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Allard W. Martinius

ABSTRACT

The Roda Sandstone Member (Lower Eocene, Tremp-Graus Basin, Spanish Pyrenees) is interpreted as a well-exposed multiscale Gilbert-type delta. It is formed by multiple prograding lobate-shaped sandstone bodies up to 5 km (3 mi) long and 2–3 km (1–2 mi) wide, each constructed by a number of smaller scale (hunderds of meters) lobes that stack in a compensational mode responding to relative base level changes. In general, the proximal part of each lobe is dominated by trough cross stratification, the medial part by impressive clinoforms, and the distal part by more tabular cross stratification. Well-developed tidal bundles occur abundantly in delta lobe-front attached and detached tidal bars; the latter are up to 5 km (3 mi) long and 2 km (1 mi) wide. Cemented layers cover both the individual lobes as well as the lobate-shaped sandstone bodies. The three-dimensional (3-D) architecture of small-scale (decimeter to meter) heterogeneities at lithofacies scale formed by millimeter- to centimeter-thick mud layers in the tidal bars have been studied to better understand hydrocarbon flow through heterolithic tide-dominated successions. The Roda Sandstone has been used as an analog to many oil and gas fields with a particular focus on 3-D lobe geometry, compartmentalization, stacking patterns, and associated correlation concepts.

INTRODUCTION

Understanding the geometry, spacing, and stacking patterns of Gilbert-type delta lobes in the subsurface is crucial to reservoir zonation, geomodeling, and drainage strategies. If timelines through a reservoir are not correctly represented, correlations will be erroneous, and drainage scenarios and production targets may fail because of the unanticipated effect of heterogeneities and

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stratigraphic compartmentalization on connectivity and fluid flow, particularly in three dimensions. Permeability contrasts between stratigraphic surfaces formed at the top of Gilbert-type delta lobes during periods of limited sediment supply and the rapidly deposited delta lobe sands will control how hydrocarbons migrate. The (commonly well-cemented) lobe surfaces typically extend all along the top of the delta lobes and commonly provide efficient barriers. Well placement and completion, in association with an efficient drainage scenario, need to consider the effect of reservoir architecture and property distributions. Smaller-scale heterogeneities associated with the shape of bedforms and bedform sets provide additional hindrance for fluid flow.

A sound outcrop-based conceptual depositional model is key to reducing these uncertainties. With limited subsurface information, outcropping analogs are crucial. The Roda Sandstone Member provides a classic and excellent opportunity to examine, consider, and understand well-exposed multiscale Gilbert-type delta lobe architecture and their clinoforms in outcrop (Martinius, 2017). In addition, the type locality of ancient tidal bundles formed in delta lobe-front attached and detached tidal bars provides insights in the three-dimensional (3-D) geometry and architecture of small-scale (centimeter-scale) heterogeneities and barriers to fluid flow.

GILBERT-TYPE DELTA IN OUTCROP

The Ypresian Roda Formation (Ypresian, Spanish Pyrenees; Figure 1) displays an overall progradational (the Roda Sandstone Member) to retrogradational (lower part of the Esdolomada Member) and aggradational (upper part of the Esdolomada Member) pattern. Six main Gilbert-type delta lobe sandstone bodies (Figure 2; labeled Roda U to Z, terminology and mapping following Tosquella, 1988; Crumeyrolle et al., 1992; López-Blanco, 1996; López-Blanco et al., 2003; Leren et al., 2010) characterize the Roda Sandstone Member. The Roda Sandstone Member is composed of the following three different coeval depositional systems.

1. A steeply dipping Gilbert-type delta lobe deposits.
2. A gently sloping smaller shoal water fan delta system.
3. An elongate tidal bar system in front of the Gilbert-type delta lobes controlled by strong tidal northwest–southeast-directed tidal currents.

The lobate Gilbert-type delta sandstone bodies (Figure 3A, B; descriptive terminology follows Gobo et al., 2015) progressively step seaward toward the southwest. The lobe deposits interfinger basinward with distal delta front and prodelta to offshore siltstones. Each sandstone body is formed by several smaller-scale delta sublobes in medial and distal areas (Figure 4) (Nio and Siegenthaler, 1978; Puigdefàbregas et al., 1987; Yang and Nio, 1989; Crumeyrolle et al., 1992; López-Blanco, 1996; Molenaar and Martinius, 1996; Crumeyrolle, 2003; López-Blanco et al., 2003; Tinterri, 2007; Leren et al., 2010). The sublobes are generally stacked vertically and laterally and amalgamate without much fine-grained sediment in between. Each sublobe contains large-scale (up to 15 m [50 ft] high) foresets that dip up to 32° basinward. Sublobe topsets are preserved in medial and distal settings (Figure 3A, B) (Tosquella, 1988; López-Blanco, 1996; Crumeyrolle, 2003; Tinterri, 2007) as the result of the combination of normal regression and differential subsidence (higher toward the central part of the basin; López-Blanco, 1996). The sublobes are formed above fair weather wave base by wave-induced suspended load and gravity flows. Sublobes cannot be correlated across large distances and are interpreted as the result of autocyclic lobe switching and abandonment (Crumeyrolle et al., 1992; Crumeyrolle, 2003; Leren et al., 2010). A notable difference exists between lobes formed in an overall progradational phase and an overall retrogradational phase of the Gilbert-type delta system. The former produces significantly thicker clinothems (and hence more widely spaced clinoforms) of larger dimensions than the latter (see also the studies by Joseph et al., 1993 and Coll et al., 2013, respectively). In both cases, significant wave reworking of lobe tops occurred during lowstand and transgressive periods. The Gilbert-type delta lobes were formed in a punctuated fashion and with variable magnitude in response to intermittent compressional tectonic movements during ongoing subsidence. River-derived discharge temporarily ceased between the successive influxes of siliciclastic sediment. Lobes responded quickly to fluctuating sediment input (magnitude and

