The sub-Phanerozoic basement surface under the Great Slave Plain of the Northwest Territories, and its influence on overlying strata

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Abstract: Basement topography and fault patterns across the southern plains of the Northwest Territories, as revealed by reflection seismic data, support the long-standing interpretation that a regionally extensive, orthogonal (northeast and a weaker northwest) pattern of structural lineaments influenced Middle Devonian facies development. Basement faults, typically of small throw and extent, fall generally into one of three groups as defined by strike direction: north-south, northeast-southwest, and northwest-southeast. A fourth set follows the crest of the Fort Simpson Magnetic Anomaly. There are both extensional and compressional linear features. The path of the Middle Devonian carbonate bank edge was affected by basement structures including: Celibeta High; north-south faults that are products of uplift; and regional lineaments, particularly the Liard Line and the boundaries of Cordova Embayment. Development of hydrothermal dolomite appears to have been enhanced on Celibeta High and along Tathlina Fault.

Résumé : La topographie du socle et la configuration des failles dans les plaines méridionales des Territoires du Nord-Ouest, telles qu'indiquées par des données de sismique réflexion, appuient l'interprétation établie de longue date selon laquelle une configuration orthogonale (nord-est et, dans une moindre mesure, nord-ouest) de linéaments structuraux, largement répandue à l'échelle régionale, aurait influencé la formation de faciès du Dévonien moyen. Les failles du socle, typiquement à faible rejet et peu étendues, se classent généralement dans l'un des trois groupes définis d'après leur direction, soit nord-sud, nord-est–sud-ouest et nord-ouest–sud-est. Un quatrième faisceau de failles suit la crête de l'anomalie magnétique de Fort Simpson. Il existe a à la fois des entités linéaires d'extension et de compression. La direction de la bordure du banc carbonaté du Dévonien moyen a été influencée par des structures du socle, notamment par la hauteur de Celibeta, par des failles nord-sud qui résultent d'un soulèvement et par des linéaments régionaux, particulièrement la ligne de Liard et les limites du rentrant de Cordova. La formation de dolomite hydrothermale semble avoir été accentuée sur la hauteur de Celibeta et le long de la faille de Tathlina.

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INTRODUCTION

A reflection seismic study of faults that offset the sub-Phanerozoic unconformity under the southern plains of the Northwest Territories (NWT) was undertaken as part of the TGI-sponsored Mississippi Valley-type (MVT) project and the Mackenzie Atlas co-operative project. As reflection seismic provides closely spaced data points between well locations, this study complements earlier work that was based exclusively on well control, which continues to provide the only data across large portions of the study area (Fig. 1). Seismic analysis was able to confirm changes in basement topography, faults, and their relationships to facies changes (e.g. the Middle Devonian carbonate bank edge) within overlying strata that had been interpreted by earlier workers.

PREVIOUS WORK

Past studies have revealed an orthogonal pattern of structural and facies distributions within Paleozoic strata of northern Alberta, northeastern British Columbia and southern Northwest Territories. In a compilation of subsurface data derived from exploration drilling, Belyea (1971) recognized linear patterns in isopach maps (e.g. Fig. 2) that she attributed to 'lines of weakness' and referred to as 'northeasterly trending lineaments crossed by less prominent northwesterly trending lineaments'. She observed a close relationship among these lineaments and the Middle Devonian carbonate front, porosity development, and dolomitization. She described some of the lineaments as faults and remarked that many underwent successive movements throughout Middle Devonian time.

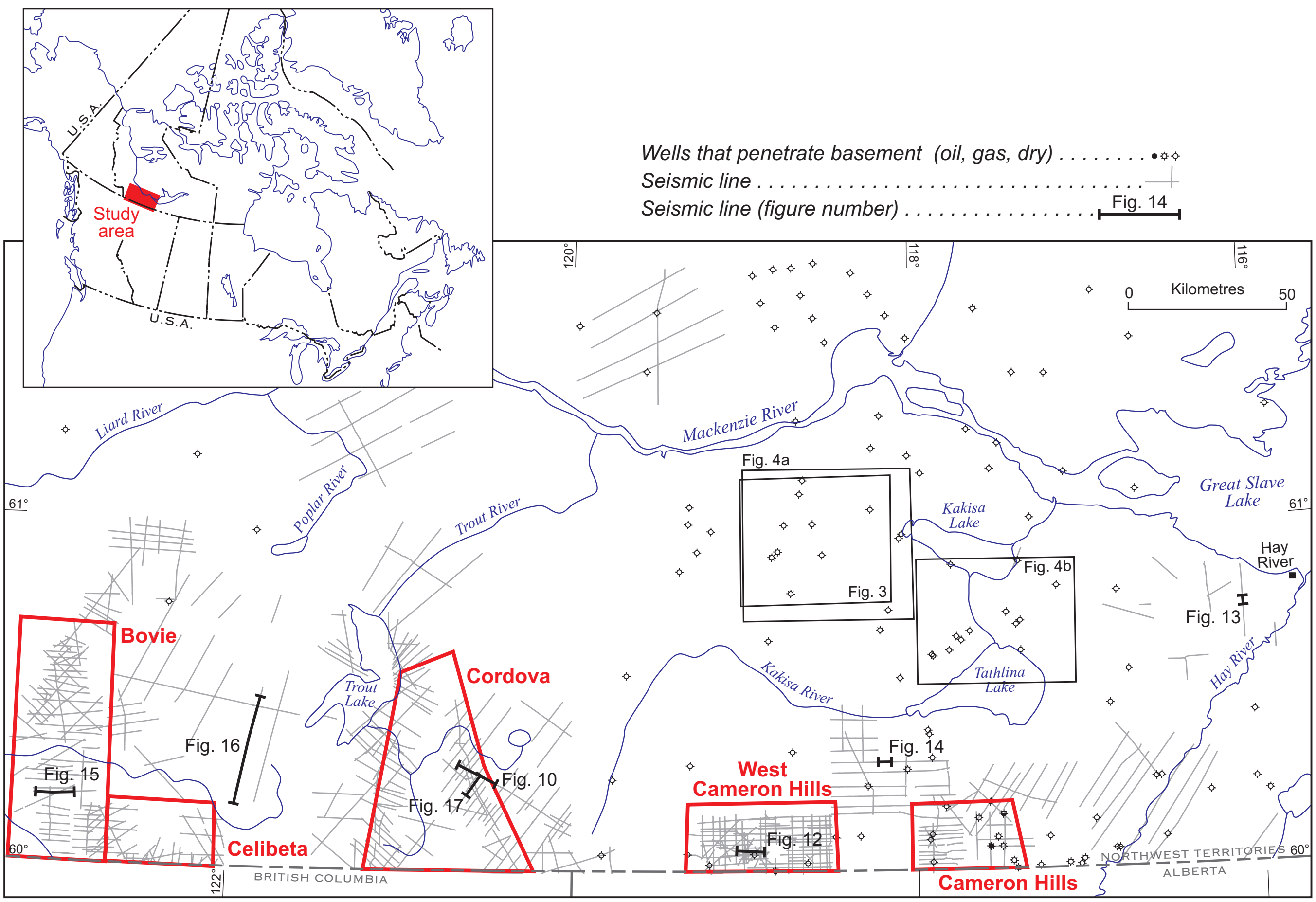


Figure 1. Location map showing reflection seismic line tracks, exploration wells that penetrate basement, and locations of seismic figures. Red polygons outline geographic areas referred to in the text. Outlines of Figures 3 and 4 are also shown.

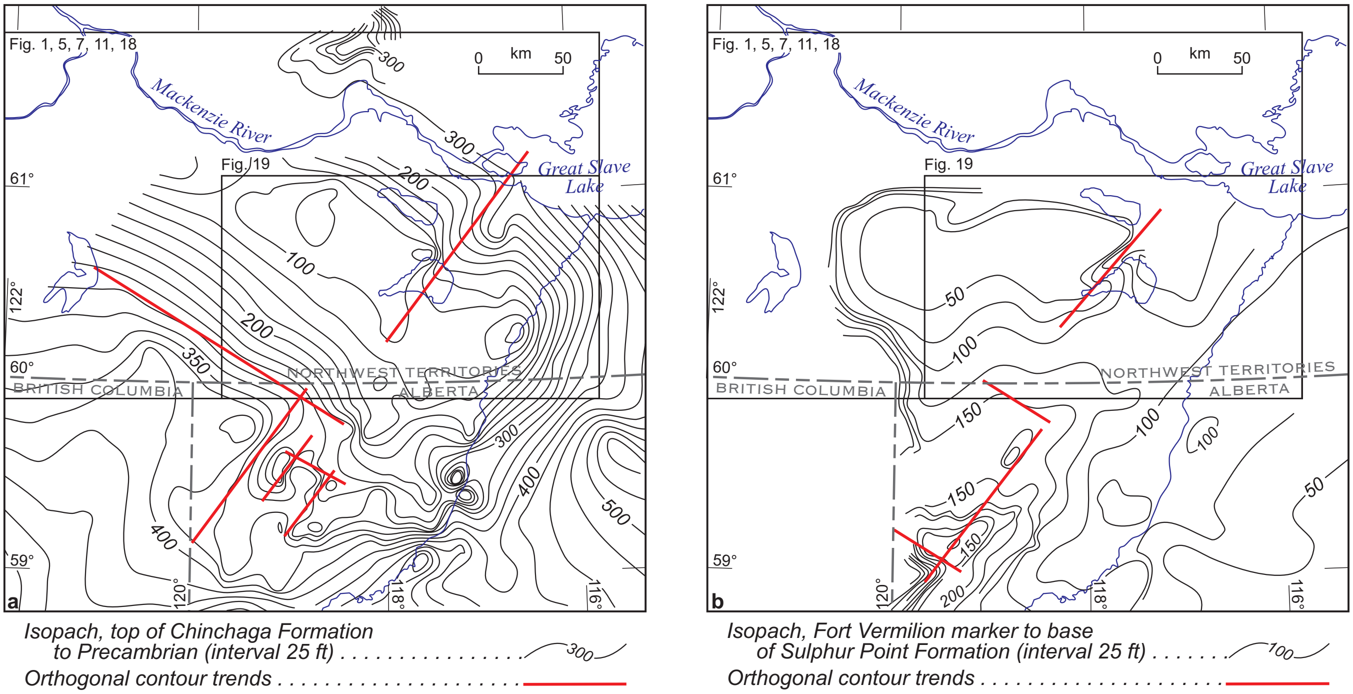


Figure 2. Two isopach maps from Belyea (1971) with orthogonal contour trends highlighted. Areas of other map figures are outlined.

