# CHAPTER 2 — ELK POINT CARBONATE RESERVOIRS

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## INTRODUCTION

The Elk Point Gp is the earliest of several cyclothems in Middle Devonian time, each constituting a transgressive and a regressive phase of the Devonian sea. The stratigraphy (Fig. 2.1) and geological history of the Elk Point Gp are synthesized from Hargeaves et al. (1960), Grayston et al. (1964), McCamis and Griffith (1967), Bassett and Stout (1967), Langton and Chin (1968), Barss et al. (1970), Hriskevich, (1970), Maiklem (1971), Klovan (1974), Gendzwill, (1978), Perrin (1982), Hills et al. (1984), Williams (1984), Campbell (1987), Gendzwill and Wilson (1981), and AGAT Laboratories (1987, 1988). This geology is described briefly in the Introduction to this volume, where it is noted that the Elk Point Gp consists of carbonates, evaporites and clastics and that the carbonates and coarse clastics form the principal reservoir facies. Clastic reservoirs are discussed in Chapter 1 (Basal Paleozoic Clastic Reservoirs).

Examples presented in this chapter include five different types of Elk Point carbonate build-ups, those of the Rainbow Mbr, Upper Keg River Reef Mbr and Zama Mbr (northwestern Alberta), the Keg River Fm (north-central Alberta) and the Winnipegosis Fm (southern Saskatchewan). Figure 2.2 shows the general locations of these different carbonate build-ups in the Middle Devonian Elk Point basin. They constitute the principal and most prospective of the Elk Point carbonates. All five were deposited within evaporite basins: the Winnipegosis Fm as pinnacles and atolls within the main Elk Point basin; the Rainbow and Upper Keg River Reef members (Keg River Fm) as pinnacles and atolls within the Black Creek basin (an Elk Point subbasin); the Keg River Fm (Senex area) as patch reefs on the fringing Keg River Fm shelf, and the Zama Mbr (Keg River Fm) as a widespread shoaling facies within the northern part of the Black Creek basin (Fig. 2.3). Production from the Rainbow, Upper Keg River Reef and Zama members dwarfs that from the Keg River Fm (Senex) or Winnipegosis Fm, however, due to recent important discoveries and current exploration interest, examples of these latter two reservoir types have a natural place in this chapter.

The five types covered, including four Keg River types plus the Winnipegosis type, are roughly time-equivalent. The reefs of the Rainbow Mbr, Upper Keg River Reef Mbr and the mounds of the Winnipegosis Fm grew on their underlying platform facies as the transgressing Elk Point seas deepened. Along the basin margins the Keg River/Winnipegosis fringing shelf developed concurrently. Shoreward of the shelf edge, in the northeastern Peace River arch or Senex area, Keg River Fm patch reefs developed, typically on or above prominent basement structures.

Keg River and Winnipegosis reef growth terminated initially in the main Elk Point basin and subsequently within the Black Creek basin as circulation became restricted and hypersaline conditions developed. All of these reefs were encased in interlayered evaporites and carbonates. Typically, the Winnipegosis Fm mounds were enveloped by thick salts and thin interbedded anhydrites of the Prairie Evaporite Fm (or Prairie Fm). The low-relief Keg River Fm patch reefs (Senex area) were overlain by interlayered salts, dolomites and anhydrites (Muskeg Fm). Reefs of the Rainbow and Upper Keg River Reef members were surrounded by the thick basinal salt of the Black Creek Mbr and an overlying succession of interlayered carbonates and anhydrites of the upper Muskeg Fm. The Zama Mbr, a shoaling carbonate facies, of the upper Muskeg Fm, was distributed within the northern part of the Black Creek basin and typically is productive where draped across reefs of the Upper Keg River Reef Mbr.

Isolated reefs of the Rainbow Mbr, Upper Keg River Reef Mbr and Winnipegosis Fm are herein classified as stratigraphic traps. The classification of the Winnipegosis build-ups as mounds or as reefs is discussed further in Part B of this chapter. Although, postdepositional structure, due to differential compaction and basinal subsidence, influences the distribution of hydrocarbons (generally the thickest gas and/or oil columns are located within the updip rims of the atolls), this effect is considered secondary to the reservoir-seal relationship of the reef to off-reef sediments. In contrast, the Keg River Fm patch reefs and the Zama Mbr shoaling facies are considered to be structural traps, as these sediments are generally productive only where draped across underlying Precambrian basement structures and the Upper Keg River Reef Mbr, respectively. Although porosity and permeability within these latter two units are stratigraphically controlled, the off-structure facies generally being tighter, these effects are considered as secondary to the drape resulting from differential compaction (McCamis and Griffith, 1967).

A broad spectrum of Elk Point Gp carbonate reservoirs is spanned by the examples analyzed within this chapter. The carbonate facies are both biohermal and biostromal, the trapping mechanisms both stratigraphic and structural, and the build-ups range from mounds, whose status as reefs is still in some doubt, to patches, pinnacles and atolls of diverse morphologies. Similarly, the seismic signatures of these evaporite-basin carbonate reservoirs are diverse (Anderson and Brown, 1987). For instance, velocity pull-up is interpreted for all five reef types but is the result of various causes. Beneath the Rainbow and Upper Keg River Reef members, pull-up is attributed primarily to drape on horizons above the reef (indeed, the reefal facies is typically of lower velocity than the adjacent off-reef sediment). Pull-up beneath the Keg River Fm patch reefs is also attributed to drape. Below the Winnipegosis Fm, such relief is principally due to the higher velocity of the reef relative to the adjacent off-reef facies. The magnitude of structural drape also changes appreciably, being a function, not only of differential compaction but also, of the timing and extent of salt dissolution in the vicinity of the reefs. (The term compaction, as used here, refers to all postdepositional volume changes, whether physically or chemically induced, except for salt dissolution which, due to its fundamentally different nature as well as its magnitude and significance, is treated as a separate mechanism). For example, closure along the Slave Point Fm across the Rainbow Mbr examples is up to 30 m. In contrast, the Prairie Evaporite Fm is locally 40 m lower on-reef than off-reef. In both examples, post-reef structures result from a combination of differential compaction and salt dissolution. The contrast between the seismic signatures of the reef and off-reef facies is as variable as the estimates of velocity pull-up and time-structural drape. For example, the seismic images of the Winnipegosis Fm are relatively easy to distinguish from those of the Prairie Evaporite Fm. In contrast, the seismic images of the Zama

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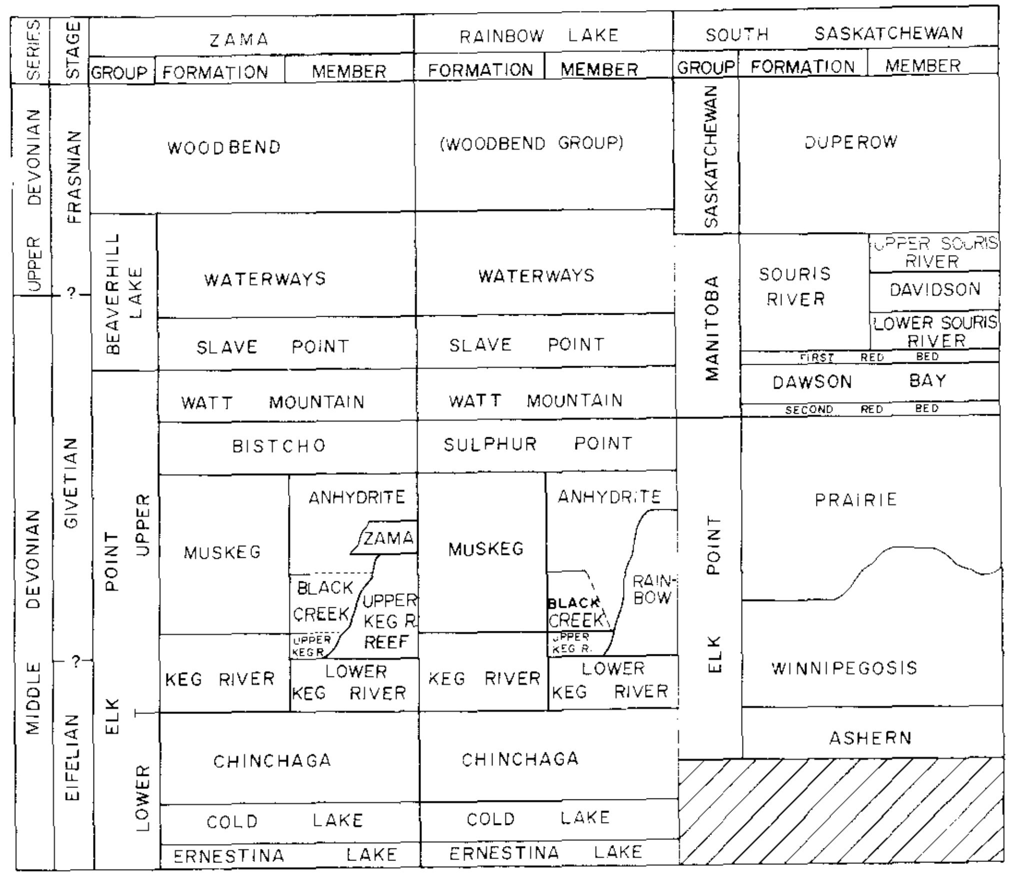


**Figure 2.1.** Stratigraphic correlation chart for part of the Devonian of northern Alberta and southern Saskatchewan. Formations for the general Senex area of north-central Alberta conform closely to those of the Rainbow Lake area but not the subdivisions into members.

Mbr and the adjacent Muskeg Fm sediment cannot be, as a rule, differentiated visually.

In the remainder of this chapter, the Keg River carbonates, essentially of Alberta, that is the Rainbow, Upper Keg River Reef

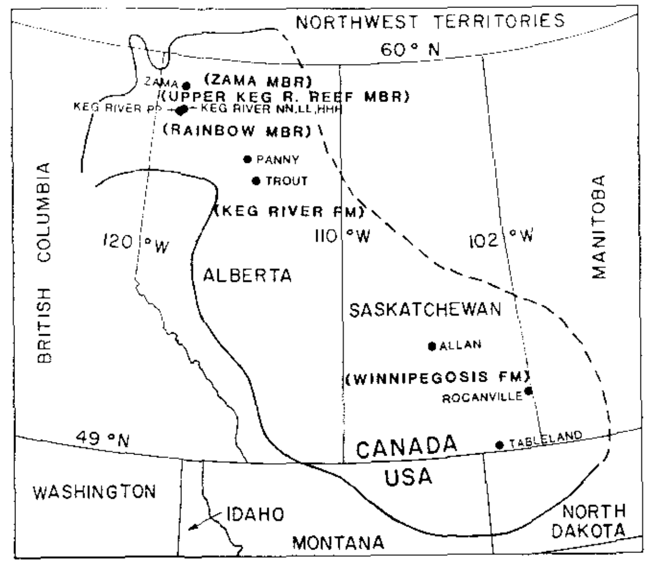


**Figure 2.2.** Map of the Elk Point basin showing the location of the examples discussed in this chapter. The dashed boundary represents an erosional edge (modified after Holter, 1969, Maiklem, 1971 and Williams, 1984).

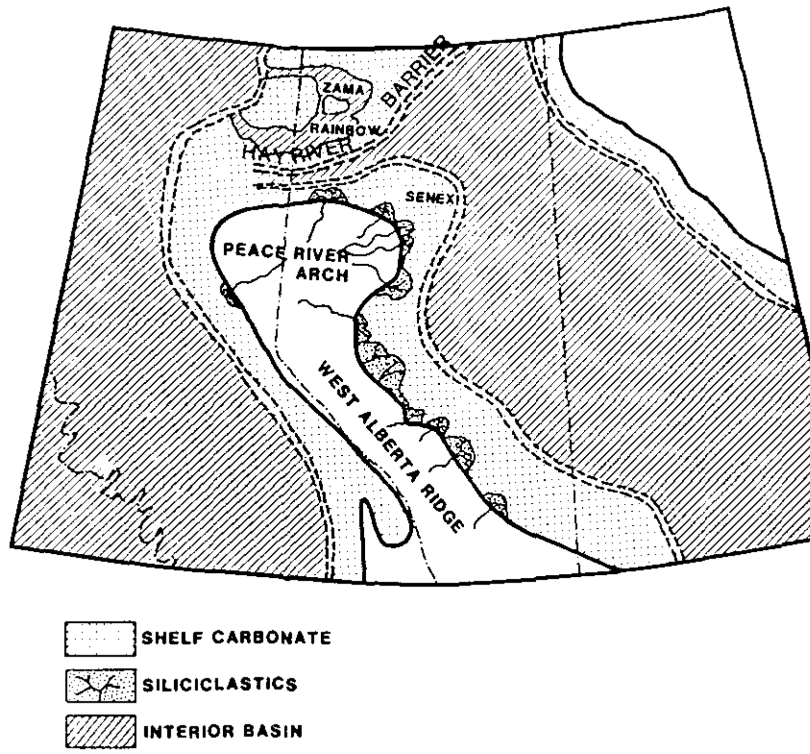


**Figure 2.3.** Paleogeography of the Canadian portion of the Elk Point basin in Keg River time (modified after Campbell, 1987 and Nelson, 1970).

and Zama members and the Keg River Fm itself, are treated in Part A. The Winnipegosis carbonates, essentially of Saskatchewan, are discussed in Part B.

# PART A: KEG RIVER CARBONATES

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## RAINBOW FIELD: Keg River HHH, LL and NN Pools

The Rainbow field is situated in the southeastern part of the Black Creek basin (Fig. 2.2). Oil production (Table 2.1) is principally from the Rainbow Mbr (Fig. 2.1). These reefs are stratigraphic traps, towering up to 200 m above the Lower Keg River Mbr platform and standing encased in the relatively impermeable interlayered dolomites and anhydrites of the Muskeg Fm. Figure 2.4 shows both the approximate location of the example seismic line, the location of the six wells of the geological cross-section (Fig. 2.5) and the estimated areal extent of the Rainbow Mbr bioherms at the Keg River HHH, LL and NN pools. Four of the six wells tied to the seismic line (Fig. 2.6) and incorporated into the geological cross-section penetrate full reef; the other two stand abandoned.

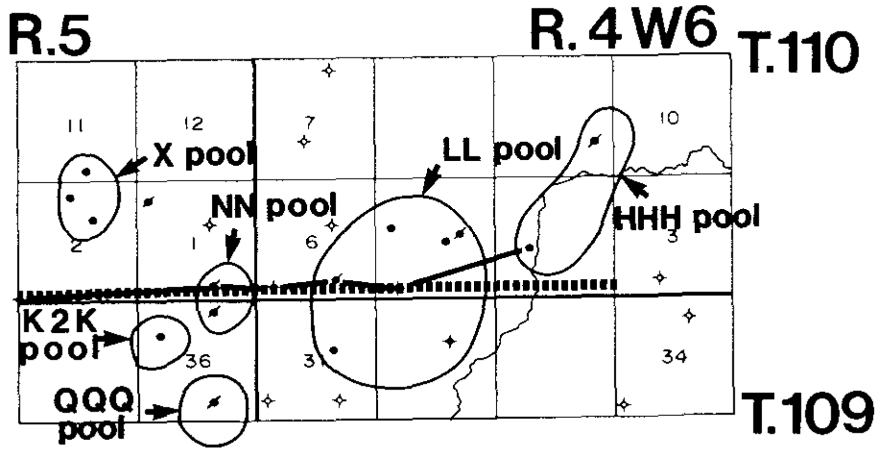


**Figure 2.4.** Area containing the Keg River HHH, LL and NN pools. Pool outlines, the six wells incorporated into the geological cross-section and the approximate location of the seismic section are shown.

**Table 2.1.** Production data for the area of the Keg River HHH, LL and NN pools, Rainbow field (courtesy of Virtual Computing Services Ltd.)

| WELL | FIELD | POOL | PRODUCING ZONE | PRODUCTION DATE | CUMULATIVE PRODUCTION Oil ($m^3$) | Gas ($E^3$ $m^3$) | Water ($m^3$) |
|---|---|---|---|---|---|---|---|
| 10-31-109-4W6 | Rainbow | Keg River LL | Keg River | 06/84 | 14,830.0 | 842.8 | 3,753.0 |
| 10-32-109-4W6 | Rainbow | Keg River LL | Keg River | 09/67 | 17.5 | 1.6 | 0.0 |
| 2-36-109-5W6 | Rainbow | Keg River QQQ | Keg River | 12/68 | 26,205.9 | 1,446.9 | 7,299.6 |
| 12-36-109-5W6 | Rainbow | Keg River K2K | Keg River | 01/86 | 7,393.7 | 626.3 | 1,755.1 |
| 15-36-109-5W6 | Rainbow | Keg River NN | Keg River | 09/67 | 62,817.6 | 4,488.5 | 28,697.9 |
| 6-4-110-4W6 | Rainbow | Keg River HHH | Keg River | 10/67 | 22,946.6 | 1,891.0 | 1,307.8 |
| 4-5-110-4W6 | Rainbow | Keg River LL | Keg River | 08/67 | 19,493.2 | 1,408.8 | 421.1 |
| 7-5-110-4W6 | Rainbow | (Unassigned) | Keg River | 00/00 | 5,787.9 | 783.5 | 95.7 |
| 10-5-110-4W6 | Rainbow | Keg River LL | Keg River | 04/67 | 63,924.0 | 5,299.3 | 2,610.1 |
| 12-5-110-4W6 | Rainbow | Keg River LL | Keg River | 10/84 | 32,159.2 | 1,784.1 | 301.4 |
| 2-6-110-4W6 | Rainbow | Keg River LL | Keg River | 11/68 | 59,430.7 | 3,877.1 | 34,253.4 |
| 8-9-110-4W6 | Rainbow | Keg River HHH | Keg River | 10/68 | 2,104.1 | 93.3 | 2.8 |
| 2-1-110-5W6 | Rainbow | Keg River NN | Keg River | 10/67 | 41,877.1 | 2,432.9 | 32,302.4 |
| 13-1-110-5W6 | Rainbow | (Unassigned) | Keg River | 03/86 | 682.8 | 451.8 | 6.3 |
| 10-2-110-5W6 | Rainbow | Keg River X | Keg River | 12/84 | 13,658.5 | 1,949.6 | 2,317.7 |
| 14-2-110-5W6 | Rainbow | Keg River X | Keg River | 05/66 | 103,187.4 | 14,187.2 | 32,359.2 |
| 2-11-110-5W6 | Rainbow | Keg River X | Keg River | 03/67 | 114,902.9 | 13,609.8 | 1,396.2 |

| FIELD | POOL | PRODUCING ZONE | NUMBER OF WELLS | CUMULATIVE PRODUCTION Oil ($m^3$) | Gas ($E^3$ $m^3$) | Water ($m^3$) |
|---|---|---|---|---|---|---|
| Rainbow | Keg River LL | Keg River | 6 | 189,854.6 | 13,213.7 | 41,339.0 |
| Rainbow | Keg River QQQ | Keg River | 4 | 203,339.9 | 13,137.8 | 27,405.7 |
| Rainbow | Keg River K2K | Keg River | 1 | 7,393.7 | 626.3 | 1,755.1 |
| Rainbow | Keg River NN | Keg River | 2 | 104,694.7 | 6,921.4 | 61,000.3 |
| Rainbow | Keg River HHH | Keg River | 2 | 43,950.7 | 1,984.0 | 1,310.6 |
| Rainbow | Keg River X | Keg River | 3 | 231,748.8 | 29,746.6 | 36,073.1 |

Where no off-reef well control is available, the morphology of the interreef areas, as illustrated in the cross-section, is inferred from the seismic data. The entire line is within the confines of the Black Creek basin.

### GEOLOGICAL CROSS-SECTION

Two of these Keg River pools were tested by two wells each and the third, the LL pool, by six wells (Fig. 2.7). The NN-pool reef is likely a small pinnacle with a basal diameter of less than 1 km and without any pronounced raised rim (Langton and Chin, 1968). In contrast, the larger LL-pool reef could be termed an atoll. However, there is no seismic evidence of a raised reef rim, a feature characteristic of differential compaction between the organic rim and the interior lagoonal facies. Therefore the LL pool is classified as a large pinnacle reef. As contoured, the HHH pool is part of the Hay River barrier, described variously as a carbonate bank or as a chain of isolated reefs (Hriskevich, 1967).

The deepest horizon identified on the geological cross-section (Fig. 2.5), the Chinchaga Fm, overlies the Precambrian, the Basal Red Beds of the flanks of the Peace River and Tathlina arches, and

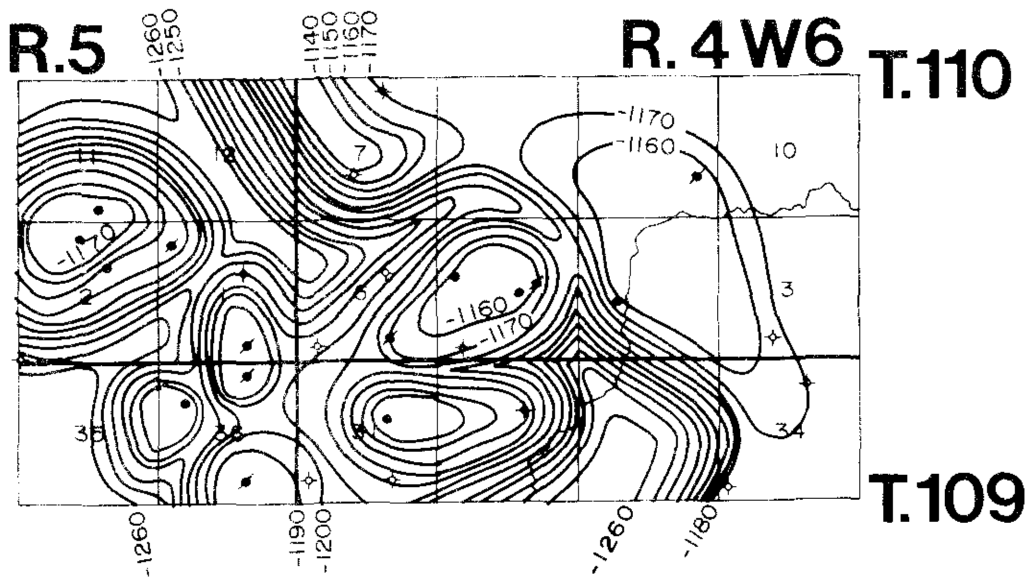


**Figure 2.7.** Structure map (in metres relative to mean sea level) of the Keg River Fm top. This and the subsequent structure maps were constructed from both well-log and available seismic control.

the Cold Lake Fm. The Basal Red Beds and Cold Lake Fm are comprised of low-velocity clastics and salts, respectively, which contrast markedly with the higher-velocity Chinchaga and Precambrian units. Consequently, both the top of the Cold Lake and the base of the Basal Red Beds generate prominent high-amplitude seismic events.

The Chinchaga Fm was penetrated by only one of the four wells on the geological cross-section (Fig. 2.5) and the regional trend shown was estimated from seismic data and regional well control. The Lower Keg River Mbr was also penetrated only once. However, this low-amplitude event could not be correlated confidently across the seismic section and is arbitrarily shown to be parallel to the Chinchaga Fm (Fig. 2.5). Since the boundaries of the Chinchaga, Muskeg, and Slave Point formations are more or less parallel on the seismic section, this extrapolation is reasonable.

The Lower Keg River Mbr is overlain by either the Rainbow Mbr or its off-reef time-equivalent, the Upper Keg River Mbr. As illustrated on the cross-section (Fig. 2.5), the reefal facies stands as much as 170 m above the platform. At their bases these bioherms are flanked by the interreef Upper Keg River Mbr which, nearer the basin depocentre, consists typically of deep-water lutites and reef talus. As these off-reef sediments have not been penetrated in the study area, neither their thickness nor their lithology can be confirmed, nor can they be correlated across the seismic section. They are shown on the cross-section to be slightly thinner than near the basin depocentre, where they are typically 50 m thick. These strata are probably more porous and permeable in the vicinity of the reefs, due to the shallower water and greater availability of reef detritus, than nearer the basin depocentre.

Near the depocentre of the Black Creek basin, the Upper Keg River Mbr is commonly overlain by remnants up to 80 m thick of the Black Creek Mbr salt. These salts were originally widespread throughout the basin but are now areally restricted due to post-depositional dissolution. The most extensive dissolution has occurred around the Rainbow Mbr build-ups and in the shallower parts of the basin. Salt was deposited about the periphery of the reefs in direct contact with porous permeable sediment, either reef or reef-detrital facies, as well as in the shallower parts of the basin where it is believed to have been underlain by sediments that are more porous and permeable than the deep-water lutites nearer the basin depocentre (Anderson, 1986; Brown et al., 1989). Presumably, salt dissolution was caused by waters percolating through these porous and permeable strata. Salt dissolution is interpreted as having occurred in some locations more or less continuously since shortly after deposition.

The Black Creek salt cannot be seen on the seismic section (Fig. 2.6) nor is it present in any of the wells in the study area. Analysis of this seismic data suggests that either the Black Creek salt was never deposited in this part of the basin or else dissolution occurred during Muskeg time. Our rationale for this is outlined below.

Since the Black Creek Mbr was deposited only in interreefal areas, the postdepositional dissolution of this salt would accentuate the closure subsequently developed over the reefs and due primarily to differential compaction. For example, if evaporites around the periphery of a reef were dissolved after the deposition of the Slave Point Fm, then drape along the Slave Point Fm (Fig. 2.8) could be attributed to both differential compaction and salt dissolution. In contrast, if salts were not deposited or if they were dissolved prior to Slave Point time, then closure across the reef at the Slave Point level could only be attributed to differential compaction. Anderson (1986), in a detailed seismic study of several Rainbow Mbr reefs, concluded that differential compaction of the reef and off-reef facies has typically resulted in 15 to 25 m of closure at the Slave Point Fm level. Closure in excess of this range is generally attributable to post-Slave Point salt dissolution.

The Muskeg Fm, like the Slave Point Fm, drapes across the Rainbow Mbr bioherms by 15 to 25 m (Fig. 2.5), in good agreement

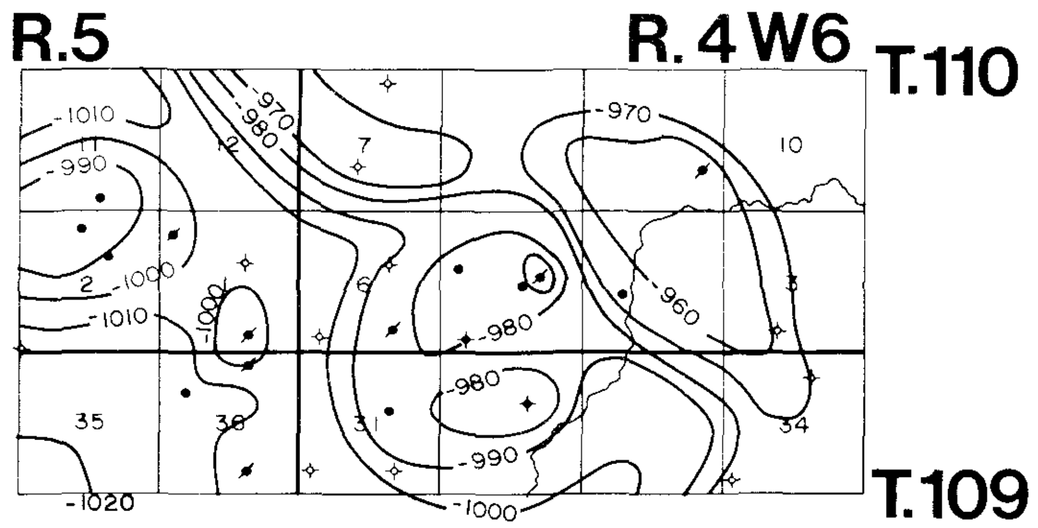


**Figure 2.8.** Structure map of the top of the Slave Point Fm (as Fig. 2.7)

with Anderson (1986). This suggests that, if salts were deposited within the study area, they were dissolved relatively early, i.e. during Muskeg Fm time. It should be kept in mind that structural relief along both the Muskeg and Slave Point formations has been inferred from the seismic data.

The Muskeg Fm, in this area, consists of interlayered dolomite and anhydrite with an average interval velocity greater than that of the encased reefs. As shown in the cross-section (Fig. 2.5), the Muskeg Fm is overlain by the Watt Mountain Fm, the Slave Point Fm and the Wabamun Gp. All of these horizons, except for the Wabamun, drape by up to 25 m across the bioherms due to differential compaction and this closure was probably not accentuated by any late phases of salt dissolution. Drape at the Wabamun top (Fig. 2.9) averages only about 5 m.

The magnitude of drape across the reefs is of significance to the interpretation of the seismic section. For example, note that the Chinchaga Fm in the 6-4 well is overlain by about 410 m of high-velocity (typically about 6000 m/s) sediment comprising the Slave Point/Chinchaga interval. Off-reef, the Slave Point/Chinchaga interval is about 20 m thinner whereas the overlying low-velocity (typically about 3300 m/s) Fort Simpson Fm and Beaverhill Lake Gp shales are about 20 m thicker. This thickening of the high-velocity carbonate section and accompanying thinning of the overlying low-velocity shale section on-reef, generate a significant component of velocity pull-up beneath the reef.

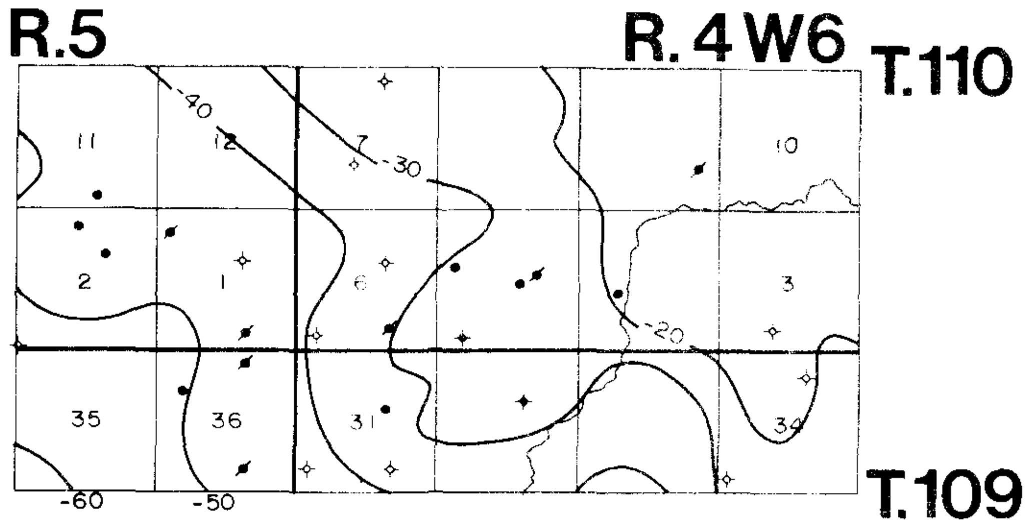


**Figure 2.9.** Structure map of the top of the Wabamun Fm (as Fig. 2.7)

## SEISMIC SECTION

The seismic line (Fig. 2.6) crosses the Keg River HHH, LL and NN pools. These data were recorded in 1981 using single 1-kg charges at depths of 15 m, a 2414-m split spread, 201-m shot intervals, and a 50.3-m group interval. In Figure 2.10, a 1D synthetic seismogram for the 6-4 well (Fig. 2.4) is presented whereas Figure 2.11 shows a 2D synthetic seismic section. The field section (Fig. 2.6) and the synthetic section (Fig. 2.11) correlate well at and beneath the Slave Point event but mistie by about 15 ms at the Wabamun. Such a poor correlation over the Wabamun/Slave Point interval on older vintage logs in the Rainbow area is common and is attributed to problems inherent in logging the Fort Simpson Fm shales. In this regard, Anderson et al. (1988a) illustrated the inaccuracy of older 1960's sonic logs through the Fort Simpson Fm which can involve two-way traveltime errors of the order of 20 ms or more. This is significant in light of the fact that observed thinning of the Wabamun/Slave Point interval of the order of 15 ms is one of the two principal criteria for geophysically interpreting Rainbow Mbr reefs (Anderson and Brown, 1987).

