E&P NOTE

Pool characterization of Ordovician Midale field: Implication for Red River play in northern Williston basin, southeastern Saskatchewan, Canada

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ABSTRACT

The Upper Ordovician Midale field is located in the northern Williston basin in southeast Saskatchewan, Canada. Hydrocarbons are hosted mainly in the dolomite reservoirs with burrowed textures in the upper Yeoman Formation. These reservoirs are characterized by intercrystalline porosity in the dolomitized matrix, with variable amounts of vugs and fractures, and can be divided into four zones. Reservoir zones 1 and 2, typically 6–10 m (20–33 ft) thick in total, are situated in the upper part of the traps and commonly bear oil. Although the underlying zones 3 and 4 are thicker, they commonly contain only water because they are located below the spillpoint of the hydrocarbon traps.

The seismic reflection of the Red River reservoirs in the Midale field is characterized by a weak- to medium-amplitude trough immediately above the positive reflection of the Winnipeg shale. Where all four zones are present, an additional peak occurs on the seismic profile above the original reservoir reflection. This additional peak, however, disappears where reservoir zones 3 and 4 pinch out. Where there is an increase in the thickness of reservoir zones 1 and 2 or amalgamation of zone 1 with zone 2, the Red River reservoirs are characterized by high-amplitude and high-frequency reflections on seismic profiles.

The Ordovician oil pools in the Midale area are associated with low-relief anticline structures. These low-relief structures are

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interpreted as the compactional drape of Red River strata over local Precambrian basement highs. The source of hydrocarbons in the Red River reservoirs is Ordovician kukersites. A wide range of API fractions for the oils from the Midale pools suggests a mixing of low-maturity oils, sourced from local kukersite beds, and high-maturity oils that migrated over a long distance from the south. The hydrocarbon production from Red River Midale pools is characterized by the fast rise of water cut and high water output, which can be attributed to the small pool size and the fracture systems connecting oil and water zones.

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INTRODUCTION

The Ordovician Midale field is located in southeast Saskatchewan in the northern part of the Williston basin, between Townships 6 and 7 in Range 11W2 (Figure 1), where the Ordovician strata gently dip south toward the center of the basin. In Canada, the Upper Ordovician Red River strata are subdivided into the Yeoman and Herald formations (Kendall, 1976) (Figure 2). Hydrocarbons are hosted mainly in the dolomite reservoirs, with burrowed textures in the upper Yeoman Formation. The first Red River production in Saskatchewan came from the Hummingbird area in 1958. For almost 40 yr until 1995, Red River production was limited to only 16 wells that were located close to the Canada–United States border in the Minton, Lake Alma, Oungre, and Bromhead areas (Haidl, 1990; Kent, 1999) (Figure 1). From 1958 to 1995, the cumulative Red River oil production in Saskatchewan was only 0.2 million m^3 (1.256 million bbl), or 33,000 bbl/yr (Figure 3A). There was a major increase in production in 1996 as a result of the discovery of the Midale field in late 1995. This heralded the first of a series of significant hydrocarbon discoveries in Ordovician Red River strata in southeast Saskatchewan (Longman and Haidl, 1996; Kreis and Kent, 2000). In the following few years, more than 15 new Red River pools were discovered; the producing pools were extended 75 km (45 mi) northward from the Canada–United States border to the Chapleau Lake area (Figure 1). Each hydrocarbon pool is characterized by small structural noses on a regional structural map at a 50-m contour interval (Kreis and Kent, 2000). Total Red River oil production in southeast Saskatchewan by the end of 2000 was approximately 1.8 million m^3 or 11.2 million bbl (Figure 3A). By the end of 2000, 52 wells had been drilled in the Midale field, and the cumulative production had reached 356,248 m^3 (2,237,237 bbl) of oil, 37,716 m^3 (440 mmscf) of gas, and 1,041,550 m^3 (6,540,433 bbl) of water (Figure 3B). One important characteristic of production was a rapid rise of water cut (Figure 3B), up from 10–50% of water in the initial production to 67.2–98.2% after 3–4 yr of production for individual wells. Of the 52 drilled wells, only 13 are still active (8 producers and 5 injectors), and 39 were abandoned because they were dry or suspended because of high water cuts.

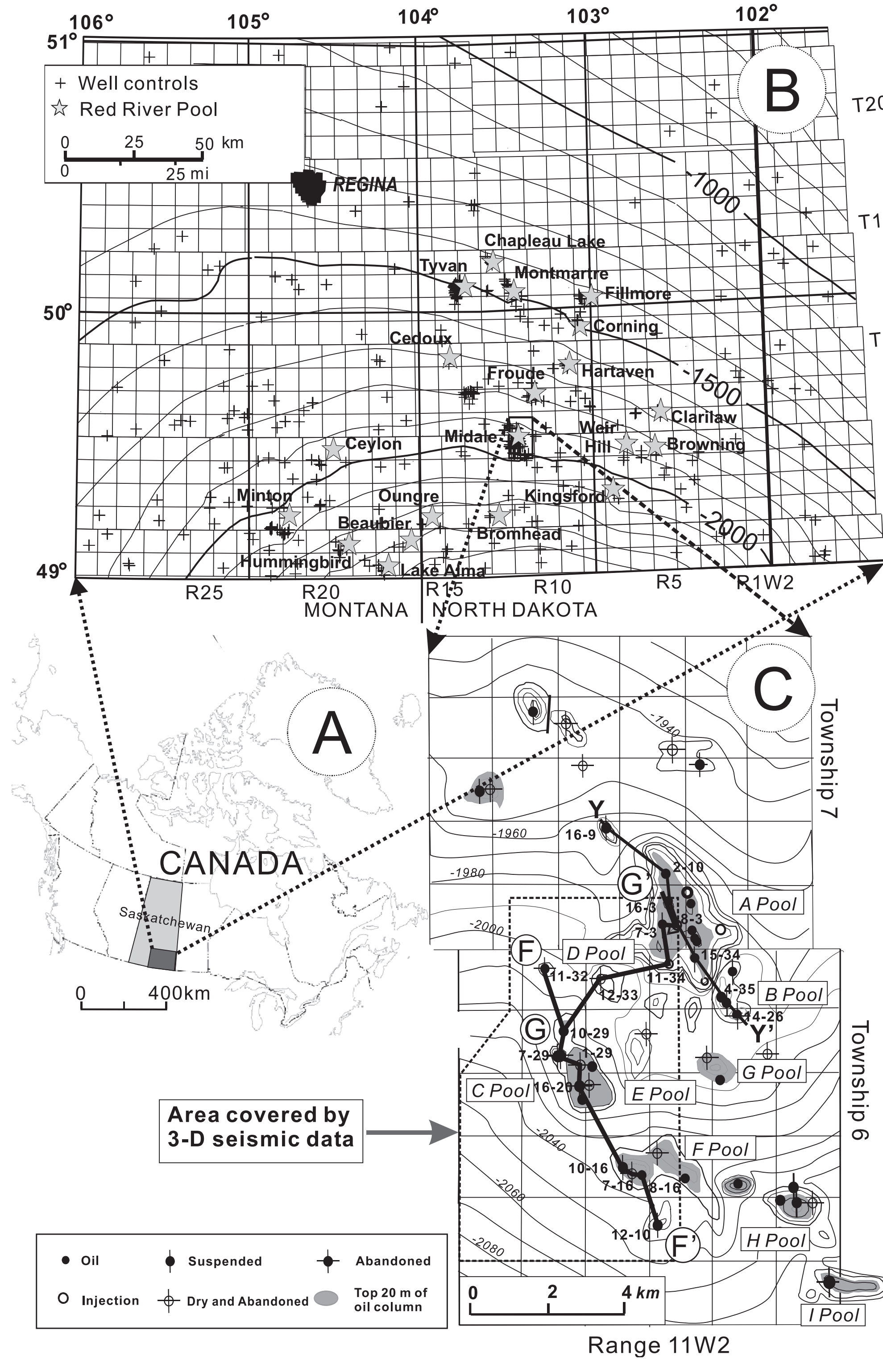

Figure 1. (A) An index map showing the location of the study area. (B) The structure contour map showing location of Red River production in southeast Saskatchewan. The contour lines are burial depth of the Red River strata below the sea level (modified after Kreis and Kent, 2000). (C) A detailed structure contour map with location of Red River pools, Midale area. The contour lines are the bottom of the Lake Alma anhydrite below sea level. The area covered by 3-D seismic data is shown in Figure 11. The well-linked seismic cross section FF′ is shown in Figure 8, and GG′ in Figure 9. Cross section YY′ is shown in Figure 12.