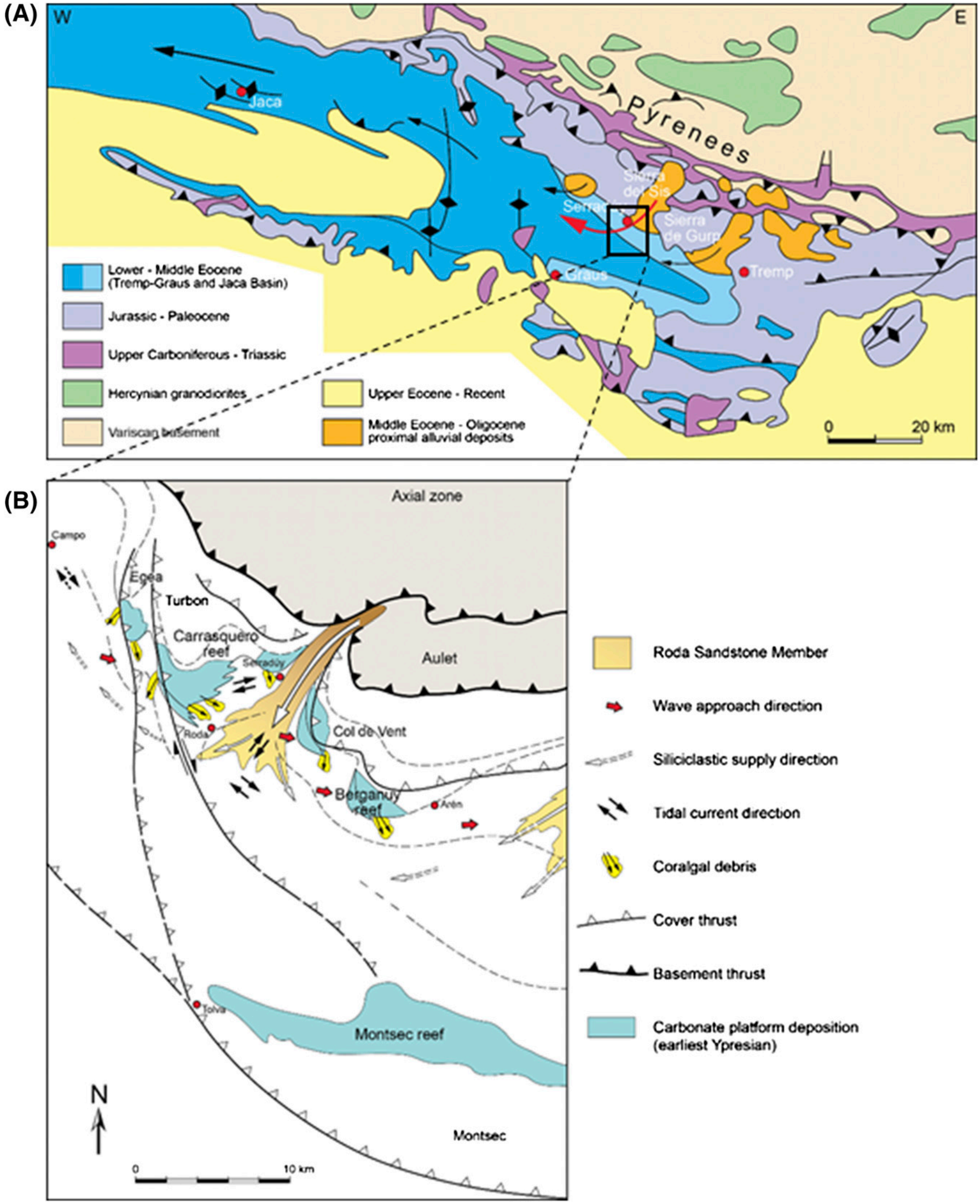

Figure 1. (A) Sketch of the estimated maximum extent of the south Pyrenean Foreland Basin illustrating the narrow, elongated geomorphology of the semienclosed sea encompassing the Jaca and Tremp–Graus Basins (modified after Choukroune and Séguret, 1973; Vincent and Elliott, 1997). (B) Schematic depositional setting of the Roda Sandstone Member with surrounding, slightly older carbonate platform deposits (and reefs). After Eichenseer (1988).