The lowest reflections identified on the seismic section (Fig. 2.6), the Cold Lake and Precambrian events, have not been penetrated by any of the wells of the geological cross-section (Fig. 2.5) but are established regional markers and are therefore confidently identified. The amplitudes of these events and their corresponding isochron values are more or less uniform across the seismic section, suggesting that during the Middle Devonian the Precambrian was locally a

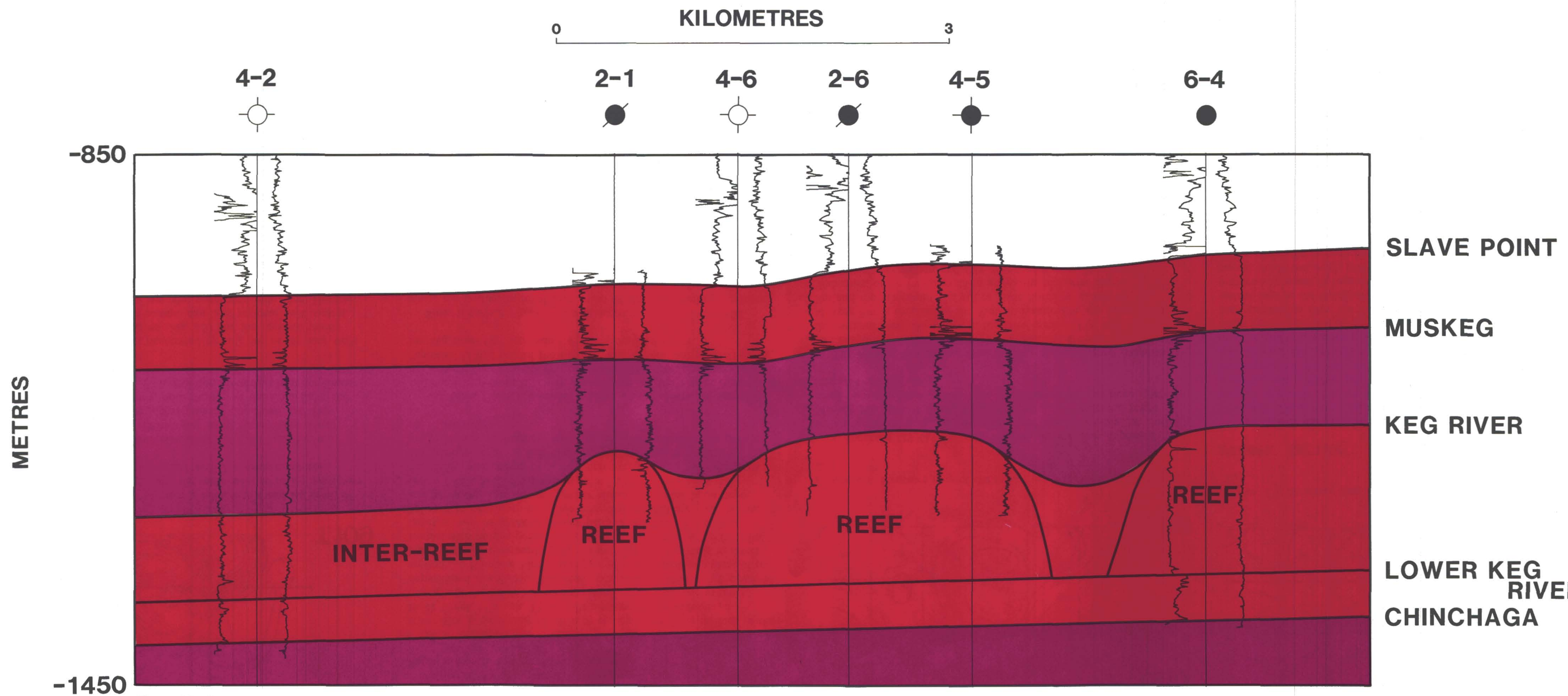


**Figure 2.5.** Geological cross-section, for the line of wells of Figure 2.4 (Keg River HHH, LL and NN pools).



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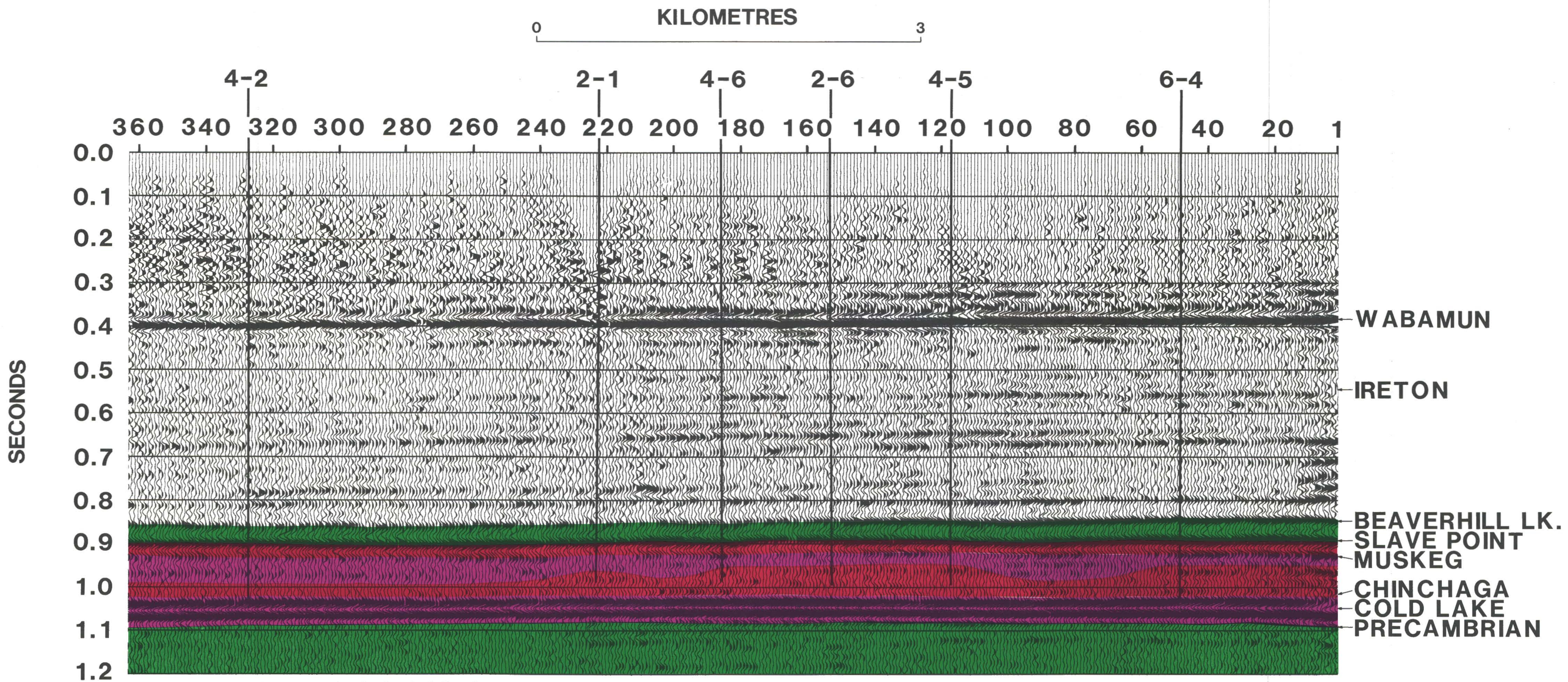


**Figure 2.6.** Normal-polarity seismic section, for the seismic line of Figure 2.4 (Keg River HHH, LL and NN pools).



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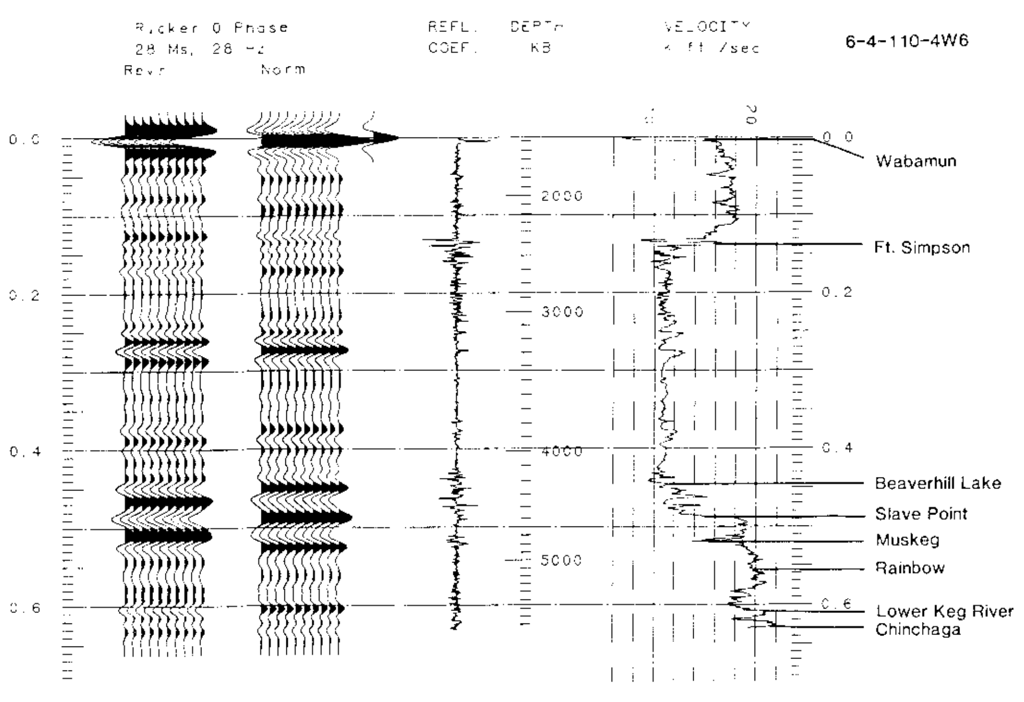
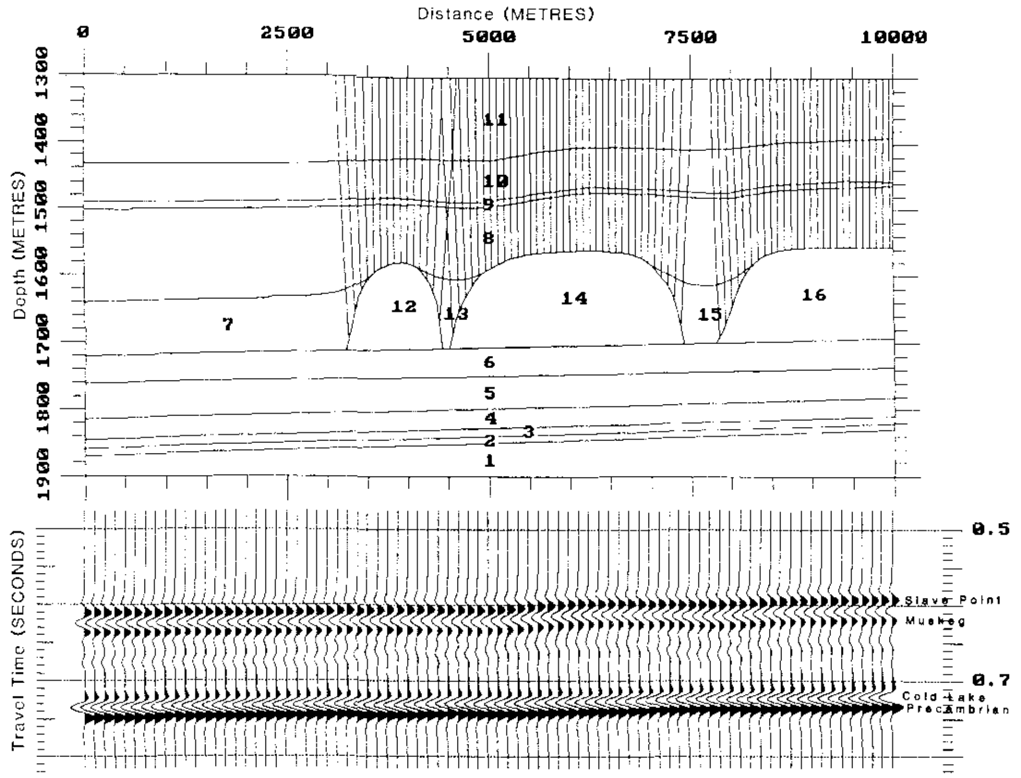



**Figure 2.10.** Synthetic seismogram for the 6-4-110-4W6 well (courtesy of GMA Ltd.).

surface of relatively little relief. Significant structure would have caused lateral variations in the thickness of the Cold Lake/Precambrian interval and corresponding changes in both the isochron values and seismic image. Both the Cold Lake and Precambrian events are about 5 ms high beneath the reefs.

The Chinchaga event is of low amplitude and more or less parallel to the Cold Lake and Precambrian reflections, suggesting that the observed 5 ms of localized relief is velocity-generated. Neither the overlying Lower Keg River, Upper Keg River nor Rainbow events can be correlated with confidence across the seismic section. And even though the average interval velocity of the overlying Muskeg Fm is higher than that of the porous reef, the contact does not generate a pronounced reflection, perhaps because of the heterogeneity of the reef and/or its relatively small areal extent. The seismic images of the Rainbow and Muskeg formations are likewise difficult to differentiate visually. The seismic images of the reefs consist of low- to moderate-amplitude discontinuous reflections, whereas the image of the Muskeg Fm is comprised of events with some lateral continuity. Such continuity may be indicative of nondeposition of the Black Creek Mbr or of an early phase of dissolution. Typically, where extensive post-Muskeg salt dissolution has occurred, the seismic image of the Muskeg Fm consists of discontinuous reflections.




| | Velocity (m/s) | Density (kg/m³) | | Velocity (m/s) | Density (kg/m³) |
|---|---|---|---|---|---|
| (1) Precambrian | 5600<br>5600 | 2650<br>2650 | (2) Basal Red Beds | 4500<br>4500 | 2650<br>2650 |
| (3) Ernestina Lake | 6000<br>6000 | 2750<br>2650 | (4) Cold Lake | 4300<br>4300 | 2200<br>2200 |
| (5) Chinchaga | 5900<br>5900 | 2750<br>2750 | (6) Lower Keg River | 6100<br>6100 | 2750<br>2750 |
| (7) Upper Keg River | 6000<br>6000 | 2750<br>2750 | (8) Muskeg | 6400<br>6400 | 2900<br>2900 |
| (9) Watt Mountain | 4700<br>4700 | 2650<br>2650 | (10) Slave Point | 6300<br>6300 | 2750<br>2750 |
| (11) Beaverhill Lake | 4700<br>4700 | 2650<br>2650 | (12) Rainbow | 5900<br>5900 | 2750<br>2750 |
| (13) Upper Keg River | 6000<br>6000 | 2750<br>2750 | (14) Rainbow | 5900<br>5900 | 2750<br>2750 |
| (15) Upper Keg River | 6000<br>6000 | 2750<br>2750 | (16) Rainbow | 5900<br>5900 | 2750<br>2750 |

**Figure 2.11.** Synthetic seismic section generated from the geological cross-section (Fig. 2.5) using a zero-phase normal-polarity, 30-Hz, Ricker wavelet (courtesy of GMA Ltd.).

As mentioned previously, the Muskeg and Slave Point events are approximately parallel and show about 10 to 12 ms of relief across the reef, indicating that little, if any, salt dissolution has occurred in post-Slave Point time. As shown in the geological cross-section (Fig. 2.5), this 10 to 12 ms of drape translates into structure of 15 to 20 m. The carbonate marker in the Fort Simpson shale also drapes across the reefs (by about 5 ms) whereas no drape can be detected along the Wabamun event. So the seismic evidence is consistent with the well logs, both indicating that the high-velocity (about 6000 m/s) Slave Point/Chinchaga interval is roughly 20 m thicker on-reef than off-reef, and that the low-velocity (about 3300 m/s) Fort Simpson/Slave Point interval is roughly 20 m thicker off-reef than on-reef. The two-way traveltime through 20 m of Fort Simpson shale is about 5 ms greater than through an equivalent thickness of the underlying carbonates, consistent with the observed pull-up below the reefs on the Cold Lake and Precambrian events. Thus, drape at the Slave Point Fm level is evidently the principal cause of this pull-up. Indeed, as noted, the Rainbow Mbr has a lower average interval velocity than the anhydrites and dolomites of the off-reef Muskeg Fm and this, if anything, partially negates pull-up due to structural drape.

## RAINBOW FIELD: Keg River PP Pool

The Keg River PP pool is geographically situated in the Rainbow area of Alberta, near the eastern edge of the Black Creek basin (Fig. 2.12). Production at the Keg River PP pool is from a small pinnacle reef of the Rainbow Mbr sealed by the impermeable interlayered dolomites and anhydrites of the Muskeg Fm (Fig. 2.1) and classified herein as a stratigraphic trap. This reef reservoir was penetrated by the 3-23-109-5W6M well which is incorporated into the geological cross-section (Fig. 2.13), along with the GG-pool reef, penetrated by the 9-17-109-5W6M well. On this cross-section, the stratigraphic and morphological relationships between these Rainbow Mbr reefs and the adjacent sedimentary section are illustrated. Figure 2.12 shows the PP and GG pools, the eastern edge of the Black Creek Mbr salt remnant, the western edge of the Hay River barrier and the approximate locations of both the seismic line and the five wells incorporated into the geological cross-section. The seismic section (Fig. 2.14) crosses the apex of the Rainbow Mbr reef of the PP pool but lies to the north of the Keg River GG-pool build-up.

Production data for the Keg River PP-pool study area are presented in Table 2.2.

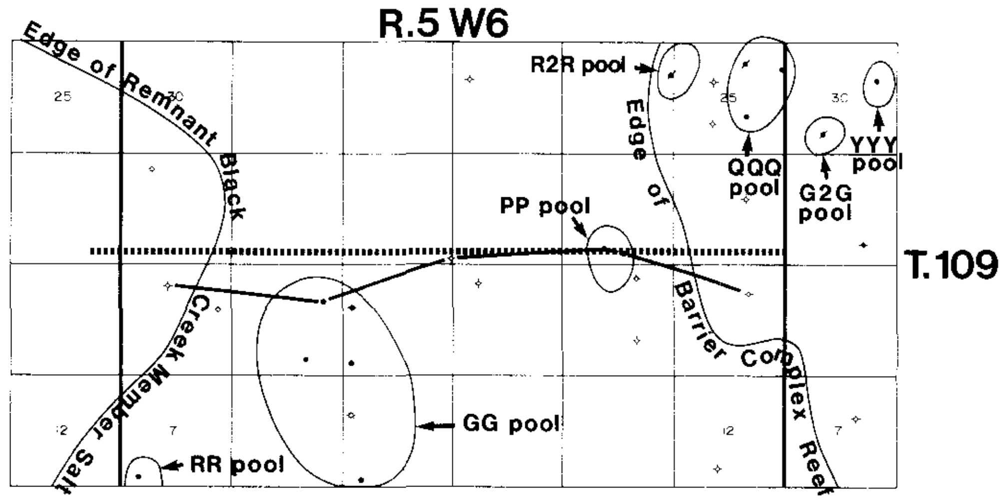



**Figure 2.12.** Keg River PP-pool study area. Pool outlines, the five wells incorporated into the geological cross-section and the location of the seismic line are shown.

**Table 2.2.** Production data for the area of the Keg River PP pool, Rainbow field (courtesy of Virtual Computing Services Ltd.)

| WELL | FIELD | POOL | PRODUCING ZONE | PRODUCTION DATE | CUMULATIVE PRODUCTION Oil (m³) | Gas (E³ m³) | Water (m³) |
|---|---|---|---|---|---|---|---|
| 3-30-109-4W6 | Rainbow | Keg River G2G | Keg River | 12/85 | 300.1 | 9.9 | 142.3 |
| 9-30-109-4W6 | Rainbow | Keg River YYY | Keg River | 11/82 | 11,752.6 | 1,393.4 | 0.0 |
| 4-7-109-5W6 | Rainbow | Keg River RR | Keg River | 02/68 | 203,699.0 | 27,208.8 | 143,028.9 |
| 4-9-109-5W6 | Rainbow | Keg River GG | Keg River | 12/86 | 10,982.1 | 589.3 | 10.5 |
| 12-9-109-5W6 | Rainbow | Keg River GG | Keg River | 06/67 | 2,949.8 | 155.0 | 505.2 |
| 4-16-109-5W6 | Rainbow | Keg River GG | Keg River | 06/85 | 44,546.1 | 2,953.7 | 25.6 |
| 12-16-109-5W6 | Rainbow | Keg River GG | Keg River | 02/67 | 119,176.0 | 5,730.7 | 33,747.7 |
| 2-17-109-5W6 | Rainbow | Keg River GG | Keg River | 02/86 | 20,993.3 | 1,475.3 | 3,667.7 |
| 9-17-109-5W6 | Rainbow | Keg River GG | Keg River | 11/66 | 297,255.2 | 17,142.8 | 70.0 |
| 2-23-109-5W6 | Rainbow | Keg River PP | Keg River | 08/83 | 42,606.5 | 3,162.5 | 1,039.8 |
| 2-23-109-5W6 | Rainbow | Keg River PP | Keg River | 02/68 | 190,669.5 | 23,153.4 | 882.6 |
| 7-25-109-5W6 | Rainbow | Keg River QQQ | Keg River | 03/70 | 90,445.1 | 5,875.5 | 3,070.9 |
| 9-25-109-5W6 | Rainbow | Keg River QQQ | Keg River | 10/86 | 20,792.9 | 1,429.8 | 92.3 |
| 15-25-109-5W6 | Rainbow | Keg River QQQ | Keg River | 03/68 | 65,896.0 | 4,385.6 | 16,942.9 |
| 9-26-109-5W6 | Rainbow | Keg River R2R | Keg River | 03/68 | 939.6 | 420.9 | 887.4 |

| FIELD | POOL | PRODUCING ZONE | NUMBER OF WELLS | CUMULATIVE PRODUCTION Oil (m³) | Gas (E³ m³) | Water (m³) |
|---|---|---|---|---|---|---|
| Rainbow | Keg River G2G | Keg River | 1 | 300.1 | 9.9 | 142.3 |
| Rainbow | Keg River YYY | Keg River | 1 | 11,752.6 | 1,393.4 | 0.0 |
| Rainbow | Keg River RR | Keg River | 1 | 203,699.0 | 27,208.8 | 143,028.9 |
| Rainbow | Keg River GG | Keg River | 6 | 495,902.5 | 28,046.8 | 38,026.7 |
| Rainbow | Keg River PP | Keg River | 2 | 23,327.6 | 26,315.9 | 1,922.4 |
| Rainbow | Keg River QQQ | Keg River | 4 | 192,376.1 | 13,137.7 | 27,393.2 |
| Rainbow | Keg River R2R | Keg River | 1 | 939.6 | 420.9 | 887.4 |

## GEOLOGICAL CROSS-SECTION

The geological cross-section (Fig. 2.13) extends from the eastern edge of a remnant of Black Creek salt (the 14-18 well) towards the western edge of the Hay River barrier (the 10-13 well) and incorporates the 1-21 off-reef well and the 3-23 PP-pool reef well. As illustrated in Figure 2.2, the Hay River barrier separates the

Black Creek basin from the main Elk Point basin to the east. This barrier has been variously postulated to be either a continuous carbonate bank or a chain of isolated reefs with interreef carbonates (Hriskevich, 1970).

The Rainbow Mbr and the carbonates of both the Hay River and Presqu'ile barriers are stratigraphically differentiated, the latter being referred to as undivided Keg River Fm. This convention is followed in the study area in spite of the close proximity of the Rainbow Mbr reef of the PP pool to the interpreted edge of the Hay River barrier and despite the uncertainty as to the exact origin of the barrier locally. Herein the Lower Keg River Mbr is referred to as the platform facies for the Rainbow Mbr reefs whereas the Keg River Fm carbonates of the Hay River barrier are undifferentiated.

The lowest labelled horizons on the geological cross-section, the Precambrian and the Cold Lake Fm, are penetrated by only the 3-23 well (Fig. 2.13). Due to lack of additional deep well control, these horizons are drafted parallel to the overlying Chinchaga Fm. The slopes, as shown, are consistent with regional geological trends and the seismic data. In particular, across the seismic section the Chinchaga/Precambrian interval is more or less uniform with respect to both time-thickness and seismic image, suggesting that the Precambrian was a surface of relatively low relief during the early Devonian.

The overlying Chinchaga Fm is penetrated by two of the wells on the cross-section. The extrapolated slope is consistent with regional geological trends and the seismic data. As shown, the Chinchaga approximately parallels the Lower Keg River Mbr, the platform facies for the Rainbow Mbr. These overlying Rainbow Mbr reefs are thought to have developed on the Lower Keg River Mbr on localized topographic highs, possibly due to underlying basement structure, faulting, dissolution of the Cold Lake Fm salt and/or organic mounds. However, such postulated features, if present, are too subtle to be confidently delineated on the basis of the limited well and seismic control and this horizon is therefore mapped on the geological cross-section as more or less flat.

The Lower Keg River Mbr is overlain by either the Rainbow Mbr or, in off-reef areas, by the Upper Keg River Mbr (Figs. 2.1 and 2.13). In this area, the respective tops of these members constitute the Keg River Fm top, whose structure is illustrated in Figure 2.15. The Lower Keg River Mbr has not been extrapolated beneath the interpreted edge of the undifferentiated Keg River Fm carbonates of the Hay River barrier. As shown in Figure 2.13, the Rainbow Mbr

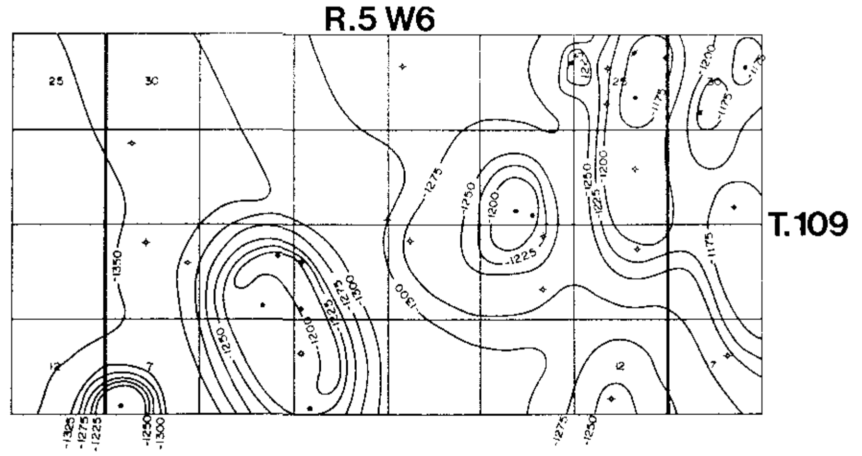



**Figure 2.15.** Structure map of the top of the Keg River Fm (as Fig. 2.7).

pinnacle reef at the PP pool, with an estimated basal diameter of less than 1 km, rises some 180 m above the platform. To the west, near the basin depocentre, these reefs attain thicknesses of over 200 m. The greater thicknesses nearer the basin depocentre reflect the depth of water in the Black Creek basin at the end of Keg River time.

In this area, the Hay River barrier edge is mapped as immediately to the east of the Rainbow Mbr PP pool reef (Fig. 2.12). The off-reef time-equivalent of the Rainbow Mbr and the Hay River barrier carbonates in the Rainbow area is the Upper Keg River Mbr, consisting typically of relatively impermeable deep-water lutites. In the vicinity of the reefs and near the margins of the barrier, significant reef talus is present, probably accompanied by increased overall permeability and possibly influencing the present-day distribution of the Black Creek Mbr salt (Figs. 2.12 and 2.13).

The Black Creek Mbr, the basal unit of the Muskeg Fm (Fig. 2.1), is thought to have been widely distributed in interreef areas within the Black Creek basin. These salts have been subjected to extensive postdepositional dissolution and now exist only as remnants, some of which are up to 80 m thick. Well and seismic control indicate that such residual salt is present only in the westernmost part of the area (Fig. 2.12). However, salt is also believed to have been deposited east of the Hay River barrier, around the reefs throughout this area. This thesis is supported by seismic and well-log data which indicate that the Slave Point/ Muskeg (inclusive) interval off-reef and east of the barrier is thickest where salt remnants are present, implying that dissolution has occurred in post-Slave Point time. The pattern of salt dissolution in the Rainbow area indicates that leaching was most extensive in the vicinity of the reefs and near the bank margins. In these areas, the Upper Keg River Mbr, being comprised partially of reef talus, is probably relatively porous and permeable.

As would be anticipated, the Slave Point Fm drapes across the Rainbow Mbr reef, the Hay River barrier and the residual salt. Drape across the salt is due to post-Slave Point dissolution, whereas drape across the carbonate buildup is due both to differential compaction and to leaching. Interpreted structure at the Slave Point and Wabamun levels, as shown in Figures 2.16 and 2.17, is based on both well and seismic control.

## SEISMIC SECTION

The approximate location of the seismic section is shown on Figure 2.12. These seismic data (Fig. 2.14) were recorded in 1981 using a 2-kg source at a depth of 15 m, a 1632-m split spread, a

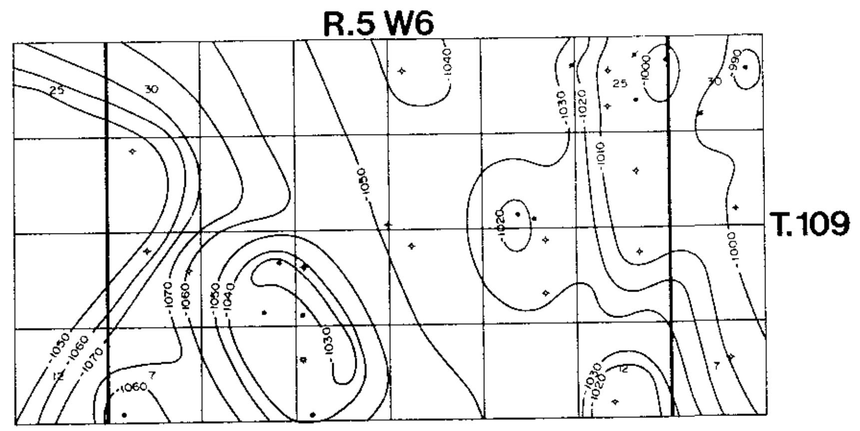



**Figure 2.16.** Structure map of the top of the Slave Point Fm (as Fig. 2.7).

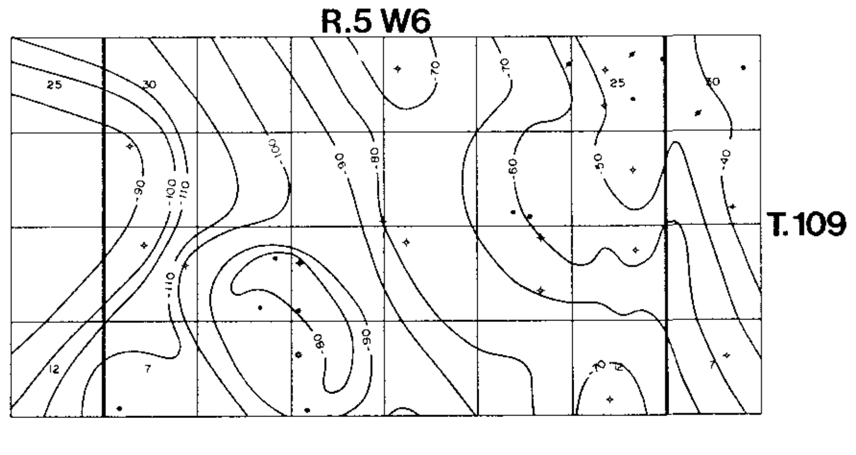



**Figure 2.17.** Structure map of the top of the Wabamun Group (as Fig. 2.7).

136-m source interval and a 34-m group interval. Figures 2.18 and 2.19 show 1D synthetic seismic traces for on-reef (3-23) and off-reef (14-18) wells, indicating the correlation between the subsurface stratigraphy and prominent seismic events. These features are related with even more clarity in the 2D synthetic seismic section of Figure 2.20.

The lowest horizon identified on this section, the Precambrian, correlates with a low-amplitude laterally continuous peak. The amplitude of this event interferes with and is significantly affected by the high-amplitude peak originating from the Ernestina Lake Fm. As shown in Figure 2.13, at the 3-23 well location these horizons are separated by only about 30 m (about 12 ms).

Similarly, the Cold Lake/Ernestina Lake interval is sufficiently small (about 40 m or 10 ms) that the respective reflections interfere. Yet both of these high-amplitude events, and indeed the Precambrian reflection as well, have more or less uniform amplitudes across the seismic section, being only slightly lower beneath the Black Creek salt remnant than elsewhere. The lower amplitudes beneath the salt are probably due to greater seismic attenuation through the salts than through an equivalent thickness of

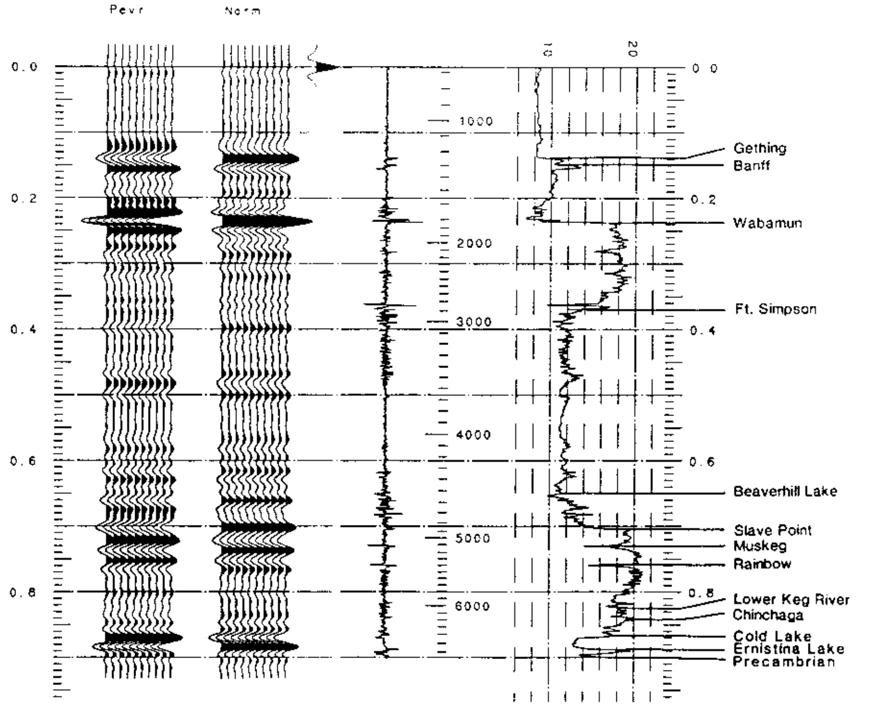



**Figure 2.18.** Synthetic seismogram for the 3-23-109-5W6 on-reef well (courtesy of GMA Ltd.).

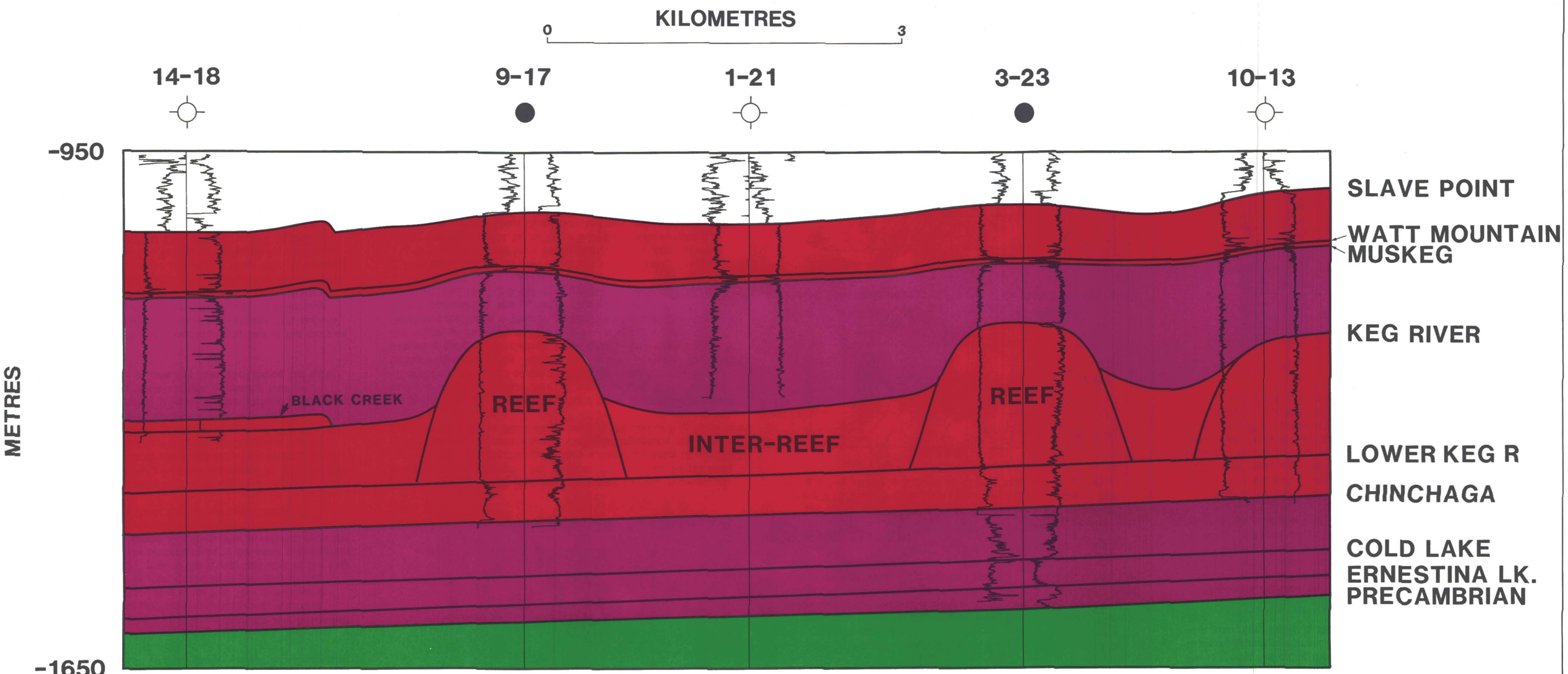



**Figure 2.13.** Geological cross-section for the line of wells of Figure 2.12 (Keg River PP pool).



DRAFTING: | LOG PLOTS: RILEY'S DATASHARE INTERNATIONAL LTD. | AUTHOR: N. ANDERSON ,R.C. HINDS

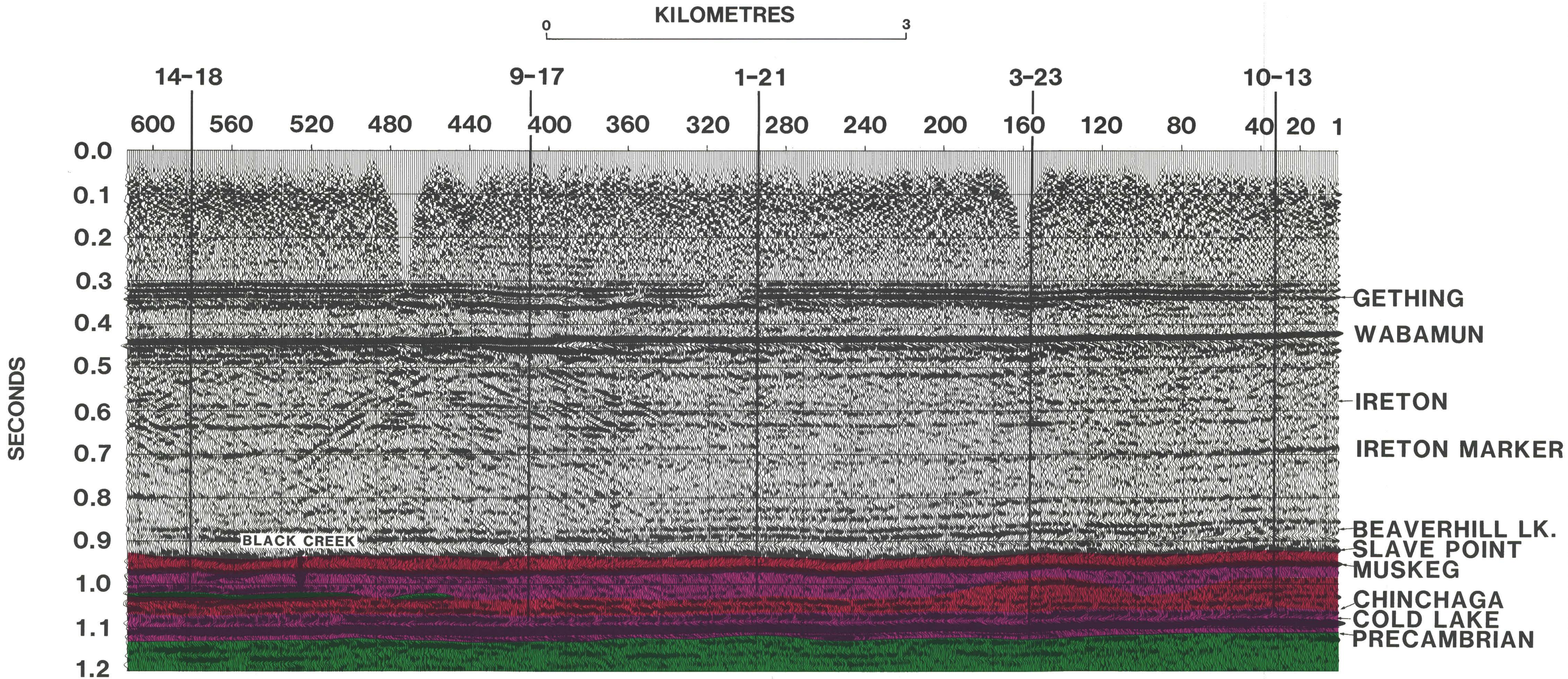



**Figure 2.14.** Normal-polarity seismic section for the seismic line of Figure 2.12 (Keg River PP pool).

DONOR: HI-TECH EXPLORATION SERVICES LTD. | PROCESSOR: VECTOR TECHNOLOGY LTD. | AUTHOR: N. ANDERSON, R.C. HINDS

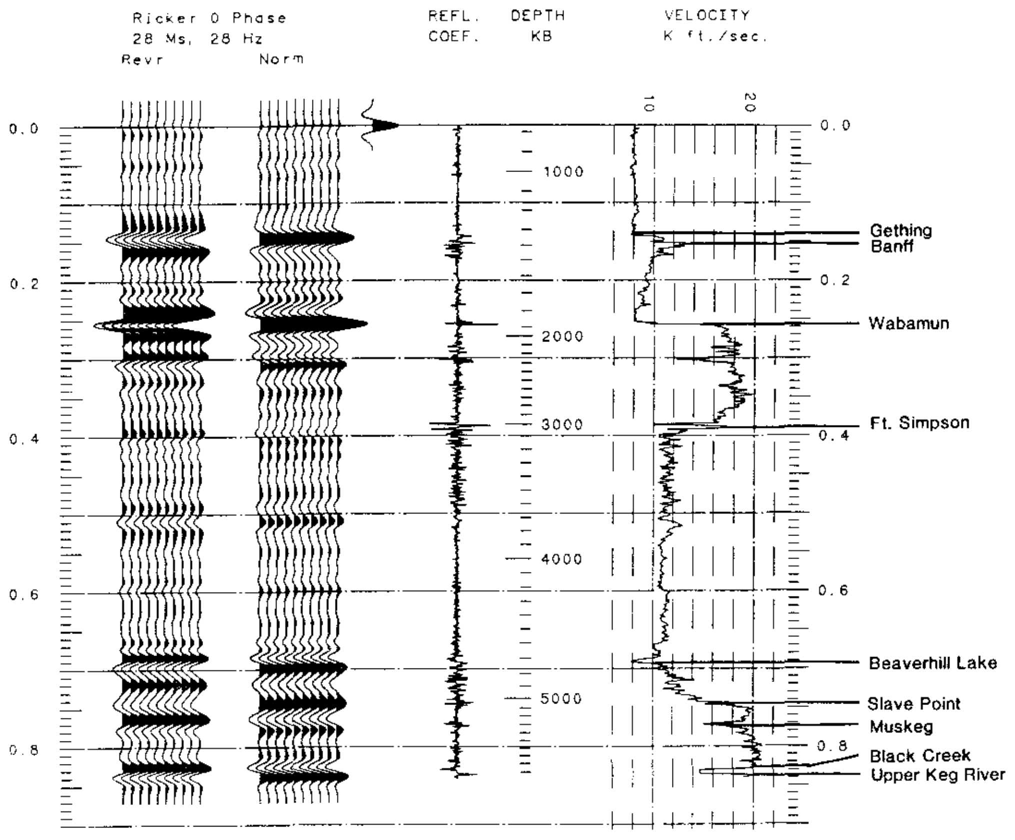
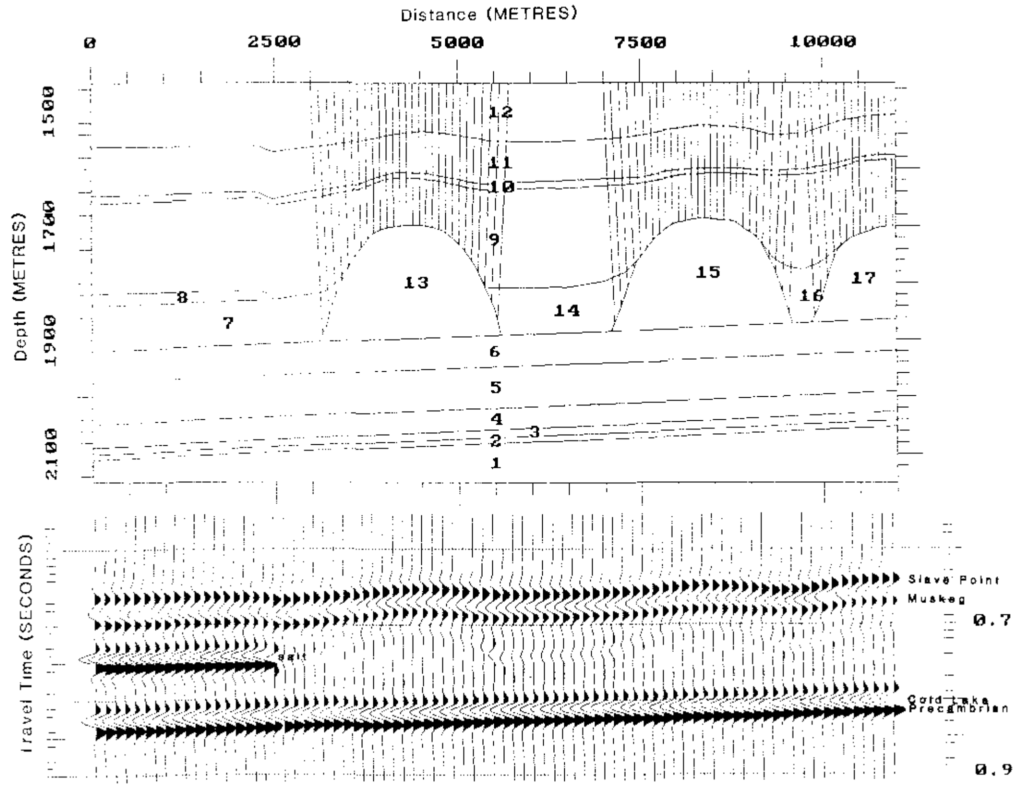



**Figure 2.19.** Synthetic seismogram for the 14-18-109-5W6 off-reef well (courtesy of GMA Ltd.).

carbonates and/or anhydrites. This more or less uniform amplitude suggests that during the Middle Devonian the Precambrian surface had little relief locally. Significant relief would have resulted in appreciable variations in the thicknesses of the Basal Red Beds, Ernestina Lake Fm and Cold Lake Fm and laterally varying interference effects along their respective seismic events.

