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# Blind thrusts and fault-related folds in the Upper Cretaceous Alberta Group, deep basin, west-central Alberta: implications for fractured reservoirs

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## Abstract

3-D seismic and log-based mapping of Upper Cretaceous units in the Deep Basin has revealed the presence of fault-related folds in the Cardium Formation and overlying units. The folds formed above low-angle thrust faults that cut clay-rich shales in the lower part of the Kaskapau Formation. Seismic data indicate a fold wavelength of approximately 5 to 8 km at the Cardium level, with fold axes trending NW-SE. Log-based stratigraphic analyses identified fault repeats of Kaskapau allomembers, whereas the 3-D seismic data show details of upward-branching fault splays and related folds. The faults also splay laterally, and transfer strain by overlapping. Post-stack processing of the original 3-D volume, including noise reduction, coherency processing, and volumetric dip analyses significantly improved our ability to image and map these structures.

The Cardium Formation produces oil in the study area from fields with orientations that are approximately parallel to the fold axes. These production trends are thought to be related primarily to depositional trends that predate the structural deformation. Nevertheless, the structures we illustrate are fractured, and so they are good analogues for potential drilling targets in similarly-deformed tight-gas reservoirs. Previously published core and borehole breakout studies support these interpretations.

## Résumé

La cartographie des unités du Crétacé Supérieur dans le Bassin Profond, basée sur un profil sismique en 3-D et des diagrammes de diagraphie, a révélé la présence de plis reliés aux failles dans la Formation de Cardium, et dans des unités superposées. Les plis se sont formés au-dessus des failles chevauchantes à faible pendage qui coupent par des schistes bitumineux, riches en argile dans la partie inférieure de la Formation de Kaskapau. Les données sismiques indiquent un pli d'une longueur d'onde d'environ 5 à 8 km au niveau du Cardium, avec des axes de plis orientés vers le nord ouest - sud est. Les analyses stratigraphiques, basées sur les diagrammes de diagraphie, identifient des réitérations de failles dans les allomembres de Kaskapau, tandis que les données sismiques en 3D révèlent des détails d'embranchement vers le haut de failles de second ordre ainsi que des plis associés. Les failles divergent également latéralement, et transfèrent la tension par un chevauchement. Le traitement du volume 3D original, après sommation, incluant une réduction de bruit, un traitement de cohérence, et des analyses d'inclinaison volumétriques, a amélioré considérablement notre capacité à représenter ces structures en image et par cartographie.

Dans la zone étudiée, la Formation de Cardium produit du pétrole provenant de champs avec des orientations approximativement parallèles aux axes de plis. Ces orientations de production sont considérées comme étant reliées aux

orientations dépositionnelles, celles-ci étant antérieures à la déformation structurale. Néanmoins, les structures que nous illustrons sont fracturées, elles présentent donc de bonnes analogies en prévision de forages potentiels dans des réservoirs étanches de gaz présentant une déformation similaire. Des comptes-rendus d'études de déblocages de carottes et de sondages, publiés antérieurement, soutiennent ces interprétations.

Traduit par Gabrielle Drivet

## Introduction

There is growing interest in using seismic methods to detect subtle structures in the subsurface because associated fractures can impact reservoir performance. For example, the enhanced permeability generated by open fractures in low-permeability ("tight") reservoirs can allow hydrocarbon production at economic rates. Hart et al. (2001, 2002), Hart (2006), Fu et al. (2006) and others show how 3-D seismic, log and production data can be integrated to demonstrate the control that "tectonic" fractures (i.e. those associated with structural features such as folds and faults; Nelson, 2001) have on generating production "sweet spots" in tight-gas reservoirs.

In this paper we illustrate the use of logs and 3-D seismic data to identify and map blind thrusts and associated fault-related folds in the Upper Cretaceous Kaskapau, Cardium and overlying formations of the Alberta Group in the Deep Basin in west-central Alberta (Fig. 1). Although the structures we describe are not associated with gas production in the study area, they might be analogues for other, similar features in the Alberta Basin or elsewhere where links are present between stratigraphy, structure, fracture development and producibility.

## Data and Methods

We integrate 3-D seismic-based imaging in the Wapiti Field area with results from an outcrop- and log-based study of the Kaskapau Formation covering an area of approximately 35,000 km$^2$ (Fig. 1). The 3-D seismic dataset used in this project consists of a time-migrated 3-D seismic volume that covers an area of approximately 460 km$^2$. The volume has a bin size of 30 x 40 m, and a 2 ms sample rate. Unfortunately, because of data confidentiality, we cannot disclose the exact location or shape of the 3-D data volume. The database for the regional Kaskapau study is described in Varban and Plint (2005).

The seismic data we analyzed was collected and processed primarily to image deeper targets, thus reducing the

