness Formation is invariably marked by a coal bed, except where fluvial sandstones locally incise the underlying marine strata. The vertical transition from shoreline deposits into coal-bearing, delta-plain deposits is a shallowing upward facies sequence, with the transition itself being necessarily diachronous on a regional scale. On the scale of a smaller area like the

Oseberg field and its surroundings, this lithostratigraphic boundary can be considered as nearly isochronous. Notably, analysis of heavy mineral compositions have shown that the Ness Formation is sourced from a different hinterland than the underlying shallow marine sandstones (Hurst & Morton 1988), implying a possible stratigraphic break at the base of the Ness Formation.

The Ness/Tarbert boundary (Fig. 3) is characterized by the superposition of a coarsening-upward unit produced by shoreline progradation (Tarbert Fm.) upon the coal-bearing, delta-plain deposits, and represents an important transgressive event. A possible ravinement surface of transgressive shoreline erosion is seen at the base of the Tarbert Formation. Furthermore, a transgressive surface or maximum flooding surface is defined within the basal mudrocks of the Tarbert Formation, representing another approximate timeline for the study area.

The biostratigraphic framework of the Brent Group in

the Oseberg area (see biozones J3–J4 in Fig. 2; timelines 8–11 in Fig. 4) is based mainly on palynological assemblages (Helland-Hansen et al. 1992; Hauger et al. 1994). In the Ness Formation, the PJ4b subzone (Fig. 2) reflects an acme of areboraceous pollen (*Corollina*) related to a temporary increase in palaeotemperature (Hauger et al. 1994). This subzone is consequently regarded as an isochronous marker whose base and top define two timelines within the Ness Formation (see timelines 8 and 9 in Fig. 4). Another timeline is recognized at the Ness/Tarbert transition at the base of common *Cerebropollenites macroverrucosus* (timeline 10 in Fig. 4). Finally, a base of common/abundant *Escharisphaeridia* spp. coupled with the top of common *Araucariacites australis* provides a timeline within the Tarbert Formation (timeline 11, Fig. 4).

Well data show that the Brent Group thickens from about 150 m in the Brage field to more than 400 m within the fault blocks in southwestern parts of the study area. The correlation panel in Fig. 4 shows that the Oseberg Formation pinches out towards the graben axis, hence the thickening of the Brent Group is limited to the overlying formations. Modest lateral thickening of the shallow marine Rannoch/Etive unit can be seen along the correlated transect, but the main thickening is clearly related to the Ness and Tarbert formations. Part of this lateral variation is due to an erosional truncation of the Brent Group towards the Horda Platform (e.g. Oseberg Gamma and Alpha structures, Brage field, Fig. 4), with juxtaposition of Late Bathonian/Early Callovian strata directly upon the truncated Brent Group. However, a considerable amount of thickening is due to differential subsidence accommodated by the main faults, particularly during the deposition of the Ness Formation.

In the ensuing analysis, it is assumed that the Ness Formation boundaries are roughly isochronous in the study area. Although the isochroneity at the Etive/Ness boundary may seem unclear, it is supported by the maximum flooding surface near the base of the Rannoch/Etive unit, and by the relatively low thickness of the Rannoch/Etive formations in the study area.

Ness Formation

Areal thickness distribution

The subregional thickness distribution of the Ness Formation is shown in Fig. 5. Where fully preserved between shallow marine deposits of the Rannoch/Etive and Tarbert formations, the Ness Formation has a minimum thickness of about 40 m at the crest of the Oseberg Alpha structure (39 m in well 30/9–1, Figs. 4 & 5). The formation thickens gradually northwards along the Oseberg Alpha fault block, and more rapidly southwards. Most conspicuous is the thickening across the smaller fault blocks to southwest of the Alpha block, where the formation thickness increases to 258 m in well 30/9–14 (Fig. 4), located about 13 km

southwest of well 30/9–1. The maximum observed thickness of the formation is 310.5 m in the southernmost part of the study area.

Partial to complete erosion of the Ness Formation in the crestal areas of the Oseberg Alpha block and other fault blocks is evident from the well data. This marked truncation is due to footwall uplift during the Late Jurassic/earliest Cretaceous phase of rifting, and thus unrelated to the depositional history of the formation itself.

Facies assemblages and depositional subenvironments

In the Oseberg field, Ryseth & Fjellbirkeland (1995) defined two principal lithofacies assemblages in the Ness Formation (Fig. 6). Assemblage 1 comprises the main sandstone bodies, generally characterized by sharp basal boundaries and an upward-fining grain-size motif. The thicker units are multistorey and can be divided into component fining-upward storeys. Sedimentary structures include dm-size, cross-stratification of both planar and trough types, planar parallel lamination and unidirectional ripple cross-lamination. This association of lithofacies clearly indicates deposition from fluctuating, confined tractional currents. The sandstone bodies are therefore representing fluvial channels and channel belts.

The deposits of assemblage 2 are much more heterogeneous, comprising laminated mudrocks, thin sandstone interbeds, palaeosols and coal beds. These are overbank deposits related to floodplain lakes and vegetated areas, with the coal beds reflecting periodical peat accretion in water-saturated areas of limited clastic supply.

Correlation studies in the Oseberg field (Ryseth 1989; Ryseth et al. 1998) have demonstrated that the reservoir quality of the Ness Formation is optimal in its upper part. Only about 15% of the coal-bearing lower part consists of fluvial channel sandstones, whereas about 40% of the upper part (excluding the coal-bearing top unit) comprises fluvial channel sandstones. Most of the coal beds occur in the lower half, and also in the thin topmost part. Calibration of these stratigraphic changes with the palynozonation shows that the coal-bearing lower half of the formation is within biozone PJ4a (Fig. 2), whereas the sandier upper part is within zone PJ4b. The coal-bearing uppermost part occurs near the PJ4b/c boundary and within the PJ4c zone. These facies changes are thus approximately isochronous and correlative throughout the Oseberg field and the adjacent areas.

The depositional environment of the Ness Formation in the Oseberg area is well-constrained by abundant core data. The thicker parts of the formation in the more central areas of the basin are only partly cored in a few wells and the depositional environments are less well constrained. These wells, however, show the same two facies assemblages as in the Oseberg field. Composite wireline log suites (including gamma ray, density and sonic curves), allow for more simplistic interpretations of lithologies that can be compared to the core observations. As shown in Fig. 7, the main sandstone bodies defined from the gamma ray