The overlying Chinchaga event is of low amplitude, is laterally continuous and is more or less parallel to the Precambrian, Ernestina Lake and Cold Lake reflections. In contrast, the Lower Keg River event cannot be correlated confidently across the seismic section. Thus, even if either the Rainbow Mbr or Hay River barrier developed on structures at the Lower Keg River level, they cannot be discerned on these seismic data. The basal Devonian events are time-structurally higher beneath the Rainbow Mbr reef and the western edge of the Hay River barrier than to the west. This relationship indicates that these build-ups may have localized on an upthrown structure of Lower Keg River age. Similar time-structural relief is observed at the Wabamun and basal Cretaceous levels, which may be real and due to erosion or to drape over the Keg River




| | Velocity (m/s) | Density (kg/m³) | | Velocity (m/s) | Density (kg/m³) |
|---|---|---|---|---|---|
| (1) Precambrian | 5600<br>5600 | 2650<br>2650 | (2) Basal Red Beds | 4500<br>4500 | 2650<br>2650 |
| (3) Ernestina Lake | 6000<br>6000 | 2750<br>2750 | (4) Cold Lake | 4300<br>4300 | 2200<br>2200 |
| (5) Chinchaga | 5900<br>5900 | 2750<br>2750 | (6) Lower Keg River | 6100<br>6100 | 2750<br>2750 |
| (7) Upper Keg River | 6000<br>6000 | 2750<br>2750 | (8) Black Creek | 4300<br>4300 | 2200<br>2200 |
| (9) Muskeg | 6400<br>6400 | 2900<br>2900 | (10) Watt Mountain | 4700<br>4700 | 2650<br>2650 |
| (11) Slave Point | 6300<br>6300 | 2750<br>2750 | (12) Beaverhill Lake | 4700<br>4700 | 2650<br>2650 |
| (13) Rainbow | 5900<br>5900 | 2750<br>2750 | (14) Upper Keg River | 6000<br>6000 | 2750<br>2750 |
| (15) Rainbow | 5900<br>5900 | 2750<br>2750 | (16) Upper Keg River | 6000<br>6000 | 2750<br>2750 |
| (17) Rainbow | 5900<br>5900 | 2750<br>2750 | | | |

**Figure 2.20.** Synthetic seismic section generated from the geological cross-section (Fig. 2.13) using a zero-phase normal-polarity, 30-Hz, Ricker wavelet (courtesy of GMA Ltd.).

Fm build-ups. On the other hand, these features may be only apparent and due to statics problems.

As noted, it is difficult to correlate the Lower Keg River event confidently across the seismic line. Within the basin, this horizon underlies either the Rainbow Mbr or its off-reef time-equivalent, the Upper Keg River Mbr, both of which have acoustic impedances similar to that of the platform unit. Where the Keg River Fm carbonates of the Hay River barrier are present, any lateral equivalent of the Lower Keg River Mbr would be similarly difficult to discern.

The high-amplitude Slave Point event drapes across the residual salt and the Keg River Fm build-ups. Drape across the salt is wholly due to post-Slave Point dissolution of the Black Creek Mbr, whereas drape across the carbonate build-up is also partly attributed to differential compaction of the Keg River Fm and an equivalent thickness of off-reef sediment.

The drape of the high-amplitude Wabamun event across the Keg River Fm build-ups is believed to be real and is attributed to differential compaction of reef and off-reef sediments, possibly accentuated by post-Devonian dissolution of the Black Creek Mbr. The diffraction pattern observed near the eastern edge of these remnant salts (Fig. 2.14, around trace 450) suggests that post-Wabamun leaching has occurred. Whether dissolution triggered fault displacement at the Wabamun level, or vice versa, cannot be discerned from these data. Anderson (1986) reported a 20-km long seismically mappable lineament at the Wabamun level across a salt remnant in the Rainbow basin and extensive associated dissolution, suggesting fault-triggered leaching, at least in that case. With respect to the present seismic line, the diffraction could emanate from an erosional feature such as that observed near trace 400.

The reflection from the top of the Upper Keg River Mbr is also difficult to map, except where the Black Creek Mbr salt is sufficiently thick (about 15 m) to be seismically visible. In these areas, the high-velocity Upper Keg River Mbr carbonates are readily distinguished from the relatively low-velocity salts. Elsewhere, the Upper Keg River Mbr is overlain by anhydrites and dolomites of the Muskeg Fm, whose acoustic impedances are not very different from those of the Upper Keg River Mbr.

The Rainbow Mbr and the Keg River Fm carbonates of the Hay River barrier are similarly difficult to differentiate from the encompassing Muskeg Fm. The acoustic-impedance contrasts between these units are small and the seismic images of all three units, where salt is absent, consist of low-amplitude discontinuous reflections.

## ZAMA FIELD: KRV, KRW, KRP2P and KRG Pools

Production at the Zama KRV, KRW, KRP2P and KRG pools (Fig. 2.21) is from the biohermal Upper Keg River Reef Mbr and the overlying biostromal Zama Mbr. In the Introduction to this Atlas the relationship between these reefs (stratigraphic traps encased in relatively impermeable interlayered dolomites and anhydrites) and the overlying Zama Mbr is discussed.

The KRV, KRW, KRP2P and KRG pools are geographically located in the northern part of the Black Creek basin, an area frequently referred to as either the Zama basin or the Zama area (Fig. 2.21). Dispersed throughout this area are numerous isolated pinnacle reefs, collectively termed the Upper Keg River Reef Mbr (McCamis and Griffith, 1967). These reefs are lithologically

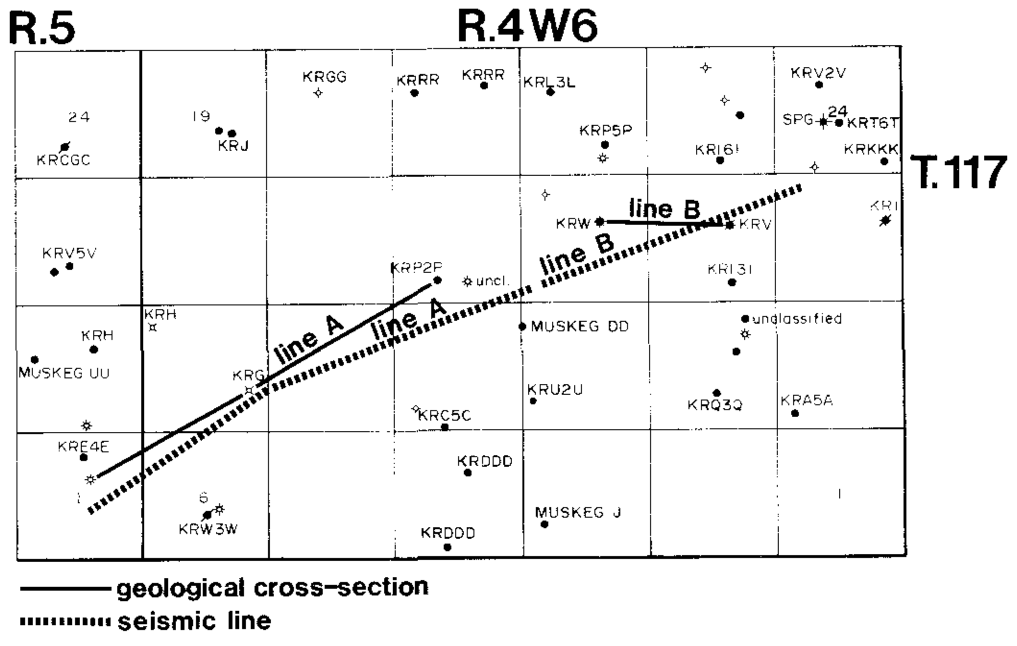



**Figure 2.21.** Zama study area. Pool classifications, the wells incorporated into geologic cross-sections A and B and the locations of the two corresponding seismic lines are shown.

differentiated from the Rainbow reefs of the Rainbow area (southern Black Creek basin) by the presence of the Zama Mbr, a widespread shoaling carbonate facies which is present in the Zama area and absent in the Rainbow area. The Zama Mbr is structurally closed across the Upper Keg River Reef Mbr as a result of differential compaction of the reefs and the off-reef Muskeg Fm facies. This was possibly accentuated by dissolution of the Black Creek Mbr salt in post-Zama time. A typical bioherm of the Upper Keg River Reef Mbr, illustrating the morphological and stratigraphic relationships between these pinnacles and the adjacent sedimentary section, is incorporated into the regional cross-section in the Introduction to this volume.

A plan view of the hydrocarbon pools in the study area and the approximate locations of the seismic and geological cross-sections are shown in Figure 2.21. Production from the example pools is from both the Upper Keg River Reef and Zama members. Table 2.3 summarizes production data for the Zama area.

## GEOLOGICAL CROSS-SECTIONS

All of the wells incorporated into the geological cross-sections of Figures 2.22 and 2.24 penetrate Upper Keg River Reef Mbr bioherms and tie the seismic line as indicated. The morphology of the interreef area has been inferred from the seismic data (Figs. 2.23 and 2.25).

The deepest horizon identified on these geological cross-sections is the Precambrian, which is overlain, in turn, by the Basal Red Beds, the Cold Lake Fm and the Chinchaga Fm. Since the 10-14 well (Fig. 2.24) is the only one to penetrate all of these strata, their regional dips could not be determined from the exhibited well logs. Rather, they were estimated from an analysis of more regional well control and the seismic section. The seismic data suggest that both the Precambrian (an erosional surface) and the overlying strata are reasonably well represented as planar surfaces. The Basal Red Beds are overlain by the Cold Lake Fm, the top of which generates a high-amplitude reflection, a diagnostic marker in analysis of the overall seismic signatures of the Upper Keg River Reef Mbr.

The Chinchaga Fm underlies the Lower Keg River Mbr platform. Although this platform is shown to be flat across the geological cross-sections (Figs. 2.22 and 2.24), it is conceivable that the reefs developed on slight topographic highs on the platform, possibly localized crinoid meadows (Langton and Chin, 1968), which cannot be resolved seismically.

**Table 2.3.** Production data for the Zama study area (courtesy of Virtual Computing Services Ltd.)

| WELL | FIELD | POOL | PRODUCING ZONE | PRODUCTION DATE | CUMULATIVE PRODUCTION Oil ($m^3$) | Gas ($E^3$ $m^3$) | Water ($m^3$) |
|---|---|---|---|---|---|---|---|
| 5-3-117-4W6 | Zama | Muskeg J | Muskeg | 04/67 | 41,164.7 | 1,790.1 | 116.6 |
| 3-4-117-4W6 | Zama | Keg River OOO | Keg River | 08/67 | 51,796.2 | 2,553.6 | 5,232.9 |
| 10-4-117-4W6 | Zama | Keg River OOO | Keg River | 10/67 | 45,746.8 | 2,109.6 | 18,398.2 |
| 7-6-117-4W6 | Zama | Keg River W5W | Keg River | 01/71 | 30,556.0 | 1,708.4 | 583.5 |
| 8-7-117-4W6 | Zama | Keg River O | Keg River | 02/67 | 92,394.0 | 3,975.7 | 40,366.9 |
| 13-7-117-4W6 | Zama | Keg River P | Keg River | 02/67 | 20,489.1 | 866.9 | 9,676.8 |
| 3-9-117-4W6 | Zama | Keg River C5C | Keg River | 04/74 | 57,077.9 | 2,943.3 | 7,275.0 |
| 4-10-117-4W6 | Zama | Keg River U2U | Keg River | 02/68 | 66,266.9 | 4,194.6 | 3,691.0 |
| 4-10-117-4W6 | Zama | (Unclassified) | | 04/85 | 473.5 | 13.7 | 1,374.0 |
| 13-10-117-4W6 | Zama | Muskeg DD | Muskeg | 10/68 | 16,751.5 | 970.5 | 445.3 |
| 7-11-117-4W6 | Zama | Keg River Q3Q | Keg River | 04/69 | 30,499.5 | 2,481.0 | 4,851.7 |
| 10-11-117-4W6 | Zama | (Unclassified) | | | 421.0 | 13.8 | 2.4 |
| 16-11-117-4W6 | Zama | Keg River I3I | Keg River | 03/87 | 2,517.3 | 154.4 | 2,452.8 |
| 4-12-117-4W6 | Zama | Keg River A5A | Keg River | 04/73 | 6,050.7 | 31,758.9 | 7,105.0 |
| 9-13-117-4W6 | Zama | Keg River I | Keg River | 03/67 | 670.1 | 31.1 | 309.5 |
| 2-14-117-4W6 | Zama | Keg River I3I | Keg River | 03/68 | 120,086.3 | 6,746.2 | 96,710.5 |
| 10-14-117-4W6 | Zama | Keg River V | Keg River | 04/67 | 73,883.4 | 1,872.0 | 13,210.8 |
| 10-15-117-4W6 | Zama | Keg River W | Keg River | 04/67 | 50,356.9 | 3,184.1 | 50,094.9 |
| 2-16-117-4W6 | Zama | (Unclassified) | | | 0.0 | 2,089.1 | 0.0 |
| [illegible]-16-117-4W6 | Zama | (Unclassified) | | | 0.0 | 2,120.1 | 0.0 |
| 3-16-117-4W6 | Zama | Keg River F2F | Keg River | 05/68 | 52,766.3 | 4,484.6 | 14,961.4 |
| 7-19-117-4W6 | Zama | Keg River J | Keg River | 04/67 | [illegible] | 551.4 | 6,851.4 |
| 7-19-117-4W6 | Zama | Keg River J | Keg River | 07/81 | 19,355.5 | 1,064.8 | 2.9 |
| 11-20-117-4W6 | Zama | Keg River GG | Keg River | 05/67 | 99,231.1 | 5,967.8 | 115,669.4 |
| 10-21-117-4W6 | Zama | Keg River RR | Keg River | 06/68 | 20,821.7 | 1,086.2 | 22,903.6 |
| 12-21-117-4W6 | Zama | Keg River RR | Keg River | 07/67 | 35,501.3 | 2,562.8 | 7,489.7 |
| 2-22-117-4W6 | Zama | Keg River P5P | Keg River | 02/84 | 25,340.9 | 1,483.8 | 5,085.5 |
| 12-22-117-4W6 | Zama | Keg River L3L | Keg River | 08/67 | 47,371.3 | 3,134.7 | 34,279.6 |
| 2-23-117-4W6 | Zama | Keg River I6I | Keg River | 06/85 | 15,925.6 | 1,084.7 | 1,205.6 |
| 1-24-117-4W6 | Zama | Keg River K | Keg River | 03/67 | 3[illegible],714.4 | 2,114.5 | 9,943.2 |
| 6-24-117-4W6 | Zama | Sulphur Point G | Sulphur Point | 03/67 | 0.0 | 748.5 | 0.0 |
| 7-24-117-4W6 | Zama | Keg River I6I | Keg River | 11/86 | 4,970.1 | 525.5 | 1,900.6 |
| 11-24-117-4W6 | Zama | Keg River V2V | Keg River | 11/68 | 8,024.8 | 437.2 | 3,602.4 |
| 15-1-117-5W6 | Zama | Keg River E4E | Keg River | 03/70 | 42,153.3 | 2,029.3 | 64,540.6 |
| 10-12-117-5W6 | Zama | Keg River H | Keg River | 03/67 | 377,173.3 | 15,117.8 | 413,336.5 |
| 12-12-117-5W6 | Zama | Muskeg JJ | Muskeg | 03/84 | 5,653.0 | 192.7 | 5,823.2 |
| 6-13-117-5W6 | Zama | Keg River V5V | Keg River | 01/84 | 6,883.0 | 397.0 | 1,868.8 |
| 3-24-117-5W6 | Zama | Keg River C6C | Keg River | 12/84 | 1,353.0 | 343.4 | 68.6 |

Off-reef, the Lower Keg River Mbr is overlain by Keg River interreef sediments. The thicknesses of these sediments cannot be determined confidently either seismically or geologically. Typically they consist of reef detritus which is lithologically different from the Upper Keg River Mbr of the Rainbow area, the deep-water off-reef equivalent of the Rainbow Mbr (McCamis and Griffith, 1967).

The Upper Keg River Reef Mbr build-ups shown on the geological cross-sections are roughly circular in plan view, with seismically estimated basal diameters of about one kilometre. They rise about 100 m above the platform facies. Typically, these isolated bioherms do not exhibit seismically recognizable raised rims and are therefore classified as pinnacles. Most of these reefs have been tested by only one well (additional wells would provide corroborative estimates of relief) and it is often difficult to differentiate the reef tops seismically from the Zama Mbr (Figs. 2.23 and 2.25).

The Upper Keg River Reef Mbr and the interreef sediment are overlain by interlayered dolomites and anhydrites of the Muskeg Fm. Throughout much of the Zama area (and possibly within the study area) the interreef sediment was originally overlain by up to 80 m of salt of the Black Creek Mbr, which, if indeed deposited within this area, has subsequently been dissolved. The distribution of the Black Creek salts is probably related to the nature of the underlying interreef sediment. The Black Creek Mbr is more widespread in the Rainbow Area where it overlies the deep-water Upper Keg River Mbr. In the Zama area, the salts were deposited above the more porous reef detritus and have since been extensively dissolved (McCamis and Griffith, 1967). Both the Upper Keg River Reef Mbr build-ups and the Black Creek Mbr salts were overlain by interlayered dolomites and anhydrites. Within the area the Zama Mbr rests more or less directly upon the Upper Keg River Reef Mbr, whereas off-reef its stratigraphic location is uncertain. If thick salts were initially deposited and subsequently dissolved, the Zama Mbr or lateral equivalent may presently overlie interreef sediments. Alternatively, if salts were never deposited, structural relief along the Zama Mbr may parallel that along the Slave Point Fm, depending on the depth of water in which the off-reef Zama Mbr was deposited. Estimates of closure at the Zama Mbr across these reefs range from a minimum of 30 m (relief along the overlying Slave Point Fm) to a maximum of 100 m (assuming that, as a result of salt dissolution, the Zama Mbr rests unconformably above a thin veneer of interreef detritus). Well control would be required to constrain these closure estimates since the Zama Mbr cannot be resolved confidently across the seismic line.

In contrast, closure along the Slave Point Fm can be estimated seismically and is on the order of 30 m. This relief is attributed both to the differential compaction of reef and off-reef sediments and to post-Slave Point dissolution of the Black Creek Mbr salts. In a detailed study of several reefs of the Upper Keg River Reef Mbr, Anderson (1986) concluded that differential compaction probably generated between 15 and 25 m of the relief observed along the Slave Point Fm horizon. If these estimates are realistic, then 5 to 15 m of salt was probably dissolved in post-Slave Point Fm time within the area. Anderson (1986) also concluded, on the basis of seismic data, that salt dissolution within the Black Creek basin likely occurred from shortly after deposition to as late as post-Mississippian time. Therefore, significantly more dissolution-induced structure could be present at the Zama Mbr level than along the Slave Point Fm.

## SEISMIC SECTIONS

Figure 2.21 shows the approximate locations of the seismic lines relative to the pools. These data (Figs. 2.23 and 2.25) were recorded in 1981 using dynamite (single charges of 2 kg at 18-m depths), a 1200-m split spread, a 100-m shotpoint spacing and a 50-m group interval. A 2D synthetic section corresponding to line A (Figs. 2.22 and 2.23) appears as Figure 2.26 whereas Figure 2.27 shows a 1D synthetic corresponding to the 10-14 well of line B (Figs. 2.24 and 2.25).

The two time-structurally lowest reflections identified on the seismic sections (Figs. 2.23 and 2.25) are the Precambrian and Cold Lake events. These two high-amplitude reflections are of uniform amplitude across the seismic sections and exhibit consistent isochron values, suggesting that the Precambrian and the Cold Lake horizons are essentially flat. The slight decrease in amplitude along these events beneath the two reefs is attributed to differential attenuation within reef and off-reef sediment and not to any lateral variations in either thickness or lithology. Furthermore, the local time-structural highs beneath these reefs (about 8 ms) is ascribed entirely to velocity pull-up and not to any basement topography.

The low-amplitude reflection from the Chinchaga Fm is confidently correlated across the seismic section, whereas the Lower Keg River event is not. The uncertainty as to the nature of the interreef sediment (detritus, Muskeg Fm dolomites or anhydrites) makes the uncontrolled correlation of the Lower Keg River event tenuous at best. The Chinchaga event parallels the Cold Lake event, supporting the incorporation of flat interfaces on the geological cross-section and the conclusion that the observed local time-structural highs beneath the reefs are velocity-generated.

The seismic image of the reefs (shaded purple in Figs. 2.23 and 2.25) is comprised of relatively low-amplitude discontinuous reflections bounded by the low-amplitude Lower Keg River and Upper Keg River Reef events. The seismic image of the off-reef Muskeg Fm similarly consists of low-amplitude discontinuous events which are difficult to distinguish visually from the seismic image of the reef. The discontinuous incoherent character of the seismic image of the Muskeg Fm is more consistent with the concept of postdepositional salt dissolution and associated collapse than with nondeposition. If Black Creek Mbr salt had not been deposited in the area, the seismic image of the Muskeg Fm would likely have a more uniform reflection pattern.

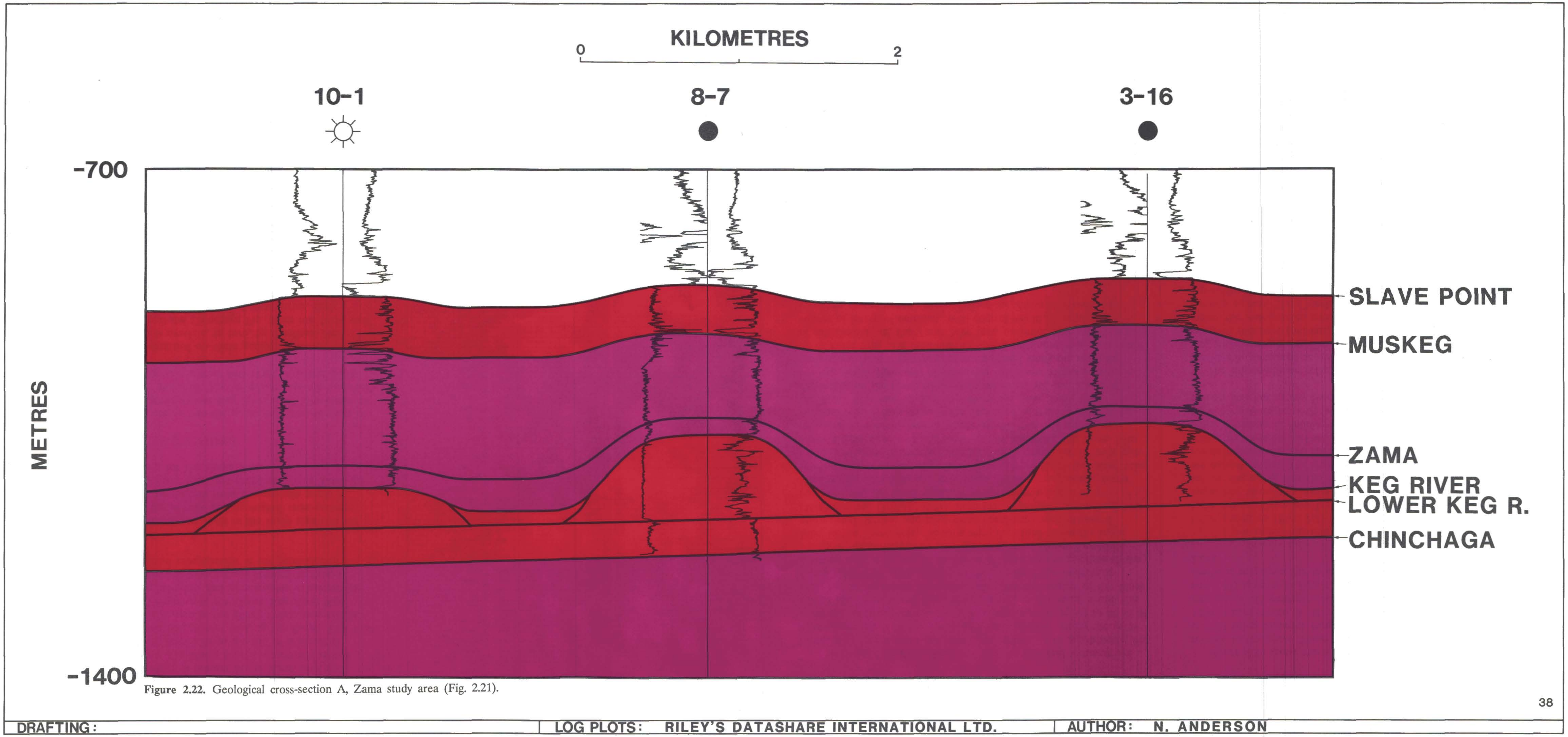



**Figure 2.22.** Geological cross-section A, Zama study area (Fig. 2.21).

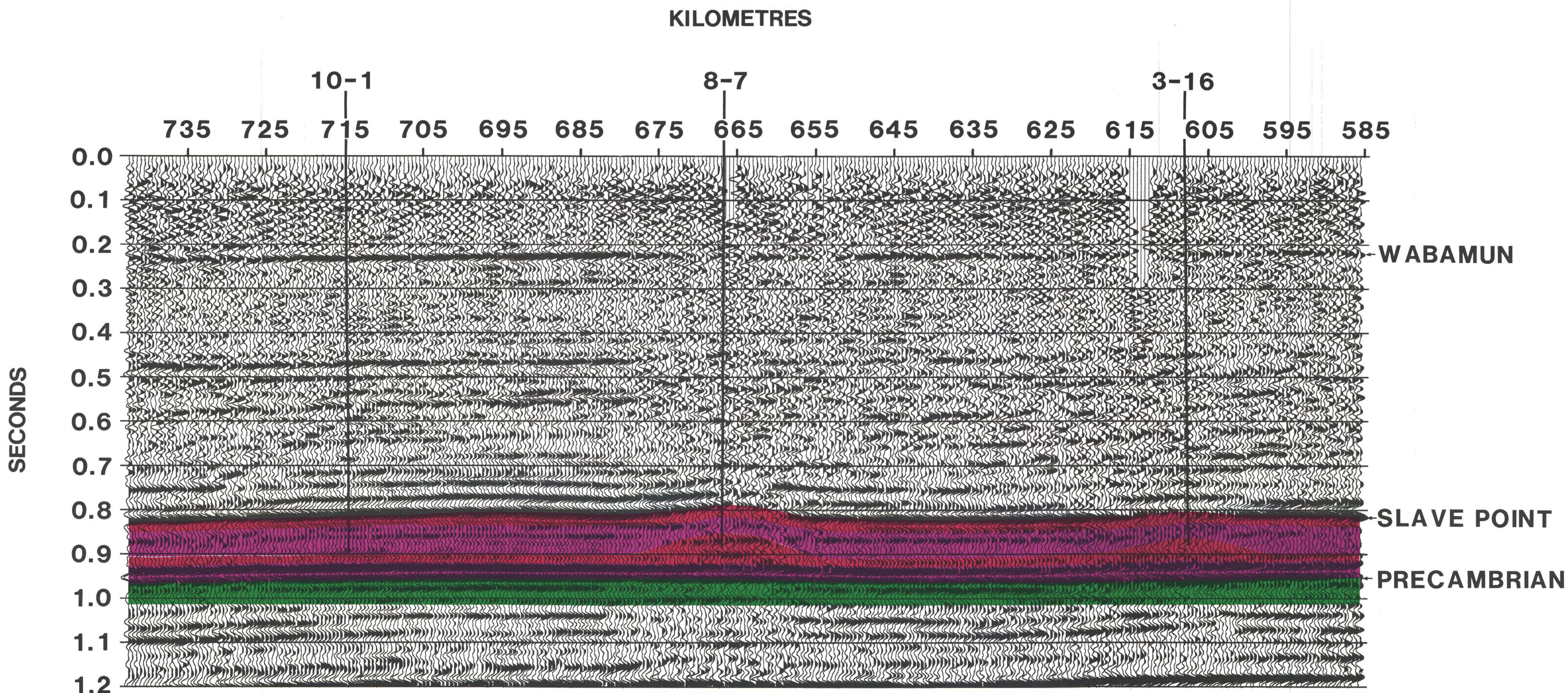



**Figure 2.23.** Normal-polarity seismic section A, Zama study area (Fig. 2.21).



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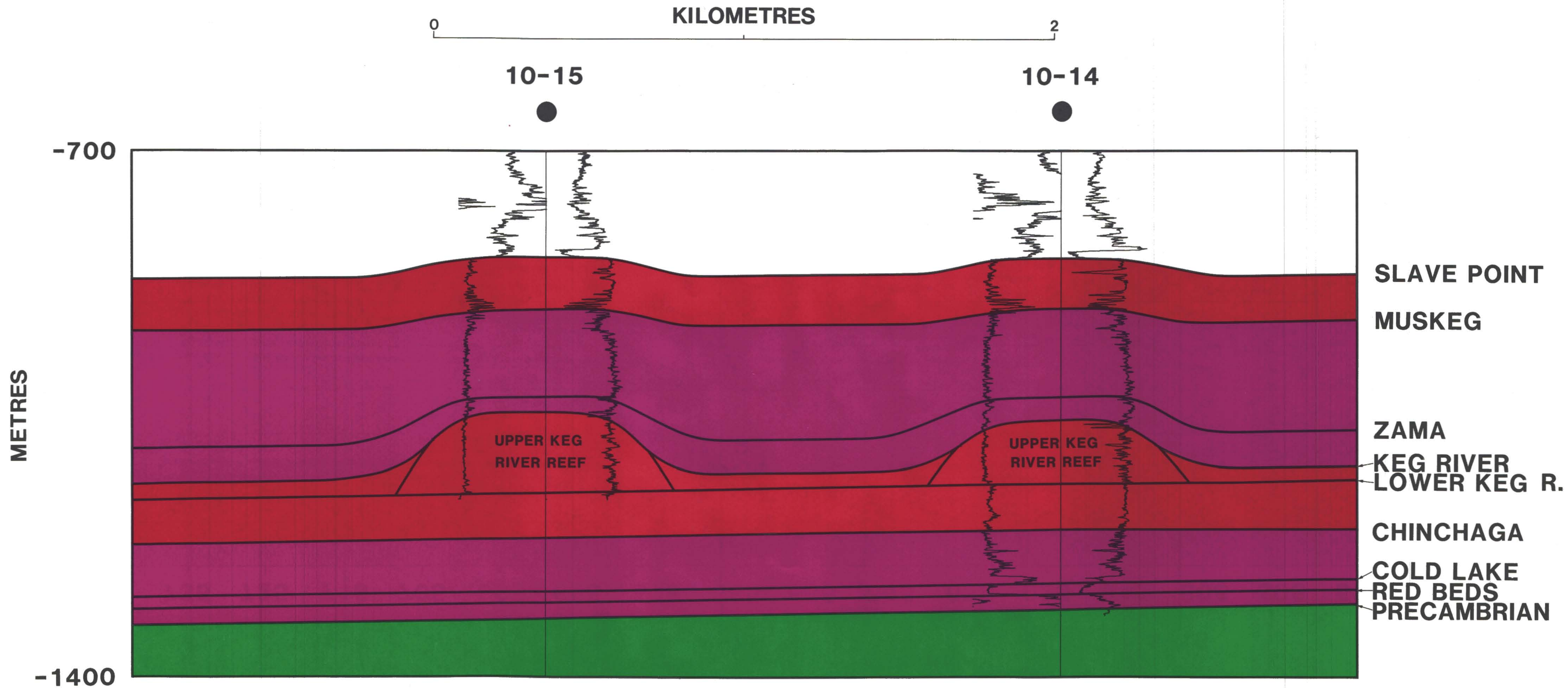