To understand the factors that control hydrocarbon accumulation in newly discovered Ordovician Red River reservoirs in southeast Saskatchewan, three-dimensional (3-D) seismic data, well logs, core samples, and thin sections were used to characterize Ordovician Red River reservoirs, pools, and traps. The results of reservoir characterization are used to understand the spatial distribution and connectivity of these reservoirs and to increase the recovery rate of existing pools. Possible stratigraphic traps in the region could expand the concept of

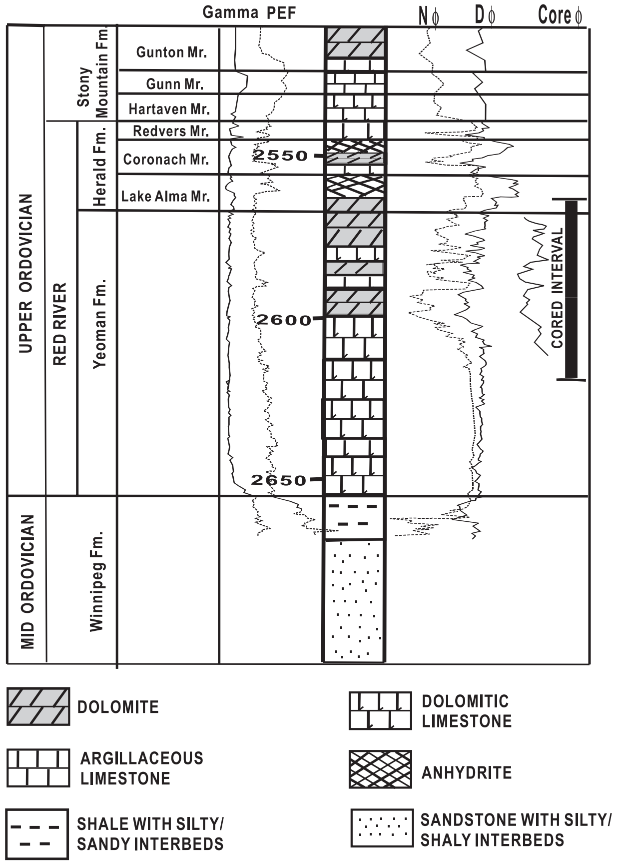

Figure 2. Stratigraphic nomenclature of Red River strata in southeast Saskatchewan with lithology and log signatures derived from well 7-3-7-11W2.

the Red River play beyond its current limits in southeast Saskatchewan.

STRATIGRAPHY

The Red River strata were interpreted to be deposited in an epeiric sea that covered much of the North American craton during the Late Ordovician (Kendall, 1976; Osadetz and Haidl, 1989; Longman and Haidl, 1996). In Canada, the Upper Ordovician Red River strata are subdivided into the Yeoman and Herald formations (Kendall, 1976) (Figure 2). In the United States, Red River strata are divided into A, B, and C members in descending order (Kohm and Louden, 1978, Longman and Haidl, 1996). There is a general trend of increasing burial depth of Red River strata from 2130 m (7000 ft) near the Tyvan pool to 3100 m (10,170 ft) southward toward the Canada–United States border in the Lake Alma area (Figure 1). The total thickness of the Red River strata also increases from 100 m (328 ft) in the Tyvan area to approximately 165 m (540 ft) at the southeast corner of Saskatchewan based on the regional Red River isopach map constructed by Saskatchewan Industry and Resources (Kreis and Haidl, 2000). The maximum thickness of the Red River strata, however, occurs in the basin center close to Bismarck, North Dakota, and is slightly more than 200 m (656 ft) (Longman and Haidl, 1996).

Red River strata consist of three carbonate-evaporite depositional sequences (Longman and Haidl, 1996). Each sequence starts with a burrowed, normal-marine mudstone to wackestone and packstone at the base, followed by a laminated mudstone representing restricted penesaline deposition, which in turn is overlain by a bedded to enterolithic evaporative anhydrite (Longman and Haidl, 1996). Red River production from the

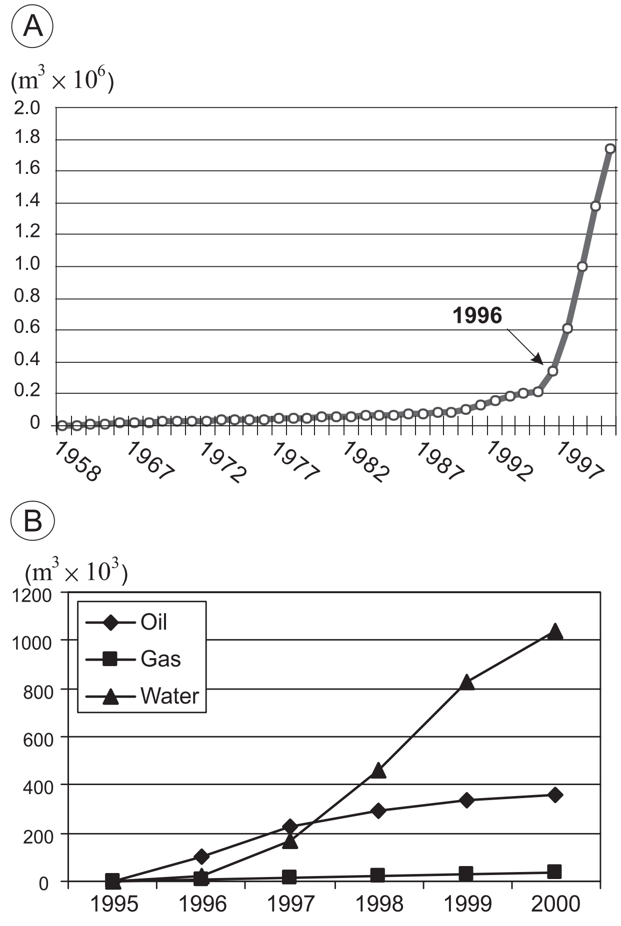

Figure 3. (A) Cumulative Ordovician Red River hydrocarbon production from 1958 to 2000 in Saskatchewan. The major increase in production in 1996 is the result of the discovery of the Midale pools in late 1995. The total Red River oil production by end of 2000 was 1.8 million m^3 (11.2 million bbl). (B) Cumulative Ordovician Red River hydrocarbon production from Midale pools. Data courtesy of Saskatchewan Industry and Resources.

Midale field is mainly from the upper part of the Yeoman Formation, where porosity is generally well developed (Figure 2). Locally, the Lake Alma Member of the lower Herald Formation also shows good reservoir qualities on well logs.

RESERVOIR ARCHITECTURE

The petrography and porosity of the Red River reservoirs were described and characterized based on core and thin-section examination, log analysis, and the reflections on 3-D seismic data. Seven cross sections were constructed across the Midale field to understand distributions of Red River carbonate reservoirs in the area. Two of seven cross sections included in this paper were aimed at defining the relationship between reservoirs and their seismic attributes (Figure 1).

Data Calibration and Standardization

Prior to interpretation of the geometry and architecture of the Red River reservoir in the Midale field, the available data were calibrated and/or standardized, including the following:

1. depth correction of the cored intervals using the method of Lucia (1999);
2. calibration of the same type of logs to one scale to assure that the similar lithology in different wells corresponded to the appropriate log value;
3. differentiation of dolomite and limestone lithologies using photoelectric factor logs. The typical values of photoelectric factor logs range from 3 to 3.5 barns/electron for dolomite and 4 to 5 barns/electron for limestone (Figure 2);
4. normalization of all neutron logs using the Lake Alma evaporite as the reference thanks to its uniform lithology and thickness. The neutron porosities of the Lake Alma evaporite were adjusted to zero for all the wells. This minimizes the discrepancies of log values resulting from different logging devices and/or processing parameters at different well sites, so that the porosity of the various wells can be compared. The Red River dolomite reservoirs have distinct higher porosities on neutron and density logs (Figure 2). There is good correlation between the calculated neutron and/or density porosity with measured core porosity (Figure 4). A higher correlative coefficient for neutron logs (Figure 4) suggests that neutron logs reflect porosity more precisely and were used to calculate porosity in the absence of cores;
5. construction of synthetic seismograms for four wells in the Midale area to calibrate the accurate positions of the Red River reservoir on the seismic data. The calibrations indicate that the top of the Red River reservoir is generally positioned at a negative trough event immediately above the positive reflection of the Winnipeg shale on 3-D seismic profiles (Figure 5). At well 7-3-7-11W2, the top of the reservoir occurs at 1.57 s on the 3-D seismic section (Figure 5).

