CHAPTER 3 – BEAVERHILL LAKE GROUP CARBONATE RESERVOIRS

Ruth M. Ferry, Total Petroleum Canada Ltd.

INTRODUCTION

Reservoirs of the Beaverhill Lake Group comprise Swan Hills Fm and Slave Point Fm carbonates. The geographic locations of reservoirs discussed in this chapter are illustrated in Figure 3.1.

Hydrocarbon potential of the Beaverhill Lake Group was first exploited in 1957, with the discovery of the Virginia Hills reef complex in the Swan Hills area of westcentral Alberta. Fong (1959) introduced the term Swan Hills Member for the reefal carbonates ascribed to the Beaverhill Lake Fm. Nearly ten years later, after the Swan Hills play evolved into twelve major oil and two gas fields, Leavitt and Fischbuch (1968) described the carbonates as Swan Hills Fm and raised the Beaverhill Lake to group status. Contemporaneous with the Swan Hills oil boom, significant gas reserves were discovered in the Slave Point Fm in northeastern British Columbia. Clarke Lake was the first in a series of major gas fields developed along the dolomitized barrier-reef system. The last 20 years of exploration have reaffirmed the economic significance of the Beaverhill Lake Group, with substantial oil reserves discovered in the Slave Point Fm, surrounding the Peace River Arch, Alberta. Total initial volume of hydrocarbons in place within Alberta is estimated to be 941.4 x 10^6 m^3 of oil and 385.94 x 10^9 m^3 of gas. Estimated total recoverable reserves are 384.9 x 10^6 m^3 of oil and 162.247 x 10^9 m^3 of marketable gas.

The Beaverhill Lake Group includes Fort Vermilion, Slave Point, Swan Hills and Waterways formations. Fort Vermilion Fm evaporites were deposited during regressive or oscillatory conditions prevailing before the main transgressive phase of late-middle Devonian. Limestones of the Slave Point and Swan Hills formations represent the organic sedimentation phase of the widespread Beaverhill Lake transgression. Cessation of carbonate production coincided with the influx of terrigenous material of the Waterways Fm, associated with continued subsidence of the basin. Slave Point sedimentation was a diachronous event, the product of shallow water deposition of an advancing marine environment. Stratigraphically, the Slave Point Fm is correlative with the Swan Hills and Waterways formations (Fig. 3.2). On a more regional scale, Griffin (1965) established the correlation between the Slave Point Fm in northeastern British Columbia and a substantial part of the Waterways Fm in Alberta ((Fig. 3.43) modified after Griffin, 1965).

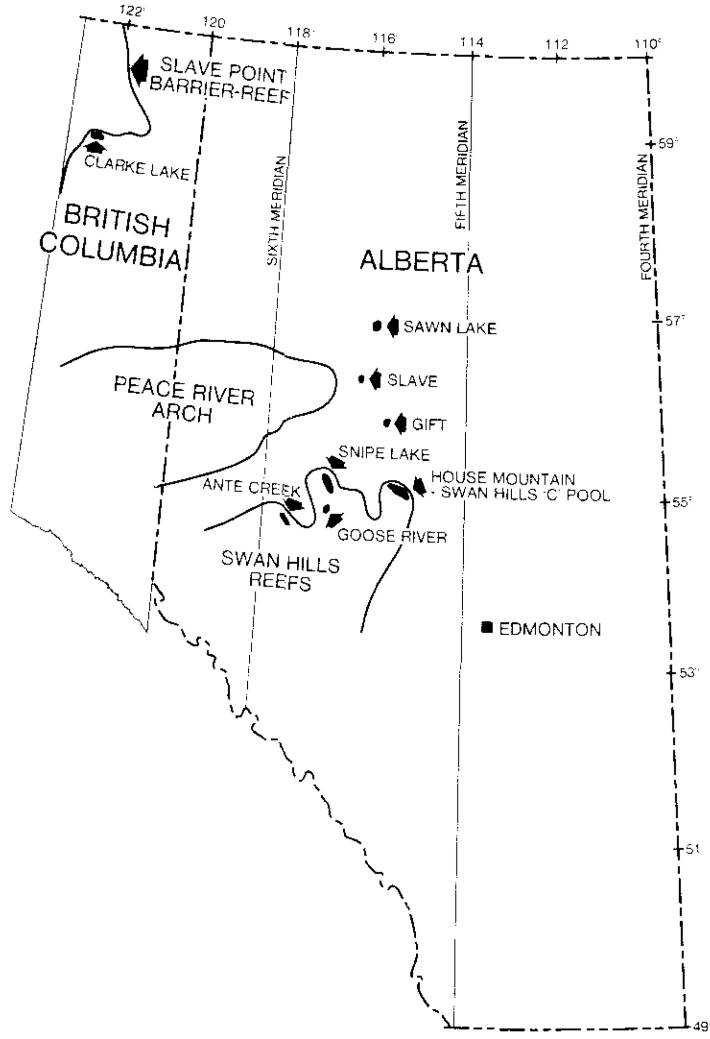

Figure 3.1 Regional setting of the Beaverhill Lake Group fields discussed in this chapter.

Swan Hills Fm reefs developed in an embayment south of the Peace River Arch (Figs. 3.1 and 3.4); platform, isolated bioherms and limestone bank facies are represented. Fischbuch (1968) divided the Swan Hills Fm into nine informal units, corresponding to distinct phases of reef growth. The stratigraphic nomenclature (Fig. 3.3) used in this study follows Fischbuch (1968) and Hemphill et al. (1970). Conditions conducive to organic reef development were probably initiated on widespread topographic highs. Jansa and Fischbuch (1974) suggested these highs were related to the paleo-topographic configuration of the underlying Gilwood delta complex. Paleotopography of the diachronous carbonate platform, surrounding the Peace River Arch, affected the facies distribution of the Slave Point Fm. Platform reefs and shoals were influenced by structural highs on the carbonate shelf, often associated with Precambrian topography. Depositional environments of the Slave Point Fm surrounding the Peace River arch are discussed in detail by Craig (1987).

Reservoirs of the Beaverhill Lake Group developed within Swan Hills Fm fringing-reef, isolated bioherms and reef-fringed carbonate bank; Slave Point Fm barrier-reef, platform reefs, shoals and carbonate banks. The limestone framework of Swan Hills carbonates is preserved, whereas some Slave Point reservoirs are enhanced by dolomitization (e.g. Clarke Lake, Slave). Porous carbonates are sealed by the enveloping argillaceous sediments of the Waterways Fm (Horn River and Muskwa formations in British Columbia). Beaverhill Lake Group hydrocarbon traps often exhibit both stratigraphic and structural components. Regional dip influences the distribution of hydrocarbons within stratigraphic traps such as carbonate banks (e.g. Ante Creek), shelf edges (e.g. Sawn Lake) and some isolated reefs (e.g. Snipe Lake, Virginia Hills); hydrocarbons being confined to the up-dip edge of these build-ups. Relief of the reservoir may be affected by Precambrian topography, imposing a structural constraint on some stratigraphic traps (e.g. Gift) due to compaction-induced drape. Paleostructural influence on the carbonate facies distribution exemplifies the mutual involvement of structure and stratigraphy (e.g. Slave, Gift).

The eight Beaverhill Lake fields discussed in this chapter (Fig. 3.1) include reservoirs within the Swan Hills reef-fringed carbonate bank (Ante Creek), isolated bioherms (Goose River, Snipe Lake), platform fringing-reef (House Mountain); Slave Point platform (Gift, Slave), carbonate shelf and platform accretions (Sawn Lake) and barrier-reef complex (Clarke Lake). The aforementioned

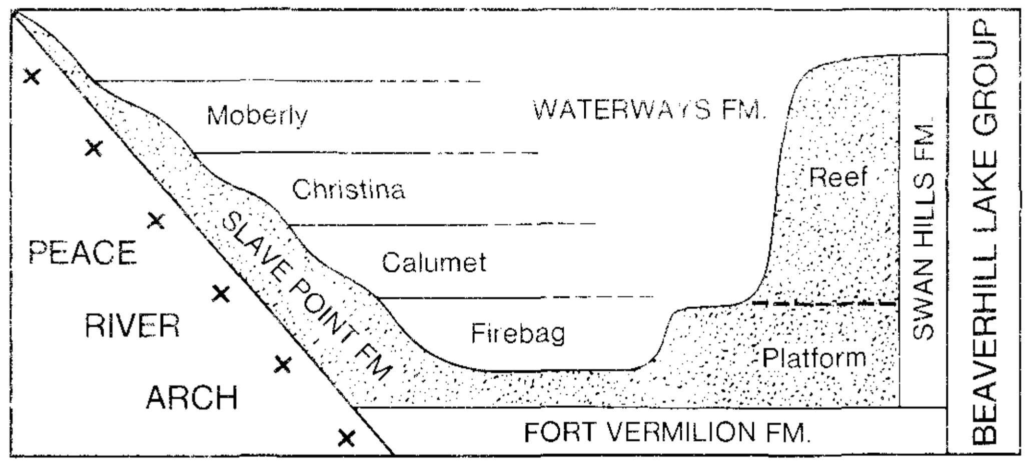

Figure 3.2 Stratigraphy of the Beaverhill Lake Group, Peace River Arch and Swan Hills regions.

reservoirs are stratigraphically diverse, due to the time transgressive nature of the carbonate facies (Figs. 3.2 and 3.43).

This chapter provides an integrated geological-geophysical approach to the interpretation of an exemplary cross-section through each field. Each morphologically distinct reservoir generates a characteristic seismic signature for which an integrated analysis is presented. Reservoir characteristics, including morphology, facies, porosity and compaction-induced drape are correlative with the seismic image. The lateral facies change between reservoir and encompassing sedimentary section is seismically defined, together with the influence of tectonic activity. Geologically significant components of the seismic response include isochron changes, amplitude (reflectivity) anomalies, amplitude and frequency modulation (waveform interference effects), time-structural relief, onlapping, and velocity generated pull-up. These criteria are discussed in detail within the individual seismic interpretation sections of the chapter. Stratigraphic seismic models, accompanying each example (except Clarke Lake), integrate the geological cross-sections and reconstruct the seismic image, thus corroborating the interpretation. The Clarke Lake example is accompanied, instead, by the seismic correlation of three synthetic seismic traces, representing distinct geological facies along the line of study.

Calcareous beds within the Ireton Fm shales generate an acoustic reflection, annotated on the appropriate examples as "Ireton marker". It should be noted that the term is used generically and the markers are not necessarily stratigraphically correlative.

ANTE CREEK

INTRODUCTION

Ante Creek field of westcentral Alberta is located approximately 280 km northwest of Edmonton in Township 65, Ranges 23-24 W5M (Fig. 3.1). Hydrocarbon production is from the Swan Hills Fm of the Beaverhill Lake Group, at 3435 m average depth. The discovery well, Atlantic Ante Creek 4-7-65-23W5, was completed November 1962 with initial potential flow of 18 m^3/day of 43.6° API gravity oil.

Stratigraphy of the Beaverhill Lake Group in the vicinity of Ante Creek is consistent with Figure 3.3, excepting the Fort Vermilion Fm which is poorly defined. Corneil (1969) referred to the 3 m of anhydritic shale, overlying the Elk Point clastics, as basal Beaverhill Lake rather than Fort Vermilion Fm. The Swan Hills Fm comprises a lower 20 m of Dark Brown platform member overlain by up to 60 m of the Light Brown biohermal unit. Argillaceous limestones and shales of the Waterways Fm envelop the Swan Hills reef complex.

The Swan Hills Fm at Ante Creek is part of a massive reef-fringed carbonate bank which includes Kaybob South and Carson Creek (Fig. 3.4). The reservoir comprises porous limestone reef, surrounding the carbonate bank complex. Production is confined to the up-dip edge of the fringing-reef. In this study, the term "reef" or "bioherm" will be used when refering to the fringing-reef associated with the carbonate bank complex. Ante Creek field is an elongate feature, approximately 12 km in length, isolated from Ante Creek Northwest by a surge channel (Fig. 3.4). The reef complex is separated from the Kaybob - Goose River - Snipe Lake reef chain by a deep embayment, filled with basinal sediments of the Waterways Fm. Ante Creek and Ante Creek Northwest are the most westerly situated Swan Hills reefs and

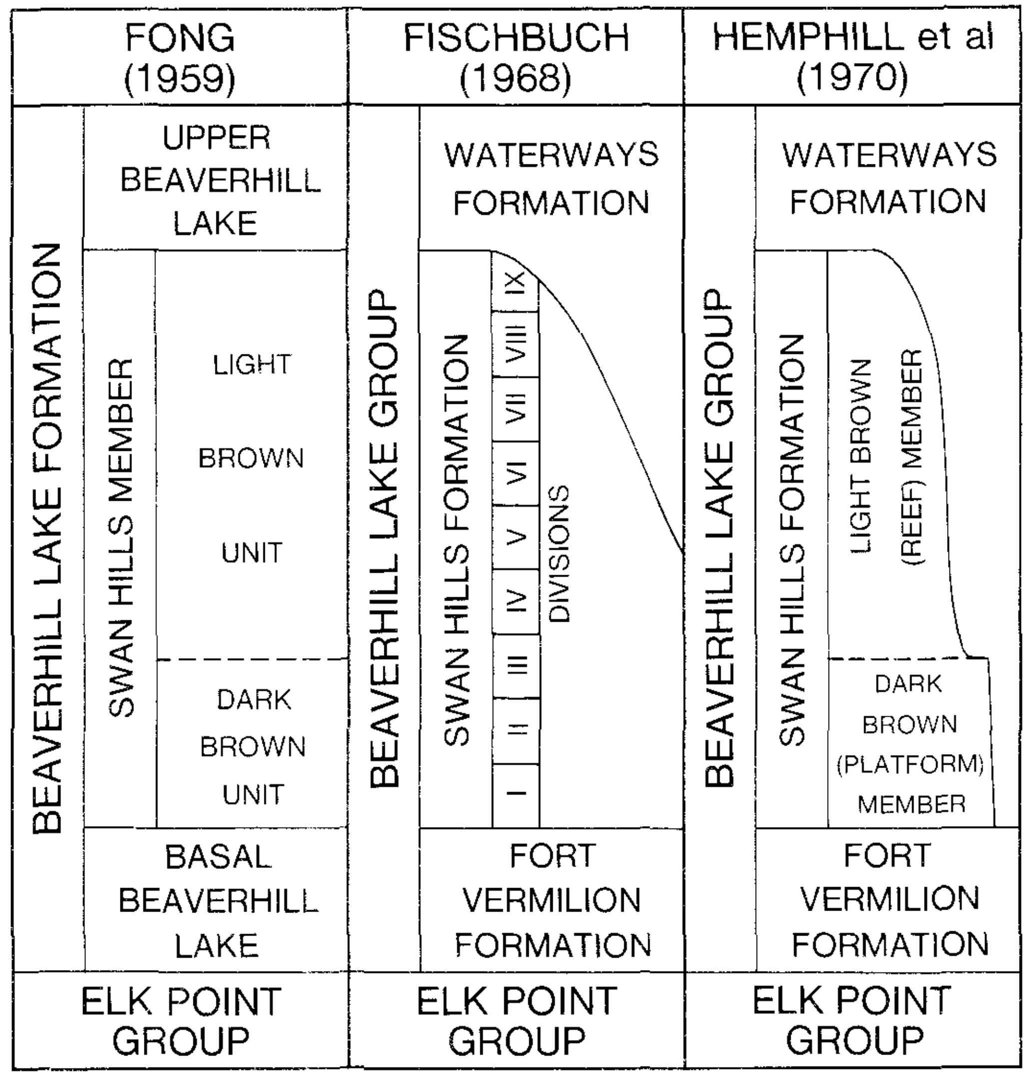

Figure 3.3 Stratigraphic nomenclature for the Beaverhill Lake Group, Swan Hills area.

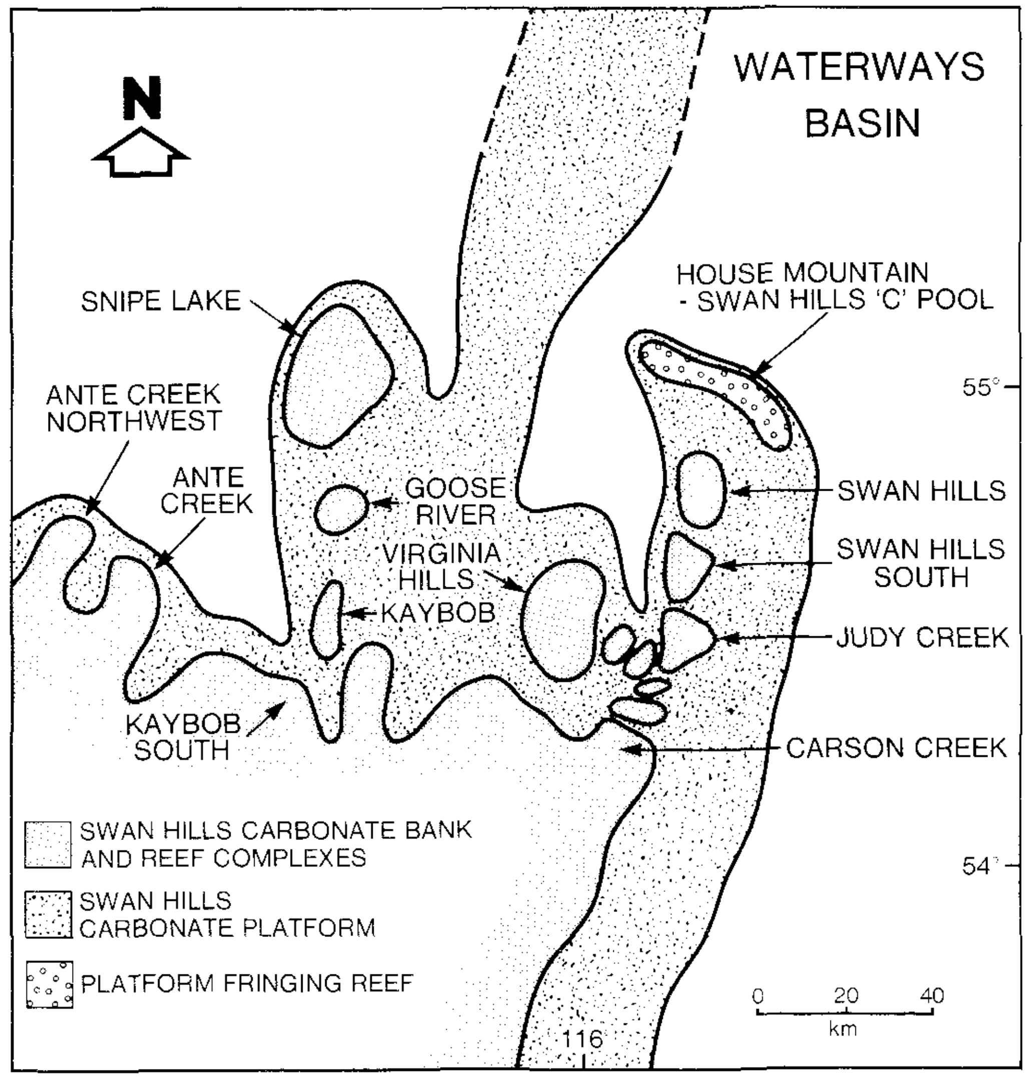

Figure 3.4 Distribution of Swan Hills Fm reefs in westcentral Alberta.

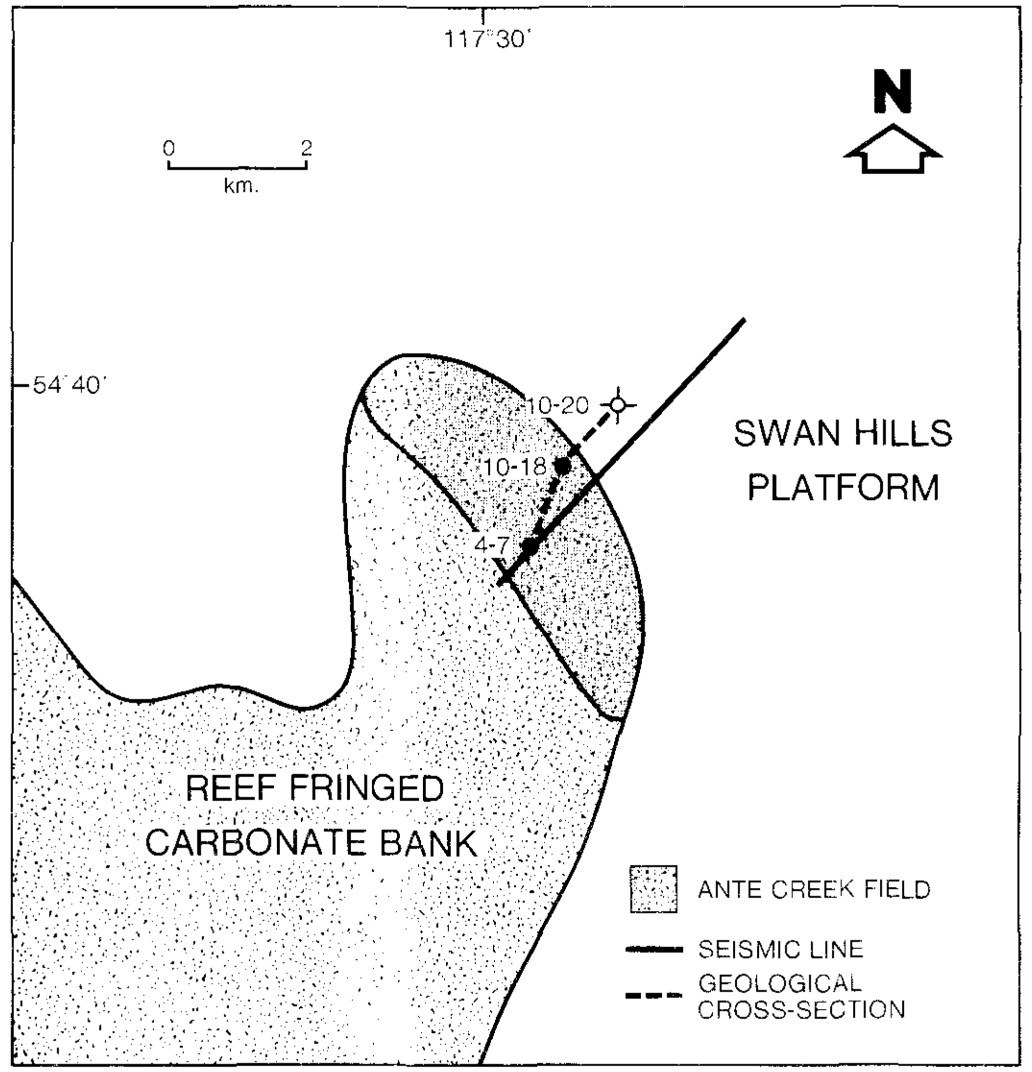

Figure 3.5 Schematic diagram of Ante Creek field, locating the seismic and geological cross-sections.

provide the only oil production from the reef-fringed carbonate bank complex; the other fields bearing gas.

Ante Creek is the deepest Swan Hills field at over 3400 m and the productive area, confined by stratigraphy and regional dip, is approximately 36 km^2. Porosity and net pay averages for the reservoir are 6.3% and 6.9 m respectively. Estimated original volume of oil in place is 5930 x 10^3 m^3 with 949 x 10^3 m^3 (primary) and 2610 x 10^3 m^3 (secondary) recoverable reserves. Cumulative production to the end of December 1987 is 1917.8 x 10^3 m^3 of 46° API gravity oil from the Beaverhill Lake pool.

Orientation of the seismic template line is normal to the reef margin (Fig. 3.5). The line of study extends from platform facies to an area of maximum Swan Hills reef development. Reflected energy from atop the Swan Hills Fm is resolved in the off-reef, platform environment. Proximal thinning of the Beaverhill Lake to Swan Hills time interval culminates in constructive interference of the events over the Swan Hills build-up; the resulting amplitude anomaly is the seismic manifestation of the Ante Creek reef complex. A postulated lower plateau in front of the main reef mass is characterized by a doublet waveform, dominated by the modulating low frequency component, generated by interference of the Beaverhill Lake and Swan Hills events.

GEOLOGICAL CROSS-SECTION

Orientation of the geological cross-section (Fig. 3.6) approximately parallels the seismic template, as shown in Figure 3.5. The line of study extends, northeast to southwest, from the off-reef platform facies (10-20), across an early reef phase (10-18) and onto the biohermal rim of the carbonate bank (4-7). Sonic - gamma ray log suites are displayed for each well in the cross-section.

The deepest stratigraphic horizon identified is the top of the Watt Mountain Fm clastics of the Elk Point Group, superposed by the carbonate platform facies of the Swan Hills Fm. For the purpose of this study, the Fort Vermilion equivalent is incorporated into the platform facies, since the thin, anhydritic unit is acoustically unresolved.

Thickness of Swan Hills platform in the distal 10-20 well is approximately 22 m. Biohermal limestone of the upper Swan Hills unit gradationally overlies the platform in the 10-18 and 4-7 wells. Sonic log response demonstrates the absence of an acoustic boundary between reef and platform facies. Total thickness of Swan Hills Fm carbonate increases from 33 m in 10-18, representing the initial phase of reef growth, to 79 m in the 4-7 well. Basinward extent of the reef phase encountered at 10-18 is inferred from the seismic interpretation. The resulting profile of the Ante Creek reef is consistent with the terraced morphology of Swan Hills bioherms described by Fischbuch (1968).

Basinal sediments of the Waterways Fm overlie the platform unit in the off-reef well and the bioherm in the proximal wells. This transgressive sequence of argillaceous limestones and calcareous shales ranges in thickness from approximately 70 m, in the distal well, to 7.5 m overlying the bioherm in 4-7, representing the final inundation of the reef complex. The abrupt lateral facies change from porous, reefal limestone to more argillaceous sediments of the Waterways Fm forms the stratigraphic trap.

The Beaverhill Lake Group is overlain by impermeable shales of the Duvernay and Ireton formations of the Woodbend Group.

Absence of structural drape on the Beaverhill Lake and younger horizons across the reef edge is apparent. The lack of differential compaction is probably due to the calcareous nature of the off-reef sediments. Regional dip to the southwest is the principal structural feature of the cross-section. A low relief structure manifested on the deeper horizons, up-dip from the main reef edge, is inferred from the seismic interpretation.

Porosity in the 4-7 discovery well is limited to the lower part of the biohermal unit and the 3 m of net pay is below average for the field. Cumulative production, however, is in excess of 53 x 10^3 m^3. The 10-18 well encountered porosity at the top of the Swan Hills Fm and has produced 18.93 x 10^3 m^3 of oil from 2.5 m of net pay.

SEISMIC SECTION

The approximate location of the seismic example is outlined schematically in Figure 3.5. These 1200% CDP seismic data were acquired in 1977 using a 4 kg dynamite source, 48 recording channels over 2 x 2400 m split spread, 200 m source intervals and 100 m group intervals. The line was reprocessed in 1987 following a conventional processing sequence, including spiking deconvolution and a final bandpass filter of 12/16 - 60/70 Hz. Full, 1200% CDP coverage is preserved at the extremities of the line.

Prominent geological horizons are identified on the interpreted data (Fig. 3.7). The Swan Hills reflector is relatively deep, occurring at approximately 1.75 seconds 2-way time.

The deepest reflection identified is from atop the Muskeg Fm at the base of low velocity Watt Mountain Fm clastics. This acoustic boundary, not penetrated by any of the wells, generates a strong, coherent seismic event. Any velocity generated pull-up would be observed along this reflector. An estimated pull-up effect of 3 ms was calculated using velocities from the 4-7 (on-reef) and 10-20 (off-reef) wells. Such a subtle velocity anomaly is difficult to distinguish from true time-structural relief of the reflection. Beaverhill Lake to Muskeg isochron increases by 12 ms from the on-reef well to the more distal off-reef example. Most of the isochron change is due to regional eastward thickening of the Beaverhill Lake and Watt Mountain isopachs but an abrupt 4 ms anomaly, between seismic traces 185 and 189, is attributed to velocity generated pull-up across the main reef edge.

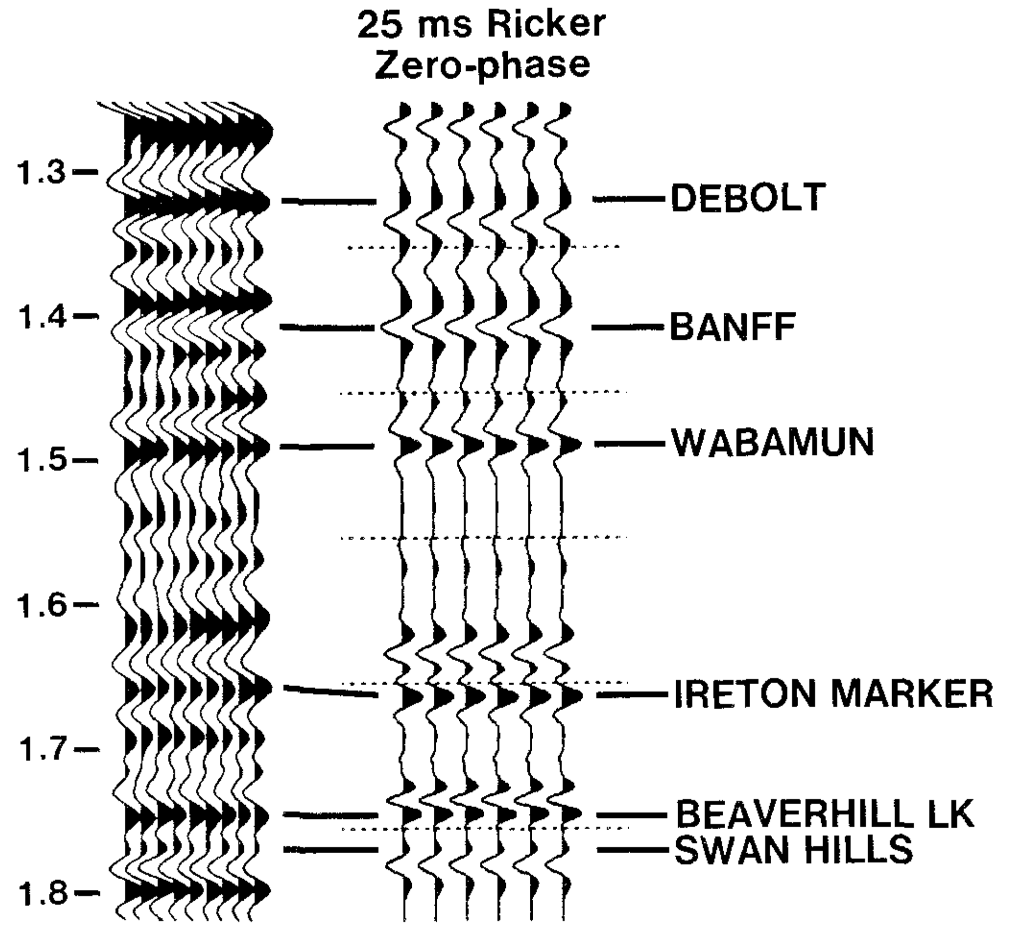

Figure 3.8 Correlation of seismic data (left) with a synthetic seismogram derived from the 10-20 sonic log (Ante Creek).