Douglas (1959, 1974) mapped the northeasterly striking Rabbit Lake Fault (RLF) at surface and his map (Fig. 3) confirms the presence of good outcrop control, particularly in the uDTR (Trout River Formation) and uDKA (Kakisa Formation) map units. He noted that the fault was approximately parallel to faults in the Precambrian and described RLF as having normal throw, down to the southeast. Its small displacement was dated as post-Devonian, probably post-Early Cretaceous. Douglas went on to note that some of the small faults found northwest of Hay River exhibit components of strike slip.

Williams (1977) described the subsurface evidence for RLF and for a parallel lineament near Tathlina Lake (Fig. 4). The manner in which Tathlina Fault defines the northwest shore of Tathlina Lake is but one example of how today's drainage pattern mimics deeper patterns (Fig. 5). This observation, if valid, suggests that the time of latest movement could have been well into the Cretaceous or perhaps even later.

The isopach map of the Middle Devonian Beaverhill Lake Formation presented by Oldale and Munday (1994) provides coverage farther to the south and west (Fig. 6). An orthogonal pattern is apparent in the rhomboid shape of Cordova Embayment and the margin of Horn River Basin.

Orthogonal trends, particularly within Hottah Terrane, are found in the shaded relief map of residual total magnetic field (Fig. 7), thus suggesting that the pattern may have its origins within basement. This map, provided by the Regional Geophysics Section of the Geological Survey of Canada

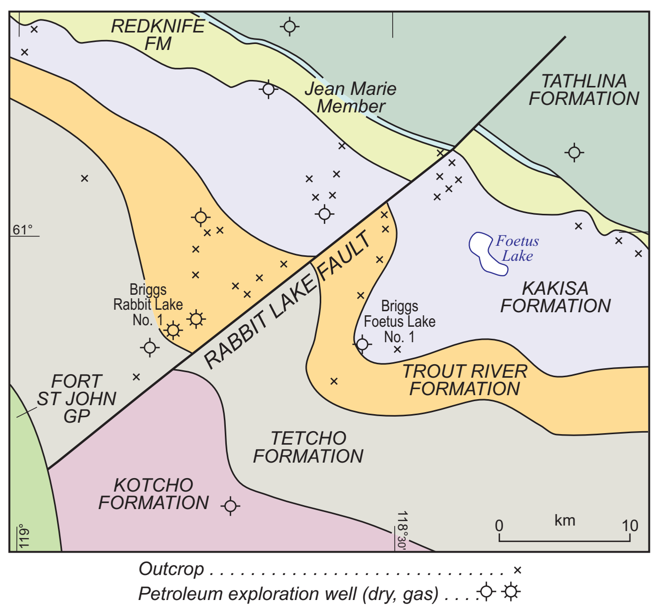
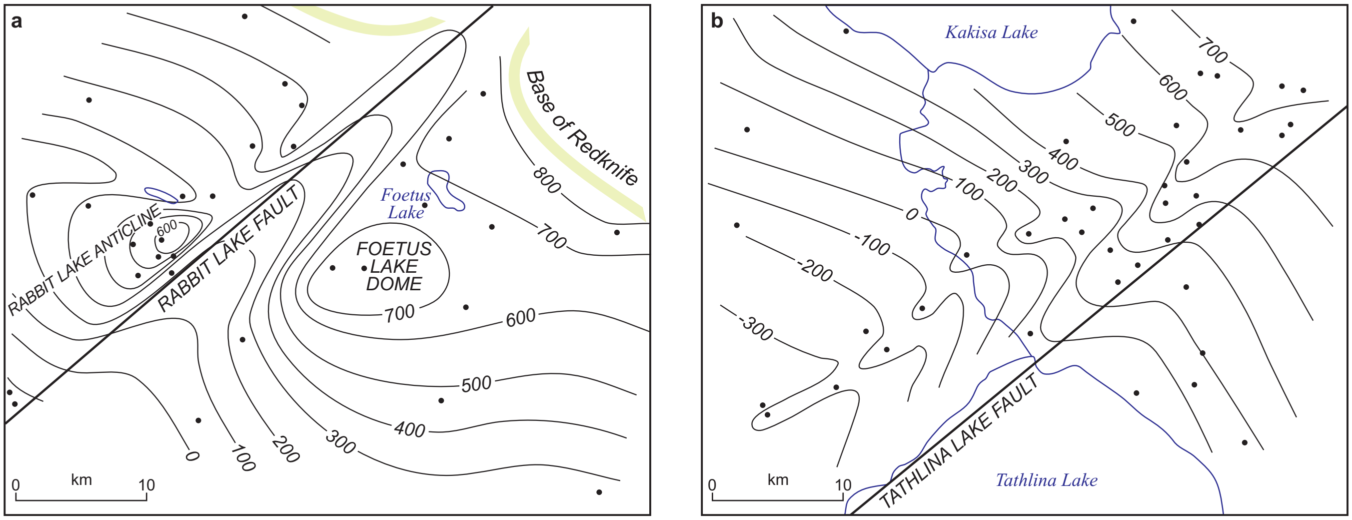


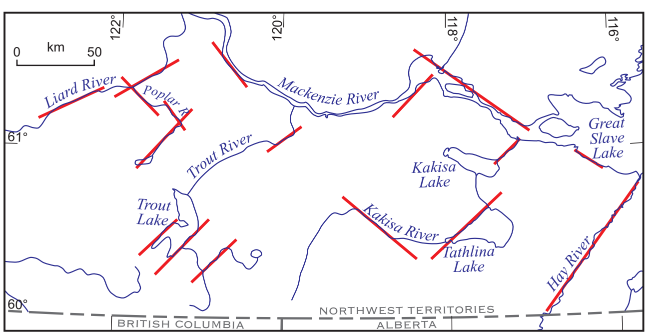
Figure 3. Portion of surface geology map by Douglas (1974) showing the Rabbit Lake Fault. Refer to Figure 1 for location.



Structure contour on top of Redknife Fm (interval 100') 700

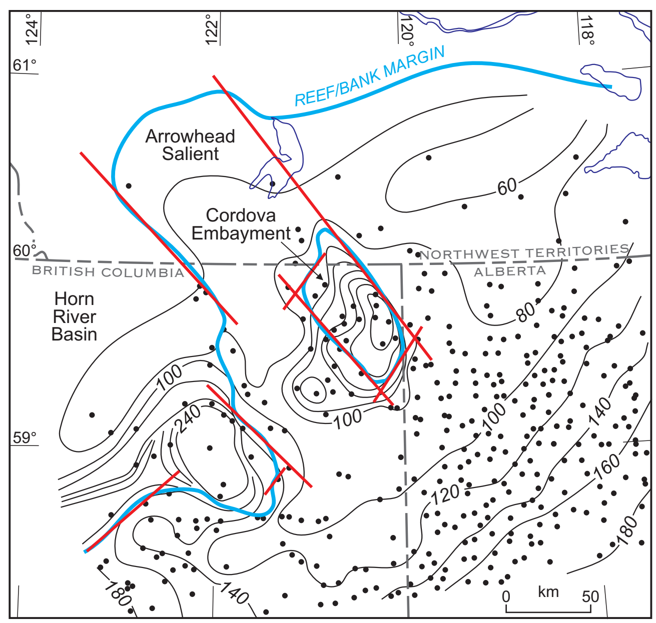
Structure contour on top of Twin Falls Fm (interval 100') 100

Figure 4. Subsurface confirmation of two northeast-trending lineaments from borehole control: **a.** anticline/syncline pair along Rabbit Lake Fault; **b.** anticline/syncline pair along Tathlina Fault. Modified from Williams (1977). *See* Figure 1 for location.



Northwest, southeast lineaments . . . .

Figure 5. Lake shapes and river courses, showing influences of northeast and southwest lineaments.



Isopach, Beaverhill Lake Formation (interval 20 m) 80

Linearities . . . .

Figure 6. Isopach map of the Middle Devonian Beaverhill Lake Formation. Northeast- and northwest-directed contours and the reef/bank edge linearities are highlighted. *Modified from* Oldale and Munday (1994).