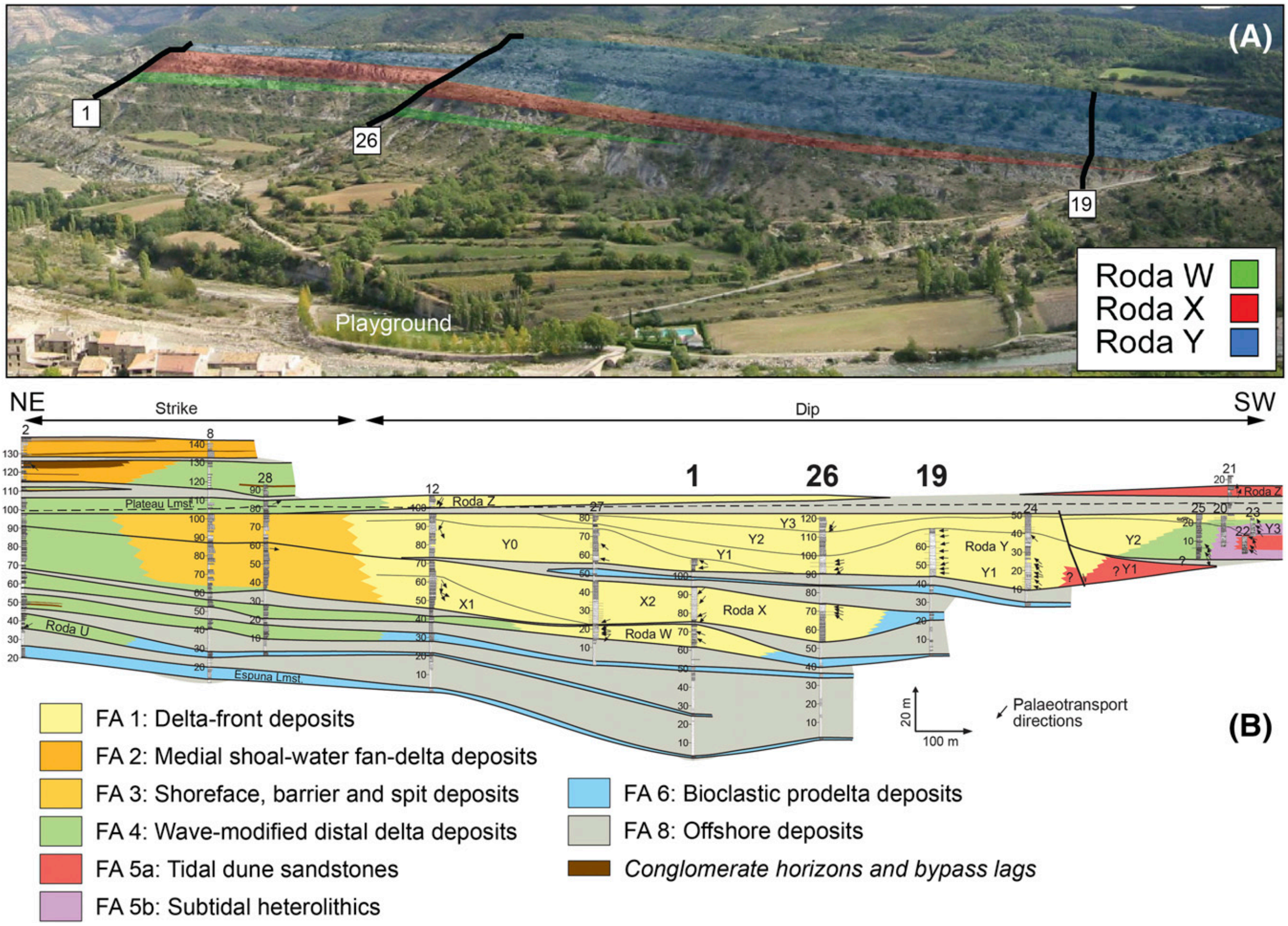

Figure 2. (A) Panoramic view of the Roda Sandstone outcrops along the Isábena valley. (B) Log correlation panel from the Roda Sandstone outcrops along the eastern side of the Isábena Valley. From southwest (log 12) to northeast (log 23) a downdip section (~4 km [~2 mi]) of the Gilbert-type delta is exposed, whereas to northeast (from log 12 to log 2) a strike section (~1 km [~0.6 mi]) through the delta flank is exposed. After Leren et al. (2010). FA = facies association.

direction) and efficiently recorded high-frequency variations in sedimentation rate.

