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GIS Compilation of Structural Elements in Northern Alberta, Release 1.0

Alberta Energy and Utilities Board
Alberta Geological Survey

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D. Pana, J. Waters, and M. Grobe

Alberta Geological Survey

March 2001

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Contents

Figures

Acknowledgments

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Abstract

Recent discoveries of kimberlites and polymetallic mineralization in the sedimentary succession of the Alberta Basin have increased interest in the mineral potential of Alberta. In order to promote exploration for and mining of non-energy minerals in Alberta, the Alberta Government is putting increased effort into providing basic geological information in support of the minerals industry.

Mineral exploration is critically related to knowledge of the location and age of fractures, which may have acted as pathways for mineralizing fluids and kimberlite emplacement. Therefore, a regional compilation of the known and interpreted subsurface and surface structural features and current knowledge of the tectonostratigraphic evolution in northern Alberta was conducted as a first step to aid government and industry in their efforts to better target possible occurrences of non-energy minerals in the province.

An innovative approach in both handling and delivering geological information has been taken in this compilation. Lineaments from various literature sources (digital and nondigital) were geospatially referenced, compiled digitally into ArcView® layers (i.e., shapefiles) and individually tagged with attribute data stored in a database.

This report provides an overview of the Late Proterozoic to Recent tectonostratigraphic evolution of northern Alberta, in order to facilitate understanding of the geological significance of the compiled structural features (accessible through ArcExplorer® on the enclosed CD-ROM).

The Phanerozoic geological evolution of northern Alberta is dominated by an east-northeast-trending geological subsurface structure, traditionally called the Peace River Arch (PRA). Several distinct phases of Phanerozoic tectonic evolution have been documented: 1) an Early to Middle Paleozoic arch phase, 2) a Carboniferous to Triassic embayment phase, and 3) a Jurassic to Cretaceous deep basin or downwarping phase.

Aspects that may be relevant for both energy and non-energy minerals are addressed, with particular emphasis on exploration for sediment-hosted mineral deposits within each tectonostratigraphic phase. Recommendations for further integrated studies, investigating the basement-sedimentary cover interactions, are made.

1 Introduction

1.1 Rationale

Committed to economic diversification, the Alberta Government promotes awareness of Alberta's opportunities for exploration and mining of non-energy minerals, such as base and precious metals, gemstones and industrial minerals, that are known to occur in the province. Estimates of the resource potential are based on an assessment of the current geological information. Recent government funding of an expanded Alberta Geological Survey (AGS) minerals program is intended to improve the province's geological knowledge base by increasing geological mapping, and conducting more thematic and, at selected locales, detailed studies.

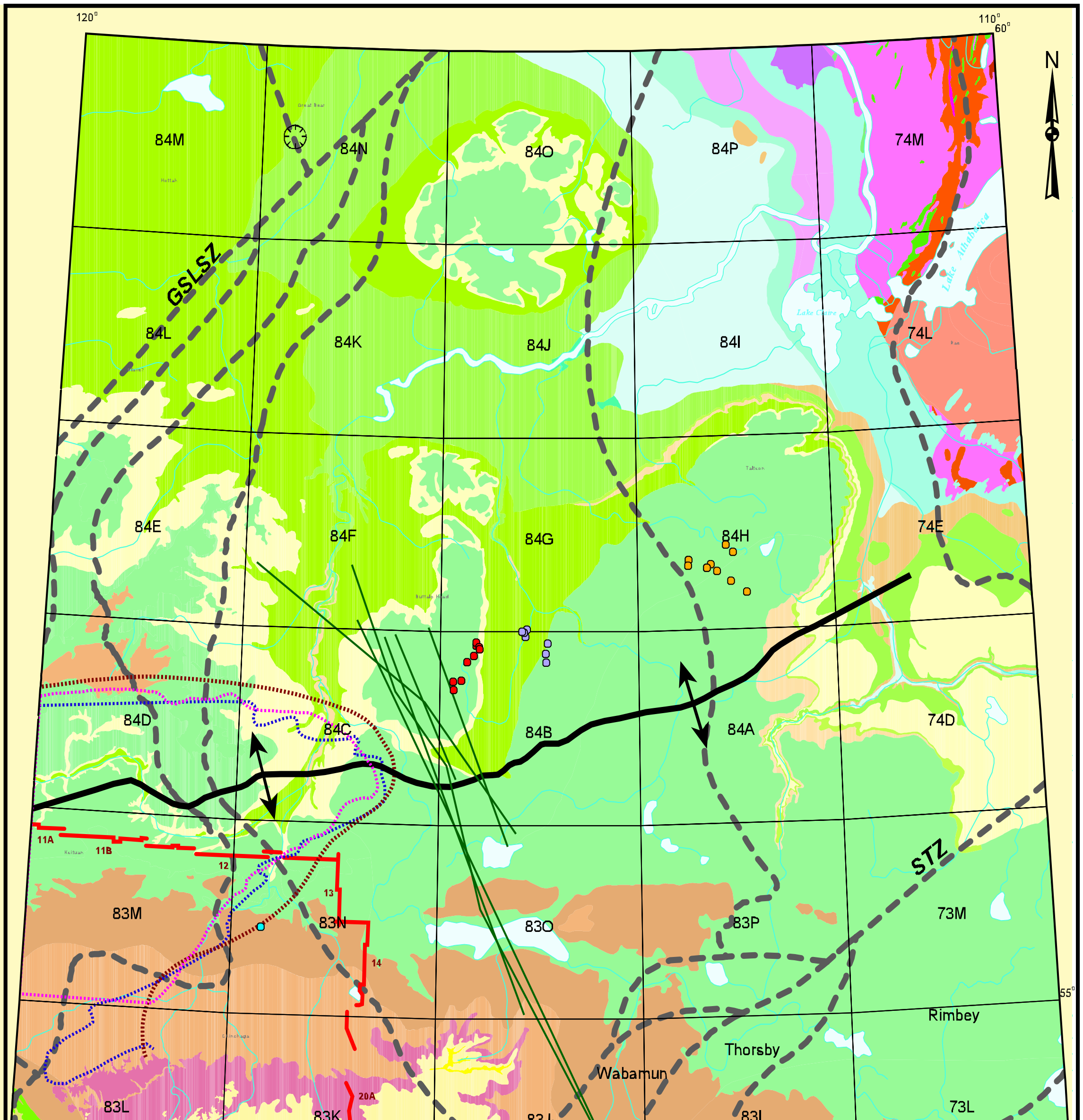
Exploration for a wide range of mineral deposits is critically dependent on knowledge of the location and age of fractures, which may have acted as pathways for mineralizing fluids and kimberlite emplacement. Although, regional structures and their controlling faults in northern Alberta have been reasonably well documented in the subsurface by the oil and gas industry, no detailed publicly available structural synthesis exists. The present compilation of subsurface and surface structural features in a state-of-the-art digital format is the first attempt to provide a tectonostratigraphic framework for metallic mineral and diamond exploration in northern Alberta. This work may inspire further comprehensive multidisciplinary studies of relationships between tectonics and mineral occurrences. The rewards can be expected to be more than just academic, because energy and non-energy minerals are still waiting to be discovered and produced in Alberta (O'Connell and Bell, 1990).