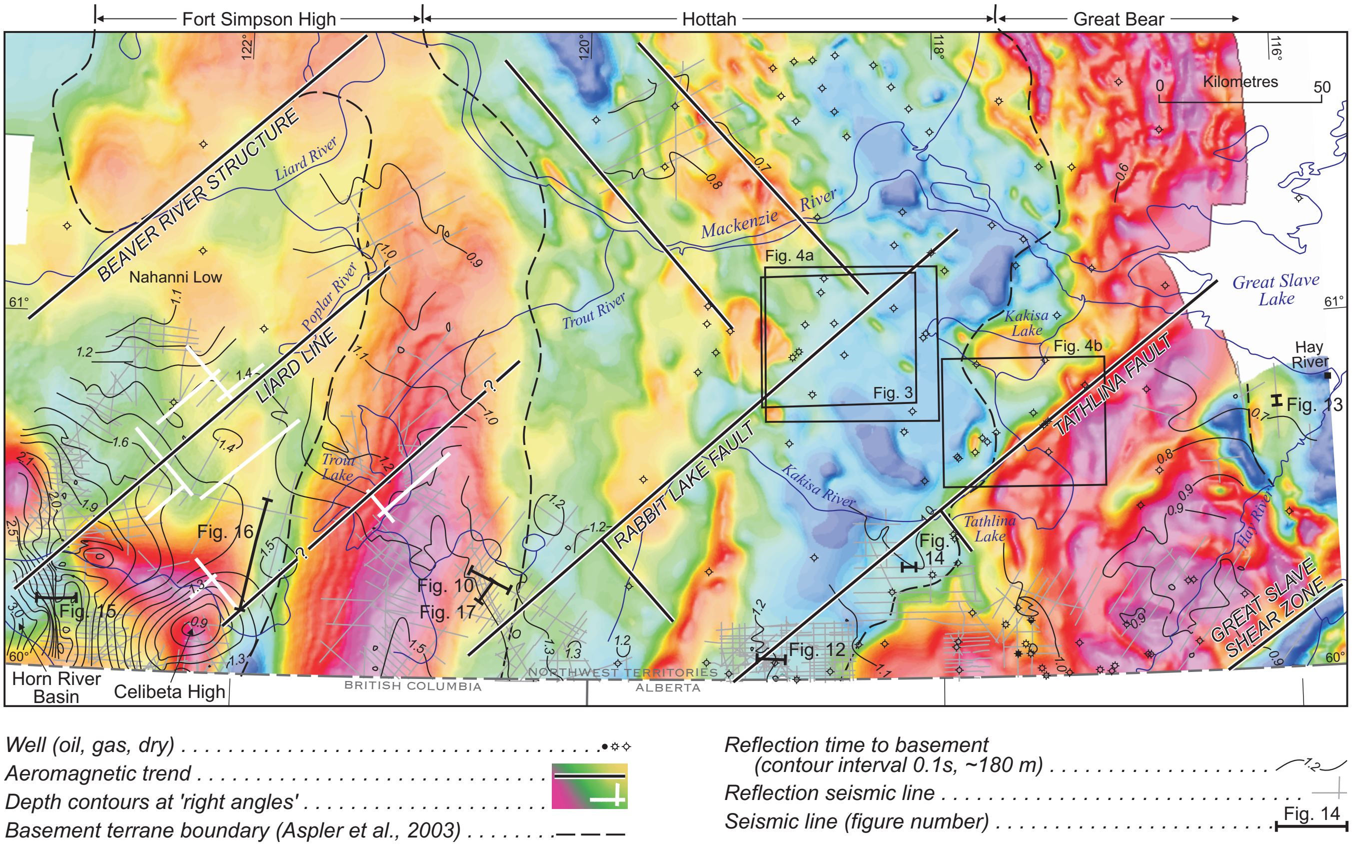


Figure 7. Magnetic map provided by the Continental Geoscience Division, Geological Survey of Canada, with seismic grid. Heavy black lines highlight an orthogonal set of linear trends. Names of major northeast trends are *from* Cecile et al. (1997), Morrow and Miles (2000) and MacLean and Morrow (2001). Overlain are the Top of Basement seismic time-depth structure contours, seismic line locations, and outlines of Figures 3 and 4. Datum is 750 m asl. White lines highlight right-angle bends in basement contours.

(GSC), is a composite of several individual datasets flown over a period of several decades; the grid interval is 400 m; and the data have been levelled to the national datum as defined by the 1 km grid for Canada (W. Miles, pers comm.). Tathlina Fault and Great Slave Shear Zone are two surface features whose locations closely match linear magnetic trends. Correlation of RLF with magnetic anomalies within the Hottah Terrane is much less clear, possibly because of the overprint of an orthogonal, northwesterly trending set.

Within the Fort Simpson and Nahanni terranes evidence of orthogonal trends is much more subdued, possibly a result of different basement materials and increased cover thickness. Beaver River Structure (Morrow and Miles, 2000) tracks along the southern boundary of a spur of the Fort Simpson High while Liard Line, interpreted by Cecile et al. (1997) as a transform fault, tracks between two magnetic highs and through a small offset of a moderately strong anomaly. The northeast trend drawn through Trout Lake (hereafter the Trout Lake trend) is speculative in that it is based on a combination of several subtle hints: it is drawn northeasterly, beginning at an offset in the Celibeta High anomaly, parallel to the remarkably linear shores of Trout Lake, then parallel to colour contours within the Fort Simpson High, and finally toward a shoulder on the east flank of Fort Simpson High. While northwest trends have not been drawn on Figure 7 west of Hottah Terrane, such trends are compatible with the rhomboid shape of the magnetic lows (shown as greens and blues) within Nahanni Low.

SEISMIC AND WELL DATA

Reflection seismic data used in this study were derived from petroleum and mining industry reports that have been made available to the public through either the National Energy Board (NEB) or the Department of Indian and Northern Affairs. Because these data were acquired by different operators over a number of years, acquisition and processing parameters varied. For the purposes of this study they have been adjusted to a common datum of 750 m asl and are displayed (with one exception) at a common scale.

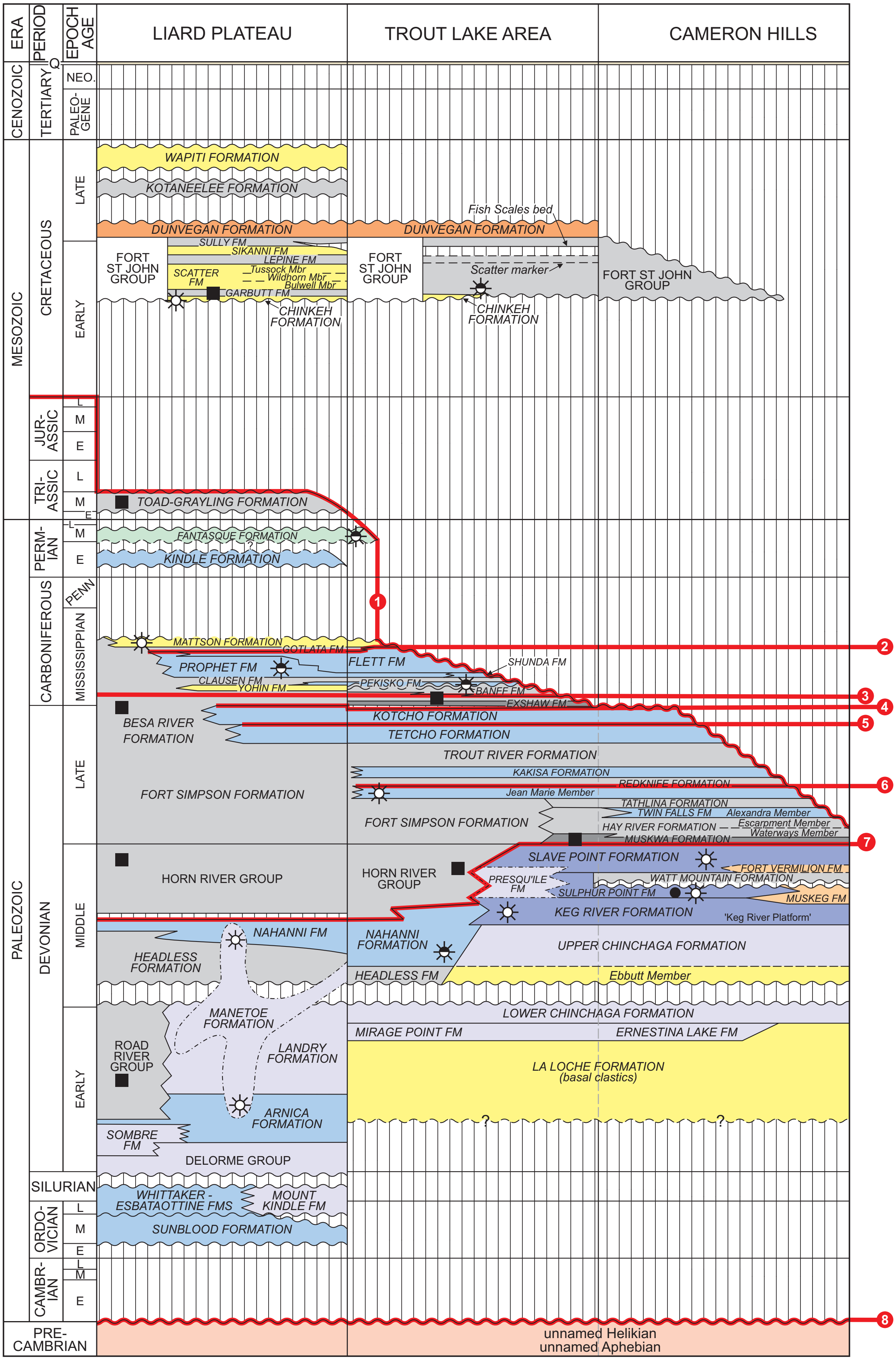


Figure 8. Table of formations with regional seismic markers identified. *Modified from* Gal and Jones (2003).