The Gilbert-type delta lobes and sublobes were deposited contemporaneous with a series of thin (up to 6 m thick) elongated tidal sandstone bodies. These are interpreted as laterally migrating lower delta front and shelf tidal bars (López-Blanco, 1996; López-Blanco et al., 2003; Tinterri, 2007; Leren et al., 2010; Olariu et al., 2012; Michaud and Dalrymple, 2016). Detached tidal bars (up to 5 km [3 mi] long and 2 km [1 mi] wide) formed in front of the Gilbert-type delta lobes because of reworking of toesets by basin axial tidal currents during transgression. The bar crests were oriented generally northwest to southeast, parallel to the tidal paleocurrents and to the nearby paleoshoreline. Small tidal bars attached to the delta lobes were formed by strong regional west–northwest-directed ebb tidal currents (Yang and Nio, 1985) and contain the type locality for the renowned Roda Sandstone Member tidal bundle deposits (Figure 3C).

The degree of lithification of delta lobe and bar tops is dependent not only on the amount of cement but, at least initially, merely on the amount of carbonate nuclei (shell fragments) present and the dispersion of the these nuclei, and thus the cement, throughout the sand. In a subtidal setting, cement precipitates by diffusion processes in fringes with more or less equal thickness from a nucleus into the open pore space. If few nuclei are present, cementation causes firmness of the sand and stabilization of the surface layer but not lithification. To obtain a completely lithified surface in mixed siliciclastic–carbonate sands, carbonate nuclei (shell fragments)

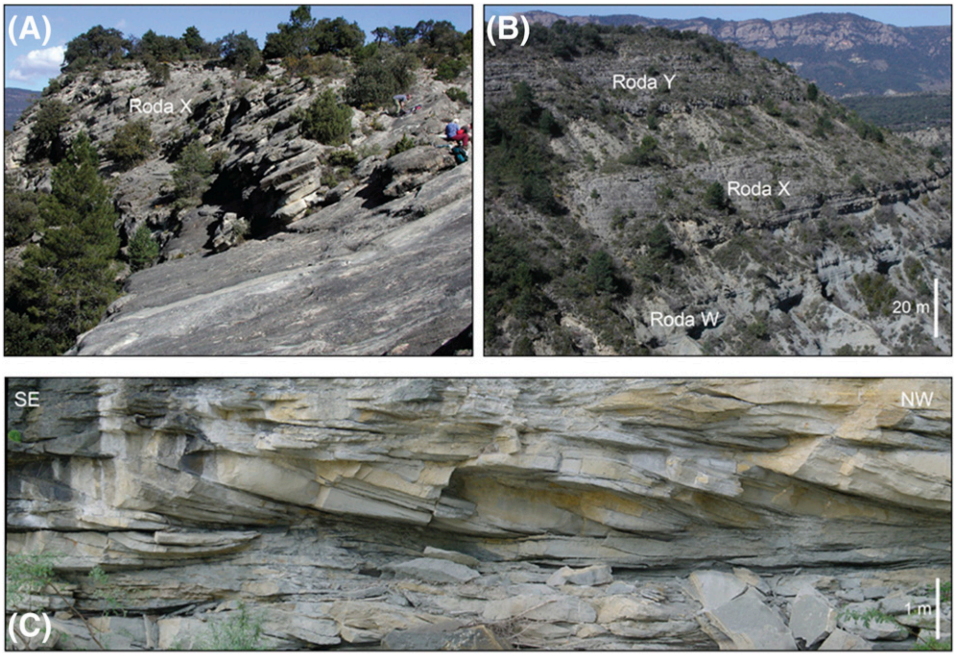

Figure 3. (A) View toward the north showing Gilbert-type delta lobe Roda X (for reference, see Figure 2B) showing well-developed clinoforms and large-scale cross stratification (people for scale). (B) View from the location of Figure 3A toward the south showing the stratigraphic position of delta lobes Roda W to Roda Y in the cliff face. (C) Photograph of an outcrop along the Isábena River showing a tidal bundle succession (dune in the middle of the photograph). Four to five neap–spring cycles are visible, suggesting that this part of the dune was formed in approximately 2 months After Yang and Nio (1985).

and cement have to be very abundant to fill the pores almost completely (Molenaar and Martinius, 1990). Lithification will only be accomplished if the pause in sedimentation is of long duration such as is the case for the well-developed hardground and their faunas present on the tops of the major Gilbert-type delta lobes (Martinius and Molenaar, 1991).

SUBSURFACE APPLICATION

Since the early 1980s, the Roda Sandstone Member has been used as an analog by the oil industry for several reservoir units on the Norwegian Continental Shelf, including the Middle Jurassic Krossfjord, Fensfjord, and Sognefjord formations in Troll; the Oseberg Formation in Veslefrikk; Huldra and Oseberg Main (Figure 5); the Ranoch Formation (Brent Group) in Gullfaks; and Cormorant on the English sector (Wehr and Brasher, 1996). Focus has mainly been on various aspects related to delta lobe morphologies, their clinoforms, and the associated cemented horizons. The Roda outcrops have been instrumental in developing the understanding of clinoform formation and their 3-D geometries.