1.2 Area Under Consideration

The Phanerozoic geological evolution of northern Alberta is dominated by an east-northeast-trending geological structure within the Western Canada Sedimentary Basin (WCSB), traditionally called the Peace River Arch (PRA). Due to its influence on the location of oil and gas accumulations, the PRA has been a magnet for hydrocarbon exploration since its discovery in 1949 (DeMille, 1958). Its history of vertical movements, anomalous with respect to the basin as a whole, and the large number of associated faults are well documented. Therefore, the PRA constituted a logical choice for the attempt to investigate spatial and temporal relationships between fractures and the occurrence of kimberlite pipes and non-energy mineral concentrations in the Alberta plains.

During the course of data compilation, it became apparent that the definition of the PRA structure has ambiguous connotations and requires clarification. The PRA axis on the 1:1 000 000 scale Geological Map of Alberta (Hamilton et al., 1999) is represented as a sinuous, generally east-northeast-trending Phanerozoic antiform across northern Alberta (within the National Topographic System [NTS] 1:250 000 map areas 84D, C, B, H and 74E) (Figure 1). In fact, this region preserves several distinct phases of Phanerozoic tectonic evolution that include an Early to Middle Paleozoic arch phase, a Carboniferous to Triassic embayment phase and a Jurassic to Cretaceous deep-basin phase (e.g., Cant, 1988; Eaton et al., 1999). The arch phase was only recorded until the end of the Devonian in the western half of this region. The PRA outline is well defined by the depositional limits of the Elk Point and Beaverhill Lake groups, and by the Leduc fringing reef (Figure 1). Structural contours and isopach maps for Late Devonian and younger strata indicate that the PRA never extended east of longitude 116°W, being confined within NTS map areas 83M and N and 84C and D. It has been long realized that the history of the Peace River Arch cannot be determined until there is a much better understanding of the Phanerozoic regional tectonic framework (Cant, 1988). Choosing latitude 55°N as an arbitrary southern border, the compilation area was expanded to encompass all of northern Alberta because

- the PRA represents only a tectonic phase in al imited area of a much larger region of complex and



▬ Peace River Arch axis (previous interpretation)
Elk Point Formation zero edge
Beaverhill Lake Formation zero edge
Leduc Formation zero edge
Axis of Late Paleozoic depositional centre (see Mossop and Shetsen, 1994)
PRAISE seismic profile, with line number
Precambrian basement terrane boundary (Ross et al., 1994)
GSLSZ Great Slave Lake Shear Zone
STZ Snowbird Tectonic Zone
Steen River astrobleme

Kimberlites

- Legend
- Peerless Lake
- Buffalo Head Hills
- Mountain Lake

Note: Bedrock geology shown in background.
See Geological Map of Alberta (Hamilton et al., 1999)
for legend detail.

Index Map

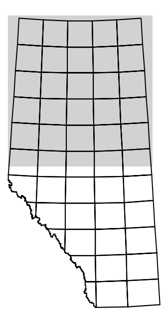


Figure 1

Peace River Arch Definition

50 0 50 100 km

1:3 500 000

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long-lasting tectonism;

- all known kimberlite clusters are situated outside the PRA *sensu stricto*;
- many of the sources used in the compilation include relevant structural elements at a scale larger than the PRA *sensu stricto*; and
- the origin of the PRA is likely related to major shear zones in the Alberta basement that may extend into the exposed Canadian Shield.

1.3 Data Sources

The literature search resulted in a list of references that includes approximately 300 titles of articles, theses and abstracts, arranged in chronological order from 1958 to 2000 (*see* accompanying CD-ROM). Due to its outstanding importance for the PRA compilation, the *Geological Atlas of the Western Canada Sedimentary Basin* (Mossop and Shetsen, 1994), published by the Alberta Geological Survey, is listed as the first reference on the CD-ROM.

Most of the articles were extracted from the GeoRef CD-ROM database of the American Geological Institute (updated to June 2000), using 'Peace River Arch' as the search criterion. In addition, the list includes recent journal articles not yet incorporated in the GeoRef database, and articles considered relevant to the topic that were not found using PRA as the search criterion. Pertinent assessment reports and press releases by mineral exploration companies exploring in northern Alberta are also included.

The reference list includes a total of 19 Ph.D., M.Sc. and B.Sc. theses. Stratigraphic and structural interpretations from some of them have been published (e.g., Trotter, 1989; Zelt, 1989), in which case preference was given to relevant structural features included in reviewed published articles. Some 33 titles in the reference list are conference abstracts and thus irrelevant for the graphical compilation. Many other articles, although meeting the PRA search criterion, contained detailed sedimentological studies that had little or no bearing on the project. The *Geological Atlas of the Western Canada Sedimentary Basin* (Mossop and Shetsen, 1994) constituted the main source for the compilation, as its chapters include synthesis articles of prior work and the data were already available in digital format.

1.4 Compilation Methods

The present compilation is an innovative approach in both handling and delivering geological information. Lineaments from various literature sources (digital and non-digital) were compiled digitally into ArcView® layers (i.e., shapefiles) and individually tagged with attribute data. The following three types of sources required variously complex conversion procedures:

Geological Atlas figures archived by AGS as digital polylines in ASCII format contain the coordinates (i.e., latitude and longitude) of each vertex along the feature polylines, and could be easily reassembled into georeferenced ArcInfo® coverage format of known projection and datum.

1. *Geological Atlas* figures archived by AGS as Windows metafiles (*.wmf) are digital graphic files (vector format) that contain registration (fiducial) marks such as latitude-longitude graticules, township grids, etc., but are not georeferenced (i.e., they were created in a graphics package using page coordinates, not map coordinates). The map projection of each figure was unknown and had to be determined by trial and error. Once the projection parameters were determined, the files were transformed from page coordinates to map coordinates, and then converted to one common projection (ten-degree Transverse Mercator projection).
2. Paper maps from journal articles (i.e., non-digital), containing small-scale or complex features, were scanned, digitized and then processed the same way as figures of Type 2. Relatively simple, large-

scale features were sketched in against, for example, a digital township grid where adequate georeferencing information was shown on the figure. The general procedure used to convert structural lineaments from various literature sources to ArcView® shapefile format is shown on Figure 2.