The seismic lines available to the public are poorly distributed within the southern NWT (Fig. 1). While there is excellent local coverage in areas such as Bovie and West Cameron Hills, the seismic grid is either coarse or nonexistent over most of the region. The large gaps in coverage are the result of either data having been acquired prior to the establishment of government rules for data submission or being held confidential under a moratorium related to unresolved land claims.

Fortunately, there are more than 120 exploration wells within the study area that penetrate basement, thus providing sufficient control for correlation of the seismic markers at a regional scale and for coverage of the northeast quadrant of the map where seismic is unavailable. Up to eight horizons were correlated from wells onto seismic (Fig. 8) and, while few checkshots are available, correlations between seismic and stratigraphy are considered to be reliable, as synthetic seismograms provide consistently good matches to the seismic reflections above basement (e.g. Fig. 9). Resolution of the top of basement reflection, here defined as representing the unconformity at the base of the Phanerozoic section, is somewhat more difficult because any wells that did encounter basement were suspended shortly thereafter. The Trainor H-28 well, shown in Figure 9, illustrates the problem. While it did encounter basement and thus provides solid information as to its depth, the well's short penetration of basement precludes synthesizing the character of the surface's seismic reflection.

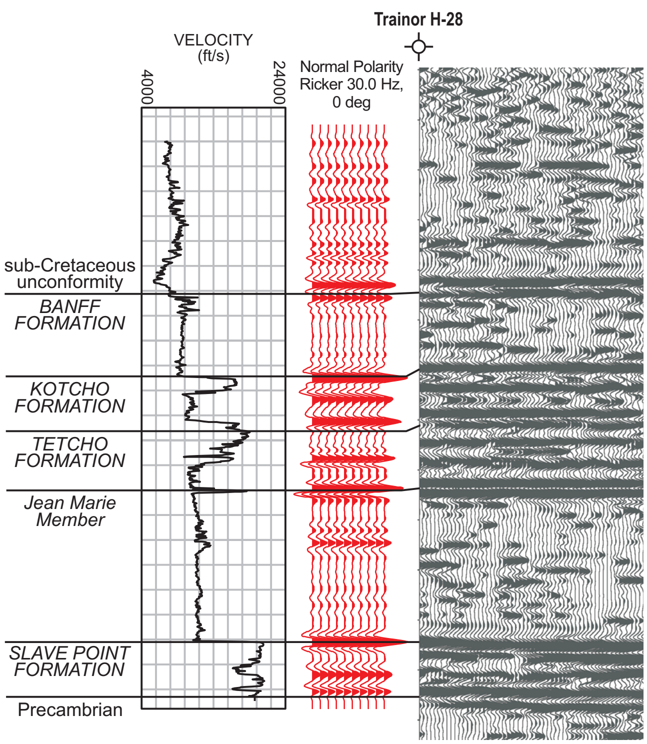


Figure 9. Illustration of a well-to-seismic correlation showing the velocity log, synthetic seismogram, and a portion of a reflection seismic line at the Trainor H-28 well.

INTERPRETATION

Basement topography

Seismic shows the basement surface dipping generally to the southwest except where it rises on Celibeta High and then plunges abruptly under Horn River Basin in the southwest corner of the study area (Fig. 7). Right-angle bends and sharp deviations in contours, some of which are highlighted in this figure, show possible influences of the orthogonal pattern described by earlier workers. This phenomenon is particularly well developed north of Celibeta High, an area that overlies a strong magnetic high and is interpreted (MacLean and Morrow, 2004) to have been uplifted by the emplacement of a large intrusion.

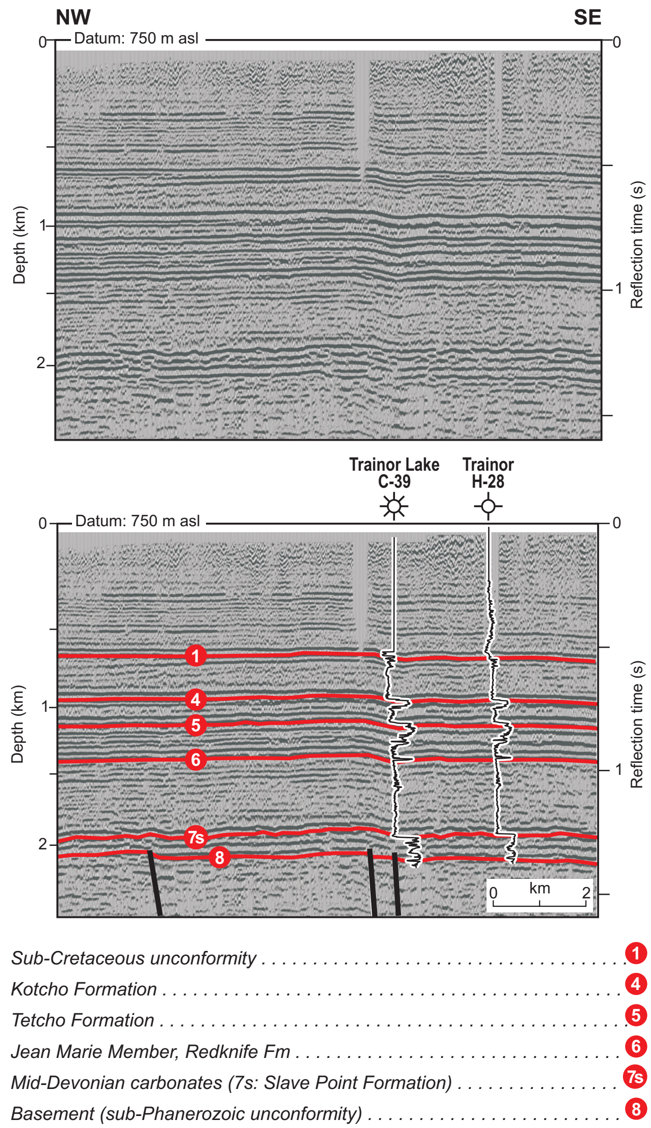


Figure 10. Portion of uninterpreted and interpreted versions of 1984 Northcor Line 21, migrated. Well sticks show velocity curves of exploration wells; both of which penetrate basement. *See* Figure 1 for location.

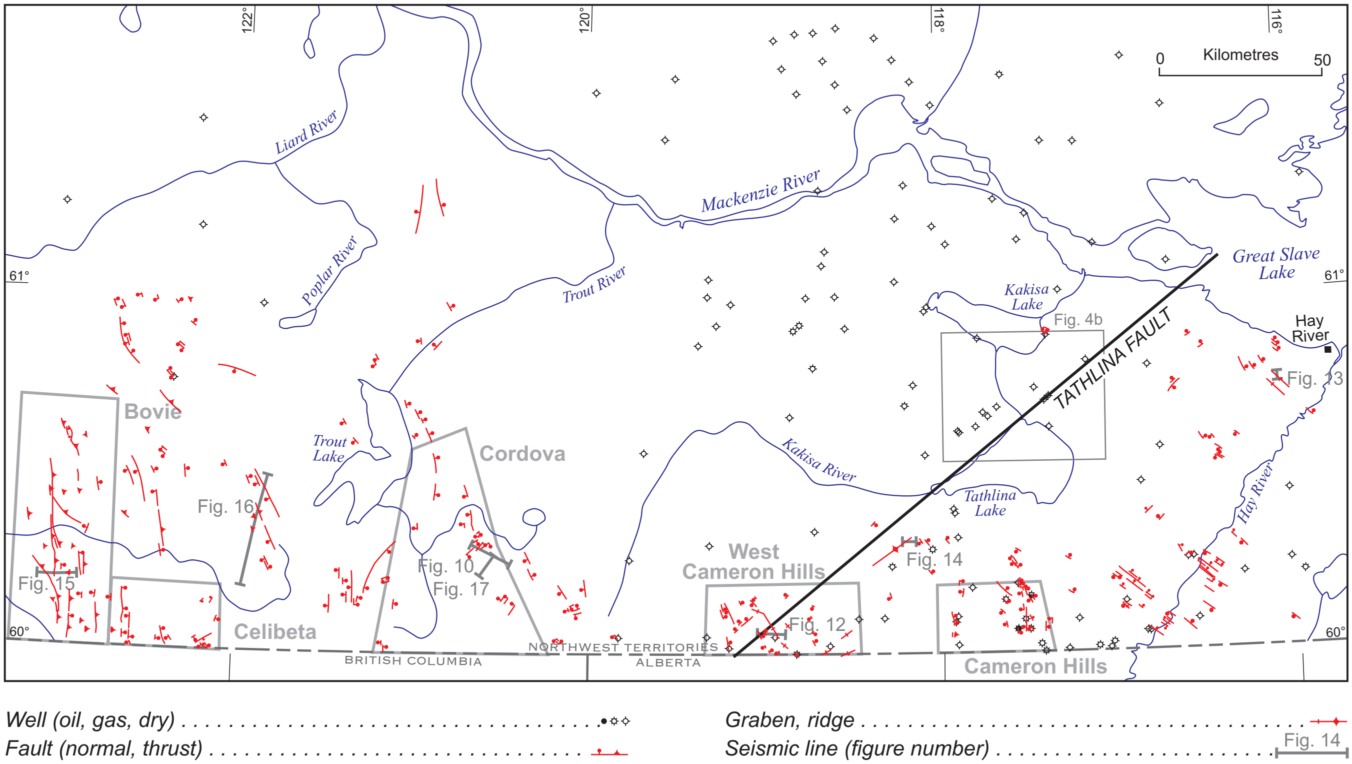


Figure 11. Faults that offset the top of basement derived from reflection seismic. Grey polygons outline geographic areas referred to in the text and outline of Figure 4b. Most seismic lines were removed for the sake of clarity. For seismic coverage of the study area, refer to Figure 18.