A key realization resulting from the Roda outcrop studies was the understanding of overall 3-D lobe geometry and the morphology of associated internal inclined clinoform surfaces and the resulting correlation strategies that were developed for the subsurface. If datable timelines and/or intervals are present from core material (based on biostratigraphic and/or Samarium–Neodymium data), the sequence stratigraphic framework can be constructed combining the outcrop analog conceptual models and the available well and seismic data of the hydrocarbon field. In addition, understanding the 3-D distribution and morphology of the cemented layers aided not only in understanding reservoir compartmentalization but also in using their presence to assist in controlling hydrocarbon flow patterns during production using purposely designed drive mechanisms. This led to a radical change in correlation schemes and associated drainage strategies. Fields that already had a production history could be better history matched with production and pressure data, which, in turn, led to the identification of remaining oil, new drilling targets, and revised improved oil recovery (IOR) strategies. For example, 20 yr ago, tongues of water were observed in parts of the Oseberg Formation in the Veslefrikk field (onstream since 1989 and operated by Statoil). Interpretation of reprocessed seismic data, with the aid of the outcrop base conceptual model, led to the identification of clinoform surfaces with an average spacing of 10–20 m (32–65 ft), a downdip length between 2 and 4 km (1 and 2 mi), and a maximum dip gradient of approximately 2° toward the southwest.

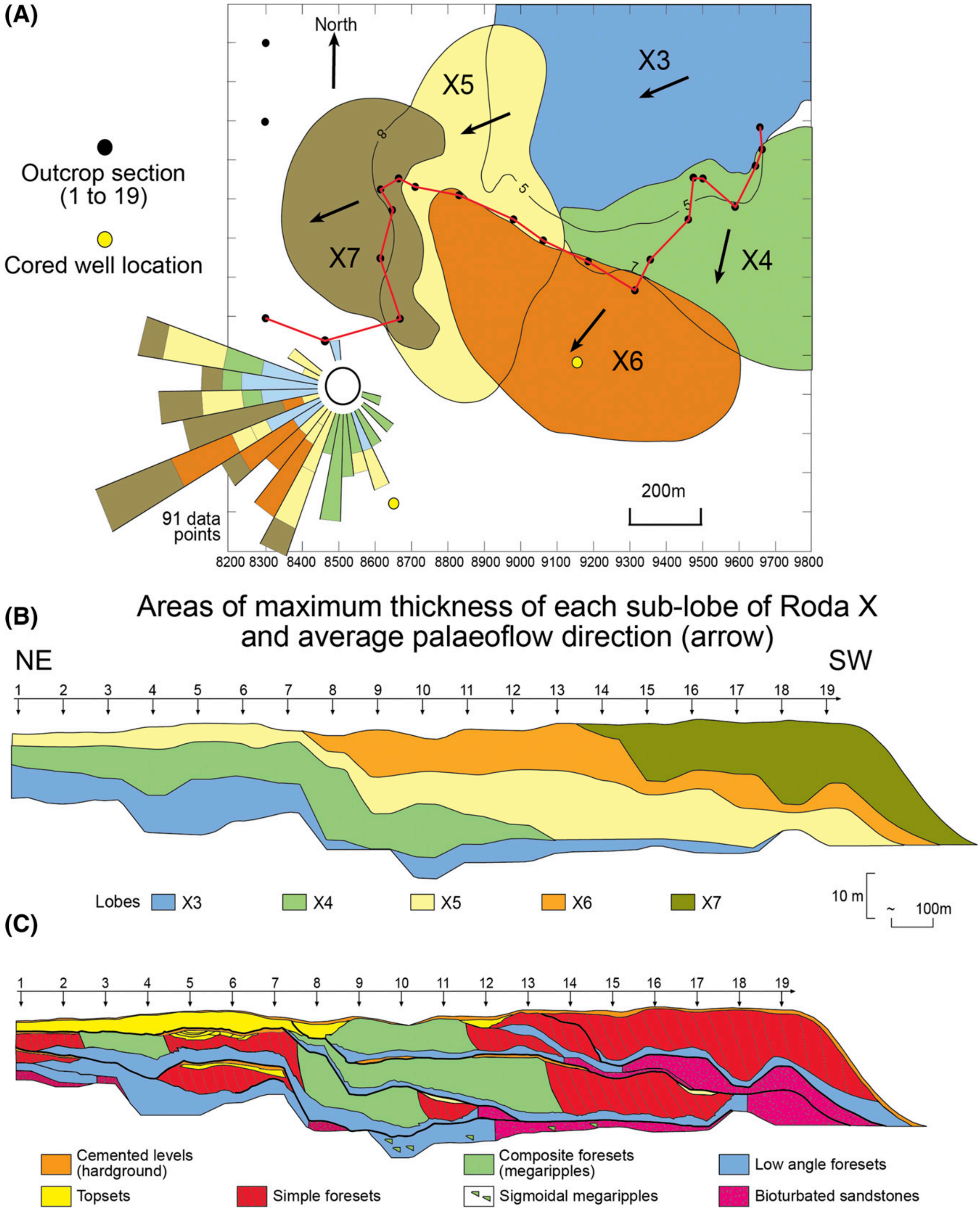

Figure 4. (A) Schematic map representation of five Roda X sublobes based on 19 outcrop sections and 2 cored boreholes showing areas of maximum thickness of each sublobe and average paleoflow direction. (B) Cross section along a northeast to southwest line of Roda X based on the 19 sedimentary sections along the outcrop showing the location and thicknesses of the five sublobes. (C) Lithofacies distributions in each of the five sublobes of Roda X. Modified from Joseph et al. (1993).