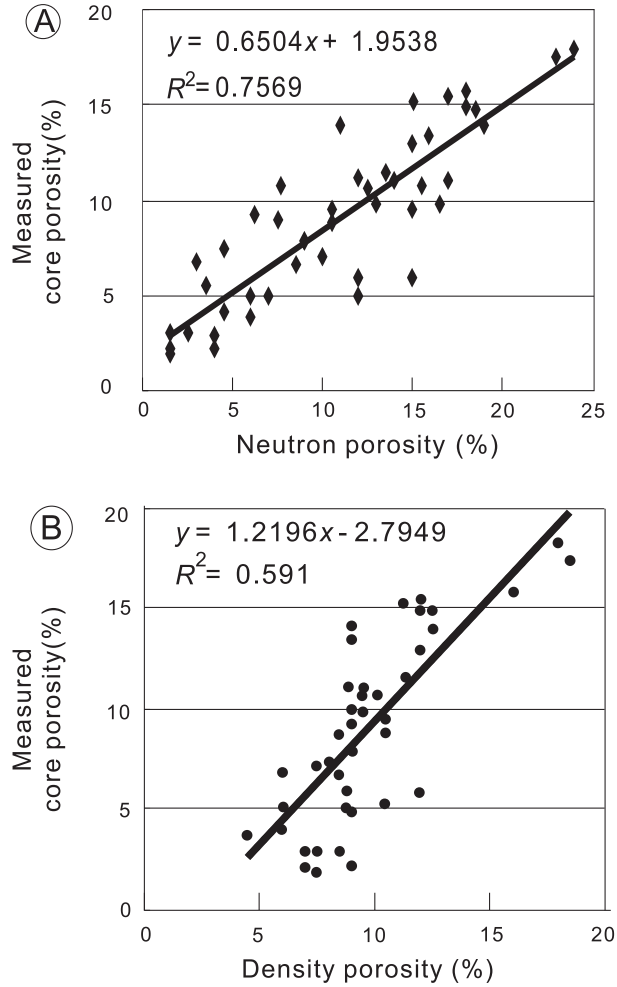

Figure 4. (A) A crossplot of measured core porosity and neutron porosity. (B) A crossplot of measured core porosity and density porosity. All the measurements and data are from well 14-16-7-11W2.

Reservoir Petrography and Porosity

The petrography and porosity of the reservoirs were described and characterized based on analyses of core samples from five wells and the examination of 30 thin

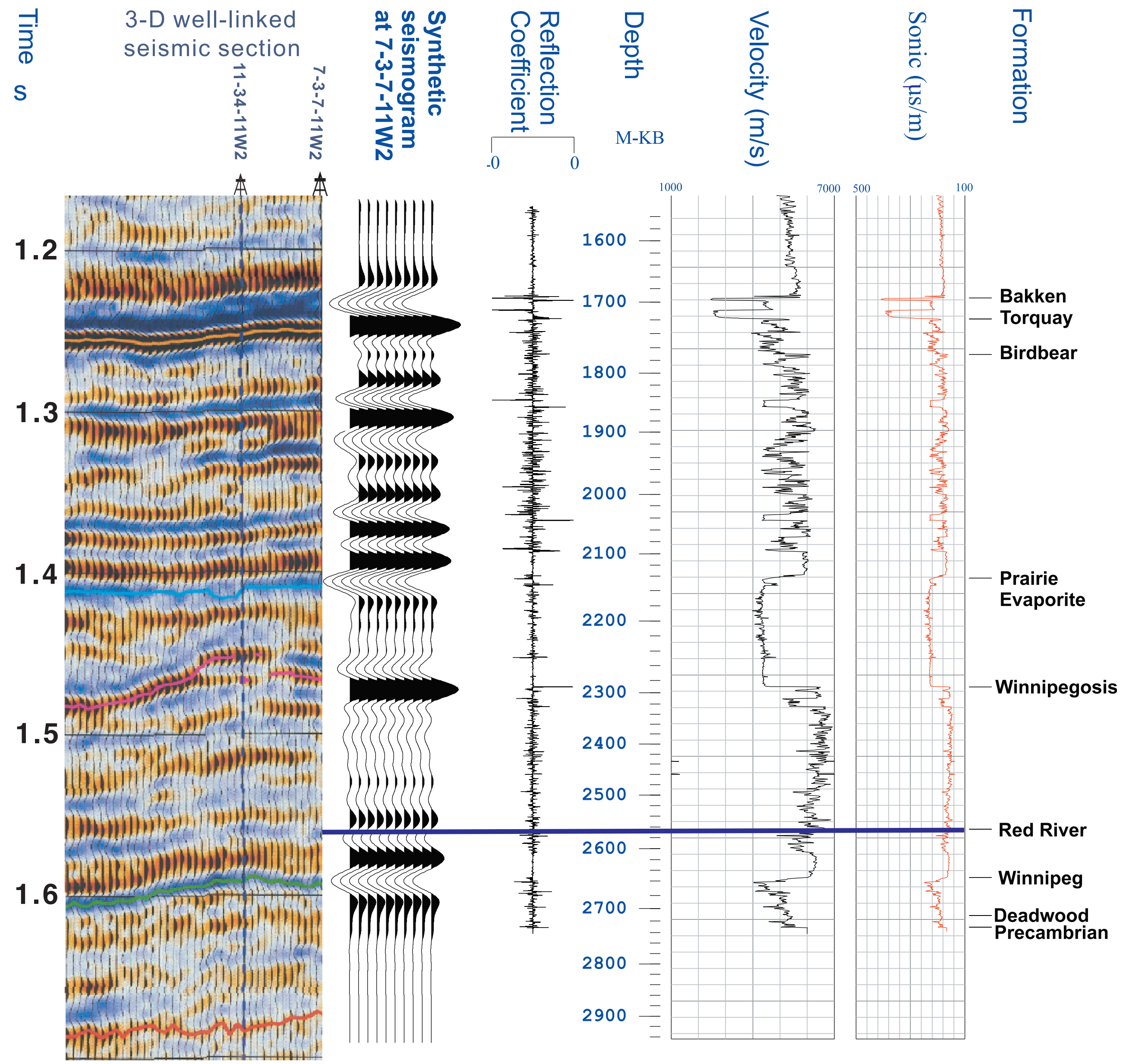

Figure 5. Calibration of the position of the Red River reservoir on seismic section. Synthetic seismogram of well 7-3-7-11W2 shows that the top of the Red River reservoir is located at 1.57 s (blue color band) of the 3-D seismic section across this well.

sections. The pattern of dolomitization in Red River carbonates is complex (Kendall, 1977; Longman and Haidl, 1996; Canter, 1998; Qing et al., 2001). In the Yeoman Formation, there is a variety of forms/patterns: (1) partial dolomitization, with dolomite preferentially located in *Thalassinoides* burrows with the host matrix preserved as limestone, (2) complete dolomitization, where both *Thalassinoides* burrows and host matrix are dolomitized, and (3) limestone sections, where both burrow infills and the host matrix have escaped dolomitization. High-porosity reservoirs only occur where the host rock was completely dolomitized.

The measured core porosities for dolomite samples in the upper Yeoman Formation from well 3-8-1-11W2 range from 3.5 to 16%, averaging 11% (Figure 6). The porosity is generally much lower (2–11%) in the limestone and/or in a partially dolomitized limestone, where dolomitization occurs preferentially in the burrows (Figure 6). The maximum permeability of the dolomite reservoirs in this well ranges from 0.5 to 60 md, with two samples exceeding 30 md, whereas the maximum permeability of all but two limestone samples is less than 7 md (Figure 6). For the Yeoman Formation, there is a good correlation between porous reservoirs,

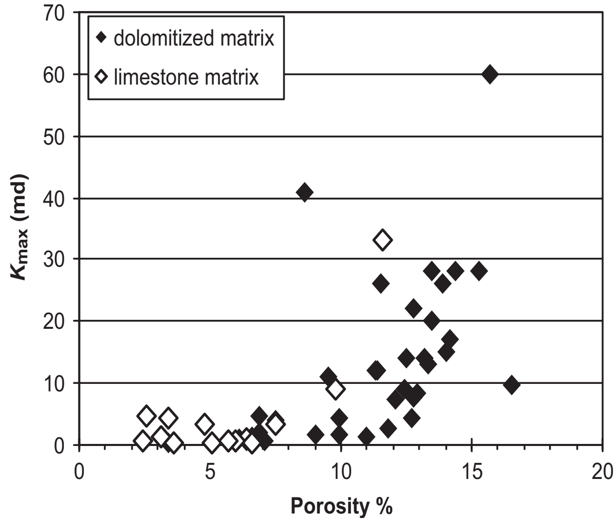

Figure 6. A crossplot of porosity and permeability of Red River reservoirs with dolomitized matrix vs. limestone matrix. All the measurements are from well 3-8-1-11W2.

as indicated by porosity logs, and dolomites, as shown by photoelectric factor logs (Figure 2).

Three types of porosity are recognized from examination of core samples and thin sections. They are intercrystalline pores, dissolution vugs, and fractures. Intercrystalline porosity is the most common and occurs between euhedral dolomite crystals (50–100 μm in size) in the matrix of host carbonate rocks (Figure 7A, B). The burrow infills, however, consist of smaller anhedral dolomite (25–50 μm), which generally have much lower porosity based on thin-section observation (Figure 7A). Oil staining occurs preferentially in matrix dolomite (Figure 7C) because of its higher porosity. Dissolution vugs are commonly observed in the oil-stained dolomitized intervals (Figure 7D). Vugs range from 1 mm to several centimeters in diameter (Figure 7D). Some vugs are connected, whereas others are isolated.