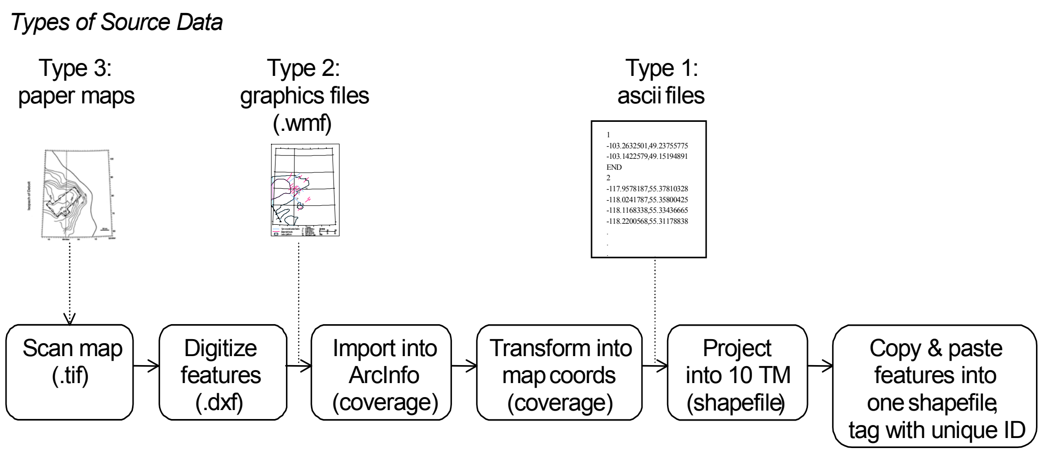


Figure 2. Lineament digitizing and georeferencing process.

Attribute information for each line feature, including unique identifier, reference, author's criteria for inferring a fault's existence (primary and secondary), formation(s) affected, fault type, dip direction of fault plane (where applicable/known) and AGS comments, were compiled into a Microsoft Access® database. Figure 3 shows the data compilation form.

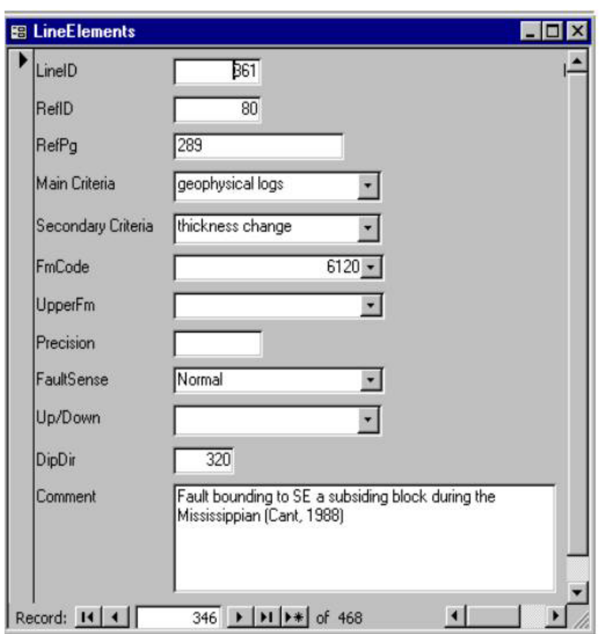

LineElements
LineID 361
RefID 80
RefPg 289
Main Criteria geophysical logs
Secondary Criteria thickness change
FmCode 6120
UpperFm
Precision
FaultSense Normal
Up/Down
DipDir 320
Comment Fault bounding to SE a subsiding block during the Mississippian (Cant, 1988)
Record: 346 of 468

Figure 3. Example of the data compilation form

Data from the Access database and the reference list were joined to the spatial elements in a shapefile, to enable queries in ArcView®. The final shapefiles that contain the compiled and inferred faults/lineaments, respectively, and their attributes are distributed on a CD-ROM with the free ArcExplorer® software supplied by Environmental Systems Research Institute (ESRI).

1.5 Accuracy, Precision and Use of the Digital Data

A geographic information system (GIS) frequently stores positional data at much higher numerical precision than the accuracy warranted by the original data, due to the fact that a computer can store many more digits than are significant (Burrough, 1988). This is especially true for natural resource data. For example, where a geological contact may be mapped to an accuracy of ±10 m on the ground, its UTM coordinates will be stored in the GIS in double precision in tenths or even hundredths of a metre (e.g., a vertex on the polyline might be stored in the computer as 5 437 753.5 m North, 569 343.34 m East). This high precision may be improperly perceived as extremely high accuracy, which may lead to potential misuse of data. It is important, therefore, to appreciate the limitations of the data/GIS features with inherent high *precision* but low to medium *accuracy*.

A typical figure in a journal article may show the northern half of the province of Alberta at a scale of 1:5 000 000. At this scale, a line 0.2 mm wide on the map covers a swath 1 km wide on the ground; a 0.5 mm line would be 2.5 km wide on the ground. Thus, using conventional drafting techniques, the positional accuracy of geological features is low on small-scale maps. Conversion of these elements into digital format may result in further degradation of their positional accuracy.

It is estimated that in this compilation, lineaments have been located to within ±2 km of the original intent of the authors (Appendix 1); however, those authors may have located features with no greater accuracy. For example, placement of a fault on a map may be based on interpolation from sparse data (e.g., logs from oil and gas wells spaced 1 km or more apart). Users should also keep in mind that 'faults', while represented as lines on a map, are frequently more zonal (or polygonal) in nature. A fault plotted on a map as a line may in fact be a shear zone and/or fault zone on the order of several kilometres wide. As a result of the inherent low spatial accuracy of typical geological data, we estimate that the lineaments captured in this compilation are positioned with an accuracy of about the same order of magnitude as that of the original source materials.

Many factors affect the positional accuracy and precision of the compiled structural features. An example of appropriate use of the Peace River Arch compilation data might be that, where a fault or an intersection of faults can be inferred to have economic potential, this should be regarded as a 'zone of interest' for further more focused investigation, not as an immediate drilling target.

1.6 Deliverables

1.6.1 Interactive Digital Database

The digital format provides a flexible structure capable of incorporating additional information and allows various options for data selection based on such query criteria as location, timing, orientation and authorship. The product is envisioned as an open, flexible structure allowing for continuous updates and refinements. Time constraints required careful selection and prioritization of sources to be converted to GIS format. Consequently, the user should be aware that other structures have been described in the geological literature but have not been yet included in the database. More importantly, it must be realized that the density of the structural features does not necessarily reflect the structural complexity of a certain area, but rather the present level of knowledge. The density of wells and published geological information in northern Alberta is highly uneven. Although well coverage in northwestern Alberta is quite good due to past and present hydrocarbon exploration, poor well coverage and the lack of published seismic data severely limit meaningful structural mapping across the WCSB toward the northeastern part of the province. Nevertheless, the compilers are confident that all structural features of major significance in northern Alberta, documented or inferred so far in the open literature, have been captured.