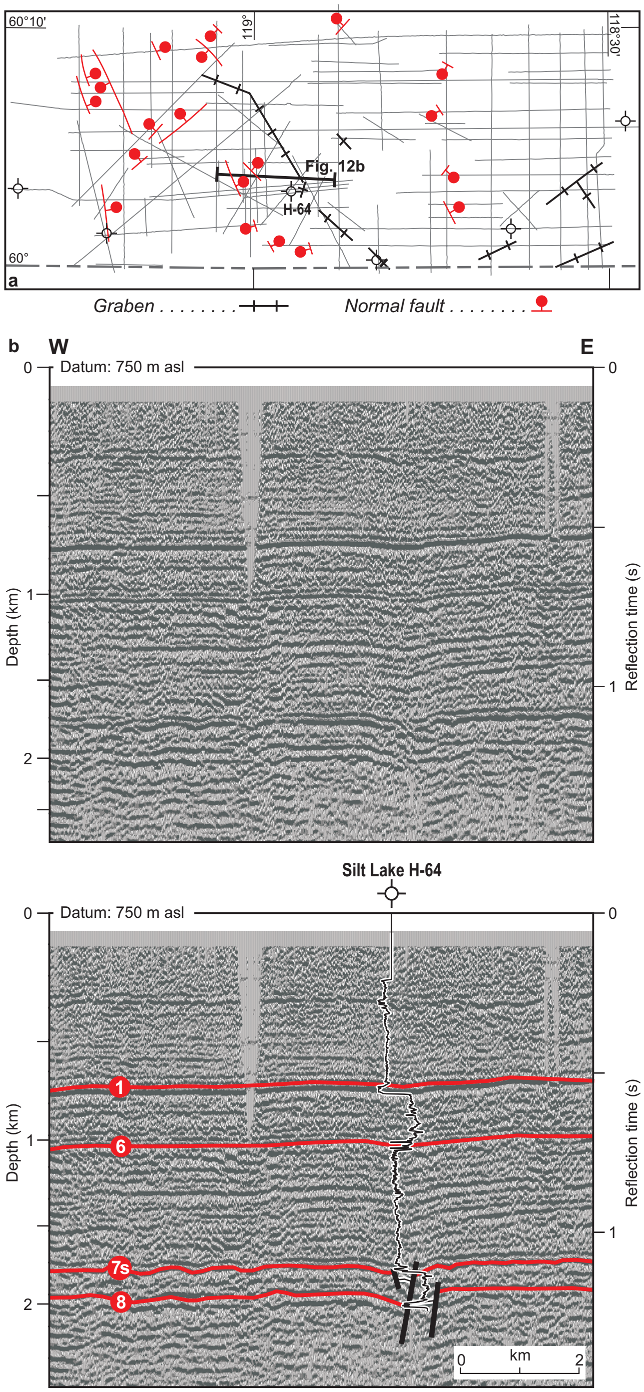
Basement faults

Faults that offset basement within the study area are typically of small throw (e.g. Fig. 10) and are commonly imaged only on a single seismic line (Fig. 11), making it difficult to ascertain strike directions. But by using longer faults as guides, it is possible to assign most to one of four categories: 1) Northwest-southeast-striking faults that are subparallel to basement depth contours; 2) a group of north-south-striking faults that are best developed in the Bovie area where they are a product of uplift (MacLean and Morrow, 2004) but are also found under Cameron Hills; 3) a small number of faults that strike northeast-southwest, such as those found midway along the eastern side of Cordova Embayment; and 4) a series of faults near Trout Lake that defines the western side of Cordova Embayment and follows the crest of the Fort Simpson magnetic anomaly (compare with Fig. 7).

Seismic lines such as that shown in Figure 10 show that fault adjustments have occurred over a long time period. For example, the fault situated farthest to the left in this figure predates deposition of the Slave Point Formation because it offsets basement but not younger strata, whereas the pair of faults under the C-39 well location moved during the Cretaceous or possibly even later. The timing of movement (and the creation of associated fracture porosity and permeability) relative to the timing and duration of fluid flow is likely critical to MVT mineralization and/or hydrocarbon accumulation since pre-existing fractures could focus and enhance the flow of porosity-enhancing and mineral-bearing fluids.

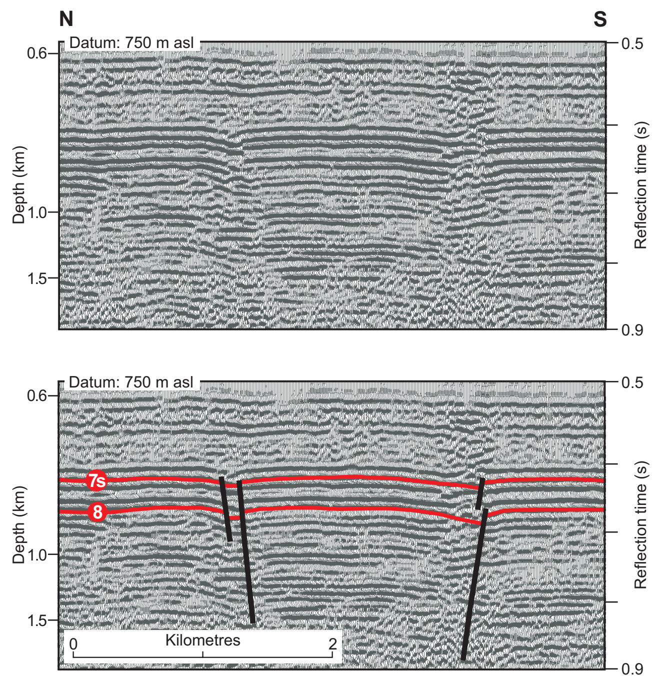
Seismic has revealed both extensional and compressional features possibly related to orthogonal lineaments. Linear, narrow grabens that strike northwestward have been interpreted in the West Cameron Hills area (Fig. 12) and near Great Slave Lake (Fig. 13). These appear as grabens at basement and at the top of the Slave Point Formation. Above them in the West Cameron Hills example, a sag zone progressively widens upsection until it has more than doubled, from 1.5 km at basement level to approximately 3.4 km. A similarly narrow and linear feature, but one which affects uplift prior to deposition of the Twin Falls Formation (due to compression or transpression?) lies parallel to, and east of, Tathlina Fault (Fig. 11, 14).

Bovie Structure contains Bovie Fault, the largest of several large, crustal-scale, very steeply dipping compressional faults in the southwest corner of the study area. MacLean (2002) and MacLean and Morrow (2004) describe Bovie Structure as being the product of two major phases of development: the first, crustal uplift and compression along Bovie Fault sometime after deposition of the Mississippian Mattson Formation but before the Cretaceous period; and the second, during the Laramide Orogeny, involving a shallow detachment fault (Fig. 15).



Sub-Cretaceous unconformity 1
Jean Marie Member, Redknife Fm 6
Mid-Devonian carbonates (7s: Slave Point Formation) 7s
Basement (sub-Phanerozoic unconformity) 8

Figure 12a. Enlargement of the West Cameron Hills area of the basement fault map (Fig. 11). **b**. A portion of the uninterpreted and interpreted versions of 1983 Coho Resources Line 99, migrated. Well stick is velocity curve of exploration well, which penetrates basement.



Mid-Devonian carbonates (7s: Slave Point Formation) 7s
Basement (sub-Phanerozoic unconformity) 8

Figure 13. Portion of uninterpreted and interpreted versions of 1980 Cominco Line A, migrated. Tie lines constrain the grabens' strikes to the northwest. Note display scale is different from other figures. *See* Figure 1 for location.