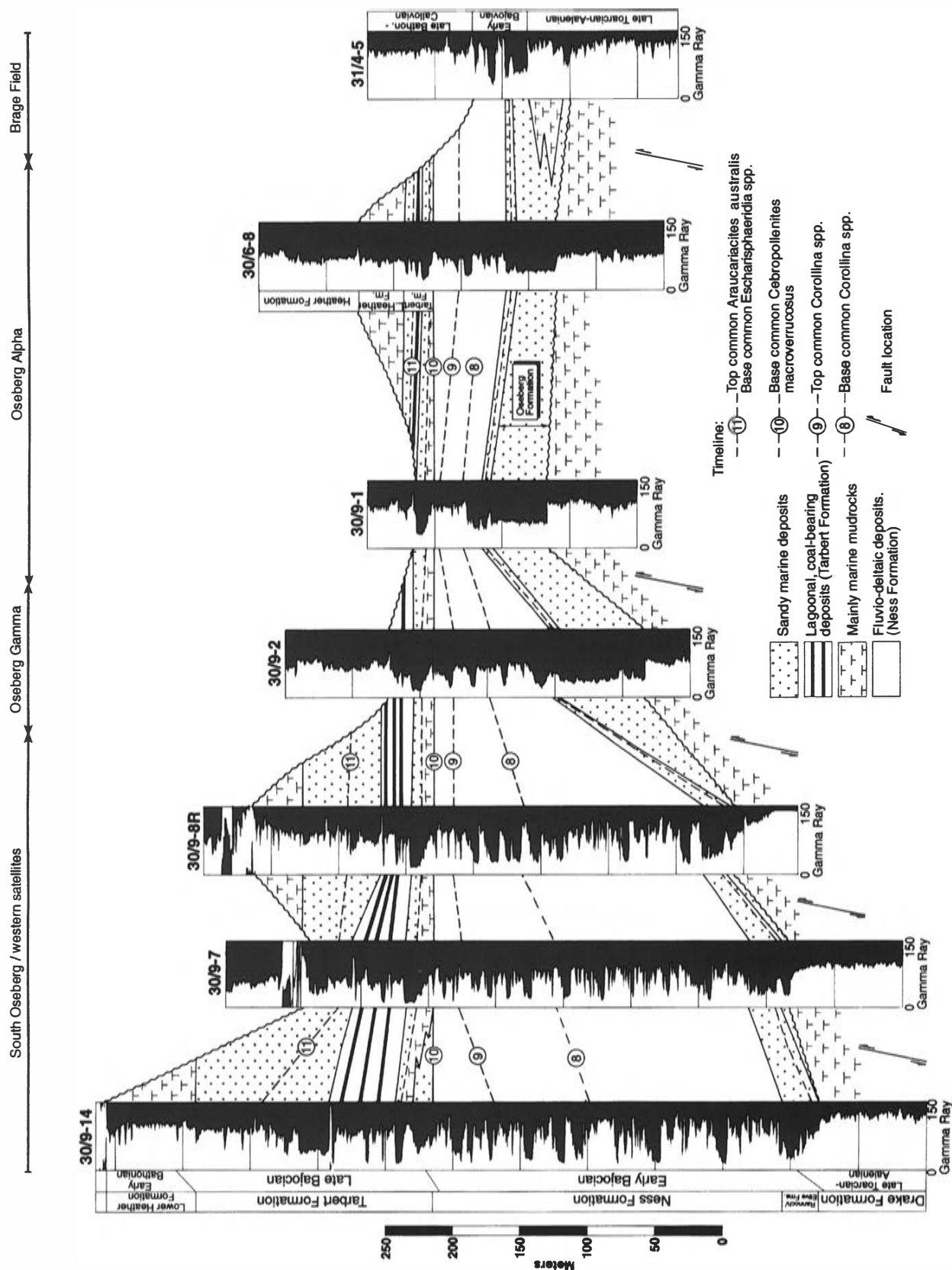


Fig. 4. Southwest-northeast oriented cross-section of the Brent Group. Note the dramatic thickening across the faults of the Horda Platform (see Fig. 1). The lateral thickening is particularly pronounced in the Ness Formation, whose complete (non-truncated) thickness increases from a minimum of 39 m at the crest of the Oseberg Alpha block, to more than 250 m in the adjacent Viking Graben to the southwest. For location, see Fig. 5.

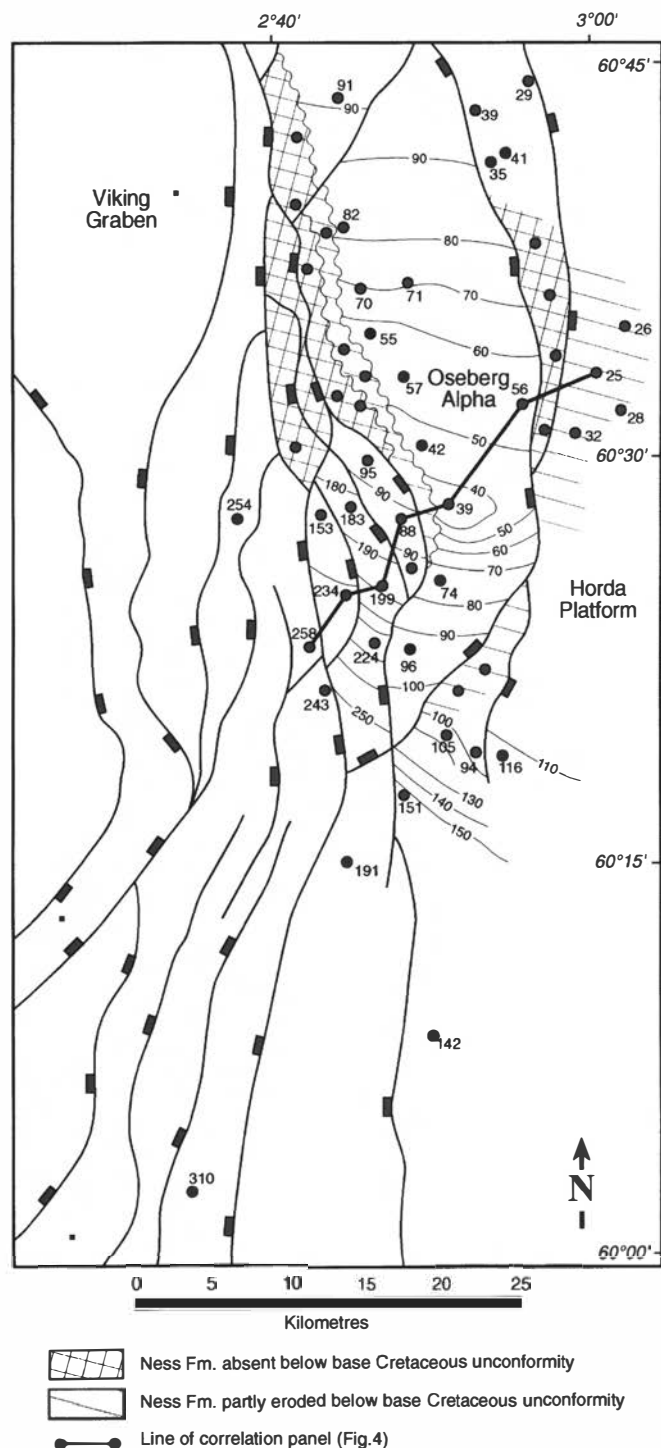


Fig. 5. The local tectonic structure and thickness distribution of the Ness Formation. Isopachs are drawn where the well spacing is sufficient. Note the gradual thickening of the formation to the north in the Oseberg Alpha block, and the more rapid thickening across the faults to the west.

curve are characterized by sharp, distinct basal contacts, and more gradational upper boundaries. The gradual upward increase in the gamma ray readings indicates a fining-upward, grain-size trend characteristic of the fluvial channel deposits of facies assemblage 1 (Fig. 6).

The surrounding, finer-grained deposits are evidently heterolithic, as indicated by the spiky and erratic character

of the gamma ray curve. Abundant peaks of low-density/high-interval transit time characterize the lower half of the Ness Formation as well as its topmost part, indicating numerous coal beds. Calibration of the log suite with the palynozonation (Fig. 7) shows that the bulk of the coal occurs within subzone PJ4a and near the PJ4b/PJ4c boundary, in the same stratigraphic position as in the Oseberg field. The lower part of biozone PJ4b is almost devoid of thick coal beds (some thin ones can be identified from the density curve), and apparently contains more densely stacked sandstone bodies than the underlying part of the succession. This pattern, too, compares well with the evidence from the Oseberg field.

Facies distribution vs. formation thickness

Modelling of alluvial stratigraphy has demonstrated that the lateral variation in subsidence rates across an alluvial plain can lead to a preferential stacking of channel sandstones in the areas of maximum subsidence (e.g. Bridge & Leeder 1979; Alexander & Leeder 1987; Bridge & Mackey 1993). In this section, the possible relationship between differential subsidence and facies distribution in the Ness Formation is examined.

As shown in Fig. 8, the total number of fluvial sandstone bodies (both simple and multistorey types) increases with the thickness (T) of the alluvial succession. Two wells penetrating complete Ness successions in the Oseberg field failed to penetrate fluvial reservoir sandstones. These two wells penetrated the Ness Formation where its depositional thickness is low (see Fig. 8). For succession thicknesses lower than about 60 m, the number of sandstone bodies per profile varies between 0 and 5, reflecting high lateral variability within the Oseberg field. As the succession thickness increases to about 100 m, the number of sandstone bodies per profile varies between 2 and 6. The thickening of the succession to more than 200 m (western 'satellite' wells) increases the number of fluvial sandstone bodies to a maximum of 11.