Compiled structural features are available on the CD-ROM in a user-friendly ArcExplorer® format. At this stage the digital compilation includes a total of 518 faults captured from published isopach and structural maps for various stratigraphic intervals in the subsurface of northern Alberta, (shown on Figures 4 and 5). In addition, the compilation includes subsurface and surface lineaments tentatively interpreted by the authors to be structurally controlled, specifically:

- a total of 294 lineaments derived from facies and/or thickness changes depicted on maps in the *Geological Atlas of the Western Canada Sedimentary Basin* (Mossop and Shetson, 1994), shown on Figure 6; and
- a large number of surface lineaments derived from the drainage pattern and added to the lineaments interpreted from satellite images in northern Alberta by Misra et al. (1991), both shown on Figure 7.

The current compilation may require more focused stratigraphic and structural analysis in selected areas and/or stratigraphic intervals in order to delineate the extension of previously known faults or discover new faults. The benefit of the current compilation in GIS form is that new data can be easily integrated in the existing digital database.

1.6.2 Overview of the Geology of Northern Alberta

This report provides a brief overview of the tectonostratigraphic evolution of northern Alberta in order to facilitate understanding of the geological significance of the compiled structural features. The stratigraphic record in northern Alberta, and the PRA region in particular, indicates several tectonic phases that resulted in distinct structures and/or reactivation of older structures (see Cant, 1988; Ross et al., 1991; O'Connell, 1994). Largely dependent on source quality, the structures that are tabulated in this compilation have been assigned to a certain tectonostratigraphic event. For illustration purposes, structural features are grouped in tectonostratigraphic divisions or 'slices' (e.g., Figures 4, 5 and 7). In order to guide the user in understanding and interpreting the illustrations in the digital database, the following chapters will briefly introduce the basic geological context of the subject tectonostratigraphic 'slice' and provide references to the essential literature.

The bounding surfaces between divisions are set either at major unconformities or at stratigraphically significant and widespread marker horizons. For example, the Wabamun–Banff unconformity, which is easily picked on seismic sections, marks the transition from a time of relative tectonic quiescence to one of active tectonism. Consequently, the top of the Wabamun Formation provides an excellent datum for stratigraphic correlation and inferences of pre–Late Devonian structural disturbance.

Chapter 2 introduces the 'Peace River Arch' structural anomaly of the Western Canada Sedimentary Basin. Chapter 3 presents the hypothetical Early Proterozoic phase of terrane accretion, emphasizing the transcrustal character of some tectonic discontinuities. Chapters 4 to 6 deal with the Paleozoic uplift and collapse of the Peace River Arch and the development of a deep Mesozoic basin across northern Alberta. Chapter 7 discusses lineaments interpreted from airphotos and satellite images, and their possible structural control. The final chapter addresses issues that may be relevant for both energy and non-energy minerals, with particular emphasis on exploration for sediment-hosted mineral deposits within each tectonostratigraphic division or 'slice'.

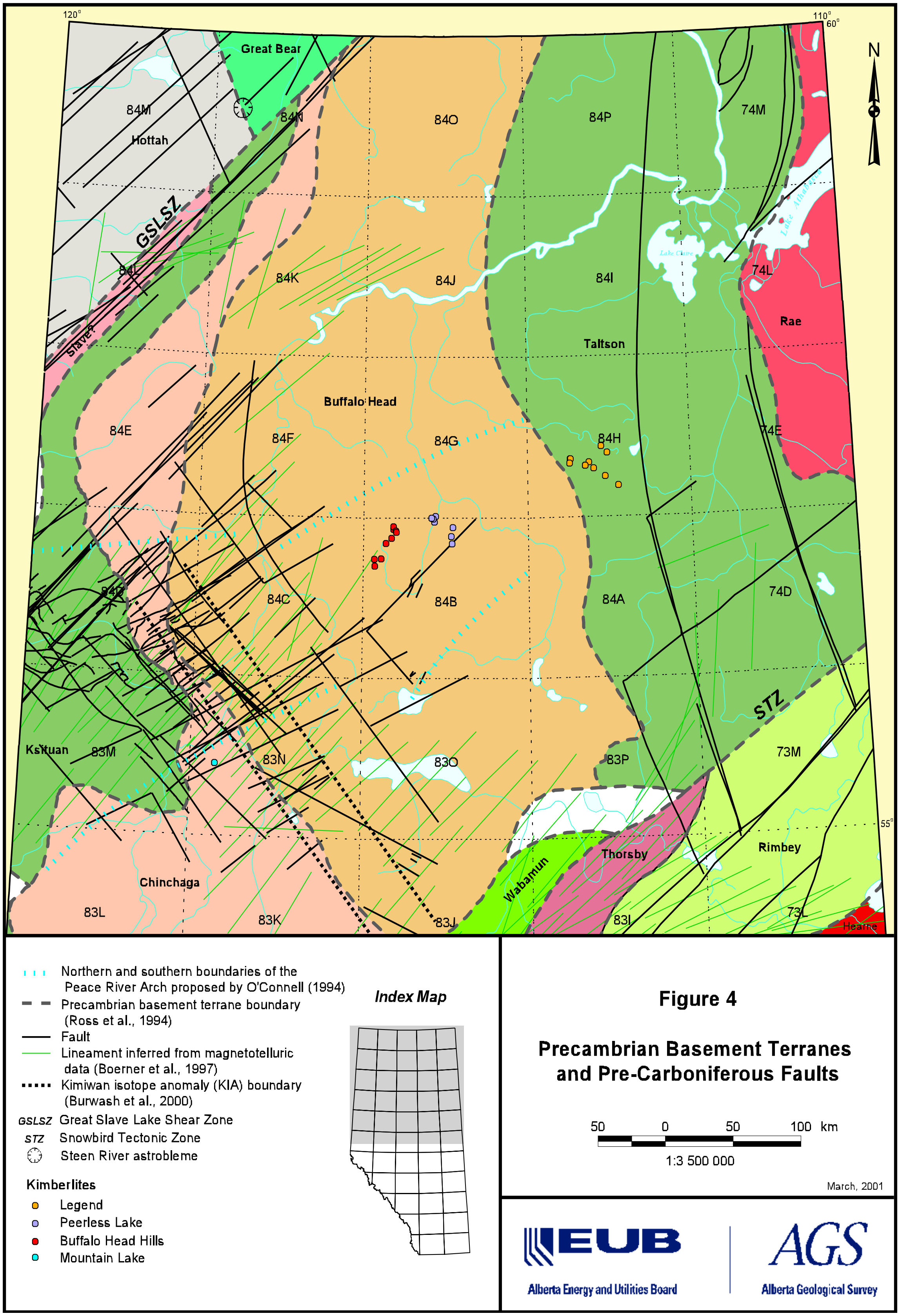
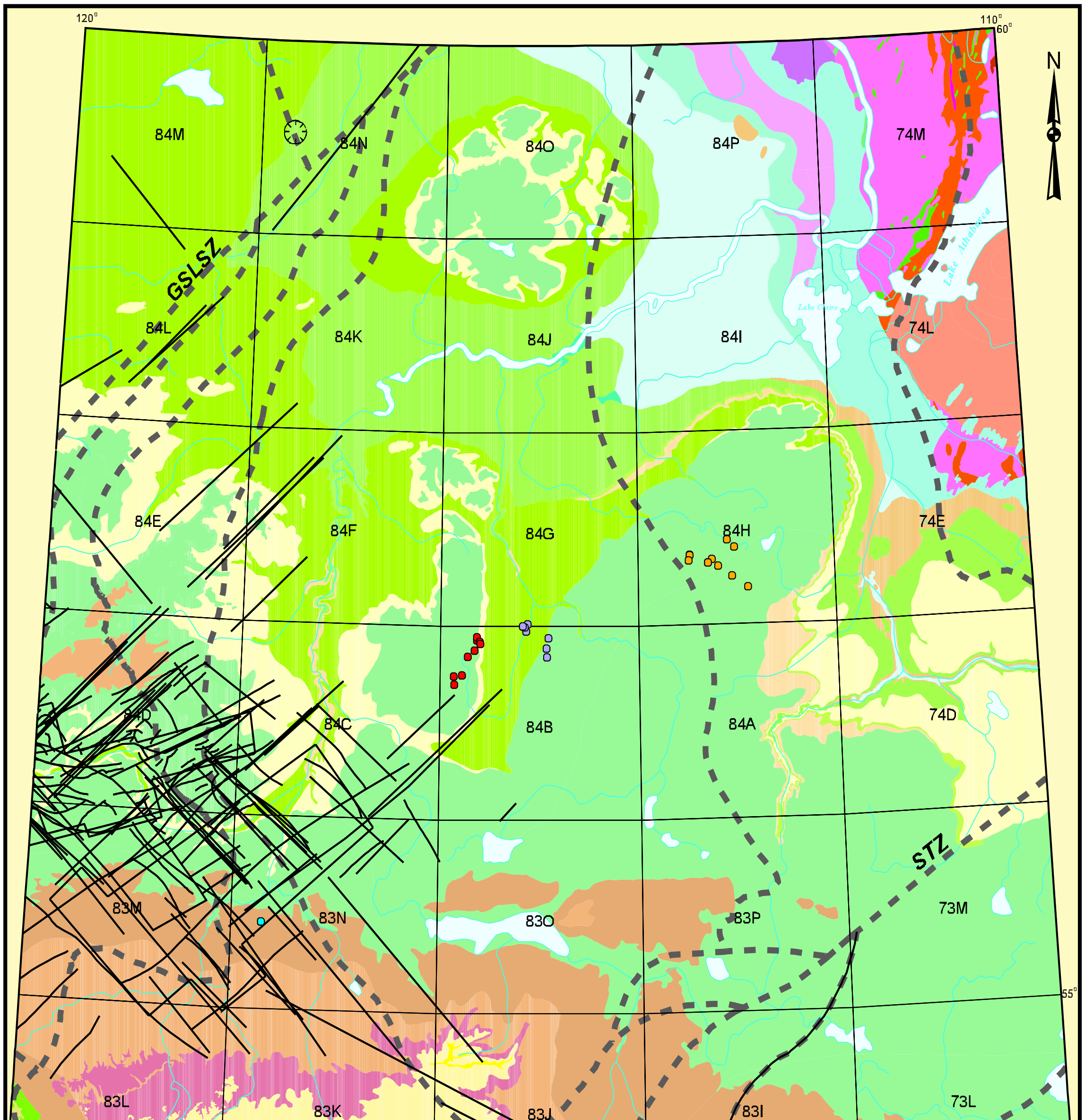


