Seismic geomorphological analysis and hydrocarbon potential of the Lower Cretaceous Cromer Knoll Group, Heidrun field, Norway

Lorena Moscardelli, Sarika K. Ramnarine, Lesli Wood, and Dallas B. Dunlap

ABSTRACT

The Heidrun field, located on the Halten Terrace of the mid-Norwegian continental shelf, was one of the first giant oil fields found in the Norwegian Sea. Traditional reservoir intervals in the Heidrun field lie within the Jurassic synrift sequence. Most Norwegian continental shelf fields have been producing from these Jurassic reservoirs for the past 30 yr. Production has since declined in these mature fields, but recently, exploration for new reservoirs has resurged in this region. The Jurassic rifted fault blocks form a narrow continental shelf in Norway, thereby greatly reducing the areal extent for exploration and development within existing fields. As the rift axis is approached farther offshore, these Jurassic reservoirs become very deep, too risky to drill, and uneconomical. This risk has prompted exploration in more recent years of the shallower Cretaceous, postrift stratigraphic succession. Cretaceous turbidites have been found in the Norwegian and North Seas, and the discovery of the Agat field in the Norwegian North Sea confirms the existence of a working petroleum system capable of charging Cretaceous reservoirs. These Cretaceous reservoirs were deposited as slope- and basin-floor fans within a series of underfilled rifted deeps along the Norwegian continental shelf and are thought to be sourced from the localized erosion of Jurassic rifted highs. We use three-dimensional seismic and well data to document the

AUTHORS

Lorena Moscardelli ~ *Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas; lorena.moscardelli@gmail.com*

Lorena Moscardelli was a research associate and lecturer at the Bureau of Economic Geology and co-principal investigator of the Quantitative Clastics Laboratory Industrial Associates program. She recently accepted a position as principal research geologist with Statoil in Austin, Texas. Her interests include seismic geomorphology of deep-water deposits, with special emphasis on mass-transport complexes, regional hydrocarbon prospectivity, planetary surface processes, and application of novel seismic visualization techniques for tackling a variety of geologic problems. She holds a B.S. degree in geology from Universidad Central de Venezuela and a Ph.D. in geology from the University of Texas at Austin.

Sarika K. Ramnarine ~ *British Petroleum Trinidad and Tobago, 5 and 5A Queens Park West Plaza, Port of Spain, Trinidad and Tobago; sarika.ramnarine@uk.bp.com*

Sarika Ramnarine received her B.S. degree in petroleum geoscience from the University of the West Indies, St. Augustine, in 2005. That year, she joined the Petroleum Company of Trinidad and Tobago as a development geologist, focusing on the Soldado acreage. She completed her M.A. degree in energy and earth resources at the University of Texas at Austin in 2011 and is currently at British Petroleum Trinidad and Tobago as a well-planning geologist.

Lesli Wood ~ *Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas; lesli.wood@beg.utexas.edu*

Lesli J. Wood is a senior research scientist and lecturer at the Bureau of Economic Geology and co-principal investigator of the Quantitative Clastics Laboratory Industrial Associates program. Her interests include seismic geomorphology, clastic depositional systems, and Martian sedimentology. She holds B.S. and M.S. degrees in geology from Arkansas Tech University and the University of Arkansas, respectively, and a Ph.D. in earth resources from Colorado State University.

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Dallas B. Dunlap ~ *Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas; dallas.dunlap@beg.utexas.edu*

Dallas B. Dunlap received his B.S. degree in geology from the University of Texas at Austin in 1996. That year, he joined the International Projects group of the Bureau of Economic Geology as a research scientist associate focused on reservoir characterization studies in Austria, Mexico, and Venezuela. In 2006, he moved to the Quantitative Clastics Laboratory, where he studies various marine depositional systems.

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geomorphology of a deep-water, Lower Cretaceous wedge (Cromer Knoll Group) within the hanging wall of a rift-related half graben formed on the Halten Terrace offshore mid-Norway. Seismic attribute extractions taken within this Lower Cretaceous wedge reveal the presence of several lobate to elongated bodies that seem to cascade over fault-bounded terraces associated with rifted structures. These high-amplitude, elongated bodies are interpreted as deep-water sedimentary conduits that are time equivalent to the Cretaceous basin-floor fans in more distal parts of the basin to the west. These half-graben fills have the potential to contain high-quality Cretaceous sandstones that might represent a potential new reservoir interval within the Heidrun field.

INTRODUCTION

Hydrocarbons in the Norwegian and North Seas occur in a variety of prerift, synrift, and postrift reservoirs (Brooks et al., 2001). Synrift reservoirs in the Norwegian Sea are Upper Jurassic and contain high-quality sandstones that stratigraphically intermingle with a mature source rock (Kimmeridge Clay). In general, distribution of reservoir facies in synrift basins is complex because the interplay between local tectonism and relative sea level fluctuations controls the creation of accommodation within each of the grabens (Brooks et al., 2001; Jackson et al., 2011). Halokinesis also played an important function in the evolution of rift sequences in the Norwegian and North Seas by influencing reservoir geometries and compartmentalization (Dooley et al., 2003). A variety of trapping mechanisms are associated with rifted fields, including tilted fault blocks, four-way dip closures, hanging-wall closures, stratigraphic closures, and combined structural-stratigraphic closures. Most boreholes in extensional basins tend to be located toward the crests of rotated footwall blocks in locations updip of synrift hanging-wall deposits (Jackson et al., 2011). The basin topography created during synrift phases heavily influences the nature of sedimentary infilling during early postrift stages, causing a great deal of lateral and vertical stratigraphic variability. Sediment routing during the early stages of a postrift phase is highly tortuous, sediment sources can be multiple from localized sources to extrabasinal input, and as a consequence, prediction of areas where sandstone accumulation can occur is challenging. We intend to explore the nature of stratigraphic intervals that were deposited during the early stages of a postrift event and that were highly influenced by the topographic configuration created during the preceding synrift

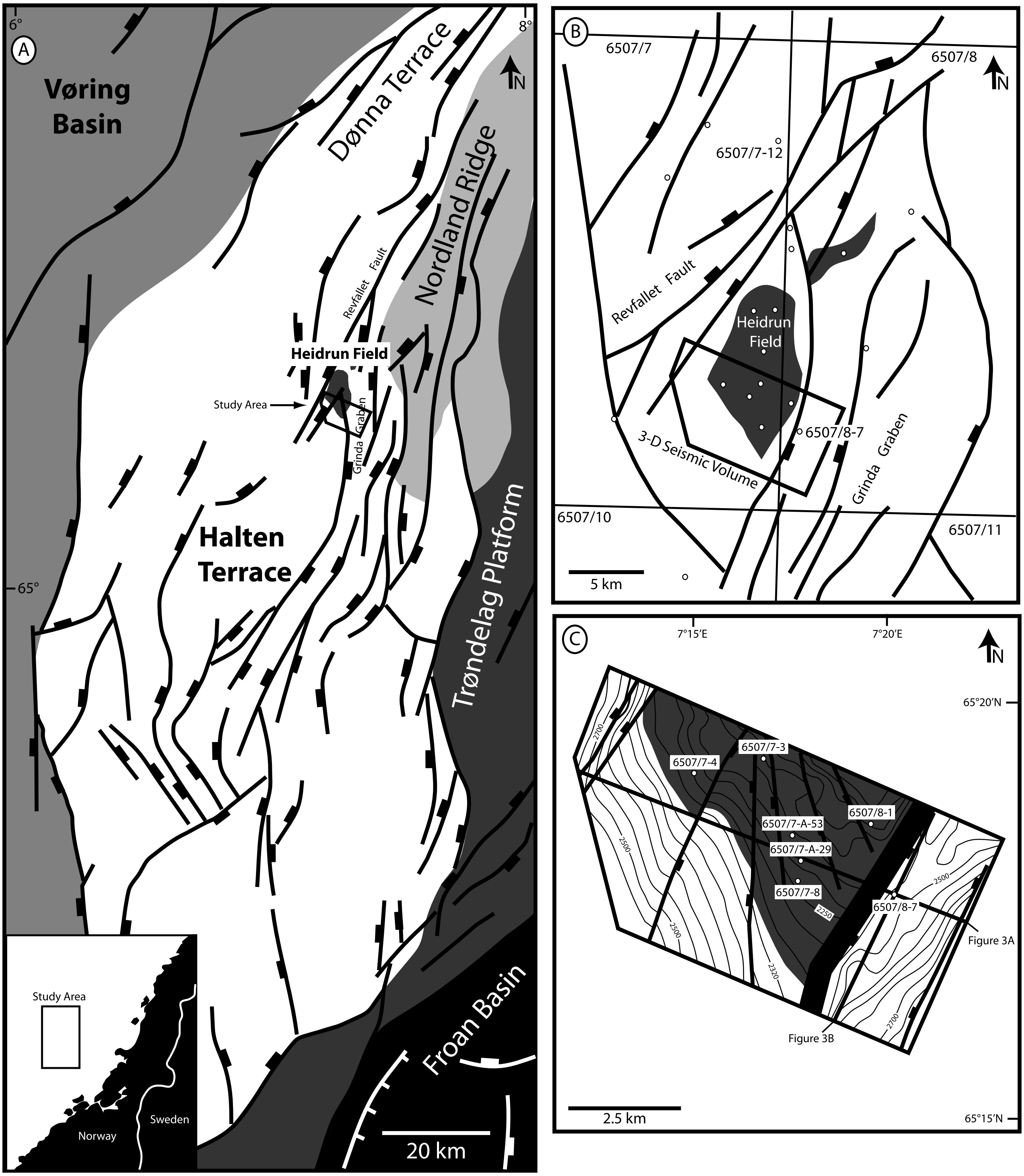

Figure 1. (A) Map showing the main tectonic elements of the Halten Terrace region, offshore mid-Norway (modified from Blystad et al., 1995). The location of the Heidrun field is highlighted. (B) Closeup of the Heidrun field showing the main structural elements as reported by the Norwegian Interactive Offshore Stratigraphic Lexicon (n.d.) and the location of the three-dimensional seismic volume used in this study. (C) Outline of the area covered by three-dimensional seismic volume and available wells. Contours correspond to base Cretaceous unconformity (S1). The shaded area is above the oil-water contact (Furre et al., 2006).