The increase in the number of sandstone bodies is accompanied by an increase in the cumulative thickness of fluvial channel deposits; the thicker the succession the more sandstone it contains (Fig. 9). The cumulative thickness of fluvial sandstones is extremely varied (approx. 0–30 m) where the total succession thickness is lower than about 60 m. There is a rapid increase in the sandstone content as the succession thickness increases from a minimum value of about 40 m to about 100 m. However, succession thicknesses greater than 100 m are not characterized by more abundant fluvial sandstones. Instead, the cumulative sandstone thickness tends to remain in the range from 40 m to 60 m, and increases weakly as the total succession thickness exceeds 200 m.

The data (Figs. 8, 9) show clearly that the net thickness of fluvial sandstone increases with increasing total thickness of the succession, but give little indication as to sandstone body connectedness, which is to a large extent controlled by the stacking density (CDP-value) of the

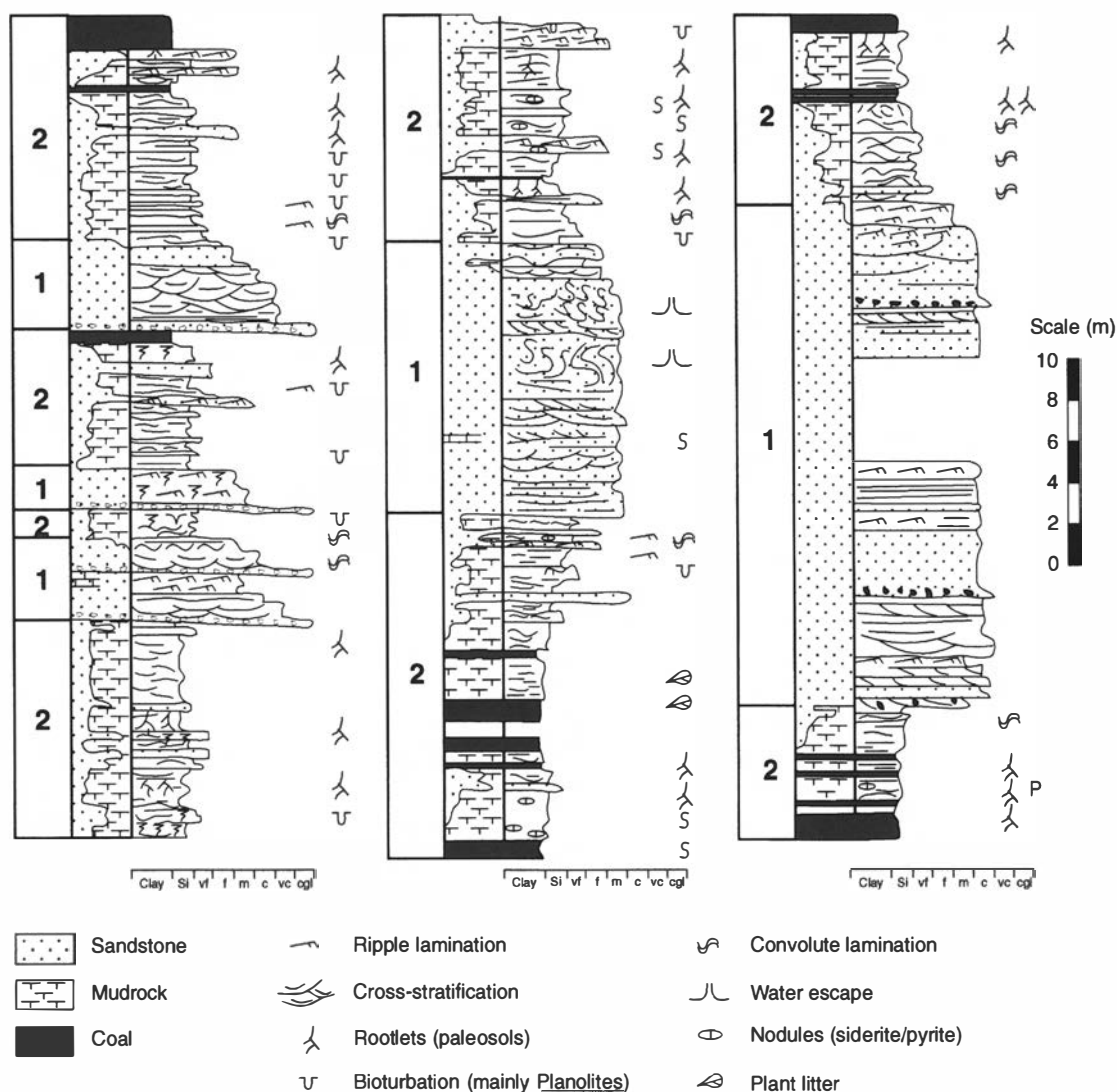


Fig. 6. Core logs of the Ness Formation, illustrating the vertical alternation of two principal facies assemblages. Fluvial channel-fill deposits (facies assemblage 1) occur as thin, single-storey fining-upward units and thicker, multistorey units. Floodplain deposits (facies assemblage 2) comprise laminated mudrocks with thin sandstone layers, rootlet (paleosol) horizons and coal beds formed in shallow lakes and swamps. After Ryseth & Fjellbirkeland (1995).

fluvial sandstones (e.g. Bridge & Mackey 1993). A cross-plot of CDP-values versus total succession thickness (Fig. 10) is therefore more crucial for the assessment of the reservoir potential. The plot (Fig. 10) shows an extreme variability in the sandstone proportion in profiles where the succession total thickness is less than about 60 m. The average CDP-value for the Ness Formation in the Oseberg field is about 0.3 (i.e. 30% of the succession thickness is fluvial sandstone), but the CDP-values for individual well profiles vary from 0 to more than 0.6 (the maximum CDP-value for the study wells). As the succession thickness increases to 100 m, the range of observed CDP-values becomes narrower, fluctuating between 0.2 and 0.5. An average CDP-value of about 0.3 is representative for the whole range of observed succession thicknesses. Possibly, there is a weak tendency for CDP-values to decrease slightly with increasing succession thickness.

A plot of the average sandstone body thickness in each well profile against the succession thickness (Fig. 11)

again demonstrates a large variability of the mean (ca. 2–14 m) where the succession is relatively thin. As the succession thickness increases to about 100 m, the variation in the average sandstone body thickness becomes lower (approx. 6–10 m). Where the succession thicknesses are greater (>100 m), the average sandstone body thickness remains in the same range (6–10 m), or decreases slightly, similar to the variation in CDP (Fig. 10).

In summary, both the number of fluvial sandstone bodies (Fig. 8) and their cumulative thickness (Fig. 9) increase with increasing total thickness of the alluvial succession, whereas the relative proportion of fluvial sandstones (CDP) is roughly the same for the succession thicknesses of about 100–300 m (Fig. 10). This trend is accompanied by a stabilization of or slight decrease in the average sandstone body thicknesses in the thicker successions (Fig. 11). Some changes in the floodplain assemblage can also be related to the variation in total succession thickness, for instance by a higher number frequency of coal beds in the