Two types of fractures are observed in the Red River carbonate reservoirs: the hairline fractures and two sets of larger fractures. Local hairline fractures occur at 0.5–1-cm intervals, forming irregular networks (Figure 7E). These hairline fractures are slightly curved, closed, and uncemented. The absence of any sign of oil in them and their occurrence in both dolomite and limestone suggest that hairline fractures had no influence on oil migration or dolomitization. Two sets of larger fractures, ranging from 10 to 40 cm in length are developed at 20–70-cm intervals in oil-stained dolostone (Figure 7F). In some places, both sets are vertical. In other places, one is vertical, and the other is horizontal (Figure 7F). The horizontal fractures locally terminate at the vertical ones, suggesting that the former postdates the latter (Figure 7F). Some of these larger fractures are oil stained, some are partly filled with coarsely crystalline anhydrite cement, and some remain unfilled. The examination of the occurrence of larger fractures in five cored wells suggests that these fractures preferentially occur in intervals containing abundant dissolution vugs. The close spatial association of fractures and dissolution vugs in dolostones suggests that these larger fractures, in contrast to the hairline fractures described previously, might have acted as conduits for fluids, which caused dolomitization and dissolution.

The photoelectric factor logs of the Lake Alma Member of the Herald Formation, lying immediately above the Yeoman Formation, indicate that it is generally dolomitized (e.g., well 7-3-7-11W2) (Figure 2). It consists of either nonporous cryptocrystalline dolomitic mudstone or finely crystalline porous dolomitic mudstone. The higher neutron and density porosities (commonly 10–20%) are observed in the lower part of Lake Alma dolomite and gradually decrease upward. In the upper part of the Lake Alma laminated dolomite, the porosity generally becomes negligible in most wells of the Midale field.

Reservoir Subdivision and Distribution

Four reservoir zones (zones 1–4 in descending order) were identified in the upper part of the Yeoman Formation in the Midale field (Figures 8A, 9A), similar to the observations of an earlier study by Canter (1998). Zone 1 is widespread throughout the Midale field with a consistent thickness, typically 3–6 m (9.8–19.7 ft) (Figures 8A, 9A). Its upper boundary, corresponding to the top of the Yeoman burrowed dolomite, is commonly located 3–9 m (10–30 ft) below the Lake Alma anhydrite. Locally, zone 1 extends upward into the Lake Alma laminated dolomite (e.g., at well 12-33-6-11W2) (Figure 9A). Based on the neutron logs from 47 wells, the porosity in zone 1 is interpreted as ranging from 7 to 21%, with an average of 12.8%. In most of these wells, the porosity of zone 1 decreases upward gradually, becoming negligible in the upper part of the Lake Alma laminated dolomite (Figures 8A, 9A).

Zone 2 is also widespread in the Midale field. Its thickness ranges from less than 1 to 6 m (3.3 to 20 ft), typically 3 to 5 m (10 to 16.4 ft) (Figures 8A, 9A). The porosity in zone 2 ranges from 6 to 24% and averages 14.5%. Zone 2 occurs immediately below zone 1 and

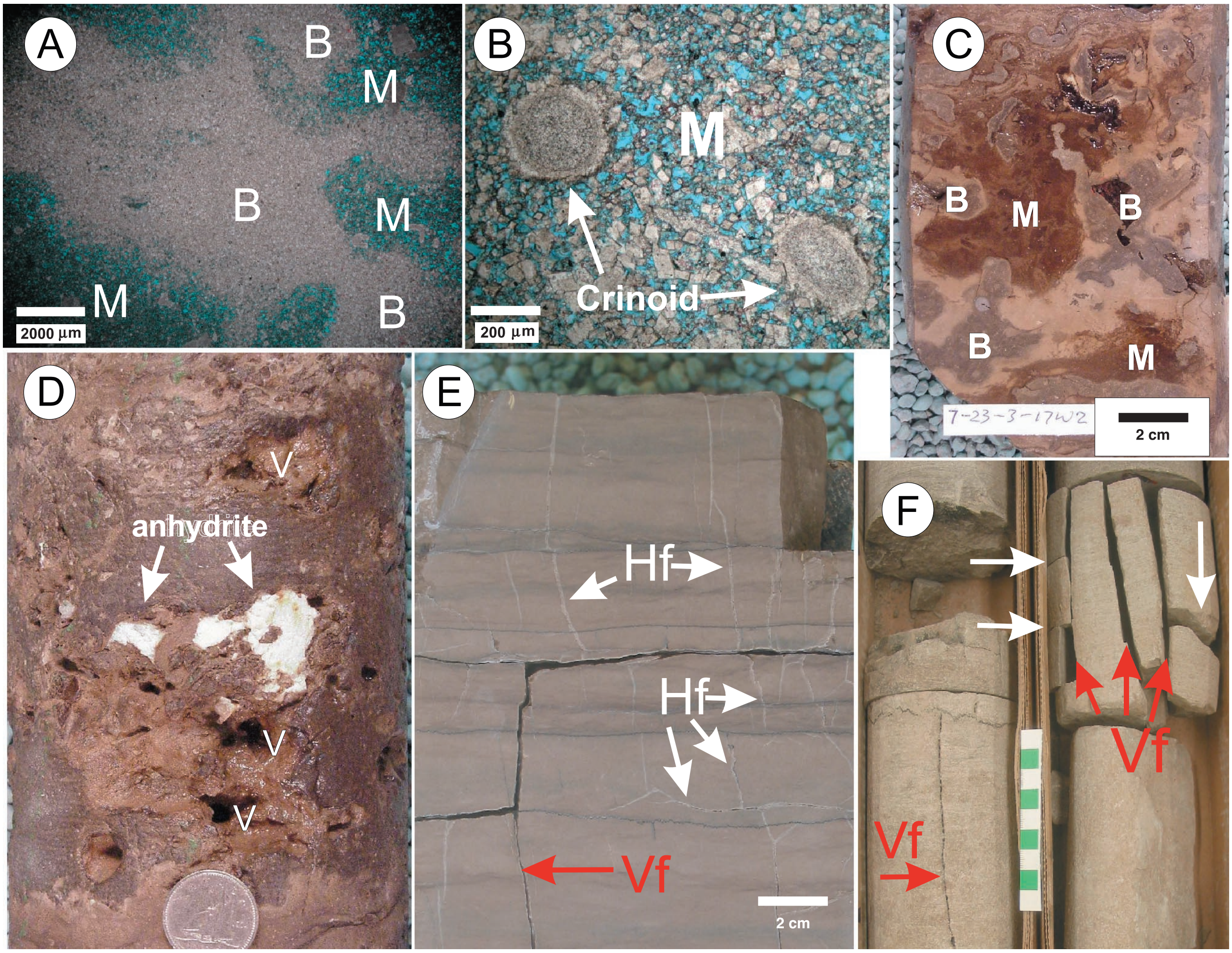

Figure 7. Petrography of Red River reservoirs. (A) Thin-section photomicrograph showing high porosity in dolomitized matrix (M), as indicated by blue epoxy-filled pore vs. much lower porosity in dolomitized burrows (B). Well 16-20-8-10W2, 2444.3 m. (B) A close-up thin-section photomicrograph showing excellent intercrystalline porosity in dolomitized matrix (M), as indicated by blue epoxy-filled pore spaces. The shape of two rounded crinoid fragments (arrows) preserved after dolomitization. Well 3-8-1-11W2, 3193.4 m. (C) Core sample showing that oil staining occurs preferentially in the dolomitized matrix (M), and burrow infills (B) are unstained. Well 7-23-3-17W2, 2991.7 m. (D) Core sample showing dissolution vugs (V) in typical Red River reservoir rock, with partial infilling by a late-stage coarsely crystalline anhydrite cement (arrows). Well 11-23-6-11W2, 2614 m. (E) Core sample showing fine hairline fractures (Hf) and vertical fractures (Vf) in a laminated dolomite. Well 7-3-7-11W2, 2566 m. (F) Core samples showing horizontal fractures (white arrows) terminating at preexisting vertical fractures (Vf) in laminated dolomite. Well 8-3-7-11W2, 2580–2581 m.

locally amalgamates with it, as indicated in well 8-3-7-11W2 (Figure 9A). As with zone 1, the contact of zone 2 with nonreservoir intervals is gradational.

The spatial distributions of lower reservoirs (zones 3 and 4) are much more restricted compared with upper reservoirs (zones 1 or 2). The cross sections show that lower reservoirs have a limited lateral distribution for several hundred meters and then pinch out (Figures 8A, 9A). The porosity in zones 3 and 4 is similar to zones 1 and 2, ranging from 9 to 21% (average 12.5%) and 5 to 23% (average 14.7%), respectively. The contacts of zones 3 and 4 with nonreservoir intervals are commonly abrupt and distinct, in contrast to zones 1 and 2.