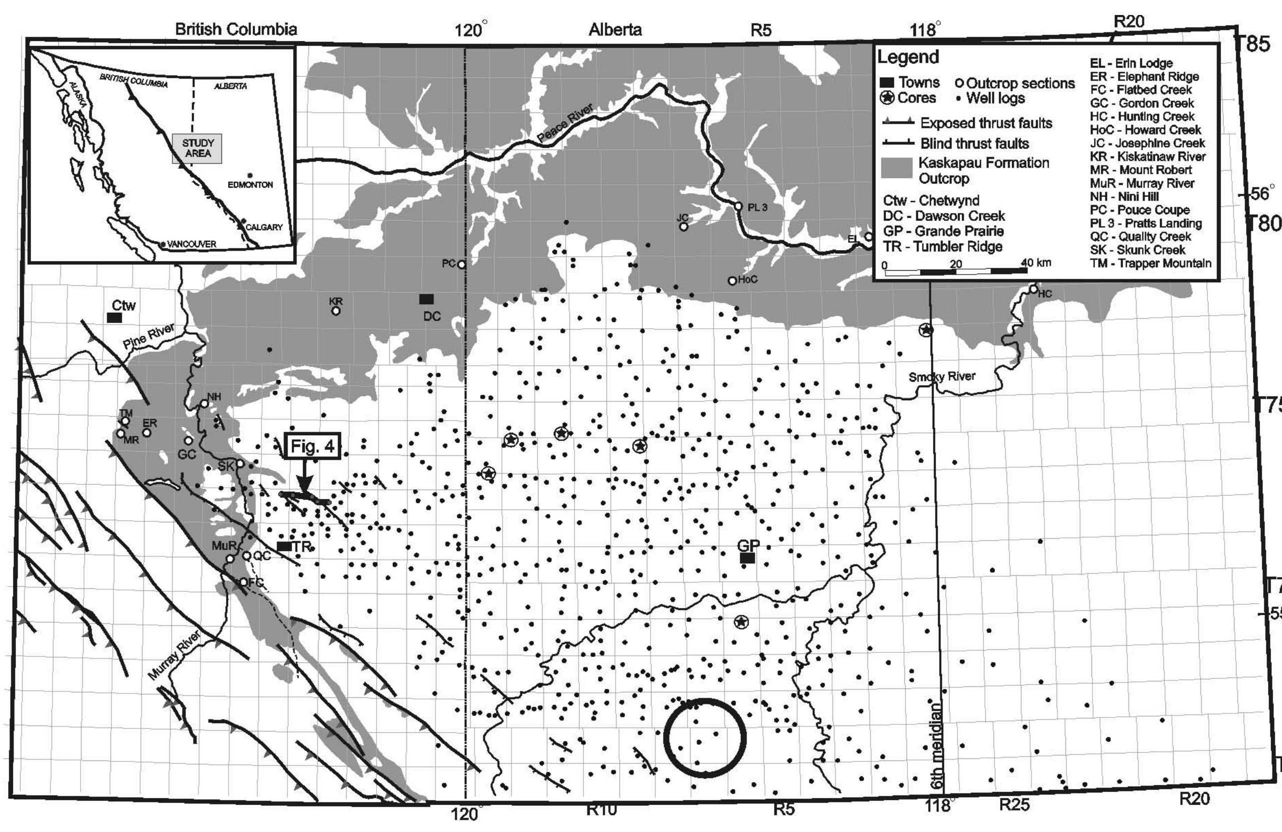


**Fig. 1.** Location map showing the regional study area of Varban (2004; Varban and Plint, 2005) and approximate location of 3-D seismic survey (actual location and outline of the survey are concealed because of data confidentiality concerns). Thrust faults include those mapped at the surface, and also subsurface structures inferred from logs and 3-D seismic data. Note location of the well log cross-section shown in Figure 4.

signal-to-noise ratio at the level of the relatively shallow stratigraphic levels described here. The data quality is notably poor below surface obstructions such as rivers. As such, we used various post-stack processing steps to reduce noise and to enhance stratigraphic and structural features at the level of interest to this study. Principal component filtering, described by Marfurt (2006) was used to enhance lateral resolution and reduce both random and coherent noise. This filtering method suppresses random noise in a way that avoids smoothing over structural and stratigraphic edges, and it also suppresses coherent noise. Unfortunately, principal component filtering will also preserve and even enhance the acquisition footprint where that footprint is slowly varying in the vertical direction. Fractures that are nearly vertical are nearly indistinguishable from this kind of acquisition footprint, and so geological analyses such as those presented below are required to distinguish acquisition footprint from structural features.

The seismic examples presented in this paper are from the post-stack filtered volume. Subsequently, we generated various attribute volumes in an attempt to identify subtle structures. In this paper we show examples from data volumes generated using both a new coherency processing algorithm, and volumetric dip. Details of the algorithms used to generate these volumes are described by Marfurt et al. (1999) and Marfurt (2006). Seismic interpreters routinely derive dip and azimuth measures from horizons picked in 3-D seismic volumes in an effort to identify subtle structures (e.g. Dalley et al., 1989). In contrast, volumetric dip is derived directly from reflections in uninterpreted 3-D seismic data cubes.

## Fault Imaging

Structures described in this paper are present in the Smoky Group of west-central Alberta (which is equivalent to the Alberta and Colorado groups farther to the south). Specifically, thrust faulting occurs in the Kaskapau Formation, with fault-related folding in the Kaskapau, Cardium and overlying units (Fig. 2). Sedimentologic and stratigraphic aspects of the Cardium and Kaskapau formations in the study area are described by Hart and Plint (1993) and Varban and Plint (2005) respectively.

Figure 3 shows the log and seismic expression of these units, together with a synthetic seismogram that illustrates the tie between log and seismic data. Prominent high-amplitude reflections are generated at the level of the Marshybank Formation, E7 surface (i.e. top) of the Cardium Formation, the Kakwa Member of the Cardium and at two highly radioactive intervals in the lower part of the Kaskapau Formation. Units above the Marshybank are not mappable throughout the entire data volume because of low signal-to-noise ratios (even after post-stack processing) at these shallow depths (Figs. 2, 3).

Varban and Plint (2005) showed that units I and II contained regional, clay-rich and highly radioactive 'hot' shales. Within unit I, a hot shale immediately overlies a subtle disconformity which locally truncates allomember 1 over the south-central part of the study area (Figs. 2, 3, 4). The upper radioactive zone corresponds to an organic-rich shale with a prominent bentonite that expands in thickness southward. This upper hot shale marks the boundary between the Sunkay and Vimy members of the Kaskapau Formation (Stott, 1967), and also the peak of the Greenhorn transgression (Kauffman and Caldwell, 1993).

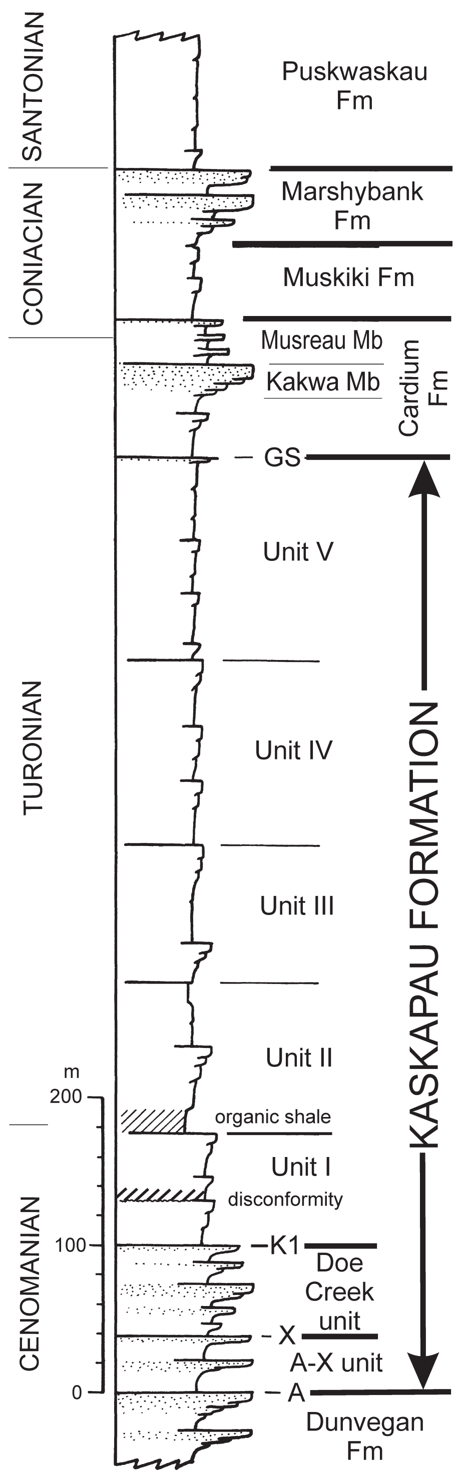


**Fig. 2.** Stratigraphic section representative of the geological units present in the area of the 3-D seismic survey, located in Figure 1.