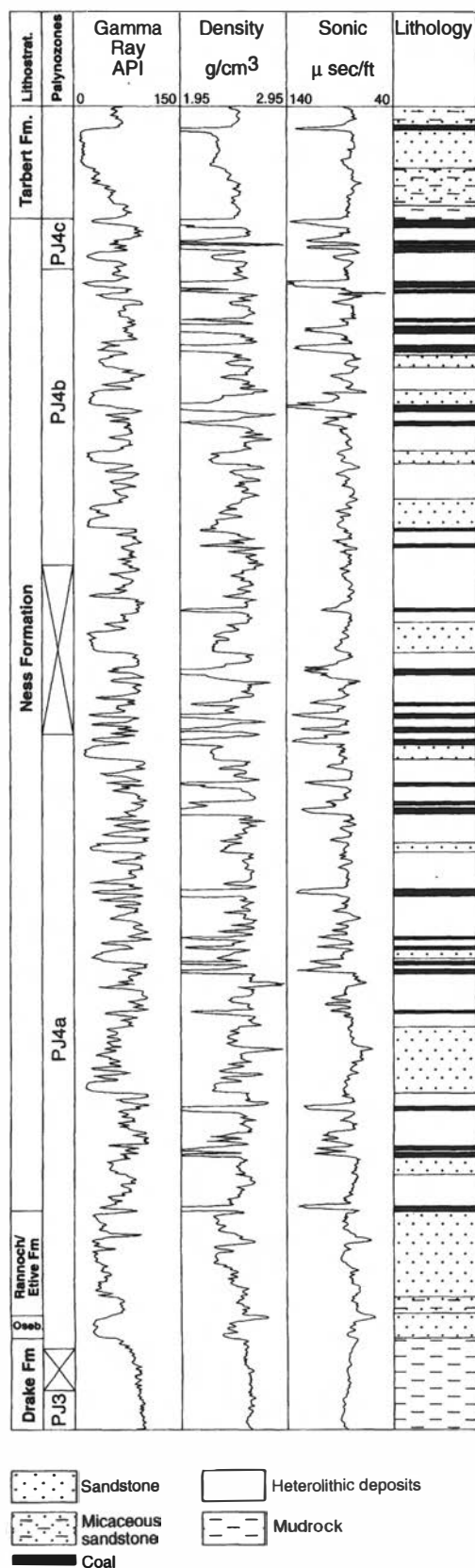


Fig. 7. The stratigraphy and main facies assemblages of the Brent Group in well 30/9-7. The Ness Formation is 234 m thick. The suite of wireline logs has allowed for a fairly detailed recognition of sedimentary facies. The sandstone bodies in the Ness Formation typically have sharp bases and gradational upper contacts (see the gamma ray curve), and are interpreted as fluvial-channel deposits. Note also the common occurrence of coal beds within the adjoining fine-grained deposits.

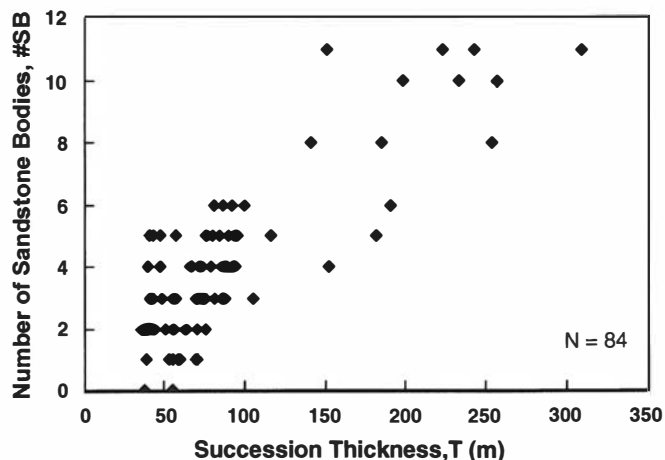


Fig. 8. Plot of the number of fluvial sandstone bodies (#SB) versus total succession thickness (T) for the Ness Formation. Note that the number of sandstone bodies increases with increasing succession thickness. N = number of data.

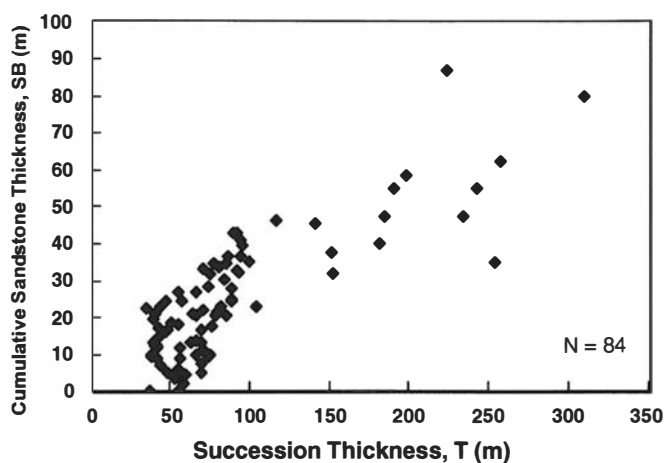


Fig. 9. Plot of the total accumulation of fluvial sandstone bodies (SB) versus the total succession thickness (T) for the Ness Formation. Note that the greater succession thicknesses are accompanied by greater cumulative sandstone thicknesses.

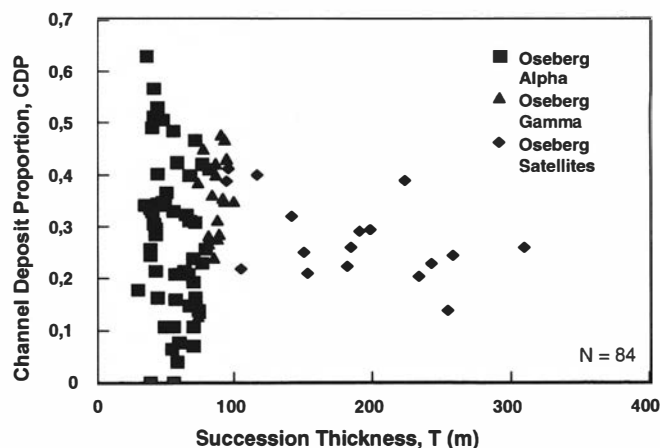


Fig. 10. Plot of the thickness proportion of fluvial sandstones (CDP) versus total succession thickness (T) for the Ness Formation. Note that the variation in CDP is greatest for the lowest succession thicknesses and tends to decrease with increasing total succession thickness.

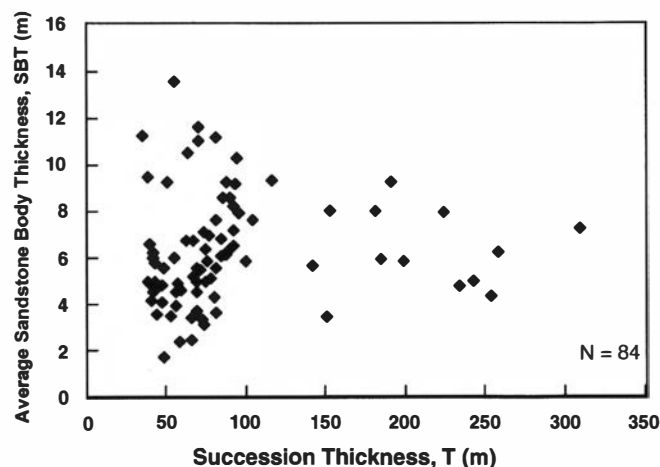


Fig. 11. Plot of the average sandstone body thickness (SBT) versus succession thickness (T) for the Ness Formation.

thicker well profiles (Fig. 12). Notably, the mean number of coal beds per profile increases by more than 10 with every 100-m increase in the succession thickness.