**Figure 2.24.** Geological cross-section B, Zama study area (Fig. 2.21).



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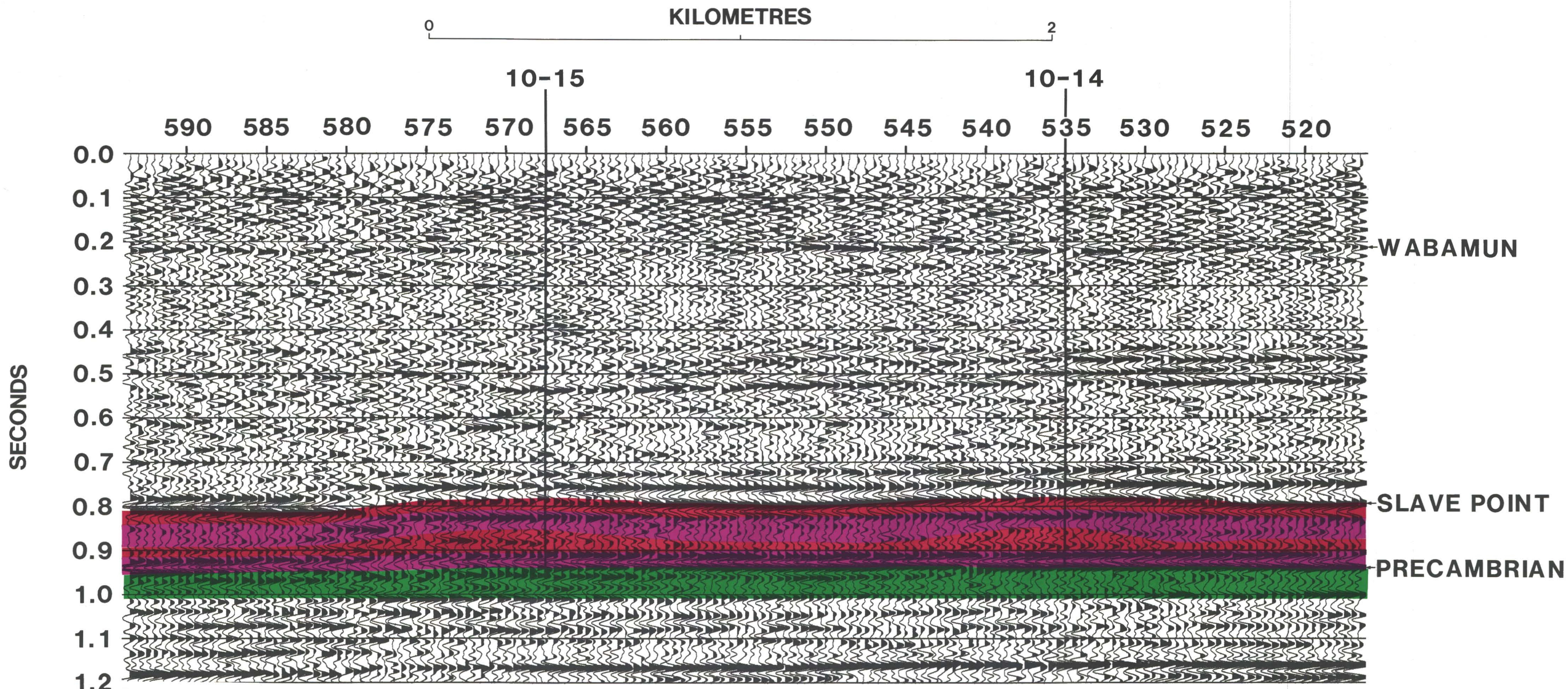
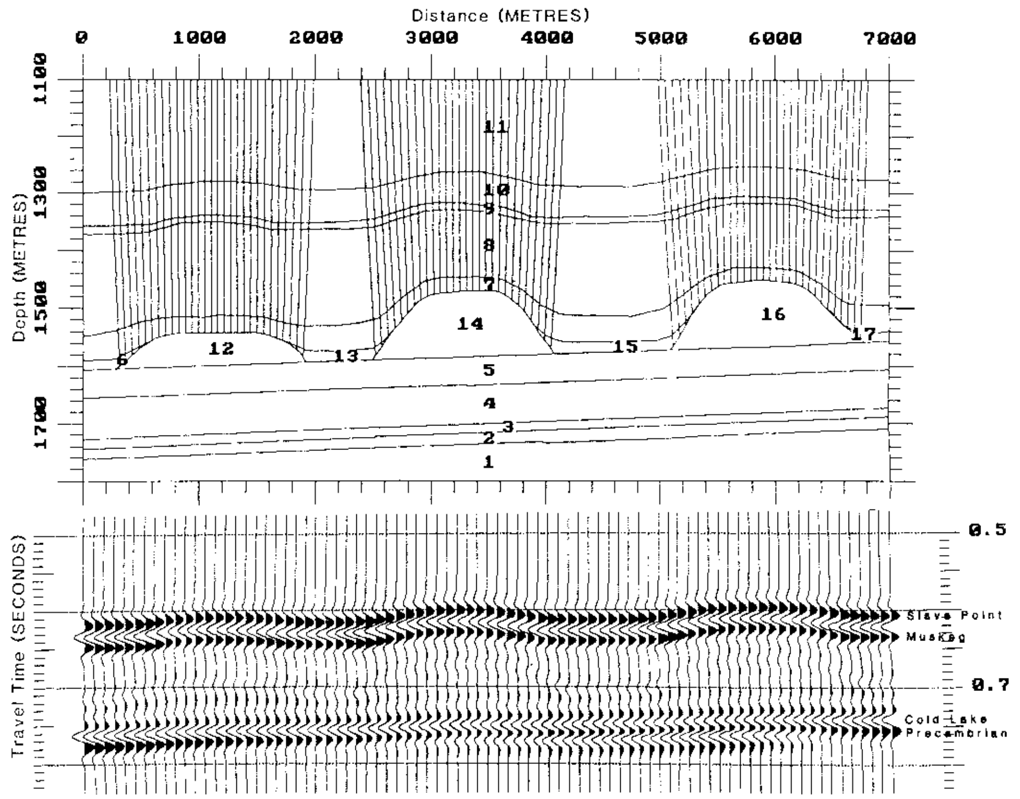



**Figure 2.25.** Normal-polarity seismic section B, Zama study area (Fig. 2.21).

DONOR: GEO-TRADES, A DIVISION OF GRANT GEOPHYSICAL LTD. | PROCESSOR: INVERSE THEORY AND APPLICATIONS INC. | AUTHOR: N. ANDERSON




| | Velocity (m/s) | Density (kg/m³) | | Velocity (m/s) | Density (kg/m³) |
|---|---|---|---|---|---|
| (1) Precambrian | 5600<br>5600 | 2650<br>2650 | (2) Basal Red Beds | 4500<br>4500 | 2650<br>2650 |
| (3) Cold Lake | 4300<br>4300 | 2200<br>2200 | (4) Chinchaga | 5600<br>5600 | 2750<br>2750 |
| (5) Lower Keg River | 6000<br>6000 | 2250<br>2250 | (6) Upper Keg River | 5800<br>5800 | 2750<br>2750 |
| (7) Muskeg | 6100<br>6100 | 2900<br>2900 | (8) Muskeg | 6100<br>6100 | 2900<br>2900 |
| (9) Watt Mountain | 4200<br>4200 | 2650<br>2650 | (10) Slave Point | 5800<br>5800 | 2750<br>2750 |
| (11) Beaverhill Lake | 4200<br>4200 | 2650<br>2650 | (12) Upper Keg River | 5800<br>5800 | 2750<br>2750 |
| (13) Upper Keg River | 5800<br>5800 | 2250<br>2250 | (14) Upper Keg River | 5800<br>5800 | 2750<br>2750 |
| (15) Upper Keg River | 5800<br>5800 | 2250<br>2250 | (16) Upper Keg River | 5800<br>5800 | 2750<br>2750 |
| (17) Upper Keg River | 5800<br>5800 | 2750<br>2750 | | | |

**Figure 2.26.** Synthetic seismic section generated from geological cross-section A (Fig. 2.22) using a zero-phase normal-polarity, 30-Hz, Ricker wavelet (courtesy of GMA Ltd.).

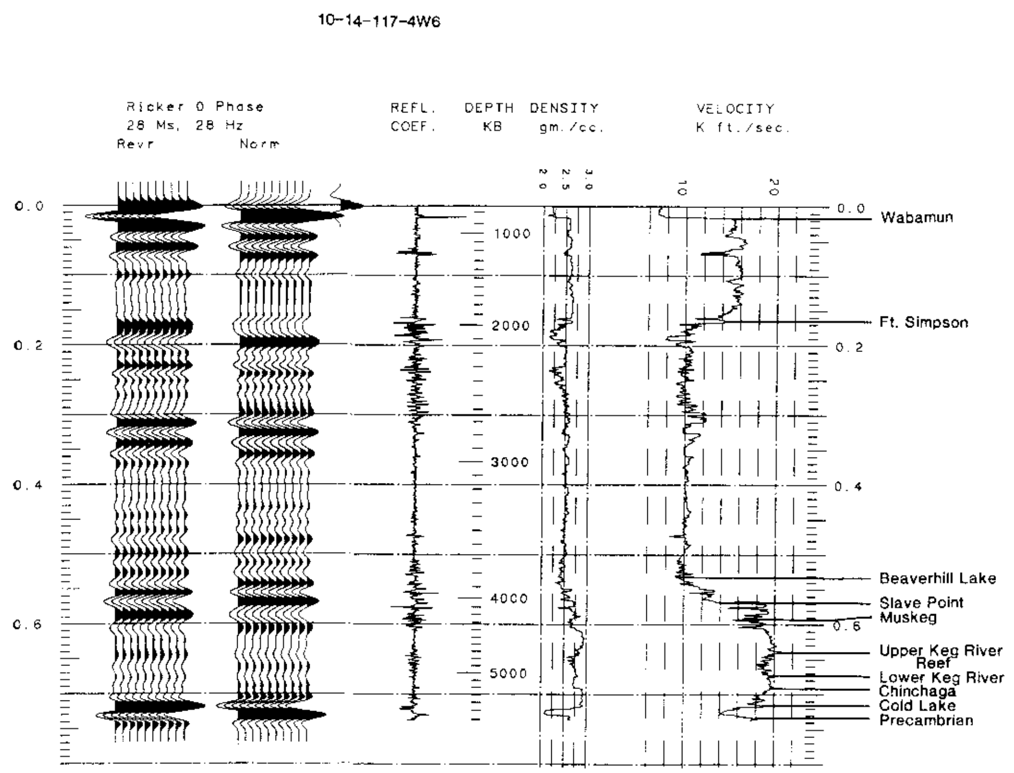



**Figure 2.27.** Synthetic seismogram for the 10-14-117-4W6M well (courtesy of GMA Ltd.).

The overlying Slave Point event is locally about 20 ms higher on-reef than off-reef, corresponding to actual structure of the order of 30 m (using a 3000 m/s average interval velocity for the overlying 600 m of Fort Simpson Fm and Beaverhill Lake Gp shales). This lateral velocity contrast (between such off-reef shales and 30 m of on-reef Slave Point Fm carbonates, with velocities around 6000 m/s) would pull-up the underlying events by about 10 ms. The difference between the estimated 10 ms of pull-up and the observed 8 ms of pull-up is probably due to the lateral velocity contrast between the high-velocity off-reef Muskeg Fm sediment and the lower-velocity reef. Indeed, the velocity contrast between reef and off-reef sediments tends to push down the events underlying the reef. In this example, the observed pull-up is entirely attributable to lateral variations in the thickness of lithological units overlying the reef and off-reef sediments.

Significantly less relief is observed along the carbonate marker in the Fort Simpson Fm which is about 5 ms higher on-reef than off-reef. Higher in the section, the Wabamun event does not appear to drape at all, indicating that little or no salt dissolution occurred in post-Devonian time and that the processed seismic line is not significantly affected by statics problems.

# PANNY FIELD

During Keg River time the Panny field of the Senex area was part of the fringing shelf surrounding the Elk Point basin in northern Alberta (Fig. 2.28). The Keg River Fm here consists of carbonates of varying argillaceous content. Locally, more argillaceous carbonates predominate in the lower Keg River Fm section whereas cleaner carbonates are predominant in the upper part of the formation. A schematic cross-section of the Senex-Peace River arch area is displayed in Figure 2.29. For further background on the geology of this area, see Campbell (1987), Anderson et al. (1988b) and Cant (1988).

The Keg River Fm is the principal reservoir facies in this study area and is typically productive where structurally closed across underlying Precambrian highs. These highs are the result of pre-Devonian tectonism and subsequent erosion with, possibly, later stages of faulting in some areas. The reservoir facies is capped by the basal anhydrite unit of the Muskeg Fm. Production data for the Panny area is summarized in Table 2.4.

Figure 2.30 shows a portion of the Panny field, the approximate orientation of the two example seismic lines and the locations of the four wells incorporated into the two geological cross-sections. Three of the four wells (1-3, 3-11 and 3-5) were drilled into closed Precambrian structures. Wells 1-3 and 3-11 produce from the Keg River Fm whereas 3-5 was abandoned. The fourth well (4-5) was drilled into a flank location and also abandoned. Log suites for these

**Table 2.4.** Production data for the Panny study area (courtesy of Virtual Computing Services Ltd.)

| WELL | FIELD | POOL | PRODUCING ZONE | PRODUCTION DATE | CUMULATIVE PRODUCTION Oil (m³) | Gas (E³ m³) | Water (m³) |
|---|---|---|---|---|---|---|---|
| 7-34-95-6W5 | Panny | Keg River D | Keg River | 05/84 | 20,2[illegible]8.7 | 1,725.9 | 6,288.7 |
| 9-34-95-6W5 | Panny | Keg River D | Keg River | 09/87 | 3,749.6 | 49.0 | 177.7 |
| 13-36-95-6W5 | Panny | Keg River S | Keg River | 01/87 | 1,035.8 | 72.0 | 598.8 |
| 11-2-96-6W5 | Panny | Keg River D | Keg River | 08/84 | 57,890.[illegible] | 1,581.0 | 34,462.7 |
| 15-2-96-6W5 | Panny | Keg River D | Keg River | 02/86 | 11,719.[illegible] | 535.6 | 63.5 |
| 1-3-96-6W5 | Panny | Keg River D | Keg River | 06/84 | 39,641.5 | 1,829.8 | 63,674.2 |
| 13-9-96-6W5 | Panny | Keg River G | Keg River | 02/85 | 33,140.5 | 2,303.2 | 79,500.3 |
| 3-11-96-6W5 | Panny | Keg River G | Keg River | 01/84 | 49,780.5 | 2,595.4 | 99,438.9 |
| 15-16-96-6w5 | Panny | Keg River E | Keg River | 11/84 | 9,569.8 | 522.9 | 87.1 |
| 14-22-96-6w5 | Panny | Keg River A | Keg River | 04/85 | 9,467.8 | 608.9 | 353.3 |
| | Panny | All | Keg River | | 234,[illegible]53.5 | 11,823.7 | 184,636.3 |

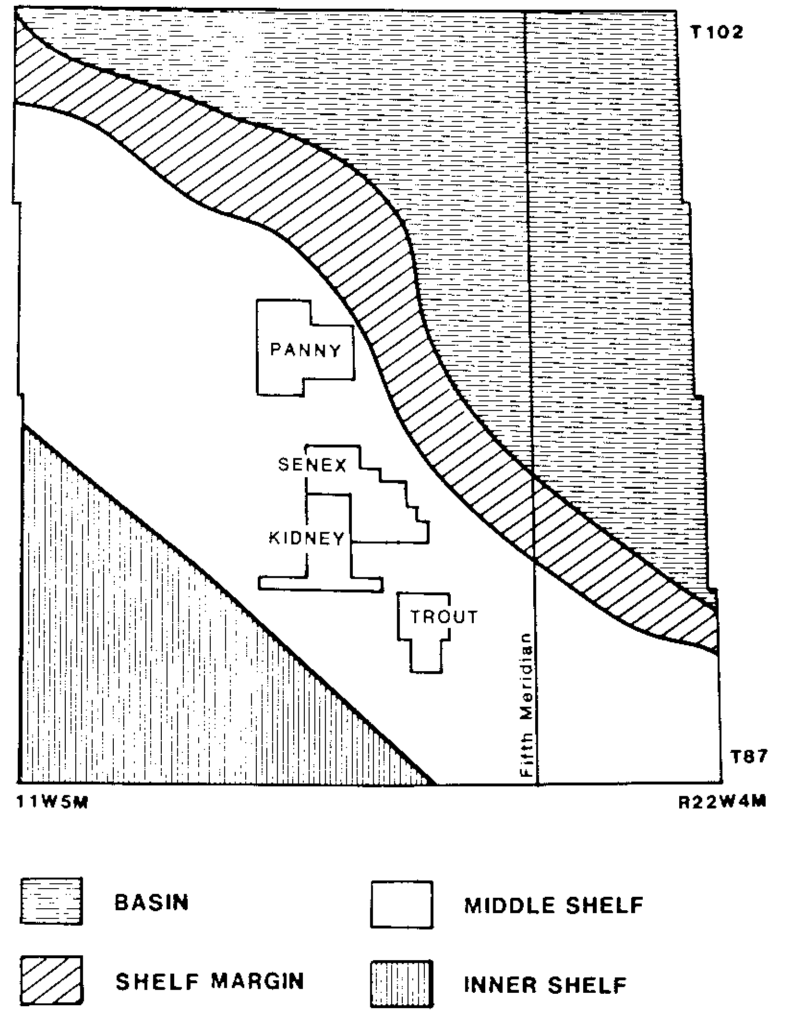



**Figure 2.28.** Map of the fields and facies of the Senex area (after Campbell, 1987).

wells are shown on the geological cross-sections of Figures 2.31 and 2.33. The corresponding seismic sections are presented in Figures 2.32 and 2.34, respectively.

## GEOLOGICAL CROSS-SECTIONS

The deepest horizon identified on the geological cross-sections of Figures 2.31 and 2.33 is the Precambrian. As illustrated, relief on this surface is typically on the order of 50 to 100 m. Anomalous

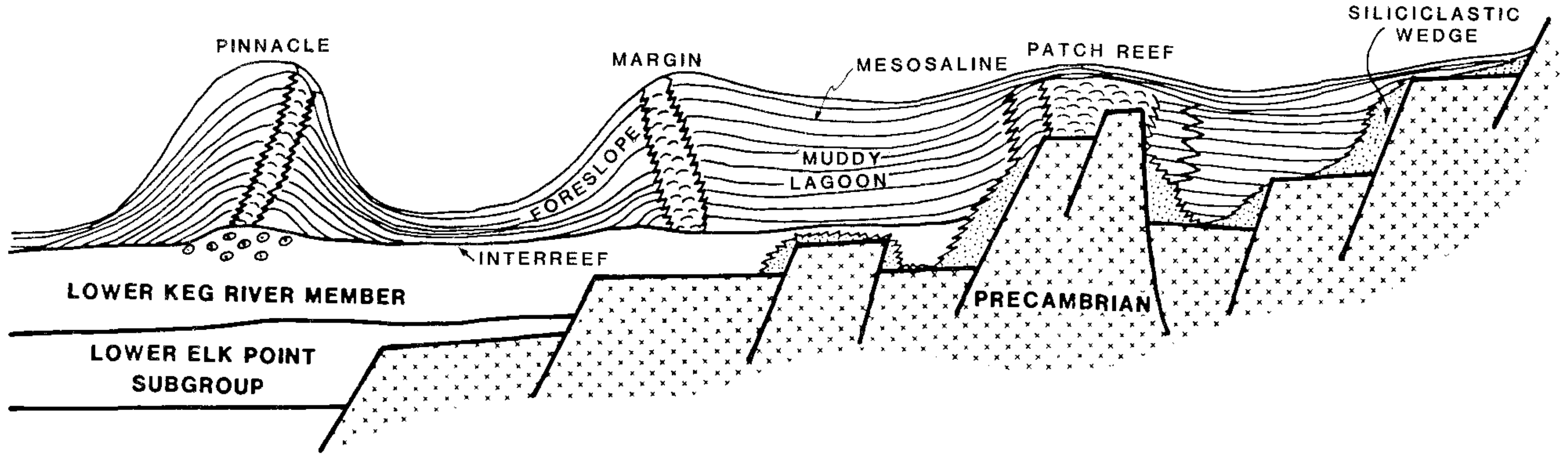



**Figure 2.29.** Schematic geological cross-section through the general Senex-Peace River arch area, Keg River to Precambrian interval (after Campbell, 1987).

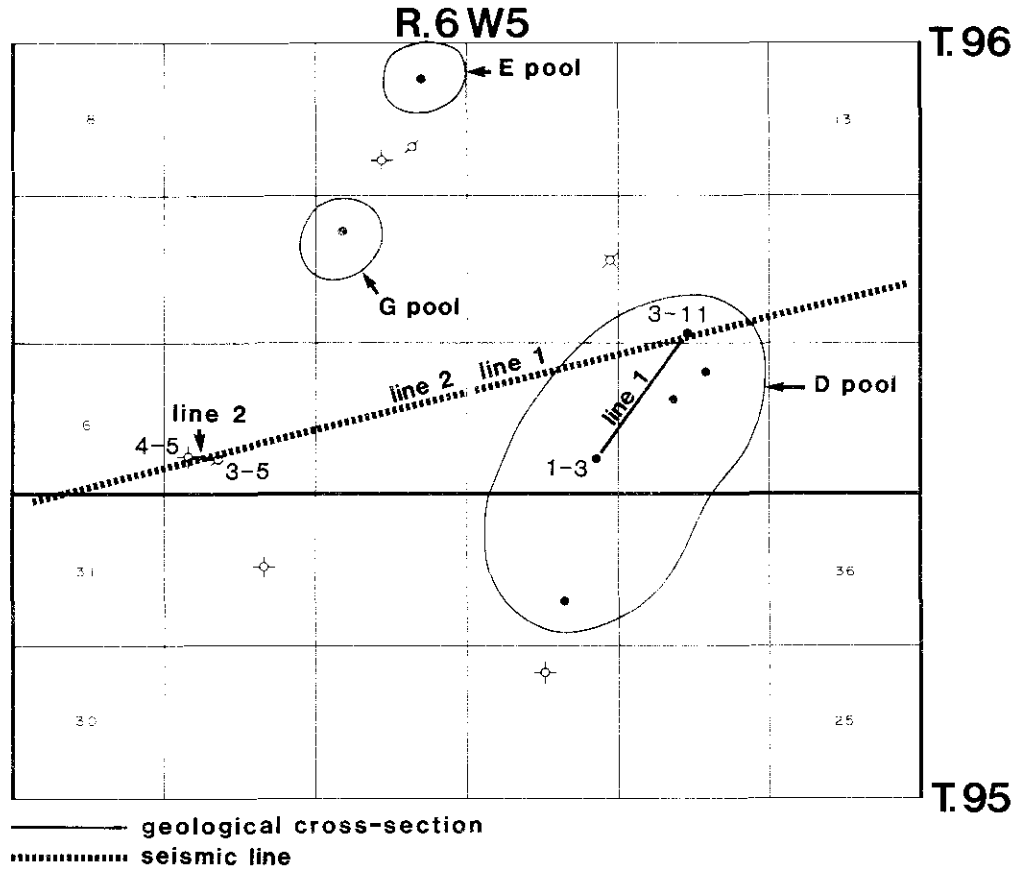



**Figure 2.30.** Panny study area. Pool outlines, the wells incorporated into the geological cross-sections 1 and 2 and the locations of the two corresponding seismic sections are shown.

structural highs, such as those beneath the 1-3, 3-11 (Fig. 2.31) and 3-5 (Fig. 2.33) wells are prevalent throughout the Panny area. Generally, such structures are mapped from the seismic data as being locally areally closed, a pattern consistent both with the idea of an erosional surface and with that of a surface fractured by conjugate sets of faults (Anderson et al., 1988b). As illustrated (Figs. 2.31 and 2.33), the basal Paleozoic clastics and Keg River Fm sediments thin significantly from off-structure to on-structure locations, supporting the thesis that relief at the Precambrian level is erosional in origin. Structural relief in interwell areas is inferred by the authors from the corresponding seismic lines.

Within the study area, the Precambrian is overlain by basal Paleozoic clastics and the Keg River Fm. Structure maps of these two horizons are shown in Figures 2.35 and 2.36, respectively. As mentioned above, the Keg River Fm is generally thinnest above Precambrian highs and thicker off-structure. For example, the Keg River Fm in the 3-5 and 4-5 wells is 4 and 45 m thick, respectively (Fig. 2.33). In addition, the Precambrian in the 3-5 well is 80 m structurally higher than in the 4-5 well, so that the top of the Keg River Fm in the 3-5 well is about 40 m higher than in the 4-5 well and is structurally closed. Relief along the top of the Keg River Fm is principally attributed to the differential compaction of the on-structure and off-structure Paleozoic section (Anderson et al., 1988b) although some workers believe that later stages of faulting played a significant role.

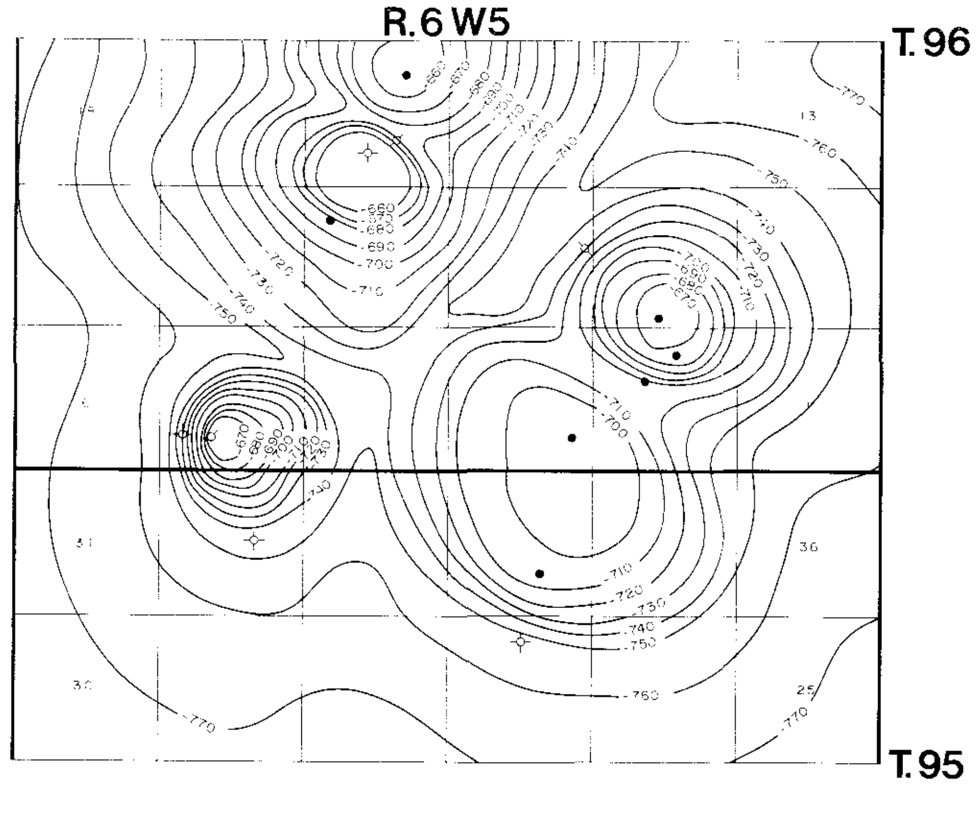



**Figure 2.35.** Structure map of the top of the basal Paleozoic clastics (as Fig. 2.7).

As determined from the log suite for the 4-5 well (Fig. 2.33) the Keg River Fm in the area consists of carbonate with a variable degree of argillaceous content. The more argillaceous carbonates predominate in the lower Keg River Fm section and cleaner biostromal carbonates are predominant in the upper portion. Typically, these upper carbonates are productive where they are structurally closed across the underlying Precambrian, such as in the 3-11 and 3-5 wells (Figs. 2.31 and 2.33). As evidenced by these two wells, the more argillaceous carbonates of the lower Keg River Fm are generally absent where the Precambrian is anomalously high.

The Keg River Fm in the Panny area is overlain by the Muskeg Fm, principally an interlayered sequence of salts and anhydrites. As shown in Figures 2.31 and 2.33, the basal anhydrite of this formation seals the Keg River Fm reservoir facies. Although this basal anhydrite has a slightly higher velocity and density than the underlying Keg River Fm, the contact between the two units cannot be mapped on the seismic data. However, the contact between this basal anhydrite and the overlying salt can be delineated seismically and is frequently referred to as the near-Keg River event. As shown on Figures 2.31 and 2.33, the basal salt/anhydrite contact is more or

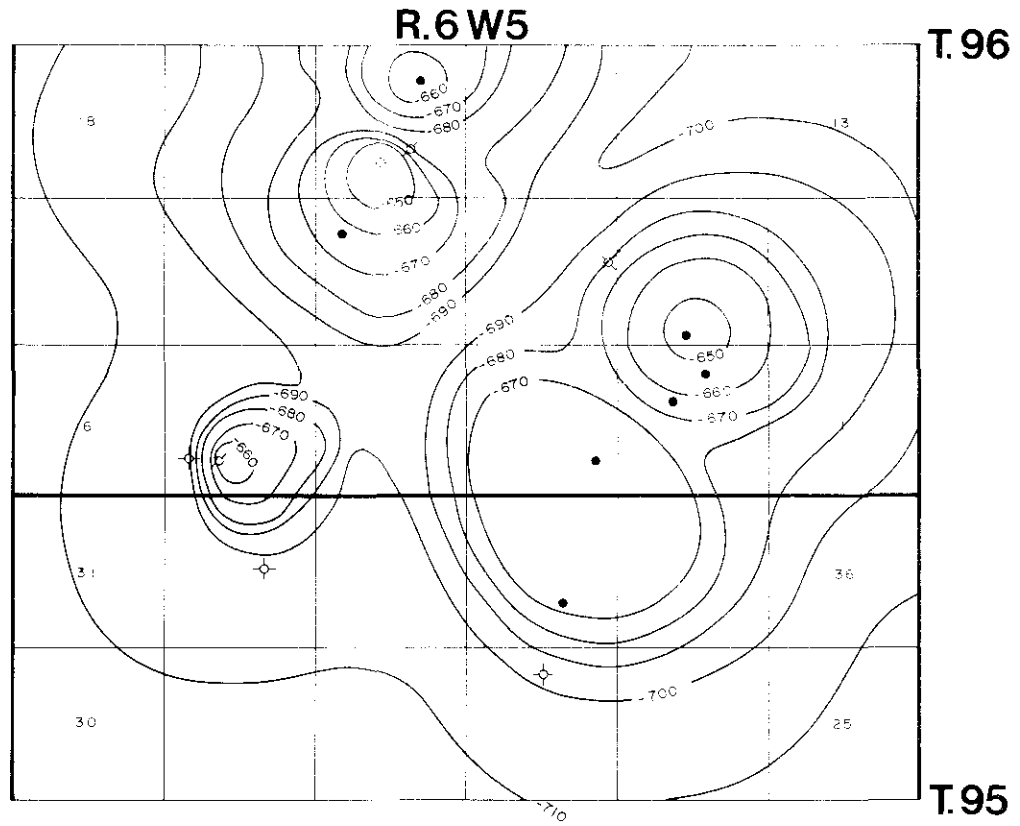



**Figure 2.36.** Structure map of the top of the Keg River Fm (as Fig. 2.7).

less parallel to the anhydrite/Keg River Fm contact. These cross-sections also show that the Muskeg Fm, the Slave Point Fm (Fig. 2.37) and the Beaverhill Lake Gp drape across the anomalous Precambrian structures. This is attributed to differential compaction of the Paleozoic section.

## SEISMIC SECTIONS

Figure 2.30 shows the location of the seismic sections (Figs. 2.32 and 2.34). The 96-trace 24-fold seismic data were recorded in 1982, using a Vibroseis source, a 1530-m split spread, 120-m shot spacing and a 24-m group interval. Figure 2.38 is a 1D synthetic seismogram for the 3-11 well. As illustrated, the synthetic and the field data (Fig. 2.32) correlate well at the Precambrian, near-Keg River (or basal anhydrite), Slave Point and Ireton events. The Wabamun event, not shown on the synthetic, is confidently identified across both seismic lines on the basis of regional correlations. The Wabamun event is usually not displayed on synthetics in the Panny area as casing is usually set below this horizon prior to logging.

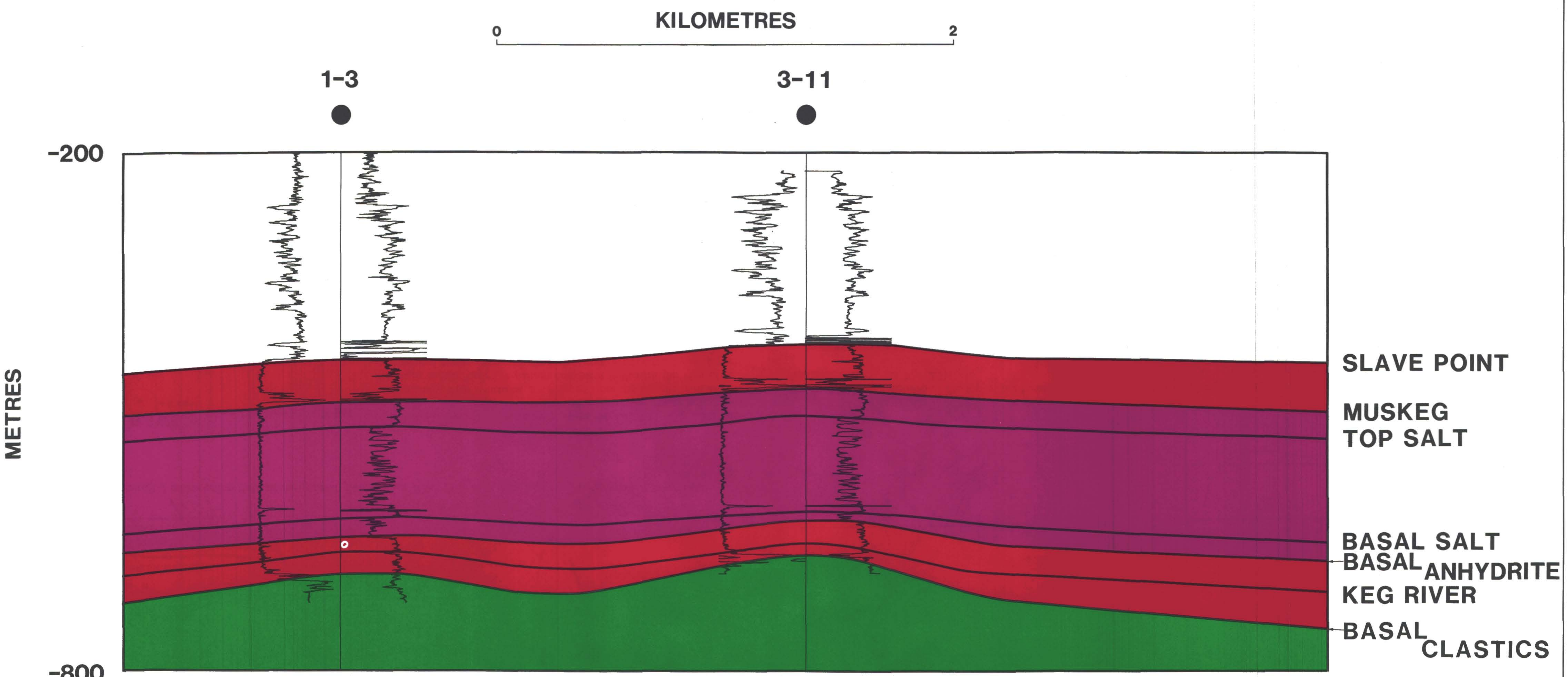



**Figure 2.31.** Geological cross-section 1, Panny study area (Fig. 2.30).



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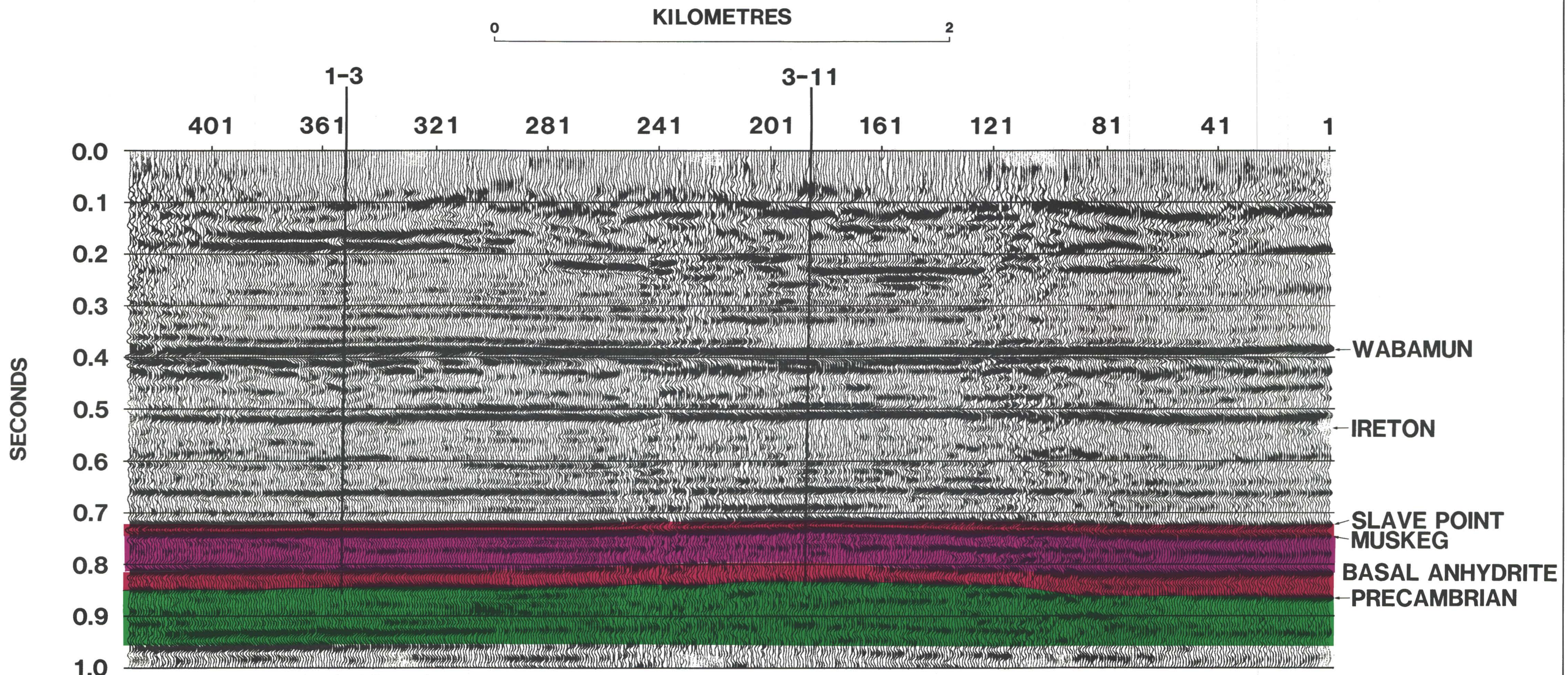