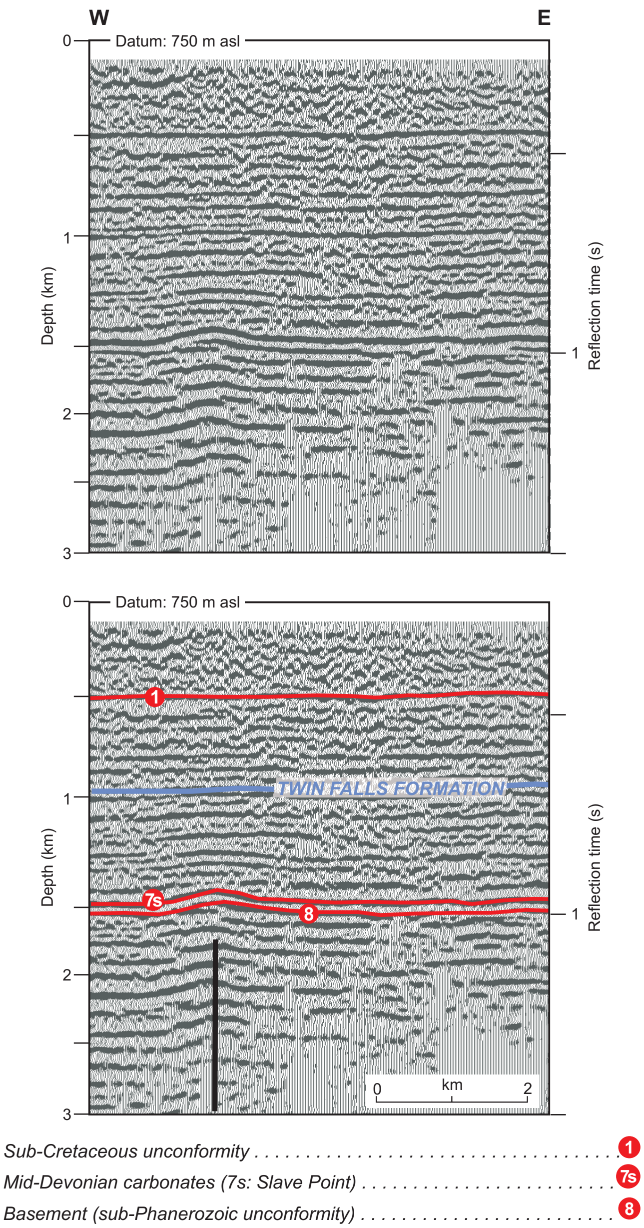


Figure 14. Uninterpreted and interpreted versions of 1984 Northcor Line 4, migrated, which crosses a linear zone of possible compression (transpression). *See* Figure 1 for location.

Reverse faults of an enigmatic nature that affect basement are found southwest of the Trout Lake A-45 well (Fig. 16) where structural repetitions of the reflections at the top of the Slave Point Formation and basement provide evidence of bed shortening and consequently, compression. Unfortunately, there are insufficient data to discover whether the compression was related to development of the small uplift (Fig. 16) situated nearby, directly above a steep basement boundary (fault?). That bulge, like the one shown in Figure 14, is considered a possible product of compression or transpression but to have developed much later, after deposition of the Banff Formation (horizon 3) but prior to Cretaceous time.

Carbonate bank edge

The Middle Devonian bank edge marks the abrupt lateral transition from carbonate strata of the Slave Point and Sulphur Point formations to their shale equivalents (Fig. 8). On seismic, the bank edge appears as an abrupt thinning of the Middle Devonian carbonate- to-basement interval combined with a marked change in amplitude of the reflection at the base of the Fort Simpson Formation. Where the large amplitude reflection produced by the shale-to-carbonate interface above the Slave Point Formation (Horizon 7s in Fig. 17) diminishes laterally, it marks the change to a shale-to-shale interface above the Otter Park (or Horn River) Formation. Since water depth is generally accepted as being a key influence on the location of a bank edge, then its track (Fig. 18) can be taken as a clue to ancient seafloor topography and, by extension, to the topography of the underlying basement. Straight segments and abrupt changes in the direction of the edge are interpreted as evidence of basement lineaments or adjustments on intersecting faults such as the north-south Bovie set.

There is sufficiently dense seismic coverage in the Bovie and Celibeta areas to permit a close tracking of the bank edge and a comparison to basement trends and faults. To the west of Celibeta High, the edge parallels the northwest lineament set and exhibits small offsets where it crosses north-south striking faults before it turns north, parallel to these faults, and next turns parallel to the Liard Line and dies out. The bank edge is re-established west of Liard Line and tracks generally northeastward along the west side of Arrowhead Salient and is deflected northward where it re-crosses the north-south Bovie fault set. In the area to the southeast of Celibeta High, the bank edge, as mapped, closely parallels the Trout Lake magnetic trend. The southwest portion of Arrowhead Salient is, therefore, interpreted to have been influenced by several basement features: Liard Line; Trout Lake trend; the north-south Bovie fault set and; very likely, a northwest lineament.

Cordova is an embayment of shale within a large platform of Middle Devonian carbonate. Within the study area, at the stratigraphic level of the Slave Point Formation, its west side parallels the Fort Simpson magnetic anomaly (compare Fig. 7 and 18) while its eastern edge trends northwestward in a remarkably linear fashion. An area of poor seismic and well control on the east side of the embayment's entrance has produced a gap in the mapped bank edge, but north of it the edge is seen to track northeastward, parallel to the Trout Lake trend before turning to follow the 61st parallel. Here the track is taken from Williams (1986) and is based solely on well control. Diversions from its easterly course both to the northeast (three examples are, near 119°45', at RLF, and east Kakisa

Contents

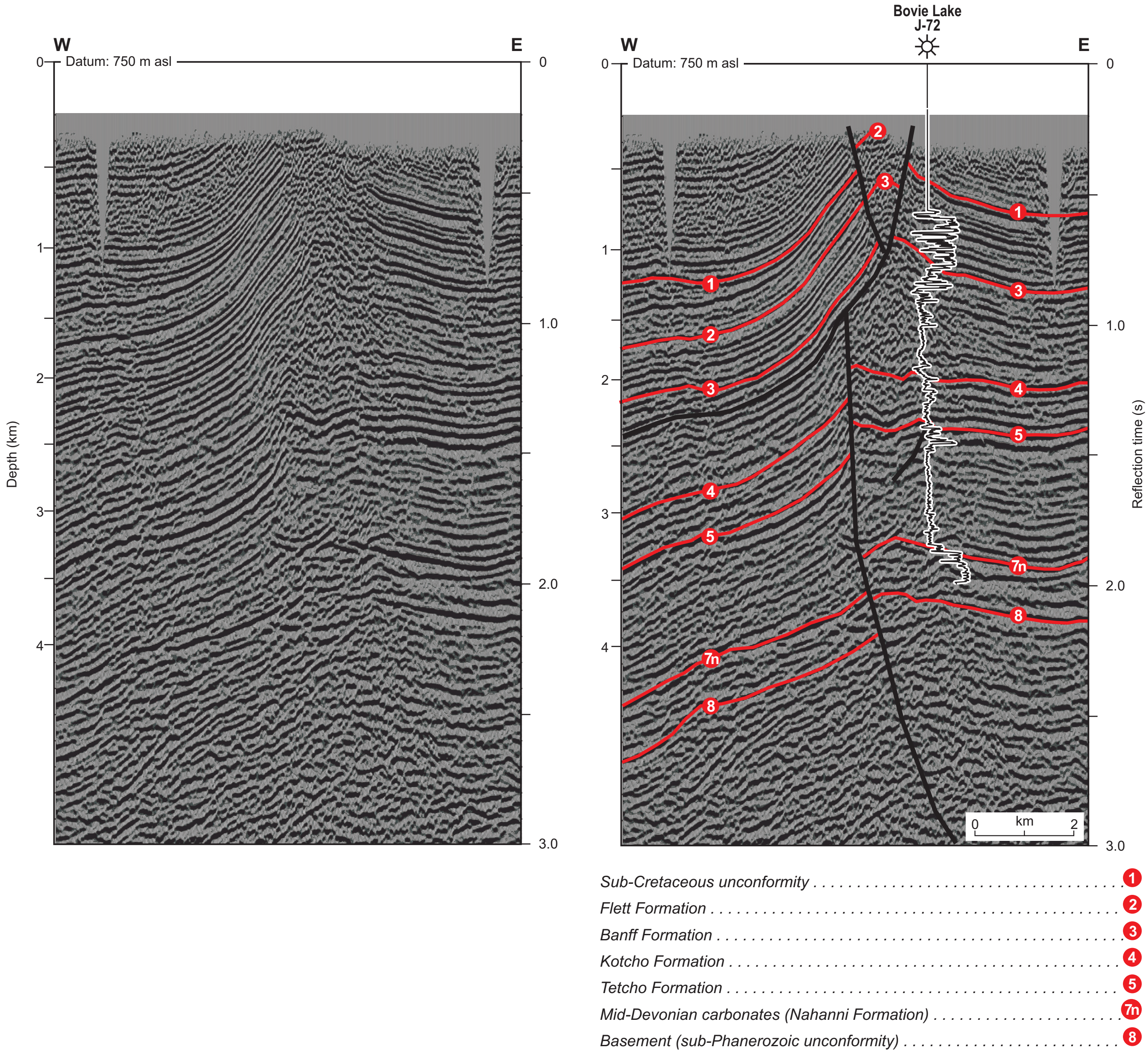


Figure 15. Portion of uninterpreted and interpreted versions of 1995 Shell Canada Line 91, migrated. Well stick is velocity curve of exploration well. Bovie Fault is the most significant of the crustal-scale compressional faults in the study area. *Modified from* MacLean (2002). *See* Figure 1 for location.