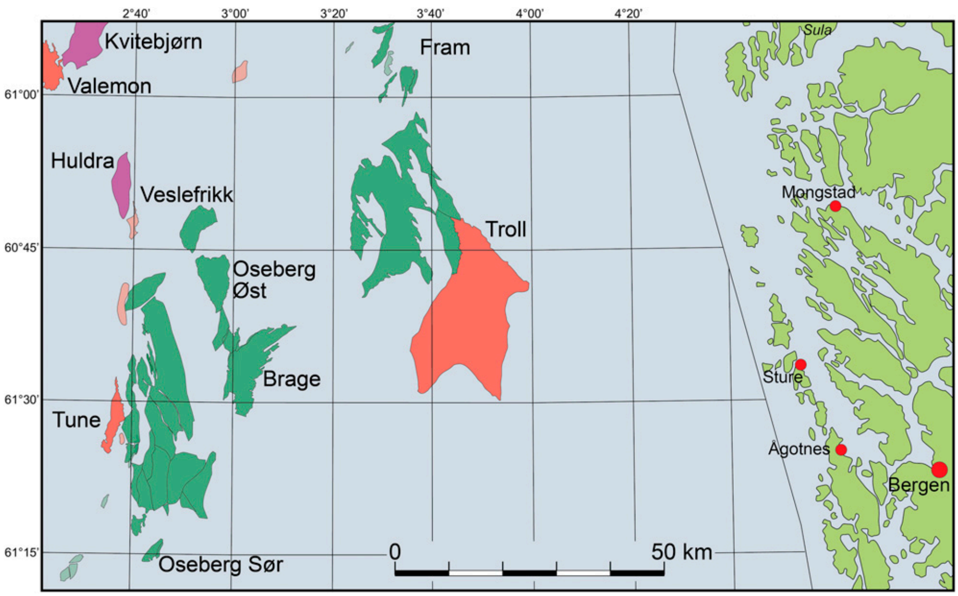

Figure 5. Location map of the Veslefrikk and Troll fields on the Norwegian Continental Shelf.

Sedimentological studies revealed the existence of depositional cycles formed by on average 15-m-thick (49 ft) upward coarsening clean sandstone units followed by on average several decimeters to 1-m-thick (3 ft) upward fining units formed by muddy, bioturbated sandstone and cemented layers (creating severe restrictions to fluid flow). Cemented layers could be linked to strongly reduced sedimentation rates and mollusk faunas developing during periods between lobe deposition (Walderhaug and Bjørkum, 1992), and each depositional cycle was interpreted as a clinothem of which 12 were mapped and correlated (Figure 6).

Although the conceptual depositional model for Gilbert-type delta lobes and clinoforms is well established now and based on several additional outcrop analog studies (mostly less lobate systems), the methods and techniques for modeling prograding depositional units and clinoforms (for example, Howell et al., 2008; Sech et al., 2009; Graham et al., 2015) and their effect on hydrocarbon flow (Jackson et al., 2009) are still continuously advancing. In