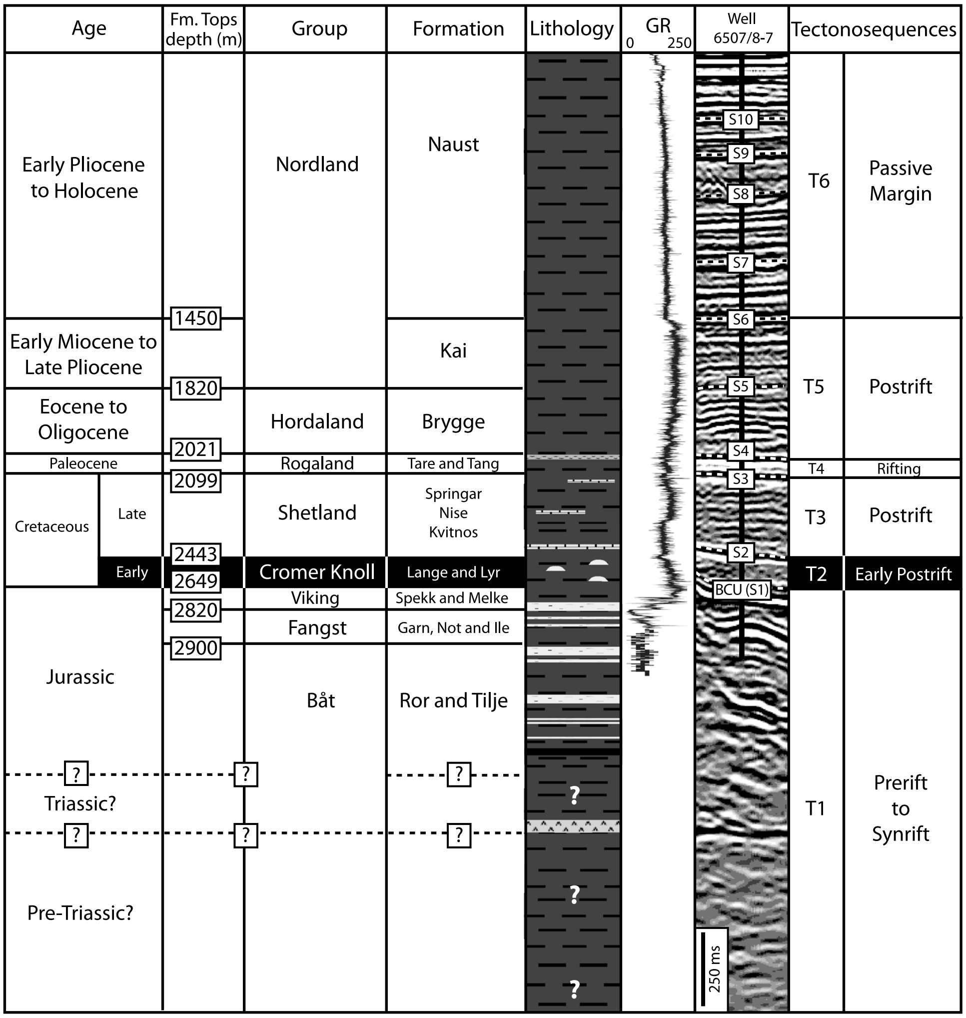

Figure 2. Chart showing lithostratigraphic units and their tectonostratigraphic equivalents. Tops and geologic ages were compiled from well reports (source: Norwegian Interactive Offshore Stratigraphic Lexicon, n.d.). BCU (S1) = base Cretaceous unconformity; Fm = Formation; GR = gamma ray.

phase. The interval of study is the Lower Cretaceous Cromer Knoll Group within the Grinda Graben to the east of the Heidrun field in offshore Norway (Figure 1). A secondary aim is to assess the economic potential of postrift stratigraphic successions for oil and gas exploration in the Norwegian Sea.

The mid-Norway continental shelf and slope can be divided into two major sedimentary basins: the Vøring and Møre Basins (Bukovics and Ziegler, 1985). The Heidrun field is located on the Halten Terrace, which lies on the eastern shoulder of the greater Vøring Rift Basin (Figure 1). The Norwegian continental margin has a hydrocarbon exploration history shorter than those of other basins around the world (Bukovics and Ziegler, 1985). Exploration for oil and gas in the mid-Norwegian continental shelf, which began in 1979, was concentrated initially in the Halten Terrace area (Figure 1) (Bukovics and Ziegler, 1985). The Heidrun field, which lies within this area, contains highly productive reservoirs in the footwalls of Jurassic rift-related normal faults (Figure 1B) (Bukovics and Ziegler, 1985). The Heidrun field, which was discovered by well 6507/7-2 in 1985 (Koenig, 1986), has 750 million bbl of recoverable oil reserves, with associated gas reserves of 0.45 tcf and free gas reserves of 1.32 tcf (Whitley, 1992). The time-equivalent intervals of these Jurassic reservoirs are considered to be too deep in the central part of the Vøring Basin to be viable targets (Doré et al., 1999). Sedimentary rocks associated with these reservoirs are composed mainly of fluvial to shallow-marine, prerift to synrift sediments (Whitley, 1992), and most of these Jurassic reservoirs have already been discovered and produced over the last few decades. Declining production, associated with the

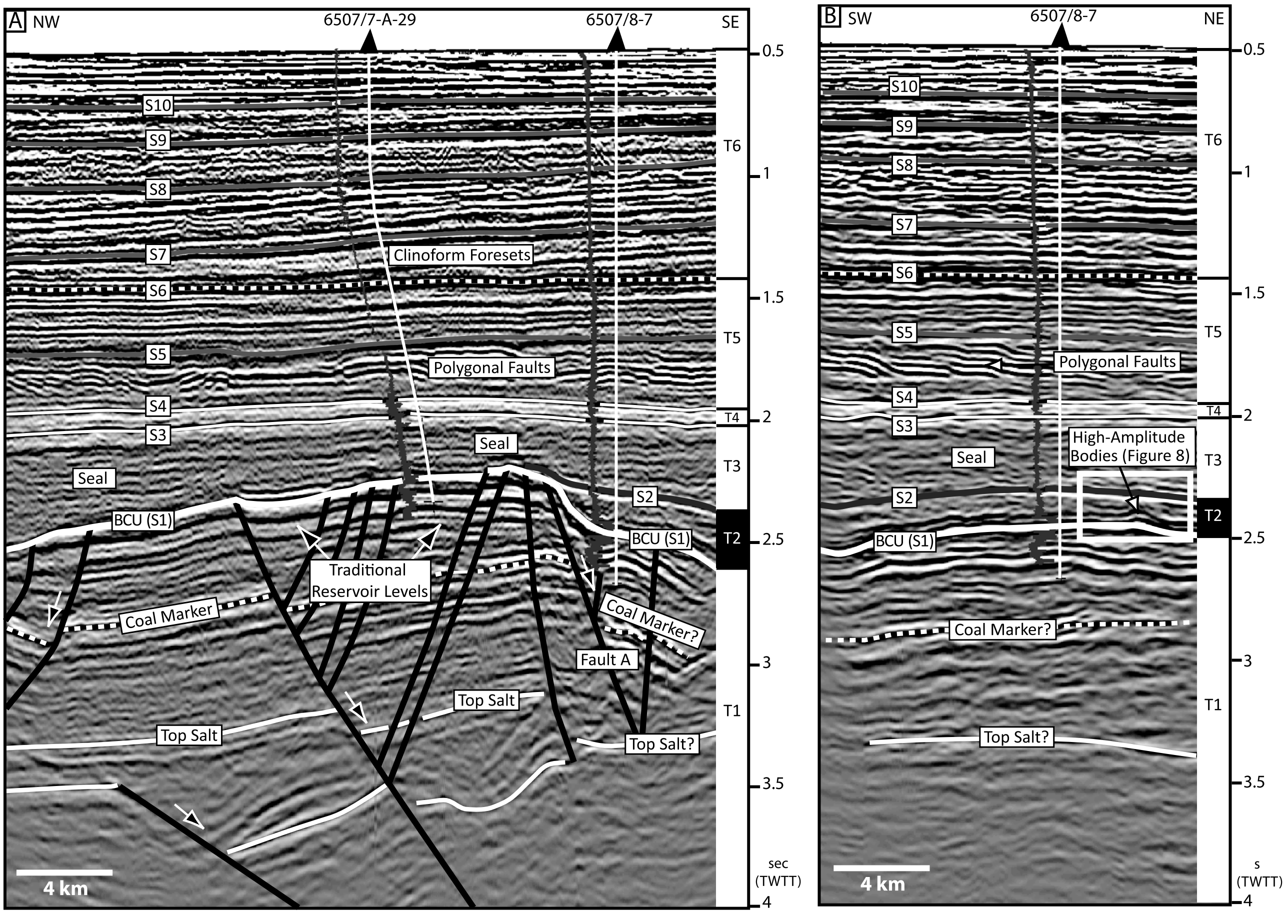

Figure 3. (A) Northwest-southeast three-dimensional seismic line showing the main structural configuration of the study area. Key stratigraphic surfaces and tectonosequences are highlighted. (B) Southwest–northeast three-dimensional seismic line covering the Lower Cretaceous wedge within the Grinda Graben. Locations are shown on Figure 1. BCU (S1) = base Cretaceous unconformity; TWTT = two-way traveltime.

depletion of Jurassic reservoirs in the study area, has recently encouraged exploration within the younger postrift Cretaceous succession (Figure 2) (Fugelli and Olsen, 2005). Unfortunately, despite renewed exploration interest in Cretaceous intervals, these units remain poorly understood from a geologic perspective. Fugelli and Olsen (2005) conducted a regional study in the Vøring Basin, focusing on the sand-rich, deep-marine clastics of the Upper Cretaceous Lysing and Springar Formations. On the basis of this study, the Lysing Formation was interpreted as a sedimentary conduit or feeder to fan complexes in more distal areas of the Vøring Basin (Fugelli and Olsen, 2005); however, an equivalent to the Lysing Formation has not been identified within the Heidrun field. Instead, Upper Cretaceous units in the Heidrun field (Shetland Group) contain thick shales that act as a regional seal for Upper Jurassic reservoirs (Figure 2). The absence of Upper Cretaceous sandstones associated with the Lysing and Springar Formations in the Heidrun field indicates that feeder systems were not present in this region at this time, and fine-grained deposition was dominant instead. Despite the lack of sand preservation in the Upper Cretaceous interval within our study area, the postrift, Lower Cretaceous Lange and Lyr Formations (Cromer Knoll Group) remain underexplored and under which paleoenvironmental conditions these units were deposited remains unclear (Figure 2). Paleoenvironmental reconstructions of the Upper Jurassic to lowermost Cretaceous interval in the Draugen field, located to the south of our study area on the Trøndelag Platform, indicate that hydrocarbon-producing, marine-bar sands developed during the Late Jurassic in this region, whereas marine and stagnant