**Figure 2.32.** Normal-polarity seismic section 1, Panny study area (Fig. 2.30).



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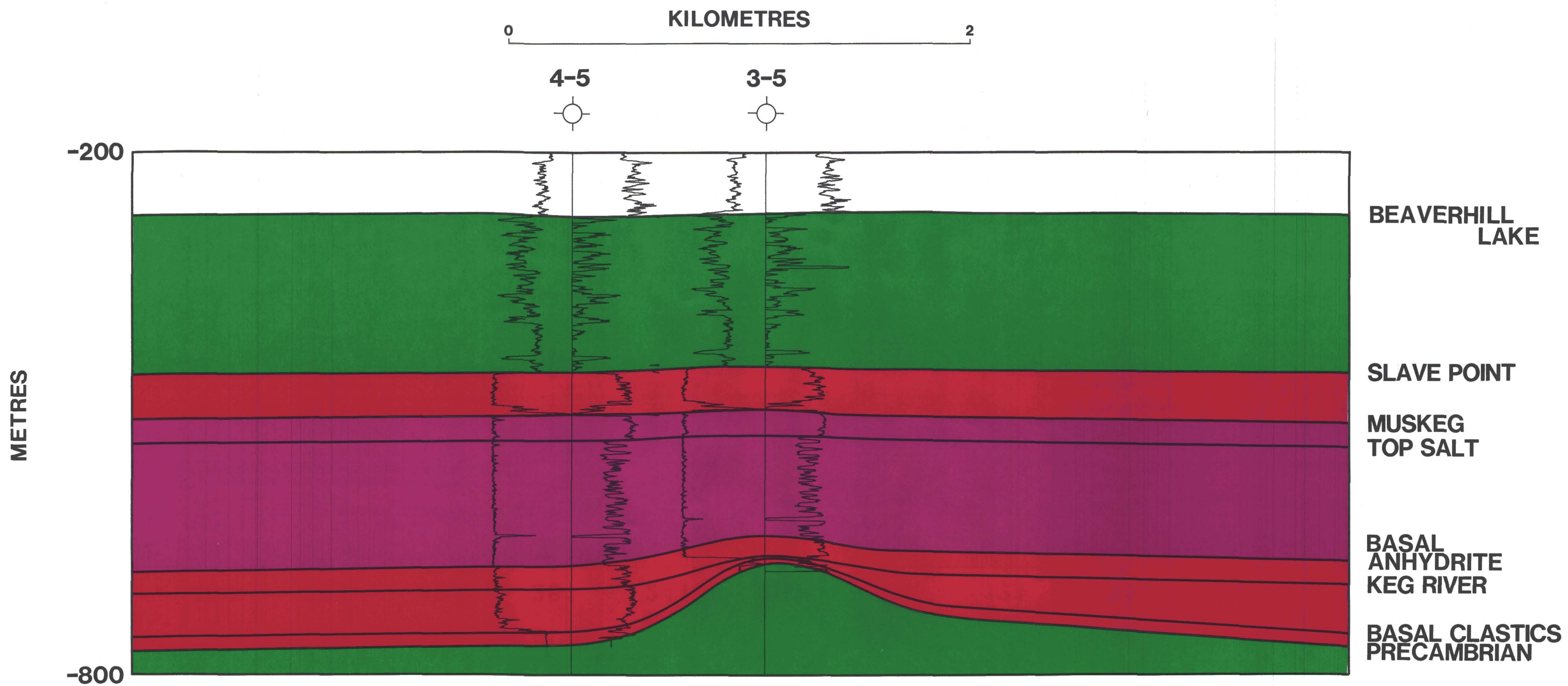


**Figure 2.33.** Geological cross-section 2, Panny study area (Fig. 2.30).



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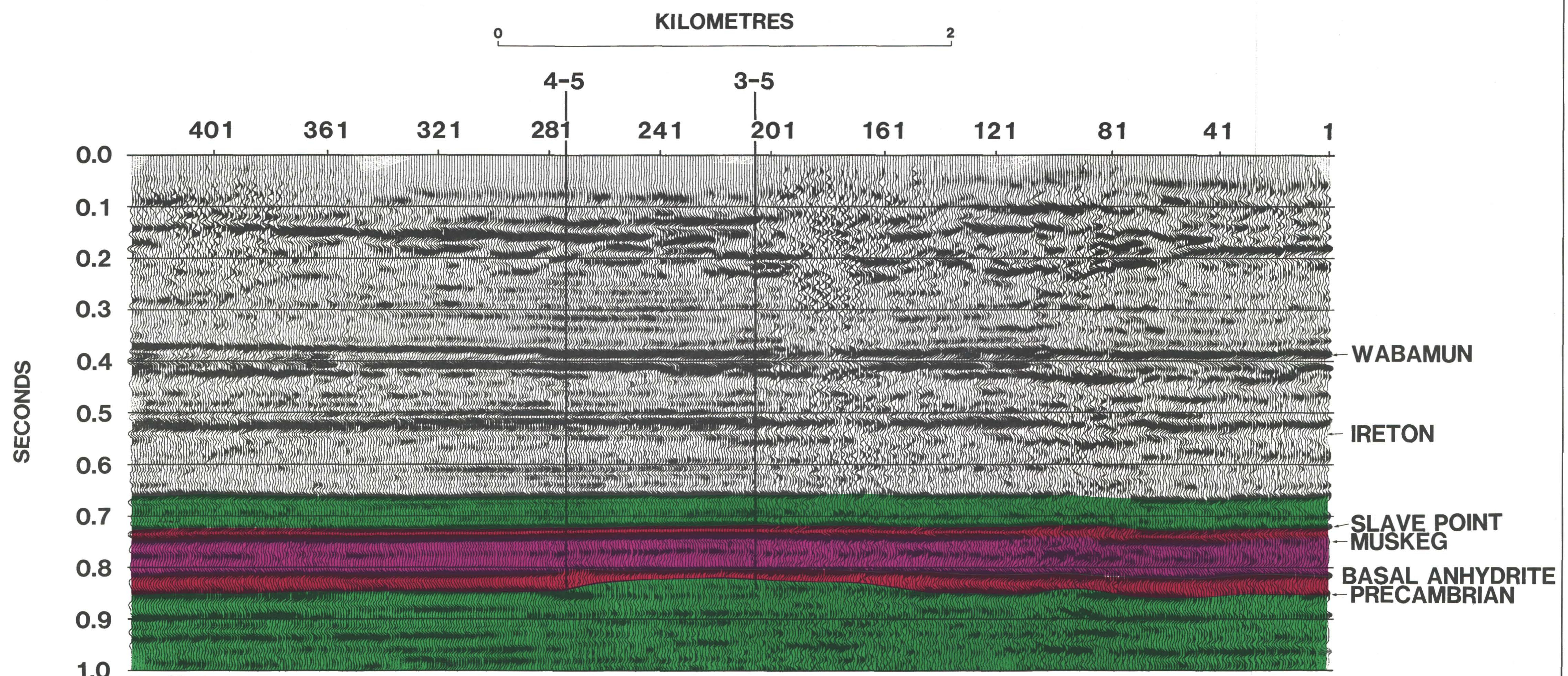


**Figure 2.34.** Normal-polarity seismic section 2, Panny study area (Fig. 2.30).



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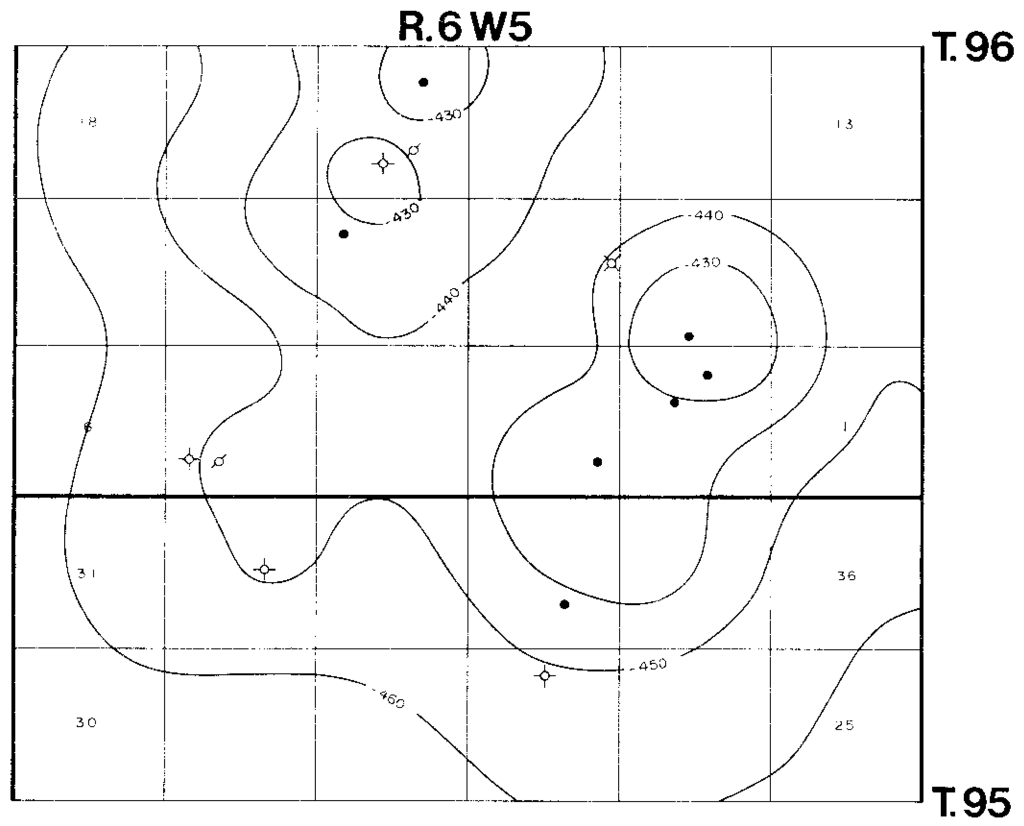



**Figure 2.37.** Structure map of the top of the Slave Point Fm (as Fig. 2.7).

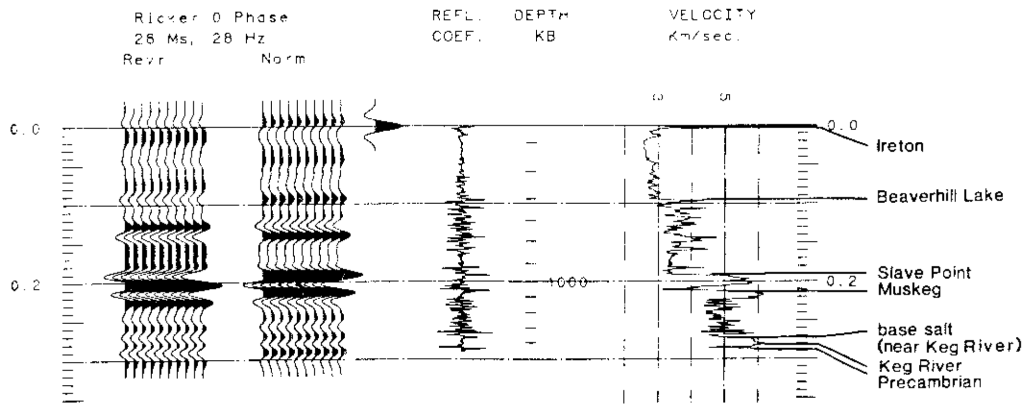



**Figure 2.38.** Synthetic seismogram for the 3-11-96-6W5M well (courtesy of GMA Ltd.).

Figures 2.39 and 2.40 show sonic-log cross-sections and corresponding synthetic seismic sections. These models demonstrate how the amplitudes of the Precambrian and near-Keg River events change as a function of relief along the Precambrian with corresponding thinning of the overlying clastics (Fig. 2.39) or anhydrite (Fig. 2.40). As the Keg River Fm is typically productive where draped across closed Precambrian highs, the recognition of

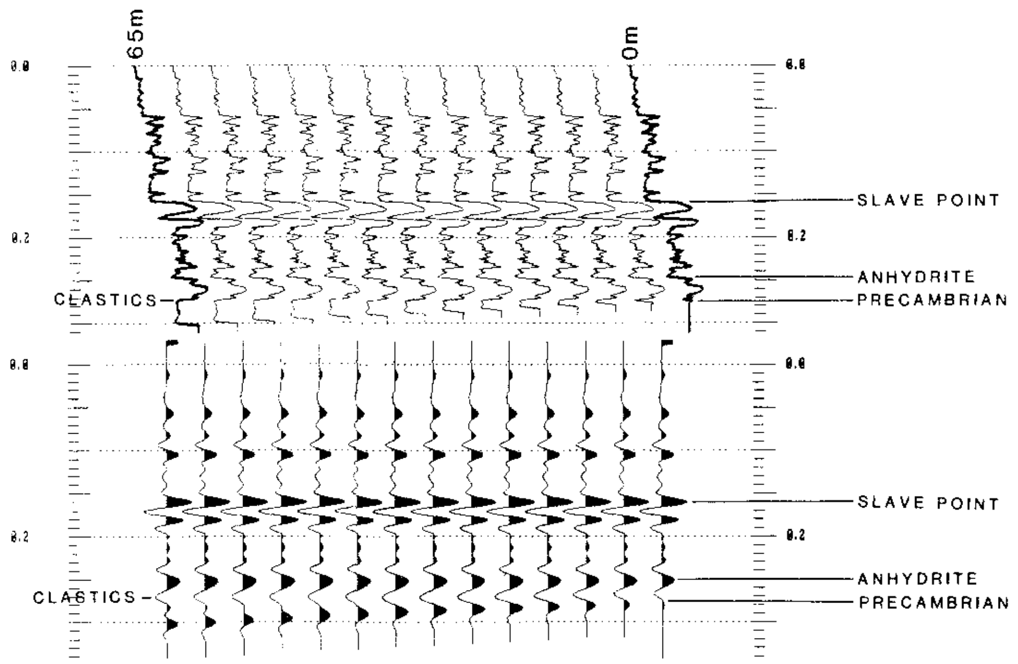



**Figure 2.39.** Sonic-log model and corresponding synthetic seismic section illustrating the effect of thinning of the basal Paleozoic clastic section (courtesy of GMA Ltd.).

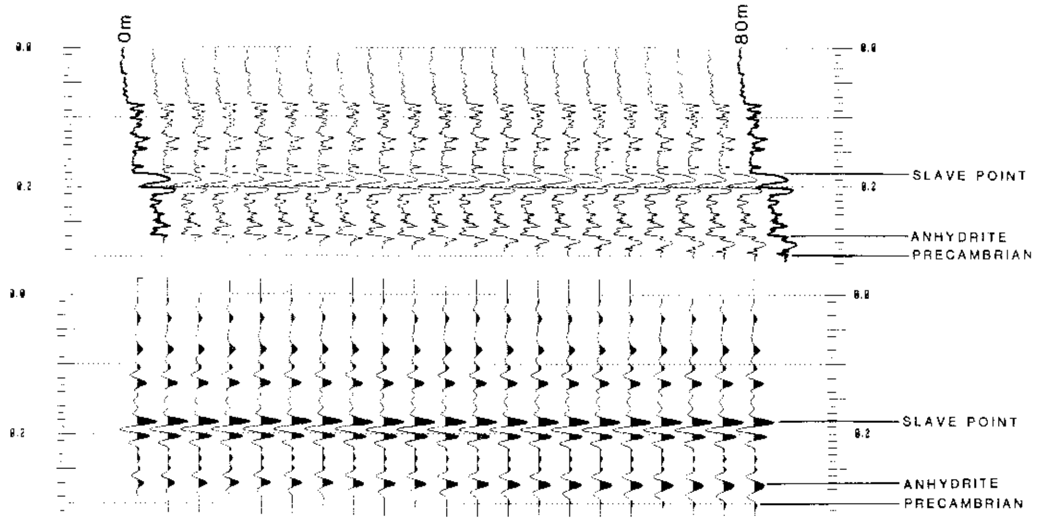



**Figure 2.40.** Sonic-log model and corresponding synthetic seismic section illustrating the effect of thinning of the basal anhydrite/Precambrian section (courtesy of GMA Ltd.).

the seismic signatures of such features is critical. On the synthetic seismic sections the amplitudes of both the Precambrian and near-Keg River events are higher off-structure than on-structure. As discussed below, these lateral amplitude changes are principally interference effects related to the on-structure thinning of both the basal Paleozoic clastic section and the basal Muskeg anhydrite/Precambrian interval.

In Figure 2.39 the thicknesses of the basal Muskeg anhydrite and Keg River intervals are kept constant whereas that of the basal Paleozoic clastics is varied from 65 m (about a half-wavelength) to zero. Optimal tuning of the reflections from the top and base of these clastics occurs at thicknesses near 32 m (about a quarter-wavelength). At thicknesses less than an eighth of a wavelength (about 16 m) the basal Paleozoic clastics cannot be resolved with confidence. At zero thickness the Precambrian is overlain by the Keg River Fm.

In Figure 2.40 the thickness of the basal Muskeg anhydrite/Precambrian section is decreased proportionately from 80 m (about a half-wavelenth) to zero. Optimal tuning of the near-Keg River and Precambrian events occurs at a thickness of a half-wavelength (about 80 m); maximum destructive interference occurs at a thickness of a quarter-wavelength (about 40 m). As this modelled thickness continues to decrease, the Precambrian and near-Keg River events become increasingly tuned to one another. At zero thickness, the Precambrian is modelled as directly overlain by this basal Muskeg Fm salt. As discussed below, this relationship is not known to occur in practice.

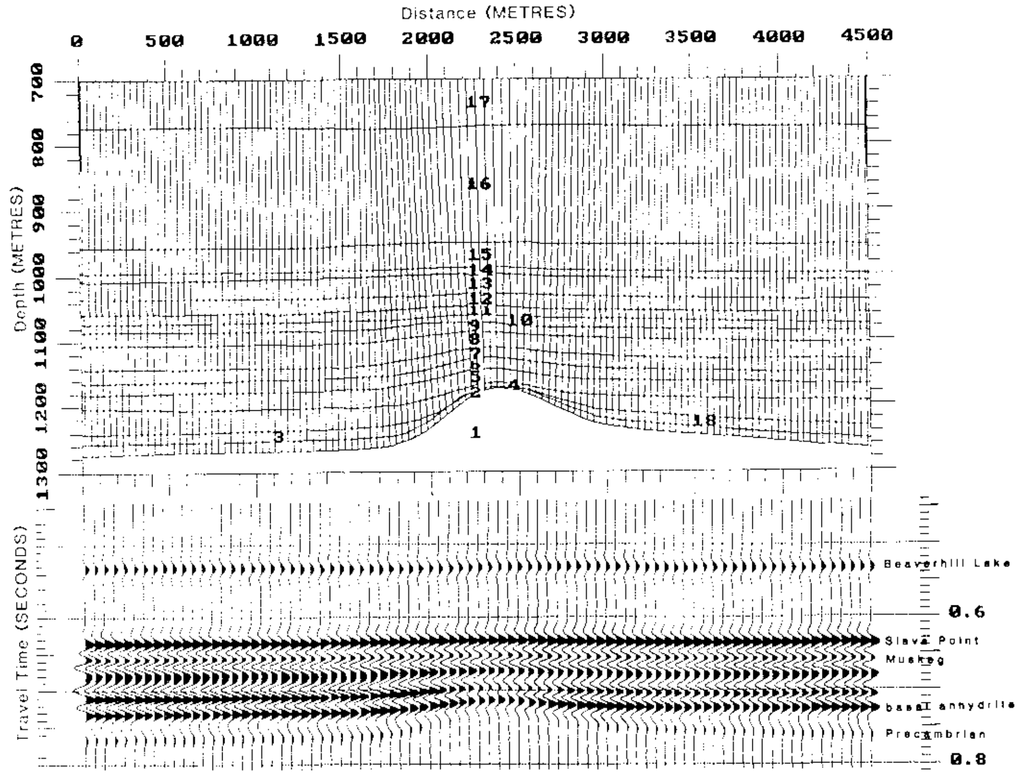
In the interpreted seismic sections, the lowest event identified, the reflection from the Precambrian surface, is time-structurally highest in the vicinity of trace 185 (Fig. 2.32) and trace 207 (Fig. 2.34), which coincide with the locations of the producing 3-11 and 3-5 wells, respectively. For comparative purposes, note that the Precambrian event at traces 41 and 301 (Fig. 2.32) is 18 and 8 ms lower, respectively, than at trace 185. At traces 61 and 281 (Fig. 2.34) the Precambrian event is about 40 and 20 ms lower, respectively, than at trace 207. As shown on the geological cross-sections (Figs. 2.31 and 2.33), these time-structural highs correlate with anomalous relief along the Precambrian surface. However, it should be recalled that the structure on the geological cross-sections in interwell areas was estimated by analysis of the seismic data. As anticipated, both the near-Keg River and Slave Point events drape across these Precambrian highs. The Slave Point/Precambrian time-thickness decreases significantly (ca. 20 to 30 ms) from off-structure to on-structure locations, indicating that the Slave Point/basal Paleozoic (inclusive) interval thins significantly from off-structure to on-structure positions. In addition, the overlying Wabamun event does not appear to drape across these Precambrian highs.

As anticipated from an analysis of the suite of synthetic models, anomalous structures along the Precambrian horizon manifest themselves as lateral amplitude changes and by time-structural relief along the Precambrian and near-Keg River events. More specifically, the amplitudes of both the Precambrian and near-Keg River events are significantly lower on-structure [near traces 185 (Fig. 2.32) and 207 (Fig. 2.34)] than off-structure. As demonstrated through modelling (Figs. 2.38 to 2.41), these lower amplitudes are interference effects caused by the on-structure thinning of the basal Paleozoic clastic section and of the basal Muskeg anhydrite/basal clastic (inclusive) section. In the vicinity of the 3-5 well (Fig. 2.34, trace 207), where the basal Muskeg Fm anhydrite/Precambrian interval is thin (about 35 m or slightly under a quarter-wavelength), the amplitude of the intervening peak is extremely low, supporting the premise of destructive interference. In the vicinity of the 3-11 well (Fig. 2.32, trace 185) the section is about 45 m thick (slightly greater than a quarter-wavelength) and the amplitude of the intervening peak is marginally higher. Presumably, with increasing relief at the Precambrian level, the amplitude of the peak would decrease to the point where the near-Keg River and Precambrian events would visually merge. Where the basal Muskeg anhydrite and the Keg River Fm sediments are absent (presumably due to nondeposition across Precambrian structure as in the 2-10-89-3W5M well of the following example) the overlying Muskeg salts are extensively dissolved. The resultant collapse features are readily identified on seismic sections.

Recognition of closed Precambrian structure is vital to successful exploration for Keg River Fm reservoirs in the Panny area. Typically, the Keg River Fm is draped across these structures as a result of differential compaction of lower Paleozoic sediments. Prospective Precambrian structures can be identified seismically where: 1) time-structural relief occurs along the Precambrian, near-Keg River and Slave Point events; 2) on-structure time-thinning of the Precambrian/Slave Point and Slave Point/Wabamun intervals occurs; and 3) on-structure decreases occur in the amplitude of both the Precambrian and near-Keg River events, without associated salt-collapse features.

## TROUT FIELD

The geological background for the Trout field of north-central Alberta closely parallels that of the nearby Panny field. The Keg River Fm, the principal reservoir facies in the Trout area, is productive where it is structurally closed across or against the flanks of underlying Precambrian highs and the reservoir facies are capped by the basal anhydrite unit of the Muskeg Fm. Production from the




| | Velocity (m/s) | Density (kg/m$^3$) | | Velocity (m/s) | Density (kg/m$^3$) |
|---|---|---|---|---|---|
| (1) Precambrian | 5500<br>5500 | 2650<br>2650 | (2) Basal Clastics | 5000<br>5000 | 2650<br>2650 |
| (3) Keg River | 5500<br>5500 | 2700<br>2700 | (4) Keg River | 5600<br>5600 | 2750<br>2750 |
| (5) Basal Anhydrite | 5600<br>5600 | 2900<br>2900 | (6) Salt | 4300<br>4300 | 2200<br>2200 |
| (7) Anhydrite | 5600<br>5600 | 2900<br>2900 | (8) Salt | 4300<br>4300 | 2200<br>2200 |
| (9) Anhydrite | 5600<br>5600 | 2900<br>2900 | (10) Salt | 4300<br>4300 | 2200<br>2200 |
| (11) Anhydrite | 5600<br>5600 | 2900<br>2900 | (12) Salt | 4300<br>4300 | 2200<br>2200 |
| (13) Muskeg | 5600<br>5600 | 2900<br>2900 | (14) Watt Mountain | 4000<br>4000 | 2650<br>2650 |
| (15) Slave Point | 5400<br>5400 | 2750<br>2750 | (16) Beaverhill Lake | 3500<br>3500 | 2700<br>2700 |
| (17) Ft. Simpson | 2900<br>2900 | 2650<br>2650 | (18) Keg River | 5500<br>5500 | 2700<br>2700 |

**Figure 2.41.** Synthetic seismic section generated from the geological cross-section (Fig. 2.33) using a zero-phase normal-polarity, 30-Hz, Ricker wavelet (courtesy of GMA Ltd.).

Trout field has also been established from the underlying basal Paleozoic sandstones. These sediments are also productive where structurally closed across or against the flanks of anomalous Precambrian structures. Production data for the Trout field are presented as Table 2.5.

## GEOLOGICAL CROSS-SECTION

Figure 2.42 is a map of the southern Trout area showing the approximate locations of the example seismic line and of the three wells incorporated into the geological cross-section (Fig. 2.43). Only one of the three, the 11-15 well (completed in 1987), currently produces from the Keg River Fm, whereas, the other two were abandoned. As illustrated in Figure 2.43, the 1-31 well is off-structure where the Keg River Fm is wet. In contrast, the 2-10 well is on-structure, and here the Keg River Fm is absent, presumably because of nondeposition.

**Table 2.5.** Production data for the Trout study area (courtesy of Virtual Computing Services Ltd.)

| WELL | FIELD | POOL | PRODUCING ZONE | PRODUCTION DATE | CUMULATIVE PRODUCTION Oil (m$^3$) | Gas (E$^3$ m$^3$) | Water (m$^3$) |
|---|---|---|---|---|---|---|---|
| 5-2-89-3W5 | Trout | Unassigned | Keg River | 02/88 | - | - | - |
| 1-3-89-3W5 | Trout | Unassigned | Keg River | 10/87 | 1,881.6 | 34.5 | 140.3 |
| 9-3-89-3W5 | Trout | Keg River K | Keg River | 06/87 | 6,569.0 | 106.6 | 1,106.2 |
| 7-8-89-3W5 | Trout | Unassigned | Keg River | 09/87 | 3,419.0 | 42.3 | 26.5 |
| 13-8-89-3W5 | Trout | Granite Wash A | Granite Wash | 01/87 | 5,944.6 | 97.7 | 997.4 |
| 13-8-89-3W5 | Trout | Keg River M | Keg River | 02/87 | 13,314.1 | 297.4 | 127.8 |
| 8-10-89-3W5 | Trout | Unassigned | Keg River | 01/88 | - | - | - |
| 9-10-89-3W5 | Trout | Keg River J | Keg River | 03/87 | 2,919.3 | 50.6 | 1,165.4 |
| 11-10-89-3W5 | Trout | Unassigned | Keg River | 01/88 | - | - | - |
| 4-11-89-3W5 | Trout | Unassigned | Keg River | 12/87 | 165.1 | 1.9 | 179.5 |
| 3-15-89-3W5 | Trout | Keg River I | Keg River | 08/87 | 3,017.5 | 46.6 | 8.4 |
| 11-15-89-3W5 | Trout | Keg River I | Keg River | 01/87 | 5,336.1 | 70.2 | 260.9 |
| 15-15-89-3W5 | Trout | Unassigned | Keg River | 02/87 | 111.2 | 8.8 | 143.1 |
| 9-18-89-3W5 | Trout | Keg River L | Keg River | 04/87 | 7,762.8 | 142.5 | 1,220.1 |
| 9-19-89-3W5 | Trout | Unassigned | Keg River | 08/87 | 936.3 | 25.1 | 1,546.4 |
| 4-20-89-3W5 | Trout | Unassigned | Keg River | 11/87 | 897.5 | 29.1 | 129.4 |
| 8-21-89-3W5 | Trout | Unassigned | Keg River | 01/88 | - | - | - |
| 16-21-89-3W5 | Trout | Unassigned | Keg River | 11/87 | 3,904.5 | 36.5 | 13.4 |
| 1-22-89-3W5 | Trout | Unassigned | Keg River | 02/88 | - | - | - |
| 5-22-89-3W5 | Trout | Keg River I | Keg River | 02/86 | 10,525.1 | 179.5 | 856.6 |
| 12-22-89-3W5 | Trout | Keg River I | Keg River | 10/87 | 2,391.6 | 41.5 | 16.1 |
| 15-22-89-3W5 | Trout | Unassigned | Keg River | 09/87 | 3,905.6 | 46.9 | 279.3 |
| 3-27-89-3W5 | Trout | Unassigned | Keg River | 12/86 | 3.6 | 0.0 | 65.8 |
| 1-30-89-3W5 | Trout | Keg River N | Keg River | 01/87 | 5,206.0 | 67.1 | 330.4 |
| 15-30-89-3W5 | Trout | Keg River N | Keg River | 10/87 | 1,897.2 | 12.0 | 2.4 |
| 2-31-89-3W5 | Trout | Unassigned | Keg River | 12/87 | 272.1 | 3.6 | 94.2 |
| 2-32-89-3W5 | Trout | Keg River O | Keg River | 07/87 | 834.7 | 31.7 | 1,790.5 |
| 3-34-89-3W5 | Trout | Keg River C | Keg River | 12/85 | 2,903.1 | 46.7 | 5,236.3 |

The lowest horizon identified on this geological cross-section is the Precambrian. In the Trout area, as for the Panny area, this is a surface of considerable relief, and basement highs are generally mapped from seismic data as being locally areally closed. As depicted in Figure 2.43, the basal Paleozoic clastics and Keg River Fm sediments thin from off-structure to on-structure, being depositionally absent in the 2-10 well, consistent with the thesis that relief at the Precambrian is erosional in origin. Note that this observed thinning from off-structure to on-structure will generate a corresponding lateral variation in the reflection (Fig. 2.44) from the Precambrian horizon. Reactivation of basement faulting [after the end of Elk Point time (Fig. 2.1)] does not have to be invoked to explain the lows on certain Beaverhill Lake markers (e.g., the Slave Point). These features are accounted for, in our interpretation, by collapse following dissolution of Muskeg salts, which occurred mainly during Beaverhill Lake time (Fig. 2.43).

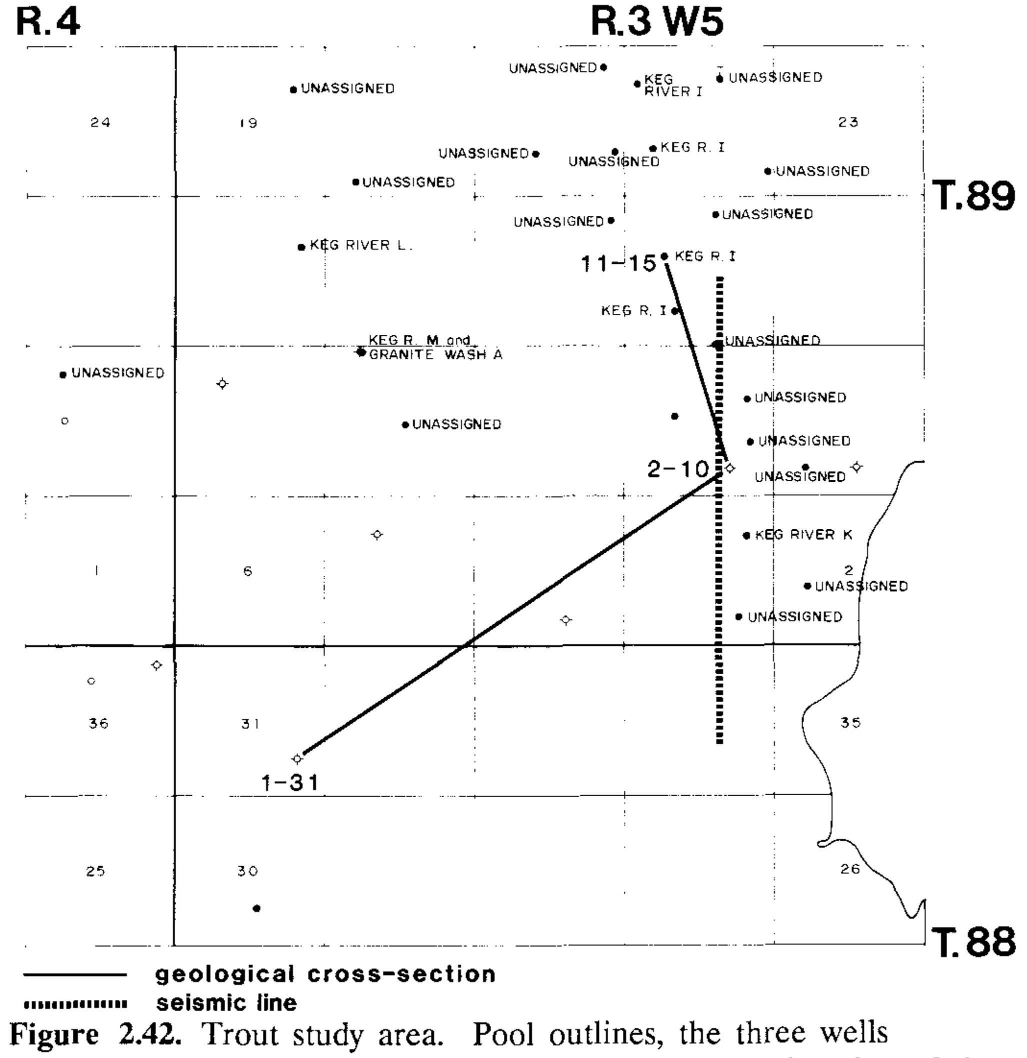



**Figure 2.42.** Trout study area. Pool outlines, the three wells incorporated into the geological cross-section and the location of the seismic line are shown.

As discussed above, both the basal Paleozoic clastics and the Keg River Fm thin from off-structure to on-structure and in extreme cases can be depositionally absent. As a result of differential compaction, both of the corresponding tops are typically closed across or against the flanks of Precambrian structures. Such closure is illustrated at the 11-15 well (Fig. 2.45).

Once again, the near-Keg River event, corresponding to the contact between the basal Muskeg anhydrite and the overlying salt, is seismically more prominent than the Keg River event itself. As was the case for the Panny field, this salt/basal anhydrite contact more or less parallels the basal anhydrite/Keg River Fm contact (Fig. 2.43).