Figure 4

Precambrian Basement Terranes and Pre-Carboniferous Faults

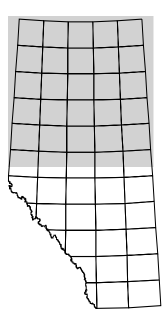


— Fault
- - Precambrian basement terrane boundary (Ross et al., 1994)
GSLSZ Great Slave Lake Shear Zone
STZ Snowbird Tectonic Zone
Steen River astrobleme

Kimberlites

- Legend
- Peerless Lake
- Buffalo Head Hills
- Mountain Lake

Index Map



Note: Bedrock geology shown in background.
See Geological Map of Alberta (Hamilton et al., 1999)
for legend detail.

Figure 5

Faults Related to the Peace River Embayment and Downwarping Tectonic Phases

50 0 50 100 km

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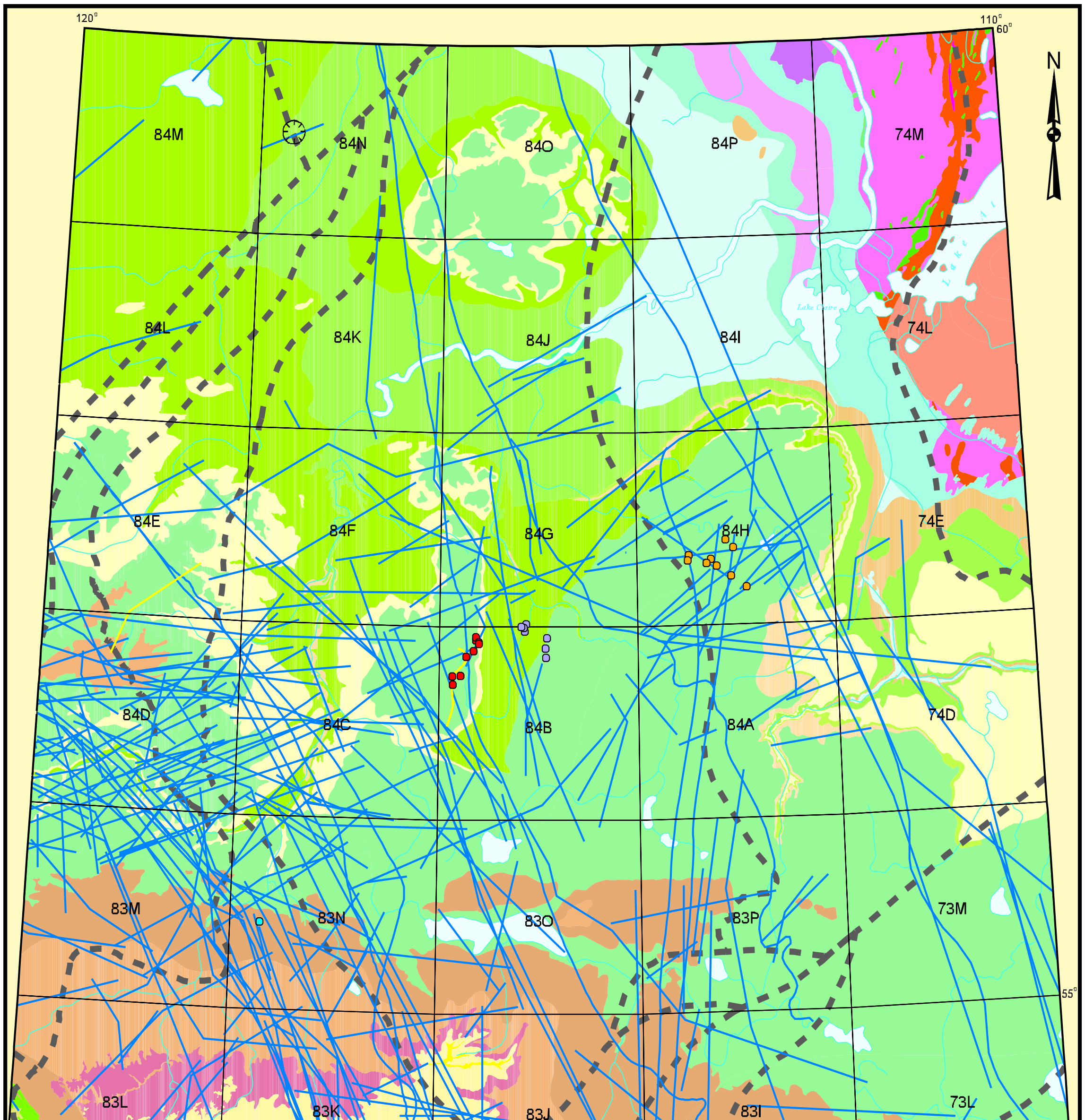