Reflected energy from the Swan Hills Fm surface is resolved in the off-reef, platform environment. Correlation with the synthetic seismogram generated from the 10-20 sonic log, shown in Figure 3.8, facilitates the interpretation. The Swan Hills amplitude response is weak compared with the Muskeg (below) and Beaverhill Lake reflection (above), compounded by the effects of destructive interference with the dominant Beaverhill Lake event. Proximal thinning of the Waterways Fm is represented by a decrease in the Beaverhill Lake to Swan Hills time interval. These events form a doublet in the vicinity of 10-18 due to the bandlimited nature of the data. The modulating low frequency component of the doublet waveform is dominant. Employing the seismic doublet as criterion, the early phase of reefing encountered at 10-18 appears to extend basinward into the vicinity of seismic trace 120 (Fig. 3.7). The limits of vertical resolution are exceeded as the Swan Hills develops into full reef (4-7), but a distinct seismic signature is generated by constructive interference of the Beaverhill Lake and Swan Hills reflections. The Ante Creek reef is manifested by an abrupt increase in amplitude of the Beaverhill Lake event over the Swan Hills build-up (seismic traces 188 to 281).

The acoustic impedance contrast between low velocity Woodbend shales and the argillaceous limestone of the Waterways Fm generates a strong, coherent Beaverhill Lake reflection. Lateral variations in amplitude of this event are attributed to the interference phenomena described above.

Absence of structural drape over the reef is apparent; instead, the deeper events exhibit the contrary time-structure reversal across the reef slope. This phenomenon is due to a low relief, positive structure, up-dip from the main reef edge (between traces 150 and 185 of Fig. 3.7). The anomaly is supported by a thinning of the Wabamun to Muskeg isochron across the feature.

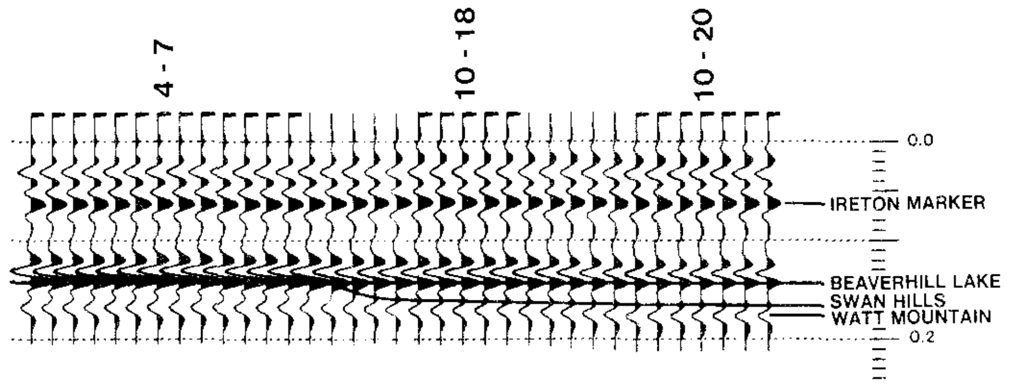

Figure 3.9. Stratigraphic seismic model of Ante Creek field, filtered with a 25 ms zero-phase Ricker wavelet.

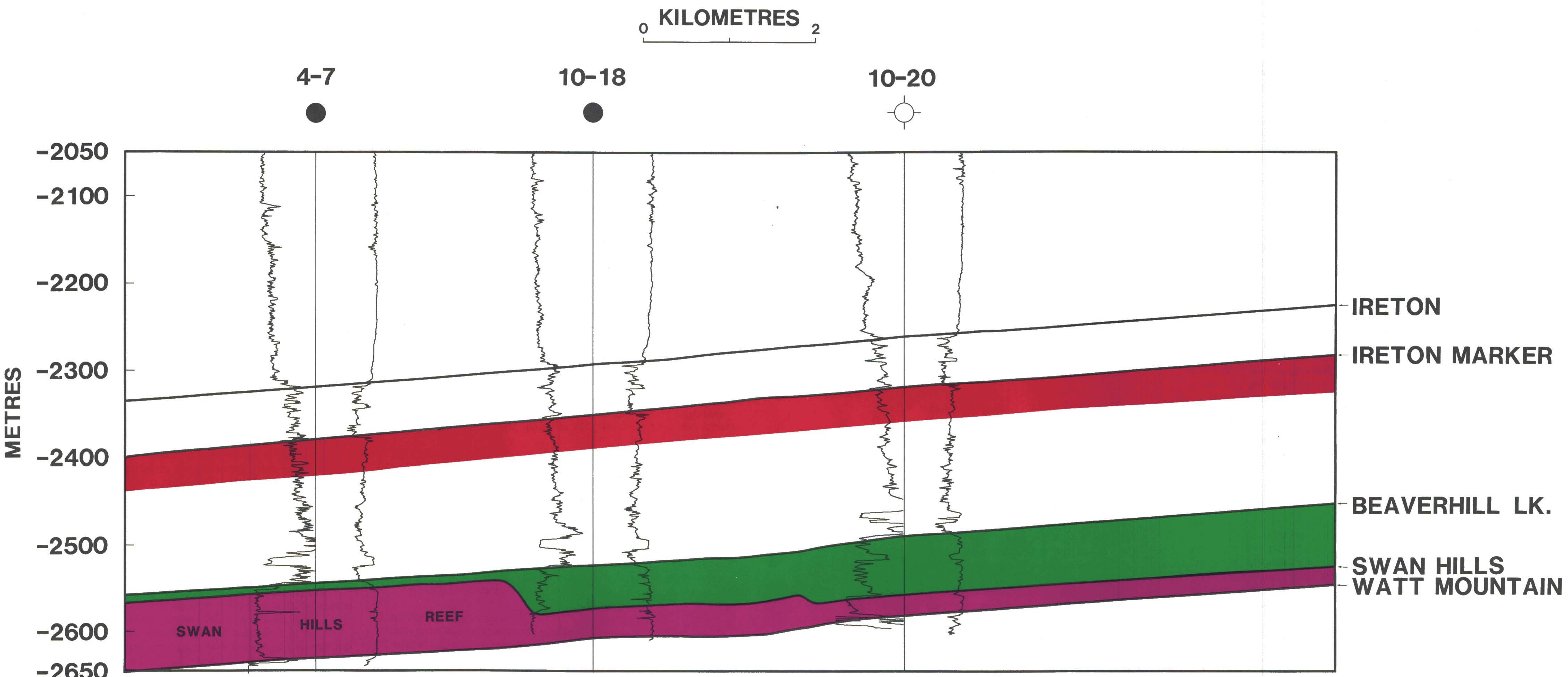

Figure 3.6 Ante Creek field geological cross-secion, incorporating the seismic interpretation (facing page)

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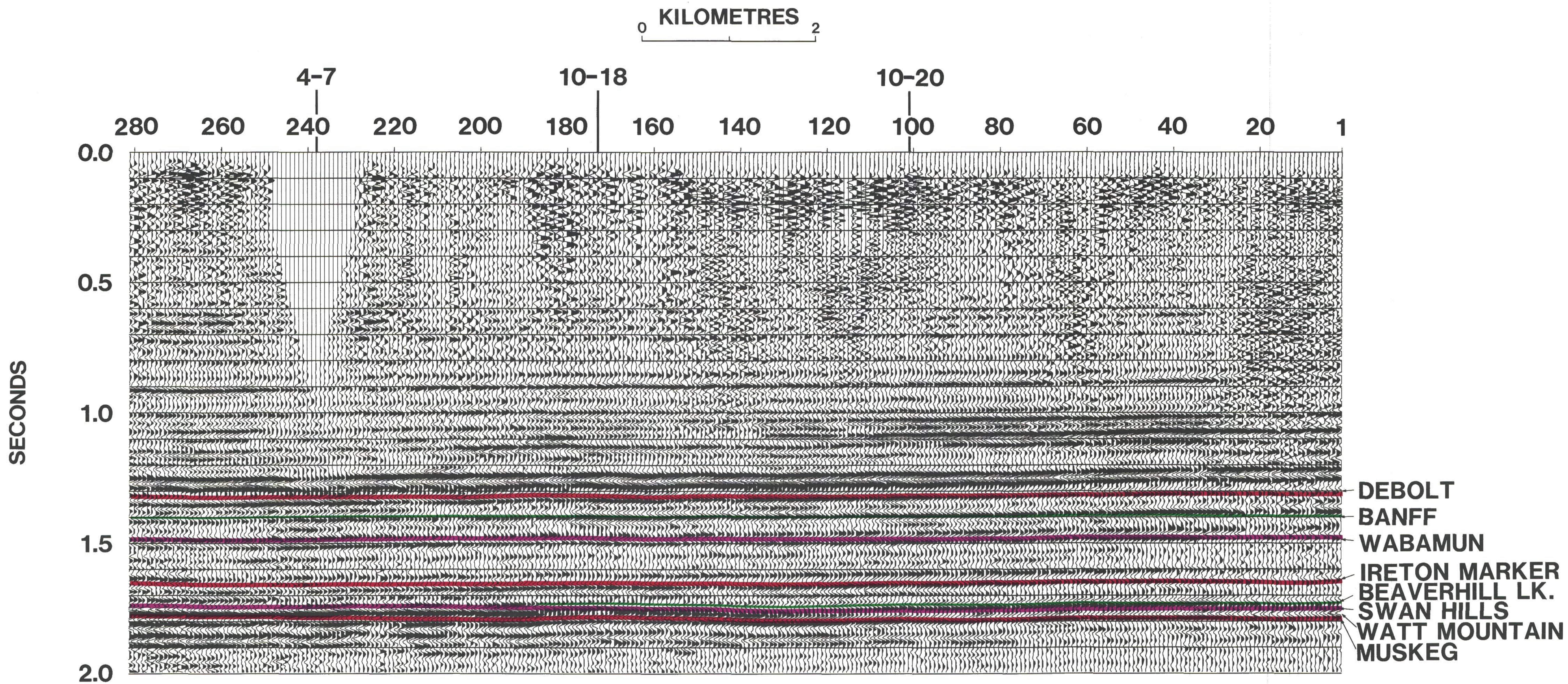

Figure 3.7 Seismic expression across Ante Creek field.

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The calcareous Ireton marker and tops of Wabamun, Banff and Debolt formations are identified on the interpreted section. Relief observed on these events is attributed to regional tilting of the sedimentary section.

To assist and corroborate the seismic interpretation a synthetic seismic section was generated using sonic logs from the three wells in the geological cross-section. The stratigraphic seismic model (Fig. 3.9) consists of zero-offset, primary reflection coefficients convolved with a 25 ms, zero-phase Ricker wavelet. The seismic model includes the geological section from Ireton to Elk Point; Ireton marker, Beaverhill Lake, Swan Hills and Watt Mountain events are identified.

The synthetic seismic section reinforces the geological significance of the acoustic image observed across the Ante Creek reef. The salient feature of the model is the proximal thinning of the Beaverhill Lake to Swan Hills cycle, forming a doublet in the vicinity of 10-18 before constructive interference generates the anomalous amplitude of the Beaverhill Lake event over the main reef mass.

GOOSE RIVER

INTRODUCTION

Goose River field of westcentral Alberta is located approximately 240 km northwest of Edmonton in Townships 66-67, Range 18 W5M (Fig. 3.1). Production is from the Swan Hills Fm of the Beaverhill Lake Group, at 2810 m average depth. The discovery well, British American Oil Co. Ltd's GooseRiver 10-4-67-18W5M, was completed in September 1963 with initial potential flow of 96 m^3/day. Cumulative production for the well is 308.58 x 10^3 m^3 of 39° API gravity oil.

Stratigraphy of the Beaverhill Lake Group in the vicinity of Goose River comprises Fort Vermilion, Swan Hills and Waterways formations (Fig. 3.3). In the study area, approximately 6 m of anhydritic Fort Vermilion Fm overlies Elk Point Group clastics. The Swan Hills Fm is subdivided and comprises 30 m of carbonate platform (Dark Brown member) and up to 62 m of biohermal limestone (Light Brown member). Argillaceous limestones and shales of the Waterways Fm encompass the reef complex.

Goose River is an isolated biohermal reef complex, separated from both the Snipe Lake and Kaybob reef masses (Fig. 3.4) by surge channels (Hemphill et al. 1970). Deeper water Beaverhill Lake sediments to the west separate this reef chain from the Swan Hills carbonate bank at Ante Creek (Fig. 3.4). Goose River is one of the smaller discrete reef complexes of the Beaverhill Lake Group, with approximate dimensions of 8 x 12 km; the longer axis trending northeast-southwest. Maximum reef development occurred in the southwest region of the complex (Jenik and Lerbekmo, 1968).

Production from the porous biohermal limestone reservoir is confined to the up-dip, eastern half of the reef, encompassing an area of approximately 36 km^2. The most porous reservoir is found in the higher energy, reef rim environment. Porosity and net pay averages for the field are 8.2% and 12 m, respectively. Estimated original volume of oil in place is 21,040 x 10^3 m^3, with 3408 x 10^3 m^3 (primary) and 5424 x 10^3 m^3 (secondary) recoverable reserves.

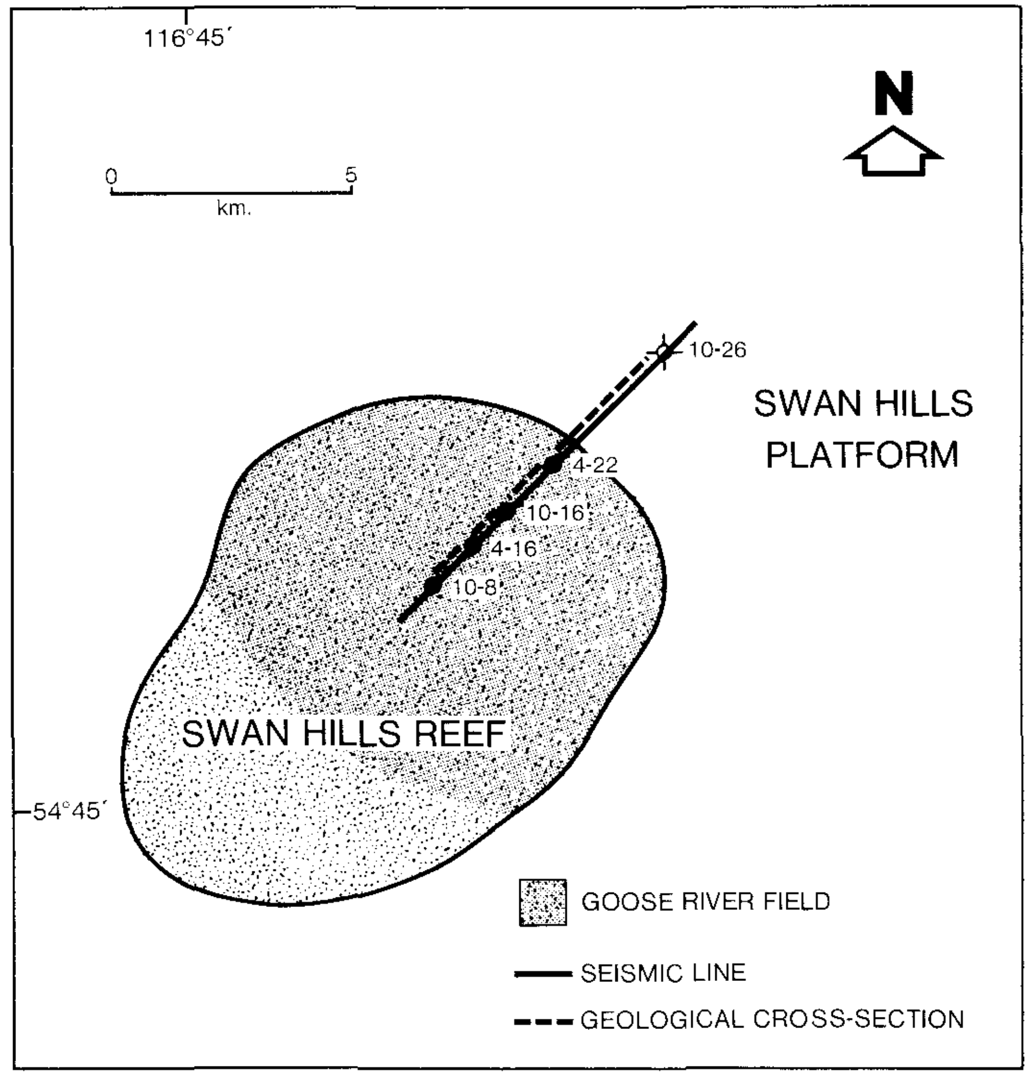

Figure 3.10 Schematic diagram of Goose River field, locating the seismic and geological cross-sections.

Cumulative production to the end of December 1987 is 5960.6 x 10^3 m^3 of 39° API gravity oil from the Beaverhill Lake 'A' pool.

The seismic template line, orientated northwest-southeast, crosses the up-dip, productive margin of the Goose River reef complex (Fig. 3.10). The line of study extends from the off-reef platform facies to the central portion of the reef mass. A discrete reflection from atop the Swan Hills Fm is resolved in the platform environment. Proximal thinning of the Beaverhill Lake to Swan Hills time interval manifests an early phase of reefing in front of the main complex. Continuity of the Swan Hills event is maintained across the reef edge, but the origin of the reflection moves to the lower boundary of the reef porosity. The porosity event, predictably, decays towards the predominantly tight, central portion of the reef mass. The top of the Swan Hills reef facies is seismically unresolved.

GEOLOGICAL CROSS-SECTION

The approximate locations of the geological cross-section (Fig. 3.11) and coincident seismic line are shown schematically in Figure 3.10. The section extends, northeast to southwest, from off-reef platform facies (10-26) across an early reef phase (4-22), biohermal rim (10-16) and onto the back-reef environment of 4-16 and 10-8 wells. Sonic - gamma ray log suites are displayed for each well except 4-16; conductivity combined with the sonic over a limited interval completes the cross-section.

The Watt Mountain Fm, Elk Point Group, is the oldest stratigraphic unit identified; penetrated by the 10-26 well, this horizon is extrapolated across the section restoring regional slope. Platform carbonates of the Swan Hills Fm overlie the Elk Point clastic sediments. The relatively thin (6 m) Fort Vermilion Fm is here included in the platform facies, since its contribution to the seismic response is negligible.

Thickness of the Swan Hills platform in the distal 10-26 well is approximately 36 m, corresponding to Divisions I to III of Fischbuch (1968). Biohermal limestone of the upper Swan Hills gradationally overlies the platform in the other wells; no acoustic boundary exists between reef and platform facies. Across the main reef edge, total thickness of Swan Hills limestone increases abruptly from an estimated 48 m at 4-22 to approximately 85 m in the 10-16 well. The reef phase encountered at 4-22 corresponds to Division IV of Fischbuch (1968); Divisions V to VIII are represented in each of the 10-16, 4-16 and 10-8 wells. Basinward extent of the lower reef phase is inferred from the seismic interpretation. Swan Hills isopach increases gradually from the reef rim to a maximum of 92 m (estimated) in the back-reef 10-8 well.

Basinal sediments of the Waterways Fm overlie both Swan Hills platform, in the off-reef environment, and the bioherm in the proximal wells. Thickness of the argillaceous limestone and calcareous shale sequence varies along the line of study from a minimum of 32 m over the bioherm to 92 m in the distal well. The Waterways Fm envelops the Goose River reef complex, as open-marine conditions prevailed after the cessation of reef growth. The abrupt lateral facies change within the Beaverhill Lake Group forms the stratigraphic trap.

Overlying the Beaverhill Lake Group are the impermeable shales of the Ireton and Duvernay formations of the Woodbend Group.

Absence of structural drape at the Beaverhill Lake horizon across the reef edge is apparent. The calcareous nature of the off-reef sediments probably precluded differential compaction. Regional dip to the southwest is the principal structural feature of the cross-section. A low relief structure manifested on the deeper horizons, up-dip from the main reef edge, is inferred from the seismic interpretation.

In the Goose River field, excellent porosity is found within biohermal limestone along the reef rim, as demonstrated by the 10-16 well. Porosity development diminishes in the lower energy back-reef environment, and the predominantly tight limestone facies, encountered at 10-8, represents the central part of the reef mass.

Cumulative production from the Swan Hills Fm for each well in the cross-section is tabulated below:

	10^3 m^3	Net pay
4-22	53.22	4 m
10-16	929.02	20 m
4-16	427.39	17 m
10- 8	51.68	5 m

SEISMIC SECTION

The approximate location of the exemplary seismic line is outlined in Figure 3.10. These 1200% CDP seismic data were acquired in 1975 using a 2 x 1 kg dynamite source array, 48 recording channels over a 2 x 1092 m split spread, 91 m source intervals and 45.5 m group intervals. The line was reprocessed in 1987 following a conventional processing sequence, including spiking deconvolution and a final bandpass filter of 12/16 - 60/70 Hz. Full, 1200% CDP coverage is preserved at the extremities of the line.

Salient geological horizons are identified on the structural stack (Fig. 3.12), with the Swan Hills zone of interest occurring at approximately 1.55 seconds 2-way time.

The deepest seismic reflection annotated is interpreted as the Muskeg event, below the Watt Mountain Fm clastics. Velocity generated pull-up on the Muskeg event, below the reef, is negligible due to the calcareous nature of the off-reef sediments. Using velocities and isopachs from wells at the extremities of the section, maximum pull-up is estimated to be only 1.5 ms. Furthermore,

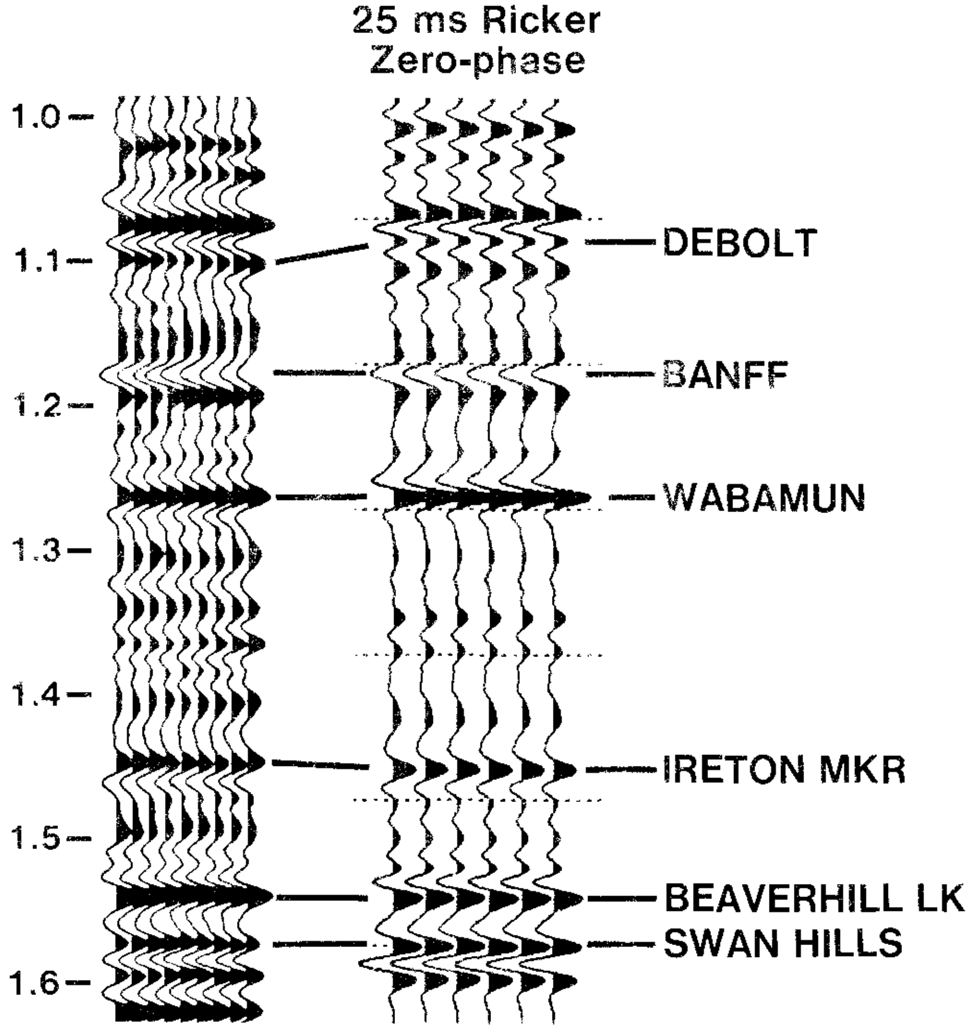

Figure 3.13 Correlation of seismic data (left) with a synthetic seismogram derived from the 10-26 sonic-log (Goose River).

porosity effects on the acoustic properties of the biohermal limestone tend to negate any velocity anomaly.

A seismic reflection from atop the Swan Hills Fm is resolved in the off-reef, platform environment. Correlation with the synthetic seismic trace derived from the 10-26 sonic log, shown in Figure 3.13, facilitates the interpretation. The initial phase of reef growth at 4-22 is manifested by a 6 ms thinning of the Beaverhill Lake to Swan Hills time interval, compared with the distal 10-26 location. Basinward extent of the early reef phase (Division IV of Fischbuch, 1968) is inferred by an abrupt (3 ms) increase in the Beaverhill Lake to Swan Hills cycle between traces 120 and 113 of Figure 3.12.

Continuity of the Swan Hills event is preserved across the reef edge, near seismic trace 169, and a strong reflection characterizes much of the bioherm (Divisions V to VII of Fischbuch, 1968). The origin of the reflected energy, however, moves to the lower boundary of the porous interval, leaving the top of the Swan Hills reef facies seismically unresolved. Diminishing porosity towards the central part of the reef mass (10-8) causes the amplitude decay observed on the porosity event. The decrease in amplitude (reflectivity) near seismic trace 260, suggests the reservoir porosity diminishes abruptly just southwest of the 4-16 well. Predictably, coherence of the seismic porosity indicator is lost as the predominantly tight, back-reefal limestone of 10-8 is encountered. In this central portion of the reef complex, the top of the Swan Hills Fm is not seismically represented, since the thinner Waterways Fm exceeds the resolution limit of the seismic bandwidth.

Recapitulating, the seismic image of the Goose River reef complex is extremely subtle, due to the excellent porosity development along the reef margin. The abrupt Swan Hills isopach increase across the reef edge is acoustically masked by the porosity effect. However, having identified the porosity event on the seismic data, the lateral extent of porosity within the reef can be mapped.

The acoustic impedance contrast between low velocity Woodbend Group shales and the argillaceous limestone of the Waterways Fm generates a strong, coherent Beaverhill Lake reflection. Absence of structural drape on this marker over the reef edge is apparent. Instead, a low relief structure up-dip from the main reef slope causes the contrary time-structure reversal observed on the Beaverhill Lake event.

The calcareous Ireton marker and tops of Wabamun, Banff and Debolt formations are annotated on the interpreted section.

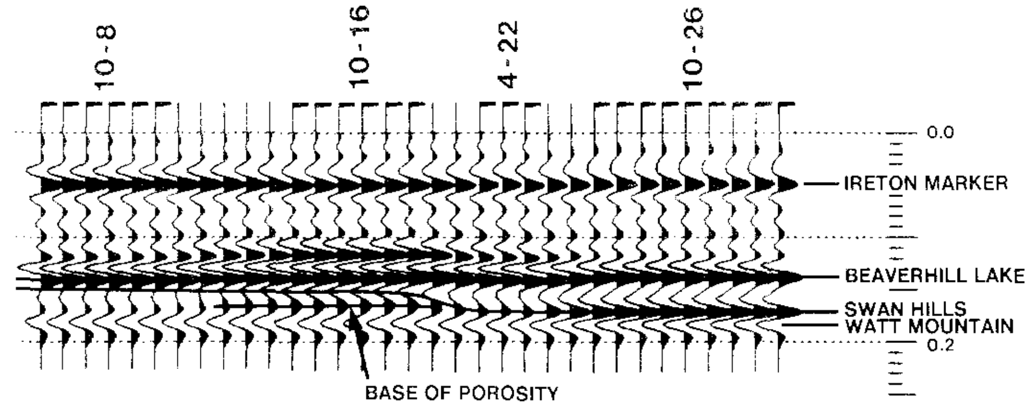

Figure 3.14 Stratigraphic seismic model of Goose River field, filtered with a 25 ms zero-phase Ricker wavelet.

Time-structural relief along these events is attributed to regional tilting of the sedimentary section.

To assist and corroborate the seismic interpretation a synthetic seismic section was generated using sonic logs from four of the wells in the geological cross-section. The stratigraphic seismic model (Fig. 3.14) comprises zero-offset, primary reflection coefficients convolved with a 25 ms, zero-phase Ricker wavelet. The seismic model includes the geological section from Ireton to Elk Point; Ireton marker, Beaverhill Lake, Swan Hills and Watt Mountain events are identified.

The synthetic seismic section reinforces the interpretation of the seismic signature observed across the Goose River reef. Proximal thinning of the Beaverhill Lake to Swan Hills cycle is apparent, accompanied by a decrease in amplitude of the Swan Hills reflection. Continuity, with subtle frequency modulation characterizes the Swan Hills event across the reef edge, between 4-22 and 10-16. Seismic imaging of the top of the reef is forfeited as a consequence of the porosity development in 10-16. Amplitude of the porosity event diminishes towards the predominantly tight, back-reef facies in 10-8.

SNIPE LAKE

INTRODUCTION

Snipe Lake field of westcentral Alberta is located approximately 260 km northwest of Edmonton in Townships 70-71, Ranges 18-19 W5M (Fig. 3.1). Production is from the Swan Hills Fm of the Beaverhill Lake Group at 2600 m average depth.

The Beaverhill Lake Group in the vicinity of Snipe Lake comprises Fort Vermilion, Swan Hills and Waterways formations (Fig. 3.3). In the study area, approximately 9 m of anhydritic Fort Vermilion Fm overlies Elk Point Group clastics. The Swan Hills Fm is subdivided and includes 30 m of carbonate platform (Dark Brown member) and up to 60 m of biohermal limestone (Light Brown member). Argillaceous limestones and shales of the Waterways Fm basinal facies envelop the reef complex.