## Log and Outcrop Expression of Faulting

The upper part of the Kaskapau Formation (units I to V) was divided into 28 allomembers that were correlated through a grid over approximately 35,000 km$^2$. The grid included 756 well logs (gamma ray and resistivity), six partially cored wells, and 16 major outcrop sections exposed along the Rocky Mountain Foothills and the Peace River (Fig. 1; Varban and Plint, 2005). In this more northerly study area, the Kaskapau strata are not intensely deformed because Late Cretaceous crustal shortening was much less than in southern Alberta (McMechan and Thompson, 1993), where Kaskapau-equivalent rocks are intensely imbricated. Because of the low level of deformation in the study area, and the overall lateral continuity of Kaskapau allomembers, it was relatively easy to recognize that the stratigraphy in some wells adjacent to the edge of the fold belt is anomalously thickened by tens of metres over distances of 3–5 km. These thickness changes far exceeded the gradual NE-thinning of allomembers, and occurred in a spatially unpredictable pattern. Detailed correlation of the 28 allomembers

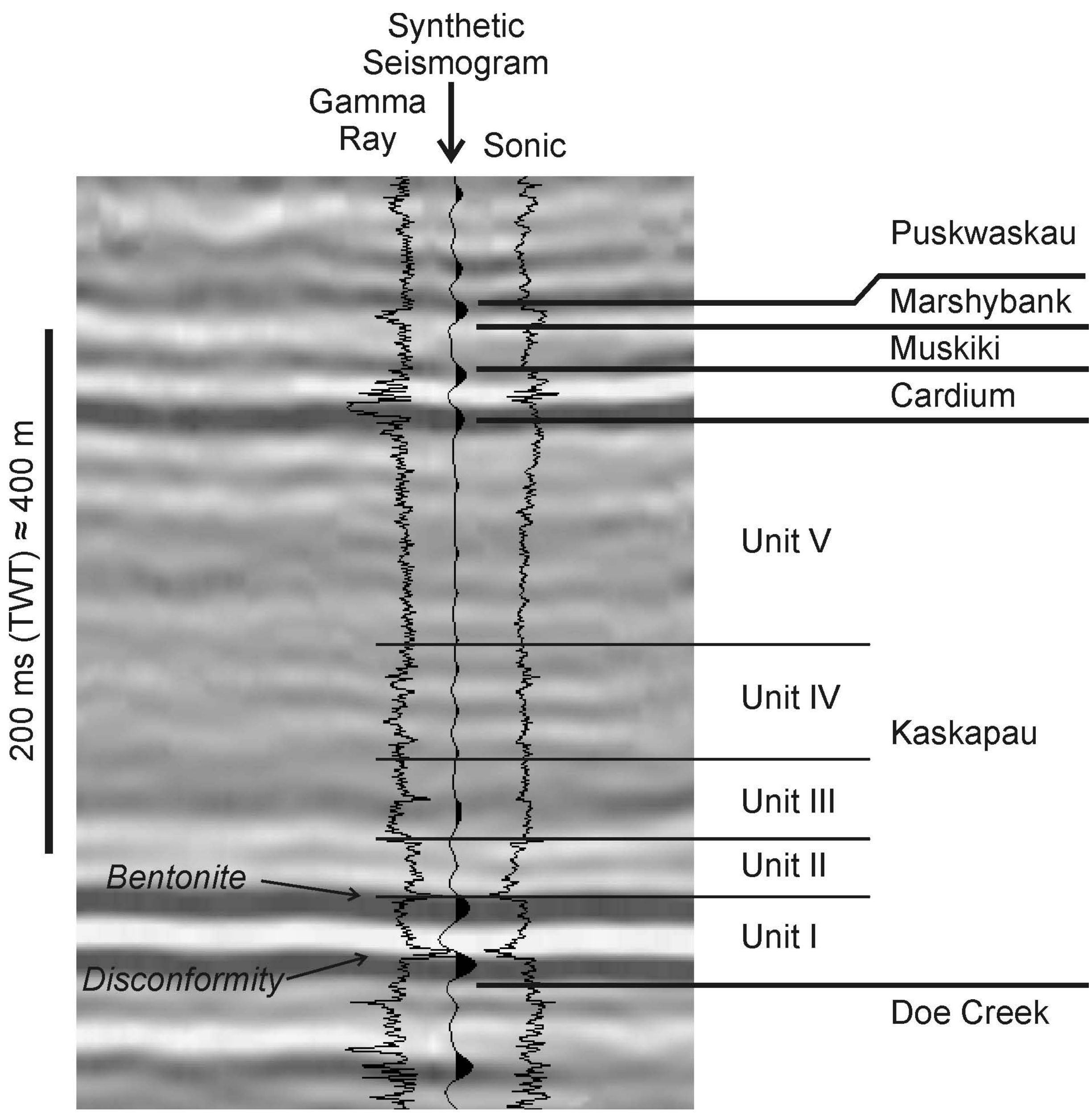


**Fig. 3.** Comparison of log- and seismic-based stratigraphy. Note the excellent match between the synthetic seismogram and the seismic data. Greyscale colour bar for the seismic data shows peaks in black, troughs in white. Stratigraphic subdivisions of the Kaskapau Formation are those of Varban and Plint (2005). A disconformity within unit I, and the contact between units I and II of the Kaskapau (approximated by a bentonite) generate reflections in the seismic data. Vertical scale shows two-way travel time (TWT) and approximate equivalent measured depth (m) based on average P-wave velocity in the Kaskapau of 4000 m/s (derived from logs).

allowed areas of abrupt stratigraphic thickening to be mapped; the inferred faults are shown in Figure 1 (after Varban and Plint, 2005). Although it is not always possible to confidently identify the repeated allomembers, most of repeated intervals tend to be concentrated within the muddier parts of the Kaskapau Formation, particularly within unit II. An example of allomember-scale stratigraphic repetition is shown in Figure 4 where allomember 8 is partially repeated in well a-89-B 93P7, and fully repeated in a-72-B 93P7. The datum in Figure 4 is the top of allomember 6, which marks the boundary between Kaskapau units I and II, and also coincides with the lithostratigraphic boundary between the Sunkay and Vimy members of the Kaskapau Formation (Stott, 1967). Figure 4 also illustrates an over-thickened zone which we tentatively interpret to involve allomember 7.

Although the well logs do not provide direct visualization of faults, it seems reasonable, given the regional compressive tectonic style, that the vertical repetition of allomembers is due to thrust faulting. Support for this hypothesis is provided by outcrop observation. For example, Figure 5 shows the SE face of Trapper Mountain (Fig. 1), where a thrust fault at the boundary between units I and II forms a ramp dipping very gently to the SW, and involves about 40 m of stratigraphic repetition. Similar faults, but of more limited lateral extent and involving only 5 to 10 m of stratigraphic repetition, were observed during aerial and ground observation along the Murray River, south of Nini Hill (Fig. 1), and are concentrated in Kaskapau strata of unit II.

## 3-D Seismic Imaging

Figure 6 shows a SW-NE oriented transect through the seismic volume, showing three fault-related folds at the Cardium and overlying stratigraphic levels. The folds are formed over foreland-directed blind thrusts in the Kaskapau Formation that occur either singly or as duplexes or upward-splaying imbricate fans. The latter structures are probably breakthrough structures (Suppe and Medwedeff, 1990). The thrusts sole out into a décollement surface that corresponds to the clay-rich, highly radioactive portions of Kaskapau unit II (Figs. 2, 3). The longest faults rise nearly 300 m stratigraphically. We were not able to consistently map any thrust faults that are hinterland directed (e.g. backthrusts), although the presence of these types of structures might be presumed based on examination of specific seismic transects, especially where noise contaminates the image (e.g. in the area of the easternmost fault shown in Fig. 4).