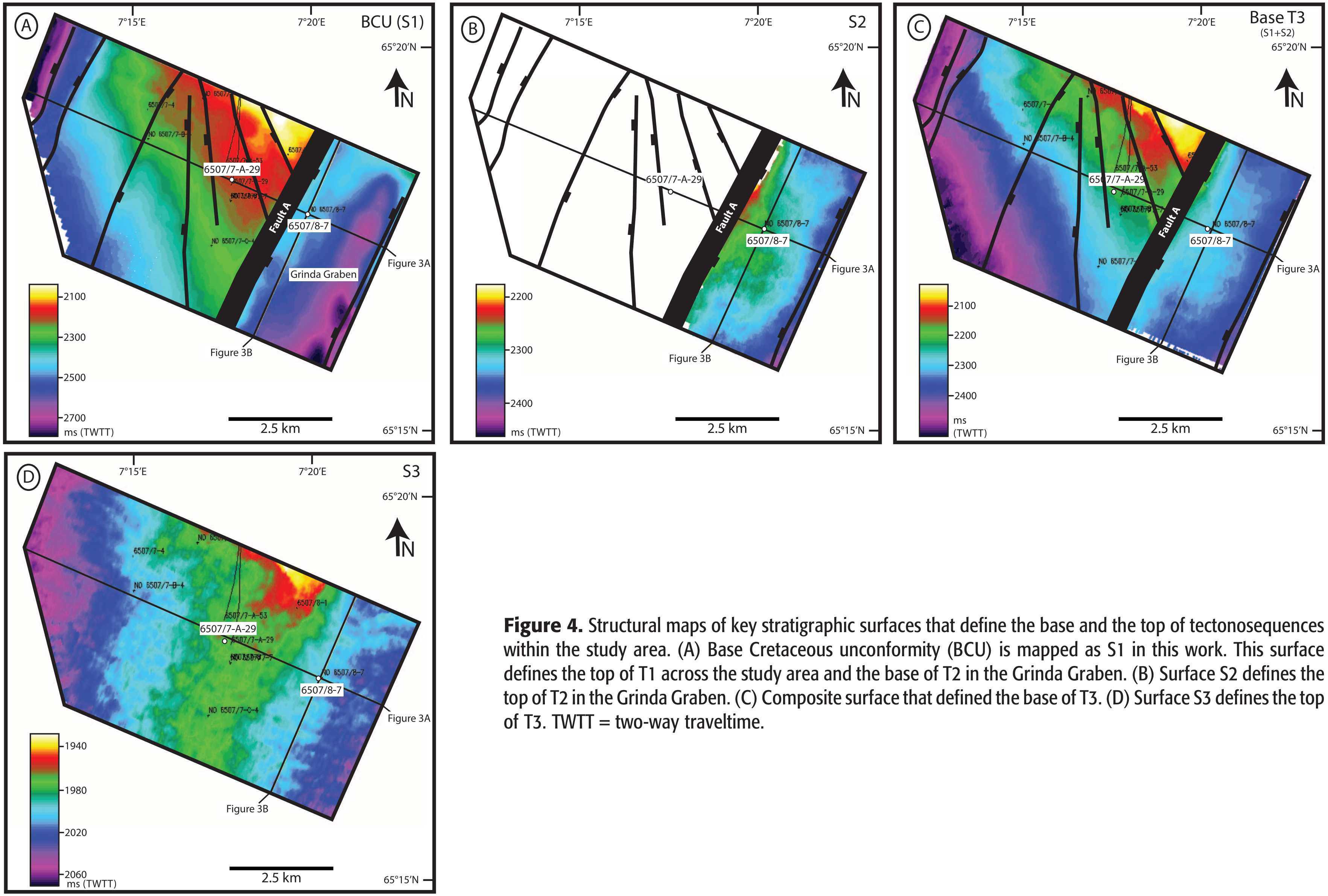

Figure 4. Structural maps of key stratigraphic surfaces that define the base and the top of tectonosequences within the study area. (A) Base Cretaceous unconformity (BCU) is mapped as S1 in this work. This surface defines the top of T1 across the study area and the base of T2 in the Grinda Graben. (B) Surface S2 defines the top of T2 in the Grinda Graben. (C) Composite surface that defined the base of T3. (D) Surface S3 defines the top of T3. TWTT = two-way traveltime.

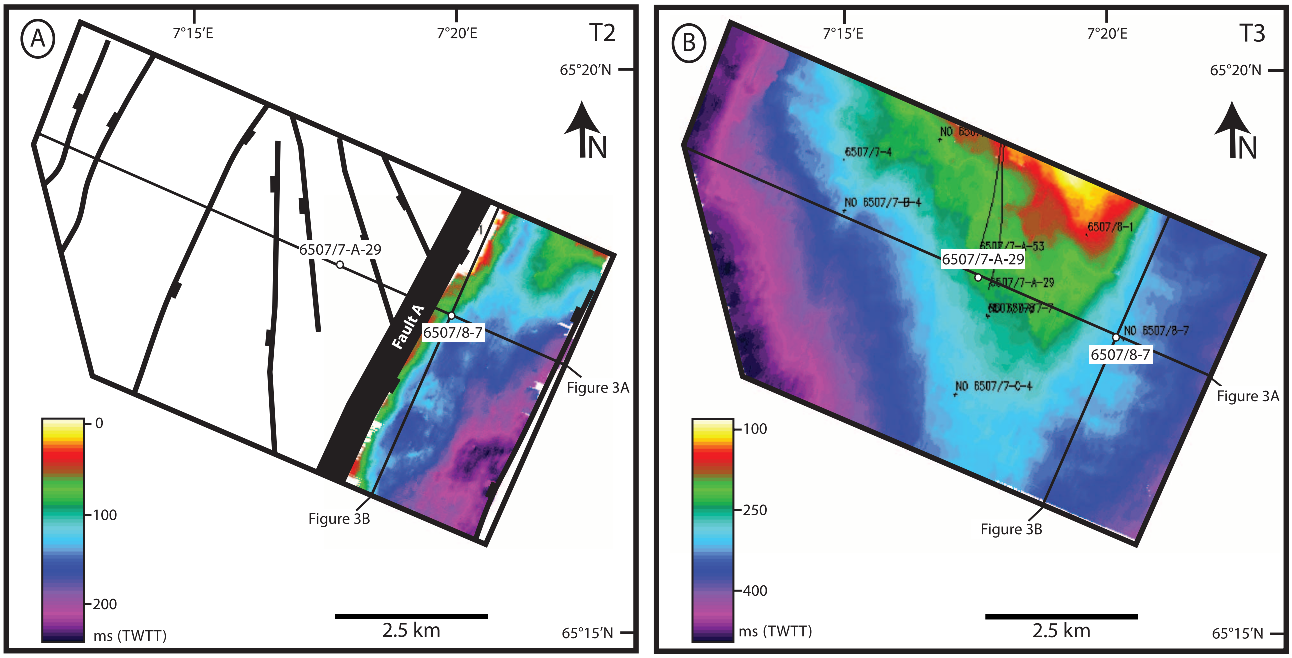

Figure 5. Isopach maps. (A) Tectonosequence T2 containing the postrift Cromer Knoll Group presents wedgelike geometry constrained to the east of fault A. The unit thickens toward the southeast. (B) Tectonosequence T3 containing the postrift Shetland Group; the isopach map shows how this interval thickens away from Jurassic highs as it infills the space generated by previous rifting episodes. TWTT = two-way traveltime.

bottom-water circulation conditions were prevalent from the Late Jurassic to the Early Cretaceous (van der Zwan, 1990). The rifting Vøring Basin was dominated by a great deal of structural variability associated with the development of multiple horst and graben structures during the synrift phase. Because the abundance of fragmented structural highs and lows across the basin influenced the paleobathymetry, paleoenvironmental conditions did not develop uniformly across the basin during the Late Jurassic to the Early Cretaceous. One of the main objectives of this study is to characterize the architecture and geomorphology of the Cromer Knoll Group within the Heidrun field to explain the tectonostratigraphic significance, paleoenvironmental configuration, and reservoir potential of this Lower Cretaceous postrift unit (Figures 2, 3).

DATA SET AND METHODS

The data set used to conduct this study of the Lower Cretaceous succession within the Heidrun field consisted of three-dimensional (3-D) seismic reflection data and well information. The available seismic volume covers 48 km^2 in the southern part of the Heidrun field, straddling production blocks 6507/7 and 6507/8 (Figure 1). The 3-D seismic volume has a total imaging depth of 4000-ms two-way traveltime (Figure 3). The seismic survey is zero phase and has a dominant frequency of 30 Hz in the interval of interest. Interval velocities were calculated using the sonic log of well 6507/8-7. Velocities for the Upper Jurassic interval range from 3800 to 4900 m/s (12,467–16,076 ft/s), whereas the Lower Cretaceous registers interval velocities that are close to 2770 m/s (9089 ft/s). Frequency analysis of these seismic data indicates that the maximum vertical resolution for the Upper Jurassic is 30 to 38 m (98–125 ft), whereas the maximum vertical resolution for the Lower Cretaceous is 22 m (72 ft). Conventional seismic interpretation methods, including seismic facies descriptions and mapping, were used to generate key surfaces that define the architecture of the stratigraphic succession within the study area (Figures 2, 3). Seismic interpretation techniques included manual and automatic picking of key amplitude horizons, interpolation, and merging of horizons to generate final