Snipe Lake is an isolated bioherm which developed on a protrusion of the Swan Hills carbonate platform into the deeper Waterways basin (Fig. 3.4). Separated from the Goose River complex, to the south, by a surge channel, Snipe Lake is the most northerly situated Swan Hills reef. A deep embayment to the west

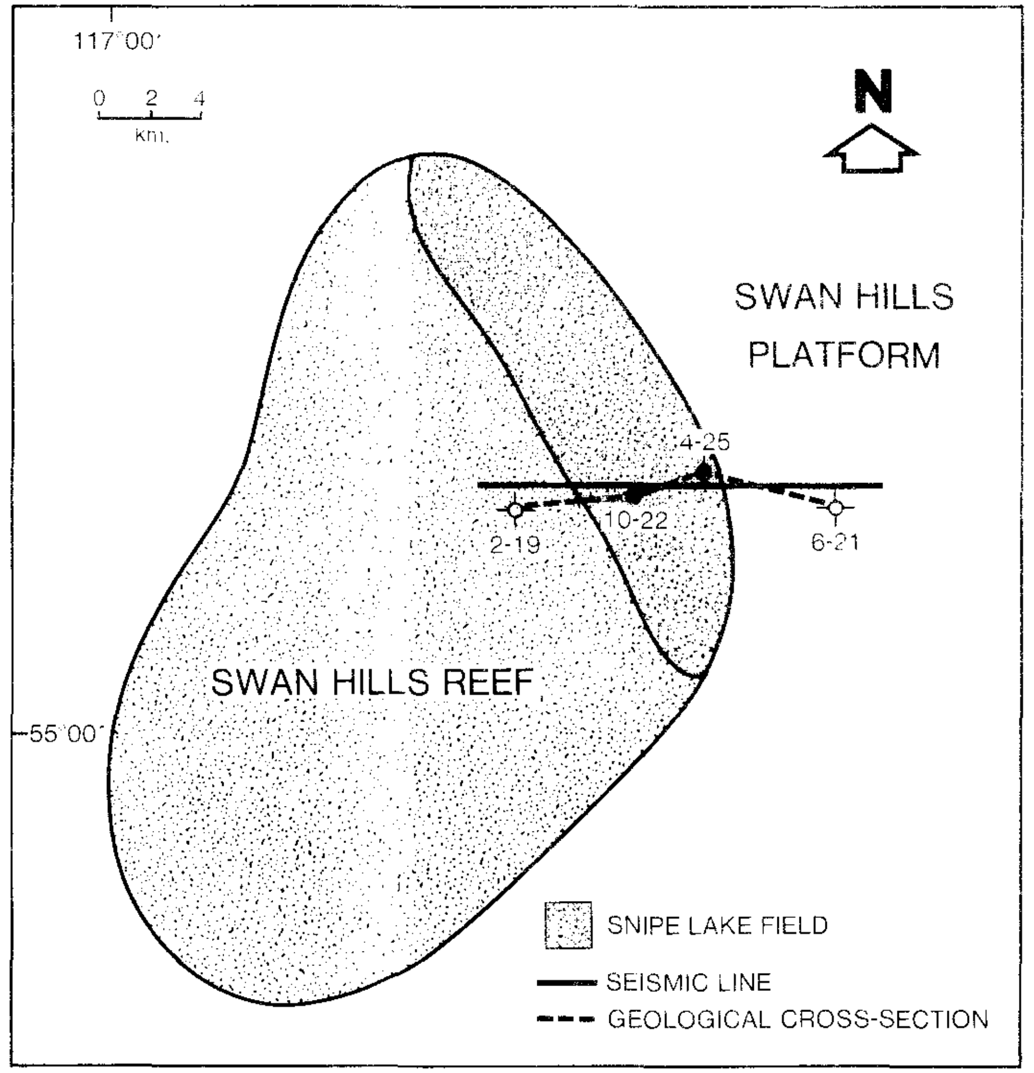

Figure 3.15 Schematic diagram of Snipe Lake field, locating the seismic and geological cross-sections.

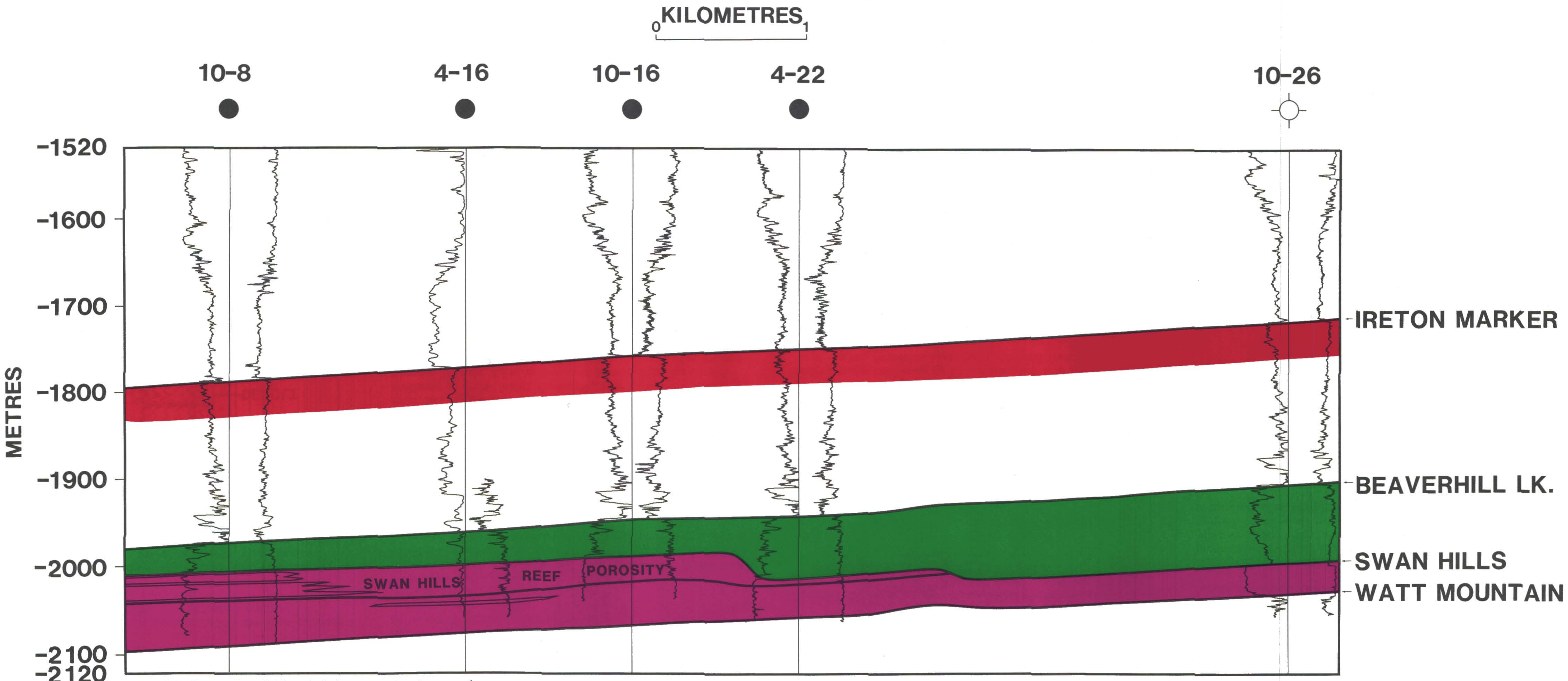

Figure 3.11 Goose River field geological cross-section, incorporating *the seismic interpretation (facing page)*

DRAFTING: | LOG PLOTS: RILEY'S DATASHARE INTERNATIONAL LTD. | AUTHOR: R.M. FERRY

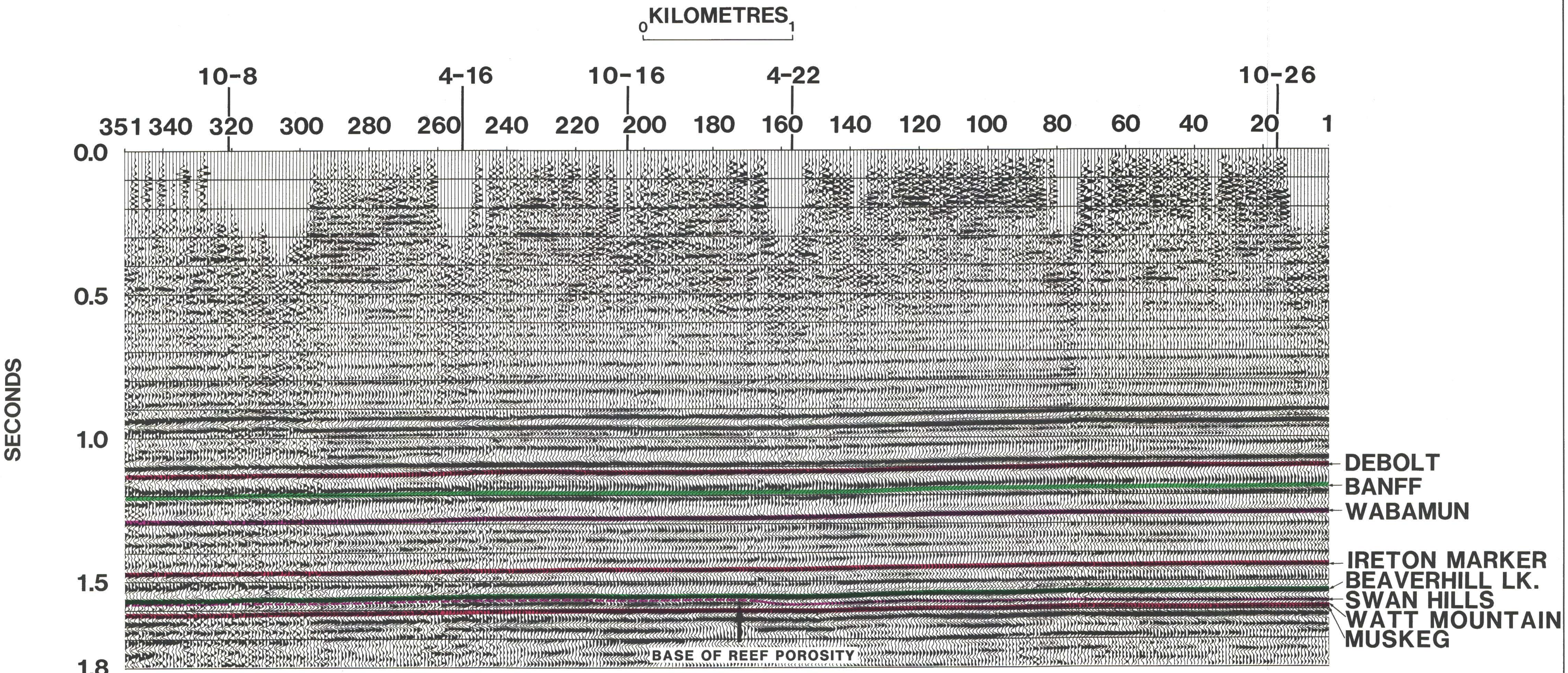

Figure 3.12 Seismic expression across Goose River field.

DONOR: TOTAL PETROLEUM CANADA LTD. | PROCESSOR: STATCOM LTD. | AUTHOR: R.M. FERRY

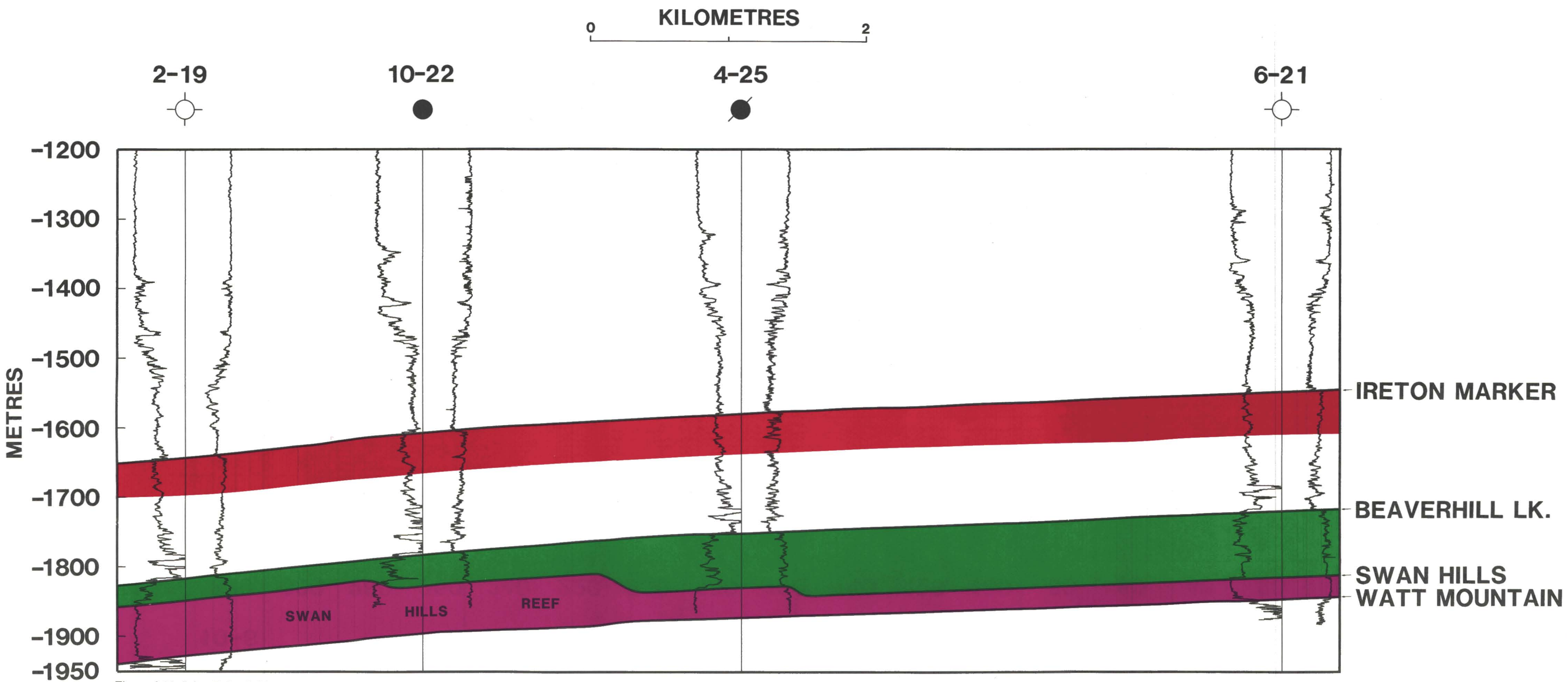

Figure 3.16 Snipe Lake field geological cross-section, incorporating the seismic interpretation (facing page)

DRAFTING: | LOG PLOTS: RILEY'S DATASHARE INTERNATIONAL LTD. | AUTHOR: R.M. FERRY

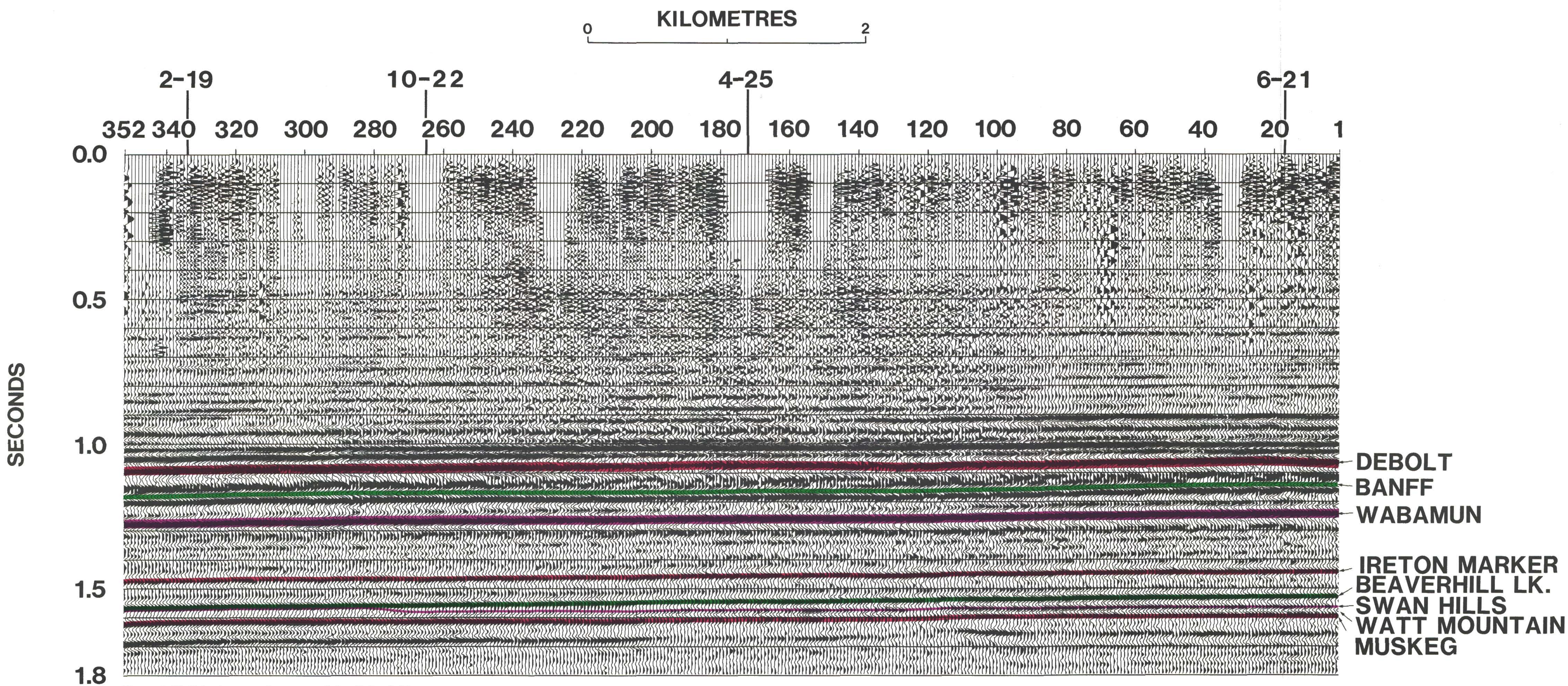

Figure 3.17 Seismic expression across Snipe Lake field.

DONOR: CHEVRON CANADA RESOURCES LTD. | PROCESSOR: STATCOM LTD. | AUTHOR: R.M. FERRY separates the Snipe Lake complex from the Swan Hills carbonate bank at Ante Creek (Fig. 3.4). Snipe Lake is the largest discrete reef complex of the Beaverhill Lake Group with an areal extent of approximately 500 km^2.

Production from the limestone reservoir is confined by regional dip to the northeast edge of the reef. The productive area of the field is approximately 73 km^2, with the most porous reservoir found in the higher energy, reef margin environment. The discovery well, S.O.B.C. Snipe Lake 10-21-70-18 W5M, drilled in October 1962, penetrated back-reef sediments and produced only 231.9 m^3 of oil. Average cumulative production for wells in the field is in the order of 72 x 10^3 m^3. Porosity and net pay averages for the reservoir are 6.8% and 10.5 m, respectively. Estimated original volume of oil in place is 31,100 x 10^3 m^3, with 3726 x 10^3 m^3 (primary) and 8680 x 10^3 m^3 (secondary) recoverable reserves. Cumulative production to the end of December 1987 is 8356.44 x 10^3 m^3 of 35° API gravity oil from the Beaverhill Lake pool.

The exemplary seismic line, orientated east-west traverses the up-dip productive margin of the Snipe Lake reef complex (Fig. 3.15). The line of study extends from the off-reef, platform facies to an area of maximum Swan Hills reef development. Reflected energy from atop the Swan Hills Fm provides four characteristic seismic signatures, representing platform and three stages of reef development. Proximal thinning of the Beaverhill Lake to Swan Hills time interval, and associated waveform interference effects, define the reef plateaus. Successive stages of reef growth are manifested by a progressive decay in amplitude of the Swan Hills event, culminating in loss of resolution as the Waterways Fm thins over the uppermost reef terrace. The present analysis of the seismic expression across Snipe Lake reef is consistent with the laterally varying interference phenomena described by Anderson et al.

GEOLOGICAL CROSS-SECTION

Orientation of the geological cross-section (Fig. 3.16) approximately parallels the seismic example as shown in Figure 3.15. The section of study extends, east to west, from off-reef platform facies (6-21) across an early reef phase (4-25) and onto the back-reef environment of the terraced bioherm (10-22 and 2-19). Sonic - gamma ray log suites are exhibited for each well in the geological cross-section.

The oldest stratigraphic unit identified, the Watt Mountain Fm, Elk Point Group, is penetrated by wells at the extremities of the cross-section and interpolated between these control points. Platform carbonates of the Swan Hills Fm overlie the Elk Point clastic sediments. For the purpose of this study, the Fort Vermilion Fm is included in the lower Swan Hills unit, since the 9 m interval of anhydrite and shale lamina has no significant effect on the seismic response.

Thickness of the Swan Hills platform in the distal 6-21 well is approximately 31 m, corresponding to Fischbuch's (1968) Divisions I and II. Biohermal limestone of the upper Swan Hills gradationally overlies the platform in the 4-25, 10-22 and 2-19 wells. Sonic-log response demonstrates the absence of an acoustic boundary between reef and platform facies. Total thickness of Swan Hills carbonate increases from an estimated 48 m in 4-25, representing the initial phase of reef growth, to 85 m in the 2-19 well. Back-stepping of progressive stages of biohermal growth resulted in the terraced morphology of the Snipe Lake reef complex. The reef phases encountered at 4-25, 10-22 and 2-19 correspond to Fischbuch's (1968) Divisions III, IV to VII and VIII, respectively. Location of the reef plateaus, along the line of study, is inferred from the seismic interpretation.

Basinal sediments of the Waterways Fm overlie the platform unit in the off-reef well and the bioherm in the proximal wells. The sequence of argillaceous limestones and calcareous shales, ranges in thickness from approximately 32 m in 2-19, to 98 m in the distal 6-21 well. Terrigenous sediments overlying the bioherm represent the final inundation of the Snipe Lake reef complex. The abrupt lateral facies change from reefal limestone to more argillaceous sediments of the Beaverhill Lake Group forms the stratigraphic trap.

The Beaverhill Lake Group is overlain by impermeable shales of the Duvernay and Ireton formations of the Woodbend Group.

Absence of structural drape on the Beaverhill Lake and younger horizons, across the reef edge, is apparent. Lack of differential compaction is probably due to the calcareous nature of the off-reef sediments. Regional dip to the southwest is the dominant structural feature of the cross-section.

Porosity in the 10-22 well is distributed within the upper biohermal unit. Cumulative production is 54.164 x 10^3 m^3 of 35° API oil from 7 m of net pay. The 2-19 well encountered a thicker reefal section but with minimal porosity in the back-reef environment and was subsequently abandoned.

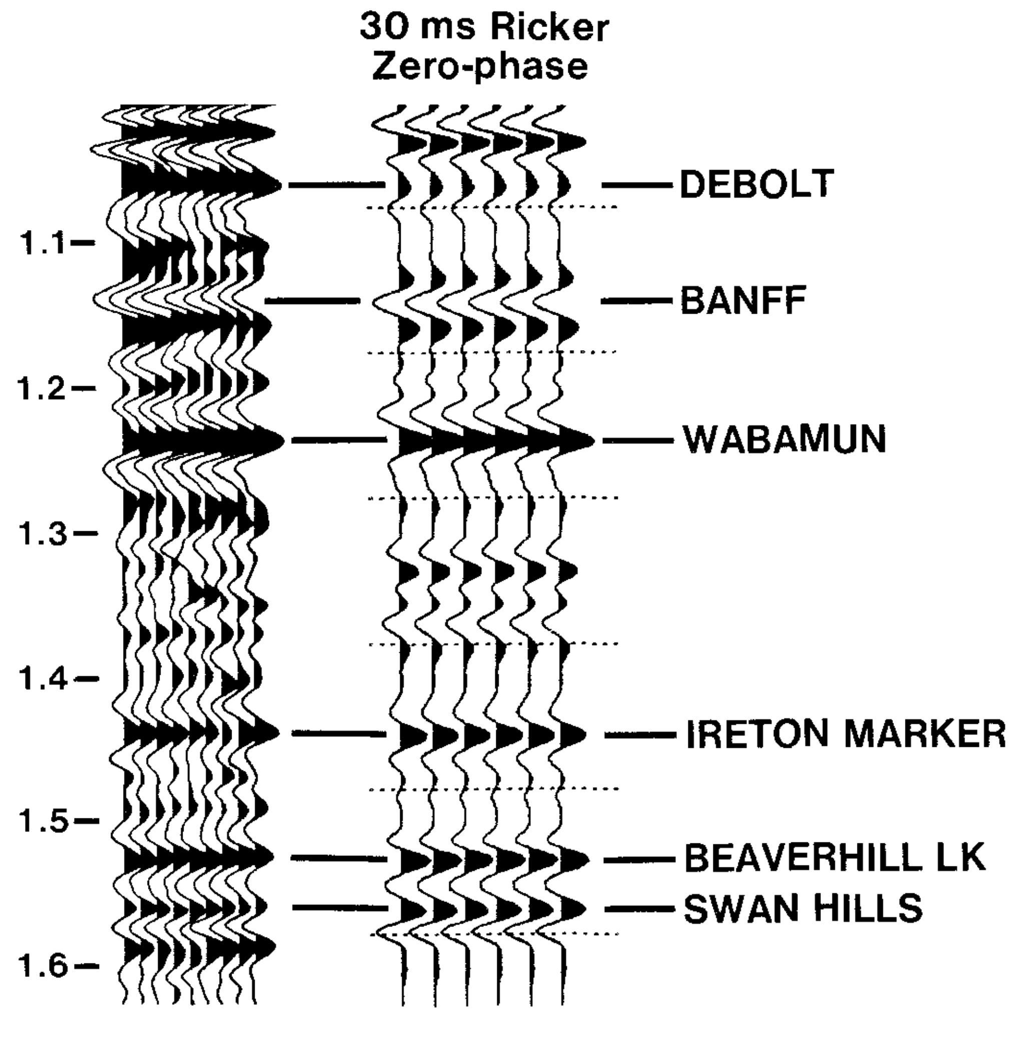

Figure 3.18 Correlation of seismic data (left) with a synthetic seismogram derived from the 6-21 sonic-log (Snipe Lake).

SEISMIC SECTION

The approximate location of the seismic template line is outlined in Figure 3.15. These 1200% CDP seismic data were acquired in 1980 using a 4 kg dynamite source, 96 recording channels over a 2 x 2400 m split spread, 200 m source intervals and 50-m group intervals. The line was reprocessed in 1987 following a conventional processing sequence, including spiking deconvolution and a final bandpass filter of 12/16 - 70/80 Hz. Full, 1200% CDP coverage is preserved at the extremities of the line.

Prominent geological horizons are identified on the interpreted data (Fig. 3.17) with the Swan Hills zone of interest occurring at approximately 1.55 seconds 2-way time. Correlation with the synthetic seismic trace derived from the 6-21 sonic log is shown in Figure 3.18.

The deepest reflection identified, is interpreted as the top of the Muskeg Fm at the base of Watt Mountain Fm clastics. The Muskeg horizon is not penetrated by any of the wells but the acoustic interface generates a strong seismic event. Any velocity generated pull-up would be observed on this event. An estimated velocity anomaly of 3 ms was calculated using the sonic logs from 2-19 (on-reef) and 6-21 (off-reef) wells. Such a subtle pull-up effect is difficult to distinguish from true time-structural relief of the reflection. Isochron values from Beaverhill Lake to Muskeg increase by 10 ms from 2-19 to the more distal off-reef well. Most of the isochron change is due to the regional eastward thickening of the Beaverhill Lake and Watt Mountain isopachs. Although a 3 ms component can be attributed to velocity generated pull-up, the terraced morphology of the reef causes a gradual, rather than abrupt, isochron anomaly.

Reflected energy from atop the Swan Hills Fm provides four characteristic seismic signatures, representing platform and three stages of reef development. The initial phase, corresponding to Division III of Fischbuch (1968), is manifested by a 5 ms thinning of the Beaverhill Lake to Swan Hills time interval between 6-21 (platform) and 4-25 (reef). Isochron thinning is accompanied by a decrease in amplitude of the Swan Hills event, due to destructive interference of the Beaverhill Lake and Swan Hills reflections. Lateral extent of the lower reef plateau is poorly defined, however, an edge is tentatively inferred by the increase in amplitude of the Swan Hills event near seismic trace 156.

Interference effects are more pronounced over the reef terrace encountered at 10-22; further suppression of amplitude of the Swan Hills event is apparent. This reef phase, corresponding to Fischbuch's Divisions IV to VII, results in an additional 6 ms thinning of the Beaverhill Lake to Swan Hills cycle. The discrete reflections tend towards a doublet in the vicinity of 10-22, due to the bandlimited nature of the seismic data. The up-dip edge of the reef terrace is seismically defined by the abrupt isochron change and associated interference phenomenon (between traces 208 and 212).

Limits of vertical resolution are exceeded by the final phase of biohermal growth (Division VIII of Fischbuch, 1968) encountered in the 2-19 well. However, a distinct seismic signature is generated by the constructive interference of the Beaverhill Lake and Swan Hills reflections. Seismic imaging of the upper plateau is described by the

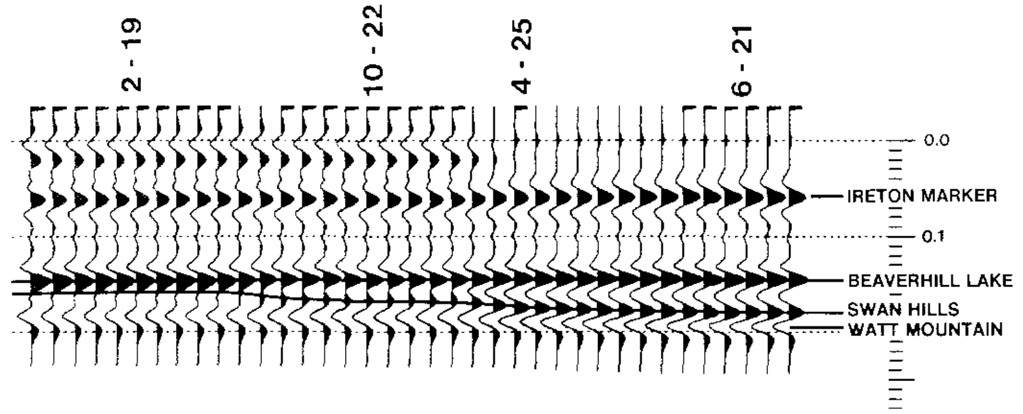

Figure 3.19 Stratigraphic seismic model of Snipe Lake field, filtered with a 30 ms zero-phase Ricker wavelet.

subtle increase in amplitude and modulation in frequency of the Beaverhill Lake event. Since the seismic signature transforms abruptly (between traces 274 and 280) the up-dip limit of the reef terrace can be identified.