Subsidence-related controls on deposition

Conceptual notions

The statistical relationships presented above (Figs. 8–12) pertain to an alluvial succession that has been deposited synchronously, as indicated by the biostratigraphic data and correlative stratigraphic surfaces (see Fig. 4). Assuming that the lateral variation in succession thickness was due to differential subsidence, the subsidence rate would appear to have been more than seven times greater in the graben area than in the adjoining platform areas to the east. According to theoretical models, differential subsidence of this magnitude would have strongly influenced the depositional architecture of the Ness Formation, especially

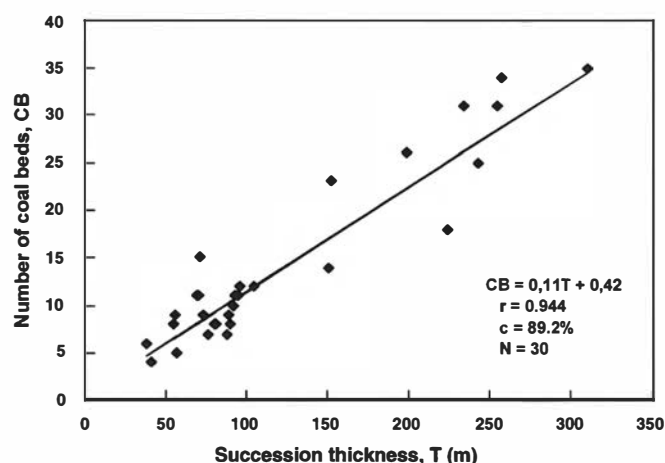


Fig. 12. Plot of the number of coal beds (CB) versus total succession thickness (T) for the Ness Formation. Letter symbols: r = coefficient of linear correlation, c = coefficient of determinations, N = number of data.

in such aspects as the sandstone body geometry, thickness and stacking density, as well the characteristics of the floodplain facies assemblage (e.g. its thickness proportion, coal-bed number, etc.).

Preferential stacking of fluvial sandstone bodies in areas of most rapid subsidence is a widely held notion in alluvial architecture modelling (Bridge & Leeder 1979; Alexander & Leeder 1987; Bridge & Mackey 1993). In these modelling studies, differential subsidence is considered as a tectonic tilting of the basin floor, with an oblique structural slope superimposed onto the pre-existing alluvial plain topography. This would attract avulsing channels into areas of most rapid subsidence (i.e. to the lowest topographic part). In turn, the focusing of the channel system in the topographically lowest area increases the local aggradation rate, resulting in differential aggradation (Mackey & Bridge 1995), which might in turn counter the effect of differential subsidence and cancel the topographic difference set up by the tectonic tilt. The theoretical effect on alluvial architecture is illustrated in Fig. 13, where a thick succession with densely stacked fluvial sandstones is formed in the area of stronger syndepositional subsidence and passes laterally into a thinner succession dominated by floodplain deposits.

Differential subsidence may also lead to more subtle lateral changes in the floodplain facies assemblage. The areas of slower subsidence may receive less sediment and be better drained, thus favouring the formation of more mature and possibly oxidized soils. In contrast, faster subsidence may favour the formation of floodplain lakes, and the proximity to active channels may cause greater flux of coarse clastics into the floodplain (i.e. by crevassing), hindering the formation of mature soils and maintaining water-saturated and generally reductive soil conditions (e.g. Besly & Fielding 1989). Another expected effect of differential subsidence, particularly relevant to a coal-bearing succession, is the splitting of individual seams across active faults. In extreme cases a single coal bed can split into a series of thinner bands separated by thick clastic deposits containing fluvial channels as well as floodplain deposits (e.g. Broadhurst & France 1986; Weisenfluh & Ferm 1984).

Implications of observations from the Ness Formation

The increase in the number and cumulative thickness of fluvial sandstone bodies with increasing total thickness of the alluvial succession (Figs. 8, 9) may well indicate preferential focusing of the fluvial channels in areas of stronger subsidence. These data imply that a persistent topographic gradient was set up by fault-related, differential subsidence. Accordingly, the thicker the succession, the more sandstone-rich it should be (cf. Fig. 13).

However, the variation in the channel deposit proportion (Fig. 10) does not support the latter prediction (Fig. 13), because the CDP-value seems to 'stabilize' or even reflect a slight decrease in the thickest successions. As the thicker successions contain higher numbers of fluvial sandstone

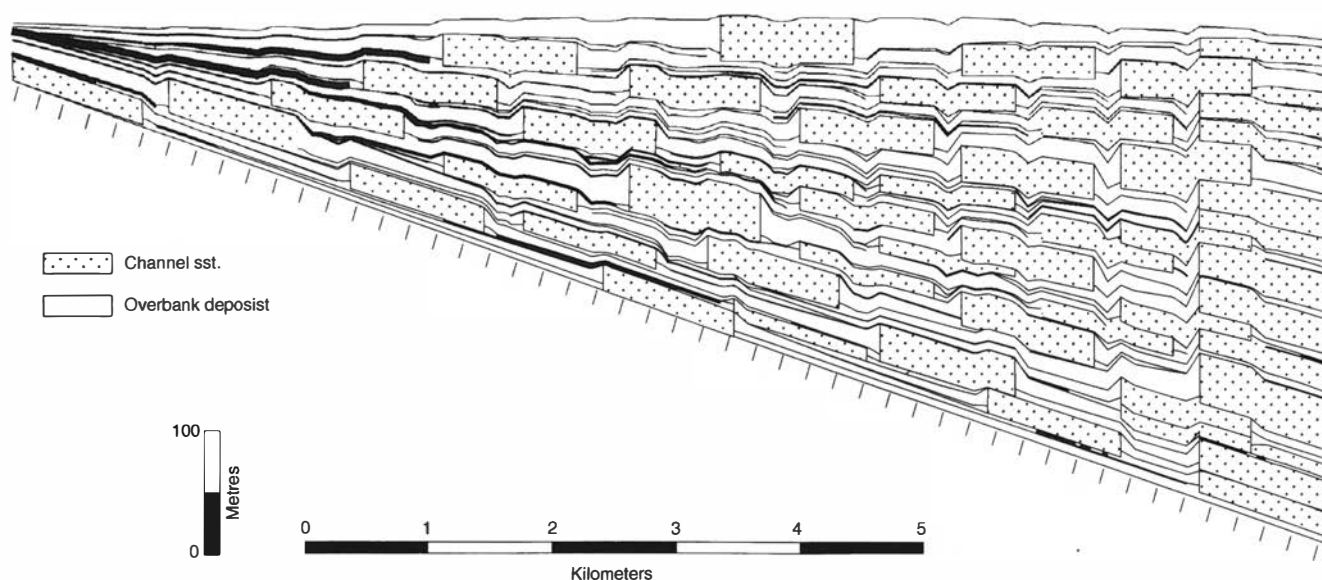


Fig. 13. A theoretical model of alluvial architecture, predicting higher frequency and greater thickness proportion of fluvial sandstones in areas of stronger subsidence. Modified from Bridge & Mackey (1993).

bodies, a likely explanation can be that the stronger subsidence also tended to increase the accumulation of floodplain deposits, with a balance developed between the accommodation space and its in-filling by alluvial processes. Channels are attracted to the faster-subsiding area, but they also bring about faster overbank deposition. Furthermore, the higher subsidence would also increase the preservation potential of deposited overbank material. As a result, the proportion of fluvial channel deposits (CDP) tends either to remain the same or to decrease, despite the increase in the number of fluvial sandstone bodies. Apparently, no such effect has been taken into account by the modelling studies (Bridge & Leeder 1979; Alexander & Leeder 1987; Bridge & Mackey 1993).

The trend in CDP shown by the Ness Formation (Fig. 10) indicates that an intensified overbank sedimentation can effectively counteract the stacking of fluvial channels, resulting in sandstone bodies composed of relatively few storeys as observed in the thicker alluvial successions. On the other hand, the large variation in the average sandstone body thickness in the thinner alluvial successions (Fig. 11) points to the development of a whole range of sandstone bodies in the areas less prone to subsidence, from single-storey to multistorey types. Detailed correlation of closely spaced well profiles in the Oseberg Alpha area (Ryseth et al. 1998) indicates that vertical stacking of smaller fluvial sandstone bodies leads to the development of the thickest reservoir sandstone units in this part of the area.

The occurrence of coal beds in even the thickest alluvial successions and the linear relationship between the succession thickness and the number of coal beds (Figs. 7, 12) have some implications for the topographic gradient induced by the differential subsidence. The considerable increase in the number of coal seams with increasing succession thickness indicates that the peat layers (coal) tend to be split by clastic sediment into two or more layers

across the active faults. This phenomenon has been documented from many coal fields, and attributed to the drowning of the peat mire in the down-thrown area, followed by rapid deposition of clastic material to the point of emergence, and renewed peat accretion (e.g. Fielding 1984, 1987; Broadhurst & France 1986). The greater number of coal beds in the thicker profiles indicates that the sediment supply was sufficiently high to compensate for the faster subsidence and keep the depositional surface close to the groundwater level (McCabe 1984).