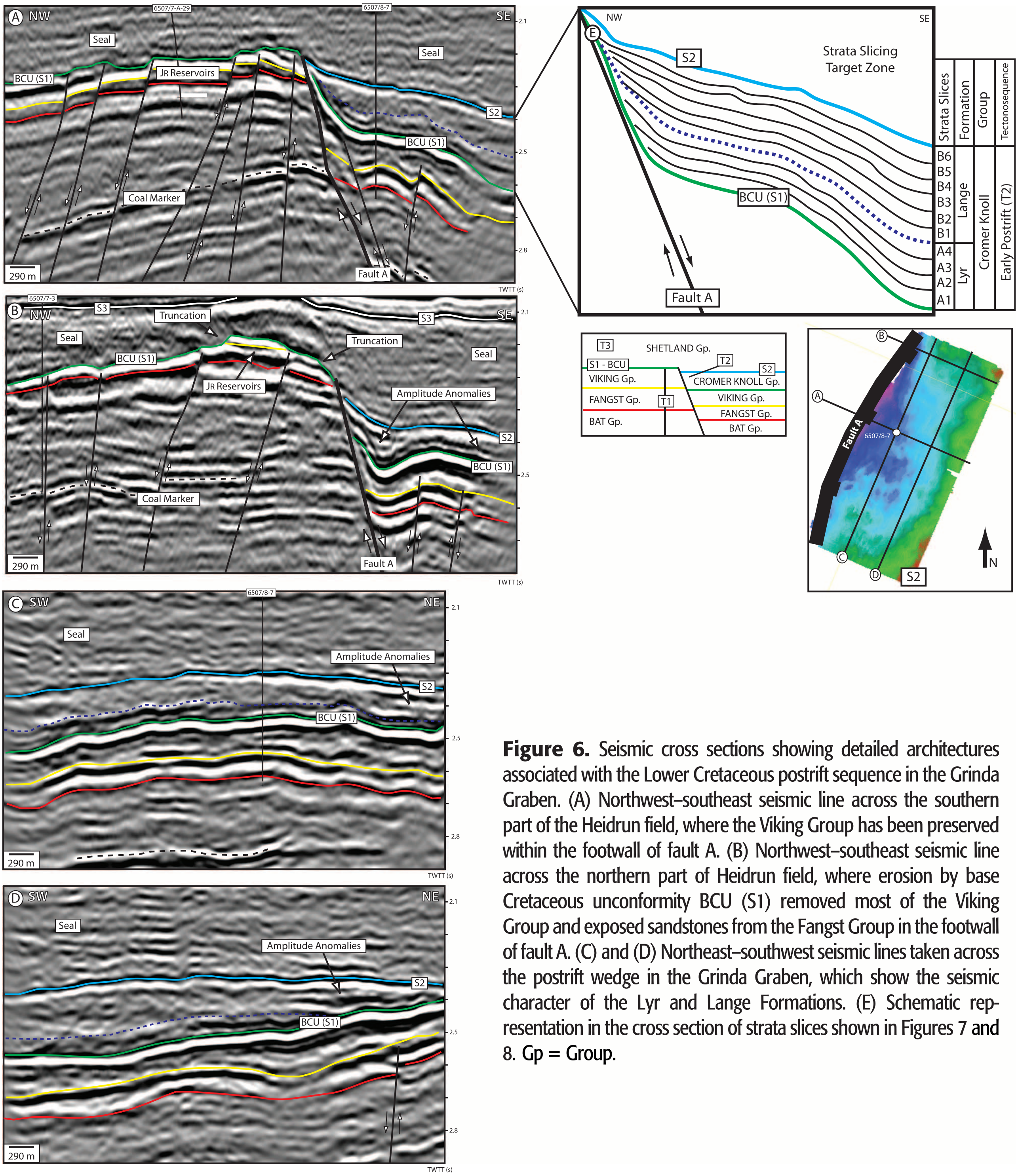

Figure 6. Seismic cross sections showing detailed architectures associated with the Lower Cretaceous postrift sequence in the Grinda Graben. (A) Northwest–southeast seismic line across the southern part of the Heidrun field, where the Viking Group has been preserved within the footwall of fault A. (B) Northwest–southeast seismic line across the northern part of Heidrun field, where erosion by base Cretaceous unconformity BCU (S1) removed most of the Viking Group and exposed sandstones from the Fangst Group in the footwall of fault A. (C) and (D) Northeast–southwest seismic lines taken across the postrift wedge in the Grinda Graben, which show the seismic character of the Lyr and Lange Formations. (E) Schematic representation in the cross section of strata slices shown in Figures 7 and 8. Gp = Group.

versions of key stratigraphic surfaces. Maps of key stratigraphic horizons and isopach maps of the stratigraphic units were generated to define the present-day structural configuration and the temporal and spatial evolution of the interval of interest (Figures 4, 5). Stratal-slice methods were also applied to the interval of interest; this methodology uses reference horizons picked above and below the targeted zone as controls for sampling the data (Figure 6E) (Zeng et al., 1998). Once stratal slices were generated within the interval of interest, a series of root-mean-square (RMS) seismic attribute extractions were

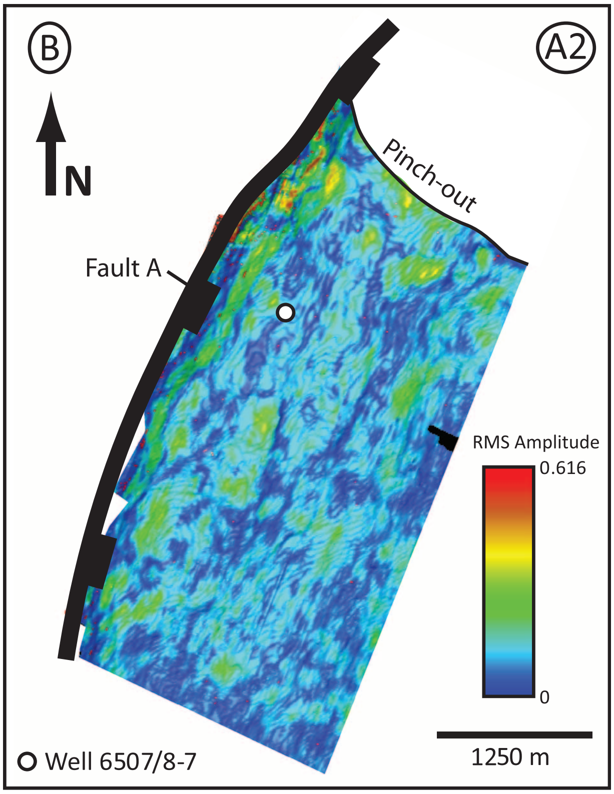

Figure 7. Representative strata slice for Lyr Formation (see Figure 6E for relative stratigraphic position). The root-mean-square stratal slices within this interval present low- to medium-amplitude responses. Patterns resemble northeast–southwest elongated bodies and suggest axial sediment-transport mechanisms acting within the half graben. Alternatively, these amplitude anomalies can also be interpreted as thin-skinned gravitational gliding structures derived from the footwall of fault A (Løseth et al., 2011).

performed to produce attribute maps (Figures 7, 8). Root-mean-square attribute extractions provide an effective way of identifying contrast between high- and low-amplitude responses within time-equivalent time slices, these lateral variations commonly correlating with the presence of stratigraphic discontinuities that have a paleoenvironmental significance (e.g., identification of sinuous patterns vs. lobate morphologies, etc.). Seismic data were interpreted using Linux workstations and Landmark subsurface interpretation software (Seisworks and Geoprobe). Six tectonosequences were identified within the study area on the basis of formation picks as reported in well reports and the seismic character of each unit (Figures 2, 3). Well data were obtained from ConocoPhillips and the Norwegian Petroleum Directorate (Figure 9); log suites included gamma-ray, resistivity, density, neutron, and sonic logs. We also had access to checkshots, vertical seismic profiles, and photoelectric-factor data. The interval of interest (Cromer Knoll Group) is penetrated by only one well (6507/8-7) (Figures 3, 6). Biostratigraphic analyses were not included on the well reports, but formation tops and lithologic descriptions were available. A synthetic seismogram was generated for well 6507/8-7 to improve the well log–seismic correlation within the Upper Jurassic to the Lower Cretaceous interval.

TECTONOSTRATIGRAPHIC EVOLUTION OF THE HEIDRUN FIELD

The mid-Norwegian continental margin has experienced a long history of basin evolution, beginning as a Middle Devonian–Carboniferous intramontane basin that was then affected by several phases of rifting from the Carboniferous to the Paleocene (Whitley, 1992). This repeated overprinting of basins allowed for the accumulation of thousands of meters of sediments in the Norwegian-Greenland area. The basement of the mid-Norwegian basin is inferred to be composed of Caledonian metamorphic and intrusive rocks (Bukovics and Ziegler, 1985). The data set used in this study records tectonic events that occurred only between the Permian–Triassic and the Holocene (Table 1; Figures 2, 3). Ten unconformities (S1 [base Cretaceous unconformity {BCU}]–S10) (Figures 2, 3) were interpreted and correlated throughout the study area using criteria of reflection terminations, as presented by Mitchum et al. (1977). These unconformities bounded six key tectonosequences, which are discriminated on the basis of their seismic character, well-log response, and lithology (Table 1 and Figure 2). The tectonostratigraphic column for the study area illustrates the relative stratigraphic position of the main unconformities, as well as well-log signatures, lithology, and the age of the interpreted units (Figure 2). Table 1 summarizes the seismic character and main geologic characteristics associated with each of the interpreted tectonosequences. The main interval of interest for this study contains the Lower Cretaceous Cromer Knoll

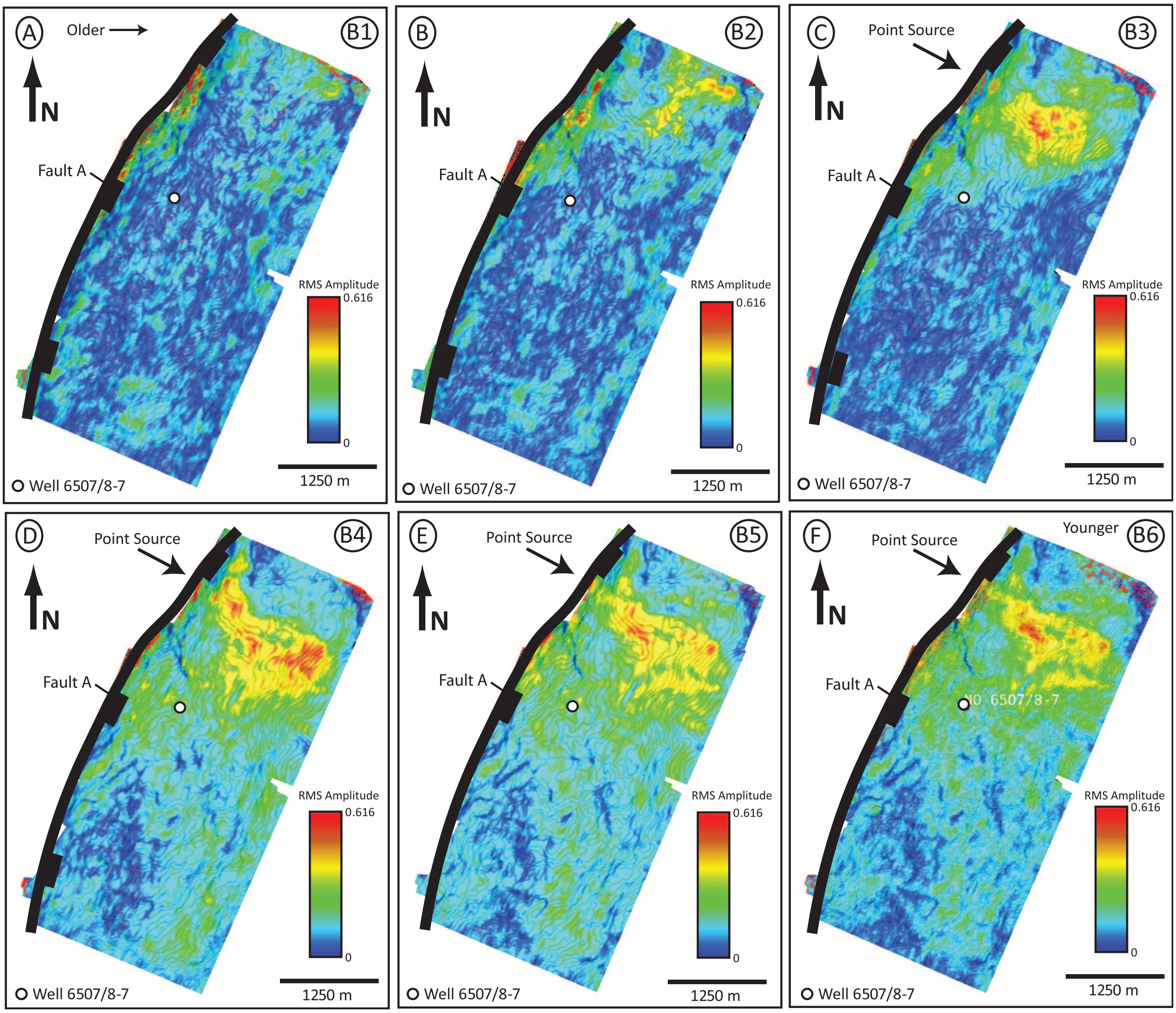

Figure 8. Stratal slice set B: Lange Formation (see Figure 6E for relative stratigraphic position). Elongated to lobate high-amplitude bodies on root-mean-square amplitude maps associated with Early Cretaceous deep-water sedimentary conduits that were transporting sediments from the footwall of fault A into the Grinda Graben to the east. RMS = root-mean-square.

Group (tectonosequence T2) (Figures 2–6). In this section, we concentrate on the description of tectonosequences T1 (prerift to synrift) to T3 (postrift) to explain the stratigraphic and structural framework in which the Cromer Knoll Group (T2) was deposited in the context of the Vøring Basin evolution.