The acoustic impedance contrast between low velocity Woodbend Group shales and the argillaceous limestone of the Waterways Fm generates a strong, coherent Beaverhill Lake reflection. Lateral amplitude variations of this event are attributed to the interference phenomena described above.

The calcareous Ireton marker and tops of Wabamun, Banff and Debolt formations are identified on the interpreted section. Regional dip is the primary structural feature of these horizons.

Absence of structural drape over the reef is apparent. Instead, the Beaverhill Lake event exhibits the contrary time-structure reversal across the main reef edge (between traces 200 and 212) conforming with a low relief time-structure on the deeper Muskeg event.

To support the interpretation, a seismic model was generated using sonic logs from the four wells in the geological cross-section. The stratigraphic, synthetic section (Fig. 3.19) comprises zero-offset, primary reflection coefficients convolved with a 30 ms, zero-phase Ricker wavelet. The seismic model represents the geological section from Ireton to Elk Point; Ireton marker, Beaverhill Lake, Swan Hills and Watt Mountain events are annotated.

The synthetic seismic section verifies the interpretation of the seismic image across Snipe Lake reef. Proximal thinning of the Beaverhill Lake to Swan Hills isochron is apparent accompanied by suppression in amplitude of the Swan Hills event. Resolution of a discrete Swan Hills reflection is denied as the Waterways Fm thins over the reef at 2-19. However, seismic waveform interference causes frequency modulation of the Beaverhill Lake reflection over the uppermost reef plateau.

HOUSE MOUNTAIN - SWAN HILLS "C" POOL

INTRODUCTION

The Swan Hills "C" pool of westcentral Alberta is located approximately 200 km northwest of Edmonton in Townships 68-70, Ranges 8-11 W5M (Fig. 3.1). Hydrocarbon production is from the House Mountain reef complex discovered in 1958. The "C" pool is the shallowest Swan Hills production at 2100 m approximate depth.

Stratigraphy of the Beaverhill Lake Group in the vicinity of House Mountain includes Fort Vermilion, Swan Hills and Waterways formations (Fig. 3.3). The Fort Vermilion Fm comprises approximately 10 m of interbedded anhydrite and dolomitic shale overlying Elk Point clastics. The overlying Swan Hills Fm is represented by approximately 25 m of the lower Dark Brown platform member, disconformably superposed by the argillaceous limestones and calcareous shales of the Waterways Fm. Sheasby (1971) informally divided the Beaverhill Lake Group, in the Swan Hills area, into eight major units on the basis of electric log correlations. Progressively younger units onlap the platform reef complex and in the current area of study units IV through VIII of the Waterways Fm (Sheasby, 1971) are present. Seismic significance of units IV, V, and VI to VIII, combined, will be discussed.

The fringing-reef complex comprising the Swan Hills "C" pool, developed along the northeastern margin of a promontory of the Swan Hills carbonate platform (Fig. 3.4). The organic barrier of the lower Swan Hills represents the final stage of reef growth in the House Mountain area. Sea level rise and the influx of terrigenous material of the Waterways Fm terminated carbonate production. Reef development continued to the south where isolated bioherms of the Swan Hills - Swan Hills South - Judy Creek reef chain were established on the salient (Fig. 3.4). The House Mountain

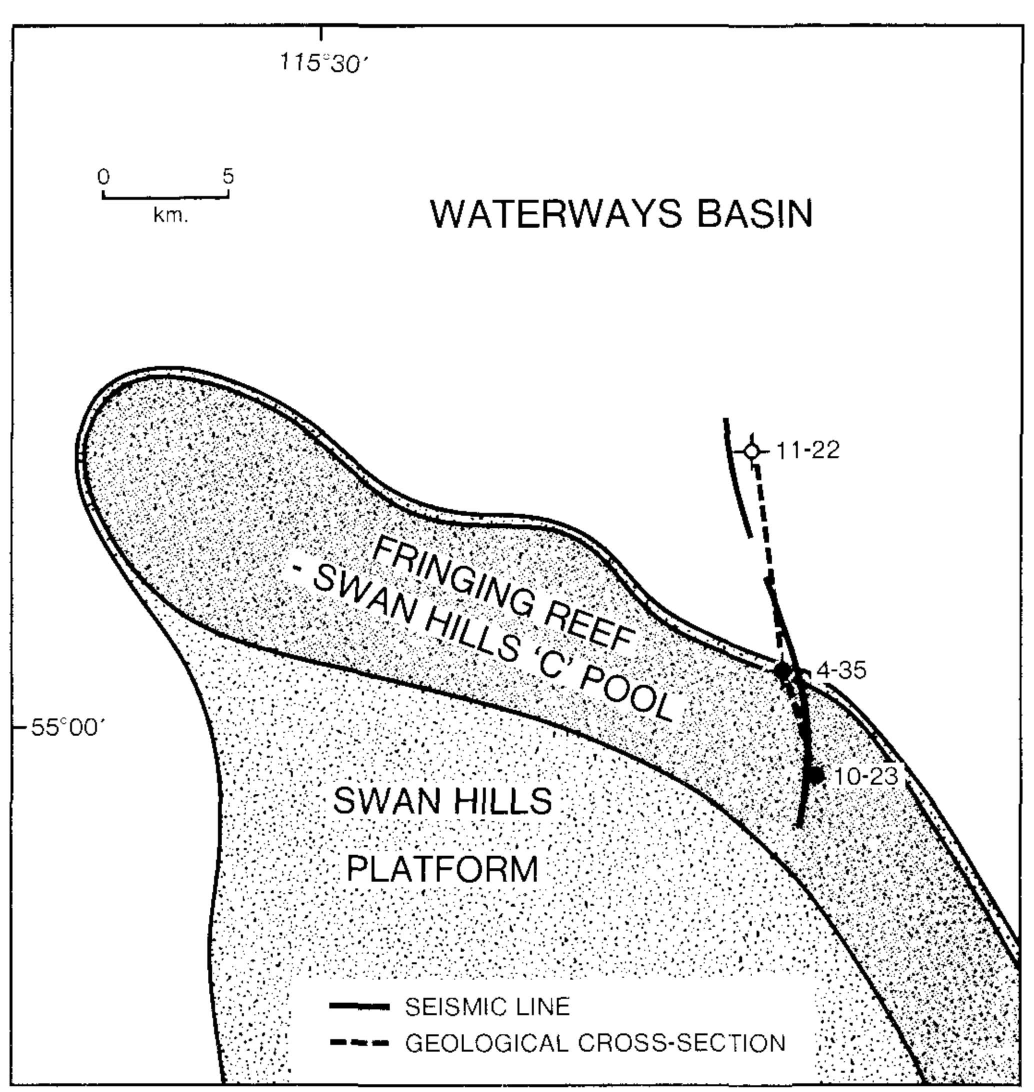

Figure 3.20 Schematic diagram of House Mountain – Swan Hills "C" pool, locating the seismic and geological cross-sections.

fringing-reef is an elongate feature trending northwest-southeast with approximate dimensions of 6 x 40 km. The "C" pool is unique amongst the major Swan Hills fields, since the porosity is developed within the lower Dark Brown platform member.

The productive area of the pool, confined by the tract of porous reservoir rather than regional dip constraints, is approximately 258 km^2. Porosity and net pay averages for the reservoir are 6.2% and 9.3 m, respectively. Estimated original volume of oil in place is 98,710 x 10^3 m^3 with 12,450 x 10^3 m^3 (primary) and 20,180 x 10^3 m^3 (secondary) recoverable reserves. Cumulative production to the end of December 1987 is 18,849.2 x 10^3 m^3 of 42° API gravity oil.

The seismic example across the field, orientated north-south, traverses the up-dip limit of the House Mountain reef-platform complex (Fig. 3.20). Argillaceous limestone of the Waterways Fm envelops the Swan Hills platform carbonate. A continuous seismic reflection, originating from atop the Waterways Fm carbonate unit IV, decreases in amplitude over the Swan Hills platform. The amplitude modulation is associated with waveform interference effects, generating a seismic doublet across the reef. The second lobe of the doublet waveform is the seismic manifestation of the Swan Hills platform.

GEOLOGICAL CROSS-SECTION

Orientation of the geological cross-section (Fig. 3.21) approximately parallels the seismic example as shown in Figure 3.20. The line of study extends, north to south, from the open-marine environment (11-22), across the Swan Hills platform edge (4-35) and onto the fringing-reef (10-23). Sonic - S.P. log suites are displayed for each well in the cross-section.

Clastic sediments of the Elk Point Group are the oldest rocks penetrated by the wells; the top of the Watt Mountain Fm being annotated on the section. The evaporitic Fort Vermilion Fm is consistent along the line of study, with an isopach of 9 m. Swan Hills platform limestones superpose the Fort Vermilion Fm in the 4-35 and 10-23 wells, where platform thickness increases from 12 m to 23 m, respectively. Swan Hills platform at House Mountain includes Divisions I to III of Fischbuch (1968). Sonic log response demonstrates the absence of an acoustic boundary between the anhydritic Fort Vermilion Fm and Swan Hills carbonates.

Basinal sediments of the Waterways Fm overlie the Swan Hills platform in the proximal wells and the Fort Vermilion Fm in the off-reef environment. The abrupt lateral facies change between carbonate platform and the argillaceous, open-marine sediments forms the stratigraphic trap. For the purpose of this study, the Waterways Fm is subdivided into three informal units corresponding to divisions IV, V and VI-VIII of Sheasby (1971). Unit IV was the first to transgress the House Mountain reef complex (Sheasby, 1971) and in the 4-35 and 11-23 wells this unit directly overlies the Swan Hills platform. Argillaceous limestone in contact with the platform carbonate is distinguished by its lack of S.P. development, due to shale content. Unit V is predominantly shale, becoming more

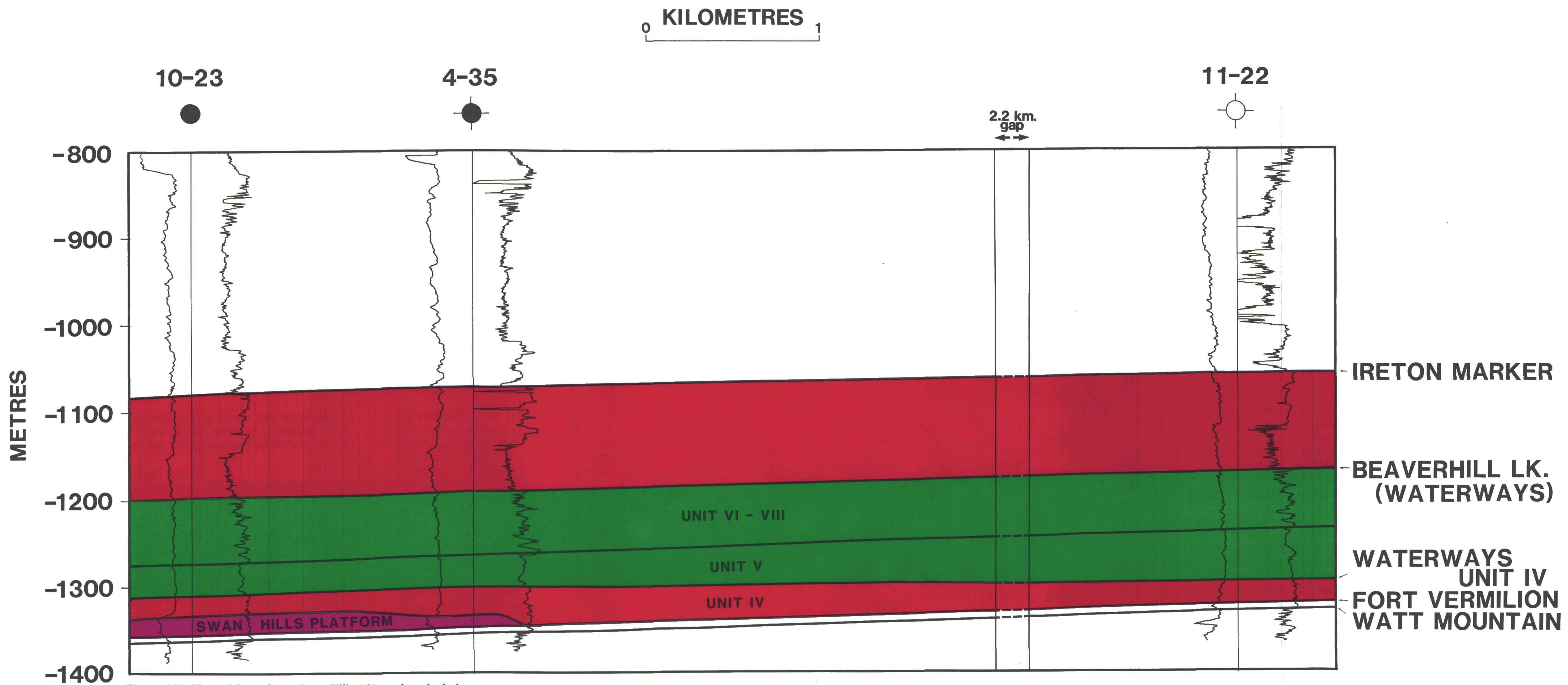

Figure 3.21 House Mountain – Swan Hills "C" pool geological cross-section, incorporating the seismic interpretation (facing page).

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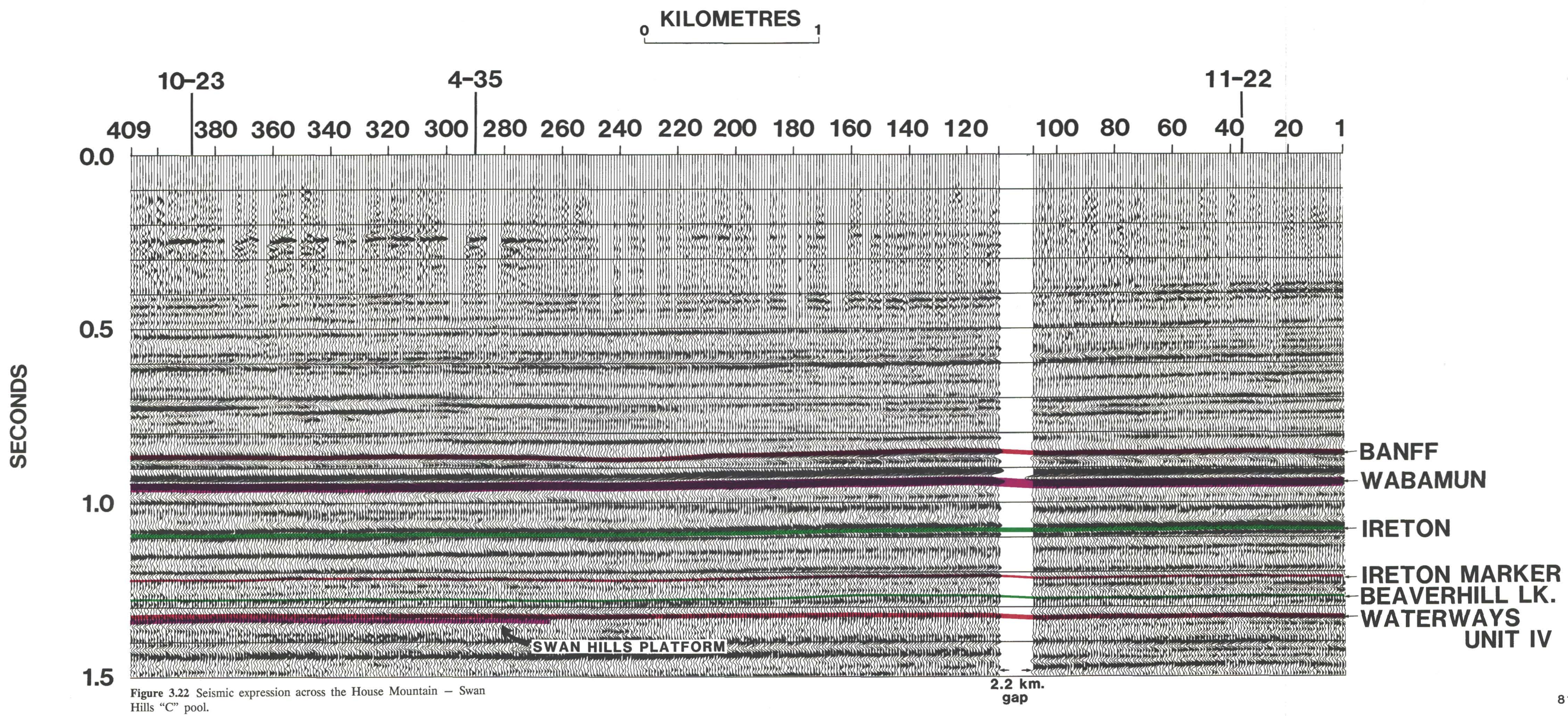

Figure 3.22 Seismic expression across the House Mountain – Swan Hills "C" pool.

DONOR: GEOTRADES, A DIVISION OF GRANT GEOPHYSICAL LTD. | PROCESSOR: STATCOM LTD. | AUTHOR: R.M. FERRY calcareous as it thickens in a basinward direction. The uppermost unit comprises interbedded argillaceous limestones and shales. The angular relationship between bedding of the Waterways Fm and the Swan Hills platform (Sheasby, 1971) is not apparent, due to orientation of the cross-section along depositional strike.

Overlying the Beaverhill Lake Group are impermeable shales and argillaceous limestones of the Duvernay and Ireton formations, Woodbend Group.

Lateral equivalence of the Swan Hills platform and the carbonate unit IV, of the Waterways Fm, precludes differential compaction across the reef edge. Absence of structural drape on the Beaverhill Lake and younger horizons is apparent. Regional dip is the principal structural feature of the cross-section.

Porosity in the 10-23 well is distributed throughout the reefal limestone of the platform. Cumulative production is 80.15 x 10^3 m^3 of 42° API oil from 7.5 m of net pay.

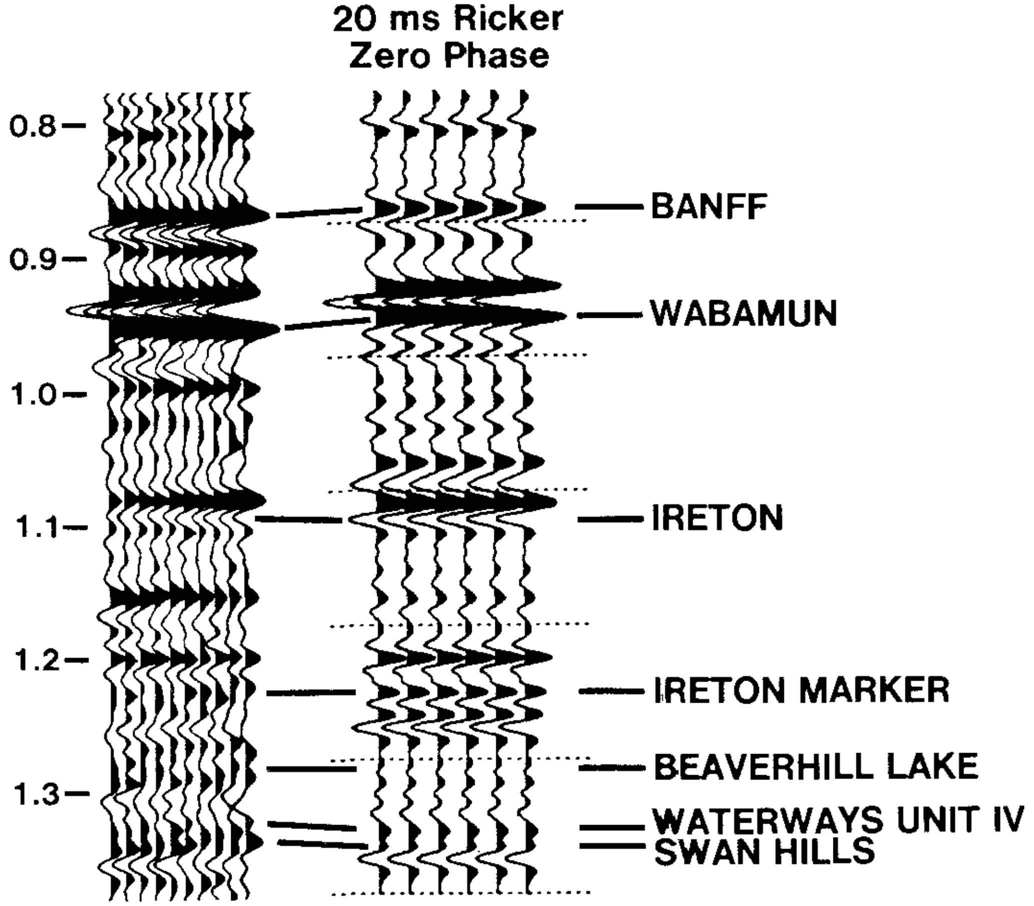

Figure 3.23 Correlation of seismic data (left) with a synthetic seismogram derived from the 10-23 sonic-log (House Mountain).

SEISMIC SECTION

The approximate location of the seismic template line is shown in Figure 3.20. These 1200% CDP Vibroseis data were acquired in 1983 using 8 x 12 second sweeps, 70-12-Hz, at 134-m source intervals. Data were recorded by 96 channels, over a 2 x 1675-m split spread, with 33.5-m group intervals. The line was reprocessed in 1987 using a conventional processing sequence, including spiking deconvolution and a final bandpass filter of 12/16 - 60/70 Hz. Full, 1200% CDP coverage is preserved at the extremities of the line.

Prominent geological horizons are identified on the structural stack (Fig. 3.22), with the Swan Hills zone of interest occurring at approximately 1.35 seconds 2-way time. A 2.2 km gap in the data exists along the northern portion of line, as indicated on the schematic of Figure 3.20. The discontinuity does not affect the seismic delineation of the Swan Hills platform edge.

Swan Hills platform carbonate is enveloped by the argillaceous limestone unit IV, of the Waterways Fm. Comparison of sonic log response of the Swan Hills and off-reef equivalent (Fig. 3.21) connotes an extremely subtle seismic response for the platform edge.

The deepest, continuous seismic event identified originates from the top of unit IV of the Waterways Fm. The acoustic interface between shales of unit V and the underlying carbonate of unit IV, generates the strong, coherent seismic event. Time-structural relief of this reflector is relatively flat, incongruous with regional slope exhibited by the younger Beaverhill Lake Group and Ireton marker events. Consequently, the Ireton marker to Waterways unit IV isochron thins by 12 ms, in a proximal sense, between the 11-22 and 10-23 well locations.

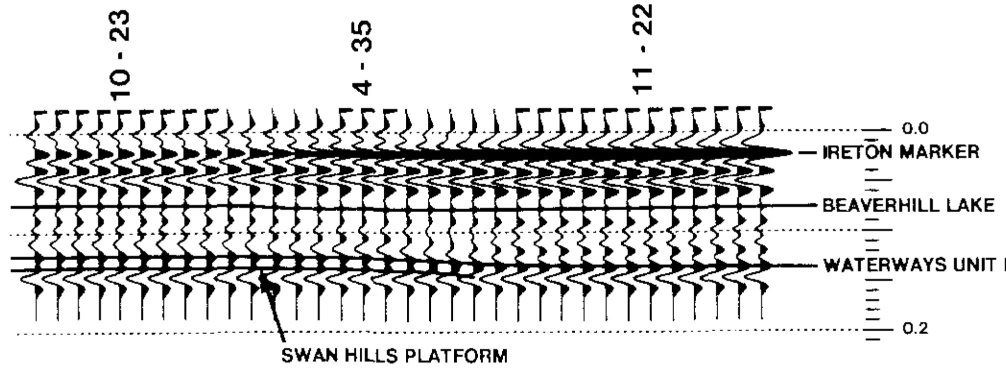

Figure 3.24 Stratigraphic seismic model of House Mountain – Swan Hills "C" pool, filtered with a 20 ms zero-phase Ricker wavelet.

In the reef environment, unit IV of the Waterways Fm directly overlies the Swan Hills platform, generating the seismic waveform doublet observed in the vicinity of the 4-35 and 10-23 wells. Correlation with the synthetic seismogram generated from the 10-23 sonic log, shown in Figure 3.23, expedites the interpretation. The reflection from unit IV decreases in amplitude over the reef and the second lobe of the doublet represents Swan Hills platform. Amplitude modulation of unit IV is attributed to destructive interference with the Swan Hills event. A doublet is formed due to the bandlimited nature of the seismic data.

Since seismic reflections depict chronostratigraphic horizons, unit IV of the Waterways Fm is, intrinsically, a time unit. It follows that sediments of the Waterways Fm must be significantly younger than the Swan Hills reef-platform complex. The corollary of the seismic interpretation is consistent with the conclusions of Sheasby's (1971) geological study.

The seismic event from the top of the Beaverhill Lake is poorly defined, due to destructive interference effects of the interbedded carbonates and shales of the uppermost Waterways units (VI-VIII). The calcareous Ireton marker and tops of Ireton, Wabamun and Banff formations are annotated on the interpreted seismic section. Time-structural relief along these events is attributed to regional tilting of the sedimentary section.

A seismic model was generated, to support the interpretation, using sonic logs from the three wells in the geological cross-section. The stratigraphic synthetic section (Fig. 3.24) comprises zero-offset, primary reflection coefficients convolved with a 20 ms, zero-phase Ricker wavelet. The seismic model includes the geological section from lower Ireton to Elk Point; Ireton marker, Beaverhill Lake, Waterways unit IV and Swan Hills events are identified.

The synthetic seismic section reaffirms the geological significance of the seismic image observed across the House Mountain reef-platform complex. Encountering Swan Hills platform, the reduced amplitude of the Waterways unit IV event is apparent, together with the associated appearance of a waveform doublet. The second lobe of the doublet is the seismic manifestation of the Swan Hills platform. Proximal thinning of the Ireton marker to Waterways unit IV isochron is also evident.

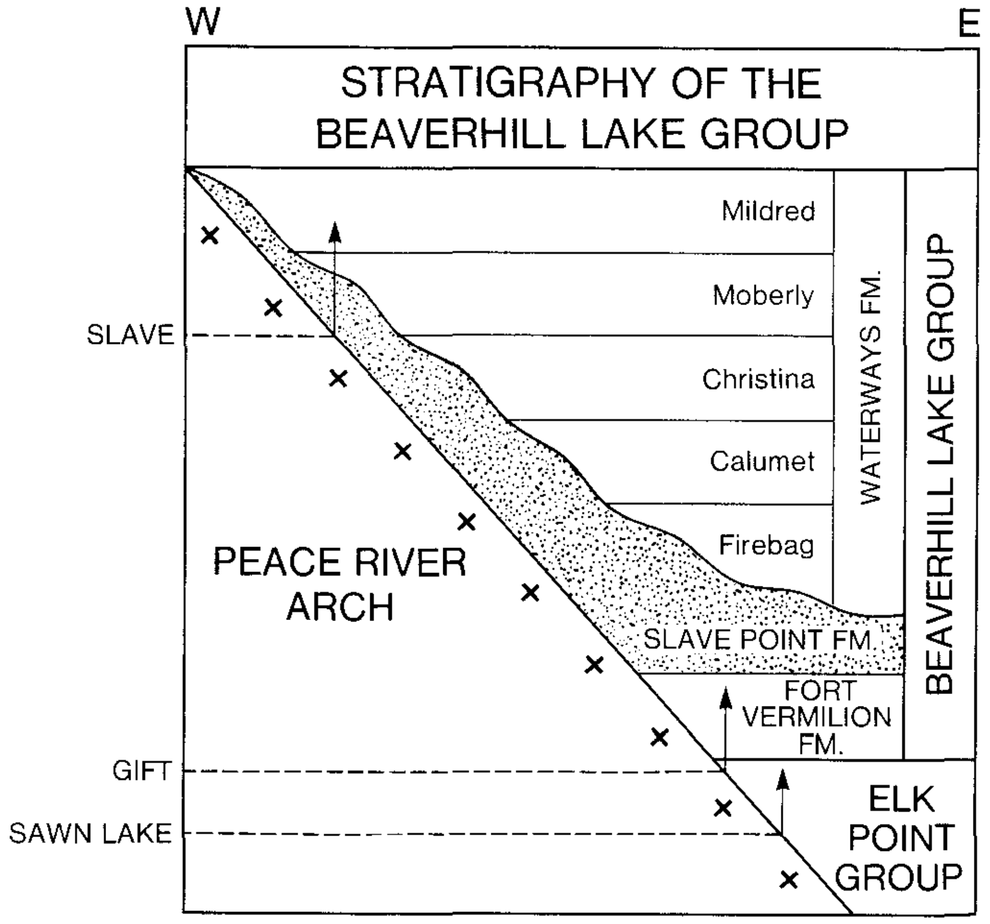

Figure 3.25 Stratigraphy of the Beaverhill Lake Group, Peace River Arch region; locating Slave, Gift and Sawn Lake fields.

GIFT FIELD

INTRODUCTION

Gift field of northcentral Alberta is located approximately 300km northwest of Edmonton in Townships 78-79, Ranges 10-11 W5M (Fig. 3.1) and is contiguous with the southwest extremity of Utikuma Lake. Hydrocarbon production is obtained from three distinct zones, the Slave Point Fm, Gilwood Fm and Granite Wash. The Gilwood oil discovery well, HB et al Kyle 10-1-79-11 W5M, was completed in November 1980 but Slave Point potential was not exploited until January 1983 when Natomas et al Nipisi 10-32-78-10 W5M was production tested. The well flowed 24.5 m^3/day of 35 API oil from a 4.5 m perforated interval of the Slave Point Fm. Cumulative production for the well is in excess of 28.44 x 10^3 m^3. Since the initial discovery, a total of 46 wells have been drilled into the Slave Point pool.