In places, as evidenced by the 2-10 well, the Precambrian is depositionally bald with respect to the basal Paleozoic clastics, the Keg River Fm and the basal portion of the Muskeg Fm. In these areas, interlayered salts and anhydrites were deposited directly on the Precambrian. Typically, such salts have been postdepositionally dissolved. Dissolution in the 2-10 well is interpreted as having

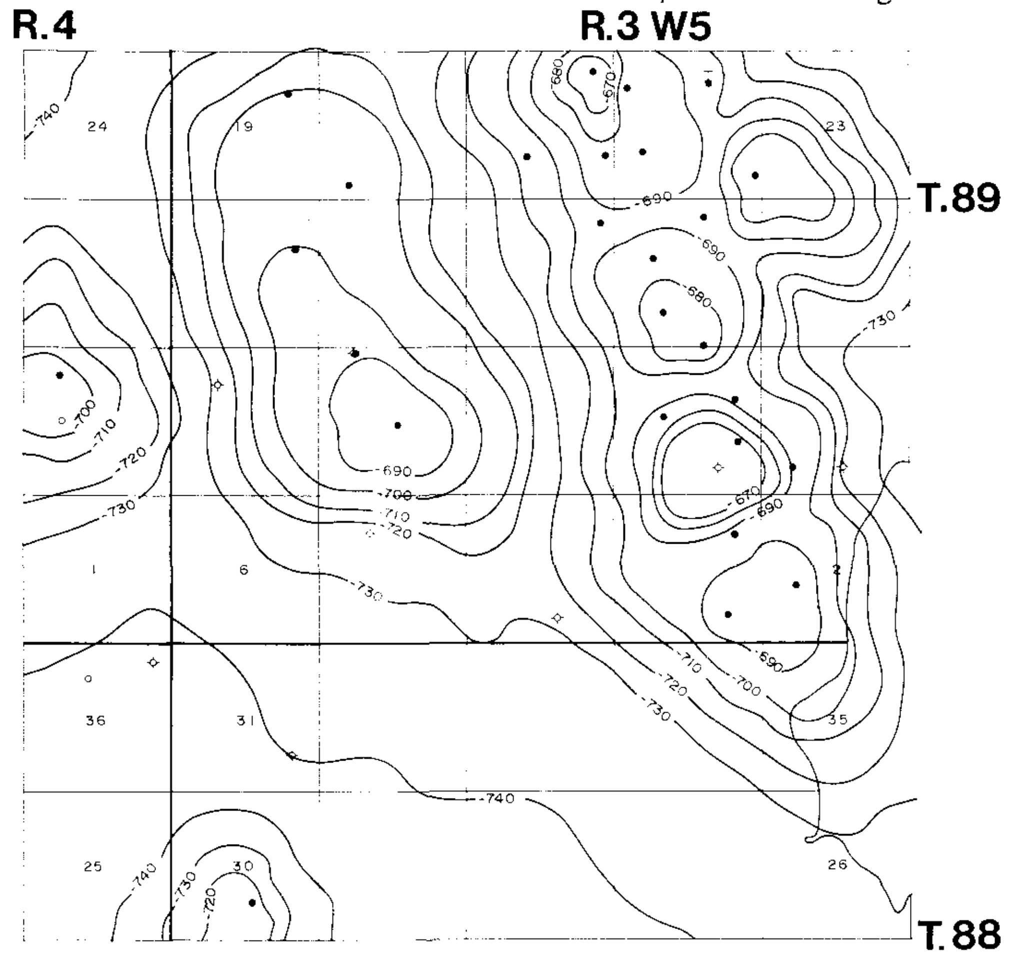



**Figure 2.45.** Structure map of the top of the Keg River Fm (as Fig. 2.7).

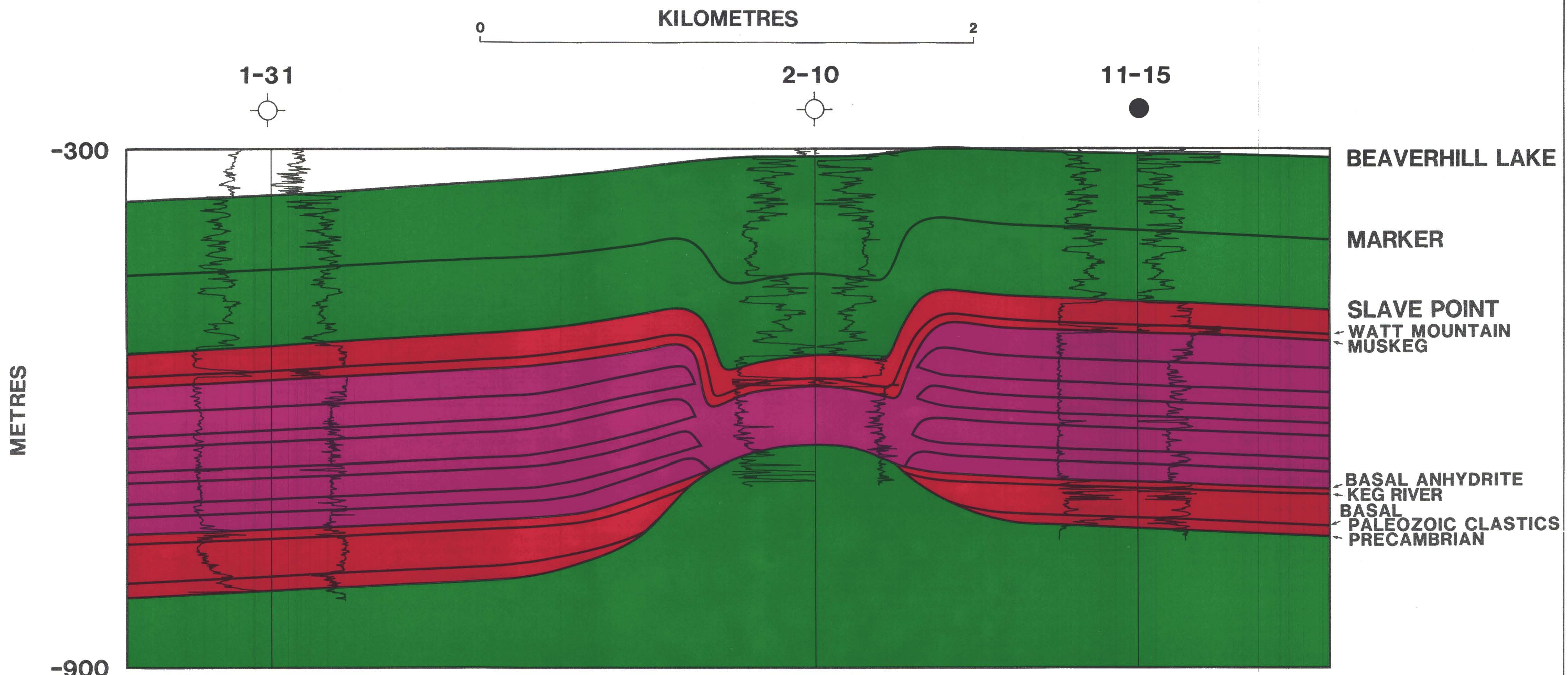



**Figure 2.43.** Geological cross-section, Trout study area (Fig. 2.42).



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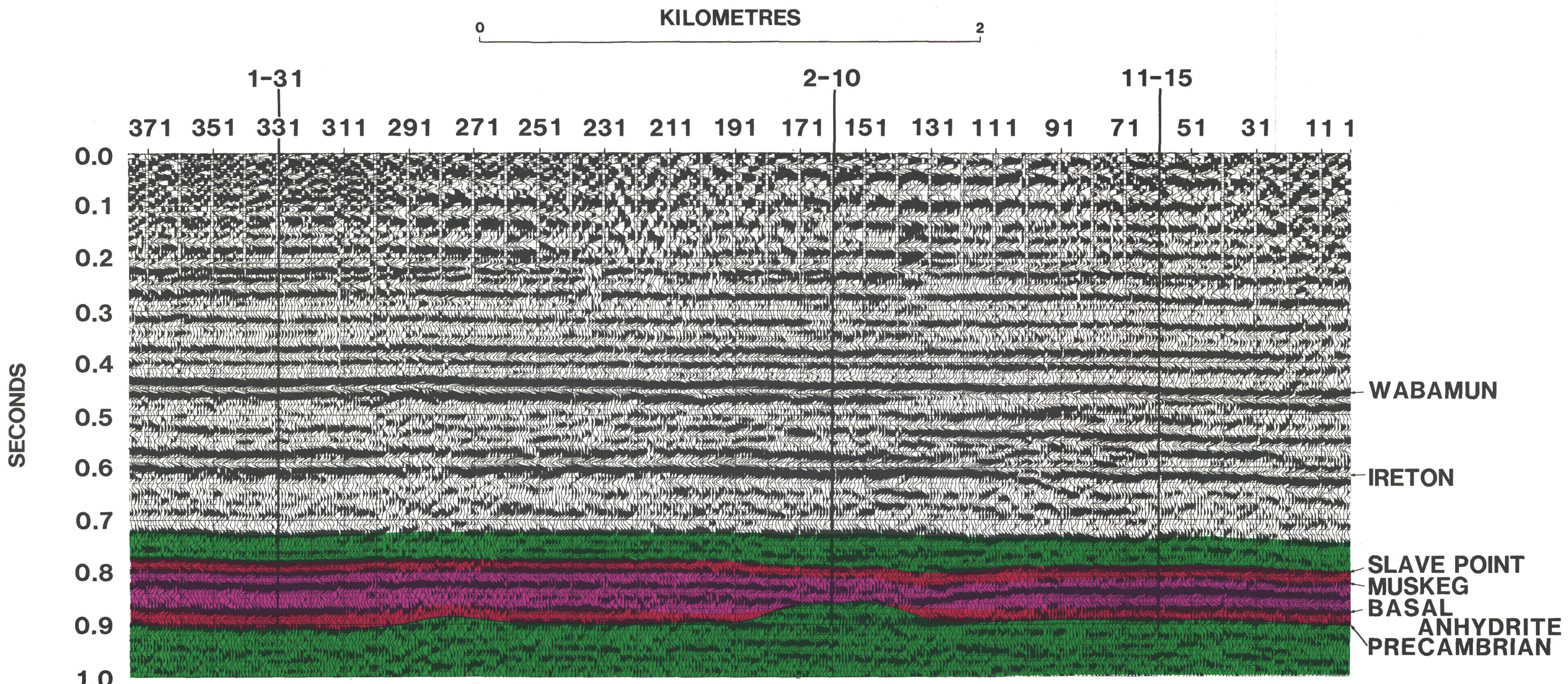


**Figure 2.44.** Normal-polarity seismic section, Trout study area (Fig. 2.42).



DONOR: CHEVRON CANADA RESOURCES LTD. | PROCESSOR: CHEVRON GEOSCIENCES COMPANY | AUTHOR: N. ANDERSON , R.J. BROWN occurred principally during Beaverhill Lake time and to have been caused by waters percolating through the weathered Precambrian (Anderson et al., 1988b). As depicted in Figure 2.43, pronounced collapse features can be associated with salt dissolution.

The Muskeg Fm and the overlying Watt Mountain and Slave Point formations typically drape across underlying Precambrian structure as a result of differential compaction. As illustrated in Figure 2.43, exceptions occur in areas of extensive salt dissolution. As evidenced by the 2-10 well, and shown in the Keg River and Slave Point structure maps of Figures 2.45 and 2.46, these horizons can be anomalously low where the Precambrian is anomalously high. The seismic interpreter should be aware of this possibility and avoid prejudiciously assuming that time-structure above the Precambrian is simply a subdued replica of basement relief.

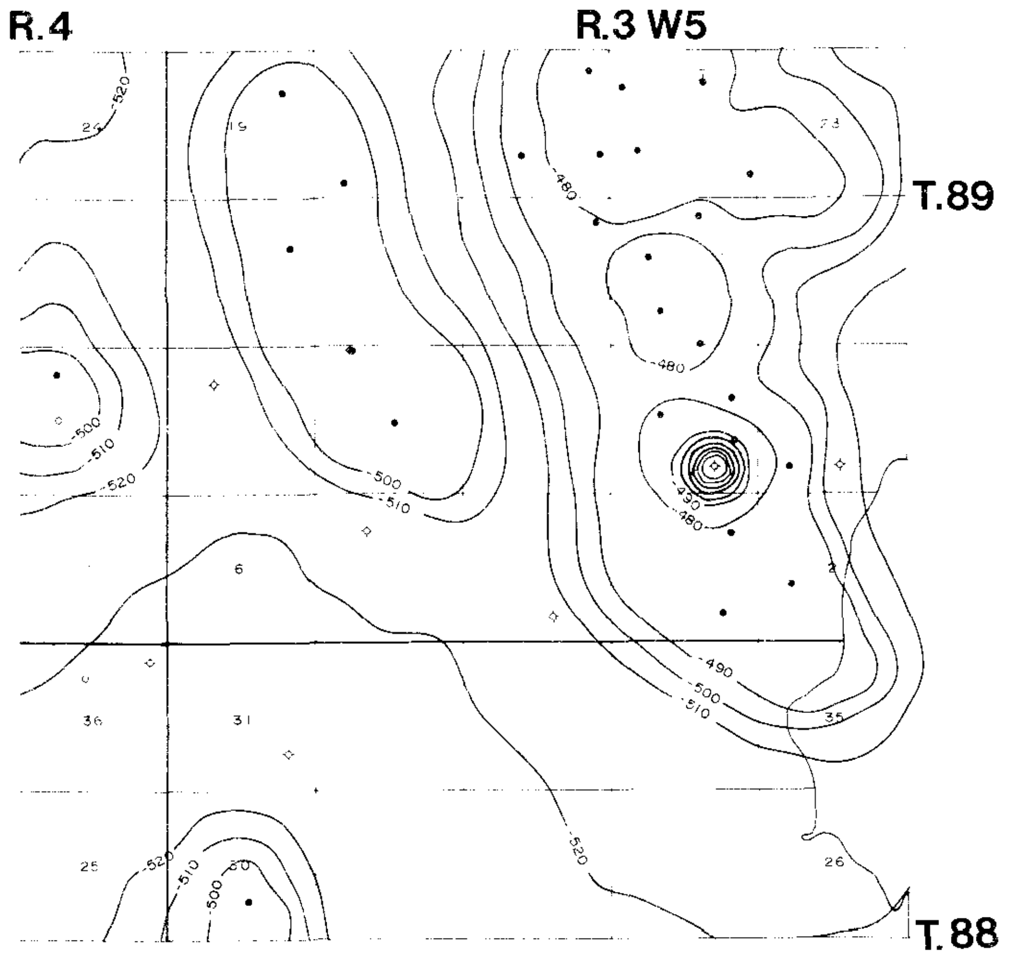


**Figure 2.46.** Structure map of the top of the Slave Point Fm (as Fig. 2.7).

## SEISMIC SECTION

The 120-trace 12-fold seismic data (Fig. 2.44) were recorded in 1979, using single 2.25-kg charges at depths of 15 m, a 1560-m split spread, 130-m shot spacing and a 26-m group interval. As was the case for the Panny examples, the labelled events are confidently identified across the seismic section (Fig. 2.44) on the basis of ties to synthetic seismograms and regional correlations.

Figures 2.39 and 2.40 (discussed in the previous section on the Panny field) demonstrate how the amplitudes of the Precambrian and near-Keg River events change as a function of relief along the Precambrian and associated thinning of overlying units (basal Paleozoic clastics and basal Muskeg Fm anhydrite). These model relationships are observed on the seismic line of Figure 2.44. For instance, the amplitude of the Precambrian event decreases as structural relief increases. In the interval from trace 141 to 191, where the Muskeg anhydrite directly overlies the Precambrian, this contact can be confidently mapped only by using sonic-log control from the 2-10 well. The amplitude of the near-Keg River event is similarly higher off-structure than on-structure. In the vicinity of trace 191, where the Muskeg Fm salts have been leached, this reflection disappears completely. The overlying Slave Point event, on the other hand, can be correlated confidently across the entire seismic section. This event drapes across the underlying Precambrian, except where the Muskeg Fm salts have been dissolved in post-Slave Point time (Fig. 2.44, traces 141 to 191). In such places, the Slave Point event is anomalously low, despite overlying a Precambrian high.

The overlying Beaverhill Lake, Ireton and Wabamun events drape only slightly across the Precambrian, suggesting that the dissolution of the Muskeg Fm salts occurred, for the most part, prior to the end of Beaverhill Lake time.

The explorationist active in the Trout area should be familiar with certain structural relationships, namely, that: 1) the Keg River Fm reservoirs are present where these sediments either drape across or pinch out against Precambrian structural highs; 2) generally the Slave Point Fm drapes across Precambrian basement highs, except where Muskeg salts have been leached in post-Slave Point time, in which case collapse has reduced or negated such drape, and 3) dissolution of these salts commonly occurs where the Precambrian is in direct contact with the Muskeg Fm (i.e. bald with respect to the Keg River Fm). It is also very important to be able to identify Precambrian structures on seismic data. Where salt dissolution has not occurred, this exercise consists merely of differentiating structural-relief effects from statics problems. Where leaching has occurred, the exercise is more complex as the Slave Point event is generally anomalously low where the Precambrian is high. As well, the Precambrian and near-Keg River events in these areas are typically difficult, if not impossible, to correlate. This lack of lateral continuity is often the key to differentiating zones of salt dissolution from structural lows at the Precambrian level. Where the Precambrian is low, both this event and the near-Keg River reflection should be of relatively high amplitude. Other features characteristic of salt dissolution include diffraction patterns and extreme time-structural relief at the Slave Point level. Compaction-generated structure at this level should be less abrupt.

# PART B: WINNIPEGOSIS CARBONATES

D.J. Gendzwill, R.M. Lundberg

## INTRODUCTION

Winnipegosis mounds are accumulations of carbonate rock, mostly dolomite, scattered through the Middle Devonian Elk Point basin. The mounds are buried to 2600 m except for the Manitoba outcrop region. They are the equivalents of the Keg River reefs of Alberta. but unlike the Keg River reefs, the Winnipegosis mounds have never produced much oil. Winnipegosis mounds have been the target of several petroleum exploration programs with little success except for a small discovery in North Dakota and the Tableland discovery of southern Saskatchewan. Nevertheless, these discoveries, taken with the general lack of knowledge of these features, sustain interest in them as exploration targets.

The economic significance of the Winnipegosis Fm has been more important to the potash mining industry because the mounds affect the potash-bearing rocks that lie over them in ways which may interfere with mining operations.

The Winnipegosis mounds are common in southern Saskatchewan but little is known about them. After more than 40 years of exploration in the province, very few of the mounds have been tested with the drill and of those tested nearly all have only one drill-hole through them. As a result, there is little reliable information, even their status as reef structures is in doubt and in this report they are referred to as mounds. However, many mounds have been crossed by seismic profiles and the seismic anomalies provide the most common type of geological information for these enigmatic features. Therefore, a description of the seismic response to these features as they are now understood may increase our knowledge of them.

## THE ELK POINT GROUP

The Elk Point Gp in Saskatchewan (Fig. 2.1) includes the: 1) Ashern Fm, a basal shale unit; 2) Winnipegosis Fm, a dolomitized carbonate unit; and 3) the Prairie Evaporite, a thick rock salt unit locally grading into anhydrite. Subsequent cyclothems are found in the Manitoba Gp which overlies the Elk Point Gp but the halite units in the Manitoba Gp are much thinner. The Elk Point Gp was deposited in the Elk Point basin, a broad shallow basin trending northwest-southeast across most of Saskatchewan and extending into North Dakota, Manitoba, and Alberta (Fig. 2.2). Most of the northeast flank of this basin is now truncated by erosion south of the exposed Precambrian. The interior basin now underlies much of southeast and central Saskatchewan and a fringing carbonate shelf fills the edge of the basin in Manitoba, North Dakota, southwest Saskatchewan, and Alberta (Fig. 2.47). Figure 2.48 shows the detailed stratigraphic column for the Elk Point and Manitoba groups of central and southeastern Saskatchewan.

### ASHERN FORMATION

The Ashern Fm, a red or grey argillaceous dolomite, is the lowest formation of the Elk Point Gp. It lies unconformably on the Silurian Interlake Fm and underlies all of southern Saskatchewan but does not exceed 18 m in thickness (Paterson, 1973). The Winnipegosis Fm overlies the Ashern Fm.

### WINNIPEGOSIS FORMATION

The Middle Devonian Winnipegosis Fm underlies nearly all of the sedimentary region of Saskatchewan, except for a region of nondeposition in the southwest corner (Jones, 1965). It crops out in only one place, near the Clearwater River. Its subcrop is truncated by erosion, together with other Devonian rocks, south of the Precambrian Shield. The Winnipegosis Fm dips steadily south, southwest, or southeast, reaching its greatest depth of about 3000 m,

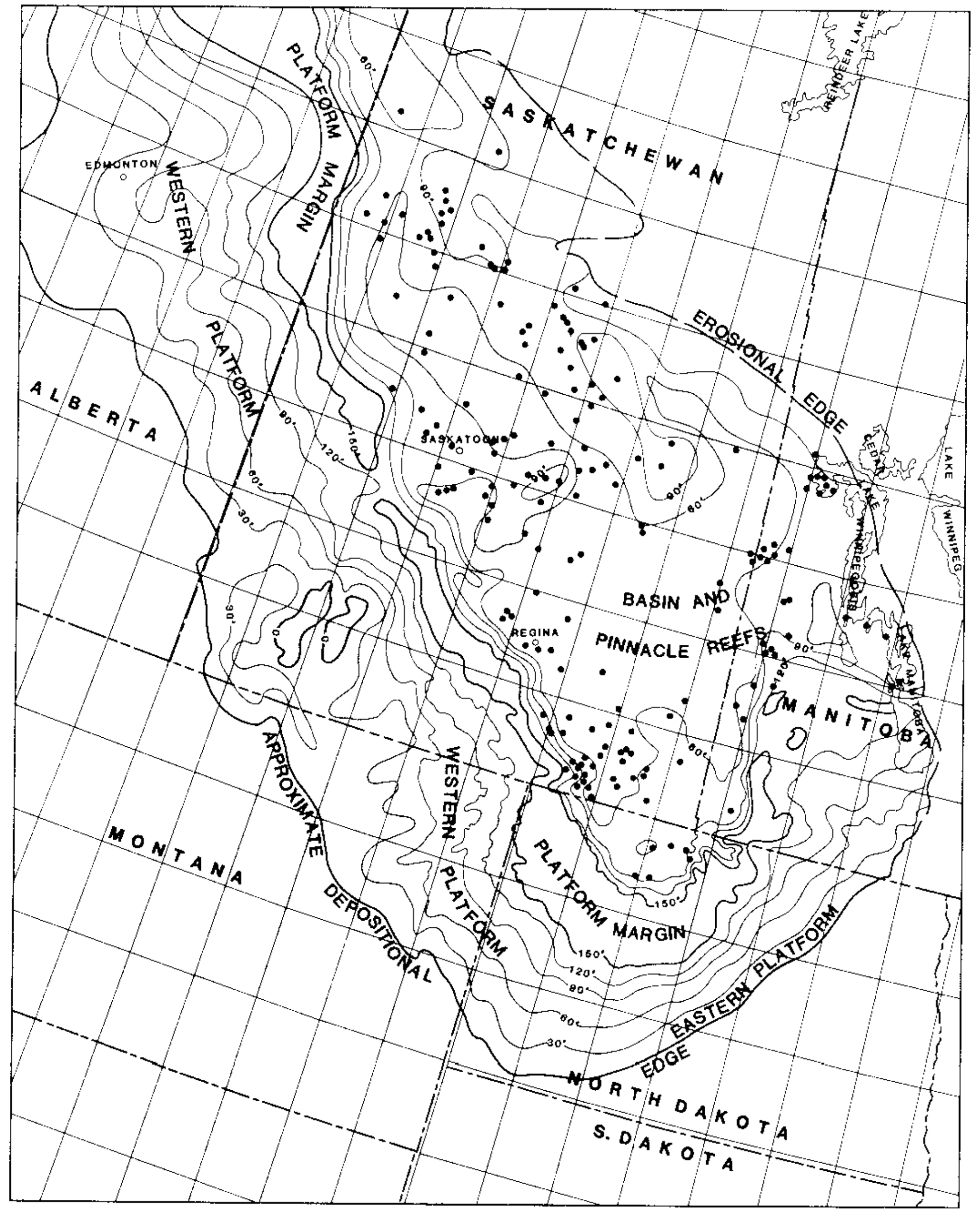


**Figure 2.47.** Regional map showing the Elk Point basin, thickness of the Winnipegosis, and some known mounds (dots). Contour interval, 30 ft (9.1 m) (courtesy of Jackalope Geological, Boulder, Colorado).

in Saskatchewan, near the U.S. border southwest of Estevan. It was divided into a lower member and upper member by Jones (1965).

The lower Winnipegosis member, called a platform member, is composed of dolomitized fossiliferous packstone. It contains algal oncolites, brachiopods, and crinoids in a poorly sorted matrix but dolomitization obscures many of the fossils (Jones, 1965). The lower

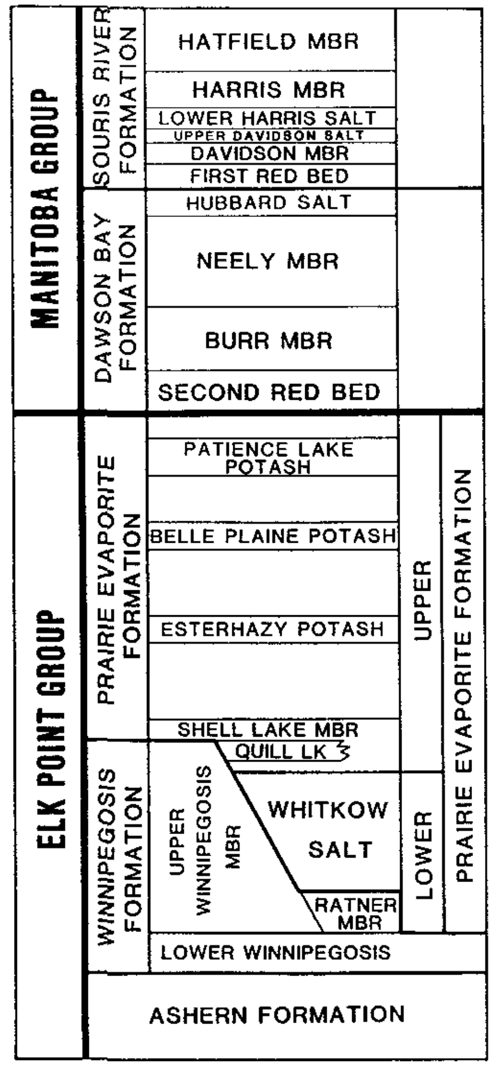


**Figure 2.48** Detailed stratigraphy of the Elk Point and Manitoba groups of southern Saskatchewan (modified after Gendzwill and Wilson, 1987).

Winnipegosis is relatively thin in the interior portion of the Elk Point basin but reaches a thickness of 40 m in the fringing carbonate shelf portion south of Regina and Moose Jaw.

The upper Winnipegosis is composed of thick carbonate mounds lying on top of the lower Winnipegosis. These mounds have been described by Gendzwill and Wilson (1987), Precht (1986), Wilson (1984), Perrin (1982), Gendzwill (1978), Wardlaw and Reinson (1971), Streeton (1971), Jones (1965) and others. Those in central Saskatchewan have been referred to as mounds rather than reefs because typical reef characteristics have not been observed in core samples. However, those in North Dakota have been called reefs by Perrin (1982) and Precht (1986). Perrin (1982) has identified three types of reefs: "pinnacle" reefs in the deeper parts of the basin, "platform or shelf edge" reefs which formed around the margins of the basin, and "patch" reefs which formed on the shelf platform or on the shelf margin.

The upper Winnipegosis mounds, studied by Gendzwill and Wilson (1987), are distributed throughout the basin interior in southern Saskatchewan. The mounds are comparable to the pinnacle reefs of Perrin (1982). The greatest numbers of mounds are found in the Saskatoon area where it is estimated that they underlie nearly 25% of the area. Few of the mounds have been penetrated by even one drill-hole but many have been recognized by their seismic signature. The mounds, as seen on seismic sections, are usually between one and six kilometres wide. The known thickness of the upper Winnipegosis ranges up to 105 m (Jones, 1965).

The mounds are composed of dolomitized carbonate (Gendzwill and Wilson, 1987). Detailed structure of individual mounds is not known but composite lithologies have been proposed based on cores of different mounds. Wilson (1984) proposed an internal subdivision of the mounds into four principal units, a peloidal grainstone, a laminated mudstone, an organic unit, and a fringing cap unit. Figure 2.49 shows a conceptual model of a Winnipegosis mound.

The most extensive unit is the peloidal grainstone which directly overlies the lower Winnipegosis. The peloidal grainstone ranges from well-sorted grainstone to a poorly-sorted wackestone. Several generations of calcium carbonate cement have reduced the porosity of this unit to less than 7% in the cores examined. However, Precht (1986) quotes porosity as high as 20% in Shell Oil Creek 41-2, a North Dakota well.

Near the edges of the mound, the peloidal grainstone grades into a narrow organic unit. The organic unit is similar to the peloidal grainstone in many respects but it contains frame-building organisms such as corals, stromatoporoids, oncolites, and shell fragments in amounts up to 30%. These fossils are usually broken and abraided and none of the organisms have been found in growth position.

The peloidal grainstone is overlain by a laminated mudstone unit or a fringing cap unit. The laminated mudstone consists of a dense, fine-grained, light-to-medium brown, extensively dolomitized lime mudstone. The porosity is very low. The laminated mudstone

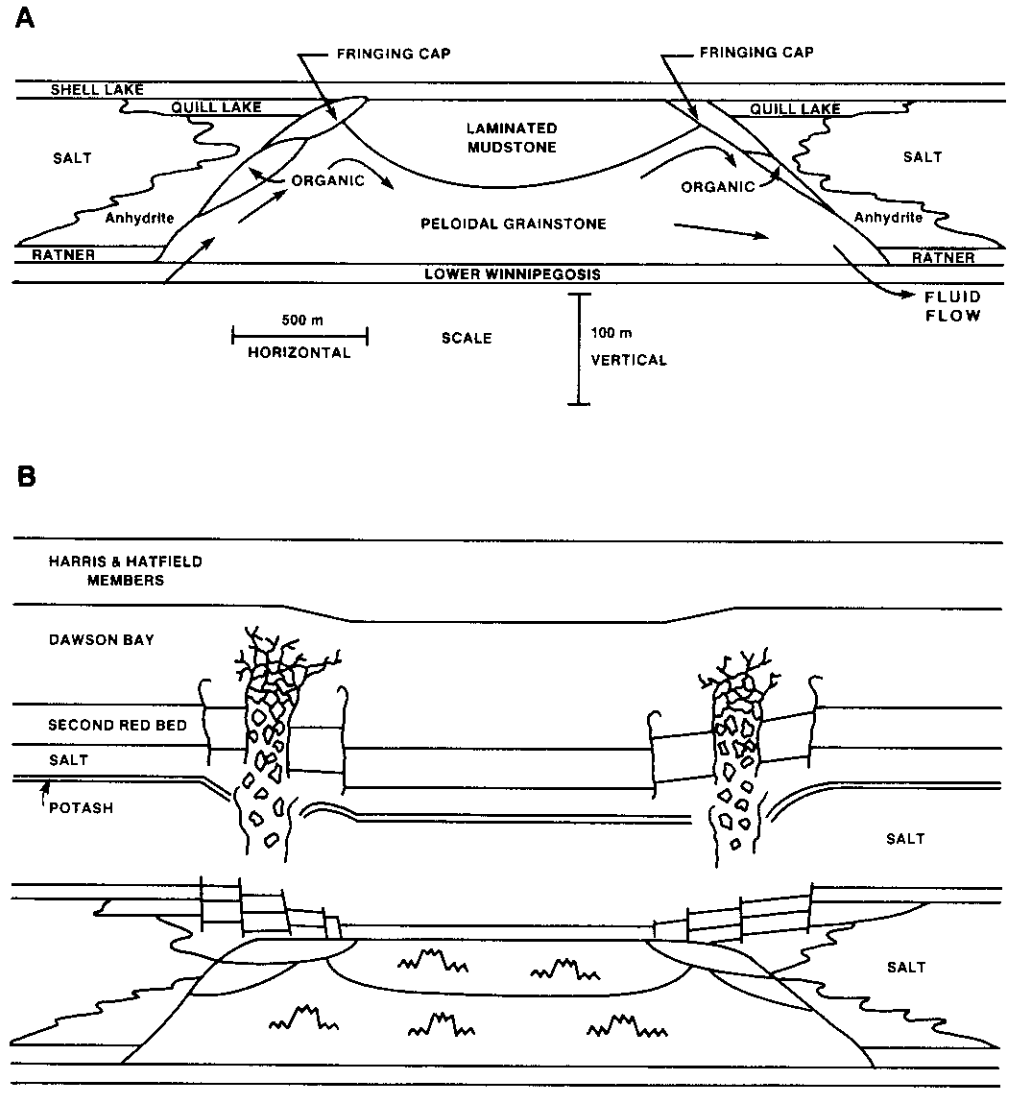


**Figure 2.49.** Structure of Winnipegosis mounds in central Saskatchewan. A is the structure when deposited, B is the structure after burial and compaction. Diagrammatic chimney-collapse structures are shown (after Gendzwill and Wilson, 1987).

contains an anhydrite fraction, which increases towards the top and grades into the overlying Shell Lake anhydrite.

Near the edges of the mound, the laminated mudstone and peloidal grainstone units are overlain by a fringing cap unit which is comprised of pisolites, peloids, and extensively dolomitized intraclasts with concretionary coatings in a micrite matrix. The pisolites are frequently fractured and brecciated. The fringing cap unit is not found in very many cores and it is thought to be confined to a marginal position around the mounds rather than entirely covering them.

The fractured and brecciated nature of fossils in the organic unit and the fringing cap unit suggests that these rocks were in a relatively high-energy environment where the sediments were frequently ripped up and redeposited. These sediments may have faced the sea whereas the laminated mudstones were protected.

### RATNER MEMBER

Between the upper Winnipegosis mounds, The Ratner member (Reinson and Wardlaw, 1972) overlies the lower Winnipegosis and flanks the upper Winnipegosis. The Ratner member consists of carbonate mudstone and/or anhydrite. Anhydrite is often found above the Ratner member. The upper Winnipegosis and Ratner members are overlain by salt of the Prairie Evaporite Fm where that salt has not been dissolved and removed.

### PRAIRIE EVAPORITE FORMATION

The Prairie Evaporite Fm underlies much of southern Saskatchewan (Holter, 1969). It is divided into two major salt units, the lower or Whitkow salt and the upper or Leofnard salt, separated by the Shell Lake anhydrite (Jordan, 1967). An anhydrite layer of variable thickness is often found at the base of the Prairie Evaporite Fm and the Whitkow salt lies on it. The Whitkow, usually composed of clean salt, fills the basin between the mounds, whereas the Shell Lake anhydrite lies on the Whitkow salt, nearly coincident with the tops of the mounds (Holter, 1969).

Because of the irregular nature of the Shell Lake anhydrite, Holter (1969) does not use it in his nomenclature. Holter defines an upper and a lower salt with the boundary at the base of the lowest potash member. However, the anhydrite produces a persistent seismic reflection in many areas so it is a useful marker in seismic stratigraphy. Near the mounds, the Shell Lake anhydrite is interlayered with a thin carbonate unit called the Quill Lake marker bed, thought to be erosional debris derived from the tops of the mounds. The Shell Lake anhydrite reaches a maximum thickness of 35 m in central Saskatchewan but it is variable and is entirely absent in the southeast.

The upper or Leofnard salt is composed mostly of halite with several thick beds of sylvinite potash ore near the top. The Patience Lake, Belle Plain, and Esterhazy potash members are mined in different areas of Saskatchewan. Thin beds and partings of dolomitic shale contaminate the upper salt and potash beds in some areas. Prairie Evaporite salt reaches a maximum thickness of 215 m southeast of Saskatoon.

## THE MANITOBA GROUP

### DAWSON BAY FORMATION

Overlying the Prairie Evaporite Fm is the Dawson Bay Fm (Dunn, 1982). The Second Red Bed, a dolomitic mudstone is at the base. The Second Red Bed is followed by the Burr Mbr, a fossiliferous limestone, and then the Neely Mbr another limestone. The final member is the Hubbard salt, a thin salt which is present in limited areas. The total Dawson Bay Fm thickness is about 50 m.

### SOURIS RIVER FORMATION

The Souris River Fm lies on the Dawson Bay Fm. This constitutes another cyclothem with the First Red Bed, a dolomitic mudstone at the base, followed by the Davidson carbonate and the Davidson halite. Above the Davidson is a thin anhydrite and another salt called the Harris salt followed by the Harris carbonate. The Davidson and Harris salts together with the interbedded anhydrite make up a thickness of 40 m (Kendall, 1976) but this occupies only a portion of the basin and has been removed by dissolution in many areas.

## COMPACTION OF WINNIPEGOSIS MOUNDS

Seismic and well-log studies of the mounds (Gendzwill, 1978) have demonstrated that substantial subsidence occurred over the mounds after burial. The subsidence has been accurately measured in surveyed elevations of underground openings of potash mines which frequently extend over areas underlain by Winnipegosis mounds. In some mines, subsidence has been observed over every known mound and the relief is as great as 40 m (Mackintosh and McVittie, 1983). Subsidence is not the same on all mounds, nor is it uniform on any single mound. Some mounds have no subsidence that can be identified, at least on seismic data.

The subsidence is attributed to compaction of the mounds (Gendzwill and Wilson, 1987) rather than to dissolution of the overlying salt (Gendzwill, 1978). The compaction appears to have taken place by dewatering (especially of the laminated mudstone), dolomitization and stylolitization. Pervasive fracturing of the dolomitic rock may have resulted from deformation associated with the volume reduction. The subsidence over the mounds is a result of differential compaction where the porous carbonate mounds are subject to compaction but the dense, nonporous salt which encases and surrounds them is incompressible.

Subsidence due to partial dissolving of the salt over a mound is thought to be unlikely because the anhydrite capping over most of the mounds forms an impermeable seal which protects the salt from water in the porous carbonate. Only where the anhydrite is fractured or missing could water in the mounds attack the salt. The anhydrite may be fractured by subsidence around the edge of a mound. Such restricted access to the salt through a narrow fracture should result in a narrow zone of salt removal.

Collapse chimneys containing breccia from formations above the mine have been found in the potash mines. The dimensions range from a few tens to a few hundreds of metres in width. Such chimneys are always found over Winnipegosis mounds (Mackintosh and McVittie, 1983) and are thought to be caused by dissolution of salt by water moving through the fractured anhydrite caprock. The water could have been derived from the laminated mudstone as it compacted.

The presence of subsidence over a Winnipegosis mound is an indication of the age of diagenesis, with compaction (and associated fluid movements) occurring as late as the youngest overlying stratum which displays subsidence. The absence of subsidence over a Winnipegosis mound is an indication that either: 1) no compaction of the mound occurred; or 2) all the compaction occurred prior to deposition of the first mappable rock layer above the mound.

There are at least three different mechanisms which could be responsible for compaction of a mound and the subsidence would be similar for any of them. Development of porosity within a mound may affect the speed of seismic waves. Thus, under favourable conditions, it may be possible to identify a seismic anomaly within or below a mound which represents that porosity; but this would be quite different from any subsidence effect.

## SALT REMOVAL BY DISSOLUTION

Salt of the Prairie Evaporite Fm has been dissolved by groundwater in many areas. The largest of these areas is the Saskatoon reentrant in which a layer of salt up to 180 m thick has been removed from more than 40 000 $km^2$ in a roughly triangular-shaped area between Swift Current, Regina, and Saskatoon. In this area, the overlying formations have been let down and brecciated. Multi-stage salt removal, with sedimentary infill between removal episodes, has created some complicated structures (Sawatzky et al., 1959). Sediments may also drape over Winnipegosis mounds when the supporting salt is removed. This regional salt removal appears to have been controlled by interstratal solutions moving along the regional hydraulic gradient from south to north.