Tectonosequence 1: Permian to Late Jurassic Transitional Stage (Prerift to Synrift)

Tectonosequence 1 (T1) includes Permian prerift and Triassic and Jurassic prerift and synrift sequences (Figures 2, 3). This tectonosequence could be subdivided into additional subunits; however, a more general description is provided here to establish only a basic framework to help explain some of the preconditioning geologic factors that controlled the development of the Lower Cretaceous postrift interval (T2). Lithologies associated with T1 include Triassic continental red beds and halite, as well as Jurassic fluvial and shallow-marine clastic units that contain reservoir-quality intervals. The Triassic halite is interpreted to be a relatively low amplitude zone that is partly continuous and that

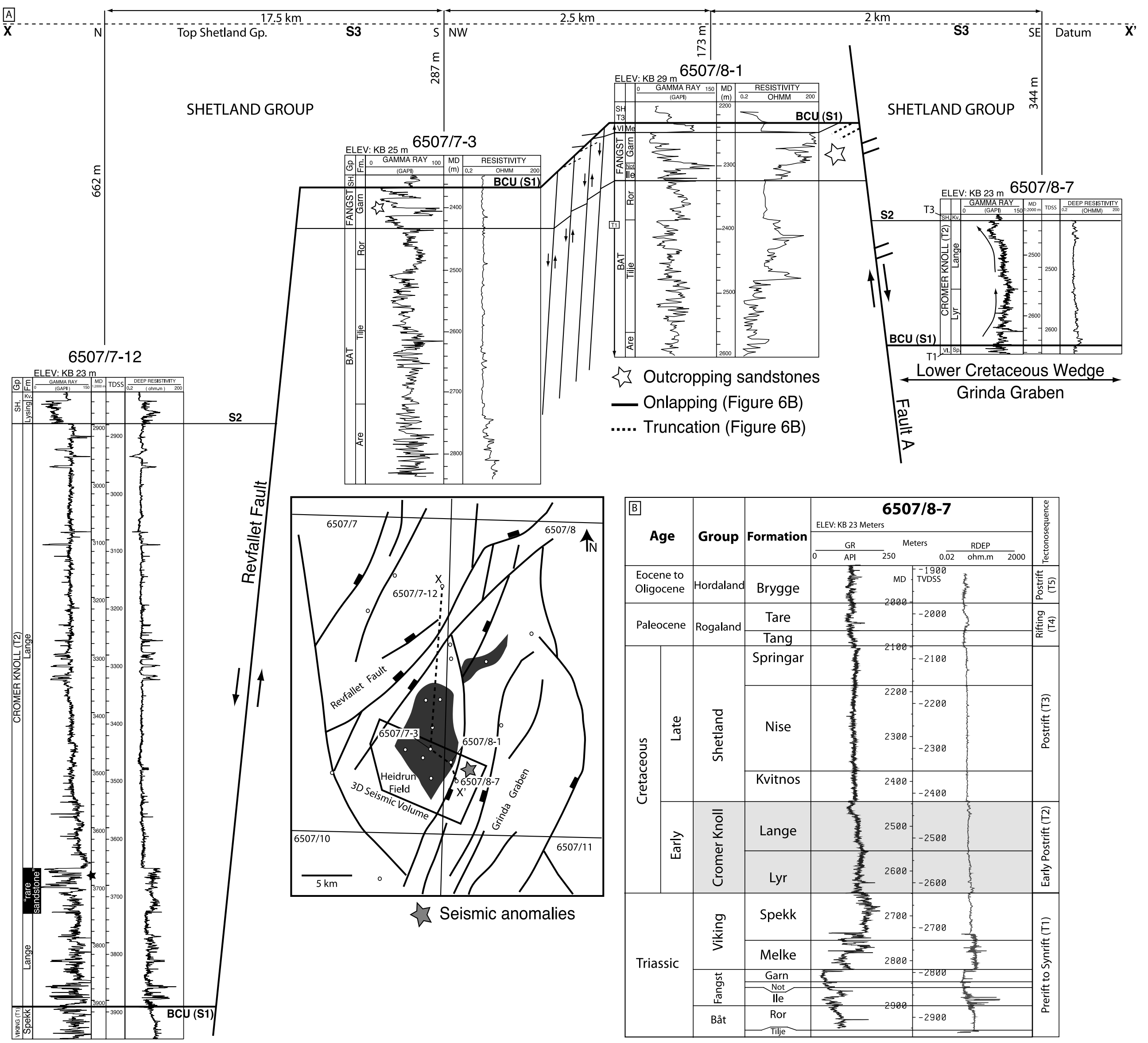

Figure 9. Semiregional well-log correlation for the Lower Cretaceous (Cromer Knoll Group). Datum top of Shetland Group. Gp = Group; GR = gamma ray; BCU = base Cretaceous unconformity; MD = measure depth; TVDSS = true vertical depth subsea.

can be identified in the Heidrun 3-D seismic volume (Figure 3). The upper boundary of T1 is defined by erosional surface S1 (Figures 3, 4A); this surface is equivalent to the BCU described across the Vøring and Møre Basins by previous authors (Bukovics and Ziegler, 1985; Swiecicki et al., 1998). Angular unconformity S1 defines the boundary between the mostly prerift to synrift Permian to Jurassic sequences and Cretaceous postrift units (Figures 2, 3). Unconformity BCU (S1), a complex structural surface having a high relief (~600 ms) within the study area (Figure 4A), truncated underlying Jurassic strata and was affected by intense faulting (Figure 4A). Unconformity BCU (S1) defines the top of a structural high (horst) in the central region of the study area and a structural low (Grinda Graben) in the southeast where sediments accumulated during the Early Cretaceous postrift event (T2) (Figures 3, 4A). T1 also contains units associated with the Spekk Formation, which is the main source rock on the mid-Norwegian continental shelf (Figure 2) (Swiecicki et al., 1998).

Table 1. Summary of the Main Geologic Characteristics Associated with Each Tectonosequence Within the Study Area

Tectonosequence	Boundaries	Seismic Character	Reflection Terminations	Structural-Isopach Maps	Lithology	Age	Paleoenvironment
T6: passive margin	Top: sea floor; base: S6	Combination of high- and low-amplitude continuous reflections (clinoform foresets)	Occasional downlap terminations against internal unconformities	Isopach maps show variations on the character and location of main depocenters	Glacial deposits, interbedded claystones, and siltstones (Naust Formation)	Pliocene–Holocene	Glacial marine
T5: postrift stage 2	Top: S6; base: S4	Combination of undulating and continuous high-amplitude reflections (polygonal faulting)	Some apparent downlapping against the base of the unit	Isopach map shows constant thickness with minor local variations	Hemipelagic deposits, calcareous and clayey siliceous mudstones	Eocene–Miocene	Deep marine
T4: rifting reactivation	Top: S4; base: S3	Very high reflectivity and lateral continuity	Conformable	Isopach map shows constant thickness and thin unit	Hemipelagic claystones (Tare Formation) and tuffaceous sandstones (Tang Formation)	Paleocene	Deep marine
T3: postrift	Top: S3; base: composite surface BCU* (S1) and S2	Low-amplitude and semicontinuous reflections	Onlaps against composite basal surface (BCU [S1] and S2)	Isopach map shows this interval thickening away from Jurassic highs	Calcareous shales and claystones (Shetland Group)	Late Cretaceous	Deep marine
T2: early postrift stage	Top: S2 (onlapping against horst and constrained to the Grinda Graben); base: BCU (S1)	Combination of high-amplitude continuous reflections and low-amplitude discontinuous reflections	Onlaps to the west against the Jurassic horst	Isopach map shows this unit as a sedimentary wedge that pinches out against the horst and thickens toward the southeast	Limestones: marls and claystones and possible sandstones (Cromer Knoll Group)	Early Cretaceous	Deep marine
T1: transitional stage (prerift to synrift)	Top: S1 (angular unconformity); base: BCU	Combination of low- and high-amplitude seismic reflections	Truncations below S1 (BCU) and onlaps above S1 (BCU)	Top of T1 (BCU [S1]): complex stratigraphic surface that defines the top of horst and graben structures	Triassic continental red beds and halite Upper Jurassic organic-rich shales (Spekk Formation), Jurassic medium- to coarse-grained sandstones, interbedded with shales and coals (Fangst and Båt Groups)	Permian to Jurassic	Fluvial to shoreface to shallow marine

*BCU = base Cretaceous unconformity.

Examination of seismic data (Figure 3) shows that T1 was affected by intense faulting associated with multiple rifting events; these faults were subsequently truncated by unconformity BCU (S1) during the final stages of rifting. Two types of faults affect T1: northeast–southwest master normal faults and associated antithetic faults (Figures 3A, 4A). Bukovics and Ziegler (1985) documented crustal extension and continental rifting in the Norwegian-Greenland Sea that accelerated into the Early Triassic and propagated south into the North Sea. The thick-skinned rift faults that were set up in the Triassic followed a generally northeast–southwest orientation similar to that of the faults observed within our study area (Figures 3A, 4A). Triassic halite may have acted as a detachment surface during the Jurassic reactivation, accommodating some of the slip on the synthetic and antithetic normal faults (Figures 3A, 4A) (Skar and Beekman, 2003). Elliot et al. (2012) pointed out that the footwall of major faults on the Halten Terrace did not experience too much differential uplift because of the thin-skinned, gravity-driven structural character of these faults. Significant erosion affected these footwalls through slope failure and collapse during the synrift phase (Elliot et al., 2012). Reactivation of some of these structures could have also caused a simple offset of strata across fault planes.

Tectonosequence 2: Early Cretaceous Postrift Stage

Tectonosequence 2 (T2) contains sediments deposited during the Early Cretaceous postrift event and represents the main interval of interest for this study (Figures 2, 3). The lower and upper stratigraphic boundaries of T2 are defined by BCU (S1) and unconformity S2, respectively (Figures 3–6). This tectonosequence is present only within the southeastern corner of the Heidrun field (Grinda Graben) (Figures 4B, 5A), and it is easily recognizable as a sedimentary wedge that pinches out against the Jurassic horst to the west (Figures 3A–6). The isopach map for this interval shows a general thickening toward the southeast (Figure 5A), with the reactivated Triassic rift fault (fault A) being the major structural control on the stratigraphic pinch-out of the postrift wedge to the west (Figures 3A–6). The postrift interval represented by T2 is confined to a fault-bounded depocenter and represents the early infilling of an underfilled relief created during the previous Late Jurassic rifting event (T1). This Early Cretaceous depocenter was infilled by the Lyr and Lange Formations of the Cromer Knoll Group (Figures 6–9). T2 has been defined as a postrift unit because, although fault activity had mostly ceased at this time, accommodation was controlled mainly by the preexisting topography created during the Jurassic rifting phase. In this particular case, the low associated with the Grinda Graben constrained the deposition of Early Cretaceous sediments to the southeast of the Heidrun field (Figures 3A–5A). In a more regional context, Early Cretaceous deposits were constrained mostly to topographic lows associated with the hanging walls of rift-related normal faults.