Differential subsidence clearly had a pronounced effect on the total thickness of the alluvial succession, with the Ness Formation thickening by a factor of about 6 (40–250 m) over a relatively short distance of approximately 13.5 km (see Fig. 4). The surficial topographic effect of this differential subsidence was, however, minimal. The depositional surface remained around the groundwater level, allowing common peat accumulation. Hence, the sediment supply was sufficiently high to balance the accommodation space in the faster-subsiding basinal areas.

The stratigraphic implications discussed above have an important bearing on the reservoir characteristics and prospectivity in the larger Oseberg area. Isolation of fluvial sandstone bodies by the surrounding fine-grained facies may cause serious production problems and low hydrocarbon recovery from production wells drilled into the thicker parts of the Ness Formation. In contrast, the hydrocarbon production from the thinner part of the Ness Formation in the Oseberg field has been reasonably successful (Ryseth et al. 1998). The direct vertical and lateral stacking of fluvial sandstone bodies in the latter area is attributed to the lower subsidence rate, which was apparently sufficient to attract fluvial channels and cause their superposition in belt-like complexes, which alternate laterally with areas devoid of reservoir sandstones (see discussion of Fig. 14 further below).

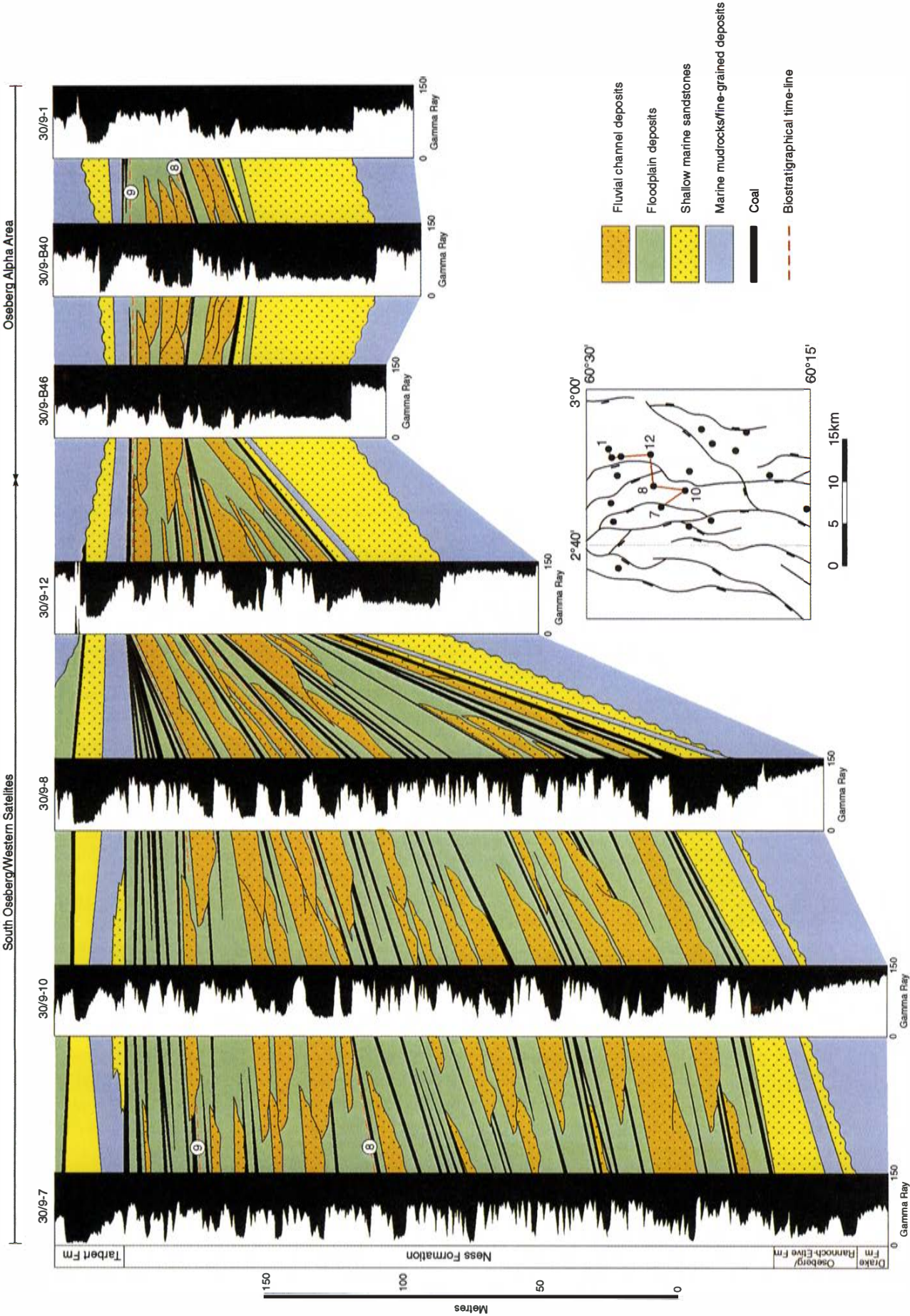


Fig. 14. Correlation of the architectural elements of the Ness Formation across the main syndepositional faults. Despite the profound thickness variation of the formation, the main architectural units are traceable throughout the area. For details, see text.

The decrease in CDP-value with increasing thickness of an alluvial succession thickness is not unique for the Ness Formation. Ryseth & Ramm (1996) have described a similar trend in the Statfjord Formation (Rhaetian–Sinemurian) in the Horda Platform area. Read & Dean (1982) have reported a clear tendency for channel deposits to concentrate in areas undergoing maximum differential subsidence in the Namurian extensional basin of Scotland. However, the latter authors have noted that this trend is much less pronounced than modelled by Bridge & Leeder (1979), and demonstrated that the thickness of channel-fill deposits decreases in the areas of strongest subsidence.

The simulation models of Bridge & Leeder (1979), Alexander & Leeder (1987) and Bridge & Mackey (1993) have high predictive capacity (see Fig. 13) and are consequently attractive to the petroleum industry. Surprisingly little effort has been made to test these conceptual models by comparing them with a wider range of 'real-life' data. A common assumption of the simulation models is that they decouple the avulsion frequency of river channels from the sedimentation rate. Heller & Paola (1996) have described scenarios where the avulsion frequency depends upon the sedimentation rate, and derived results that differ significantly from those of the original models. However, these authors did not examine the effects of cross-basinal differential subsidence (as shown in Fig. 13), and it is thus difficult to evaluate their results in the context of the present study. In particular, the possibility that overbank aggradation may overprint the effects of channel-belt concentration in areas of stronger subsidence should be tested in future simulation studies, as it may have important implications for the resulting alluvial architecture.

Implications for sequence stratigraphy

Depositional architecture

Studies of the alluvial architecture of the Ness Formation in the Oseberg field (Ryseth et al. 1998) have shown that the stacking density of channel sandstones varies with stratigraphic level. As shown in Fig. 2, relatively thick and laterally persistent sandstone bodies are recognizable near the base of the formation, where they are locally incised into the underlying shallow marine sandstones. This basal fluvial sandstone represents a composite, incised valley/multilateral sheet sandstone within the Oseberg field. Above this lower fluvial reservoir, the remaining lower part of the Ness Formation is dominated by coal-bearing, floodplain deposits with isolated fluvial sandstone bodies of both simple and multistorey character.

In the upper part of the Ness Formation, numerous fluvial multistorey/multilateral sandstone bodies interfinger with contemporary floodplain deposits, and the whole succession culminates in a coal-bearing unit underlying the Tarbert Formation. As indicated earlier, the large-scale lithological variation is correlative across the area.