Thrust faults, visible as reflection offsets on vertical transects, are recognized as lineations in slices through the data volumes in the lower part of the Kaskapau Formation (Fig. 7). Fault splays bifurcate laterally. The strike of the thrusts, including splays and single faults, ranges from approximately 300º to 310º. The splay systems overlap somewhat laterally, indicating that displacement was being transferred in the strike direction by *en echelon* overlap rather than by tear faults.

At higher levels in the Kaskapau Formation, faults are poorly defined on timeslices (through all versions of the seismic data),

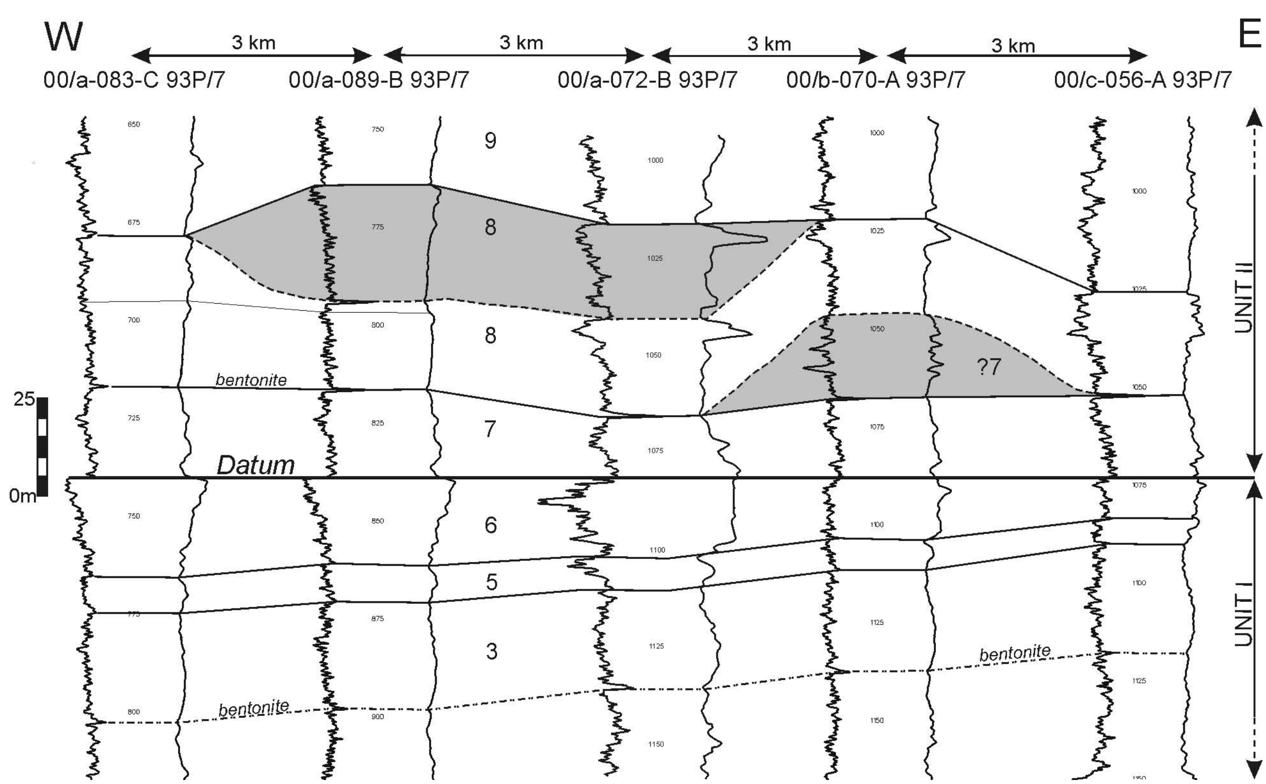


**Fig. 4.** Log cross-section showing abrupt changes in thickness of stratigraphic units within the Kaskapau Formation that are probably related to thrust repeats. Numbered units are allomembers of Varban and Plint (2005). Shaded areas represent repeat section. Modified from Varban (2004). See Figure 1 for location.

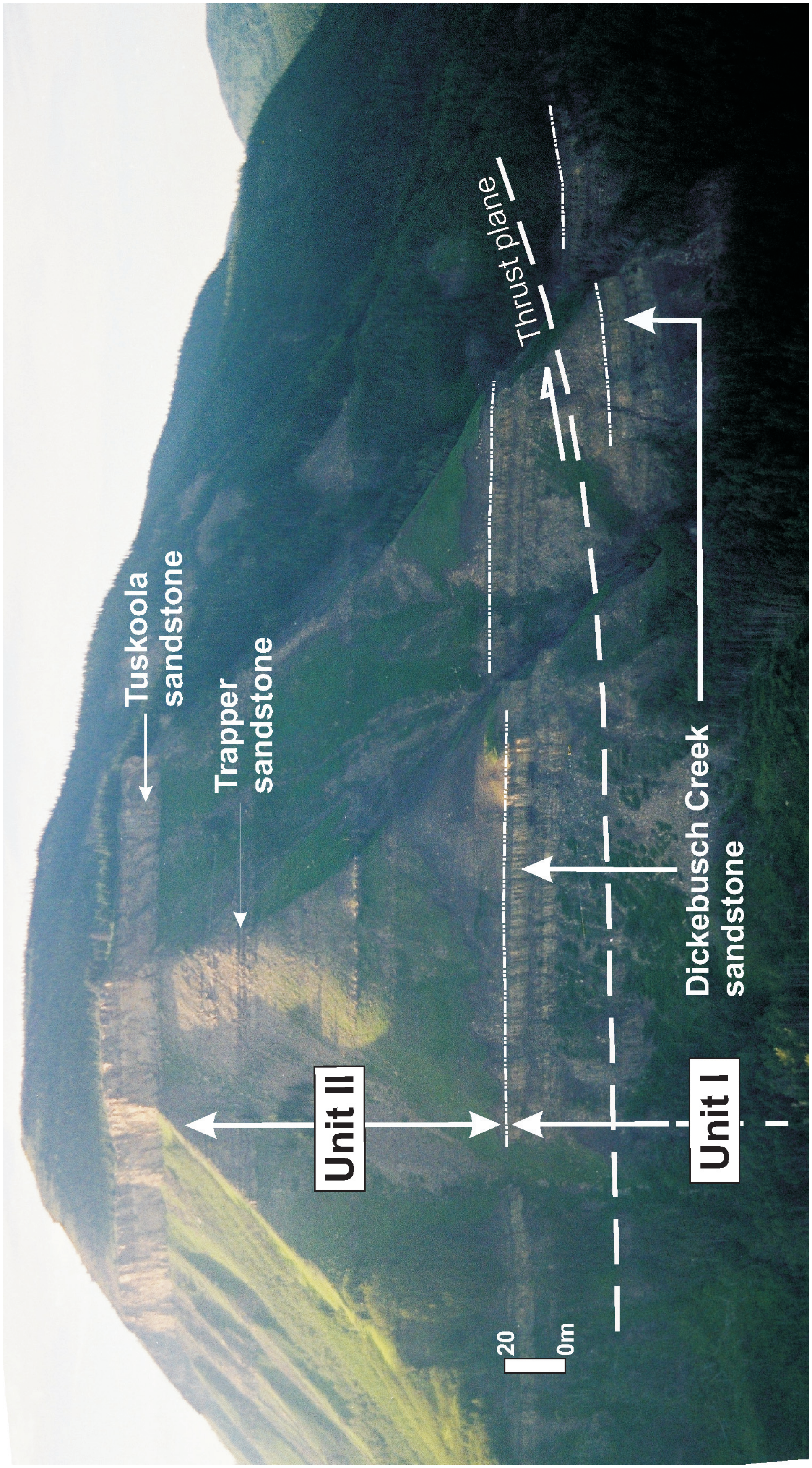


**Fig. 5.** Aerial view of thrust fault in outcrop on the SE face of Trapper Mountain, 30 km South of Chetwynd, B.C. (Fig. 1). Note that the thrust fault is developed just above the boundary between units I and II, in about the same position in which thrust faults are inferred to have developed in subsurface (see Figs. 4, 6).