Tectonosequence 3: Late Cretaceous Postrift Stage

The base of T3 is defined by a composite surface that contains segments of BCU (S1) and S2 to the west and east of fault A, respectively (Figures 3A, 4C). Seismic reflections within this unit present a characteristic low-amplitude and semicontinuous response (Figures 3–6). The top of T3 is defined by unconformity S3 (Figure 4D), which is easily recognizable as a high-amplitude and continuous seismic reflection that can be mapped across the study area (Figure 3). Unconformity S3 represents the Cretaceous–Tertiary boundary within the study area (Figure 3). The isopach map for T3 shows the interval thickening away from the Jurassic high, with maximum thickness variations at approximately 350 ms (Figure 5B). In the Heidrun field, higher sedimentation rates associated with the deposition of T3 allowed this unit to cover topographic highs created during the Jurassic rifting phase (T1) and that had remained exposed during the Early Cretaceous postrift event (T2) (Figure 3A). Drill-cutting descriptions and well-log signatures indicate that T3 contains fine-grained sediments associated with the Shetland Group (Figures 2–9).

PETROLEUM SYSTEM OF THE MID-NORWEGIAN MARGIN

Rift-related normal faults contained within T1 formed the dominant structural traps and migration pathways for hydrocarbon accumulations in the Heidrun field and other fields throughout the mid-Norwegian continental shelf and the North Sea (Figure 3A) (Bukovics and Ziegler, 1985). The traps in the Heidrun field were formed during the Cimmerian tectonic event (Whitley, 1992). Reservoirs on the mid-Norwegian continental shelf and in the North Sea are found within Jurassic fluvial and shallow-marine sandstones (T1), which define the best reservoir-quality intervals in this region (Figures 2–9). The Jurassic fluvial and shallow-marine siliciclastic units that define these reservoirs, part of the Fangst and Båt Groups in the Heidrun field (Figures 2–9), are equivalent to those of the Brent Group in the North Sea (Swiecicki et al., 1998). In addition, older shallow-marine sandstones from the Åre–Tilje Formations also represent reservoir targets (Figure 9). The BCU (S1) defines the top of a horst structure in the central region of the study area that contains most of the targeted Jurassic reservoirs within the Heidrun field (Figures 4–6). Calcareous shales and claystones from the Upper Cretaceous Kvitnos, Nise, and Springar Formations (Shetland Group–T3) act as seals for these Jurassic reservoirs. The Shetland Group is also a potential seal for Lower Cretaceous intervals (T2) (Figure 6); however, lateral facies changes and localized faulting and fracturing patterns have the capacity to alter the sealing integrity of this unit. The Spekk Formation (T1), which is equivalent to the Kimmeridge Clay in the North Sea, is the primary oil- and gas-generating source rock on the mid-Norwegian continental shelf, and it was deposited under marine, anoxic, bottom-water conditions (Swiecicki et al., 1998). The gamma-ray log (well 6507/8-7) shows a sharp peak at the base of the Spekk Formation, representing a decrease in gamma radiation, which is useful for identifying the base of the unit when well logs are being examined (Figure 9B). The Spekk Formation has the highest gamma-ray readings in the Halten Terrace area, and it is a rich source rock with a total organic carbon content of as much as 13%, averaging 4% (Whitley, 1992; Swiecicki et al., 1998). The thickness of the Spekk Formation in the study area is approximately 100 m (328 ft), as reported in well 6507/8-7 (Figure 9B); however, this thickness is expected to increase to the east and southeast. The Åre Formation (Båt Group–Middle Jurassic) (T1) contains thick coal beds that generate continuous, high-amplitude seismic reflections that can be observed clearly on the 3-D seismic volume and that can be used as a correlation marker (Figure 3). The coal beds associated with the Åre Formation are also interpreted as a secondary gas-prone source rock that was deposited under paralic and swampy conditions during the Rhaetian and Early Jurassic (Whitley, 1992; Swiecicki et al., 1998). Because these two source rocks are mature in the downdip areas 5 to 15 km (3–9 mi) southwest and west of the Heidrun field, long migration paths have been inferred (Whitley, 1992).

The most eastwardly normal fault within our study area (fault A) represents the west boundary of a graben structure (Grinda Graben) where Early Cretaceous sediments accumulated (Figures 3, 5A). Fault A also connects the underlying Triassic and Jurassic sections (T1) with the Lower Cretaceous postrift unit (T2) (Figure 3A). This fault connectivity suggests, at least from a geometric perspective, that upward fluid migration between these units might have been possible (Figure 3A). Fugelli and Olsen (2005) suggested that Cretaceous and Tertiary plays might constitute 50% of the undiscovered resources of the Norwegian Sea. Successful discoveries targeting Upper Cretaceous reservoirs in this region include the giant Omen Lange field (turbidite sandstones of Late Cretaceous to early Paleocene age); the Nyk High in which Upper Cretaceous turbidites displayed a prominent flat spot; and the Snadd prospect, where an Upper Cretaceous combination trap was associated with turbidite sandstones from the Lysing Formation (Fugelli and Olsen, 2005). Despite some success in the exploration of Upper Cretaceous units in the Norwegian Sea, the prospectivity of Lower Cretaceous intervals remains unknown. Because Lower Jurassic reservoir levels seem to be almost depleted, the oil and gas industry has launched an active campaign to explore the potential of the Upper Jurassic and Cretaceous intervals in more distal settings of the Vøring Basin to the west. We think that a closer examination of the postrift Lower Cretaceous wedge (T2) within the Heidrun field is important for unraveling the character and hydrocarbon potential of this interval. In addition, characterization of this Lower Cretaceous unit will improve our understanding of the connection between proximal and more distal depositional systems across the greater Vøring Basin. A more detailed analysis of this interval will be provided in an upcoming section of this article.

SEISMIC GEOMORPHOLOGICAL ANALYSIS T2 POSTRIFT GROUP: CROMER KNOLL GROUP

A northwest–southeast seismic line illustrates the typical wedgelike geometry associated with the T2 postrift interval of interest (Figures 3–6). A well-based stratigraphic correlation also shows the character of the Lower Cretaceous wedge in the southeastern part of the study area (Figure 9). This sedimentary wedge thickens toward the east and southeast and onlaps against the Jurassic horst to the west (Figures 5A, 6). This unit was deposited in a half graben (Grinda Graben) created by Jurassic rift faulting (Figures 1–3). The onlap observed within the Cromer Knoll Group against the Cimmerian structures (horst) is a reflection of the rapid subsidence that occurred during the Cretaceous west of the Halten Terrace (Whitley, 1992). Seismic attribute analysis was conducted within this Lower Cretaceous postrift interval so that its geomorphological evolution through time could be unraveled (Figures 7, 8). The postrift sedimentary wedge was proportionally sliced into 10 stratal slices such that the maximum thickness of each slice was approximately 34 m (~103 ft) (Figure 6E) (Zeng et al., 1998). Root-mean-square amplitude extractions were computed for each slice to generate individual maps (Figures 7, 8). Only one well (6507/8-7) penetrated the Lower Cretaceous postrift unit (T2) (Figures 6–9). Two distinctive stratigraphic units were described on the basis of their seismic geomorphological characteristics and well-log signatures.

Stratal Slice Set A: Lyr Formation (Berriasian to Valanginian)

Stratal slice set A is located in the lower section of the Lower Cretaceous postrift wedge (T2) (Figure 6E), containing sediments associated with the Lyr Formation (Figures 2–9). This interval is characterized in cross section by the presence of low-amplitude and semicontinuous seismic reflections (Figure 6). The RMS stratal slices within this interval present low- to medium-amplitude responses, showing some patterns that resemble northeast-southwest elongated bodies that parallel the strike orientation of fault A to the west (Figure 7). Seismic-based correlations indicate that the Lyr Formation pinches out toward the northeast and that it is absent on the northeastern corner of the Lower Cretaceous wedge (Figures 6, 7). The gamma-ray response for the Lyr Formation in well 6507/8-7 is consistent with a mudstone interpretation, and a slight upward-fining pattern can be observed (Figure 9). Dalland et al. (1988) reported that the Lyr Formation consists of interbedded marls, calcareous mudstones, and mudstones, with occasional stringers of limestone. The mineralogical contrast between the underlying organic-rich Spekk Formation and the mostly marine, calcareous Lyr Formation allows for the recognition of a sharp basal contact on the gamma-ray log (Figure 9B).

The Lyr Formation was deposited under open-marine conditions during the Berriasian to the Valanginian (Gradstein et al., 1999). We explored several potential interpretations to try to explain the northeast–southwest amplitude patterns observed on the RMS strata slices for the Lyr Formation (Figure 7). Because most of these amplitude anomalies are parallel to the strike orientation of fault A and are in close proximity to the fault plane, a shadowing effect associated with the fault geometry might be causing these amplitude patterns. However, we discarded this option because the amplitude anomalies are on the hanging wall of normal fault A, and, therefore, the interference of the fault plane with ray paths during seismic acquisition was unlikely. An alternative interpretation could be associated with the acquisition design of the seismic survey because the orientation of the cross lines is parallel to the orientation of the amplitude anomalies. Attribute-extraction maps from stratigraphic intervals above and below the Lyr Formation show that this elongated northeast–southwest orientation is not prevalent through the stratigraphic succession (Figure 8), and we therefore concluded that acquisition parameters did not cause the orientations observed in the Lyr Formation (Figure 7). Because fault geometry interference and/or seismic acquisition design issues are not linked to the northeast–southwest amplitude patterns observed within the Lyr Formation, we infer that these patterns must have a stratigraphic and paleoenvironmental significance. We have two potential paleoenvironmental interpretations for this unit. In the first one, amplitude patterns within the Lyr Formation are expression of axial sediment transport mechanisms acting within the half graben (Færseth and Lien, 2002). The well-log character of the Lyr Formation (6507/8-7) indicates a predominately mudstone lithology, but the upward-fining pattern also suggests variations in grain-size distribution (Figure 9B). The amplitude contrast observed on the RMS attribute maps of the Lyr Formation could be reflecting the sorting that occurred within the unit under the action of axial currents at the time of deposition (Figure 7). Løseth et al. (2011) also provided an alternative paleoenvironmental interpretation for amplitude anomalies that can form in mudstone-dominated systems in the North Sea and along the mid-Norwegian margin. According to their interpretation, the amplitude anomalies observed within the Lyr Formation in the study area can be associated with thin-skinned gravitational gliding structures that transported sediments by mass wasting from the footwall of fault A downslope into the Grinda Graben (detached mass-transport deposits) (Moscardelli and Wood, 2008; Løseth et al., 2011). The only well penetrating this unit in the study area is 6507/8-7, and at this point, having a definite interpretation without additional well control is difficult.