Vertical Connectivity of Reservoir Zones

Although four reservoir zones are separated by less porous limestone at most well sites, tenuous vertical connections and amalgamations of different reservoir zones, because of more extensive dolomitization, were identified locally. An amalgamation of zones 1–3 was recognized at well 8-3-7-11W2 (Figure 9A), and a

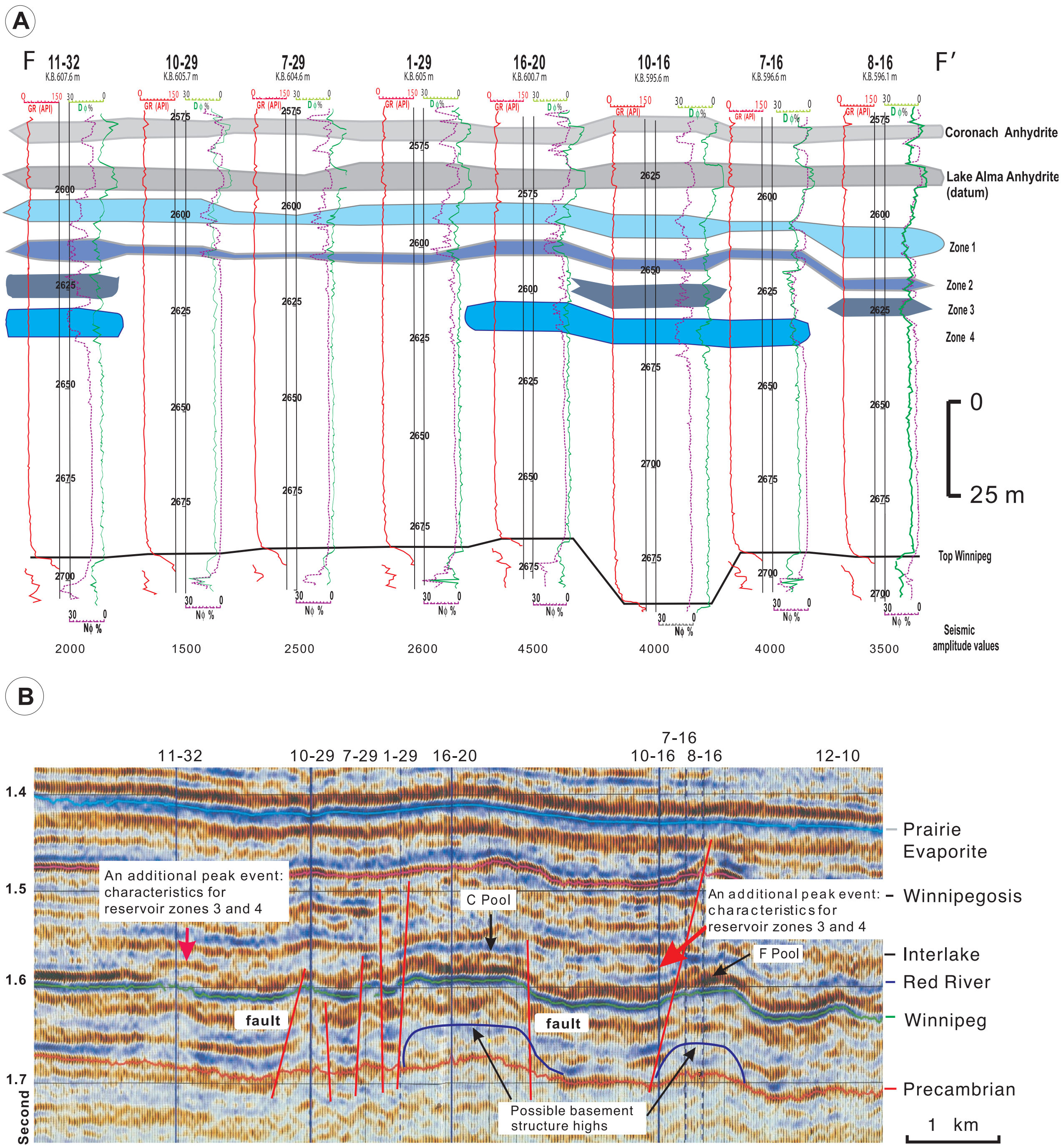

Figure 8. Well-linked seismic profiles and log cross sections FF′, Midale field (see Figures 1 and 12 for location of the cross section). (A) Well-log cross section, showing thick reservoir zones 3 and 4 occurring in wells 11-32-6-11W2 and 10-16-6-11W2, but pinching out laterally at other sites. The bottom of the Lake Alma anhydrite is used as the datum. The value of seismic amplitude for each well was extrapolated from 3-D seismic map (Figure 12). (B) Well-linked 3-D seismic profiles, corresponding to cross section FF′, showing the characteristics of seismic reflections related to reservoir zones 3 and 4. At wells 11-32-6-11W2 and 10-16-6-11W2, where reservoir zones 3 and 4 are relatively thick, an additional crest reflection occurs between the trough reflections of the Winnipeg top and the Yeoman top (red arrows), and the amplitude of the Winnipeg trough decreases dramatically. Red lines are possible steep normal faults with small offsets.

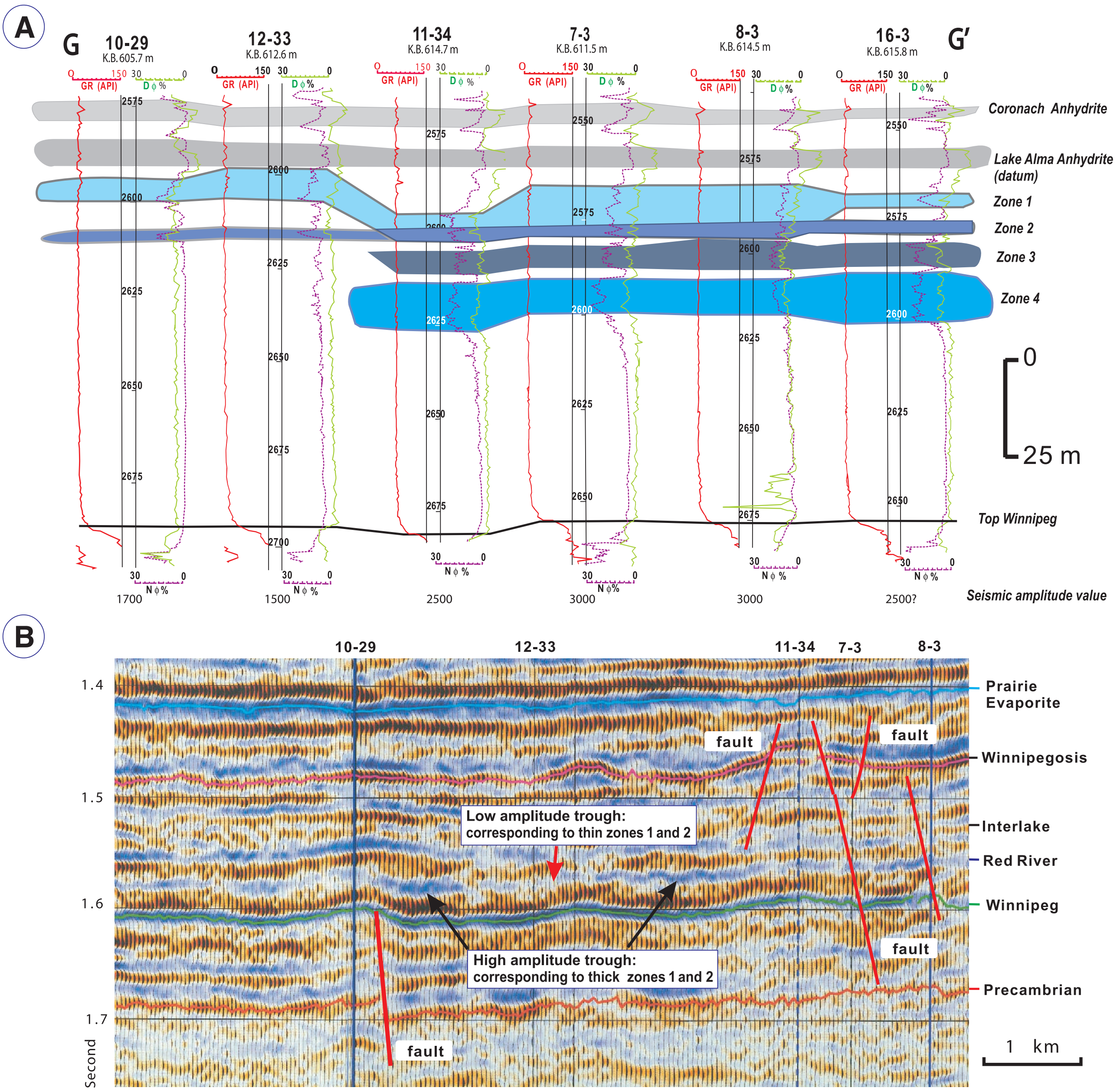

Figure 9. Well-linked seismic profiles and log cross sections GG′, Midale field (see Figures 1 and 12 for location of GG′). (A) Well-log cross section GG′ with the bottom of the Lake Alma anhydrite as the datum. A thicker reservoir zone occurs at well 8-3-7-11W2 and well 7-3-7-11W2 because of increases in the thickness or amalgamation of zones 1 and 2. (B) Well-linked 3-D seismic profile corresponding to GG′. The black arrows highlight high-amplitude and high-frequency reflections associated with thicker reservoir zones at wells 8-3-7-11W2 and 7-3-7-11W2. Red lines are possible steep normal faults with small offsets.

tenuous connection between reservoir zones 1 and 2 was also identified in the other five wells. In some places, the nonreservoir limestone interbeds between the different reservoir zones may be too thin (<1 m) to serve as effective seals between them. The vertical connection between different reservoir zones is also supported by a common oil-water contact for apparently different reservoir zones in the same trap.