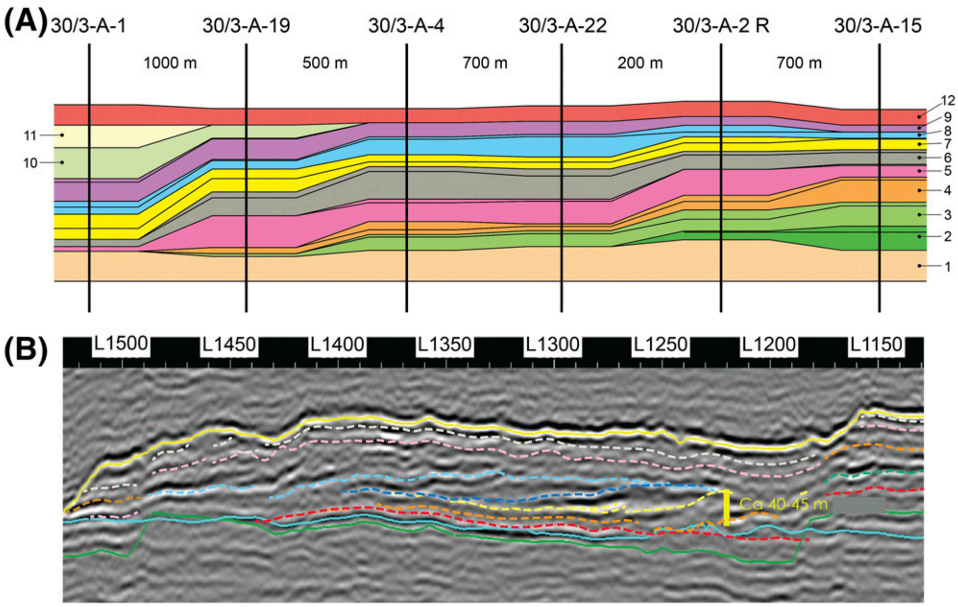

Figure 6. (A) Well correlation of a part of the Oseberg Formation in the Veslefrikk field, which used the conceptual model of delta lobes and clinoforms surfaces as based on the Roda Sandstone Member. Clinoforms have an average spacing of 10–20 m (32–65 ft), a downdip length between 2 and 4 km (1 and 2 mi), and a maximum dip gradient of approximately 2° toward the southwest. Several on average 15-m-thick (49 ft) coarsening-then fining-upward clinothems were mapped and correlated. (B) Seismic section of the northern part of the Troll field showing distinct clinoforms.

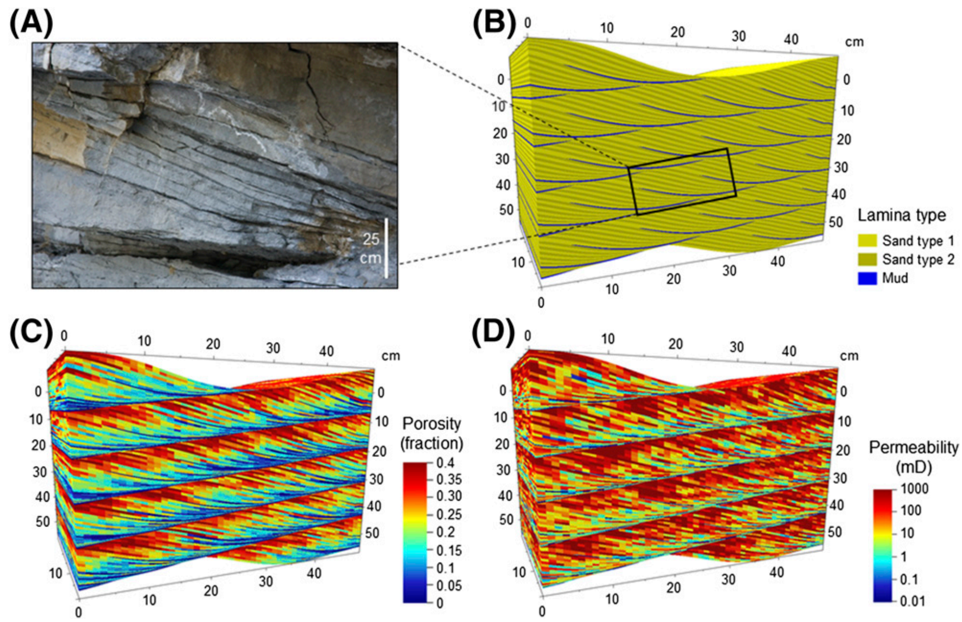

Figure 7. (A) Detail of a tidal bundle as exposed along the Isábena valley. (B) SBED^{TM} model of a stacked series of the tidal dune structure seen in (A) (courtesy K. Nordahl, Statoil ASA; Wen et al., 1998). Sand types 1 and 2 represent two different grainsizes in the laminae; mud represents the tidal diurnal mud layers. (C) An SBED^{TM} model of (B) populated with assigned porosity values related to grain size distribution. (D) An SBED^{TM} model of (B) populated with permeability. Note the effect of the mud drapes as barriers to fluid flow.

particular, the depositional, static and dynamic models for the hydrocarbon-bearing formations are still advancing with the aid of new high-quality and high-resolution seismic data that image the lobe and clinoform geometries (Holgate et al., 2013, 2014, 2015; Zeng et al., 2013; Patruno et al., 2015a, b) and are used to develop advanced IOR schemes (for example, Hansen, 2009). Forward seismic modeling helps to bridge the gap in spatial scales and sampling volumes between well and seismic reflection data (Holgate et al., 2014). These authors also concluded that clinoforms are imaged appropriately where they are marked by interfingering of facies associations with different acoustic properties and/or lined by relatively thick (>50 cm [>1.6 ft]) carbonate-cemented layers. Thin (10 cm [3.9 in.]) carbonate-cemented layers along clinoforms can cause destructive interference that results in lower