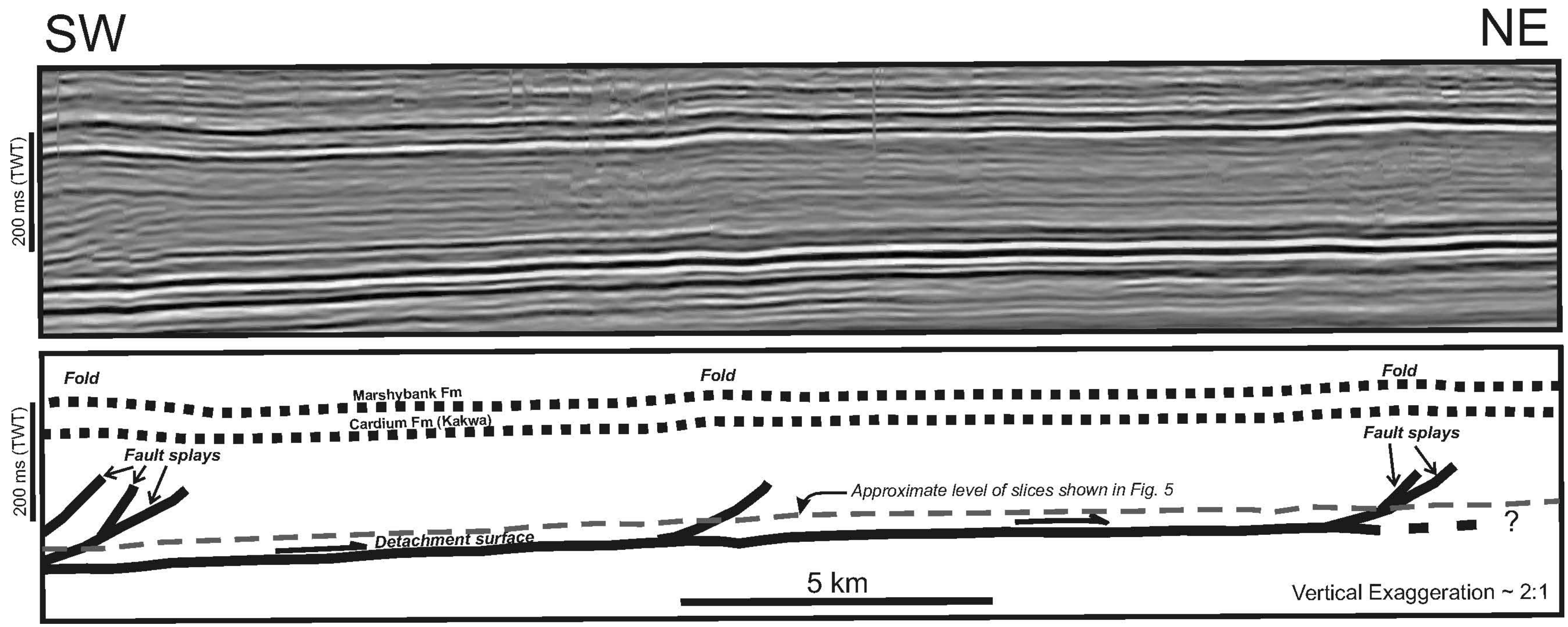


**Fig. 6.** Structural dip-oriented transect through 3-D seismic volume showing thrust faults in the Kaskapau Formation, including fault splays and isolated thrusts. Faults detach from a surface within unit II of the Kaskapau, and single faults and fault systems are overlain by folds of the Cardium and overlying formations (Figs. 2, 3). Note tectonic thickening of the interval between the detachment surface near the base of the Kaskapau unit II and the Cardium. The presence of backthrusts might be interpreted based on fold asymmetry at the Cardium level and reflection terminations in the Kaskapau. However, these features, if present, cannot be consistently mapped in the 3-D volume and so they are not interpreted here.

perhaps because of the relatively shallow dips of the fault ramps and the lack of high-amplitude reflections in the shales. The faults are typically several kilometres long, but the length of most fault segments cannot be determined because the faults extend beyond the 3-D survey area.

The upper part of the Kaskapau and overlying strata (e.g. Cardium) are deformed into low-relief asymmetrical anticlines above the faults (Fig. 6). The folds are superimposed on a regional dip to the southwest. The folds extend upward in a conformable manner at least up into the Puskwaskau Formation (Fig. 2), but above that level, seismic data quality is too poor to confidently interpret structure. The spacing between folds in a SW-NE direction ranges from 5 to 8 km. Fold crests can be curved near their lateral margins but, like the underlying faults, generally strike between 300º–310º. An isochron map of the interval between the basal detachment and the Cardium Formation (Fig. 8) shows fold locations as tectonically thickened, elongate features superimposed on the general depositional thinning to the northeast that reflects the original flexural accommodation pattern (Hart and Plint, 1993; Varban and Plint, 2005).

## Discussion

The structures we describe extend in subsurface for at least 50 km to the NE of the nearest exposed thrusts mapped in the Foothills (Fig. 1). Several previous seismic studies have identified thrust systems that developed from a detachment surface in the lower part of the Kaskapau Formation (e.g. Cooper, 1992; Skuce et al., 1992; Skuce, 1996; Dechesne, 1994; Wright et al., 1994; Spratt and Lawton, 1996;). The clay-rich nature of this unit, possibly combined with overpressuring (Dechesne, 1994) appears to have made this a mechanically weak zone. To our knowledge, only the studies of Skuce et al. (1992) and Skuce (1996) showed seismic examples of thrusts that extend as far into the foreland (up to 50 km) as the structures we describe. Those studies were based on 2-D seismic data and did not address the along-strike variability that we were able to observe in the 3-D data. The seismic data suggest that the faulting and folding developed some time after deposition of the Puskwaskau Formation. We see no thinning of stratigraphic units either in the Kaskapau Formation, or above the Cardium Formation or other evidence (e.g. Shaw et al., 2005), that would suggest that the faults and folds were of syn-depositional origin. The seismic data indicate that the faults generally form thrust systems, rather than individual thrusts. Comparison of the 5 to 8 km wavelength of the folds mapped in the seismic data (Figs. 6, 7, 8,) with the position and spacing of thrust faults inferred from log correlation (Fig. 1) suggests that fault and fold systems are probably more common in the subsurface than are indicated in the log-based mapping.