In the area of study, the Beaverhill Lake Group comprises Fort Vermilion, Slave Point and Waterways formations (Fig. 3.25). The stratigraphic chart illustrates the time transgressive nature of the Slave Point Fm as sediments of the Beaverhill Lake Group transgress the Peace River Arch. Slave Point sedimentation at Gift field is stratigraphically equivalent to the Firebag Mbr of the Waterways Fm (Fig. 3.25). A relatively thin (8 m), evaporitic Fort Vermilion Fm is overlain by 25 m of Slave Point Fm limestone platform. The comparatively thick sequence of argillaceous limestones and shales of the Waterways Fm completes the Beaverhill Lake stratigraphy. The Waterways Fm is subdivided into the Firebag (shale), Calumet (carbonate), Christina (shale), Moberly (carbonate) and Mildred (interbedded shale-carbonate) members.

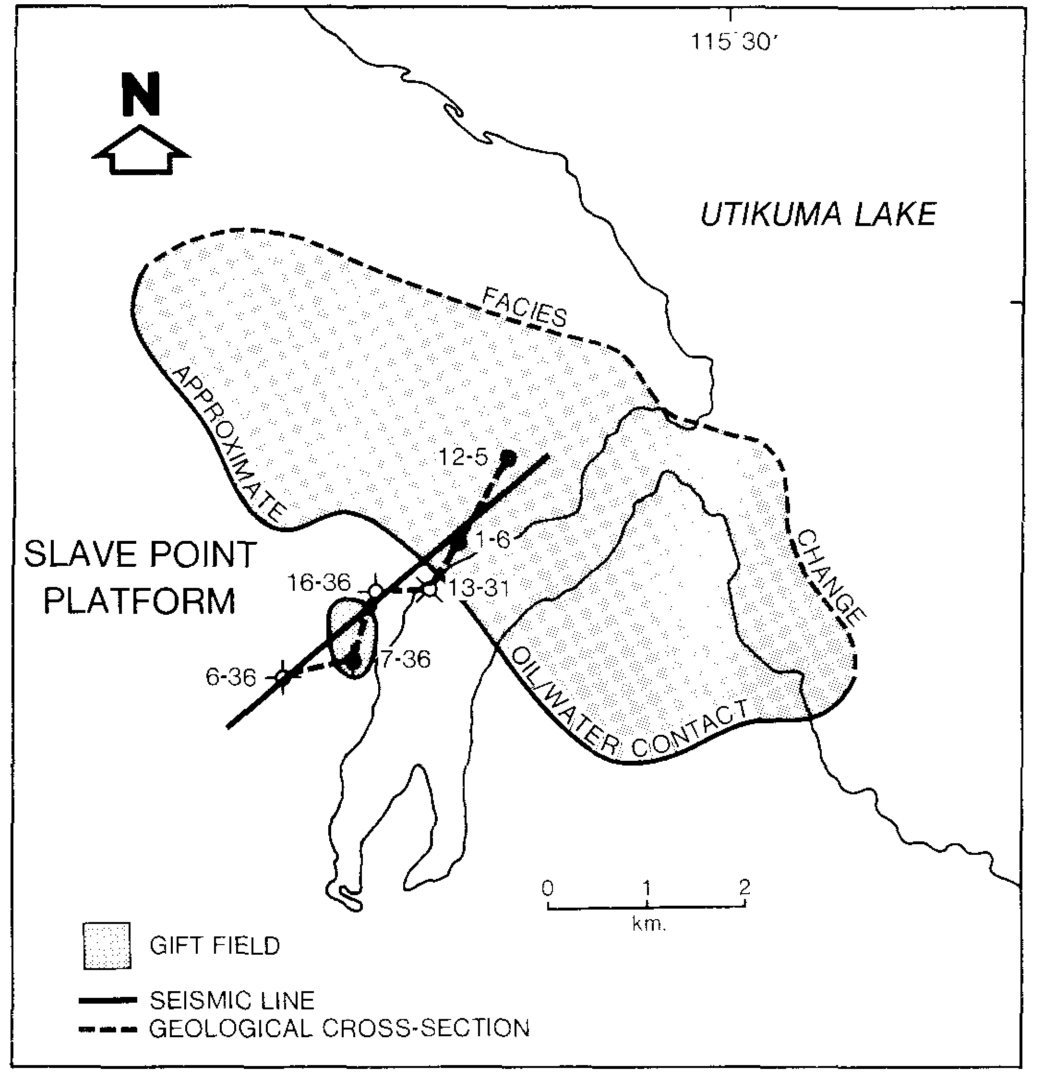

Figure 3.26 Schematic diagram of Gift field, locating the seismic and geological cross-section.

In the Gift area, shallow water carbonates of the Slave Point Fm were deposited as the Beaverhill Lake sea transgressed the eastern flank of the Peace River Arch. Precambrian basement topography appears to have influenced the Slave Point facies distribution with carbonate reef reservoir developing in the vicinity of a major basement structure. A facies change from fore-reef to distal fore-reef (Tooth and Davies, 1987) provides the updip, stratigraphic seal for the reservoir. Slave Point Fm lithofacies in the Gift field area are described in detail by Tooth and Davies (1987). Hydrocarbon distribution is confined by Slave Point structure to an area of approximately 20 km^2. Porosity and net pay averages for the reservoir are 8.4% and 8.5 m, respectively. Estimated original volume of oil in place is 11,360 x 10^3 m^3, with 1104.3 x 10^3 m^3 (primary) and 959 x 10^3 m^3 (secondary) recoverable reserves. Cumulative production to the end of December 1987 is 346 x 10^3 m^3 of 35° API gravity oil from the Slave Point pools. Gilwood and Granite Wash pools augment the above reserves and production figures.

The seismic template line, orientated northeast-southwest, straddles the southwest boundary of Gift field (Fig. 3.26). The line of study crosses a small, isolated, basement feature before encountering the main Precambrian structure controlling the field. Seismic time-structure on the Precambrian event images the erratic topography of the granitic basement. The steep scarps of a basement depression are apparent, bounding Gift field to the southwest. Compaction-induced drape on the Slave Point carbonate reservoir is manifested as time-structure on the Slave Point event. This event is relatively weak because Slave Point porosity, ubiquitous along the line of study, decreases the acoustic impedance contrast between the overlying shales and Slave Point carbonate. Although the seismic example does not transect the up-dip facies change (Fig. 3.26), a logical inferrence would be an increase in amplitude of the Slave Point event as the tight carbonate is encountered.

GEOLOGICAL CROSS-SECTION

The approximate locations of the geological cross-section and accompanying seismic example are shown in Figure 3.26. Crossing the southwest boundary of the field, the section includes six wells to illustrate the extremely erratic topography on the Precambrian basement (Fig. 3.27). Sonic- gamma ray log suites are displayed for each well location.

Precambrian basement rocks are penetrated by all wells, excepting 13-31, for which basement structure is inferred from the seismic interpretation. Paleotopography of the Precambrian surface influenced Granite Wash sedimentation, demonstrated by the 50 m of basal clastics encountered in the depression (16-36) compared with 8 -10 m overlying Precambrian highs (12-5, 1-6 and 7-36).

The Elk Point Group is represented by an evaporitic Muskeg Fm overlain by Gilwood clastics. Gift field straddles the depositional edge of the Muskeg Fm, and the northeast end of geological cross-section approaches the Muskeg Fm zero edge. Associated regional thinning of the Elk Point sequence is apparent. Platform carbonates of the Slave Point Fm overlie the Gilwood Mbr. For the purpose of this study, Fort Vermilion sediments are included in the Slave Point Fm since the thin (8 m), anhydritic unit is acoustically unresolved.

Precambrian influence on Slave Point deposition is manifested by an additional few metres of carbonate encountered over the basement depression, indicating differential compaction on the Fort Vermilion paleosurface. Basinal sediments of the Waterways Fm

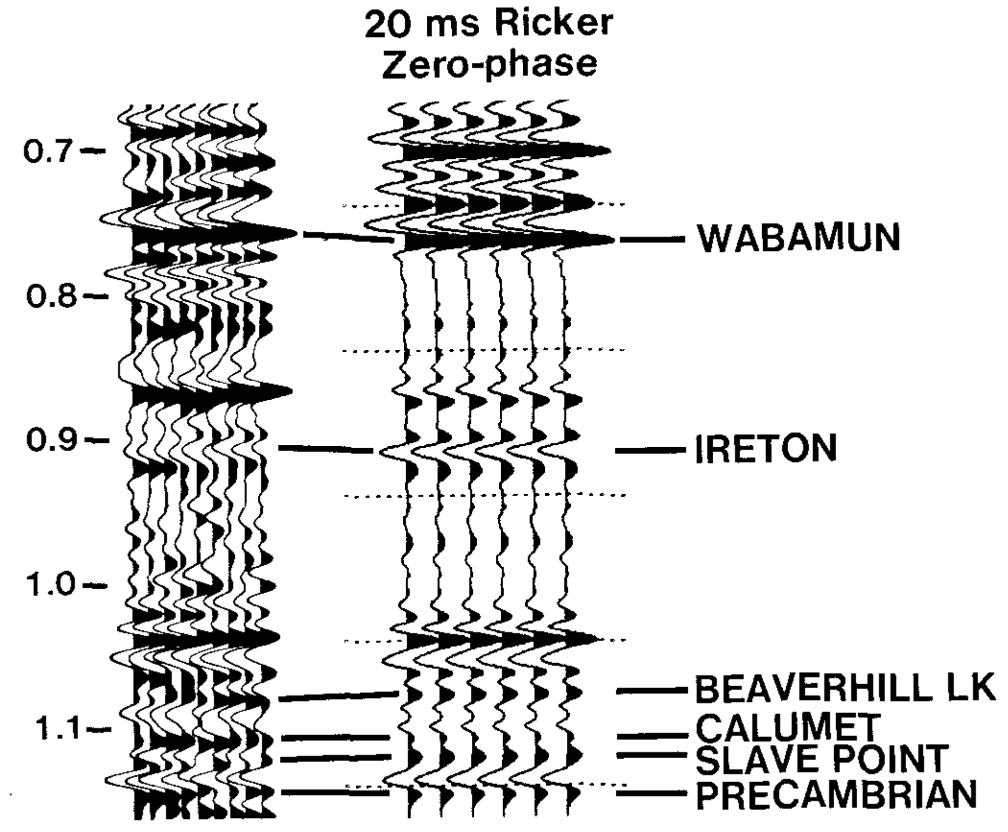

Figure 3.29 Correlation of seismic data (left) with a synthetic seismogram derived from the 7-36 sonic-log (Gift).

overlie the Slave Point carbonate facies. The uniform sequence of argillaceous limestones and shales represents the continued transgression of the Beaverhill Lake sea.

Effects of differential compaction on the sedimentary sequence are apparent throughout the Beaverhill Lake Group and into the shales of the Ireton Fm. Structural drape on the Slave Point horizon is of particular interest with 17 m of relief between the 1-6 and 13-31 wells. Hydrocarbon production is confined to the Slave Point structure encountered by the 1-6 and 12-5 wells. Porosity development in the upper 16 m of Slave Point limestone is ubiquitous along the line of study, but an up-dip facies change within the limestone provides a stratigraphic seal for the reservoir. This stratigraphic boundary is not transected by the seismic example and, therefore, not included in the geological cross-section.

Cumulative production since 1984, from the Slave Point reservoir at 12-5 and 1-6 is 15.38 x 10^3m^3 from 11 m net pay and 10.11 x 10^3m^3 from 9 m net pay, respectively. Both wells are dual zone producers augmenting the total production.

SEISMIC SECTION

Approximate location of the seismic template line is shown schematically in Figure 3.26. These 1200% CDP seismic data were acquired in 1984 using a 1 kg dynamite source, 120 recording channels over a 2 x 1500-m split spread, 125-m source intervals and 25-m group intervals. The line was reprocessed in 1987 following a conventional processing sequence, including spiking deconvolution and a final bandpass filter of 12/16 - 70/80-Hz. Full, 1200% CDP coverage is maintained at the extremities of the line.

Major geological horizons are annotated on the interpreted data (Fig. 3.28), with the Slave Point zone of interest occurring at approximately 1.10 seconds 2-way time. Correlation with the synthetic seismogram generated from the 6-36 sonic log is shown in Figure 3.29.

The acoustic and Precambrian basements are coincident, due to the presence of low velocity, Granite Wash sediments overlying the Precambrian surface. Thinning of Granite Wash over basement structures is manifested by a decrease in amplitude of the Precambrian reflection. Erratic time-structure on the basement event images the Precambrian surface as depicted on the accompanying geological cross-section. The southwest flank of the structure encountered at 7-36 has a relatively gradual slope of 80 m/km (8%

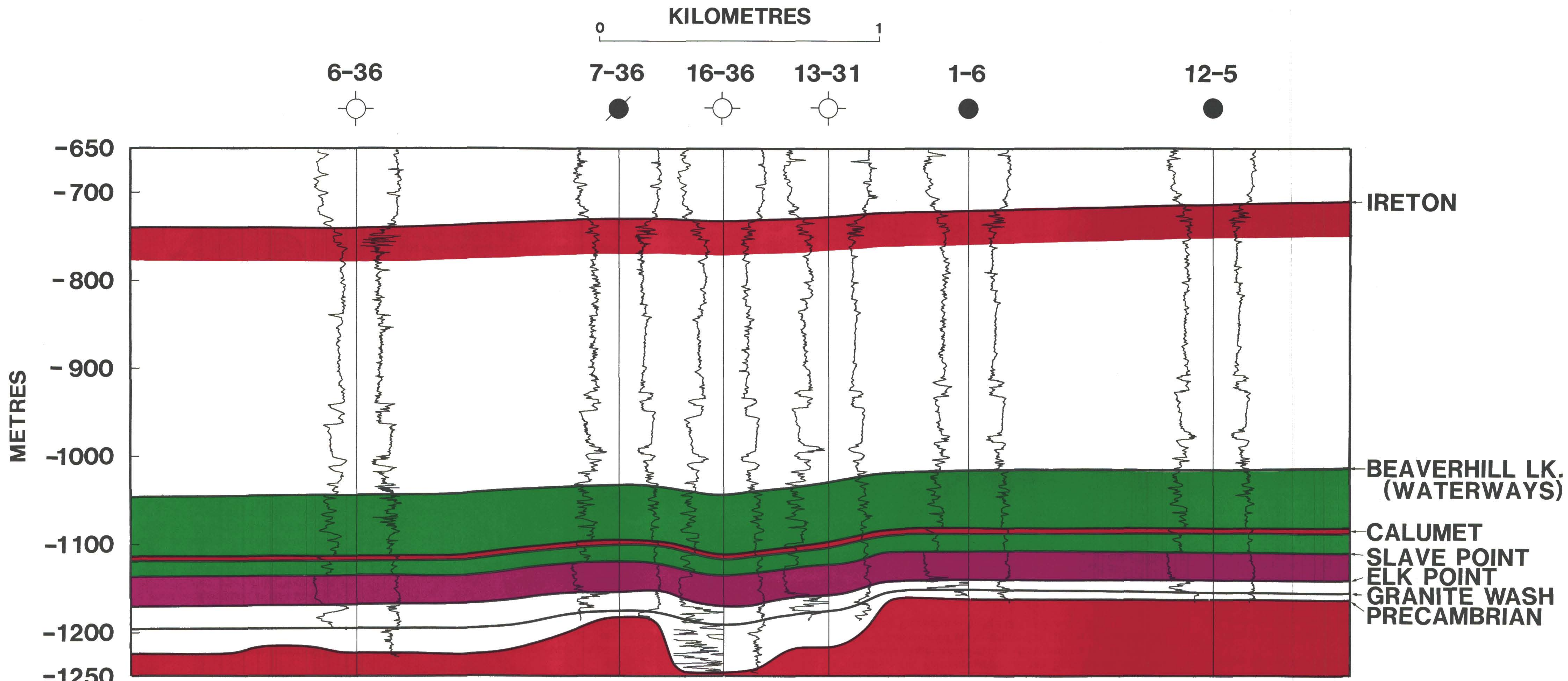

Figure 3.27 Gift field geological cross-section, incorporating the seismic interpretation (facing page).

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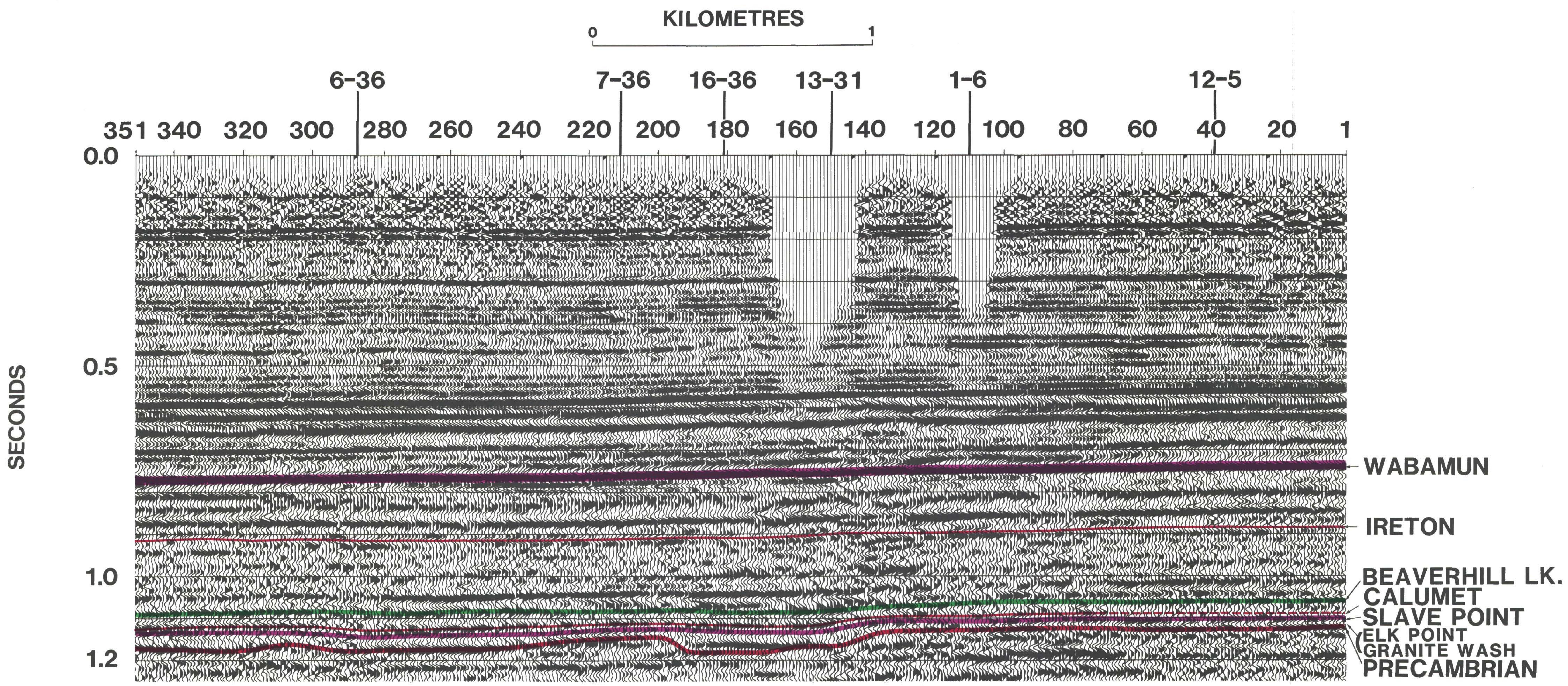

Figure 3.28 Seismic expression across Gift field.

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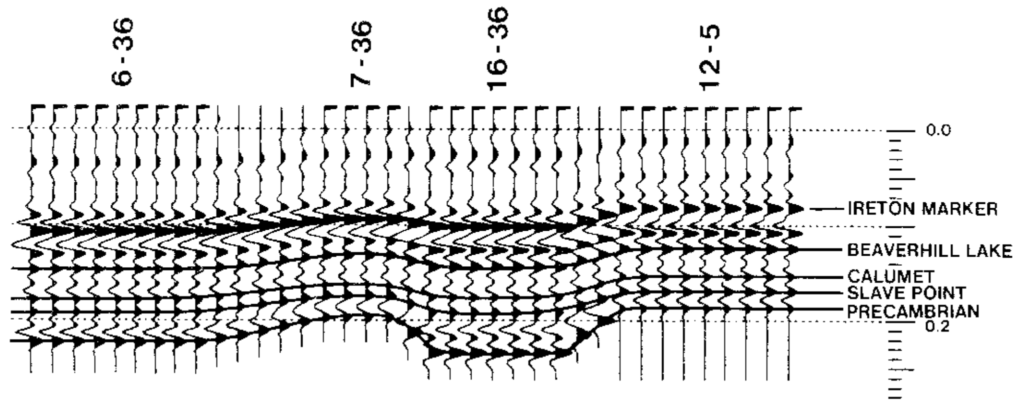

Figure 3.30 Vertical incidence seismic model of Gift field, filtered with a 20 ms zero-phase Ricker wavelet.

gradient) compared with the abrupt scarp on the up-dip side. Approximately 60 m of vertical relief exists between the 7-36 and 16-36 wells. Converting the Slave Point to Precambrian isochron at 13-31 to an isopach, vertical relief of the counterscarp of the depression is estimated at 50 m.

Limestone porosity at the top of the Slave Point Fm decreases the acoustic impedance contrast between Firebag Mbr shales and Slave Point Fm carbonates, generating a weak, but discernable, seismic event. Although the seismic example does not transect the updip Slave Point facies change (Fig. 3.26), an increase in amplitude of the Slave Point event would be anticipated as the tight carbonate is encountered. One cycle (18 ms) above the Slave Point reflection, the Calumet Mbr of the Waterways Fm is resolved. Coherency of the peak diminishes towards the northeast extremity of the line. Seismic events from the top of the Beaverhill Lake Group, Ireton and Wabamun formations are also annotated on the structural section.

Time-structure on the Slave Point event and younger Beaverhill Lake Group markers reflects the underlying Precambrian topography. Compaction of thick Granite Wash sediment, deposited in basement depressions, induced the topographic relief on the younger horizons. Hydrocarbon distribution is influenced by structural drape on the Slave Point reservoir. Gift field is confined to an area of high relief and drape on the Slave Point event, between the 1-6 and 13-31 wells, delineates the southwest boundary of the field. Compaction-induced structures and regional tilting of the sedimentary section are superimposed on the deeper seismic events. The effects of regional dip, minus the local structures, can be observed on the Ireton and Wabamun events.

To assist and corroborate the interpretation, a seismic model was generated using sonic logs from four wells in the geological cross-section; 12-5, 16-36, 7-36 and 6-36. The wells represent the major structural features along the line of study. The synthetic seismic section (Fig. 3.30) comprises zero-offset, primary reflection coefficients convolved with a 20 ms, zero-phase Ricker wavelet. The model incorporates the stratigraphy from lower Ireton to Precambrian basement; Ireton marker, Beaverhill Lake, Calumet, Slave Point and Precambrian events are identified.

Although vertical incidence modeling results in a crude image of the steeper slopes, structural features of the seismic model are consistent with the previously described interpretation. The amplitude decrease of the Precambrian event, associated with topographic highs, is also substantiated by the model.

SLAVE FIELD

INTRODUCTION

Slave field of northcentral Alberta is situated on the east flank of the Peace River Arch, approximately 340 km northwest of Edmonton, in Township 84, Range 14 W5M (Fig. 3.1). Hydrocarbon production is from the Slave Point Fm of the Beaverhill Lake Group, at 1750 m average depth. The discovery well, CDCOG Union Slave 16-15-84-14 W5M, was completed in December 1980 with initial potential flow of 81 m^3/day of 35° API gravity oil. To date, the well has produced in excess of 46.65 x 10^3 m^3 from 13 m of net pay.

In the area of study, the Beaverhill Lake Group comprises Slave Point and Waterways formations (Fig. 3.25). The stratigraphic chart illustrates the diachronous nature of the Slave Point Fm as sediments of the Beaverhill Lake Group transgress the Peace River Arch. Slave

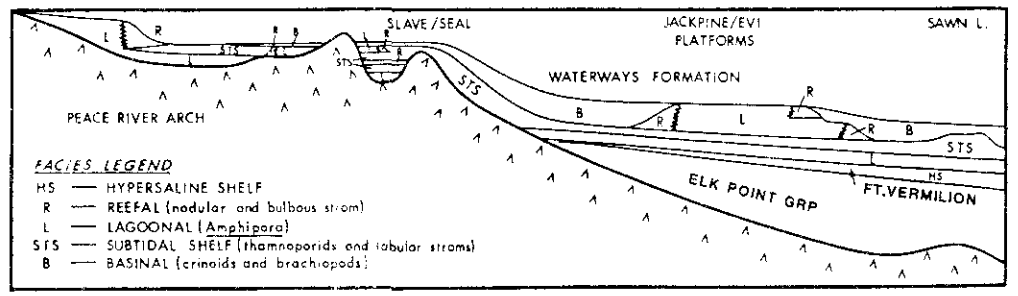

Figure 3.31. Schematic representation of Slave Point facies surrounding the Peace River Arch (after Craig, 1987).

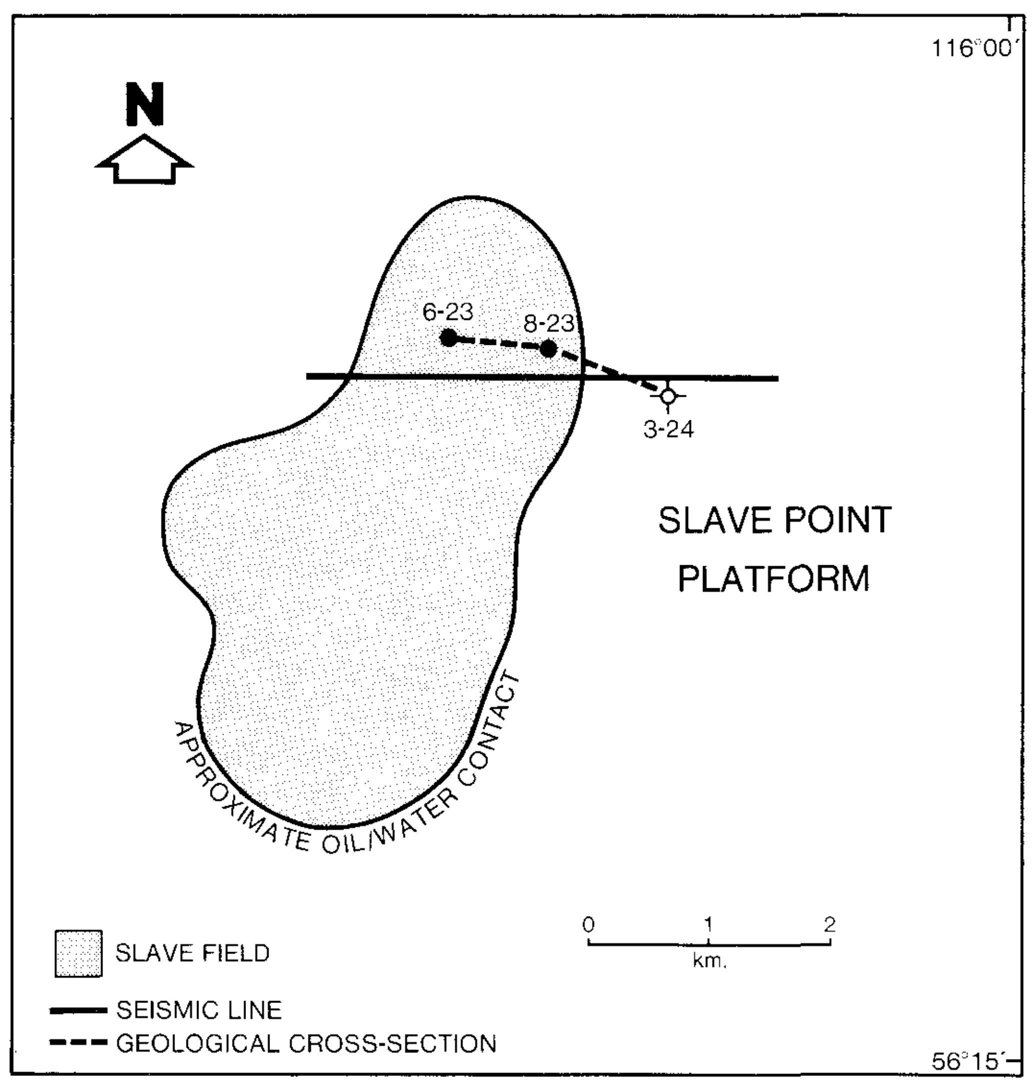

Figure 3.32 Schematic diagram of Slave field, locating the seismic and geological cross-sections.

Point sedimentation at Slave field appears to be stratigraphically equivalent to the upper part of the Waterways Fm, as indicated in Figure 3.25. Precambrian basement topography controls the abrupt changes in thickness of both Granite Wash clastics and Slave Point Fm carbonates. Overlying shales of the Waterways Fm are more uniform (15 - 30 m), with variations in thickness attributed to basement topography and the encroaching carbonate deposition of the Slave Point facies.

The depositional environment of the Slave Point Fm at Slave field is illustrated schematically in Fig. 3.31 (after Craig, 1987). Slave field comprises shallow water carbonates of the Slave Point Fm, surrounding a localized basement high on the eastern flank of the Peace River Arch. Dunham et al. (1983) demonstrated that relative sea level rise resulted in the upward growth of a carbonate bank, fringing the granite knolls. Continued sea level rise and the influx of terrigenous clastics of the Waterways Fm, terminated carbonate production in the area.

Porosity of the carbonate reservoir, enhanced by dolomitization, averages 8.5%, with an average net pay of 8.3 m. Trapping is structurally controlled and the productive area of the field is approximately 9 km^2. Estimated original volume of oil in place is 12,308.3 x 10^3 m^3, with 3498.5 x 10^3 m^3 of primary recoverable reserves. Cumulative production to the end of December 1987 is 895.8 x 10^3 m^3 of 35° API gravity oil from the Slave Point pools.

The seismic template line, orientated east-west, crosses the northern part of the basement structure controlling Slave field (Fig. 3.32). A weak reflection from the Precambrian surface is restricted to areas of low relief, where thick Granite Wash clastics exist, Slave Point sediments represent acoustic basement over the granite knoll. The field boundary is manifested by time-structural relief of the Slave Point and Beaverhill Lake reflections. These events form a doublet waveform over the highest part of the basement knoll, due to thinning of the Waterways Fm beyond the resolution limit of the seismic bandwidth.

GEOLOGICAL CROSS-SECTION

Orientation of the geological cross-section (Fig. 3.33) approximately parallels the seismic example, as shown in Figure 3.32. The cross-section extends, east to west, from shallow marine environment (3-24), across the northeast flank of the structure (8-23) and onto the basement knoll (6-23). Sonic- gamma ray log suites are displayed for each well in the section.