Inferred fault and/or structural lineament
Precambrian basement terrane boundary (Ross et al., 1994)
GSLSZ Great Slave Lake Shear Zone
STZ Snowbird Tectonic Zone
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Index Map

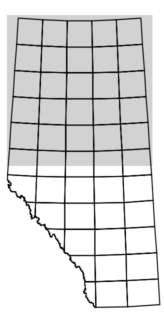

Figure 6

Possibly Structurally Controlled Lineaments of Facies and/or Thickness Change

50 0 50 100 km

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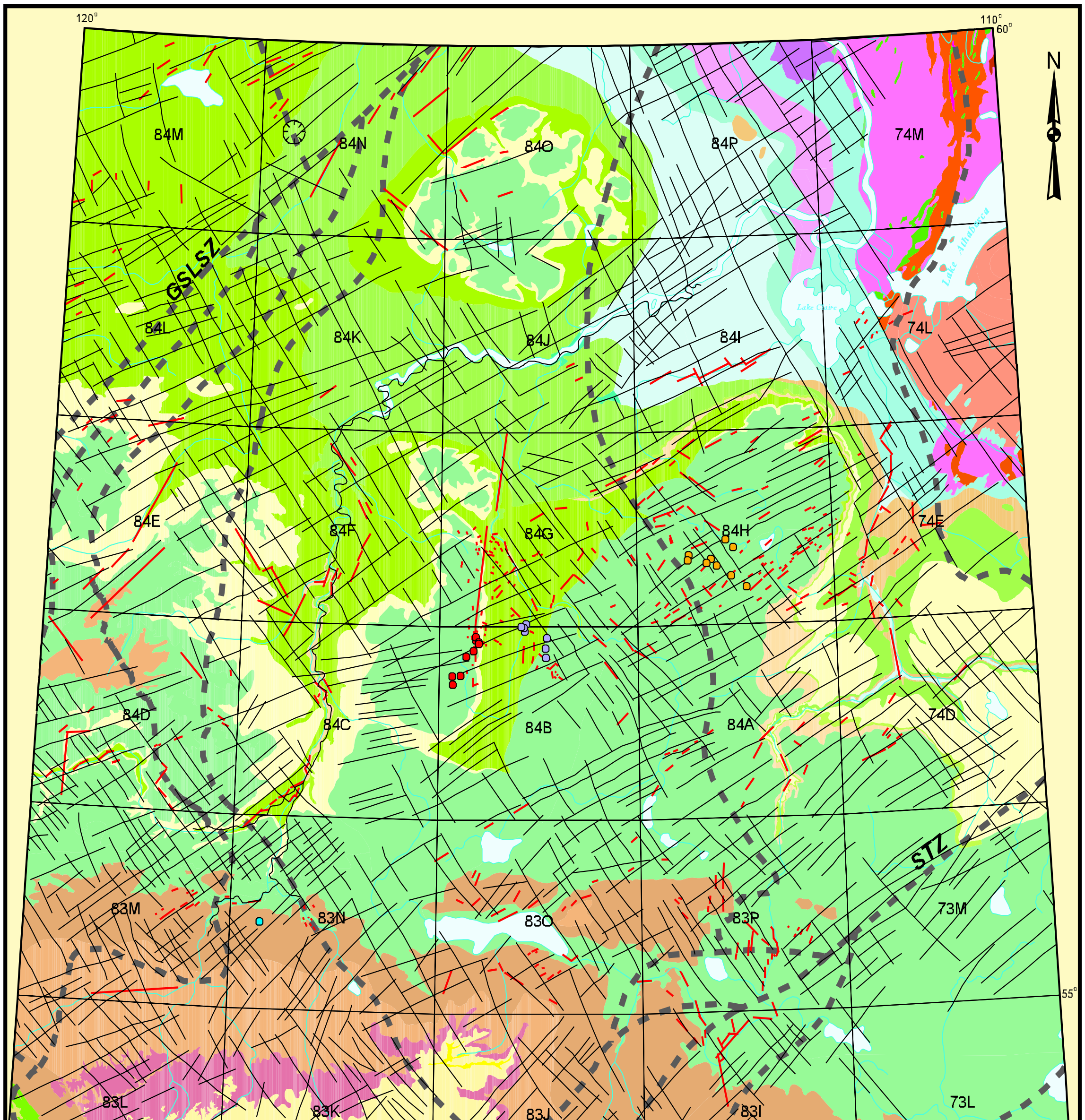

Surface lineament, visible in satellite imagery (Misra, 1991)
Selected DEM lineaments
Precambrian basement terrane boundary (Ross et al., 1994)
GSLSZ Great Slave Lake Shear Zone
STZ Snowbird Tectonic Zone
Steen River astrobleme

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- Legend
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Note: Bedrock geology shown in background.
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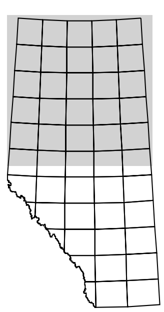

Figure 7

Structurally Controlled Surface Lineaments Inferred from Satellite Imagery and DEM

50 0 50 100 km

1:3 500 000

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2 General Architecture of the Western Canada Sedimentary Basin and the Peace River Arch Structural Anomaly

2.1 Western Canada Sedimentary Basin

The major sedimentary sequences of the Western Canada Sedimentary Basin (WCSB) comprise two fundamentally different tectonosedimentary environments: Late Proterozoic to Middle Jurassic passive continental margin and Middle Jurassic to Oligocene foreland basin. Most of the Western Canada Sedimentary Basin (WCSB) is underlain by pre 1.8 Ga, variably retrogressed high-grade metamorphic rocks and associated igneous rocks (e.g., Ross et al., 1994) and, in a limited area of northeastern Alberta, by clastic strata of the Athabasca Group with inferred ages of 1.75 to 1.3 (Wilson, 1985, Ramaekers, personal communication, 2001). In this report, pre-Late Proterozoic "crystalline" and sedimentary rocks will be referred to as the "Precambrian basement" or simply "basement" of the much younger WCSB.