Although the structures described in this paper have tectonic significance, we choose to focus the rest of this discussion on relationships between folding and fractures because of the growing interest in understanding relationships between subtle structures, fracture development, and production from low-permeability reservoirs (e.g. Hart et al., 2001, 2002; Hart, 2006).

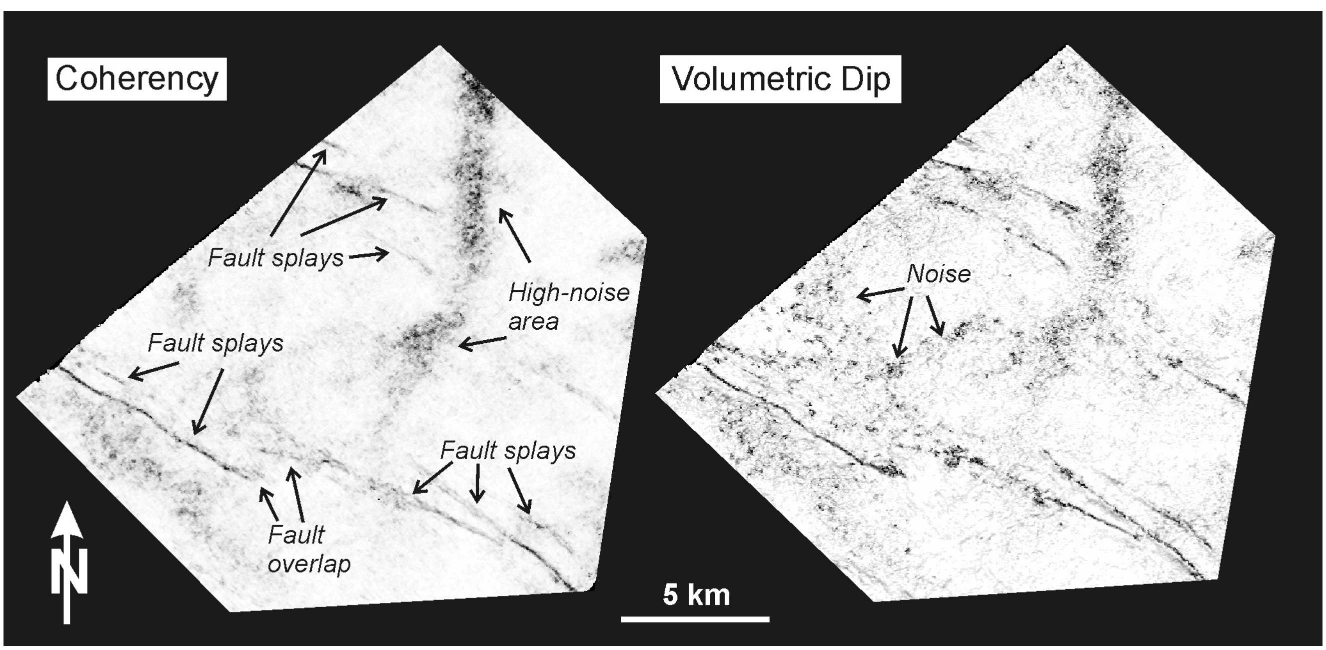


**Fig. 7.** Slices through coherency (left) and dip (right) volumes, both of which highlight discontinuities (black) in the data. The faults are more sharply defined in the dip volume, but the image is degraded by enhanced noise in some areas. Both slices are from a level in the data volume that is parallel to, but 40 ms above a prominent high-amplitude trough in unit I of the Kaskapau Formation (Fig. 6). Note the plan-view expression of fault splays from the imbricate fans. At depth, the thrust splays converge toward the detachment horizon, as seen in Figure 6. Also note the lateral overlap between faults. High-noise area labeled on the coherency slice is due to imaging problems beneath a modern valley.

Caliper log data can be used to infer the presence of fracture swarms related to folding in the Cardium Formation. Figure 9 shows two logs through that formation, one located on the crest of a fold, and the other in a relatively undeformed area less than 4 km away. The well from the undeformed area shows minor borehole cave-ins in shaley units above the Kakwa sandstone, whereas the well from the fold crest shows significant borehole enlargement in the Kakwa sandstone. Similar borehole enlargement is seen in tight-gas reservoir rocks of the Cennomanian Dakota Formation in the San Juan Basin (e.g. Hart, 2006). There, the borehole enlargement occurs in heavily fractured, quartzose (i.e. "clean") shoreface sandstones, and its presence is considered to be an indication that fracture permeability is well developed in the Dakota Formation at the well location. In contrast, operators in the Canadian Deep Basin consider borehole enlargement in Cretaceous sandstones to be an indicator of poor reservoir quality (i.e. rocks with low matrix permeability). The orientation (horizontal *vs.* vertical, azimuth) of the fractures cannot be determined from unoriented caliper logs alone but, and as described below, previous whole core observations and borehole breakout studies suggest that the fractures are vertical and have preferred orientations. Also, available well control does not allow us to test how representative the caliper log signatures shown in Figure 9 are.

Nelson (2001) summarized various models for fracture generation in compressional settings associated with folding. Extension-mode fractures oriented parallel to the maximum horizontal compressive stress often develop on the limbs of folds, and regional fracture sets (joints) can also form with the same orientation in areas of relatively minor tectonic shortening. In the current study area, the orientation of thrusts and fold axes indicates shortening in the SW-NE direction, consistent with the results of borehole breakout data that provide information about modern *in-situ* stresses (Bell et al., 1994).

In the Wapiti Field, less than 10 km north of our study area, McLellan (1988) reported the presence of natural fractures in the Cardium Formation striking approximately 030º. That orientation is approximately perpendicular to the strike (about 300º) of the faults described in this paper, and hence is consistent with 030º being the orientation of tectonic shortening. Significantly, McLellan (1988) also reported the presence of a natural fracture set in the Cardium Formation having a mean orientation of 300º, approximately parallel to the fold axes described herein. These observations suggest that hinge-parallel fractures, associated with extension on the fold crest, are at least locally developed.

Although the observed lateral *en echelon* overlap of thrusts argues against the presence of large tear faults, zones of enhanced fracture density with NE-SW orientations might be present near fold or fault tips. Figure 10 shows a model for fracture development that is consistent with our observations of fold and fault geometries, theoretical models for fracture development on folds, and McLellan's (1988) observation of natural fractures in the Cardium Formation in this area. Borehole image logs, oriented core and production interference, not available for this study, could be used to test our model in an area where such data were available. The model has potential application in areas where fault-related folds affect the Cardium Formation, or other low-permeability rocks.