Precambrian basement rocks, penetrated by each well, exhibit 68 m of structural relief between the 6-23 and 3-24 well locations. Basement relief at the extremities of the cross-section is inferred from the seismic interpretation. Precambrian topography influenced deposition of the Granite Wash clastic sediments, encountered in the 3-24 well (10 m) and 8-23 location (3 m). The Precambrian knoll also affected carbonate sedimentation during the subsequent Beaverhill Lake transgression. The 6-23 well, devoid of Granite Wash, encountered 8 m of Slave Point Fm carbonate overlying the granitic basement. Thickness of the dolomitized carbonate facies increases to 20 m in the 8-23 flank location and 30 m in the more distal environment of 3-24.

A significant acoustic boundary between the Granite Wash clastics and Precambrian basement is apparent from the sonic log response of 3-24. In this location, the geologic and acoustic basements are coincident. However, absence of this sonic interface in the other wells alludes to the Slave Point horizon as representing acoustic basement.

The overlying calcareous shales of the Waterways Fm represent the final inundation of the basement knoll and surrounding carbonate bank. Waterways Fm sediments increase in thickness from 25 m over the structural high at 6-23, to 37 m in the other wells. The thicker Waterways Fm west of the well control is inferred from the seismic interpretation. Thinning of the shale facies over the granitic hill is attributed to the progressive onlap of the time transgressive carbonate facies of the Beaverhill Lake Group. The upper part of the Slave Point Fm in the 8-23 and 3-24 wells is stratigraphically equivalent to the Moberly Mbr of the Waterways Fm (Fig. 3.25); whereas, Slave Point carbonate on the basement knoll, at 6-23, encroaches on the Mildred Mbr.

The Beaverhill Lake Group is overlain by shales of the Duvernay and Ireton formations which are superposed by the more calcareous sediments of the Winterburn Group and Wabamun Fm.

The structural trapping mechanism of Slave field is apparent with the Slave Point horizon exhibiting 36 m of structure reversal along the cross-section. Existence of steep slopes on the Slave Point and Beaverhill Lake horizons, concurrent with an underlying basement scarp, is inferred from the seismic interpretation. Beaverhill Lake topographic relief is attributed to post-Beaverhill Lake tectonics and differential compaction across the basement scarp. The tectonic influence is inferred by the extent of structural deformation. Structural drape, of lesser degree, is apparent on the shallower Ireton horizon.

Porosity of the Slave Point carbonate facies at Slave field is enhanced by dolomitization. Cumulative oil production and net pay thickness for the 6-23 and 8-23 wells are 36.48 x 10^3 m^3 (8 m) and 31.20 x 10^3 m^3 (6 m), respectively.

SEISMIC SECTION

The approximate location of the seismic template line is shown schematically in Figure 3.32. These 1200% CDP seismic data were acquired in 1984 using a 1 kg dynamite source, 96 recording channels over 2 x 1608 m split spread, 134 m source intervals and 33.5 m

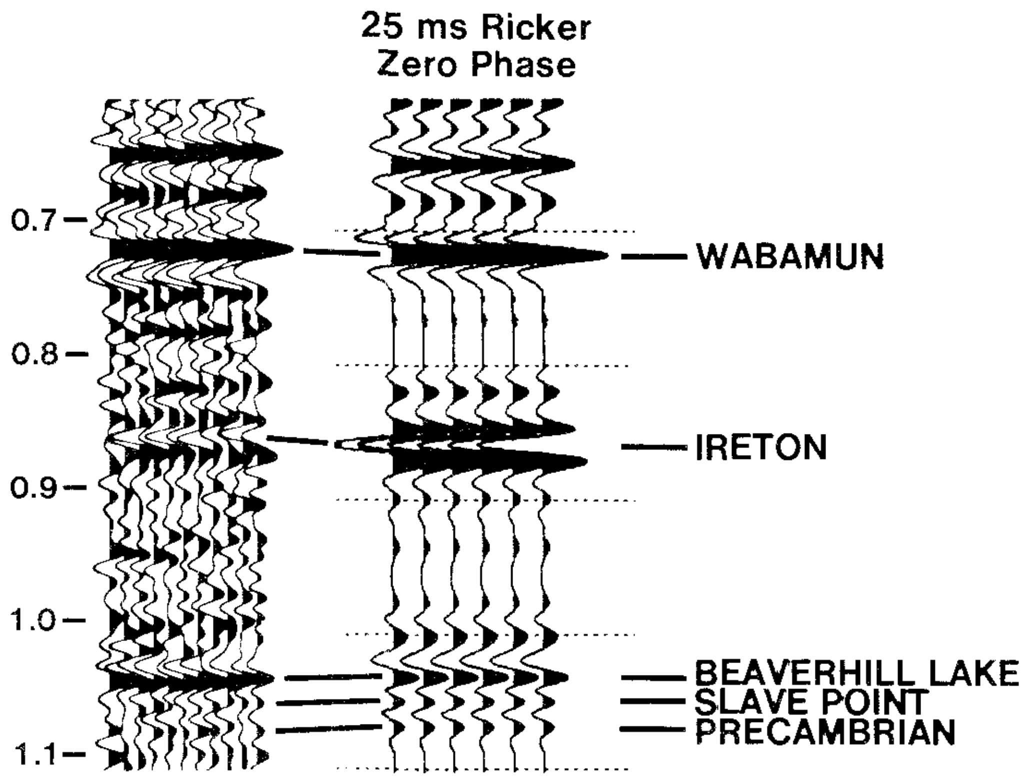

Figure 3.35 Correlation of seismic data (left) with a synthetic seismogram derived from the 3-24 sonic-log (Slave).

group intervals. The line was reprocessed in 1987 following a conventional processing sequence, including spiking deconvolution and a final bandpass filter of 12/16 - 70/80 Hz. Full, 1200% CDP coverage is preserved at the extremities of the line.

Salient geological horizons are identified on the structural stack (Fig. 3.34) with the Beaverhill Lake zone of interest occurring at approximately 1.05 seconds 2-way time.

The deepest, continuous seismic event identified, originates from the top of the Beaverhill Lake Group. The acoustic interface between low velocity shales of the Woodbend Group and the more calcareous Waterways Fm sediments generates a strong, coherent seismic event. Slave field is manifested by approximately 15 ms of time-structural relief on the Beaverhill Lake reflection; time-structure over the field is relatively static with steep slopes occurring on the flanks of the feature. Structural relief between the 6-23 and 8-23 wells, as depicted on the geological cross-section, is not apparent on the accompanying seismic section. In an area of extremely variable topography, the discrepancy is attributed to projecting the 6-23 well onto the seismic section from 400 m off-line.

Acoustic energy below the Beaverhill Lake event is relatively weak but correlation with the synthetic seismic trace at 3-24 (Fig. 3.35) permits identification of Slave Point and Precambrian events. A weak reflection from the Precambrian surface is restricted to areas of low relief, where a thicker section of Granite Wash clastics provides the necessary acoustic boundary. Over the Slave field basement knoll, Granite Wash is virtually absent and the Slave Point reflection represents acoustic basement. A coherent, albeit weak, event from the Slave Point horizon can be correlated across much of the section. At the 8-23 and 3-24 well locations, thickness of Waterways Fm shale and frequency content of the data are such that a temporally discrete, Slave Point event is resolved. However, on the basement structure immediately west of 8-23, the Beaverhill Lake and Slave Point events form a seismic doublet. The doublet waveform continues westward to the projected location of the 6-23 well. Assuming a constant seismic bandwidth, the above phenomenon infers a thinning of the Waterways Fm which, in turn, implies a structurally higher basement. Thus, although the Precambrian surface underlying Slave field is not seismically resolved, characteristics of the acoustic basement event suggest the highest part of the Precambrian knoll exists between the 8-23 and 6-23 projected locations. West of the structure, a thicker section of Waterways Fm shales is inferred from the broader time cycle from Beaverhill Lake to Slave Point, occurring between traces 172 and 211.

To the east of 8-23, a basement scarp is inferred by the abrupt termination of the Precambrian reflection and accompanying steep slopes on the overlying Slave Point and Beaverhill Lake events. The opposite flank of the structure is similarly steep.

Reflections from the top of the Ireton and Wabamun formations are annotated on the seismic section. Both events exhibit relatively constant time-structure, excepting some minor drape on the Ireton reflection over Slave field.

To assist and corroborate the interpretation, a seismic model was generated using sonic logs from the three wells in the geological cross-section. For simplicity, a model symmetrical about the 6-23 well was constructed by repeating the 8-23 and 3-24 logs on the opposite side. The synthetic seismic section (Fig. 3.36) comprises zero-offset, primary reflection coefficients convolved with a 25 ms, zero-phase Ricker wavelet. The model incorporates the stratigraphy from lower Winterburn to Precambrian basement; Ireton, Beaverhill Lake, Slave Point and Precambrian events are identified.

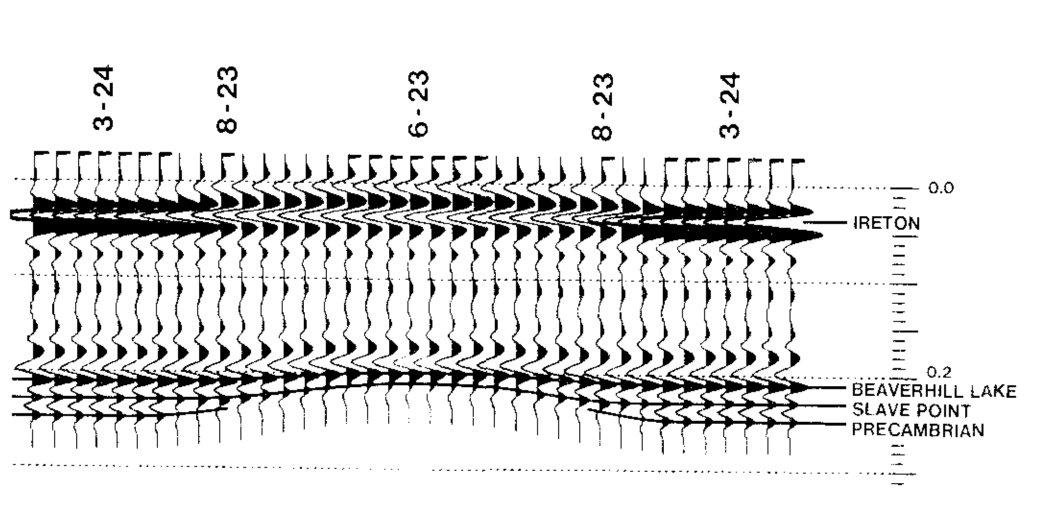

Figure 3.36 Vertical incidence seismic model of Slave field, filtered with a 25 ms zero-phase Ricker wavelet.

Structural features of the seismic model and associated waveform characteristics are consistent with the previously described interpretation. Structure on the Beaverhill Lake and Slave Point reflections over the basement high, and related termination of the Precambrian event are both apparent. The discrete Slave Point reflection at the 8-23 location, representing acoustic basement, eventually forms a doublet with the Beaverhill Lake event as Precambrian relief increases (6-23). Thinning of the Waterways Fm shales over the structure, combined with the bandlimited nature of the seismic data, account for the loss of resolution. Subtle structural drape on the Ireton event is also expressed on the synthetic section.

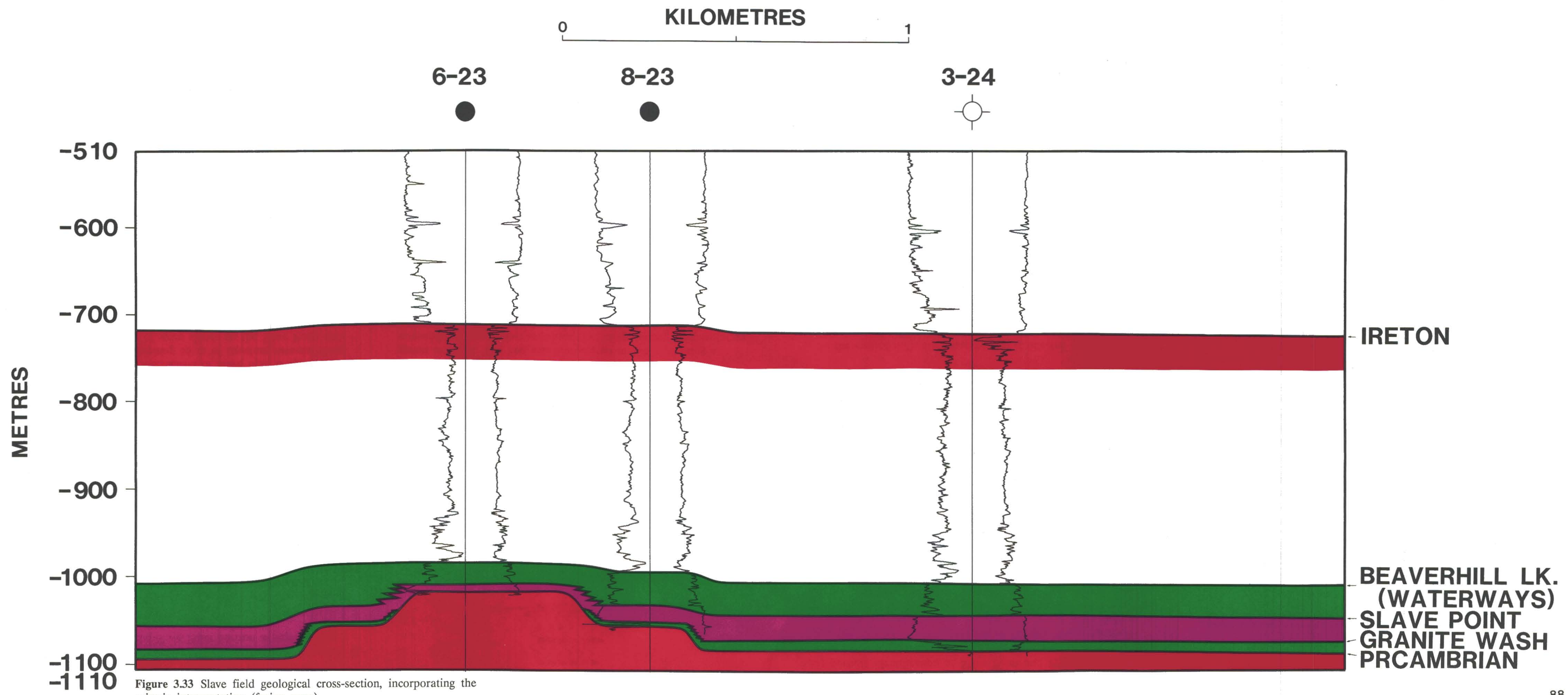

Figure 3.33 Slave field geological cross-section, incorporating the seismic interpretation (facing page).

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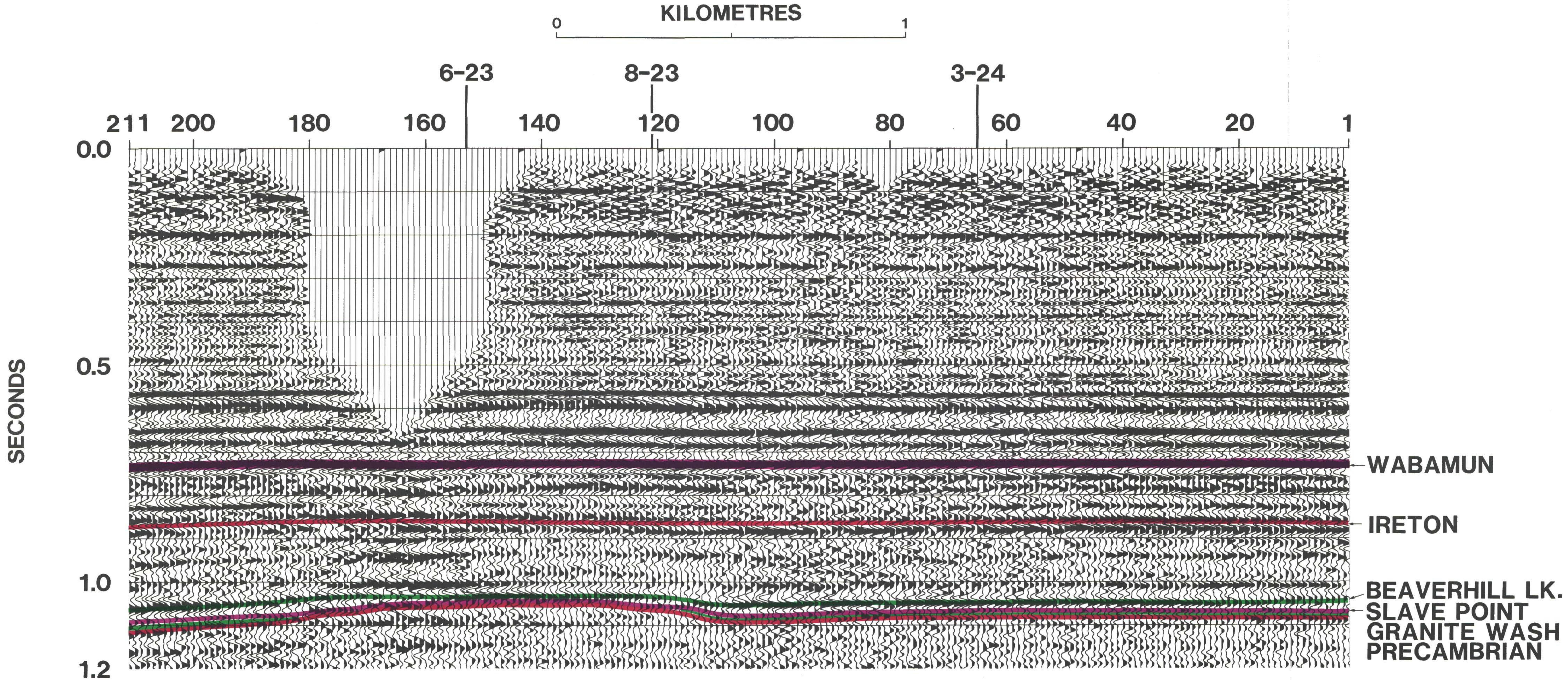

Figure 3.34 Seismic expression across Slave field.

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Precambrian event are both apparent. The discrete Slave Point reflection at the 8-23 location, representing acoustic basement, eventually forms a doublet with the Beaverhill Lake event as Precambrian relief increases (6-23). Thinning of the Waterways Fm shales over the structure, combined with the bandlimited nature of the seismic data, account for the loss of resolution. Subtle structural drape on the Ireton event is also expressed on the synthetic section.

SAWN LAKE FIELD

INTRODUCTION

Sawn Lake field of northcentral Alberta is located approximately 400 km northwest of Edmonton in Township 91, Ranges 12-13 W5M (Fig. 3.1). Situated on the northeast flank of the Peace River Arch, hydrocarbon production is from the Slave Point Fm of the Beaverhill Lake Group at 1600 m average depth. The discovery well, Roxy et al. Sawn Lake 8-32-91-12 W5M, was completed in March 1983 and flowed 95.7 m^3/day of 39° API oil on production test. Cumulative production for the well is in excess of 25.87 x 10^3 m^3. Since the initial discovery, a total of 35 wells have been drilled into the pool.

Stratigraphy of the Beaverhill Lake Group at Sawn Lake consists of Fort Vermilion, Slave Point and Waterways formations (Fig. 3.25). The stratigraphic chart illustrates the diachronous nature of the Slave Point Fm as sediments of the Beaverhill Lake Group transgress the Peace River Arch. Slave Point sedimentation at Sawn Lake field is stratigraphically equivalent to the Firebag Mbr of the Waterways Fm (Fig. 3.25).

The Fort Vermilion Fm comprises approximately 20 m of interbedded carbonate and anhydrite overlying Elk Point clastic sediments. The evaporitic Fort Vermilion Fm is superposed by the Slave Point Fm limestone platform of variable thickness (10 - 30 m). A relatively thick sequence of argillaceous limestones and shales of the Waterways Fm completes the Beaverhill Lake Group stratigraphy. The Waterways Fm is subdivided into the Firebag (shale), Calumet (carbonate), Christina (shale), Moberly (carbonate) and Mildred (interbedded shale-carbonate) members.

At Sawn Lake, shallow water carbonates of the Slave Point Fm were deposited as the Beaverhill Lake sea transgressed the northeast flank of the Peace River Arch. The depositional environment of the Slave Point Fm at Sawn Lake is illustrated schematically in Figure

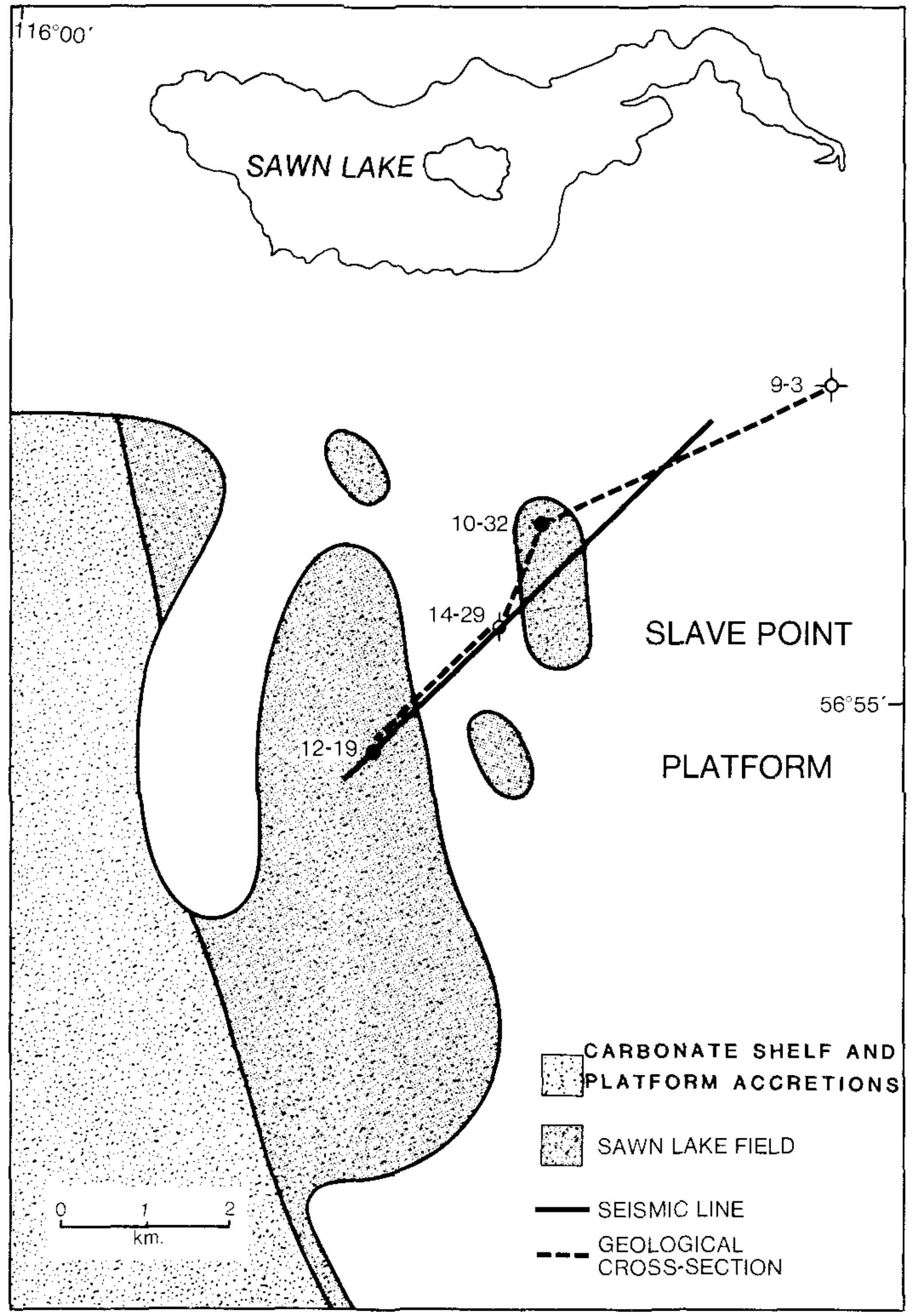

Figure 3.37 Schematic diagram of Sawn Lake field, locating the seismic and geological cross-section.

3.31 (after Craig, 1987). Increased carbonate production in the area resulted in the upward growth of the limestone shelf and contemporaneous, isolated reef or shoal development. Integrating well log information with limited seismic control, Sawn Lake field is here interpreted as an assemblage of stratigraphic traps. Hydrocarbons are confined by a postulated up-dip salient of the Slave Point shelf edge, in addition to the discrete carbonate build-ups (Fig. 3.37). The term "platform reef" will be used informally to describe the isolated carbonate aggregates.

Sawn Lake is the most northerly situated Slave Point oil field discovered to date. Productive area of the field is confined by stratigraphy and regional dip to approximately 26 km^2. Porosity and net pay averages for the reservoir are 7.2% and 9.6 m, respectively. Estimated original volume of oil in place is 12,827 x 10^3 m^3, with 2863.3 x 10^3 m^3 (primary) and 375 x 10^3 m^3 (secondary) recoverable reserves. Cumulative production to the end of December 1987 is 261.2 x 10^3 m^3 of 39° API gravity oil from the Slave Point pools.

The seismic template line, orientated northeast-southwest, crosses the northern part of Sawn Lake field (Fig. 3.37). The line of study extends from Slave Point platform, across an isolated platform reef and onto the carbonate shelf. Carbonate build-ups are manifested by thickening of the Slave Point to Muskeg isochron and associated thinning of the overlying Waterways Fm time interval. Onlapping of the lowermost shale interval within the Firebag Mbr is apparent. Structural interpretation suggests that conditions conducive to reef growth were probably initiated by remnant topographic highs.

GEOLOGICAL CROSS-SECTION

Orientation of the geological cross-section (Fig. 3.38) approximately parallels the seismic example, as depicted in Figure 3.37. The cross-section extends, northeast to southwest, from the Slave Point platform facies (9-3), across an isolated platform reef (10-32) and channel (14-29), and onto the carbonate shelf (12-19). Sonic- gamma ray log suites are displayed for each well in the section.

Paleotopography of the Precambrian basement influenced the deposition of Granite Wash clastic sediments. The Elk Point Group is represented by a more uniform, interbedded evaporitic sequence of the Muskeg Fm, superposed by Watt Mountain Fm clastics.

The Fort Vermilion Fm, a carbonate-evaporite sequence at the base of the Beaverhill Lake Group, is overlain by the Slave Point carbonate platform. The isopach of the Fort Vermilion Fm is relatively constant (19 - 22 m), compared with that of the Slave Point carbonate facies (10 - 27 m). Sonic log response demonstrates the absence of a significant acoustic boundary between these formations. Since the Slave Point-Fort Vermilion assemblage forms a single acoustic unit, the uniformity of the evaporitic sequence is an important criterion for the seismic interpretation (see next section).

Only 10 m of Slave Point carbonate platform were encountered in the most distal well at 9-3. An additional limestone facies gradationally overlies the platform in the 12-19 and 10-32 wells, representing carbonate shelf and platform reef, respectively. Basinal sediments of the Firebag Mbr overlie the platform in the distal (9-3) and channel (14-29) environments and also envelop the carbonate shelf and platform reefs. Influx of this terrigenous material inundated the limestone bank, terminating carbonate production in the area. Deeper water sediments, stratigraphically equivalent to the Slave Point carbonate facies, are more argillaceous in the channel environment; consistent with lower energy, less turbulent conditions prevailing behind the reefs. The abrupt lateral facies change within the Beaverhill Lake Group forms the stratigraphic trap.

Overlying the Firebag shale, the remaining members of the Waterways Fm are more uniform; the sequence of argillaceous limestones and shales thinning proximally by 8 m across the section. The Beaverhill Lake Group is overlain by argillaceous limestones and shales of the Ireton Fm, Woodbend Group.

Excepting Precambrian basement topography, the principal structural component of the cross-section is regional dip to the southwest. The relatively low relief carbonate build-ups have no significant influence on the structure of overlying beds.

Porosity in the upper limestone facies of the Slave Point Fm averages approximately 9% in the 10-32 (reef) well and only 6% in the 12-19 (shelf) location. Oil production figures reflect the porosity variation with cumulative 27.36 x 10^3 m^3 (since 1984) and 5.65 x 10^3 m^3 (since 1985) produced, respectively.

SEISMIC SECTION

The approximate location of the seismic template line is shown schematically in Figure 3.37. These 1200% CDP seismic data were acquired in 1984 using a 2 x 1 kg dynamite source, 96 recording channels over 2 x 1200 m split spread, 100 m source intervals and 25 m group intervals. The line was reprocessed in 1987 following a conventional processing sequence, including spiking deconvolution

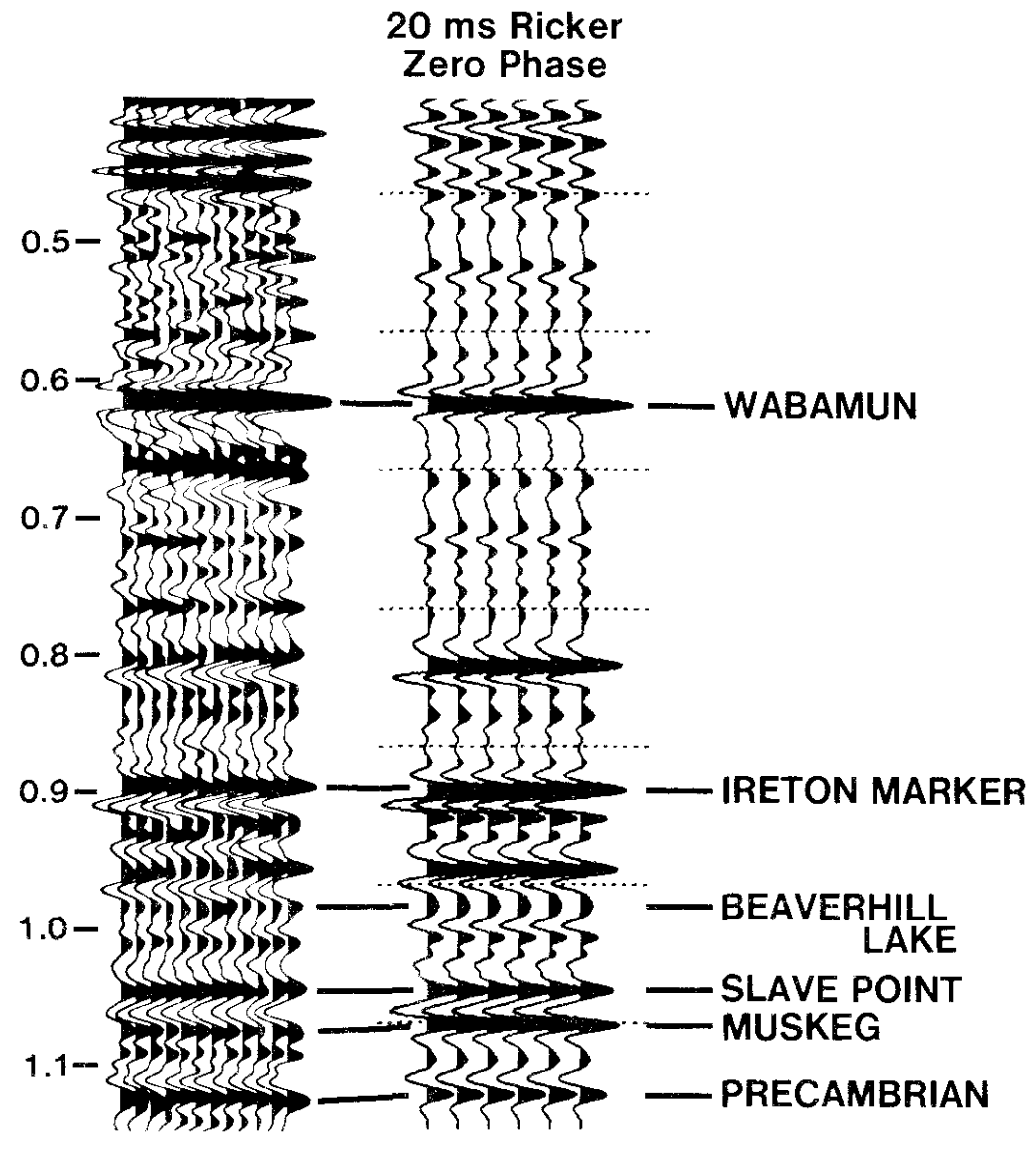

Figure 3.40 Correlation of seismic data (left) with a synthetic seismogram derived from the 10-32 sonic-log (Sawn Lake).

and a final bandpass filter of 14/18 - 85/95 Hz. Full, 1200% CDP coverage is maintained at the extremities of the line.