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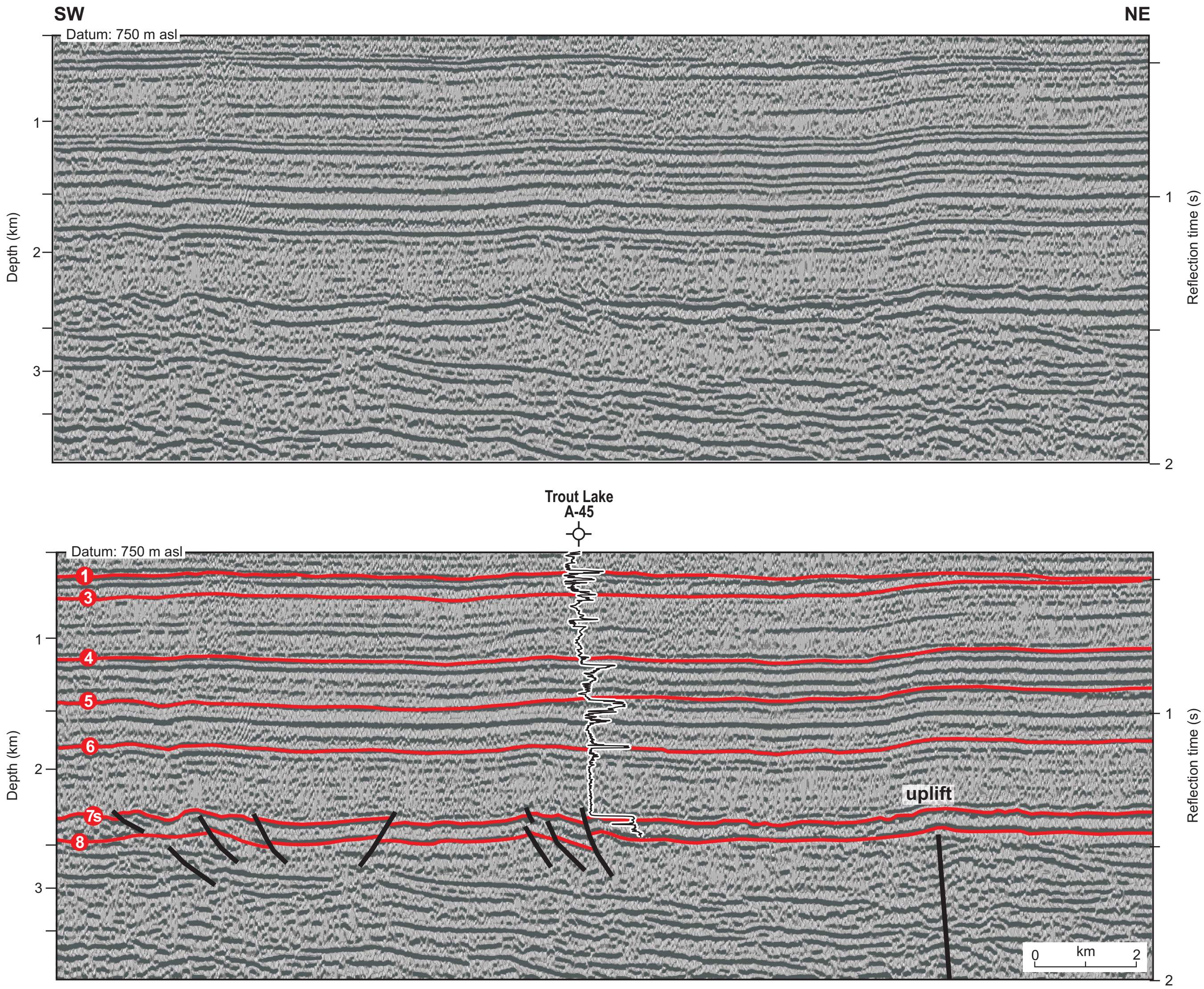


Sub-Cretaceous unconformity 1
Banff Formation 3
Kotcho Formation 4
Tetcho Formation 5
Jean Marie Member, Redknife Fm 6
Mid-Devonian carbonates (7s: Slave Point Formation) 7s
Basement (sub-Phanerozoic unconformity) 8

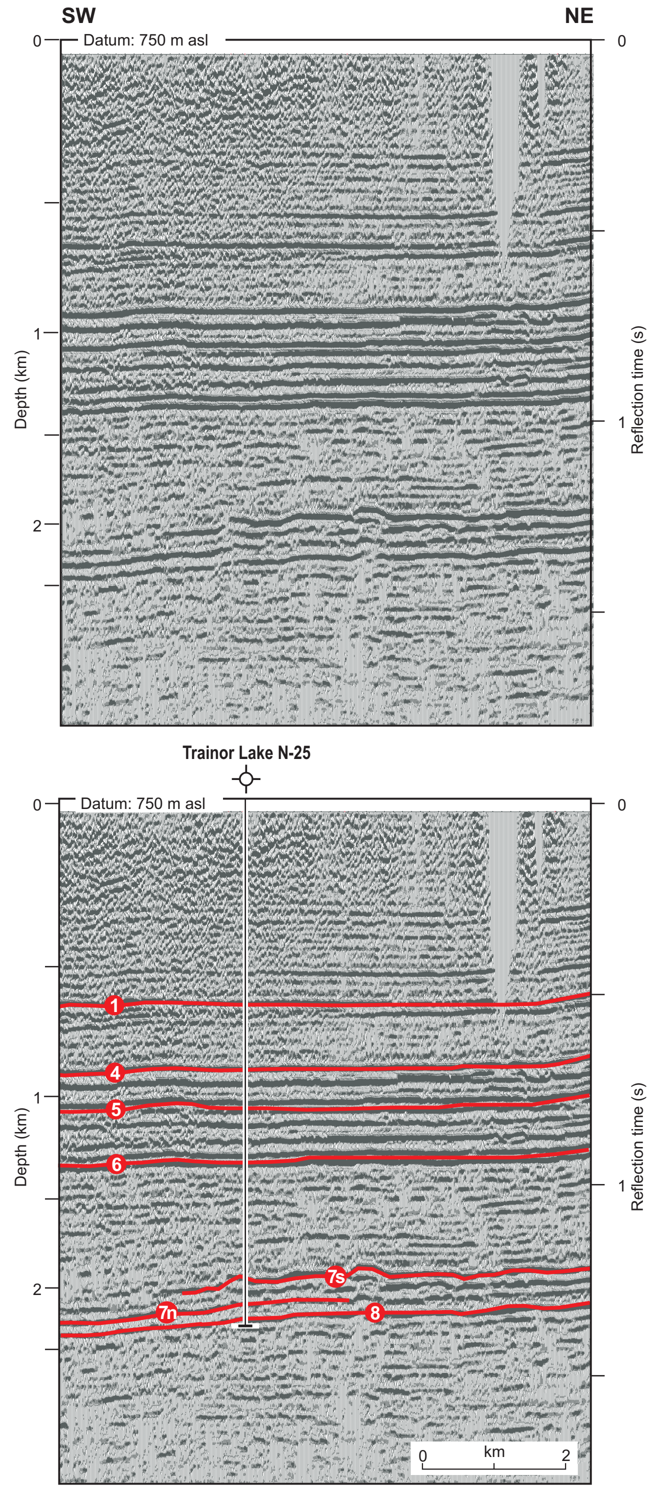
Figure 16. Portion of uninterpreted and interpreted versions of 1986 Petro-Canada Line 8049, migrated. Well stick is velocity curve of exploration well. Small uplift on right portion of section is referred to in the text. Enigmatic minor compressional faults have produced structural repeats of both basement and top of the Middle Devonian carbonate reflectors. This may be related to pre-Cretaceous compression (transpression?), focused along the pre-existing vertical basement boundary (fault?). Compare with Figure 14. Refer to Figure 1 for location.

Lake), and to the southeast (two examples are, at 119°15', and east of RLF) may be products of basement adjustments on the orthogonal lineaments, but closer well or seismic control is needed to test this hypothesis.

Lower Paleozoic

Hydrothermal dolomite is a key element in petroleum and MVT exploration models, and ascertaining what relationship, if any, exists between it and basement structure was one of the goals of this study. The evidence for a link is inconclusive but suggestive. The area of hydrothermal dolomite presented by Janicki (2006) and included in Figure 18, shows a generally northeast grain and a strong association with Tathlina Fault (TF). Unfortunately, no seismic data from there were available to this author. In the southwest, Meijer-Drees (1993) noted five occurrences of white dolostone facies on Celibeta High and another, situated somewhat to the north, which is revealed by Figure 18 to be situated above the intersection of a reverse basement fault with a sharp bend in a basement depth contour. These observations lead to the conclusions that an early stage of uplift at Celibeta as well as adjustment(s) along the northeast-striking Tathlina Fault both played some role in hydrothermal dolomitization. No such relationship can be inferred at Rabbit Lake Fault. The relative timing of movement and fluid flow is critical to faults playing a role in MVT or petroleum trapping because fault movement needs to precede the flow of porosity-enhancing and mineral-bearing fluids through the system. Unfortunately, a comparison of the timing of the RLF and TF must await the availability of additional data.

A time-thickness map (Fig. 19) was constructed for the eastern half of the study area by subtracting the two-way travel time to the top of the Middle Devonian carbonate from that of the basement reflector (#7 from #8 in Fig. 8). This area lies south of the bank edge and is therefore one of platformal carbonate deposits. If one makes the assumption that the top of the carbonate was once horizontal, then thickness changes should reflect basement paleotopography, linear features might indicate pre-Slave Point faulting, and thicks potentially contain more strata suitable for dolomitization and thus might be areas of greatest potential dolomite thickness. The map in Figure 19 provides a somewhat confusing picture, partly due to inconsistent data density and the presence of large gaps in seismic coverage. There is, however, a linear thin/thick pair trending northeastward near the present-day Hay River, and two 'zero contours' show that basement was exposed along a ridge parallel to, and east of, the Tathlina Fault. Elsewhere, data gaps and numerous small basement faults combine to hide any regional patterns.