The Wapiti and Bilbo pools produce oil from the Cardium Formation in areas that are just beyond our 3-D seismic data. Both pools are elongate in the NW-SE direction, roughly parallel to the fold axes illustrated in this paper. Although some component of structural trapping may be present at these locations, production from the Cardium at the Wapiti pool is

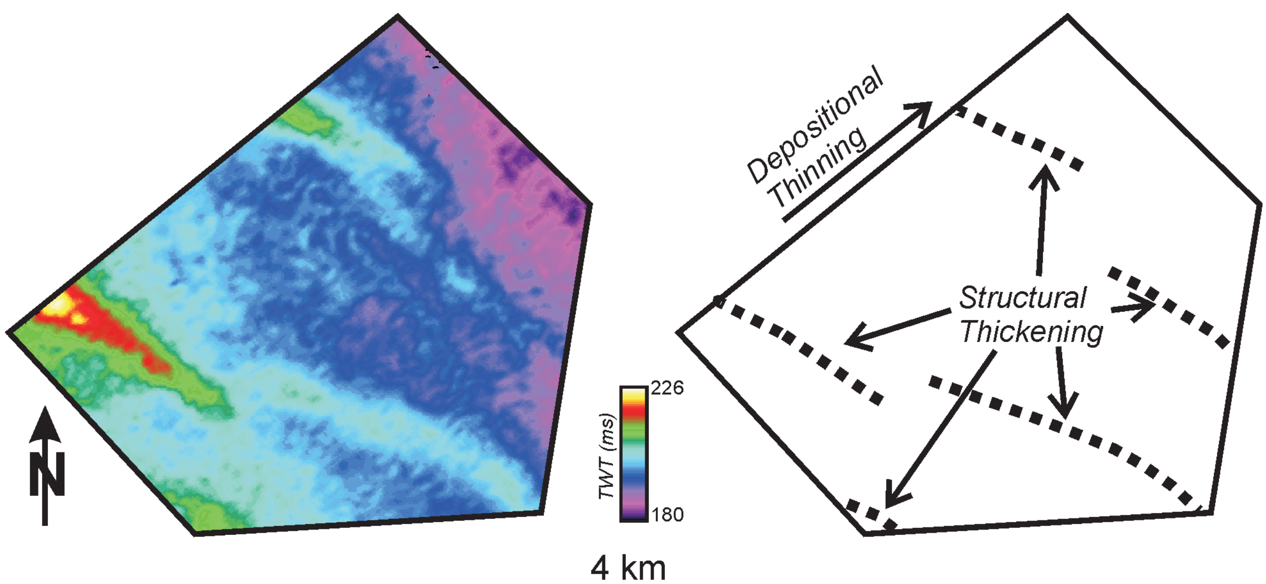


**Fig. 8.** Isochron map of the interval between the basal detachment surface in the lower Kaskapau, and the seismic horizon corresponding to the Kakwa Member of the Cardium Formation. The interval shows depositional thinning to the northeast, upon which are superimposed NW-SE trending, tectonically thickened intervals which indicate the location of fault-related folds.

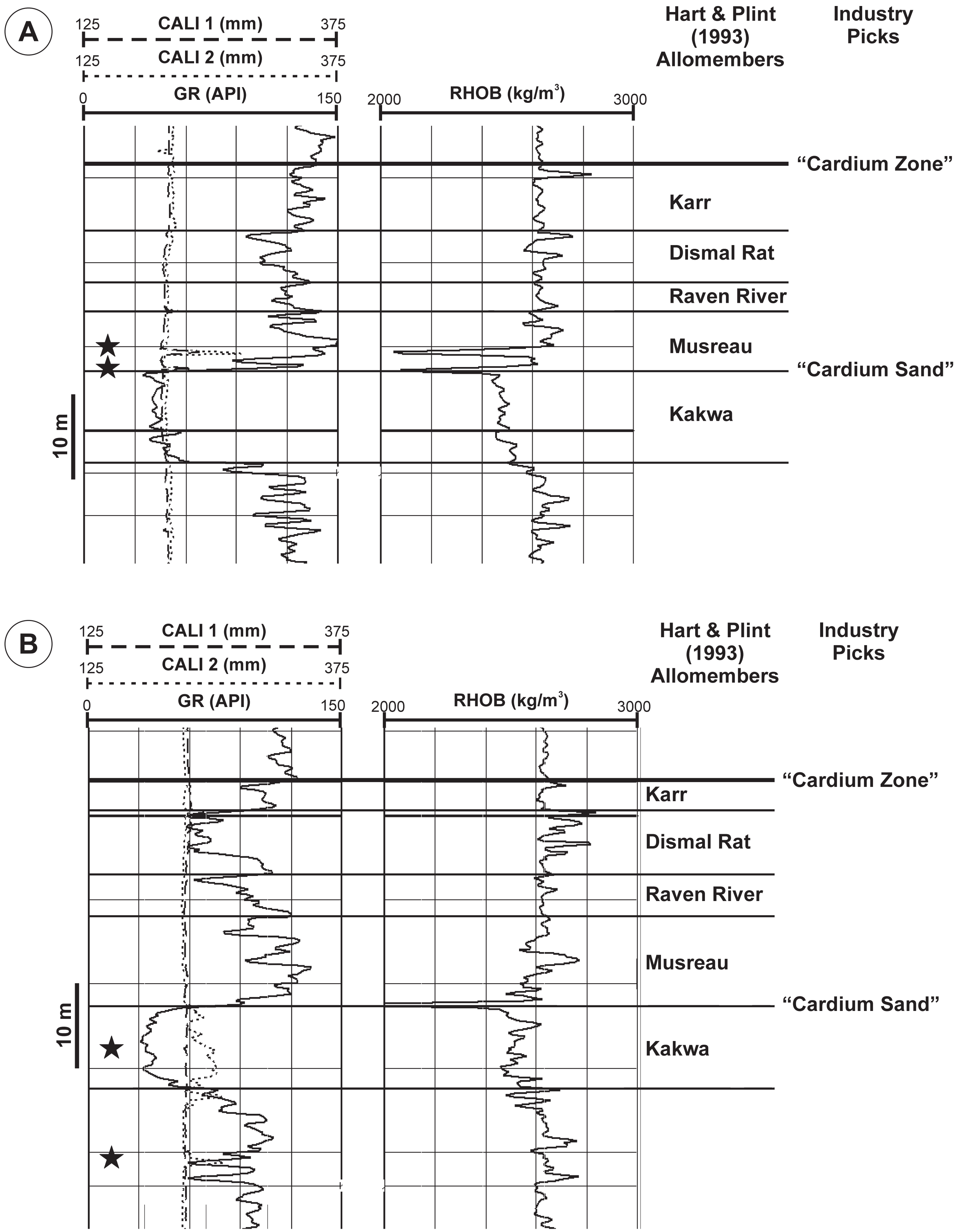


**Fig. 9.** Logs from two wells located approximately 3.6 km apart. A) Typical well from an unfolded area. It shows borehole enlargement and density "spikes" at two depths in the Musreau Member of the Cardium Formation (indicated by stars) that probably correspond to carbonaceous shales in the lower part of the non-marine Musreau Member (Hart and Plint, 2003). B) Well from the crest of a fault-related fold showing borehole enlargement in clean sandstones of the Kakwa Member and an underlying level (indicated by stars). This type of enlargement is typical of fractured, low-permeability brittle sandstones (e.g. Hart, 2006). Differences between the two caliper logs in this well indicate that the borehole is not circular at these depths.