The correlation panel in Fig. 14 shows the architecture

of the Ness Formation across some of the main syndepositional faults. No basal, incised valley feature exists in this transect, but a possible multilateral sandstone sheet is correlated at the base of the cross-section, pinching out both to the southwest (well 30/9–7) and to the north in the Oseberg field (Ryseth et al. 1998). Coal-bearing, floodplain deposits with isolated fluvial sandstone bodies persist within the remaining parts of the lower Ness Formation (i.e. below timeline 8 in Fig. 14) throughout the cross-section. Local clusters of fluvial sandstone within the lower Ness Formation (e.g. wells 30/9–10 and 30/9–12) seem to split and thin over rather short distances, indicating a laterally restricted sandstone body geometry.

The sandstone-rich character of the upper part of the Ness Formation is evident throughout the cross-section. The multistorey sandstone bodies in wells 30/9–8 and 30/9–10 split and thin both eastwards (well 30/9–12) and westwards (well 30/9–7) irrespective of the thickness variation. Where the formation is thin (Oseberg Alpha block), the lateral facies changes between adjacent wells are remarkably high, with thick, multistorey sandstone bodies alternating laterally with mudrock-dominated floodplain deposits within short distances (<500 m between wells B40 and 30/9–1). Splitting of coal seams into areas of greater formation thickness can be inferred throughout the correlated cross-section, particularly where the most prominent fault-related thickening takes place.

The correlation panel (Fig. 14) demonstrates that some of the large-scale architectural features of the Ness Formation persist throughout the study area, and are independent of the variation in thickness of the formation. These large-scale features include (1) a basal fluvial sheet sandstone locally incised into the underlying marine strata (in the Oseberg field, not shown in Fig. 14), but otherwise surrounded by floodplain deposits; (2) a thick, coal-bearing lower part of the formation above the basal sandstone, with isolated fluvial sandstone bodies that locally form discontinuous multilateral sandstone clusters (below timeline 8 in Fig. 14); (3) a sandstone-rich upper Ness interval, with abundant multistorey and partly multilateral fluvial sandstones encased in floodplain deposits (between timelines 8 and 9 in Fig. 14); and (4) a coal-bearing topmost part of the formation (above timeline 9 in Fig. 14).

The lateral persistence of these major architectural features, irrespective of the formations' thickness, may seem rather unexpected in the light of the data given in Figs. 8–12, which indicate a clear relationship between succession thickness and, for instance, the thickness proportion of channel deposits. However, these statistical trends (Figs. 8–12) reflect internal variation in the large-scale architecture.

Temporal changes in accommodation space development

Recognition of key stratal surfaces such as sequence boundaries is of primary importance to stratigraphic analysis (e.g. Posamentier & Vail 1988). As noted by Shanley & McCabe (1994), sequence boundaries reflecting

allocyclic forcing can be identified from stratal geometries signifying abrupt changes in the rate of accommodation space development. Shanley & McCabe also pointed out that a regional incision of a fluvial sandstone body on a depth and width scale greater than that of the component fluvial channels (indicating stratigraphic base level fall), or the formation of multilateral/multistorey sandstone sheets (recording low rates of stratigraphic base level rise) are the best criteria to identify sequence boundaries in alluvial successions.

The modelling of alluvial stratigraphy has shown that the temporal variation in subsidence rate (i.e. accommodation space development) controls the stacking density of channel sandstone bodies (e.g. Allen, 1978; Bridge & Leeder, 1979; Bridge & Mackey, 1993). High subsidence rates will result in alluvial successions with a relatively low thickness proportion of fluvial sandstones, where the sandstone bodies are isolated in floodplain deposits. A decrease in the subsidence rate may cause denser stacking of the fluvial sandstones in the resulting alluvial succession, and out-of-scale incision may be the result if a net uplift of the basin floor occurs.

The basal part of the Ness Formation contains fluvial sandstones incised into the underlying marine deposits and passing laterally into a possible multilateral sandstone sheet (Figs. 2, 14), indicating a sequence boundary at this stratigraphic level. The incision of a fluvial valley, its infilling and the subsequent deposition of a multilateral sheet outside the area of incision would be a record of a temporally reduced rate of accommodation space development. The inferred change in provenance area at the boundary between the Etive and Ness formations (Hurst & Morton 1988) supports the notion of a sequence boundary below the basal fluvial sandstone. The overlying, coal-bearing lower part of the Ness Formation with more isolated fluvial sandstone bodies would then reflect a significantly higher rate of accommodation space development.

Based on the same criteria, the increase in the thickness proportion of sandstone bodies seen in the upper part of the Ness Formation (Fig. 14, above timeline 8) may reflect a new phase of slower accommodation space development, which would indicate another sequence boundary at this stratigraphic level. No incision is recognized here, and this sandstone-rich interval is probably best explained by a concentration of mobile channel belts, as the individual fluvial sandstone bodies are demonstrably intercalated with contemporaneous floodplain deposits (Fig. 14; see also Ryseth et al. 1998). The coal-bearing unit capping the Ness Formation extends throughout the study area and can be attributed to another phase of higher rate of accommodation space development, this time leading eventually to marine transgression and the deposition of the shallow marine Tarbert Formation.

The definition of systems tracts in alluvial successions is problematic because of the absence of key stratal surfaces such as a transgressive surface and a maximum flooding surface. However, the distinction between architectural

elements indicative of high and low-accommodation regimes has recently been used to define systems tracts in alluvial successions (Dreyer et al. 1995; Currie 1997; Martinsen et al. 1999). Dreyer et al. (1995) and Martinsen et al. (1999) considered sequences of two principal systems tracts, reflecting conditions of low and high accommodation, respectively. The boundaries between the two tracts are the sequence boundary and the expansion surface (see Martinsen et al. 1999 for a definition of this surface), which reflect changes from high to low, and low- to high-accommodation rates, respectively.

In the present case two phases of a reduced rate of accommodation space development have been recorded: (1) during the basal valley incision and formation of the multilateral sandstone sheet, and (2) during the deposition of the sandstone-rich upper part of the Ness Formation. Each of these low-accommodation systems tracts is succeeded by coal-bearing, floodplain deposits with isolated fluvial sandstones, indicating significantly higher rates of accommodation space development. The Ness Formation thus consists of two main sequences, each comprising a low accommodation tract and a high-accommodation tract (Fig. 15).

The correlativeness of the main architectural elements, or systems tracts, throughout the entire measured thickness range of the formation (Fig. 14) is an indication that the temporal variation in the rate of accommodation space development was controlled by factors other than the spatially variable subsidence rate reflected in the thickness variation of the formation. Regional stratigraphic correlations (Norsk Hydro, unpublished data) indicate that the coal-bearing lower part of the Ness Formation (i.e. the high-accommodation systems tract of the lower sequence) coincides with a major marine transgression of the Brent delta north of the study area. Furthermore, the correlation of the biozone J4b across the Viking Graben shows that the stacking of fluvial sandstones in the upper part of the Ness Formation (the low-accommodation systems tract of the upper sequence) corresponds to a major phase of delta progradation and shoreline regression. Apparently, the low- and high-accommodation facies tracts in the Ness Formation can be linked to major regressive and transgressive phases of the Brent delta.