Major geological horizons are annotated on the interpreted data (Fig. 3.39), with the Slave Point zone of interest occurring at approximately 1.05 seconds 2-way time. Correlation with the synthetic seismogram derived from the 10-32 sonic log is shown in Figure 3.40.

The acoustic and Precambrian basements are coincident due to the presence of low velocity, Granite Wash sediments overlying the

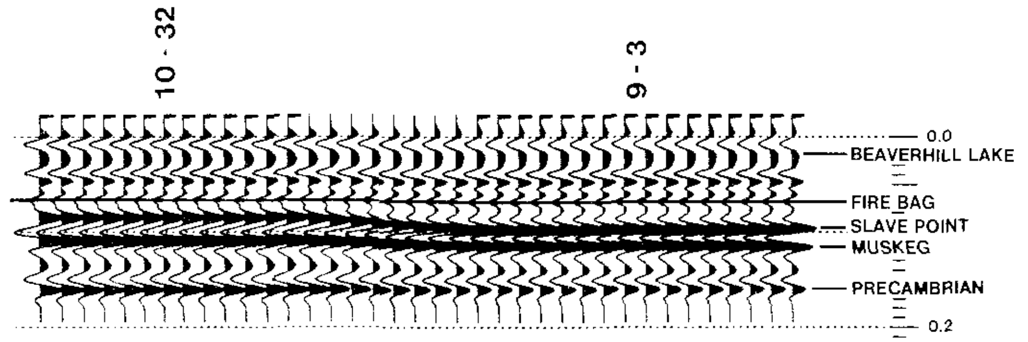

Figure 3.41 Stratigraphic seismic model of Sawn Lake field, filtered with a 20 ms zero-phase Ricker wavelet.

Precambrian surface. Thinning of Granite Wash over basement structures is manifested by a decrease in amplitude of the Precambrian event. Time-structural relief of the basement is incompatible with the accompanying geological cross-section and the discrepancy is attributed to projecting all wells, excepting 14-29, onto the seismic section from off-line locations. The projection of 10-32 suggests the well is flanking a Precambrian basement structure with 20 ms (30 m) of relief on the down-dip side and 12 ms (18 m) of up-dip closure. A Precambrian structure associated with the 12-19 well location is also apparent.

In the vicinity of the 10-32 and 14-29 wells, a positive time-structure on the overlying Muskeg reflection indicates a post-Muskeg tectonic component to the basement feature. In contrast, the paleostructure associated with the 12-19 well appears to be pre-Muskeg. Below the anomalously thick Slave Point facies, velocity generated pull-up on the Muskeg event is negligible. An estimated velocity anomaly of only 2 ms was calculated comparing sonic logs from the 14-29 and 12-19 wells.

Acoustic impedance contrast between Firebag shales and Slave Point carbonate generates a strong, coherent seismic reflection. Seismic delineation of the Slave Point Fm carbonate shelf (12-19) and platform reef (10-32) is achieved by an 8 ms thickening of the Slave Point to Muskeg time interval, compared with the distal (9-3) and channel (14-29) seismic image. The isochron anomaly is attributed to Slave Point carbonate build-up, since the isopachs of Fort Vermilion and Watt Mountain formations are relatively constant. On the distal side of the platform reef, a weak but discernable seismic event precedes the Slave Point reflection by one cycle (18 ms). This event originates from within the Firebag Mbr and onlaps the Slave Point carbonate build-up. The weak reflection is absent in the channel environment behind the reef, due to regional thinning of the Firebag Mbr, combined with the bandlimited nature of the seismic data.

As an acoustic marker, the top of the Beaverhill Lake Group is poorly defined. Regardless, the seismic approximation of the Beaverhill Lake horizon is indicated, to illustrate thinning of the Waterways Fm time interval over the Slave Point carbonate shelf and platform reef. Reflections from the calcareous Ireton marker and top of the Wabamun Fm are annotated on the seismic section. Relying on the structural integrity of the seismic data, positive time structures on the younger horizons suggest a relatively late stage tectonic component to the basement feature in the vicinity of 10-32.

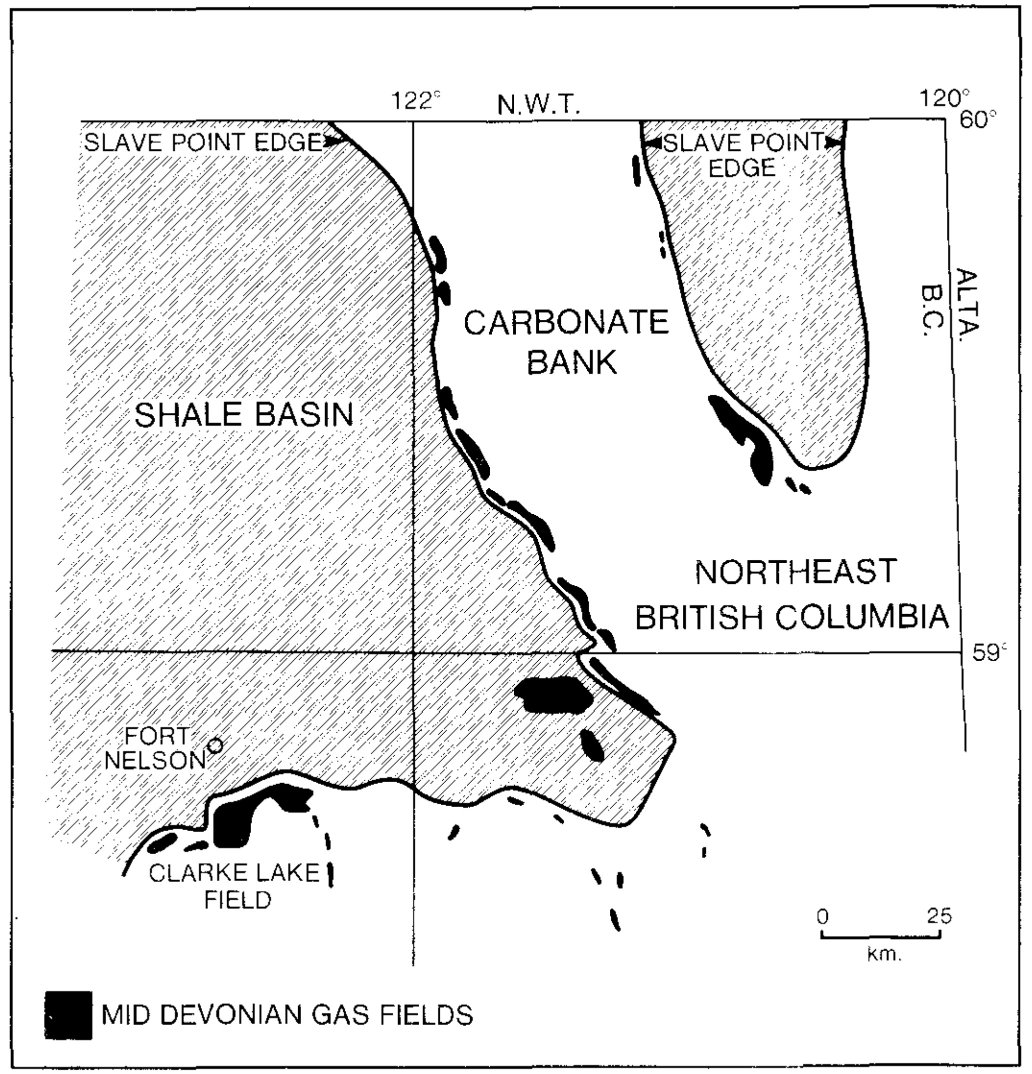

Figure 3.42. Regional setting of Clarke Lake field along the mid-Devonian carbonate front (modified after Phipps, 1982).

The seismic interpretation suggests that conditions conducive to reef or shoal development were probably initiated by remnant topographic highs related to the underlying basement structures.

To support the seismic interpretation an acoustic model was generated using sonic logs from the 9-3 and 10-32 wells. The stratigraphic, synthetic section (Fig. 3.41) comprises zero-offset, primary reflection coefficients convolved with a 20 ms, zero-phase Ricker wavelet. The model incorporates the stratigraphy from lower Ireton to Precambrian basement; Beaverhill Lake, Firebag, Slave Point, Muskeg and Precambrian events are annotated.

The acoustic model verifies the interpretation of the seismic image across Sawn Lake field. Proximal thickening of the Slave Point to Muskeg isochron is evident, accompanied by thinning of the Firebag Mbr time interval over the reef. Onlap of the lowermost section of Firebag shale is also apparent. Structural relationships cannot be compared since the stratigraphic model is flattened on the Beaverhill Lake event.

CLARKE LAKE FIELD

INTRODUCTION

Clarke Lake field of northeastern British Columbia, located approximately 12 km south of Fort Nelson, was the first of a series of significant gas fields discovered along the mid-Devonian barrier-reef system (Figs. 3.1 and 3.42). The carbonate front meanders over 1500 km from the Rocky Mountains in British Columbia to Great Slave Lake in the Northwest Territories. Production at Clarke Lake is from the Slave Point Fm at 1900 m approximate depth.

Gas was discovered in the dolomitized Slave Point Fm in 1957 by Western Natural Gas Company of Houston, who operated the well Prophet River No 1, now known as Pex et al. Clarke C-47-J. The well penetrated the flank of the barrier-reef complex. Commercial quantities of gas were discovered the following year by Western Natural - Imperial Clarke Lake d-88-L which encountered the dolomitized Slave Point carbonate ina structurally higher position on the edge of the barrier. Cumulative production from the well, now known as Pex Esso Clarke d-88-L, is in excess of 2,520 x 10^6 m^3.

The Slave Point Fm at Clarke Lake field attains a maximum thickness of approximately 120 m and together with the underlying

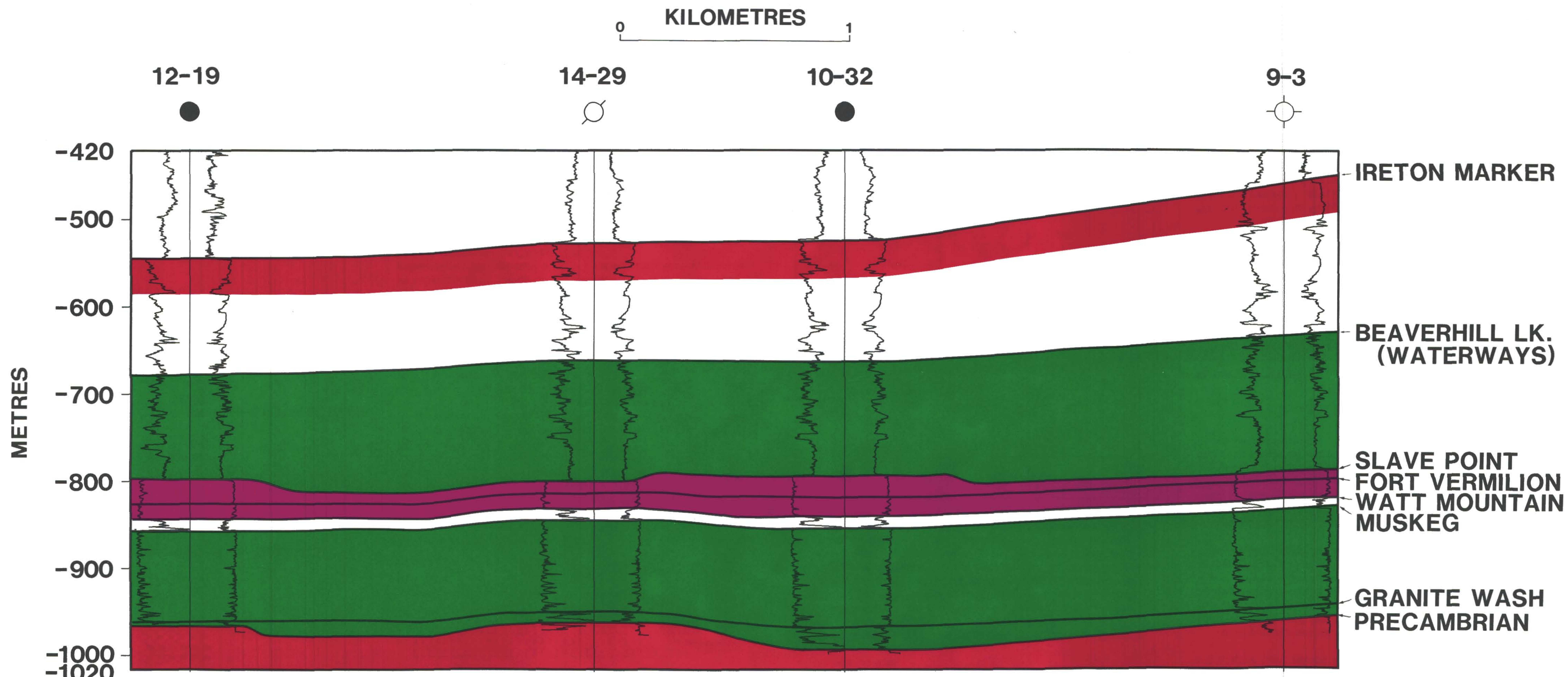

Figure 3.38 Sawn Lake field geological cross-section, incorporating the seismic interpretation (facing page).

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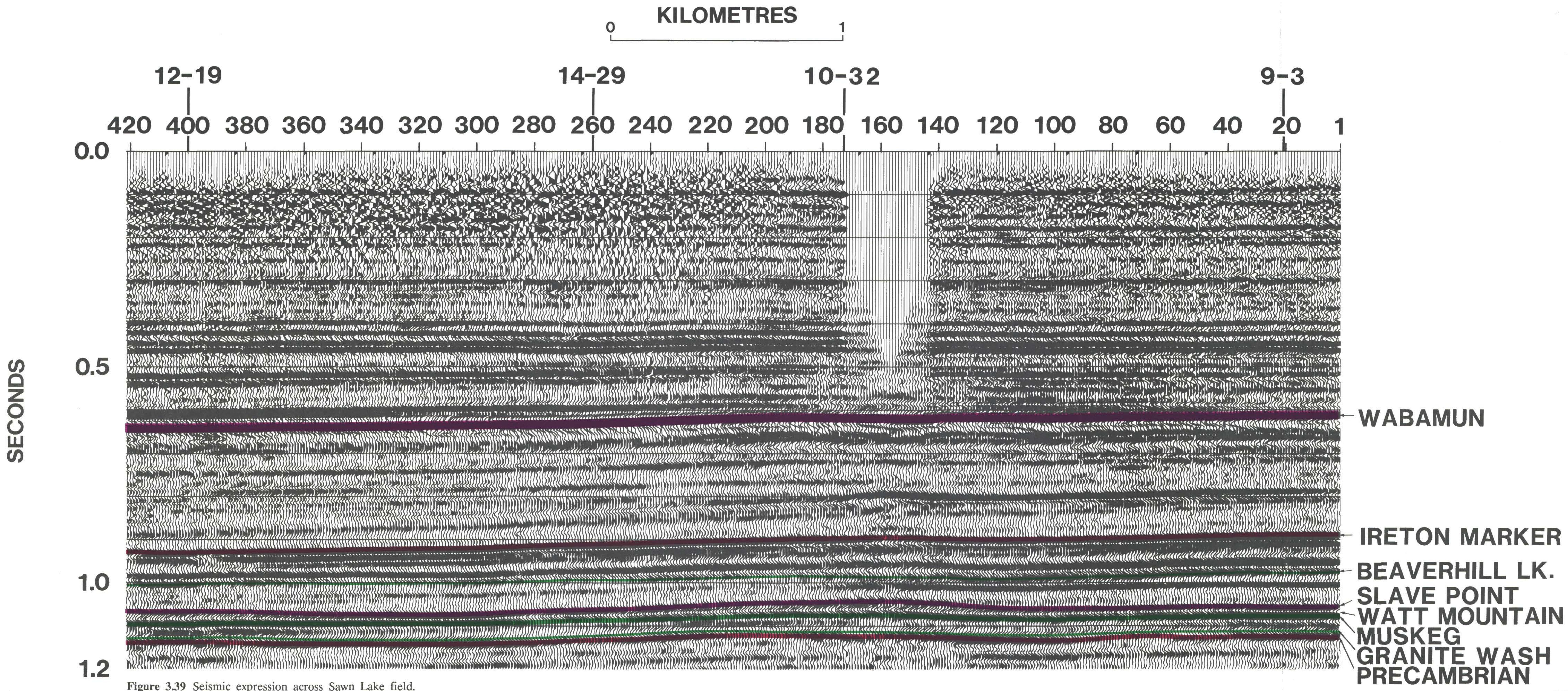

Figure 3.39 Seismic expression across Sawn Lake field.

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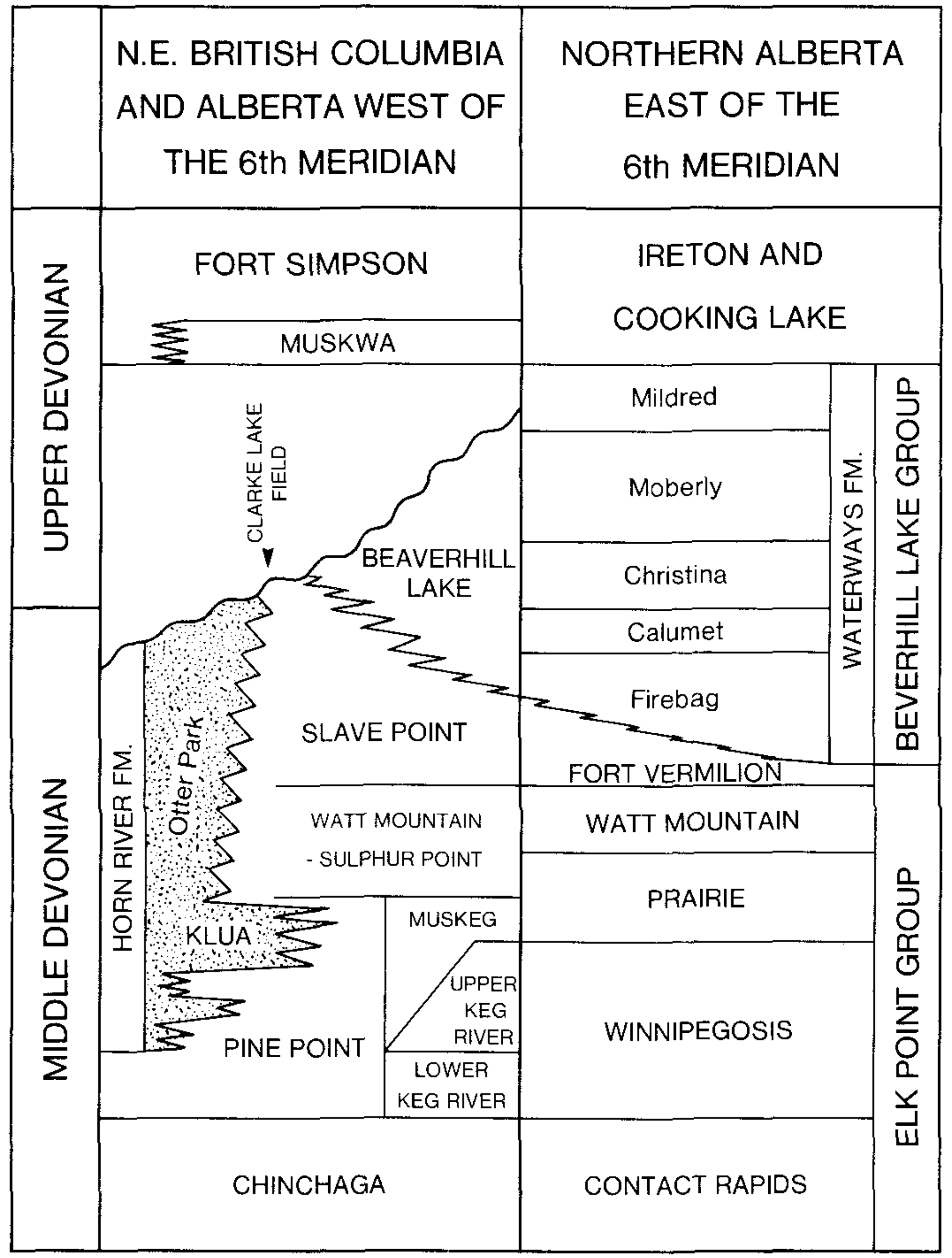

Figure 3.43 Stratigraphy of the Elk Point and Beaverhill Lake groups, showing the location of Clarke Lake field (modified after Griffin, 1965).

Elk Point carbonates forms a massive dolomitized barrier-reef in excess of 340 m thick. Illustrating the stratigraphic context of the Slave Point Fm in the study area, Figure 3.43 compares the Middle Devonian stratigraphy in Northeastern British Columbia and

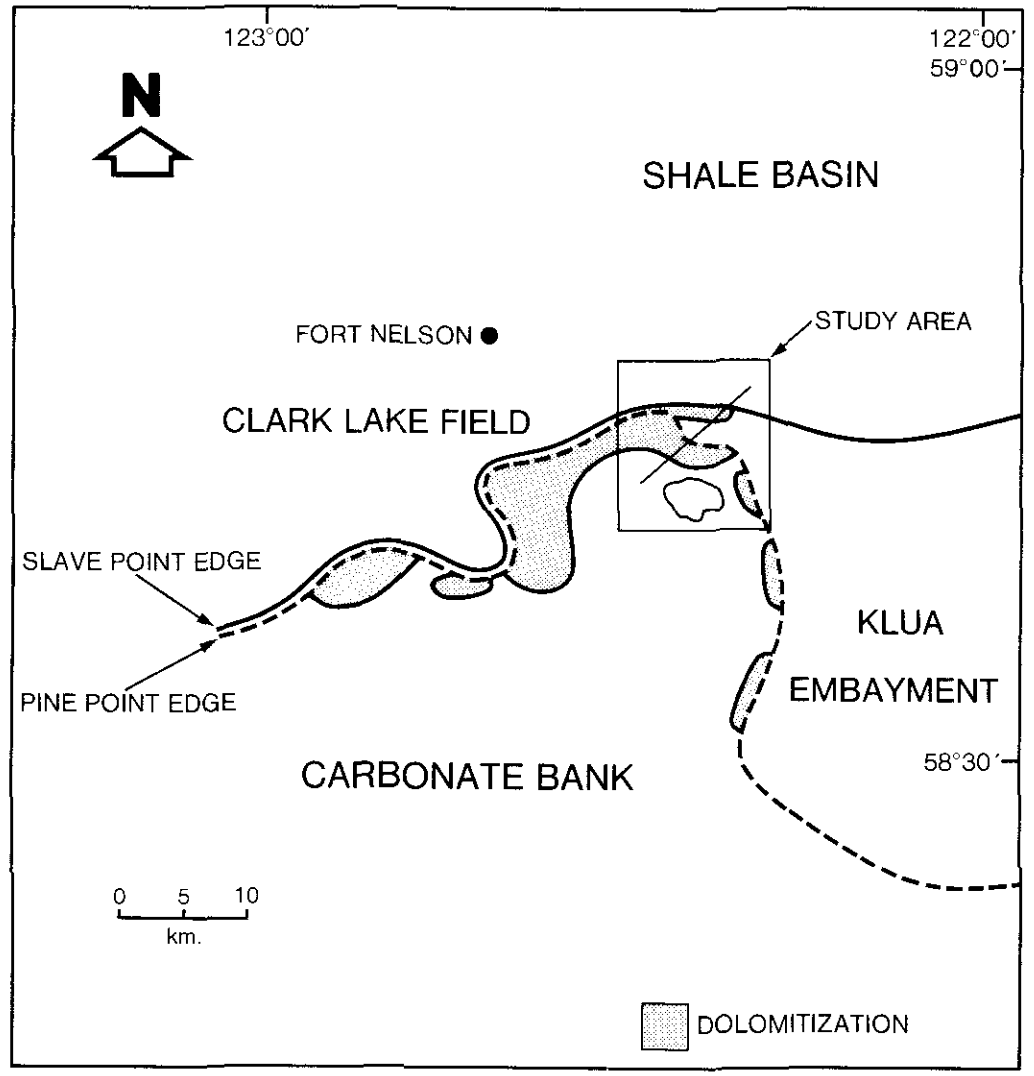

Figure 3.44 Schematic diagram of Clarke Lake field, locating the study area (Fig. 3.45).

Northern Alberta. Regionally, the Slave Point Fm is diachronous and the reef front carbonate at Clarke Lake is the facies equivalent of the lower members of the argillaceous Waterways Fm. Locally, an abrupt facies change occurs where the Slave Point - Sulphur Point carbonate barrier passes, precipitously, into basinal shales of the Horn River Fm.

Clarke Lake field is of sigmoidal form, 40 km in extent and between 2.5 and 6 km wide (Fig. 3.44). In the western part of the field, dolomite reservoir is spacially interspersed by zones of non-porous limestone. The northeast extremity of the gas pool is situated over the Klua shale embayment (Fig. 3.44), characterized by a tongue of Horn River shales underlying the Sulphur Point Fm.

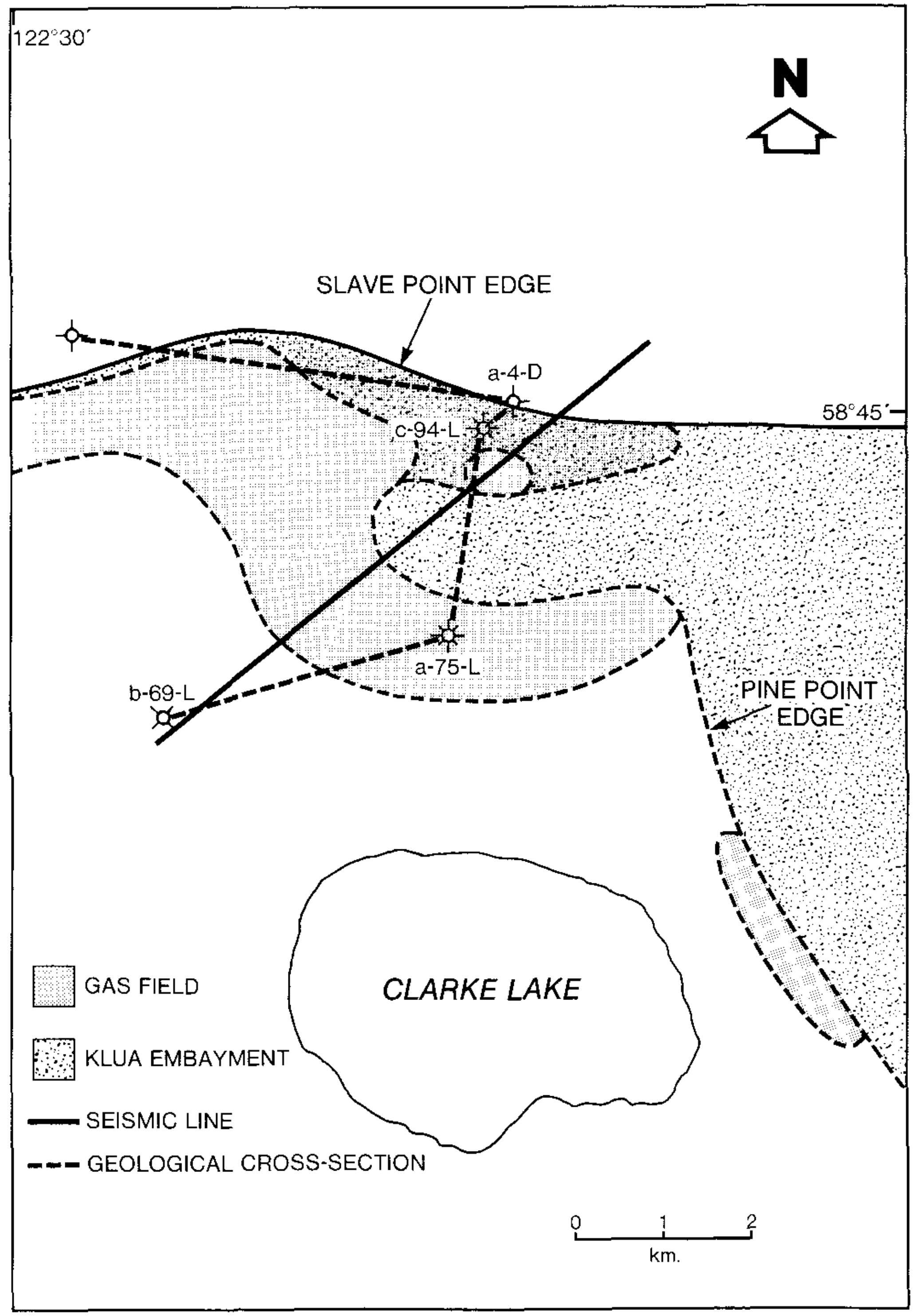

Figure 3.45 Schematic diagram of Clarke Lake field, locating the seismic and geological cross-sections.