Stratal Slice Set B: Lange Formation (Aptian to Albian)

Seismic Description

The upper part of the Lower Cretaceous postrift wedge contains rocks associated with the Lange Formation (Figures 6–9). The stratal slices taken within the Lange Formation revealed a distinctive seismic geomorphological pattern not observed in the older Lyr Formation (Figure 8). Toward the base of the Lange Formation, RMS stratal slice B1 (Figure 8A) shows low- to medium-amplitude responses that are distributed in a seemingly random pattern; however, stratal slice B2 (Figure 8B) starts to show distinctive high-amplitude responses clustered toward the northern part of the seismic volume. These high-amplitude patterns have a lobate to elongated architecture, are vertically stacked, increase in size as they become stratigraphically younger, and seem to be point source fed from the west (see stratal slices B3–B6) (Figures 6E, 8). The main axis of these high-amplitude features is approximately 2 km (1 mi) long and perpendicular to the strike orientation of fault A to the west (Figure 8). The lack of seismic coverage to the east hinders our ability to measure the real dimensions of these bodies (Figures 1B–8). The minimum width of the high-amplitude features near normal fault A is approximately 500 m (1640 ft), but the features widen toward the east until reaching a maximum width of approximately 1000 m (3281 ft) near the edge of the 3-D seismic volume (Figure 8). These high-amplitude features extend beyond the boundaries of the 3-D seismic survey, and we think that their overall geometry is more elongated than what we can appreciate within the boundaries of our data set. Northwest–southeast seismic cross sections taken across these high-amplitude, lobate to elongate bodies show a clear truncation of reflections updip on the footwall of fault A (horst) (Figure 6B). This level of truncation caused by the BCU (S1) is not as acute on the southern part of the horst structure (Figure 6A).

Wireline-Log Description

Most wells in the Møre and Vøring Basins have not tested the Cretaceous or Paleocene stratigraphic succession in optimal positions (Fugelli and Olsen, 2005). Well 6507/8-7 was drilled through the postrift wedge in the Heidrun field, but this penetration did not directly target the high-amplitude zone shown on the strata slices (Figures 8, 9). The wellbore history of well 6507/8-7 indicates that the top of the Cromer Knoll Group consists of interbedded limestones, marls, and claystones linked to the Lange Formation. However, the gamma-ray log shows a general upward-coarsening pattern (Figure 9B) that correlates laterally with the interval where the high-amplitude bodies were identified on the seismic data (Figures 6C, 8). In a regional context, the Lange Formation consists predominantly of mudstones containing some stringers of limestones and occasional sandstone bodies. Well 6507/7-12, which was drilled to the north of the Heidrun field, in the hanging wall of the Revfallet fault complex separating the Dønna Terrace from the Nordland-Trøndelag Platform, reported the existence of one rare Lower Cretaceous sandstone (Figure 9) (source: Norwegian Interactive Offshore Stratigraphic Lexicon, n.d.). Well 6507/7-12 is located in a structural configuration analogous to the position of well 6507/8-7 in our study area (Lower Cretaceous section drilled in the hanging wall of a normal fault) (Figure 9). The well cross section shown in Figure 9 illustrates a stratigraphic correlation for the Cromer Knoll Group, which was generated using wells to the north of the Revfallet fault system (6507/7-12), within the horst structure in the Heidrun field (6507/7-3 and 6507/8-1) and to the east of fault A in the Grinda Graben (6507/8-7). The well-log correlation suggests that the Lange Formation is much thicker to the north of the Revfallet fault system (1022 m [3353 ft] thick) than it is to the east of fault A in the Grinda Graben (132 m [433 ft]) (Figure 9). However, the Lange Formation is contained within Lower Cretaceous postrift wedges that pinch out against major fault systems, and well 6507/8-7 is located only 132 m (433 ft) to the east of fault A in the Grinda Graben. Well 6507/7-12 is located 1022 m (3353 ft) to the north of the Revfallet fault where the section is thicker (Figure 9). The relative proximity of wells to fault planes explains the apparent differences in thickness reported by wells 6507/8-7 and 6507/7-12 for the Lange Formation. The isopach map of the Cromer Knoll Group in the Grinda Graben clearly shows a thickening of the unit toward the east and southeast, and the Lange Formation also follows this thickening pattern (Figure 5A). Examination of well information within the study area also indicates that erosion associated with the development of the BCU (S1) was more intense in the northern part of the study area (Figure 9). Most wells located in the Heidrun field (horst structure) reported the presence of a thin interval of Upper Jurassic shales (Viking Group) conformably capping Middle Jurassic sandstones from the Fangst Group (reservoirs) (Figure 6A). However, in well 6507/7-3 to the north, the Upper Cretaceous Shetland Group was found directly overlying the Middle Jurassic Garn Formation (Fangst Group), indicating that shales from the Viking Group were completely eroded by the BCU (S1) event (Figures 6B–9). Removal of these Upper Jurassic shales (Spekk and Melke Formations) allowed for the subcropping of sandstones to the north, as illustrated by seismic data and well cross sections (Figures 6B–9).

Interpretation of Stratigraphic Context and Evolution

A wide range of deep-water deposits exists in the Møre and Vøring Basins, from slope- to basin-floor fan deposits (Fugelli and Olsen, 2005). We interpret the vertically stacked, high-amplitude lobate to elongated features identified within the Lange Formation in the Heidrun field (Figure 8) as parts of a sedimentary conduit that was transferring sediments from the western footwall block into a half graben to the east (Figure 10). Increased levels of erosion by the BCU (S1) unconformity in the northern parts of the horst structure within the Heidrun field are well documented by our data set, and subcropping of the Fangst Group is clearly visible (Figures 6, 9). Whitley (1992) also pointed out that Cimmerian block faulting during the Late Jurassic and Early Cretaceous caused local erosion of the Spekk Formation to the north of the Heidrun field (see his figures 16, 17). This Late Jurassic to Early Cretaceous erosional event caused a severe truncation of Jurassic reservoirs on the northern edge of the study area (Figures 6, 9). Sediments derived from the erosion of Jurassic sandstones

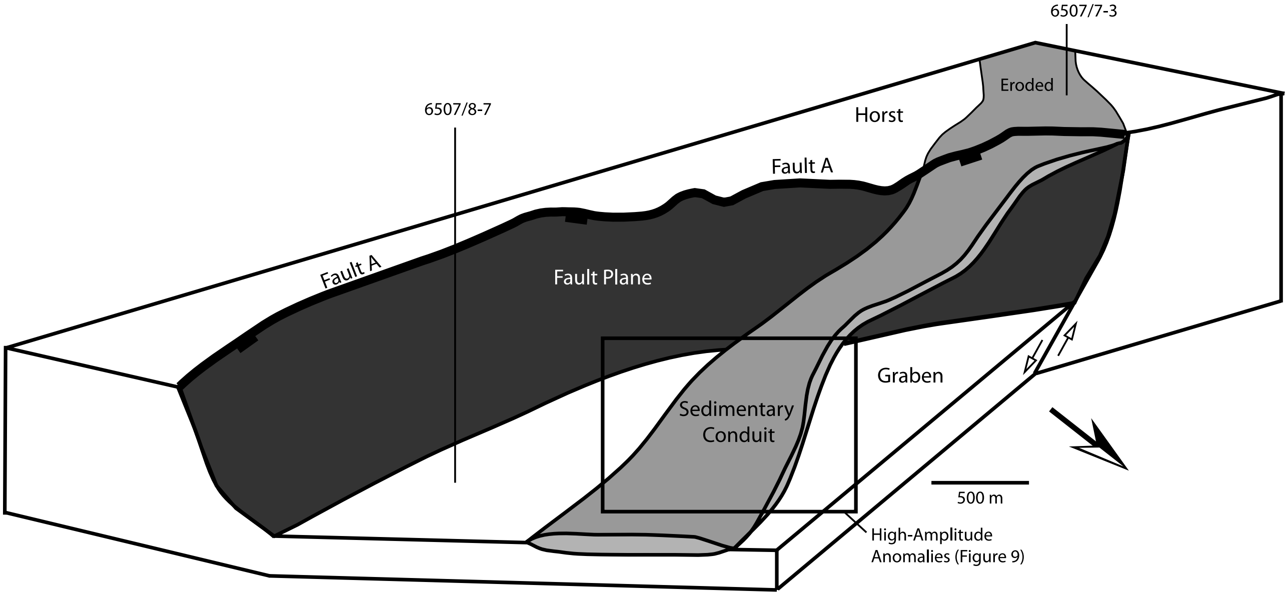

Figure 10. Schematic representation of the Early Cretaceous (Lange Formation) deep-water sedimentary conduit. Sands were sourced from the footwall of fault A.

(Fangst Group) in the horst region were transported both to the northwest and southeast, depending on the local gradient (Figure 6B). Sediments that were transported toward the southeast across fault A were deposited in the Grinda Graben through a sedimentary pathway observed on the attribute-extraction maps as a lobate to elongated area dominated by high seismic amplitudes (Figure 8). Limitations in the area covered by the 3-D seismic volume allowed us to image only the part of the conduit that was most proximal to normal fault A (Figure 8). Sediment-transport mechanisms envisioned for the Lange Formation within the Heidrun field are somewhat similar to the processes described by Fugelli and Olsen (2005) in the northern Dønna Terrace for the K72 Lysing Formation. These authors interpreted the high amplitudes as sedimentary conduits that cascade over fault-bounded terraces feeding basin-floor fans in the distal parts of the basin (Figure 10) (Fugelli and Olsen, 2005). The Popo channel from the Delaware Basin could represent a valid outcrop analog for the Lange Formation (Gardner and Borer, 2000; Fugelli and Olsen, 2005); however, the RMS attribute maps in our study area do not show a clear development of channelized features (Figure 8). The absence of well-imaged, sinuous channels within the interval of interest might be caused by the poor seismic resolution at these depths. Alternatively, sediment-transport mechanisms operating in deep-water sedimentary conduits do not have to necessarily generate sinuous channels, especially when local gradients are high within fault zones. According to this model, the upward-coarsening interval of the Lange Formation, as observed in well 6507/8-7, could possibly transition laterally into a sandier unit toward the north, where the high-amplitude bodies are located (Figures 6C–8).