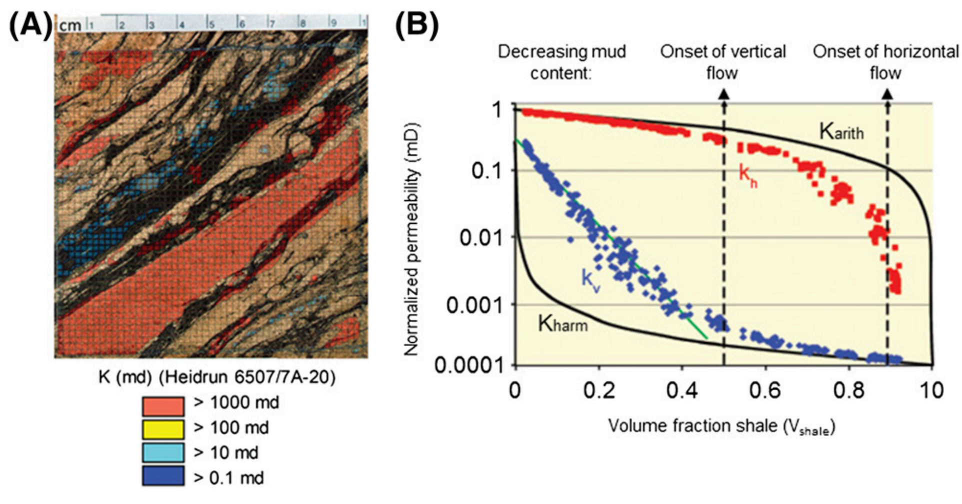

Figure 8. (A) Detailed permeability mapping of a core interval of tide-dominated heterolithic facies of the Tilje Formation in the Heidrun field (well 6507/7A-20; grid millimeter scale; courtesy P. S. Ringrose, Statoil ASA). Note the large contrast between clean sandstone layers and (burrowed) mudstone laminae. (B) Plot of permeability versus the volume fraction of shale in a tidal dune from upscaled SBED^{TM} models. Red and blue dots are upscaled vertical (k_v) and horizontal (k_h) permeability from dm-scale models of tidal structures from the Tilje Formation (Heidrun field). Thin lines are arithmetic (K_{arith}) and harmonic (K_{harm}) averages. Each dune is compartmentalized by successive slack-water tidal mud drapes and has a mud-dominated bottom set. It is also eroded at the top and overlain by the next dune (with a mud-dominated bottom set). This leads to a large difference in vertical permeability vs. horizontal permeability in the *x* and *y* directions, with a complicated three-dimensional fluid flow path. Optimal fluid flow is in the strike direction of the sandstone layers or along the plane of the sandstone layers. After Elfenbein et al. (2005).

continuity of reflections. Cemented layers at the top of Gilbert-type delta lobes may pose significant challenges during drilling operations because the drill bit may rebound if the angle of approach with respect to the orientation of the cemented layer is too low.

The characteristics of the small-scale (centimeter to decimeter) heterogeneities of the Roda tidal bundles (Figure 7A) were applied to build bedform-scale geomodels of the heterolitic tidal units of the Tilje and Ile Formations (Heidrun, Åsgard, and Tyrihans fields). Recovery factors of these heterolithic units are typically less than 30% and pose one of the main challenges on the Halten Terrace (mid-Norway; Martinius et al., 2005). The key to improving predictions of reservoir performance was to represent the observed heterogeneities in detail using the depositional process-mimicking modeling tool SBED™ (Figure 7B) (Wen et al., 1998) and evaluate their effect on flow properties (Elfenbein et al., 2005; Nordahl et al., 2005). The main characteristics are tidal bar dimensions and geometries and, in particular, the small-scale mud drapes and fluid muds that occur in the tidal bedforms and that form a complex 3-D network.

Inspired by the results, other tidal facies present in the Tilje and Ile Formations were analyzed and modeled in a similar fashion using the Vectis Formation as an outcrop analog (Jackson et al., 2005). The effect of small-scale mud drapes on the horizontal and vertical permeability distribution and fluid flow is profound causing depositional compartmentalization at centimeter to meter scale. The detailed SBED™ tidal bundle model realizations were populated with petrophysical data (such as porosity and permeability) derived from core plug and well log measurements (Figures 7C, D; 8A). Upscaling of these petrophysical models resulted in effective porosity and permeability values for the tidal bundle facies and was used to generate type curves showing the relationship between permeability and shale volumes (Figure 8B). Results indicate how much sand must be present before the reservoir will be producible (i.e., at the onset of vertical flow and horizontal flow; Figure 8B). Based on the results, more accurate drainage and produced water treatment strategies were implemented (Elfenbein et al., 2005).

CONCLUDING REMARKS

The outcrops of the Roda Gilbert-type delta succession are packed with relevant information for analogous hydrocarbon-bearing formations, such as those on the mid-Norwegian continental shelf. They provide an excellent laboratory from which important qualitative and quantitative information has been obtained. The relatively small size and accessibility of the Roda delta lobes allows for a comprehensive understanding and mental visualization in a relatively short amount of time. The outcrops serve as a high-quality teaching ground for industry geologists, engineers, and university students alike to understand Gilbert-type delta lobe architecture and 3-D morphology.

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