Encroaching basinal shales represent a temporary deepening of the Elk Point basin. In this area, the front of the Slave Point - Sulphur Point carbonate assemblage oversteps the underlying Pine Point carbonate bank edge, as depicted in Figure 3.43.

Reservoir at Clarke Lake is restricted to an area defined by the front of the Pine Point reef where dolomitization pervaded the massive Slave Point-Elk Point barrier-reef. Slave Point and Pine Point carbonate fronts diverge at the Klua embayment and vermicular zones of dolomitization coincide with the edge of the deeper reef (Fig. 3.44). Barrier-limestone facies overlying the Klua embayment remain unaltered. A detailed explanation of the distribution of Slave Point dolomites is provided by the geological model used by Phipps (1982). In summary, the model suggests that dolomitized zones should occur in reefal carbonates in communication with both fresh and marine waters. Phipps (1982) proposed that the edges of the main barrier and Klua embayments were exposed to such conditions.

Hydrocarbons are structurally and stratigraphically trapped in the dolomites at Clarke Lake. The productive area of the field is approximately 120 km^2; porosity and net pay averages are 7.1% and 35.4 m, respectively. Estimated original volume of gas in place is 62,025 x 10^6 m^3, with 35,294 x 10^6 m^3 of recoverable reserves. Cumulative production to the end of December 1987, is 38,846 x 10^6 m^3 of gas, exceeding the estimated recoverable reserves.

The exemplary seismic line, situated at the northeast corner of the Klua embayment, crosses the Slave Point edge, Klua embayment and onto the Pine Point reef (Fig. 3.45). Morphology of the middle Devonian barrier-reef complex is exemplified by Slave Point time-structure, and porous zones within the Slave Point - Sulphur Point assemblage are inferred by seismic "bright spot" anomalies. Spacial distribution of the porosity indicators is consistent with dolomitization pervading the barrier-reef where Slave Point-Sulphur Point and Pine Point carbonates are superposed. Compaction induced drape on the Muskwa Fm is manifested by time-structural relief on the Otter Park reflection (basinal equivalent of Slave Point event).

The Pine Point carbonate surface provides four characteristic seismic signatures representing distinct geological facies:

1) Within the shale basin, reflections from atop the Pine Point surface and the base of the shale tongue (within the Pine Point interval) are both resolved,

2) Klua shale - Pine Point carbonate interface provides a strong acoustic boundary for seismic delineation of the Klua embayment,

3) Within the Klua embayment, a seismic 'bright spot' anomaly, formed by a polarity reversal of the Klua event, is interpreted as Pine Point reef; and

4) Across the massive Slave Point-Elk Point carbonate barrier, seismic definition of the Pine Point horizon is nebulous.

Seismic criteria also include time-structural drape on the Slave Point reflector over the Klua embayment, and velocity generated pull-up on the Pine Point event below the reefs.

GEOLOGICAL CROSS-SECTION

Orientation of the geological cross-section (Fig. 3.46) approximately parallels the seismic example, excepting the deviation to the d-10-A well, as shown in Figure 3.45. The section extends, north to south, from shale basin (d-10-A) across the Slave Point reef flank (a-4-D) and dolomitized barrier-reef facies (c-94-L, a-75-L) onto the back-reef environment (b-69-L). The line of study also transects the Klua shale embayment. Sonic- gamma ray log suites are displayed for each well in the geological cross-section, excepting c-94-L for which gamma ray - neutron is substituted.

The oldest rocks encountered in the c-94-L well are quartzite, probably Cambrian or Precambrian in age (Gray and Kassube, 1963). The oldest Middle Devonian unit, the Chinchaga Fm, consists of interbedded dolomite, anhydrite and terrigenous clastics. Pre-Devonian and Chinchaga horizons, penetrated by the c-94-L well, are extrapolated across the section paralleling younger horizons. Interpretation of the overlying Middle Devonian section incorporates the seismic analysis, providing information between well control and below TD. The interpretive cross-section illustrates the distribution of laterally equivalent stratigraphic sequences described below.

Pine Point Fm overlies Chinchaga sediments and the Pine Point carbonate bank edge is situated just north of the a-75-L well. Klua shales (62 m thick) encountered in the c-94-L well, represent the basinal facies equivalent of the Pine Point reef. The more distal, d-10-A, well encountered a shale tongue (9 m thick) within the Pine Point Fm, representing a temporary deepening of the basin, analogous to the younger Klua shale embayment. A promontory of the Pine Point bank edge or an isolated reef within the Klua shale basin is postulated from the seismic interpretation and illustrated on the geological cross-section.

The overlying Slave Point - Sulphur Point barrier-reef system oversteps the Pine Point bank edge, representing a relatively abrupt marine regression. Otter Park shales of the Horn River Fm, encountered in the a-4-D (flank) and d-10-A (distal) wells, represent basinal facies equivalent of the reefal carbonates. Dolomitized Slave Point - Sulphur Point carbonate barrier facies, pass precipitously into basinal shales, forming the stratigraphic trap for hydrocarbons. The c-94-L and b-69-L wells drilled through the Slave Point Fm, encountering 113 m and 117 m of section, respectively. Two distinct Slave Point facies are recognized; porous, dolomitized barrier-reef carbonates within the field (c-94-L) and non-porous back-reef limestone (b-69-L). Lateral distribution of an upper, porous zone within the Slave Point Fm is inferred from seismic interpretation. Impermeable shales of the Muskwa and Fort Simpson formations unconformably superpose the Slave Point carbonate barrier, thus sealing the dolomite reservoir.

Slave Point and Muskwa formations exhibit 35 m of structural drape over the Pine Point reefs, due to the effects of differential compaction of reefal carbonate and Klua shale. An additional 75 m of compaction-induced drape on the Muskwa Fm coincides with the Slave Point - Sulphur Point reef front. Hence, in the absence of the Klua embayment, the Muskwa Fm should manifest approximately 110 m of compaction-induced relief over the massive barrier-reef complex.

Dolomite reservoir with 8-12% porosity is present in the c-94-L well, which produced 1214.98 x 10^6 m^3 of gas from 49 m of net pay. At the northwest corner of the Klua embayment, the shale tongue is relatively narrow and a few wells encountered dolomitized Slave Point reef, despite the underlying shale section; c-94-L is such a case.

SEISMIC SECTION

Approximate location of the exemplary seismic line is depicted in Figure 3.45. These 1200% CDP seismic data were acquired in 1983 using a 2 x 1 kg dynamite source, 96 recording channels over 2 x 2400 m split spread, 160 m source intervals and 40 m group intervals. The line was reprocessed in 1987 using a conventional processing sequence, including spiking deconvolution, post-stack wave-equation migration and a final bandpass filter of 12/16 - 65/75 Hz. Full, 1200% CDP coverage is preserved at the extremities of the line.

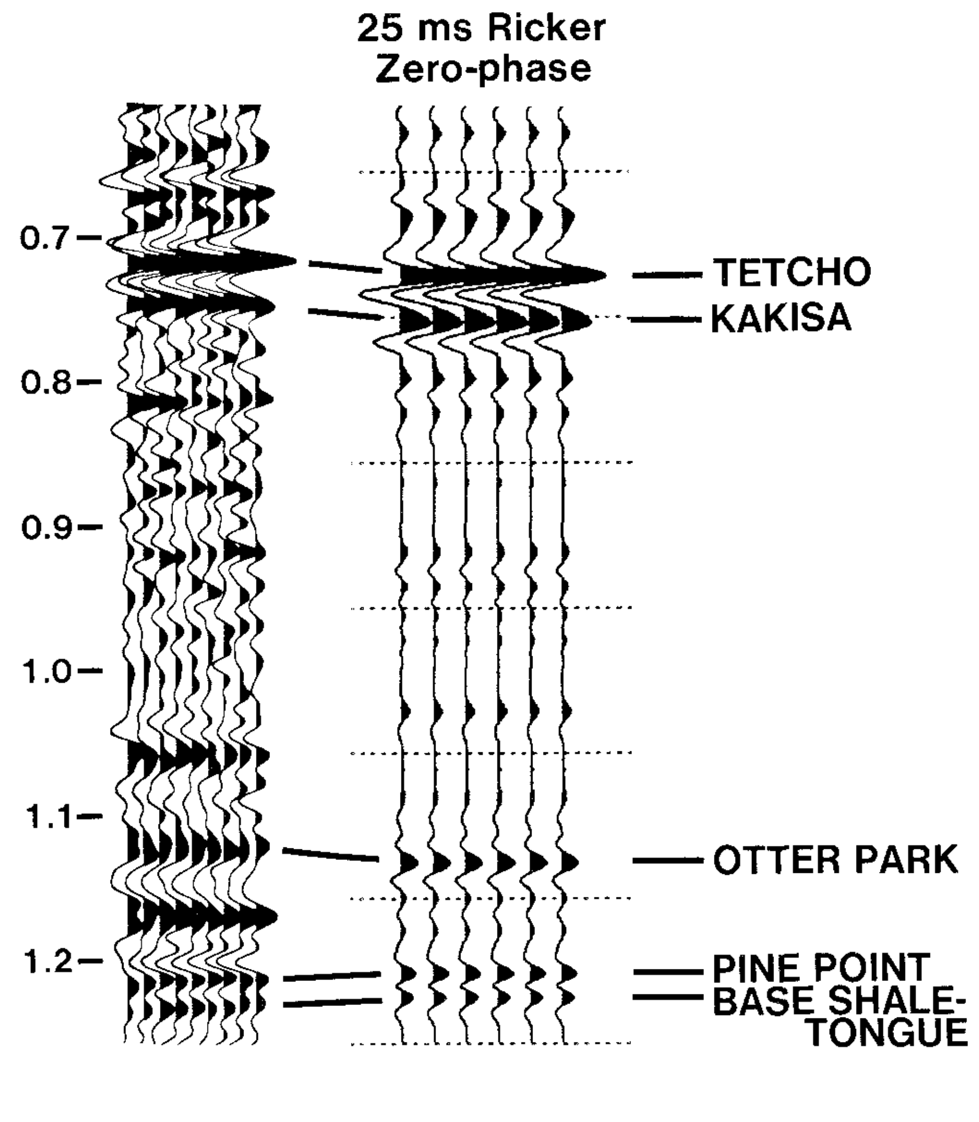

Figure 3.48 Correlation of seismic data (left) with a synthetic seismogram derived from the d-10-A sonic-log (Clarke Lake).

Prominent geological horizons are identified on the interpreted data (Fig. 3.47), with the Slave Point zone of interest occurring at 1.05 to 1.08 seconds 2-way time.

The deepest reflection identified represents the Pine Point Fm carbonate surface, penetrated by the c-94-L and d-10-A wells. The discontinuous Pine Point event includes four characteristic seismic signatures, representing distinct geological facies.

1) Within the shale basin, correlation with the synthetic seismogram generated from the d-10-A sonic log expedites the interpretation (Fig. 3.48). Reflected energy (peak) from atop the Pine Point Fm is weaker than anticipated from the intrinsic reflectivity of a shale - tight carbonate boundary. The following cycle (peak) reflects from the base of the thin tongue of shales within the carbonate interval; although the shale excursion is resolved destructive interference with the Pine Point event weakens the amplitude response of the reflectivity sequence. The basinward limit of the overstepping

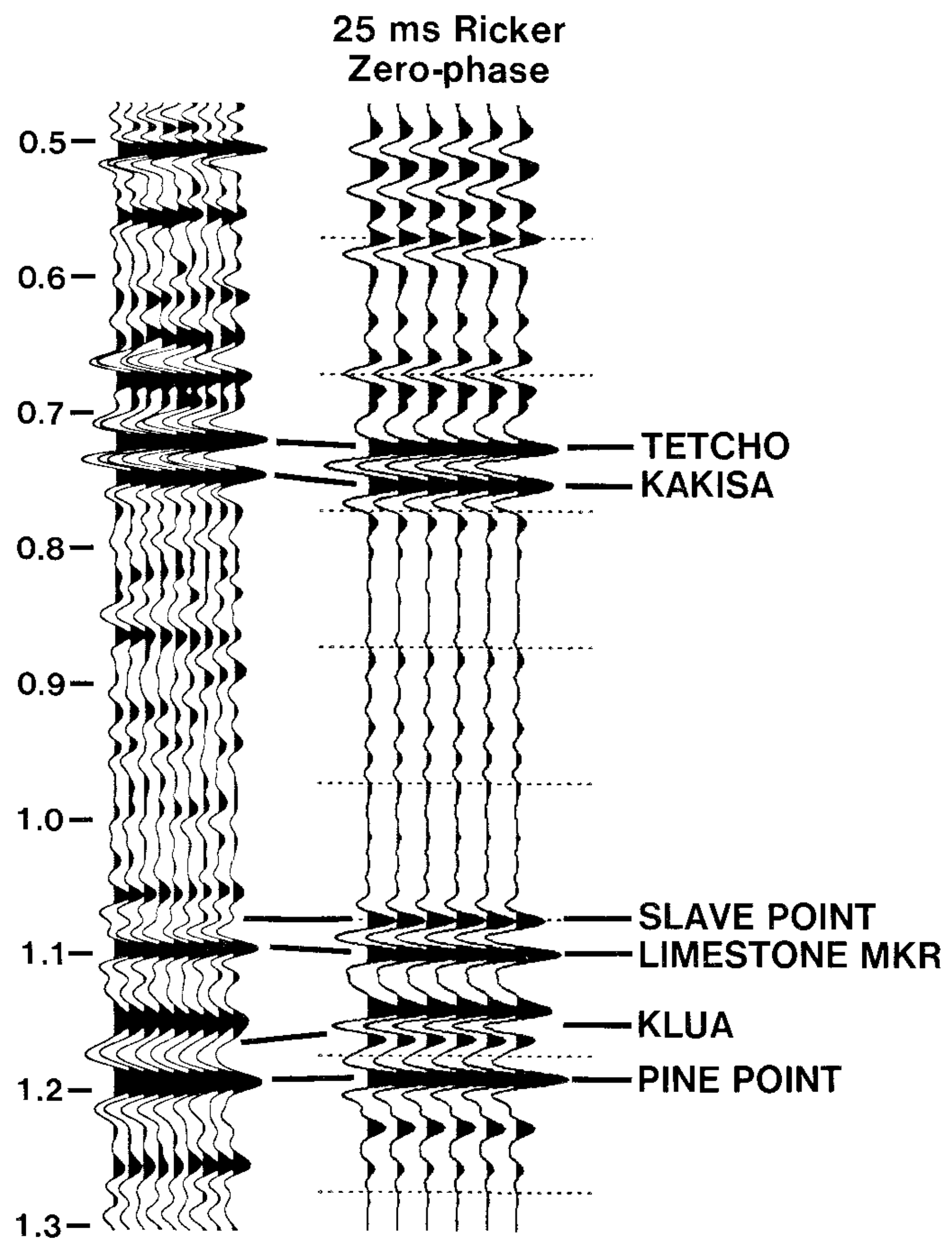

Figure 3.49 Correlation of seismic data (left) with a synthetic seismogram derived from the combined c-94-L/d-96-L sonic-logs (Clarke Lake).

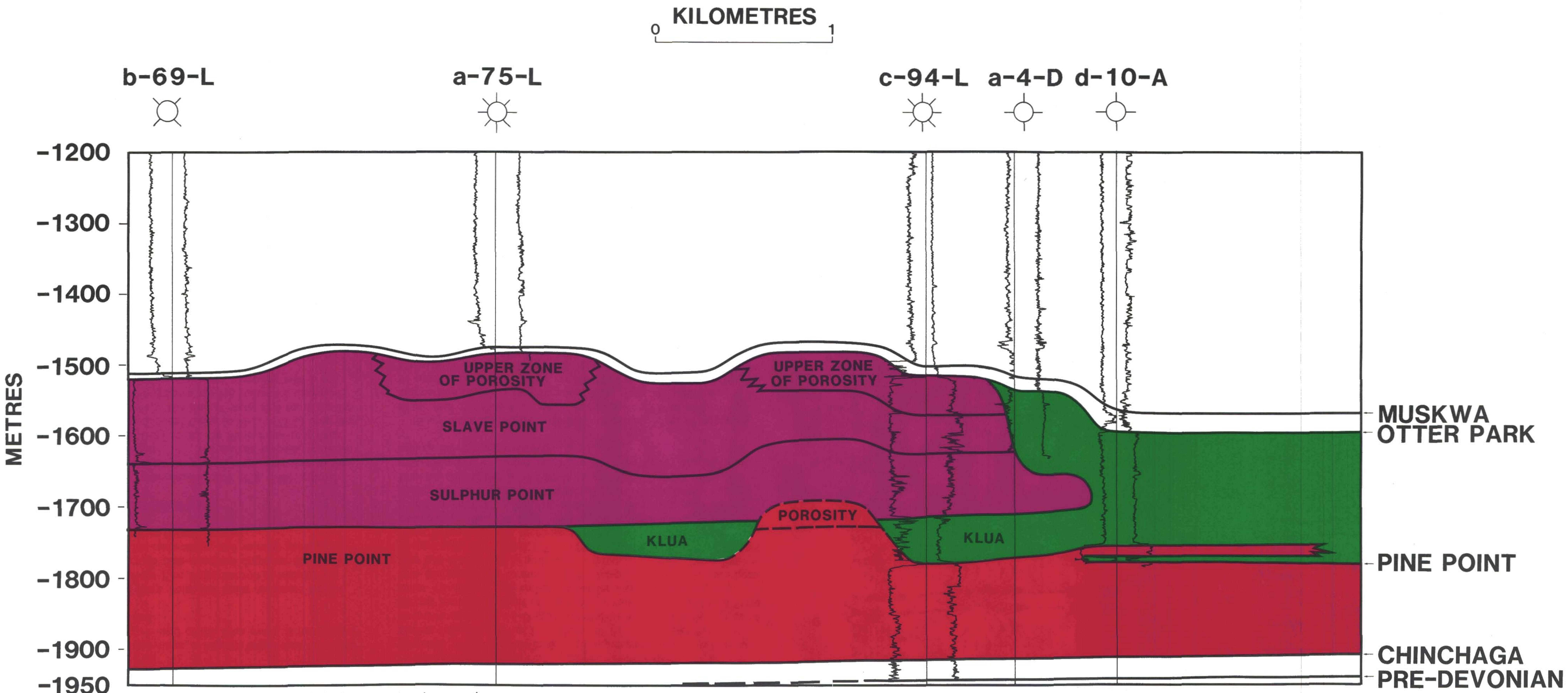

Figure 3.46 Clarke Lake field geological cross-section, incorporating the seismic interpretation (facing page).

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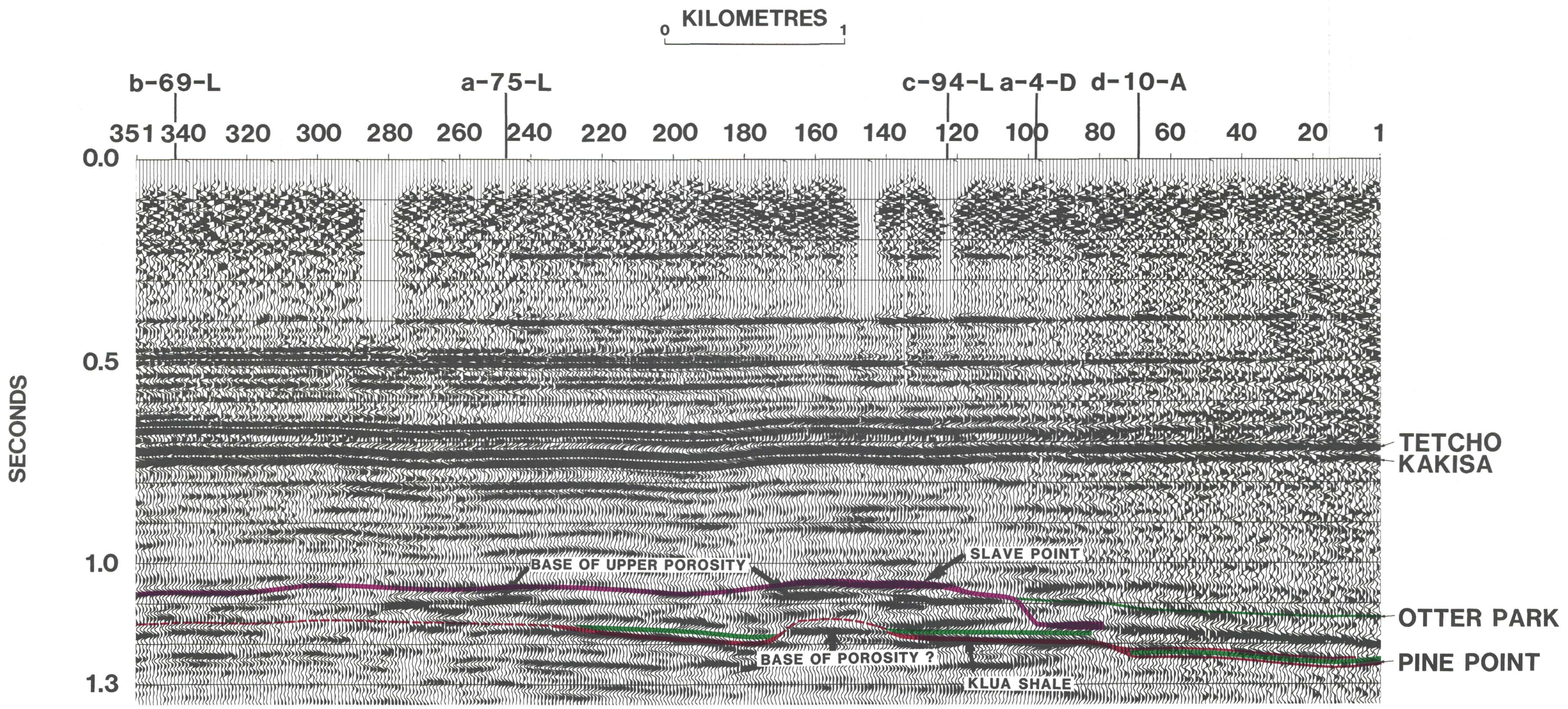

Figure 3.47 Seismic expression across Clarke Lake field.

DONOR: DOME PETROLEUM LTD. | PROCESSOR: SEISMIC DATA PROCESSORS LTD. | AUTHOR: R.M. FERRY carbonate is inferred from the discontinuity and increase in amplitude of the Pine Point reflection (at trace 9 of Fig. 3.47).

2) Across the Klua embayment, an abrupt increase in amplitude and decrease in frequency of the seismic image characterizes the Pine Point carbonate surface. Correlation with the synthetic seismic trace derived from the combined c-94-L (>1950 m) and d-96-L (<1950 m) sonic logs is shown in Figure 3.49. Lateral distribution of the shale tongue is inferred from the extent of the strong, coherent Pine Point reflection (traces 79 to 128 and 175 to 223).

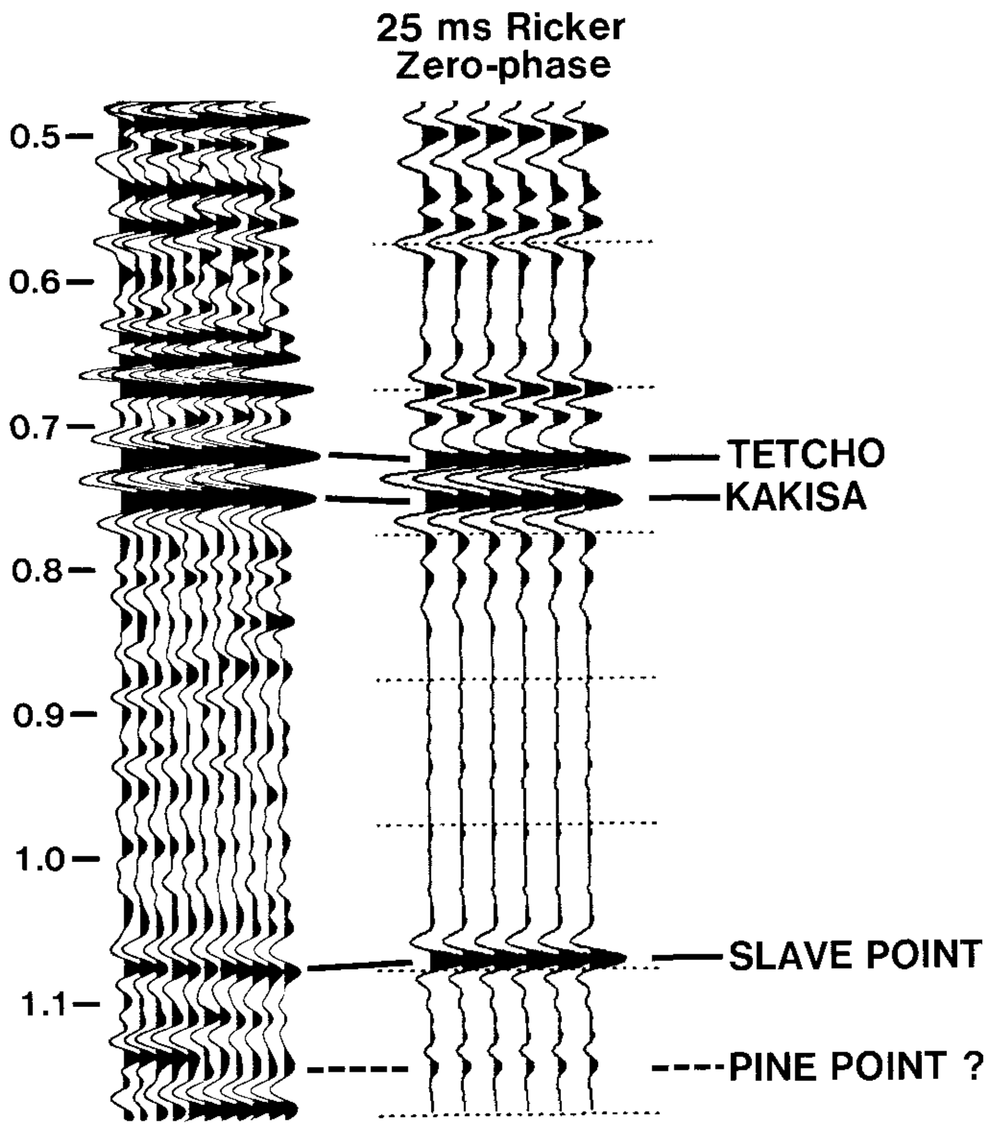

Figure 3.50 Correlation of seismic data (left) with a synthetic seismogram derived from the b-69-L sonic-log (Clarke Lake).

3) Within the Klua shale embayment, an abrupt transformation of seismic signature (between traces 129 and 174 of Fig. 3.47) is here interpreted as either a promontory of the Pine Point bank edge or an isolated Pine Point reef. Seismic characteristics of the Klua shale - Pine Point carbonate interface are replaced by an apparent polarity reversal of the Klua shale trough. The resulting "bright spot" could represent an interval of tight limestone within a porous, dolomitized Pine Point reef; surrounded by Klua shale.

4) On the proximal side of the Klua embayment, Slave Point, Sulphur Point and Pine Point reefs form a massive carbonate barrier which precludes seismic recognition of the Pine Point horizon. Correlation of a nebulous seismic event (between traces 224 and 351 of Fig. 3.47) is intended to depict the approximate location of the Pine Point Fm.

Velocity generated pull-up and/or time-structure on the Pine Point event below younger reefs is superimposed on the variable seismic signature. The reflection exhibits 17 ms of apparent time-structure between shale basin (d-10-A) and carbonate barrier (c-94-L). Incongruity with Pine Point structure depicted on the geological cross-section is attributed to projecting the d-10-A well onto the seismic section from nearly 6 km off-line.

The reflection from atop the Slave Point Fm delineates the morphology of the barrier-reef complex. Time-structural drape on the Slave Point event over the Pine Point bank edge is attributed to differential compaction, augmented by late stage tectonic activity. Within the Klua embayment, a compaction-induced Slave Point time-structure coincides with the postulated Pine Point reef, giving credence to the interpretation. The a-4-D well penetrated the flank of the barrier-reef complex, where a slope of 35° is estimated from the seismic image. At the base of the slope, a lip of Sulphur Point carbonate is seismically apparent, projecting 320 m into the basin (between traces 79 and 95). A coincident time-structure on the deeper Pine Point event is partially attributed to velocity generated pull-up.

Porous zones within the Slave Point-Sulphur Point sequence can be inferred from the seismic response of the carbonate interval. Correlating the synthetic seismograms for b-69-L and c-94-L with the seismic line illustrates the concept. The b-69-L well penetrated a non-porous limestone sequence which produces a relatively quiet seismic response below the dominant Slave Point event (Fig. 3.50). In contrast, porous dolomite facies predominates at c-94-L and a subordinate limestone interval generates a strong seismic event below the Slave Point reflector (Fig. 3.49). The high amplitude trough, half a cycle below the Slave Point event, reflects porosity and the following peak is generated at the porous dolomite - tight limestone boundary. Thus, the non-porous limestone interval facilitates seismic detection of the porous, dolomitized zones. In the absence of the limestone band, seismic response of ubiquitous porosity would resemble that of the tight, back-reef facies (Fig. 3.50). Distribution of seismic "bright spot" anomalies within the Slave Point-Sulphur Point interval, indicates the upper zone of porous dolomite occurs in conjunction with the edges of the underlying Pine Point reefs.

Within the shale basin, acoustic impedance contrast between dark, bituminous shales of the Muskwa Fm and calcareous shales of the Otter Park Mbr allows seismic recognition of the boundary. The Otter Park reflector is the off-reef equivalent of the Slave Point event. Difference in time-structure (28 ms) of these equivalent markers across the barrier-reef edge, manifests the compaction-induced drape on the overlying Muskwa Fm. An additional 20 ms of time-structural drape on the Otter Park event coincides with the edge of the postulated Sulphur Point protrusion in front of the main reef.

Shallower reflections from the Upper Devonian Tetcho and Kakisa formations are identified on the interpreted seismic section. Tetcho (or Kakisa) to Slave Point isochron delineates maximum reefal development (isochron thins) and confirms time-structural drape on the Slave Point event over the Klua embayment (isochron thicks). Time-structure on the Upper Devonian events manifests post-Devonian tectonics with a subordinate contribution from structural drape.

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