Seismic Signature of the Reservoir

The seismic reflection of the normal Red River reservoir in the Midale field is characterized by a weak- to medium-amplitude trough (Figures 8B, 9B). By comparison of log cross sections (Figures 8A, 9A) with their corresponding seismic profiles (Figures 8B, 9B), two patterns of seismic responses of the Red River reservoirs are evident where these Red River reservoirs become sufficiently thick to influence the seismic expression.

The first seismic characteristic of Red River reservoirs is related to occurrence of four reservoir zones that are separated from one another at roughly equal intervals, as represented by wells 11-32-6-11W2 and 10-16-6-11W2 (Figure 8A). In this case, an additional crest reflection occurs between the trough reflections of the Winnipeg top and the Yeoman top (Figure 8B), whereas the amplitude of the Winnipeg trough decreases dramatically, e.g., near well 11-32-6-11W2, as highlighted by the arrow in Figure 8B. This additional crest reflection, however, terminates where the underlying reservoir zones 3 and 4 pinch out (Figure 8B). To further characterize this seismic expression in the area where zones 3 and 4 pinch out, forward modeling (Figure 10A) was carried out using (1) the actual rock thickness and sonic and density logs of well 11-32-6-11W2 and (2) the frequency (30 Hz) and polarity as actual 3-D seismic data from the Midale field. In this modeling, reservoir zones 3 and 4 were designed to pinch out toward the left side of the profile. The result of modeling shows that the seismic reflection terminates where reservoir zones 3 and 4 pinch out (Figure 10A), similar to the actual seismic profile at well 11-32-6-11W2 (Figure 8B).

The second type of seismic reflection of the Red River reservoir is related to local increase in the thickness of zones 1 and 2 and/or amalgamation of different zones to form a thicker reservoir, e.g., merger of zone 1 with zone 2 at well 8-3-7-11W2 (Figure 9A). The corresponding seismic response is characterized by a high-amplitude and high-frequency reflection (Figure 9B). Forward modeling was conducted to confirm the high-amplitude and high-frequency reflection of these thicker reservoirs. The geological model was based on well 8-3-7-11W2, where reservoir zones 1 and 2 are amalgamated into one thicker zone (Figures 9A). Reservoir zones 3 and 4 were designed to pinch out at different positions to characterize the seismic response associated with the occurrence of two or three reservoir zones. The forward seismic modeling shows that the amplitude, which corresponds to the Red River reservoirs at 104–108 ms, increases where the total thickness of the reservoirs increases (Figure 10B). However, where either zone 3 or 4 is missing, the corresponding seismic amplitude decreases (Figure 10B).

The variation of the seismic amplitude of the Red River reservoirs in the Midale area is shown in the amplitude contour map constructed based on the 3-D seismic data (Figure 11). The seismic amplitudes at each well in the cross section FF′ and GG′ can be measured from this map and then transferred to the relevant positions on the cross sections (Figures 8A, 9A). It shows where there is thicker reservoir (e.g., 22 m [72 ft] at well 10-16-6-11W2; 24 m [80 ft] at well 7-3-7-11W2), the corresponding amplitude value is higher (from 3000 to 4000; red arrows in Figure 11), whereas thinner reservoir (e.g., 9 m at well 12-33-6-11W2; 6 m [20 ft] at well 10-29-6-11W2) is characterized by lower amplitude (from 1500 and 1700; black arrows in Figure 11). Therefore, the seismic amplitude generally increases with the cumulative thickness of the Red River reservoirs, but there are some exceptions. For example, the amplitude is relatively low, only 2500, for a 28-m (92-ft)-thick reservoir at well 8-3-7-11-W2, but is rather high, 4500, for a 15-m (50-ft)-thick reservoir at well 16-20-6-11W2 (Figure 11). The discrepancy of amplitude and reservoir thickness is interpreted to be related to the following two factors:

1. The amplitude of Red River reservoir is not extracted from the exact position of the Red River trough reflection. The horizon interpreted as a Red River trough event is extrapolated from the Winnipeg Shale horizon by subtracting 30 ms. This extrapolation could result in positioning errors for the Red River reservoirs.
2. The thick Red River reservoirs are commonly characterized by high amplitudes as well as high frequencies as discussed above. A change in frequency will inevitably modify the corresponding amplitude in the same time interval. Therefore, a method of modeling that considers both amplitude and frequency could better characterize and predict reservoirs. This kind of modeling will be carried out in future studies.

In summary, the seismic reflection of the normal Red River reservoir in the Midale field is characterized by a weak- to medium-amplitude trough (Figures 8B, 9B). However, an additional crest reflection occurs between the trough reflections of the Winnipeg top and the Yeoman top, where four reservoir zones are separated from one another at roughly equal intervals. Forward modeling shows that the termination of this additional crest reflection is related to the pinch-out of reservoir zones 3 and 4. This feature can be used to identify possible stratigraphic traps related to the pinch-out of zones 3 and 4. Where there is an increase in the reservoir thickness, especially the amalgamation of zones 1 and 2, the corresponding seismic reflections

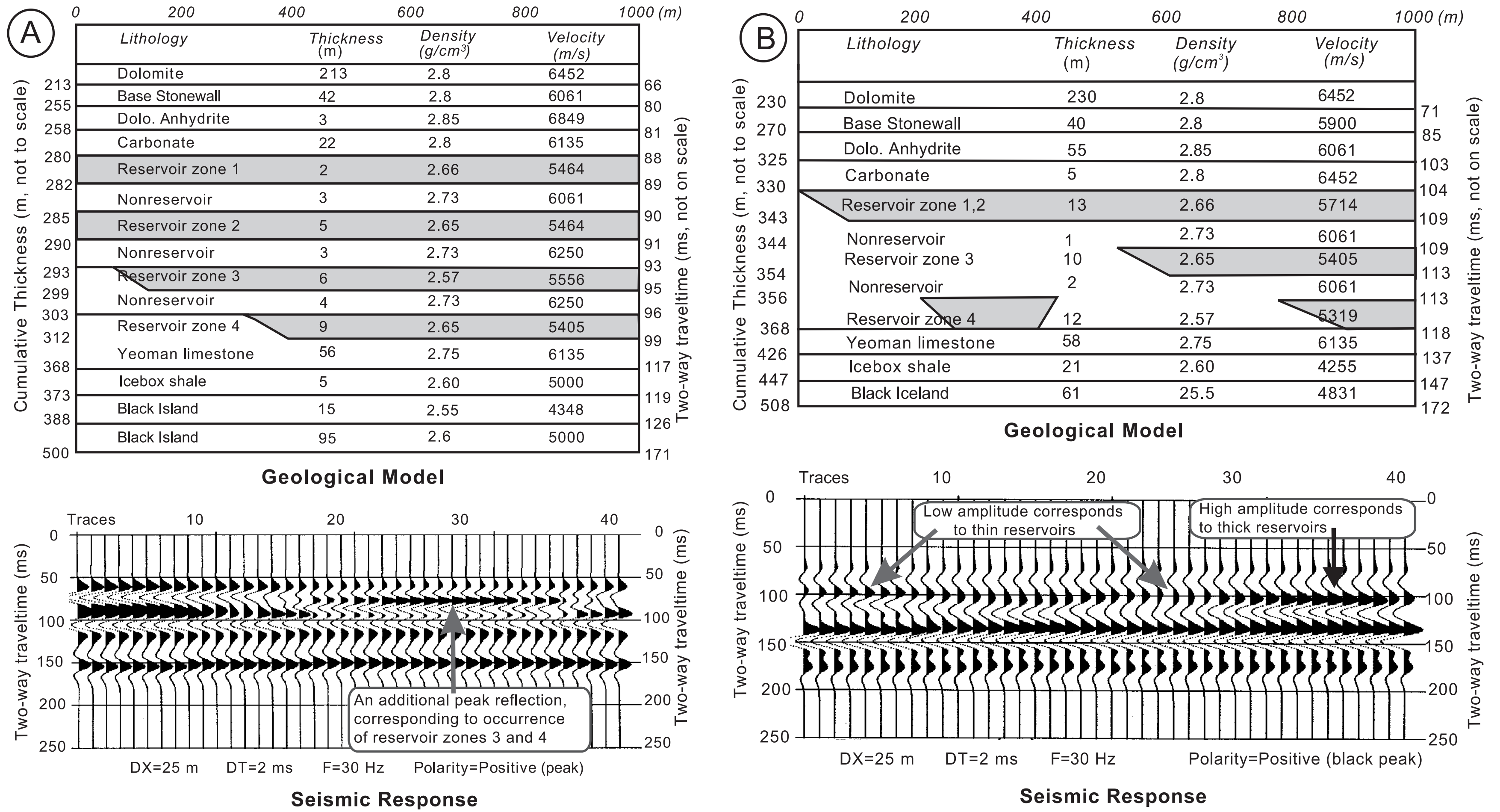

Figure 10. Forward modeling of reflection pattern for different occurring reservoir zones (shaded zones in the geological model). (A) A geological model based on well 11-32-6-11W2 (Figure 8A), where four reservoir zones (shaded zones) are evenly separated. The forward modeling of the reflection pattern shows that an additional reflection peak occurs (arrow) where all four zones are present, as observed at well 11-32-6-11W2 in the actual seismic profile (Figure 8B). This additional reflection, however, terminates where reservoir zones 3 and 4 pinch out. (B) A geological model based on well 8-3-7-11W2 (Figure 9A), where zones 1 and 2 amalgamated as thicker reservoir. The forward modeling of the reflection pattern shows an increase in the seismic amplitudes related to this amalgamated thicker reservoir (black arrow). However, the seismic amplitudes decrease where either zone 3 or zone 4 is missing (gray arrows).