Prairie Evaporite Fm salt has been completely or partially removed in many "salt-removal structures" in the interior of the huge salt layer. These range in size from a few tens of metres in diameter for "chimney collapse" to several hundred square kilometres, such as the "Rosetown Low". The amplitude of the synclinal depression produced may be as large as 200 m. The smallest of these are controlled by Winnipegosis mounds as described above and the larger ones are probably controlled by either basement faults or intrasedimentary faults. Younger salts such as the Hubbard Evaporite (Dawson Bay Fm) and Davidson Evaporite (Souris River Fm) are usually removed wherever the Prairie Evaporite Fm has been removed. The younger salts may also have been removed in some places where the Prairie Evaporite Fm salt remains, or, perhaps they were never deposited. Salt was removed in several episodes from the Devonian to the present (Holter, 1969). Salt springs issuing in northern Saskatchewan and Manitoba and evidence presented by Gendzwill and Hajnal (1971) and Christiansen (1971) indicate that salt is being dissolved today. Interpretation of some seismic features, together with comparison of stratigraphy in potash mines, provides evidence that salt has been removed from the top of the Prairie Evaporite Fm in some areas, from the bottom in other areas, and sometimes from both top and bottom, depending to some degree on how much salt has been removed and how much disturbance has been caused.

Salt removal from the periphery of Rainbow reefs, forming a crude "rim syncline", has been cited by Anderson (1986) as a diagnostic feature for the recognition of such reefs in Alberta. Similar features have been noted near some Winnipegosis mounds but the feature seems to be less prevalent in Saskatchewan than in

Alberta. Narrow collapse chimneys over the mounds, such as are found in the potash mines, seem to be most common but these are seldom visible on seismic data. Such small features are rarely crossed by widely spaced seismic lines and, if one is crossed by chance, it would not be recognized if its dimension is less than that of the Fresnel zone for seismic waves.

## SEISMIC REFLECTION FEATURES OF DEVONIAN ROCKS IN SASKATCHEWAN

The appearance of these rocks on seismic reflection data is affected by their physical properties and their stratigraphy. The rocks are mostly carbonates and salt with some shale. The seismic speed through these materials ranges from about 4400 m/s for salt and some shales to 6000 m/s for dense dolomites and anhydrites. The speed for porous carbonates is variable and depends on the porosity. With these speeds, a 50-Hz seismic wave is about 100 m in length, so it is advantageous to use seismic frequencies as high as possible in order to improve the resolution. The actual structure of the seismograms frequently appears to be controlled by "tuning effects". This is demonstrated by sonic logs which show cyclic patterns of acoustic speed. The physical length of the patterns may match seismic wavelengths, providing constructive reinforcement and large-amplitude reflections.

A second characteristic of these bedded carbonate rocks is their generally uniform nature. On the scale of a seismic wave they are laterally uniform for long distances and dips are gentle except for local structures. The best seismic reflectors in the Devonian rocks of Saskatchewan are the contrasts between salt and carbonate rocks or between the thicker shale units and carbonates.

Where a Winnipegosis mound exists, the otherwise uniform patterns of reflectivity are interrupted. There may be a sloping reflection from the edge of the mound. The reflection from the base of the salt is changed because high-speed carbonate rock is present instead of low-speed salt.

If the Shell Lake Mbr anhydrite is present, the reflection from the anhydrite tends to interfere with that from the mound in a manner that depends on the thickness of the anhydrite and the consequent strength of its reflection, on the thickness of the Whitkow Mbr salt and on the height of the mound. Normally, the Shell Lake Mbr anhydrite is about level with the top of the mounds. Where the Whitkow Mbr salt is substantially less than 100 m in thickness, the effect of the mounds is that of a thin bed between two prominent reflectors: i.e. the anhydrite and the base of the Winnipegosis; so the visual effect on a seismogram is much reduced. Also, if there is a thick basal anhydrite in the Whitkow Mbr, it may cover or nearly cover a carbonate mound, reducing or even eliminating any seismic indication.

Where the Shell Lake Mbr anhydrite does not exist, the problem is simpler. Anhydrite may overlie the mound but there is no interference because it is conformable to the shape of the mound and the seismic anomaly looks like a mound: i.e. a bump in an otherwise smooth reflection. If the mound is thin, the effect is less obvious; and if the total salt thickness is small, there will be interference from the top-of-salt reflection similar to that from the Shell Lake Mbr.

A second feature that may be seen is subsidence of shallower strata over all or portions of the mound. The subsidence is a result of the compaction of the mound and is most obvious on the Dawson Bay reflection, with lesser effects on younger strata. The subsidence time-structure may exceed 10 ms in amplitude.

A third effect that may be seen is the decrease in seismic travel-time through the high-speed carbonate mound, compared to that through the low-speed salt. This causes the so called "velocity pull-up" in which reflections from deeper strata appear slightly earlier under a mound than elsewhere. This may amount to a time differential of as much as 15 ms for central Saskatchewan mounds. The time difference may even be used to check thickness estimates. The combination of subsidence above and pull-up below a mound creates a distinctive pinched appearance to the seismic reflections which would otherwise be straight and parallel.

A fourth criterion that may indicate Winnipegosis mounds is a change in the seismic reflection structure immediately under the mound. This occurs because the reflection from the base of the salt is eliminated under a mound and is replaced by other primary and multiple reflections.

Dissolution of salt from the flanks of a mound has been used by Anderson (1986) to recognize Rainbow reefs in Alberta but the effect seems to be less common in Saskatchewan. When it occurs, the result is a positive structure instead of the more usual negative subsidence structure in Saskatchewan.

The pull-up anomaly may be analyzed by comparing the seismic time through the salt with the seismic time from the top of salt to some marker bed below (Fig. 2.50).

The time through the salt, $T_s$, is given by:

$$T_s = Z_s / V_s = (Z_o - Z_m)/V_s \quad (1)$$

where $Z_s$ is salt thickness wherever it is measured, $Z_o$ is the full thickness of the salt where there is no mound, $Z_m$ is the height of the mound above normal salt base, $V_s$ is the seismic speed through salt.

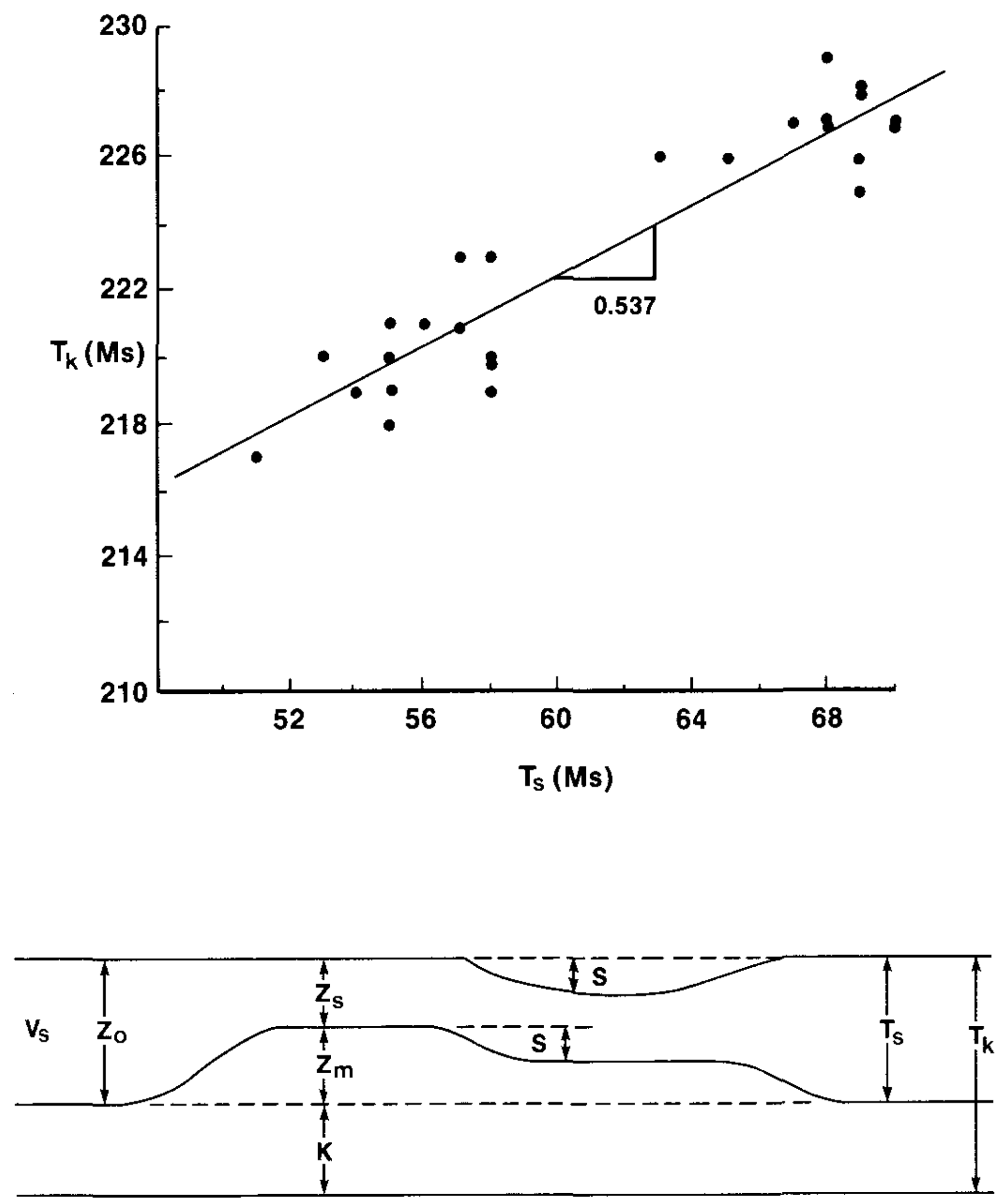


**Figure 2.50.** Subsidence model showing dimensions for "velocity pull-up" study, and crossplot of times for Tableland anomaly.

Similarly the time to a deeper marker bed, $T_k$, is given by:

$$T_k = (Z_o - Z_m)/V_s + Z_m/V_m + K \quad (2)$$

where $V_m$ is seismic speed through the mound, and $K$ is additional traveltime to a deeper reflector.

If subsidence $S$ has occurred due to compaction of the mound but no salt has been dissolved, equation (2) is modified to:

$$T_k = (Z_o - Z_m)/V_s + (Z_m - S)/V_m + K . \quad (3)$$

Differentiating (1) and (3) with respect to mound height gives:

$$dT_s / dZ_m = -1/V_s \quad (4)$$

$$dT_k / dZ_m = -1/V_s + (1 - dS / dZ_m)/V_m \quad (5)$$

and dividing (5) by (4) produces:

$$dT_k / dT_s = 1 + V_s (1 - dS / dZ_m)/V_m . \quad (6)$$

A similar analysis may be made with the assumption that subsidence is due to salt removal instead of compaction of the carbonates. In that case the equation is:

$$dT_k / dT_s = 1 + V_s / [V_m (1 + dS / dZ_m)] . \quad (7)$$

These equations may be used to estimate seismic speed and subsidence relations of a mound anomaly by crossplotting the seismic times through the salt ($T_s$) with seismic times from top of salt to a marker bed ($T_k$). The slope of the line may be diagnostic.

## SEISMOGRAMS OF WINNIPEGOSIS MOUNDS

Three examples of Winnipegosis mounds in Saskatchewan are presented here, one from Estevan (southeast area), one from Rocanville (east area), and one from Allan (central area). Figure 2.2 shows the general location of these mounds. Processing parameters for the seismic sections are shown in Table 2.6.

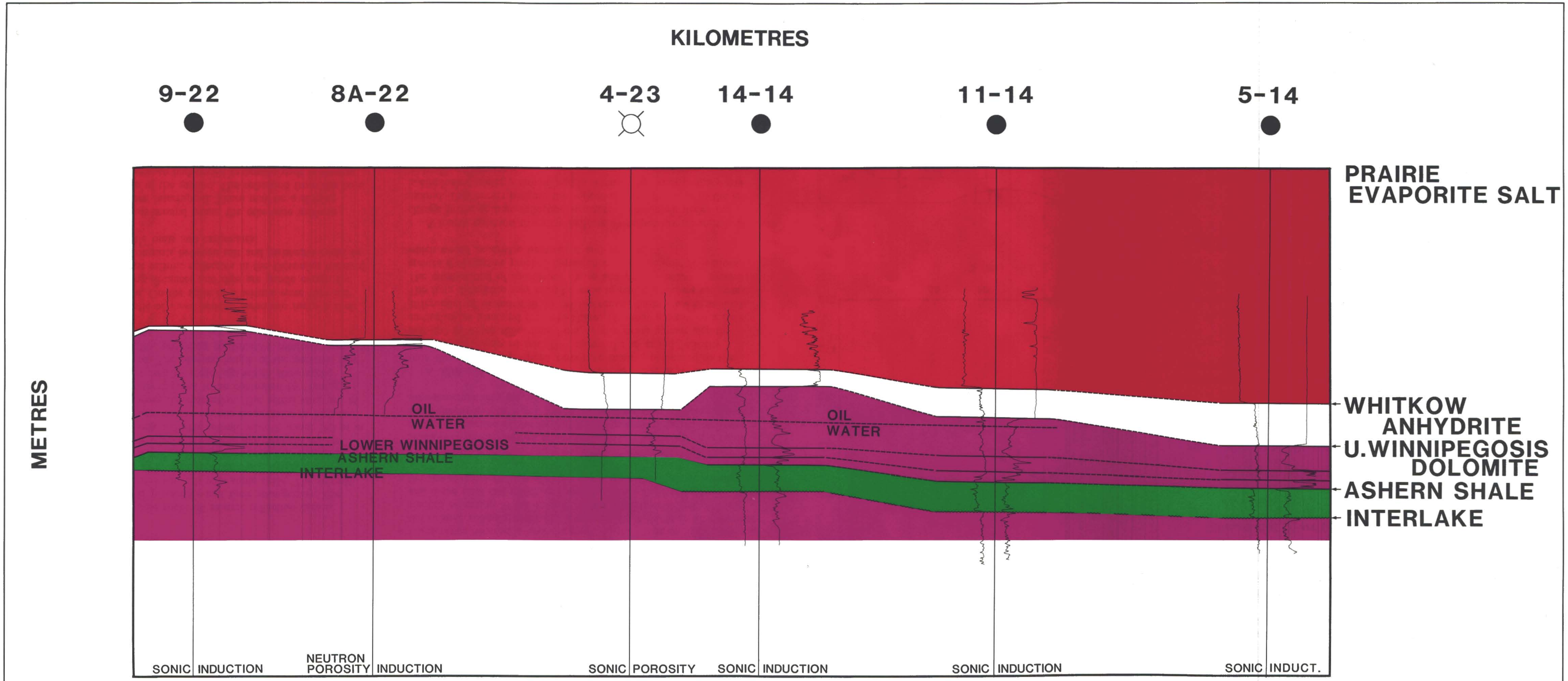


**Figure 2.52.** Well-log section for the Tableland mound (Courtesy of Home Oil Company Ltd.).



DRAFTING: LOG PLOTS: AUTHOR: D. GENDZWILL

**Table 2.6.** Acquisition and processing parameters for the three Winnipegosis seismic lines

| | Tableland | Allan | Rocanville |
|---|---|---|---|
| DATA COLLECTION | | | |
| Date Shot | May 1985 | Jan 1975 | Sep 1983 |
| Contractor | Pioneer Expl. | Century Geoph. | Grant Geoph. |
| Instruments | DFSV/120 ch | DFSIII/48 ch | DFSV/48 ch |
| Filters | 8/128 Hz | 12/124 Hz | out/128 Hz |
| Source | Dynamite | Dynamite | Vibroseis |
| | 1 kg/17 m | 0.2 kg/18 m | 10-60 Hz/8 s |
| interval | 134 m | 134 m | 134 m |
| Receivers | Geospace 14 Hz | Mark 14 Hz | Mark 10 Hz |
| array | 9/33.5 m | 9/33.5 m | 9/33.5 m |
| interval | 33.5 m | 33.5 m | 33.5 m |
| DATA PROCESSING | | | |
| Date | Nov 1987 | Sep 1986 | Sep 1986 |
| Contractor | Western | Western | Western |
| Demux | 2450 ms | 1200 ms | 1200 ms |
| Line Geometry | x | x | x |
| Inst. Phase | x | x | x |
| Amp. Comp. | | x | x |
| Deconvolution | Minimum Phase Spiking 100 ms | Minimum Phase Frequency 80 ms | Zero Phase Frequency 80 ms |
| Trace Equal. | x | | |
| Drift Statics interactive | $V_w$ = 610 m/s $V_2$ = 2000 m/s | $V_w$ = 610 m/s $V_1$ = 1890 m/s | $V_w$ = 610 m/s $V_1$ = 1890 m/s |
| CMP Sort | x | x | x |
| Auto Statics | x | x | x |
| Velocity Anal. | x | x | x |
| Normal Moveout | x | x | x |
| Mute | | x | x |
| Auto Statics | x | x | |
| Dip Moveout | x | | |
| Mute | x | | |
| Filter | | 10/15-80/90 Hz | |
| Stack | 1200% | 1200% | 1200% |
| Filter | | | 12-70 Hz |
| F.D. Migration | x | x | x |
| Filter | 12-70 Hz | 10/15-80/90 Hz | 10/15-80/90 Hz |
| RMS Gain | x | x | x |
| Display | x | x | x |

## TABLELAND ANOMALY

The Dome Scurry Tableland 11-14-2-9W2M well was drilled in 1975. It encountered 116 m of Prairie Evaporite Fm salt over 16 m of anhydrite and 34 m of Winnipegosis Fm dolomite. The well produced 4956 $m^3$ of oil and 651 600 $m^3$ of gas until 1983. A 1985 exploration program resulted in the drilling of Home et al. Tableland 8A-22-2-9W2M in 1986 and Home SRO Tableland 9-22-2-9W2M in 1987, both within 1300 m northwest of the first well on the same structure (Fig. 2.51). These two wells encountered 63 and 69 m of Winnipegosis Fm dolomite. To the end of 1987 these last wells produced 50 070 $m^3$ of oil and 5 034 900 $m^3$ of gas.

Figure 2.52 shows the structure and a well-log section for the mound. Significant features include the thick porous (9-10%) dolomite of the mound and a thin (2 m) anhydrite capping. Off the mound, the Whitkow Mbr anhydrite thickens to 20 or 25 m and the porous dolomite is replaced by a thin (5-10 m), dense Ratner member.

Figure 2.53 shows a geological cross-section interpreted from seismic line AEN 85-2 (Fig. 2.54). This seismic section shows the Tableland mound anomaly. The recording and processing parameters are shown in Table 2.6. Figure 2.55 shows a compressed plot of the seismogram to emphasize the small features. The most obvious feature is the mound anomaly itself which appears as a positive structural feature with 10 to 15 ms of relief. The highest point on the seismic anomaly appears to correspond to the thickest accumulation of dolomite as found in the holes 8A-22 and 9-22 (Fig. 2.52). The seismogram structure is composed of a positive reflection peak corresponding to the top of the Winnipegosis Fm and a weaker

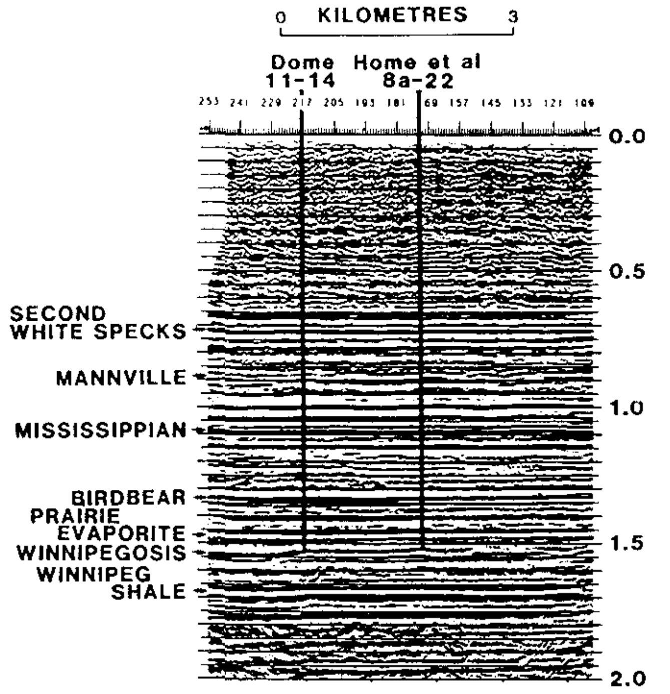


**Figure 2.55.** Compressed seismic plot for Tableland seismic line AEN 85-2 emphasizing subsidence and pull-up features.

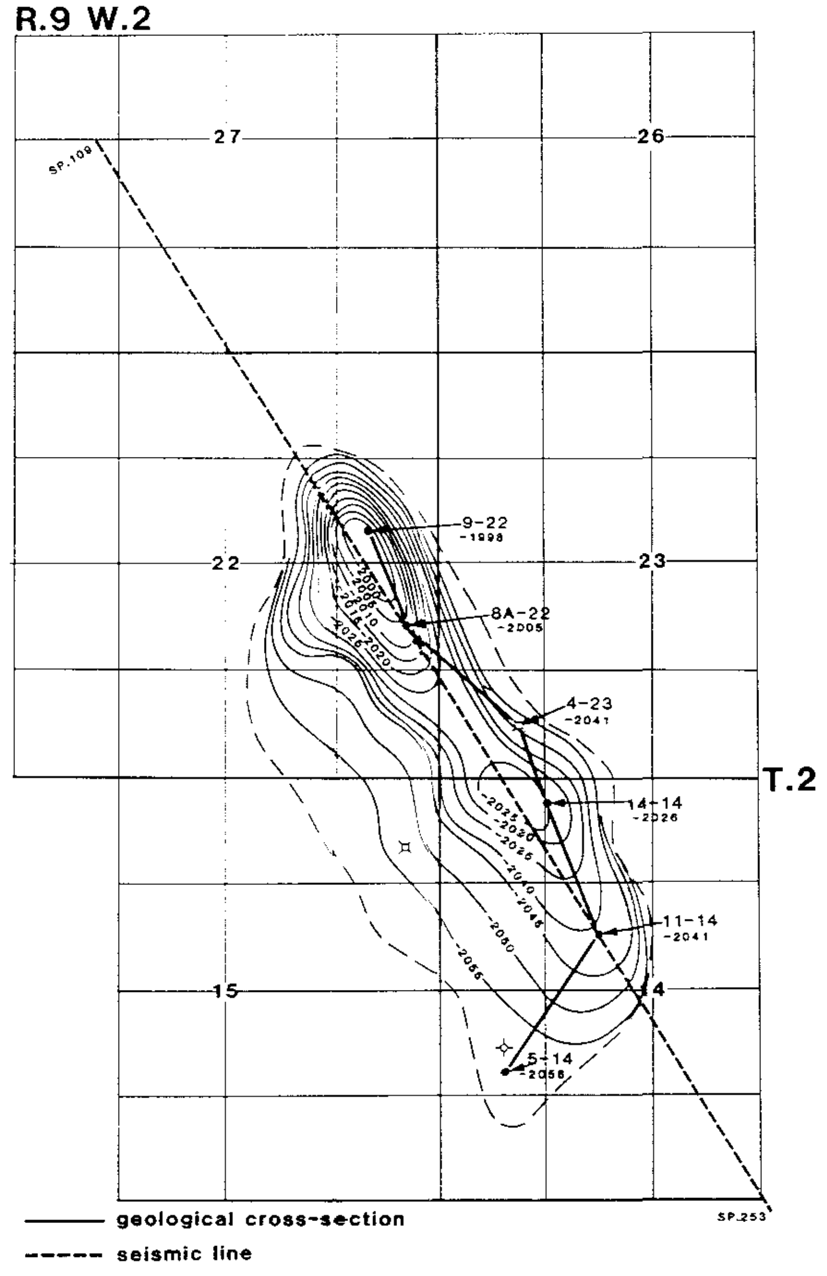


**Figure 2.51.** Map of contoured porosity thickness in Tableland mound (courtesy of Home Oil Company Ltd.).

positive peak corresponding to the base of the Ashern Fm. Short-period multiples may modify the shape of these peaks. In the vicinity of the Home 8A-22 well (trace 171) the amplitude of both these reflection peaks diminishes. The reduced amplitude may be due to the thinning of the anhydrite cover and the lower seismic speed of the porous dolomite (both features as shown in the well log), resulting in smaller contrasts of acoustic speed and reflectivity with the other rock. A seismic anomaly at the north end of the line suggests the presence of another mound.

There is about 4-5 ms of subsidence over this mound. The subsidence may be examined by using dividers to compare seismic traveltimes over the mound with those off the mound or by folding the section and overlaying different parts to obtain exact comparisons. Such comparison shows that there is differential thickening in the interval between the Watrous Fm (Cretaceous) and Mississippian reflections but little or none between the Mississippian and Prairie Evaporite Fm. This suggests that significant subsidence over this mound occurred only after the Mississippian and before the deposition of the Watrous Fm. As most of the oil in the Estevan area is found in Mississippian rocks, one may speculate that subsidence and oil emplacement may have been simultaneous in the mound.

The pull-up anomaly under the mound may be analyzed using equations (6) and (7). These equations compare seismic times from the top of salt to the base of salt ($T_s$) with seismic times from the top of salt to a deeper marker ($T_k$) which is supposed to be flat. Figure 2.50 shows a crossplot of useable times picked from the section at 100-m intervals. The best fit line to the point scatter has a slope of 0.537 ($dT_k$ / $dT_s$). Using well-log data, the ratio of $V_s$ / $V_m$ is 0.77 and from equation (6) (the limestone-compaction model) we derive $dS/dZ_m$ is 0.40. Near the northwest end, the mound anomaly has relief ($Z_m$) of 13 ms and near the southeast end relief is about 11 ms. Using times instead of thicknesses (let $dZ_m$ = 13), the check for $dS$ (subsidence due to compaction) is: 0.4 x 13 ms = 5.2 ms at the northwest and 0.40 x 11 ms = 4.4 ms at the southeast, which is in reasonable agreement with the visual estimate from the seismogram of 4 ms. Using equation (7) (the salt-removal model) we obtain $dS/dZ_m$ = 0.66 and the check on $dS$ (subsidence due to salt removal) gives 0.66 x 13 ms = 8.6 ms at the northwest and 0.66 x 11 ms = 7.3 ms at the southeast. This is rather more subsidence than the 4 ms seen on the seismogram so we do not accept the premise of (7) which is that salt has been removed.

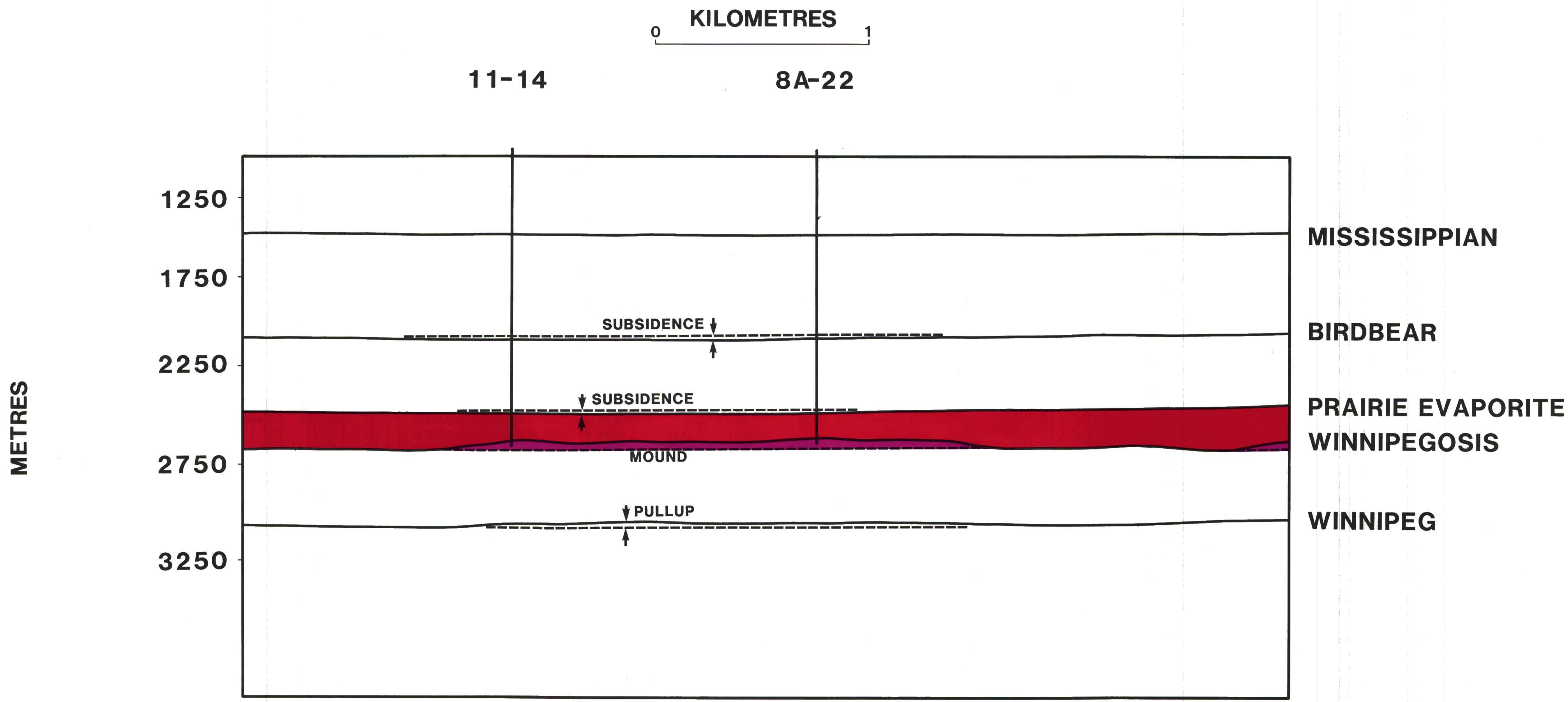


**Figure 2.53.** Interpretation sketch for Tableland seismic section AEN 85-2.



DRAFTING: | LOG PLOTS: | AUTHOR: D. GENDZWILL R. LUNDBERG

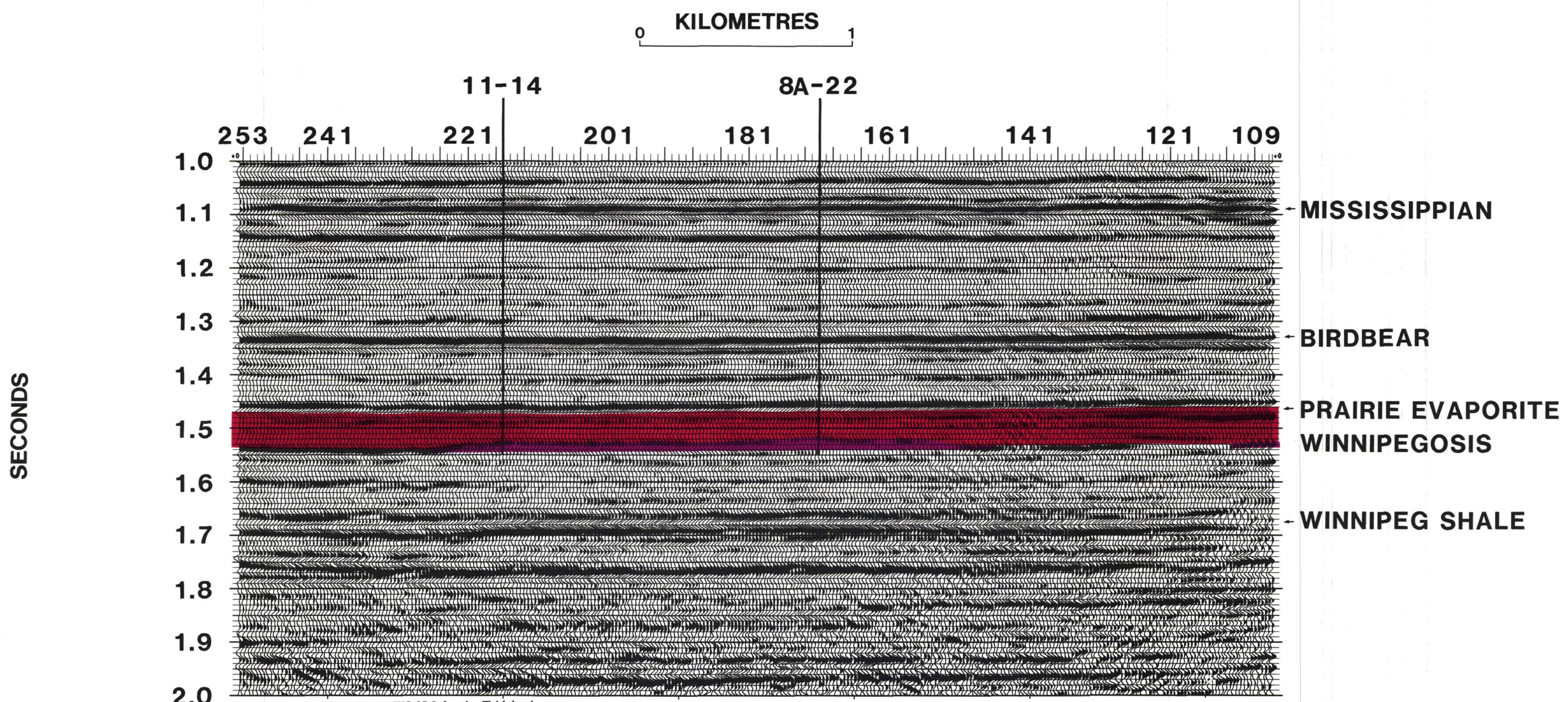


**Figure 2.54.** Seismic section AEN 85-2 for the Tableland Winnipegosis mound.



DONOR: DIAMOND SHAMROCK CANADA LTD. | PROCESSOR: WESTERN GEOPHYSICAL CANADA | AUTHOR: D. GENDZWILL R. LUNDBERG

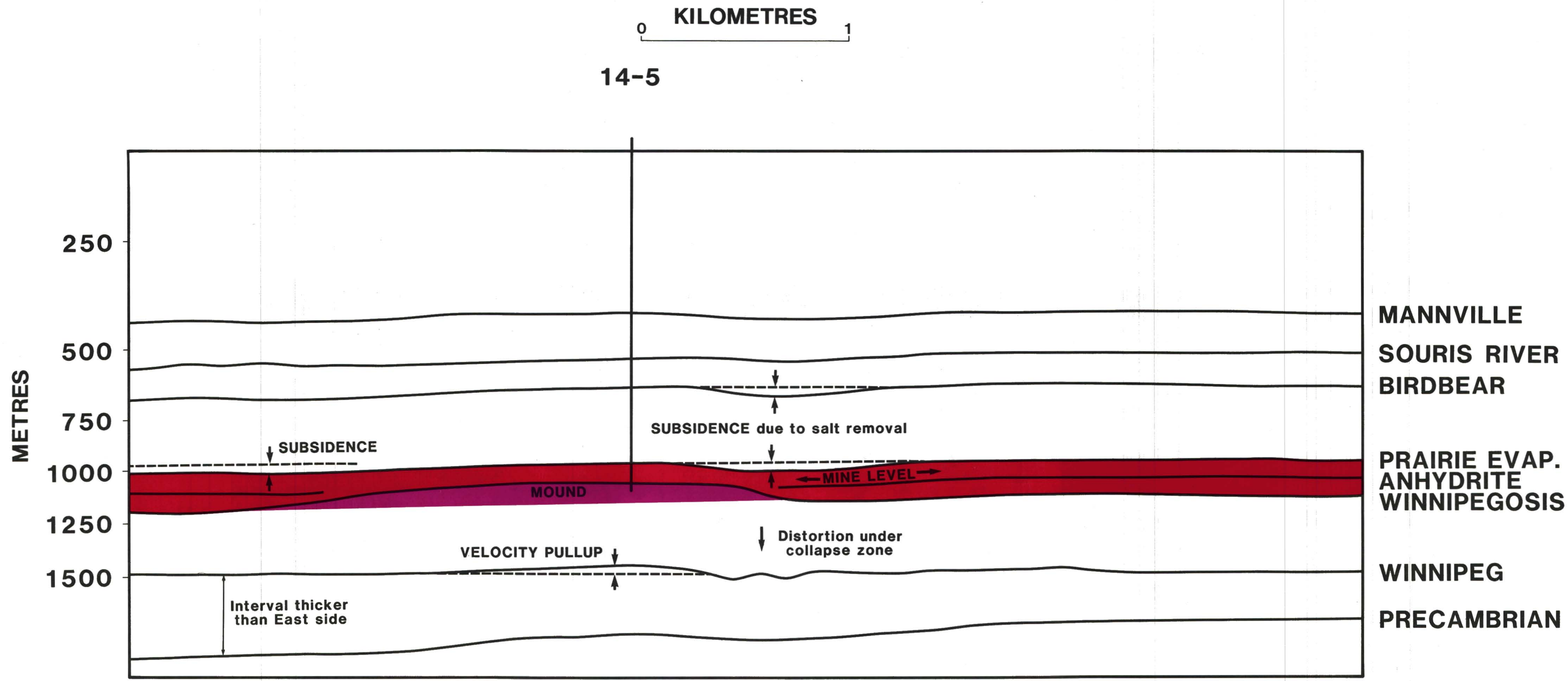


**Figure 2.57.** Interpretation sketch for Rocanville seismic section T17-1.0.



DRAFTING: | LOG PLOTS: | AUTHOR: D. GENDZWILL

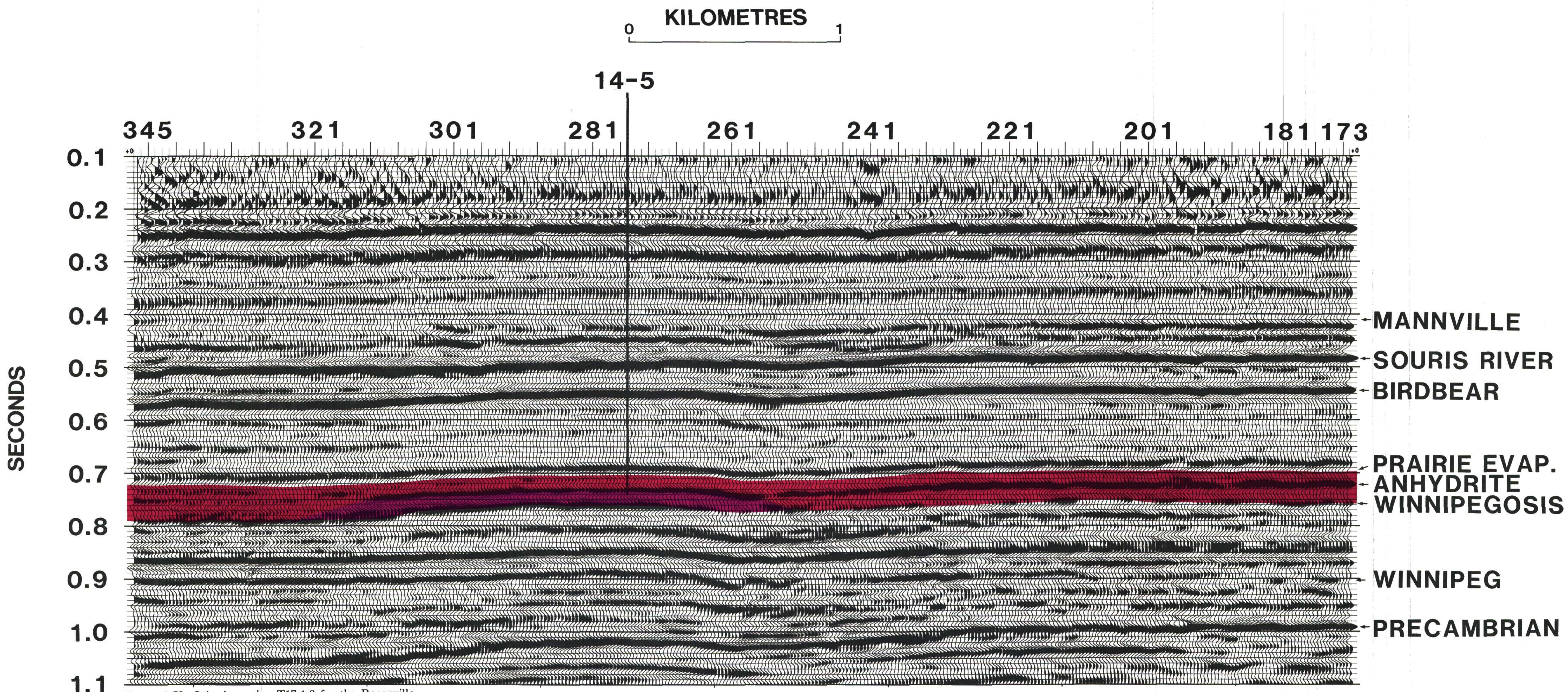


**Figure 2.58.** Seismic section T17-1.0 for the Raconville Winnipegosis mound.



DONOR: POTASH CORP. OF SASKATCHEWAN, ROCANVILLE DIV. | PROCESSOR: WESTERN GEOPHYSICAL CANADA | AUTHOR: D. GENDZWILL

The interpretation from this is that all of the seismic pull-up anomaly can be explained by observed features of the mound. Subsidence over the mound can best be explained as due to compaction of the mound rather than thinning of the salt, and there is no structural anomaly under the mound within the resolution of this interpretation.