The interpretations presented above are compatible with other studies focusing on the possible controls on Brent Group deposition. Cannon et al. (1992) concluded that a major phase of delta retreat is recorded in the Ness Formation of the East Shetland Basin (Fig. 1). Mitchener et al. (1992) concluded that the Brent Group contains several stratigraphic sequences developed by a combination of eustatic sea-level change, basin subsidence and variation in sediment supply related to hinterland rejuvenation and degradation. Other studies (e.g. Johannessen et al. 1995; Fjellanger et al. 1996) have advocated relative sea-level changes, in addition to basin subsidence, as the main factor controlling the sequence stratigraphy of the Brent Group. Sea-level changes and/or hinterland evolution, superimposed upon the differential basin subsidence may have

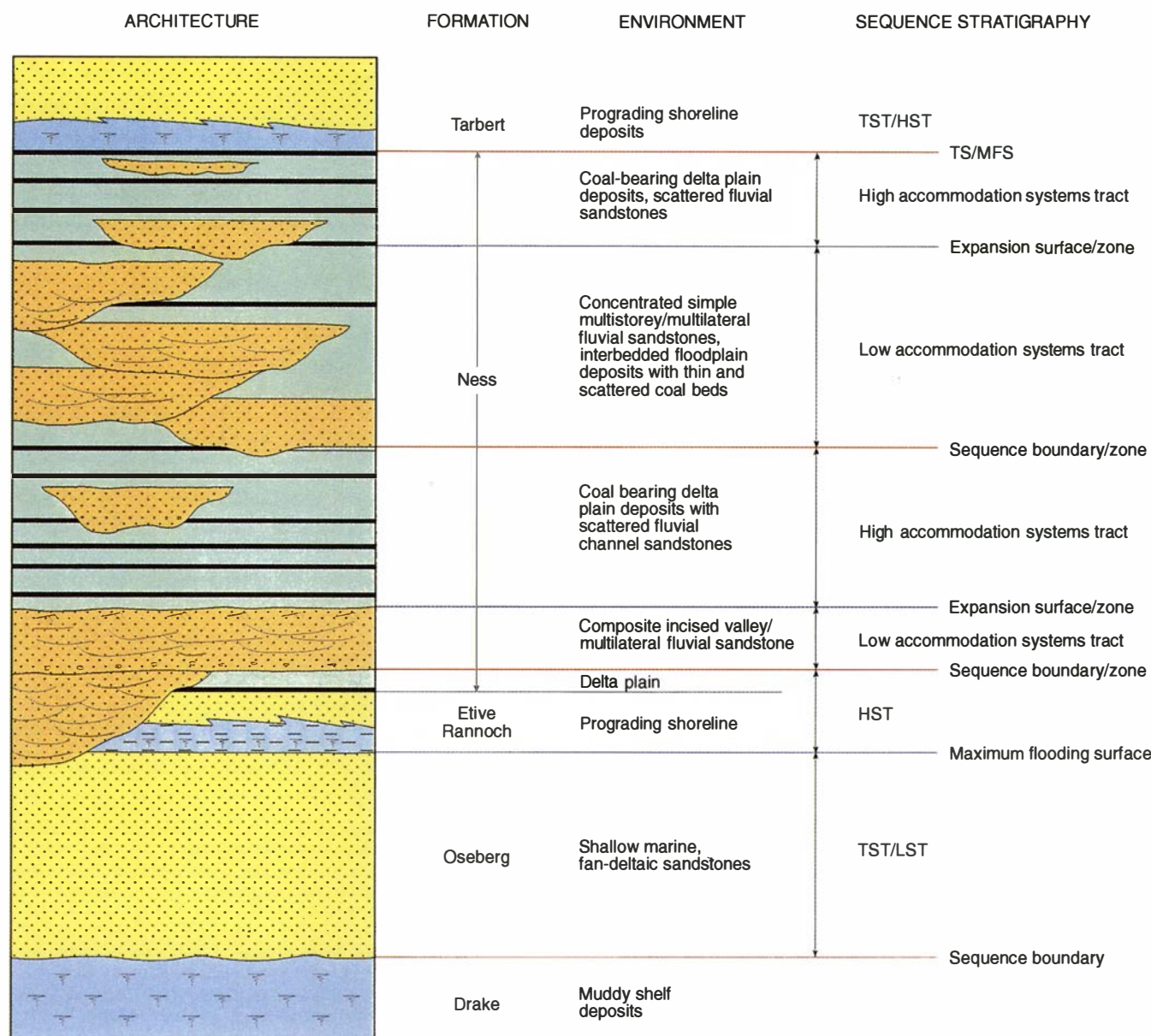


Fig. 15. Sequence stratigraphic interpretation of the Ness Formation in the broader context of the Brent Group. See text for further discussion.

combined to produce the alluvial architecture depicted by the stratigraphic model (Fig. 15). For example, a period of reduced accommodation space development in the fluvi-ally dominated delta plain may correspond to a significant basinward shift of facies belts in more marine deltaic domains (Shanley & McCabe 1994). A period of higher accommodation in the delta plain may correspond to phases of landward shoreline migration, so that the high-accommodation systems tracts correspond to transgressive and early high-stand deposition (e.g. Wright & Marriott 1993; Martinsen et al. 1999).

Discussion and conclusions

The alluvial architecture of the Ness Formation in the Oseberg area indicates a relationship between the total

thickness of the alluvial succession, and the volumetric proportion of fluvial sandstones and finer grained floodplain deposits. The number of fluvial sandstone bodies and their total cumulative thickness increase as the formation's thickness increases. In contrast, the thickness proportion of fluvial sandstones, reflecting the stacking density of migrating channels, shows no simple relationship to the total succession thickness. Where the formation is relatively thin (30–60 m), the CDP-value averages about 0.3 but shows large variation between wells. The variation decreases as the formation thickness increases to about 100 m, with the thicker profiles showing 'stabilised' or even slightly reduced CDP-values. This trend is accompanied by a stabilization or weak decrease in the average sandstone body thickness per profile, and a clear increase in the number of coal beds within the thickest successions of the Ness Formation.

The areal thickness variation of the formation and the associated variation in the component facies assemblages are ascribed to syndepositional differential subsidence, with the thinner profiles in the Horda Platform area being the condensed versions of the thicker profiles in the Viking Graben to the west. The distribution of the channel-fill and floodplain assemblages in the Ness Formation is in marked contrast to the results of the conceptual simulation models of alluvial stratigraphy, which predict that the stacking density of fluvial sandstones (CDP-value) should be greater in areas undergoing maximum subsidence (cf. Bridge & Leeder 1979; Alexander & Leeder 1987; Bridge & Mackey 1993). The present study does not support this notion.

Although stronger subsidence clearly attracts fluvial channels, as shown by the higher number frequency of palaeochannels in the thicker alluvial successions, the higher recurrence of channels necessarily increases the rate of coeval floodplain aggradation and keeps the depositional surface flat, thus counteracting the topographic effect of differential subsidence. Furthermore, the preservation potential of the floodplain deposits apparently increases in areas of higher subsidence. Consequently, the higher recurrence of fluvial channels is insufficient to increase the stacking density (CDP) of fluvial sandstone bodies. In essence, fluvial sandstone bodies are most frequent in areas of stronger subsidence, but these sandstone bodies are generally thinner and separated by thicker floodplain deposits than in the areas undergoing slower subsidence. However, the lateral variation between sandstone-rich and sandstone-poor successions is more pronounced where the formation is relatively thin.

Importantly, the depositional trends summarized above have by no means obliterated the principal, large-scale architecture of the alluvial succession, which here consists of four correlative elements (approximate chronostratigraphic units) that extend over a lateral distance of at least 10 km. The four units define two main component sequences of the Ness Formation, each comprising a low-accommodation systems tract overlain by a high-accommodation systems tract. The sequences reflect temporal changes in the rate of accommodation space development, upon which the spatial effects of differential subsidence have been superimposed. The facies record of the systems tracts thickens and thins in accordance with the total thickness of the alluvial succession. In effect, the relative proportion of floodplain deposits increases in both low- and high-accommodation tracts as the tract's total thickness increases, making the distinction between the two systems tracts less clear towards the basin centre.

The alluvial architecture and spatial trends recognized in the Ness Formation have important implications for the hydrocarbon exploration and production in the area. Hydrocarbon production from the thicker Ness Formation may be problematic, because of limited fluvial sandstone body thickness and isolation of the fluvial reservoir sandstones in the surrounding floodplain deposits. Optimal hydrocarbon recovery from the thicker parts of the Ness

Formation therefore requires very accurate mapping of potential fluvial reservoirs. These implications may also apply to the Ness Formation outside the study area and to other alluvial successions affected by differential subsidence.

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