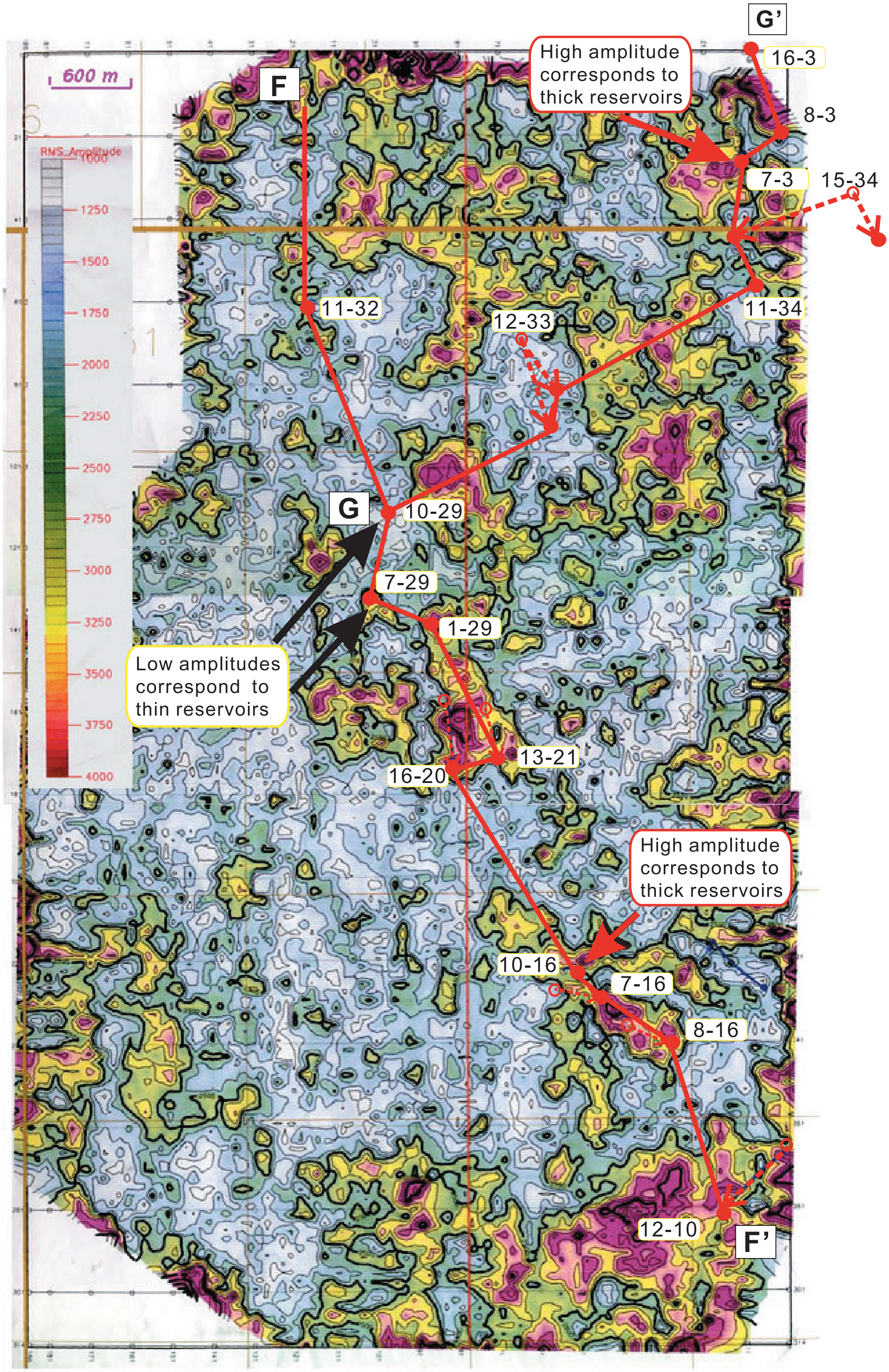

Figure 11. A contour map of the seismic amplitude value of the Red River trough event within the 25-ms time window based on the 3-D seismic data (see Figure 1 for the location of 3-D seismic area). Where there is a thicker reservoir, e.g., at well 10-16-6-11W2 (22 m; 72 ft) and at well 7-3-7-11W2 (24 m; 80 ft), the corresponding amplitude value is higher (from 3000 to 4000) (red arrows), whereas thinner reservoirs, e.g., at 12-33-6-11W2 (9 m; 30 ft) and at 10-29-6-11W2 (6 m; 20 ft) are characterized by lower amplitudes (from 1500 and 1700) (black arrows).

are characterized by relatively higher amplitudes and higher frequencies (Figures 9, 11). This attribute is important for exploration of structural traps because most Red River oils are contained in zones 1 and 2.

Influences of Faults on Reservoirs

The reactivation of Precambrian basement features could have some influence on Phanerozoic sedimentation and localized hydrocarbon accumulations in the northern Williston basin in southeast Saskatchewan (Kent, 1973; Potter and St. Onge, 1991; Gibson, 1995; Kissling, 1997; Haidl et al., 2000; Kreis and Haidl, 2000; Kreis and Kent, 2000).

Some Red River pools in the Midale field are associated with basement highs that are bounded by faults as interpreted from 3-D seismic data (e.g., C and F pools in Figure 8B). These basement faults are expressed as weak-amplitude linear shadows in the seismic profiles and appear to be steep normal faults. The faults are more easily identified at depth, but become subtle at shallower levels, perhaps because of decreasing offset (Figures 8B, 9B). Most of the basement faults terminate at the unconformity between Silurian and Middle Devonian strata and do not extend into the Middle Devonian Prairie evaporite. The faults might have acted as conduits for fluid flow during the formation of dolomitized reservoirs. In the area outside of the Midale field, large-offset normal faults in Paleozoic strata have also been identified in southern Saskatchewan according to interpreted two-dimensional seismic data (Zhu, 1992).

TRAP STRUCTURE

Based on the 3-D seismic structural map of the Red River reservoir top, the hydrocarbon traps of the Midale pools are small low-relief anticlines (Figure 1), which are commonly superimposed on the top of basement highs (Figure 8B). The origin of these low-relief anticlines over the basement highs can be interpreted either as drape structures because of the differential compaction over the basement highs and/or as the result of multistage movement of basement topographic highs. The anticlines are oval in shape, normally 1.5–4 km long and 1–3 km wide (0.9–7.6 mi by 0.6–1.8 mi), with 20–35 m (66–115 ft) of vertical closure (Figure 1).

The characteristics of trap and oil-water contact of two Red River pools are illustrated in a cross section in the Midale field (Figure 12). Oil is confined in structural closures and generally completely fills the trap. As a result, the oil-water contacts coincide with the spillpoint of each trap (Figure 12). Based on resistivity logs and core examination, there is no indication of oil accumulation below spillpoints and outside closures in the Midale area, suggesting a structural control on oil accumulation. From north-northwest to south-southeast, the depths of individual pools increase gradually from −1960 to −2060 m (−6430 to −6760 ft) (Figure 1), reflecting the regional tilting of the Red River strata in southeast Saskatchewan.

The depth of oil-water contact can be interpreted from porosity logs, resistivity logs, and oil staining in the cores. In the Midale field, when the neutron porosity ranges from 10 to 15.5%, the corresponding resistivity is about 3–8 ohm m for the oil zones and about 1–2 ohm m for the water zones (Figure 12). However, if porosity is lower than 10%, the resistivity for both oil and water zones is higher. For example, the oil-water contact, based on resistivity logs, occurs at 2594.3 m (8510 ft) in well 8-3-7-11W2 (Figure 12), which corresponds to oil-water contact determined from oil staining in cores (2595.5 m [8515 ft] before depth correction). This is also the depth of the spill-point of the structure. Normally, different reservoir zones in the same anticline should have different areas of enclosure and different oil-water contact depths. In most Midale pools, however, different oil zones in the same trap share a common oil-water contact, although they are separated by nonreservoir intervals (Figure 12), suggesting that these reservoir zones are connected.