The passive margin or 'miogeoclinal stage' was initiated during the Late Proterozoic. Transgressive onlap onto the North American cratonic platform from Middle Cambrian to Middle Jurassic resulted in the deposition of dominantly shallow-water carbonate and evaporite successions with Cambrian clastic rock at the base. During the Columbian (Middle Jurassic to Early Cretaceous) and Laramide (Late Cretaceous to Paleogene) orogenies, tectonic loading was driven by eastward advancement of the Cordilleran deformation front. The WCSB developed into a foreland basin as a result of isostatic flexure and depression of the North American continental lithosphere. Erosion of the evolving Cordillera from the Middle Jurassic to about the Oligocene filled the foreland basin with clastic detritus (e.g., Cant, 1988; Leckie, 1986, 1989).

Long considered to be a stable Atlantic-type trailing margin, the ancestral western continental shelf of North America has a history that appears to be punctuated by several periods of extension and rifting (Cecile et al., 1997). Northeast-trending linear features, interpreted to represent ancestral strike-slip or transfer faults, separate at least six major block segments with independent tectonic histories. The Alberta block, bordered to the north by the Hay River–Great Slave Lake tectonic zone and to the south by the Moyie–Dibble Creek faults near the Alberta–Montana border, is divided into the Peace River and Southern Prairies sub-blocks along the Rimbey Magnetic and Snowbird Tectonic zones (Cecile et al., 1997). Three main tectonic phases, which are recorded in the adjacent Cordilleran orogen, influenced deposition in the Alberta Basin (e.g., Price, 1994; Ross and Eaton, 1999). The first phase corresponds to the Late Proterozoic to early Paleozoic extension and continental break-up, and is recorded by passive-margin deposition up to the Late Silurian. The second phase corresponds to several loosely constrained tectonic environments of the Devonian to Early Jurassic, including the Devonian–Early Carboniferous development and collapse of the Peace River Arch contemporaneous with Antler Orogeny. Beginning with the deposition of the Fernie Group turbidites, the third phase is represented by Jurassic to Eocene foreland-basin development during formation of the Cordilleran fold-and-thrust belt, followed by isostatic recovery and erosion throughout the Tertiary.

2.2 'Peace River Arch' Structural Anomaly

A roughly east-northeast-striking zone of long-lasting structural disturbance cuts across the WCSB in northwestern Alberta. This zone recorded the longest history of tectonic activity within the WCSB, with controlling basement faults active over an extended period of time or reactivated episodically through time. Conjugate northeast- and northwest-trending faults control the basement topography and subsequent Phanerozoic sedimentation patterns in the westernmost part of this area (Cant, 1988; Figure 4). The

Phanerozoic tectonic evolution of the region consists of three distinct phases (e.g., Cant, 1988; O'Connell et al., 1990).

Phase I is represented by the pre-Late Devonian development (or preservation; see section 4.1) of the topographically high PRA on the WCSB passive margin of proto–North America. Regional stratigraphic patterns and provenance indicators in Devonian and older siliciclastic units indicate that the PRA formed a topographic high throughout the early Paleozoic and contributed clastic sediments that were deposited within and along the Cordilleran miogeocline (McMechan, 1990; Norford, 1990; Ross et al., 1993; Gehrels et al., 1995; Ross and Villeneuve, 1997; Gehrels and Ross, 1998). Throughout this initial phase, the PRA was part of an intersecting network of cratonic arches, temporally and spatially linked with intervening intracratonic basins, that caused a broad segmentation and physiographic subdivision of the epeirogenic sedimentary cover of the North American craton (Porter et al., 1982). The PRA was an asymmetrical structure that reached a maximum width of 140 km at the sixth meridian (118ºW) and a maximum elevation of about 1000 m above the surrounding WCSB, and had a steeply dipping northern flank and a more gently dipping southern slope (e.g., O'Connell et al., 1990). During this phase, total deposition immediately to the north of the arch was several hundred metres thicker than it was to the south.

Phase II of the PRA evolution started with Early Carboniferous collapse and reversal of its topographic expression from a highland arch to an embayment (Peace River Embayment [PRE]), with enhanced subsidence relative to the WCSB as a whole persisting through the Triassic (e.g., Beaumont et al*.,* 1993). During the Early Carboniferous, an elongated zone of maximum subsidence formed along the northern margin of the Devonian PRA. During the Late Carboniferous, tectonic inversion of the Devonian PRA resulted in localized subsidence along the former axis of the arch within the Dawson Creek Graben Complex (DCGC), a system of grabens comprising the Fort St. John Graben, the principal seaward opening in the west, and the Hines Creek, Whitelaw and Cindy satellite grabens in the east. Formation of these grabens during deposition of the late Carboniferous Stoddart Group was apparently not accompanied by igneous activity, and was followed by more widespread subsidence during the Permian and Triassic (Barclay et al., 1990*).*

Phase III of PRA evolution was characterized by enhanced Mesozoic subsidence within the PRE and was coeval with the initiation and evolution of thrust loading (Columbian and Laramide orogenies) in the Cordilleran orogen (O'Connell et al., 1990).

2.3 Tectonic Models for the Peace River Arch–Peace River Embayment Evolution

The underlying tectonic cause(s) for the Peace River Arch-Embayment have remained an enigma for over half a century. Potential-field (aeromagnetic and gravity) studies and crustal-refraction experiments have failed to identify potentially causative anomalous bodies within either the crust or mantle (e.g., Zelt and Ellis, 1989; Stephenson et al*.,* 1989, Ross, 1990). The PRA was considered partly coincident and therefore genetically linked to a Moho uplift (Stephenson et al., 1989; Zelt, 1989). However, recent Lithoprobe reflection data do not support this interpretation (Ross, personal communication, 2001). Various mechanisms have been proposed for the origin and development of the PRA, interpreting it either as a passive or an active structure:

1. Potassium enrichment within the crust in the Peace River region caused simple isostatic uplift of basement rocks (Burwash and Krupička, 1969, 1970; Burwash et al., 1973).
2. Continental drift over a stationary mantle hot spot drove metasomatism and crustal uplift (Stelck et al., 1978).