Sub-Cretaceous unconformity 1
Kotcho Formation 4
Tetcho Formation 5
Jean Marie Member, Redknife Fm 6
Mid-Devonian carbonates (7s: Slave Point 7n: Nahanni formations) . . . 7s 7n
Basement (sub-Phanerozoic unconformity) 8

Figure 17. Portion of uninterpreted and interpreted versions of 1984 Northcor Line 23, migrated. This line shows the Middle Devonian carbonate bank edge (shale-out of horizon 7s) on the east side of Cordova Embayment. *See* Figure 1 for location.

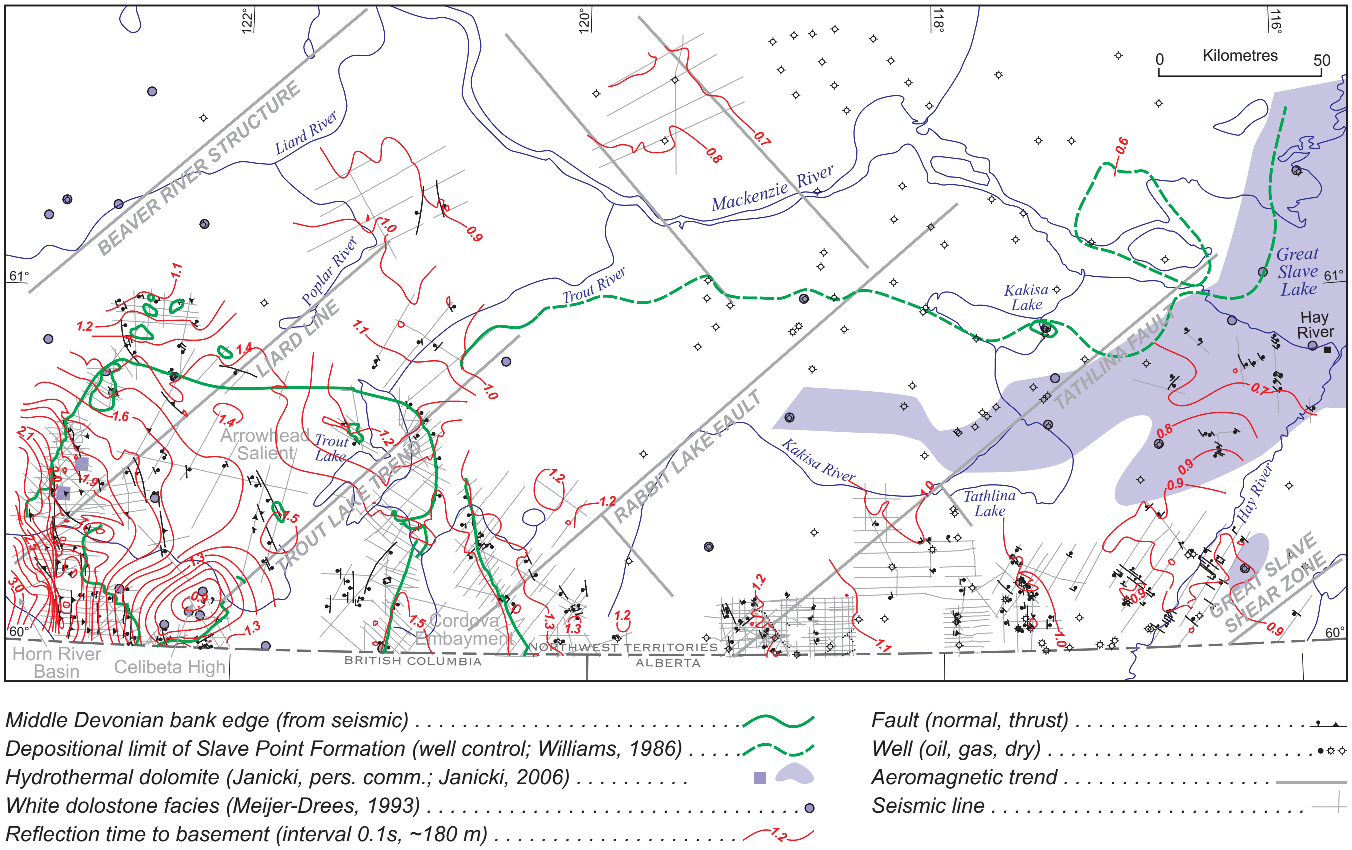


Figure 18. Middle Devonian facies boundaries, basement faults, and basement seismic time-depth structure contours. Datum is 750 m asl.

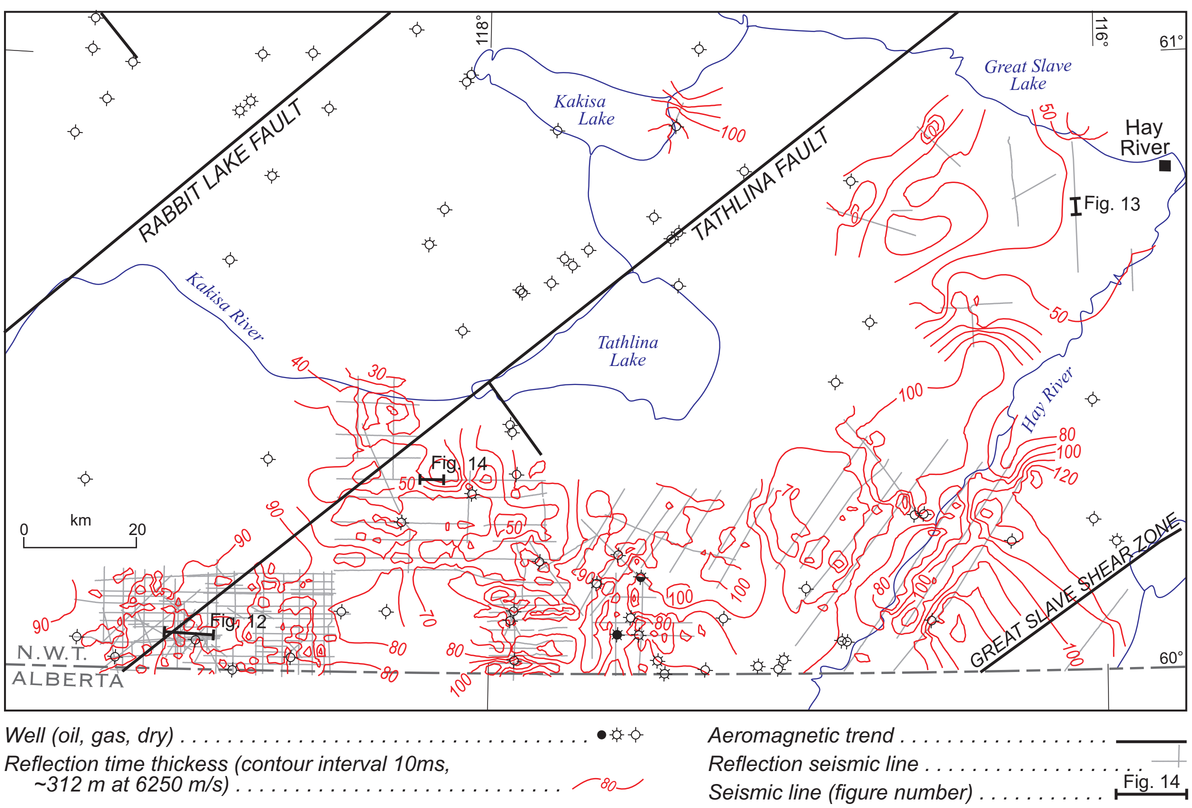


Figure 19. Seismic thickness map of the interval between top of basement and, in the west, the top of Middle Devonian carbonate (Slave Point or Nahanni formation).

CONCLUSIONS

Seismic depth contour maps support the interpretation of Belyea (1971) that an orthogonal pattern of ‘lines of weakness’ has influenced deposition and facies in the southern NWT. These lines of weakness are sometimes exhibited as faults with sufficient offset to be imaged on present-day seismic, but more often show simply as linear depressions and ridges in basement topography. The northeast trend appears to be better developed than the northwest one.

Basement structural adjustments have occurred throughout the Paleozoic and Mesozoic, from prior to deposition of the Slave Point Formation to during the Cretaceous or possibly even later, if evidence of an orthogonal pattern in today’s drainage pattern is accepted.

Most faults with sufficient throw to be imaged on seismic are of limited length. Those long enough to permit determination of strike direction generally fall into three groups: north-south, northwest-southeast and northeast-southwest-trending.

The track of the Middle Devonian carbonate bank edge was influenced by linear trends in basement topography.

The carbonate bank edge in the Celibeta and Bovie areas is interpreted to have been influenced by local uplift, crustal-scale north-south faults, the Liard Line, the Trout Lake trend, and, possibly, by a northwest-trending basement lineament.

The development of hydrothermal dolomite was indirectly enhanced by adjustments on some basement features (e.g. Celibeta High area and Tathlina Fault) but not others (e.g. Rabbit Lake Fault).

Differences in the timing of fault development may explain why hydrothermal dolomite developed within Middle Devonian carbonate near Tathlina Fault but not near Rabbit Lake Fault. There are insufficient data to test this hypothesis.

ACKNOWLEDGMENTS

The author would like to thank Warner Miles of GSC-Ottawa for providing the aeromagnetic map. Discussions with David Morrow on the stratigraphic complexities of the Middle Devonian succession were of great assistance. Thanks also to Peter Hannigan, the project leader, for his patience and assistance.

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