The production history of the Midale pools shows a rapid water influx and quick increases in water cuts in every well (Figure 2). At well 16-3-7-11W2, for example, the oil production in August 1996 was 9095 bbl, and water production was only 1761 bbl. In 2.5 yr, monthly oil output was reduced to 1944 bbl, water increased to 43,503 bbl, and water cut reached as high as 95%. The geologic factors that contributed to the fast rise of the water cut and high water output are small pool size caused by the low structural relief and small structural enclosures and the fracture systems that connect oil and water zones. The other factor may be related to the government's economic policy (i.e., reduced royalties for deep exploration and development wells for the first 2 yr of production) (Kreis and Kent, 2000). As a result, the producers may have tried to produce as much oil as possible during the first 2 yr to maximize the benefits of the royalty holidays (R. Alway, 2002, personal communication).

SOURCES AND MATURATION OF HYDRCARBONS

The source of hydrocarbons in the Red River reservoirs in southeast Saskatchewan is interpreted to be related to organic-rich rocks called kukersites (Kendall, 1976; Osadetz et al., 1989; Stasiuk and Osadetz, 1990;

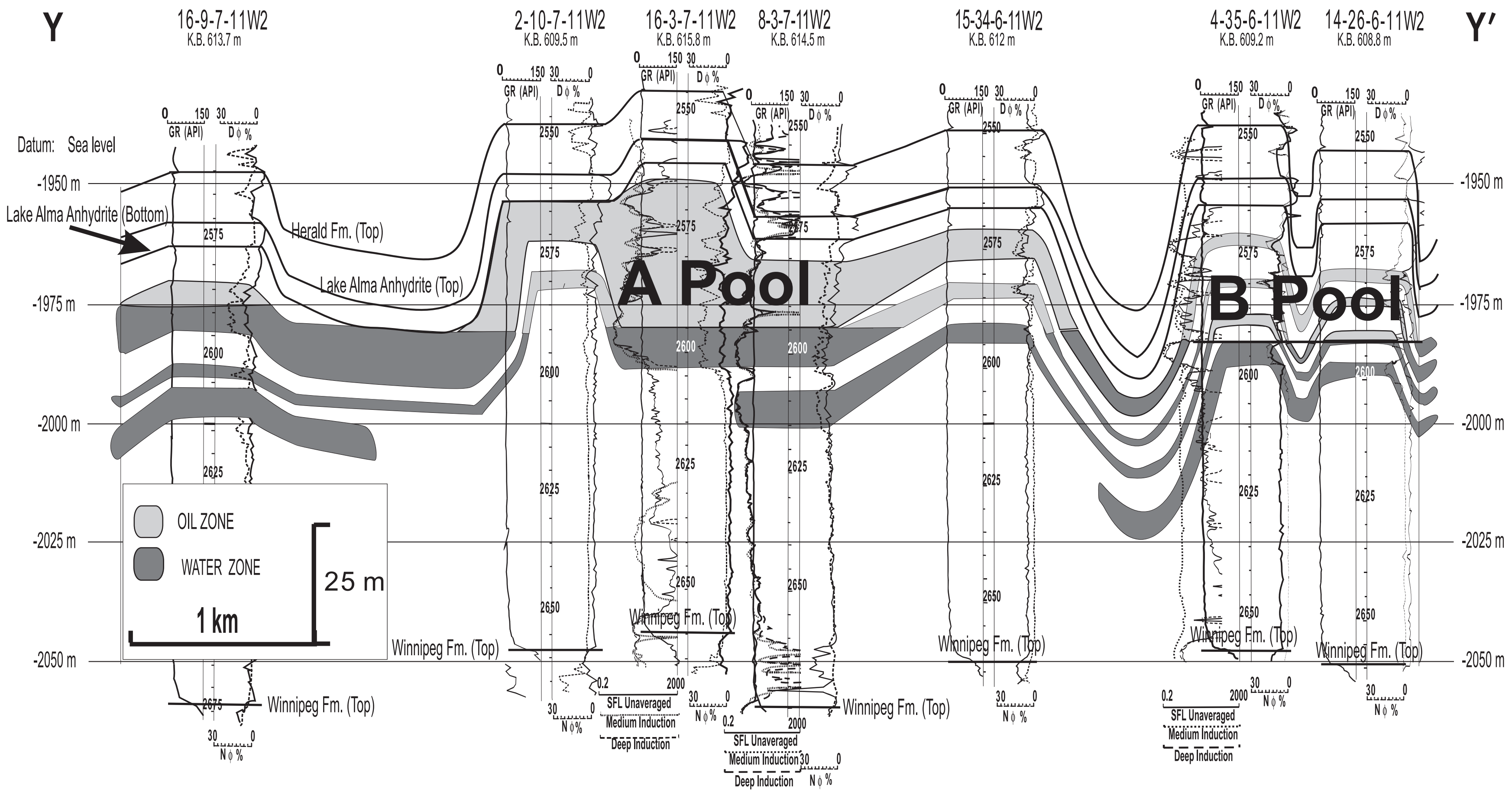

Figure 12. Structural cross section YY′ (see Figure 1 for the location of the cross section). It shows that the depth of the oil-water contacts of different zones is similar in the same trap, suggesting the possible connection of these zones, although they appear to be compartmentalized in cross section.

Stasiuk et al., 1991; Stasiuk and Osadetz, 1993; Osadetz and Snowdon, 1995; Stasiuk and Addison, 1999). These kukersites occur as thin beds in the Yeoman Formation. The main component of the kukersite is *Gloeocapsomorpha prisca*, a type of algae (Stasiuk and Osadetz, 1990; Stasiuk et al., 1991; Osadetz and Snowdon, 1995; Stasiuk and Addison, 1999). Fluorescence and reflectance studies of *G. prisca* in the Yeoman Formation by Stasiuk and Osadetz (1993), Fowler et al. (1998), and Stasiuk and Addison (1999) show that it has not yet reached the oil window in much of southeast Saskatchewan. However, there are some localized areas of thermal anomalies where the kukersites are actually mature, corresponding to the late oil window to early gas zone, as defined in the aforementioned studies.

The oil generation and initial oil migration in the Ordovician strata in the Williston basin probably took place between the Permian to Early Cretaceous, when Red River strata reached a burial depth over 2000 m (6560 ft) (Dow, 1974; Majorowicz et al., 1986; Brooks et al., 1987). The burial depth of oil generation generally ranges from 2800 to 3050 m (8534 to 10,000 ft) in the Williston basin according to Osadetz and Snowdon (1995). However, depth of oil window could be shallower, about 2450 m (8040 ft), because of the higher heat-flow areas in association with the North American Central Plains conductivity anomaly (Osadetz and Snowdon, 1995). The burial depths of the kukersite source rocks in the area close to the Canada–United States border ranged from 1000 to 2000 m (3280 to 6560 ft) during the Late Cretaceous. Oil generation further south, where the source rocks were more deeply buried, may have begun mainly during the Late Cretaceous. A recent study by Fowler et al. (1998) indicated a wide range of API gravity (26–42°) fraction for the Red River oils from the Midale area. This variation was interpreted as a result of the mixing of oils from two different sources: low-maturity oils generated from local kukersite source beds and high-maturity oils that migrated over long distances, about 50 km (30 mi) or more, from deeper parts of the basin to the south. Li et al. (1998) reached a similar conclusion based on their analyses of molecular tracers (pyrrolic nitrogen compounds) in Midale Red River crude oils.

CONCLUSIONS

The Red River reservoirs in the Midale field are characterized by intercrystalline porosity in the matrix of dolomitized burrowed carbonates. Dissolution vugs and fractures are also important in terms of improved reservoir quality. In the Midale field, the dolomite reservoirs can be divided into four zones, which may be connected, as they share a common oil-water contact in the same structure. The major oil reservoirs, zones 1 and 2, are typically 6–10 m (10–33 ft) thick. They occur higher in the structural traps and have a widespread spatial distribution. The underlying zones 3 and 4 are thicker, but they commonly contain only water because they are located below the spillpoint of hydrocarbon traps.

The seismic reflection of Red River reservoir is characterized by a weak- to medium-amplitude trough immediately above the positive reflection of the Winnipeg shale based on the log signatures and corresponding well-linked 3-D seismic profiles. However, an additional crest reflection occurs where four reservoir zones are separated from one another at roughly equal intervals. The termination of this additional crest reflection is related to the pinch-out of reservoir zones 3 and 4 as demonstrated by the forward modeling. This feature, therefore, can be used to identify possible stratigraphic traps related to the pinch-out of zones 3 and 4. Where there is a local increase in the thickness of reservoirs, especially the amalgamation of zones 1 and 2, the seismic reflections are characterized by relatively higher amplitudes and higher frequencies. This attribute is important for exploration of structural traps, because normally, only zones 1 and 2 are located in enclosure of Red River traps and contain oils.

The oil pools of the Midale area are characterized by low-relief anticline structures, which are interpreted as compactional drapes over the basement highs. The hydrocarbons in the Midale Red River pools are a mixture of low-maturity oils, sourced from local kukersite beds, and high-maturity oils that migrated over a long distance from the south. The production from Red River pools is characterized by a rapid water influx and fast increases in water cuts, which is partly caused by the small pool size and the fracture systems that connect oil and water zones.

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