The presence of Lower Cretaceous sandstone bodies in well 6507/7-12 (rare sandstone) could be a good indicator of the potential presence of time-equivalent sandstones in deeper undrilled parts of the Vøring Basin to the west (Figure 9). Well-log correlation (Figure 9) and seismic geomorphological analysis (Figures 6–8) also provided us with good arguments to suggest that time-equivalent Lower Cretaceous sandstones could be present to the east within the Grinda Graben. Traditional rift models (Ravnås and Steel, 1998) have suggested that synrift and postrift sequences receive sediments from the erosion of neighboring footwall highs, and our data indicate that this model applies to the Lange Formation within our study area (Figure 10). Provenance analyses of Upper Cretaceous samples in the Vøring Basin have indicated

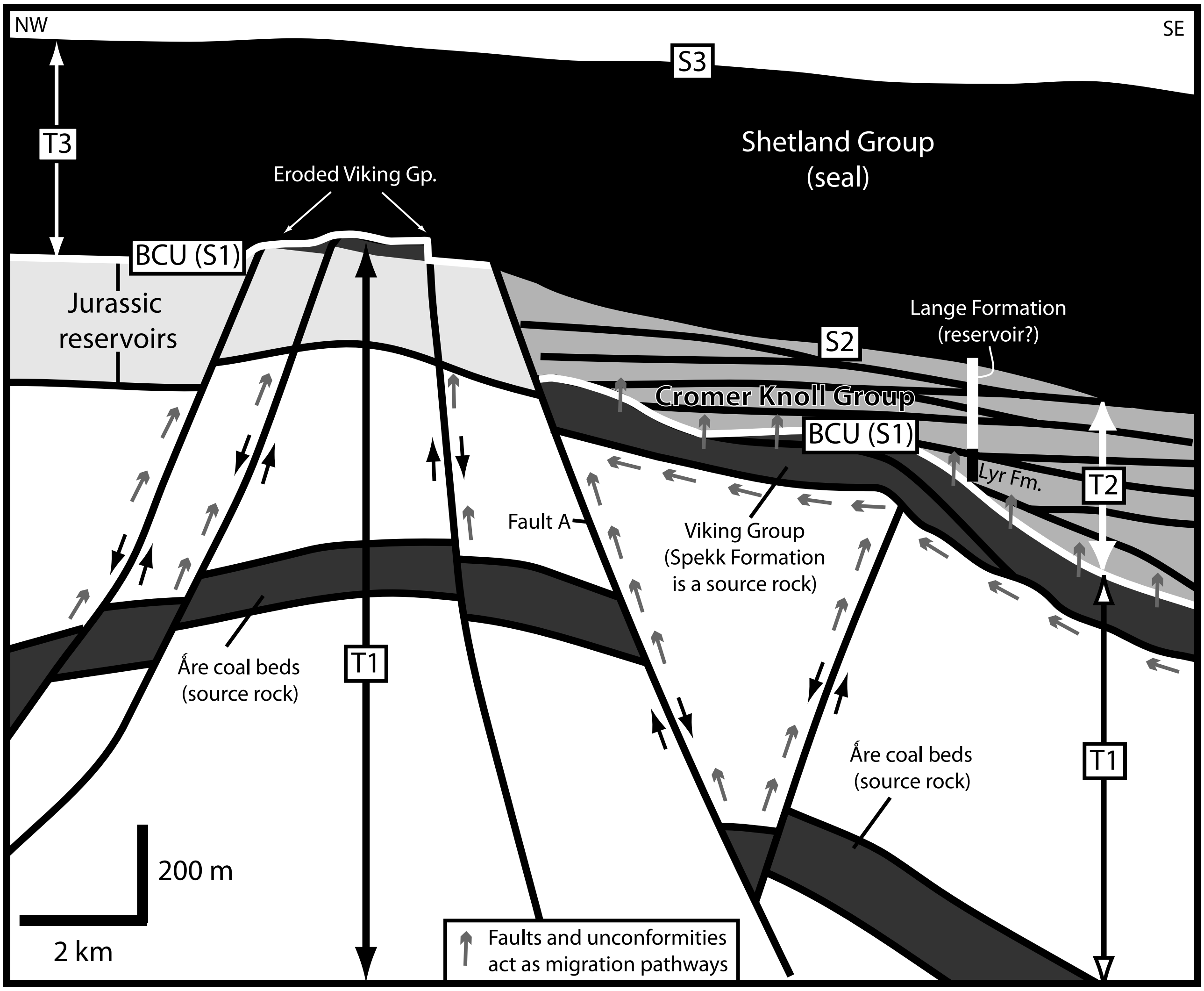

Figure 11. Petroleum system elements operating in the Heidrun field. Production data indicate that the petroleum system successfully charged Jurassic reservoirs. Whether potential reservoirs in postrift Cretaceous units (Lange Formation) could have been charged successfully with hydrocarbons remains unclear. Gp = Group; Fm = Formation; BCU = base Cretaceous unconformity.

that inland sedimentary sources, as well as sediments derived from footwall erosion, were available during the Late Cretaceous postrift phase (Morton and Grant, 1998; Morton and Chenery, 2009). Many of the wells that were used to perform these provenance studies are located within the Halten Terrace, and one well (6507/7-1) in particular is only 15 km (9 mi) to the northeast of the Heidrun field (Morton and Grant, 1998). We are not aware of any published studies addressing the issue of sediment provenance for the Lower Cretaceous succession within our study area, and the size of our seismic data set (48 km^2 [19 mi^2]) is too small to assess this topic at a regional scale. However, a hypothetical early influx of sediments into the basin from the continent during the Aptian to the Albian would have encouraged a dual system of local and extrabasinal sedimentation that could have increased the chances of sandstone deposition.

LANGE FORMATION: INTERNAL ARCHITECTURE AND IMPLICATIONS FOR HYDROCARBON MIGRATION AND ENTRAPMENT

Seismic amplitude anomalies in the Lower Cretaceous stratigraphic succession in the Heidrun field (Lange Formation) have been interpreted to represent the infill of sediment pathways that transported sediments from the footwall of fault A into more distal basinal deposits in the Grinda Graben (Figure 10). These sediment fairways can also contain reservoir-quality intervals. Note that the Viking and Cromer Knoll Groups present different internal reflection geometries within the Grinda Graben (Figures 6, 11). The Viking Group wedges against fault A while thickening to the south with deepening of the half-graben structure (Figure 6). However, the Cromer Knoll Group shows onlapping reflections and backfilling architectures that occupy the central to marginal regions of the half graben (Figure 11). During the Early Cretaceous, accommodation was filled to the southeast before sediments stepped northwestward to onlap onto the underlying Spekk Formation (Figure 11). The difference in stratal architecture between these two groups is critical to the charging of potential reservoirs in the Cromer Knoll Group. The Spekk Formation (source rock) drapes lows in the half graben, whereas the Cromer Knoll Group onlaps onto the source rock; this configuration could have allowed for the vertical and lateral migration of hydrocarbons into the Cromer Knoll Group (Figure 11). Secondary source rocks, like the coalbeds associated with the Åre Formation, could have also expelled hydrocarbons that migrated upward through Triassic and Jurassic fault systems until reaching the postrift wedge (T2) (Figure 11). Lateral migration could have also occurred through permeable surfaces like the BCU (S1) unconformity or permeable sandstone bodies, allowing for the migration of hydrocarbons from the western parts of the basin, where the source rocks are more mature (Figure 11). Finally, the Shetland Group (T3) acts as a regional seal for both proven Jurassic reservoirs and potential Lower Cretaceous reservoirs associated with the Lange Formation (Figure 11).

Risk factors associated with the Lower Cretaceous play include the quality of potential reservoir rocks associated with high-amplitude anomalies within the Lange Formation (Figures 8, 9), the character of potential migration pathways (faults and unconformities), the sealing integrity of the Shetland Group, and the geometry of the trap (Figure 11). Sedimentary conduits associated with the Lange Formation in the study area may contain shale intervals or fine-grained sandstones with poor permeability (Figure 9). At the same time, the claystone-rich Lyr Formation could have prevented effective vertical migration of hydrocarbons from the Spekk into the Lange Formation (Figures 9–11). Whether the Triassic and Jurassic faults affecting the basal interval of the synrift unit are open or closed faults is also unclear. Similarly, whether the BCU (S1) unconformity allowed for the lateral migration of fluids or whether it was a sealing surface is also unclear (Figure 11). The Shetland Group is known as a regional sealing unit across the area, but local variations could cause breaching of the seal and promote vertical fluid escape. Finally, well 6507/8-7 was drilled on what seems to be a structural closure associated with the top of the Lange Formation (Cromer Knoll Group) (Figure 4B); however, the high-amplitude anomalies that were interpreted as deep-water sedimentary conduits in this study are located to the north of this structural high (Figure 8). If the high-amplitude anomalies associated with these deep-water sedimentary conduits contained reservoir-quality rocks, then they would be mostly stratigraphic traps off structure, increasing the exploration risk of such a play. Despite all these uncertainties, we know that the petroleum system charged Jurassic reservoirs to the west within the footwall of fault A, and in our opinion, the biggest of all exploration risks for the Lower Cretaceous stratigraphic succession is the presence of good-quality reservoir rocks. Sandstone bodies have been previously documented within the Lange Formation in other locations not far from our study area (see well 6507/7-12 in Figure 9), and oil shows have been reported within these sandstones (Norwegian Interactive Offshore Stratigraphic Lexicon, n.d.). Although risks associated with the exploration of Lower Cretaceous intervals in the Norwegian Sea seem to be high, a better understanding of depositional systems associated with the genesis of these units could lead to an improved capacity to predict sandstone presence and a better chance of making new discoveries in this region.

CONCLUSIONS

The Norwegian continental shelf has experienced a long and complex tectonic evolution. A multitude of tectonic events allowed the setup of a prolific Jurassic petroleum system, not unlike its neighbor, the North Sea. Both the North Sea and Norwegian continental shelf are reaching the limit of exploration in the Jurassic, and now, explorationists are looking at the Cretaceous for new reservoirs. The Heidrun area shows a typical stratigraphic column for the Vøring Basin. Proven reservoirs within the Heidrun field are contained within an Upper Jurassic synrift sequence (T1). The final stages of evolution of the synrift sequence influenced the location of Early Cretaceous depocenters associated with postrift units represented by the Cromer Knoll Group (T2) in the Grinda Basin. Seismic interpretation analysis and well-log correlations that were performed across the study area suggest that the upper part of the Cromer Knoll Group (Lange Formation) was preserved as part of a deep-water sedimentary conduit active during the Early Cretaceous in the northern parts of the Heidrun field. This sedimentary conduit was transporting sediments that were eroded from the footwall of fault A (horst) toward the east into the Grinda Graben. Well-log information (6507/7-3) and key seismic cross sections indicate that the Viking Group was completely eroded in some areas of the footwall (horst structure) to the north of the study area and that sandstones of the Garn Formation were subcropping in this region. Our data and interpretations suggest that sedimentary sources associated with the Lange feeder system (Early Cretaceous) can be linked to the subcropping sandstones from the Upper Jurassic Garn Formation to the west (footwall of fault A). The presence of Lower Cretaceous rare sandstones with oil shows is not unprecedented in the Norwegian continental shelf, as reported by well 6507/7-12 located 17.5 km (10.9 mi) north of our study area. The high-amplitude seismic bodies contained within the Lange Formation and that have been interpreted as deep-water sedimentary conduits in this study have not been drilled yet, and we think potential exists for these units to contain reservoir-quality sandstones. Fugelli and Olsen (2005) pointed out that most of the Cretaceous and Paleocene postrift sandstones were not deposited or preserved along the margins of the Møre and Vøring Basins and should be explored for in the basin centers. However, our analysis of the Lower Cretaceous postrift wedge in the Heidrun field suggests that some of these sedimentary conduits could be preserved on the margins of these basins. The Upper Cretaceous, postrift Shetland Group (T3) is a well-known regional shale that overlies the Lange Formation, providing a good seal for this unit. Preliminary analysis of the petroleum system indicates that a good chance exists for these intervals to be charged with hydrocarbons; however, uncertainties associated with the quality of migration pathways, the presence of reservoir-quality rocks, and the sealing integrity remain. In the Heidrun field, the location of the Lower Cretaceous prospective interval seems to be off structure and might represent an additional risk factor for this particular location; however, the potential presence of similar sedimentary conduits within time-equivalent units across the Halten Terrace could represent an encouraging exploration sign that needs to be tested with new exploration wells.

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