Synthetic seismograms have been constructed for several of the sonic logs, (Fig. 2.56). From the logs, the highest part of the Winnipegosis mound contains 70 m of anhydrite and carbonate above the Ashern Fm. Two-way seismic time through this mass is about 25 ms, time enough for two 80-Hz wavelets, and on the 90-Hz synthetic seismogram for the 11-14 well there appears some detail in that interval corresponding to detail on the sonic log. Unfortunately, no similar detail appears on the seismogram even though the upper filter cutoff is 80 Hz. Most of the seismic energy is around 50 to 60 Hz. Reduced amplitude of the seismic reflections near 9-22 and 8A-22 may indicate reduced reflectivity contrast but the lack of high-frequency content in the seismogram limits the amount of detailed information.

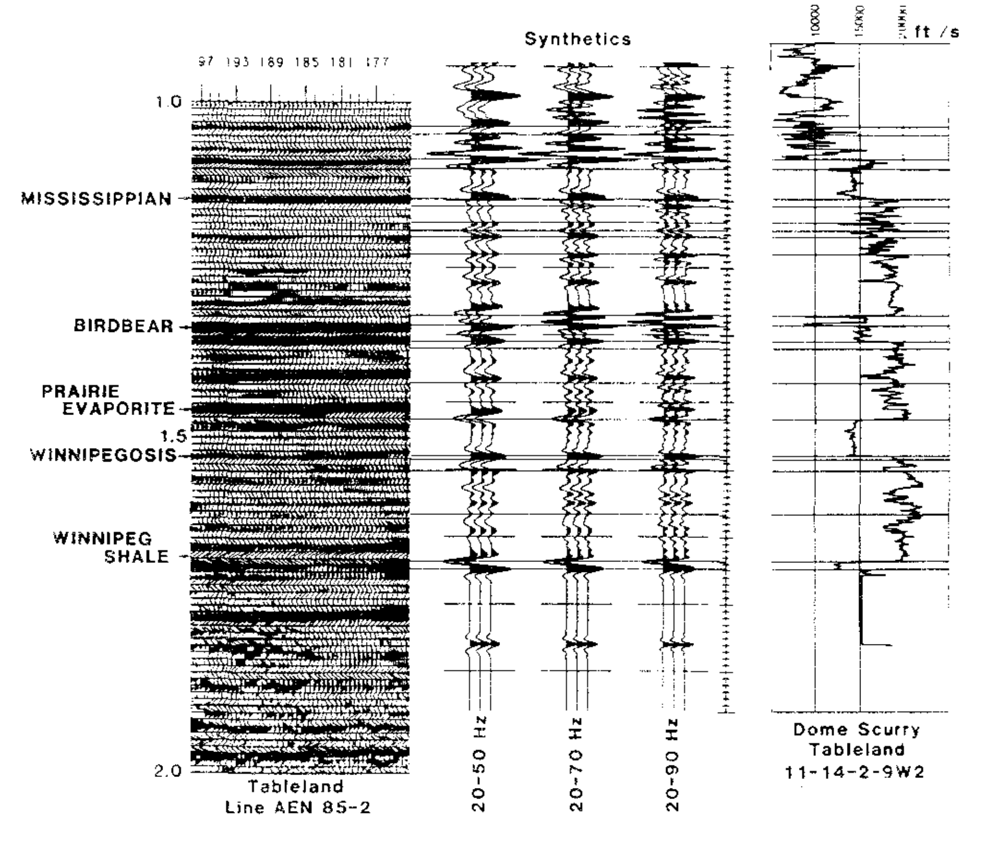


**Figure 2.56.** Comparison of synthetic seismograms for Tableland well 11-14.

## ROCANVILLE ANOMALY

The Sylvite Ste. Marthe 14-5-17-30W1M well was drilled in 1969 as a potash test. It encountered 64 m of Prairie Evaporite Fm salt, 17 m of anhydrite, and 17 m of porous Winnipegosis Fm dolomite at the bottom of the well. According to Holter (1969), about 130 m of salt was expected in this area. Normally, the thickness of the mound plus the remaining Prairie Evaporite Fm above the mound is approximately equal to the total thickness of nearby salt where there is no mound. Therefore, an additional 32 m of Winnipegosis Fm could lie below the bottom of the hole. No tests other than geophysical logs were done in the hole. The Shell Lake Mbr anhydrite exists here but most holes only penetrate to the potash level.

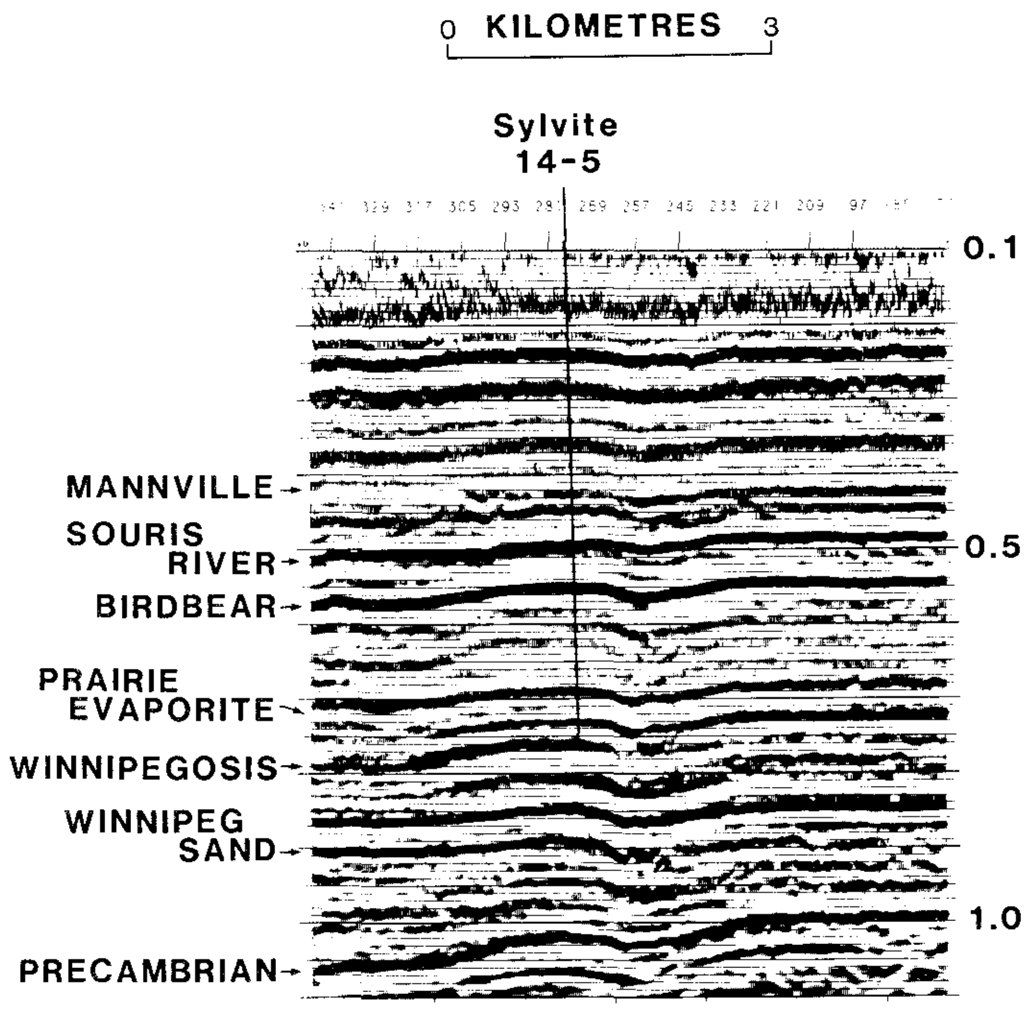


**Figure 2.59.** Compressed seismic plot for Rocanville seismic line T17-1.0 emphasizing subsidence and pull-up features.

A seismic profile was shot near the well in 1969 but the Winnipegosis mound was not clearly identifiable in the data. A second profile was shot in 1982 and reprocessed with the result that the anomaly is clearer. Figure 2.57 shows an interpretation of the seismogram in Figure 2.58 whereas Figure 2.59 shows a compressed plot emphasizing the small features of the data.

The seismic line shows a gradual dip to the west of all strata and a thickening toward the west, especially of the deep Ordovician and Silurian strata. There is an increase in the rate of thickening of the Ordovician and Silurian rocks in the vicinity of the Winnipegosis mound. Therefore, it may be speculated that this mound grew at a place where the water depth changed. The Devonian rocks, except for the salt, are consistent in thickness. The Cretaceous rocks thicken westward but not as much as the Ordovician and Silurian. These gradual stratigraphic thickenings may be related to the development of the Williston basin and the position of the study area near the margin of the basin.

The synthetic seismograms (Fig. 2.60) show the strong reflection contrasts of the Souris River and Birdbear formations which tended to mask the deeper reflections in some earlier surveys.

The anomaly representing the mound is more difficult to interpret than other mound anomalies in central Saskatchewan because there is no angular reflection representing the flank of the mound on either side. The reflection from the top of the mound is more or less continuous on the east side with a reflection identified as the Shell Lake Mbr. Consequently, there is no clearly identifiable seismic anomaly directly associated with the mound. On the west side, the large-amplitude reflection from the top of the mound suddenly diminishes. This change in amplitude may represent the edge of the mound build-up because the Shell Lake Mbr may be thinner and less reflective on the west side than on the east side.

There is a "sag" on the east side of the mound which affects reflections at all depths, approximately between traces 245 and 261. However, unlike the effect of a near-surface low-speed zone, the time-structure of the sag is not the same at all depths, being nearly 20 ms below the Prairie Evaporite Fm but less than 10 ms above. Recently, a large depression-and-collapse structure in the Prairie Evaporite Fm was found in an underground potash mine near this location so there is a real geological subsidence structure which is the probable cause of this seismic anomaly. Changes in seismic speed through the shallower disturbed rocks apparently cause the time delay to reflectors below the Prairie Evaporite Fm.

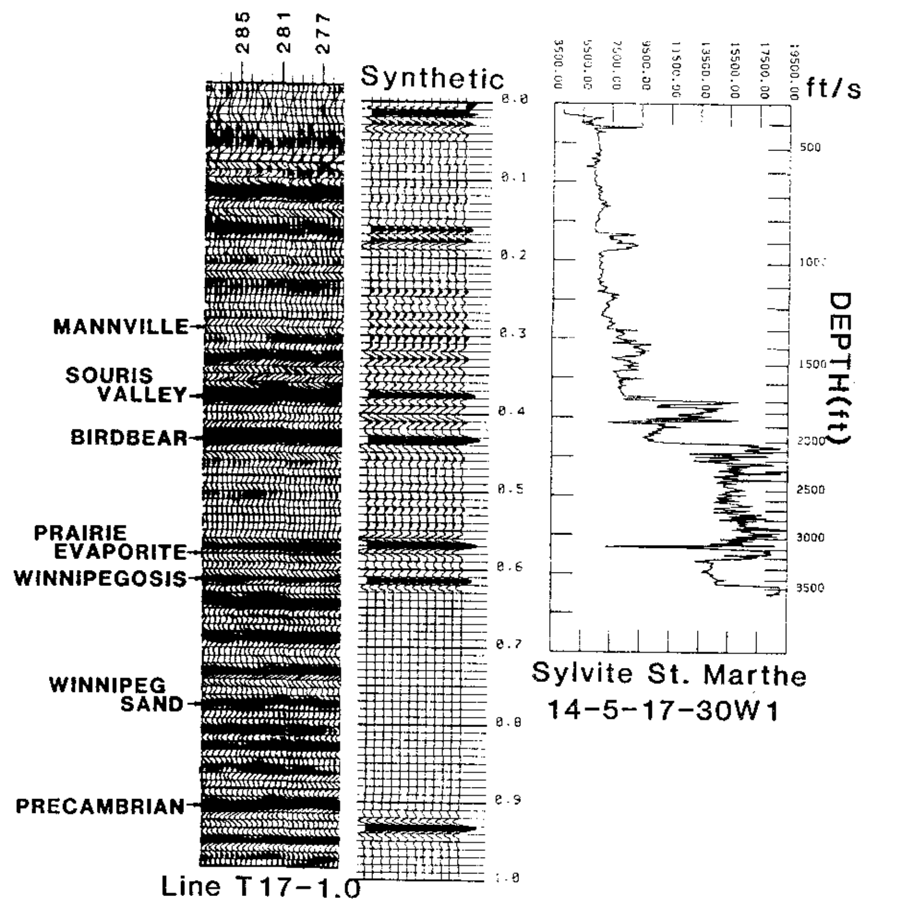


**Figure 2.60.** Comparison of synthetic seismograms for Rocanville well 14-5.

On the west side of the mound, the top of the Prairie Evaporite Fm drops slightly and the seismic interval between top and bottom is slightly thinner than it is on the east side, suggesting that the salt is thinner on the west than on the east, contrary to the regional trends. The effect of thinning of the salt adjacent to the mound seems to match the effect of velocity pull-up under the mound so the seismic time from the top of salt to markers below the Winnipegosis is about the same over or west of the mound. The combined effect of the collapse structure on the east and the salt thinning on the west is to create a positive drape structure over the mound. If compaction has occurred it is not recognizable.

A velocity pull-up anomaly is a distinctive feature. It is present on all the reflectors below the mound, modified by the regional dip and exaggerated by the subsidence on the east flank. Figure 2.59 shows these structures in high relief.

The change in character of the seismogram under the mound is caused by a reduction in the high-frequency content of the signal, giving the appearance of a lower-frequency signal below the mound than on either side. The most dominant seismic features of this mound seem to be the decrease in dominant frequency below it and the velocity pull-up structure.

## ALLAN MOUND

Drill-hole Altair Elstow 15-24-34-1W3M was drilled by Altair Oil Ltd. in January 1960 in order to test the Winnipegosis and Interlake formations. It encountered 107 m of Prairie Evaporite Fm salt, 9 m of anhydrite, and 99 m of upper and lower Winnipegosis dolomite, continuing 104 m into the middle of the Interlake Fm. Drill-stem tests produced 46 m of mud from the Winnipegosis Fm and 235 m of muddy salt water from the Interlake Fm. Total salt thickness in the area is 190 m in drill-hole U.S. Borax 9-27-34-1W3M, about 3 km west of the 15-24 drill-hole. The Shell Lake Mbr is present in 9-27.

A seismic program for the nearby Allan potash mine in 1975 outlined the Winnipegosis mounds of the area, including the one tested by Altair Elstow 15-24. Figure 2.61 shows the seismic coverage and configuration of the mounds. A description of some of these

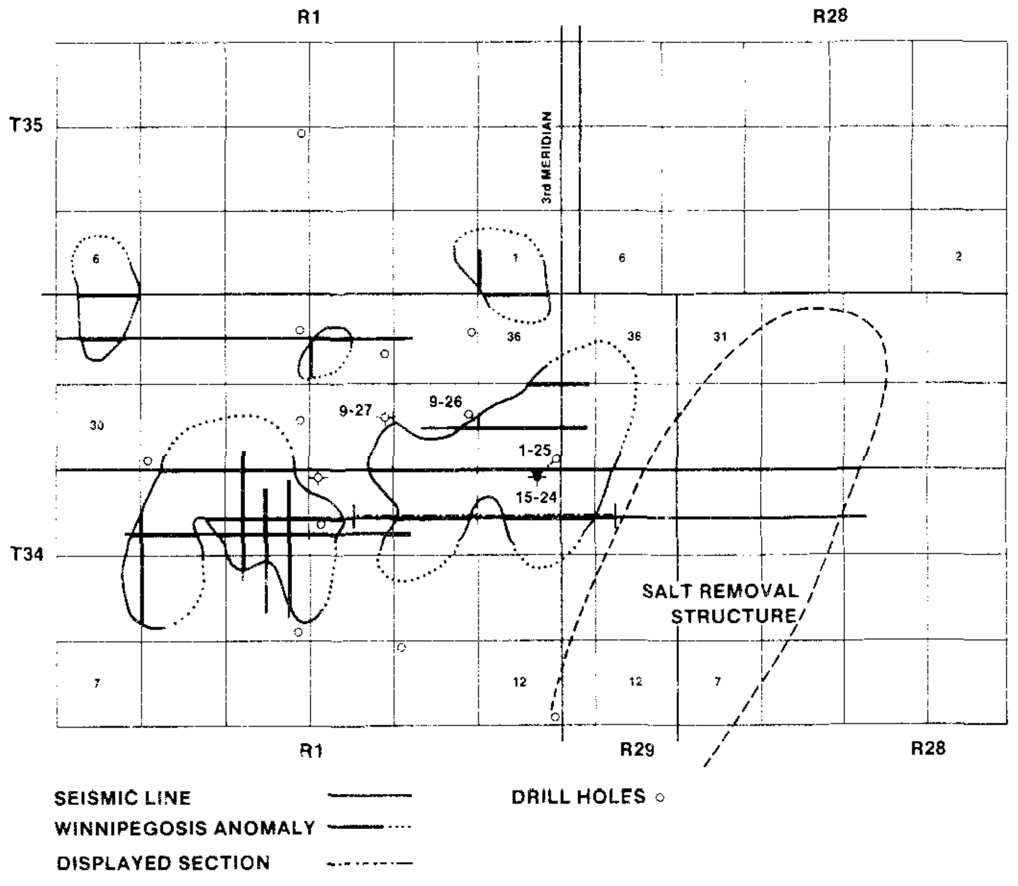


**Figure 2.61.** Allan area showing seismic coverage and known Winnipegosis mounds (after Gendzwill, 1978).

data, including comparisons of well-log and mine elevation profiles, was given by Gendzwill (1978) but Figures 2.62 and 2.63 showing the geological interpretation and seismic section for seismic line T34-3.5 have not been previously published. Figure 2.64 shows a detailed portion of T34-3.5 with the sonic and synthetic seismogram from U.S. Borax 5A-22 which is about 1 km west of the end of the line. No well has been drilled on this seismic line. Altair Elstow 15-24 is approximately 600 m north of trace 50 but there was no sonic log for the well.

The mound is approximately 5 to 6 km long by 3 to 4 km wide but is quite irregular in shape. A salt-removal structure 3 to 4 km wide lies a short distance east of the mound but the mound does not

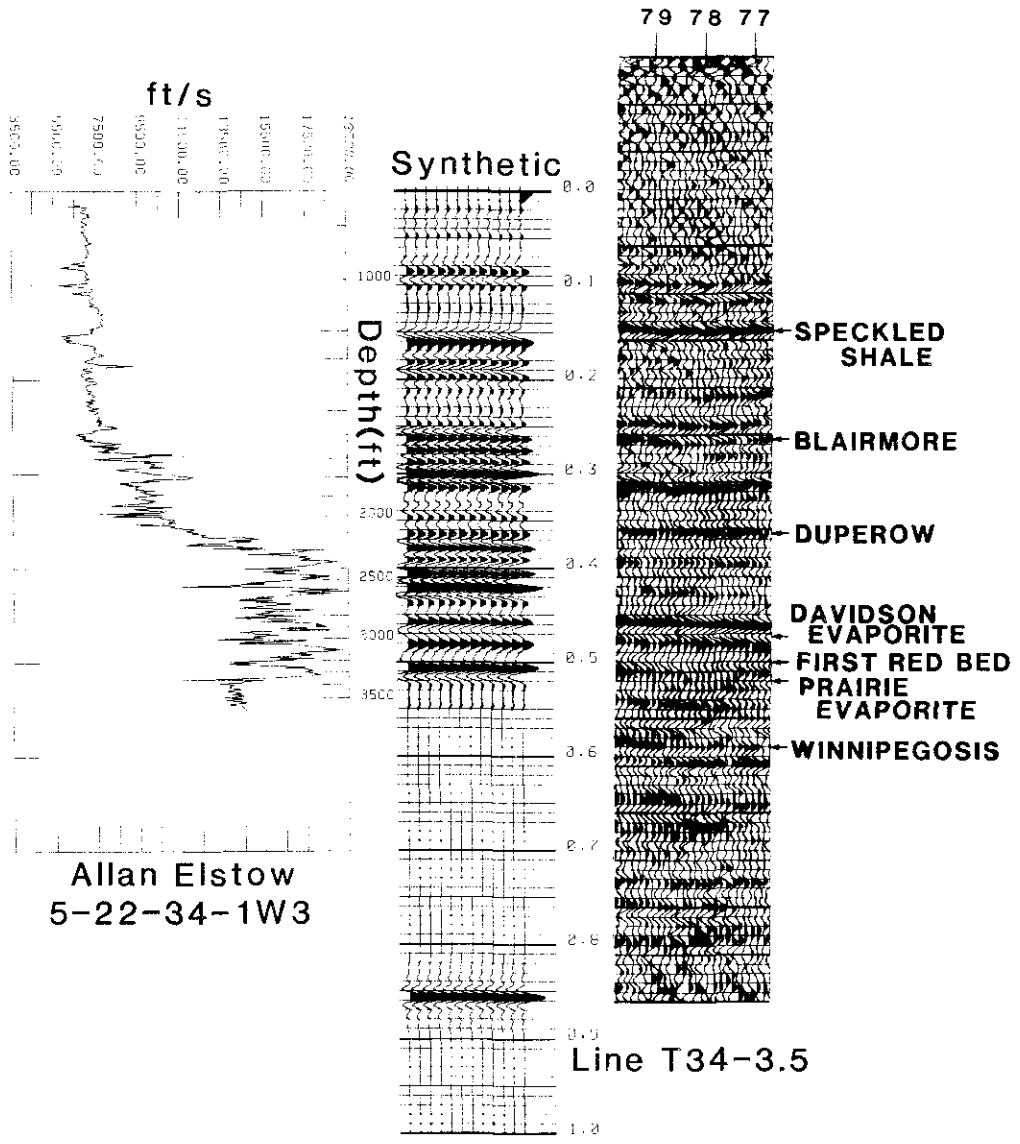


**Figure 2.64.** Comparison of synthetic seismograms for Allan well 5-22.

seem to be involved in the structure. Other mounds are located nearby. From maps of this type (Fig. 2.61) in the Saskatoon area, the ratio of length of seismic line underlain by mound to total length of seismic line shot in the area, suggests that about 25% of the area is underlain by Winnipegosis mounds.

The Allan mound displays all of the features considered to be characteristic. There is a clear reflection from the surface of the mound, including the sloping flanks, but this mound has a structure with high rims on each side and a low depression in the middle. The next seismic line, 0.8 km to the north, shows a single broad anomaly so the two bumps on T34-3.5 probably represent two lobes extending south from a single large mound. The high lobe has about 40 ms of seismic relief corresponding to 88 m of Winnipegosis thickening which is in reasonable agreement with the drilled thickness 600 m to the north. The reflection from the Shell Lake Mbr appears at about the same height as the top of the mound but the amplitude of the reflection is smaller than that from the top of the mound, probably because the anhydrite is too thin to produce a strong reflection. The anhydrite reflection has an "onlap" relationship to the mound.

There is a compaction-subsidence anomaly of about 10 to 15 ms in the strata over this mound. The greatest amount of subsidence appears at the top of the Prairie Evaporite Fm and lesser amounts appear at shallower depth. The subsidence is best displayed at the west end because salt removal effects interfere at the east end. Also at the west end of the mound, an irregular structure in the reflection from the top of salt suggests that the potash beds may be disturbed over a limited area. Figure 2.65 shows these features with emphasized relief.

A velocity pull-up anomaly under the mound mimics the shape of the mound. There is a change in the structure of the seismogram in the region below the mound. This character change is a result of a reduction in the amplitude of the higher-frequency content of the signal so that the anomaly appears to become lower in frequency, especially under the high rim segments.

Above the mound is a typical reflection structure composed of three reflection peaks about 25 ms apart and consistent laterally for a long distance. These represent, from top to bottom, the upper Davidson/lower Harris salt, the First Red Bed, and the Second Red Bed/Prairie Evaporite. Near the east edge of the mound, the topmost of these reflections disappears and there is a corresponding subsidence structure which appears in shallower reflections. This anomaly represents the removal by dissolving of 26 m of upper

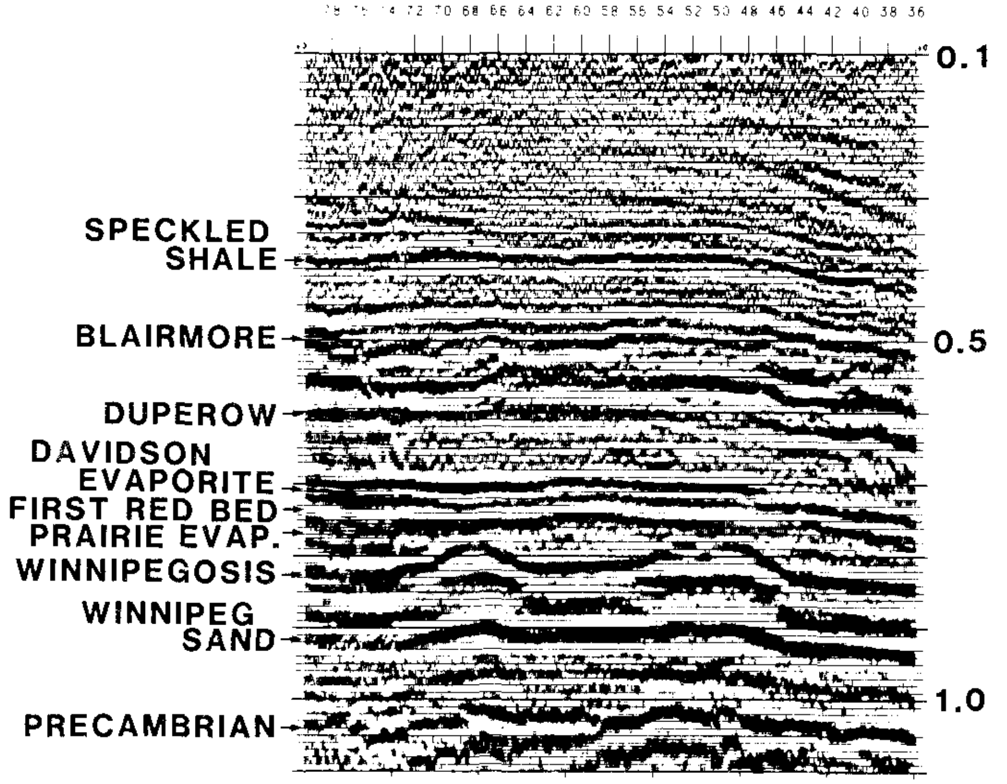


**Figure 2.65.** Compressed seismic plot for Allan seismic line T34-3.5 emphasizing subsidence and pull-up features.

Davidson and lower Harris halites in the Souris River Fm. This is a peripheral effect of the complete removal of the Prairie Evaporite Fm in the Colonsay (a nearby village) collapse structure a short distance east of the displayed seismic line as shown on Figure 2.61. This anomaly was considered an indication that water was or is circulating in the adjacent rocks. According to Phillips (1983) the ore reserves and mining plans for the Allan potash mine were changed, on the basis of this interpretation, to avoid the hazard of a potential water inflow to the mine. Although the Davidson Evaporite is dissolved up to the eastern edge of the mound, the main Prairie Evaporite Fm salt is intact at the eastern edge and for some distance eastward so that the mound does not seem to be directly related to the Colonsay collapse structure.

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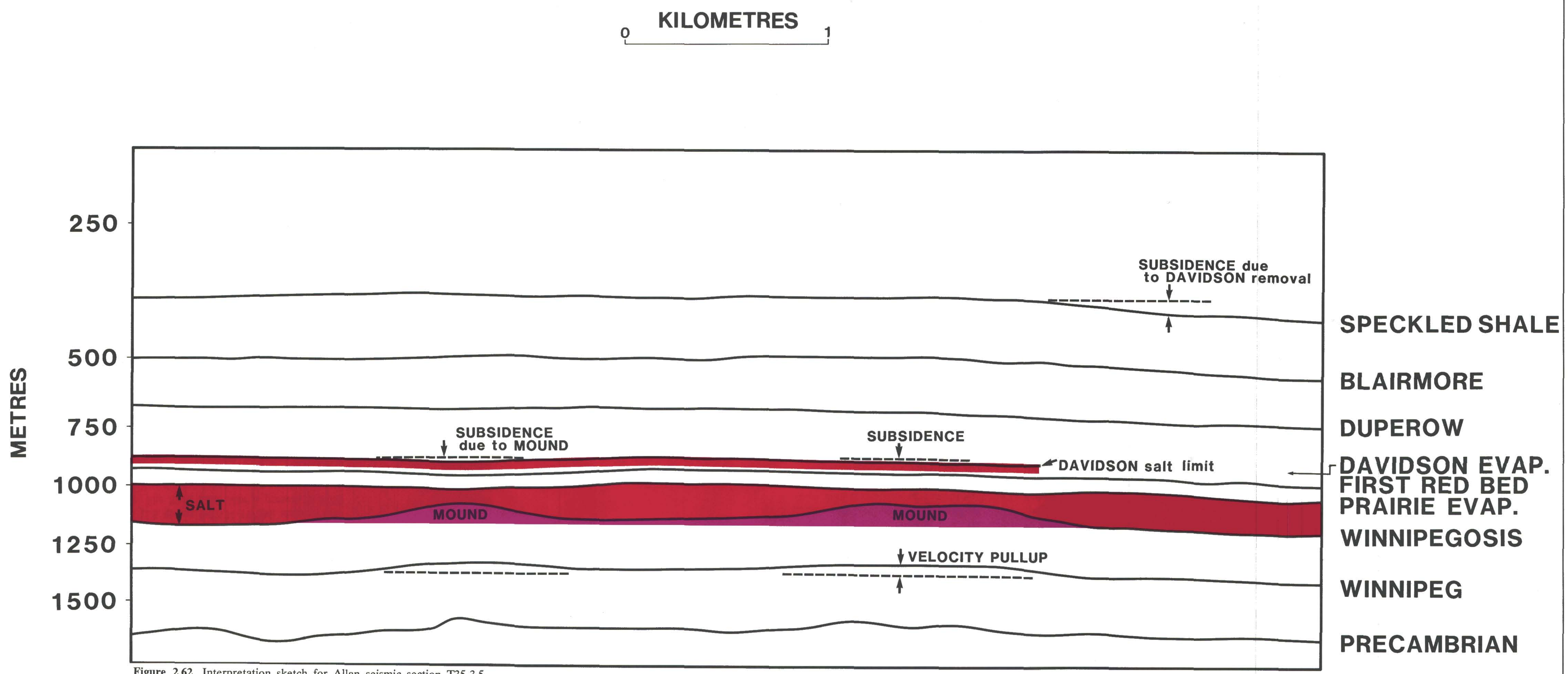


**Figure 2.62.** Interpretation sketch for Allan seismic section T35-3.5.



DRAFTING: | LOG PLOTS: | AUTHOR: D. GENDZWILL

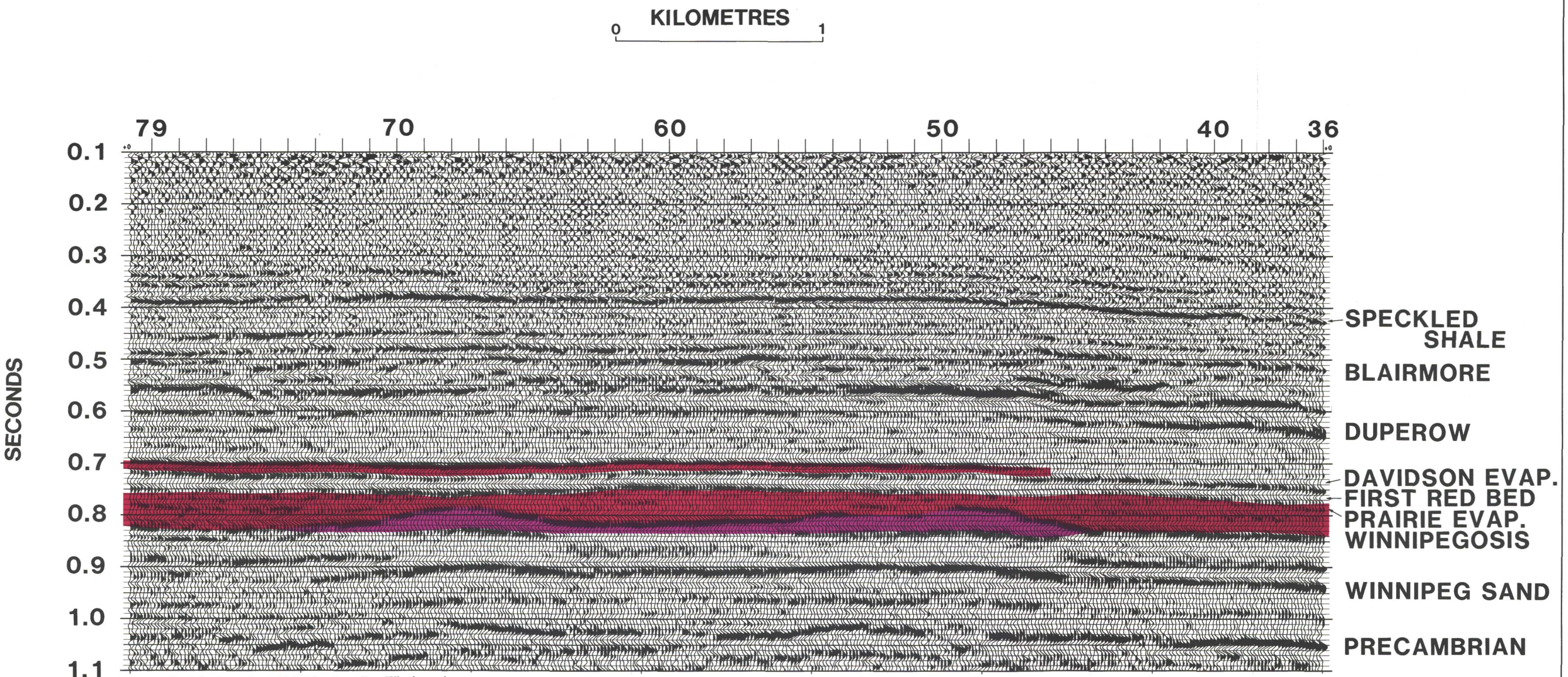


**Figure 2.63.** Seismic section T35-3.5 for the Allan Winnipegosis mound.



DONOR: POTASH CORP. OF SASKATCHEWAN, ALLAN DIVISION | PROCESSOR: WESTERN GEOPHYSICAL CANADA | AUTHOR: D. GENDZWILL

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