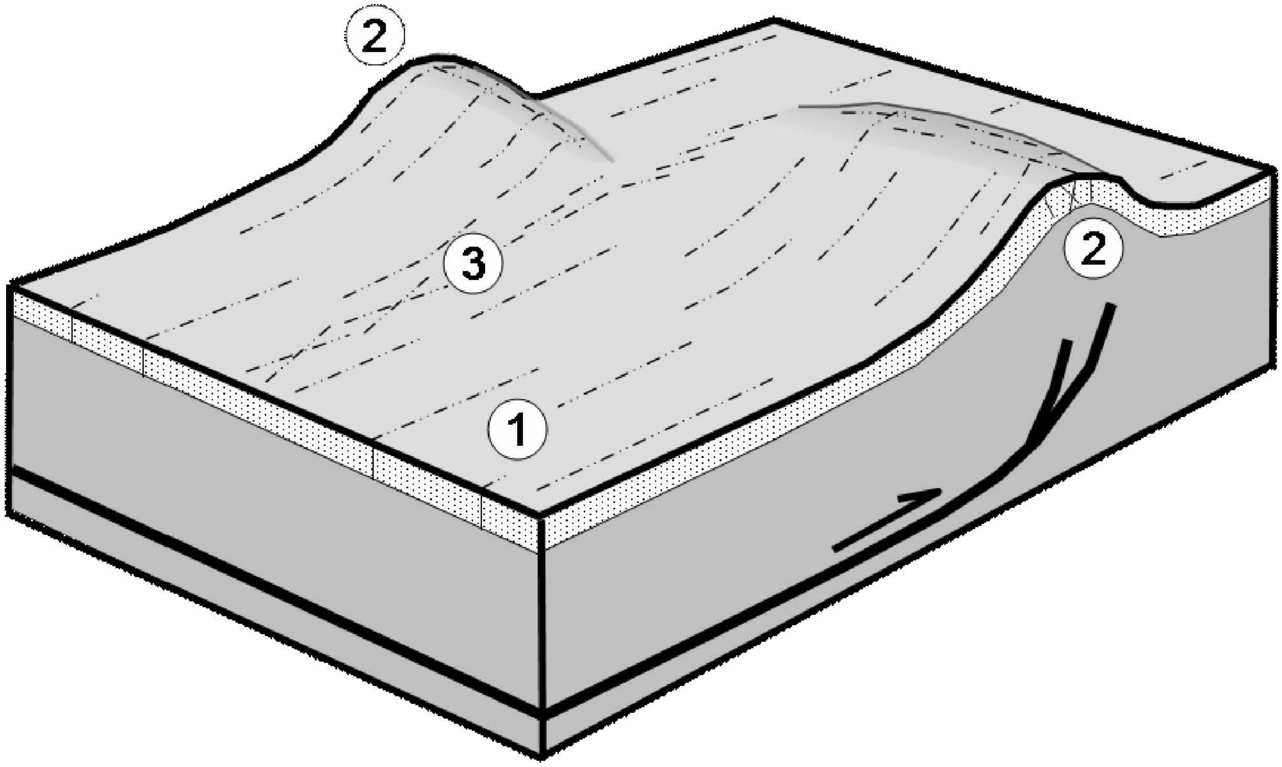


**Fig. 10.** Model of fracture development in a sandstone layer, such as the Kakwa Member of the Cardium Formation, associated with fault-related folds. Compression leads to "regional" (*sensu* Nelson, 2001) extension-mode fractures that are parallel to the shortening direction (fracture set 1). Extension on fold crests generates fracture set parallel to fold hinge lines (fracture set 2). Shear fractures, either as conjugate or *en echelon* sets, may form high-density zones in areas of incipient tear (fracture set 3). The presence of fracture sets 1 and 2 in the Cardium Formation is supported by core observations of McLellan (1988).

associated with relatively high-permeability rocks in the Kakwa Member. Completion reports suggest that production from the Bilbo pool is from a narrow, linear conglomerate body just below the E7 surface of the Cardium. The NW-SE orientation of the reservoir-quality rocks in both pools is parallel to the paleoshoreline orientation (Hart and Plint, 1993), indicating a primarily stratigraphic control on production. Although fractures may influence production in these areas, these two pools are not formally considered to be fractured tight-gas sandstones.

Well-based mapping led Murray et al. (1994) to interpret the presence of horsts and grabens with displacements of 15–20 metres at the level of the Cardium Formation in an area that overlaps our 3-D seismic volume. However, our seismic data provide no evidence to indicate the presence of normal faults with this amount of offset (these types of structures, if they existed, would be easily detectable), and the presence of large horsts and grabens is inconsistent with the abundant evidence for compressional tectonics. Instead, we suggest that the structures mapped by Murray et al. (1994) are the product of: a) folds at the Cardium level, like the ones illustrated herein; and b) inadequate stratigraphic analyses. Hart and Plint (1993) demonstrated the existence of minor syn-depositional faulting in the Kakwa Field, and Hart and Plint (1990) identified syndepositional normal faulting affecting the Cardium in areas farther west (i.e. towards the contemporaneous thrust belt). However, those studies documented significant changes in thickness of stratigraphic units within the Cardium Formation that are most reasonably related to syn-depositional erosion surfaces and to changes in progradational style. We suggest that those depositional trends could be misidentified as being structurally related if, like the study of Murray et al. (1994), the interpretation rests on lithostratigraphic correlations that focus only on the top of the Cardium ("Cardium Zone" of Industry) and the top of the Kakwa Sandstone ("Cardium Sand" of Industry).

This study has demonstrated the value of making detailed stratigraphic correlations in shale units. Exploration and production teams typically focus on details of stratigraphic correlations in reservoir-quality rocks (e.g. conglomerates and sandstones) where stratigraphic surfaces may compartmentalize reservoirs or otherwise act as barriers or baffles to fluid flow. The results presented here show that it is possible to interpret structural styles and map, at least at a reconnaissance level, structural elements such as thrust faults and detachment surfaces through detailed log correlations in non-reservoir shales. Conceivably, and at least locally, fractures in the Kaskapau Formation could be sufficiently dense and interconnected to make a viable shale-gas play.

## Conclusions

1) Three-dimensional seismic data and log-based analyses of the Kaskapau, Cardium and overlying formations in the Deep Basin area show that these rocks are deformed into northwest-southeast striking fault-related folds formed over splays that sole out into a mechanically weak shale layer in the lower part of the Kaskapau Formation. Faults rise stratigraphically through up to 300 m of Kaskapau strata, and spacing between fault-related folds varies between 5 and 8 km. The faults imaged in the 3-D seismic data extend in subsurface for approximately 50 km to the NE of the most easterly thrusts that reach the surface.

2) The seismic data show details of the 3-D geometry of the fault systems, including lateral and vertical splays, and fault overlap. Post-stack processing of the seismic data, including principal component filtering and the generation of coherency and volumetric dip volumes, significantly improved our ability to resolve fine-scale details of the fault systems.

3) Log and seismic observations were integrated with fracture kinematics and previously-published core and borehole breakout data to generate a model of fracture development. Extension-mode fractures oriented parallel to the shortening direction are expected throughout the area, but hinge-parallel fractures are likely to be present locally on fold crests. Zones of incipient tear at fault or fold tips may have elevated fracture density. This fracture model could be used to explore for, and develop, fractured low-permeability reservoirs in the Western Canada Sedimentary Basin and elsewhere.

4) A published interpretation of abundant normal faulting in the Cardium Formation in the Deep Basin is not supported by our seismic data.

## Acknowledgments

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