3. Isostatic re-equilibration occurred as a consequence of differential loading with sedimentary rocks of a stable platform. Flexural deformation of the lithosphere may have induced stresses in the upper crust, resulting in faulting and folding of non-orogenic tectonic style (Walcott, 1970).
4. Flexural interaction occurred between the foreland and the cratonic basins. The arch would have formed in the interference zone of their peripheral bulges (e.g., Quinlan and Beaumont, 1984; Beaumont et al., 1993).
5. Uplift occurred over an incipient rift that extended from the western continental margin into the proto–North American continent along Precambrian faults (Cant, 1988).
6. Basement highs occurred along the continental extension of an oceanic fracture zone transverse to the proto–North American passive margin (oceanic transform model; O'Connell et al., 1990).
7. The PRA/PRE formed as a result of anomalous geodynamic conditions (i.e., the extension of an upper plate-lower plate transfer zone within the Cordilleran miogeocline) in an area of unusual crustal properties represented by the presence of the Winigami Reflection Sequence beneath the central and eastern parts of the Arch (Eaton et al., 1999).

Although none of the hypotheses fully explains PRA evolution, each draws attention to important tectonic processes that may have contributed to the rise and fall of the PRA. The most recent hypothesis (7), a variation on the oceanic transform model (6), attempts to integrate the initially passive arch structure into a more regional picture, and points to a combination of factors that may have favoured the localization and complex evolution of the PRA. It is therefore emphasized that the PRA is located just inboard (toward the craton) from a transfer zone where the geometry of the miogeocline changes from upper plate in the south to lower plate in the north (Cecile et al., 1997). The approximate northern limit of this transfer zone is located where the Hay River Fault intersects the Cordillera. Transfer zones that accommodate a change in passive-margin polarity and salient reentrant geometries represent probable areas of locally anomalous intraplate stresses. The early evolution of the PRA may reflect stress buildups and elastic deflections generated due to both the presence of the Winagami Reflection Sequence (WRS), and the break-up and formation of the paleo-Pacific margin in the Canadian Cordillera (Ross and Eaton, 1997; Eaton et al., 1999).

3 Early Proterozoic Tectonism and Related Structures

The oldest tectonism in northern Alberta is recorded by the Precambrian crystalline basement of the WCSB. Although progressively attenuated by the increasing thickness of Phanerozoic sedimentary rocks to the west, the aeromagnetic signature of tectonic domains exposed in the Canadian Shield can be traced in the Alberta subcrop all the way to the Southern Rocky Mountain Trench (e.g., Hoffman, 1988; Ross et al., 1991, Pilkington et al., 2000). Based on the overall aeromagnetic signature and internal 'grain', and the U-Pb geochronology of basement drill core recovered during hydrocarbon exploration, the buried basement of northern Alberta has been subdivided into four distinct, predominantly north-trending curvilinear crustal domains (e.g., Ross et al., 1989, 1991; Villeneuve et al., 1991, 1993) (Figure 4). From west to east, the basement subdivisions are the Ksituan, Chinchaga, Buffalo Head and Taltson domains. Two major transcurrent shear zones that are exposed in the Canadian Shield, the Great Slave Lake Shear Zone and the Snowbird Tectonic Zone, can be confidently mapped in the Alberta subsurface, based on truncation of potential-field fabric elements. In the northwestern corner of Alberta, Precambrian basement rocks are assigned to the Hottah and Great Bear domains north of the Great Slave Lake Shear Zone, and a narrow sliver of the Archean Slave Province is interpreted along the southern side of the shear zone (Ross et al., 1994). In the northeastern corner of Alberta, basement rocks are assigned to the Archean Rae Province (Figure 4).

3.1 Precollisional Crustal Discontinuities

Crystalline basement rocks of northern Alberta comprise Early Proterozoic igneous, meta-igneous and, less commonly, metasedimentary rocks (e.g., Ross et al., 1991; Villeneuve et al., 1991, 1993; Burwash et al., 2000). The predominance of igneous rocks in the Ksituan and Taltson domains was interpreted as evidence of evolution in a subduction-arc system, analogous to modern continental arc systems (e.g., Hoffman, 1988; Thériault and Ross, 1991). The arcuate pattern of magnetic anomalies and well-developed east-dipping reflection panels are interpreted to be the result of ductile deformation in the upper and middle crust (Eaton et al., 1999).

The configuration of the northern Alberta basement terranes is thought to have resulted from the Early Proterozoic assembly of Laurentia by lateral accretion of formerly disparate slivers of continental-arc crust to a cluster of Archean provinces. The continental-scale model for the assembly of western Laurentia includes subduction under the Rae Province and development of the Thelon–Taltson magmatic arc, collision between the Slave and Rae provinces, and indentation of the Rae Province by the Slave Province, partly accommodated by the right-lateral Great Slave Lake Shear Zone (e.g., Gibb and Thomas, 1977; Gibb, 1978; Hoffman, 1988; McDonough et al., 2000). South of the indentation zone, a crustal wedge bounded by the Great Slave Lake and Rutledge–Allen shear zones was extruded southwestward.

A more detailed model at the scale of northern Alberta postulated the existence of a Buffalo Head–Chinchaga microcontinent of composite Archean–Early Proterozoic crust, separated from Archean cratons by oceanic crust. Bilateral subduction to the west under the Nova (Slave?) continental fragment and to the east under the Archean Rae continental fragment, resulted in the formation of the Ksituan and Taltson magmatic arcs, respectively (e.g., Thériault and Ross, 1991). The model implies that the curvilinear Ksituan–Chinchaga and Buffalo Head–Taltson contacts are cryptic suture zones transposed by ductile shear zones with a potentially large strike-slip component.

Variously metamorphosed igneous rocks from the Precambrian basement of northern Alberta have yielded U-Pb zircon ages between 2324 and 1900 Ma, whereas Sm-Nd analyses yielded T_{DM} model ages ranging from 3.0 to 2.4 Ga (Thériault and Ross, 1991; Villeneuve et al., 1991, 1993). Late Archean T_{DM} model ages older than the U-Pb emplacement ages suggest the presence of Archean crust in the protolith of the Early Proterozoic rocks, thus implying that crust-mantle differentiation occurred during the Archean. Residual depleted and cold Archean mantle that usually coincides with regions of diamondiferous kimberlitic-lamproitic igneous activity may be present beneath western Canada in spite of substantial modification during Proterozoic orogenesis (Ross et al., 1993).

K-Ar data from basement rocks in northern Alberta range from approximately 2300 to 1400 Ma in the Buffalo Head Terrane and are as young as ca. 1000 Ma near Fort St. John, in the slice of the Archean Slave Terrane (Burwash et al., 1994). These anomalously young dates indicate Ar loss due to subsequent heating and/or tectonism, and have limited geological significance. Two $^{40}Ar/^{39}Ar$ plateau ages, 1934 ± 12 Ma on hornblende from the southern part of the Chinchaga Domain and 1882 ± 12 Ma on muscovite from the Buffalo Head Domain, suggest simultaneous uplift and cooling following Early Proterozoic (ca. 2.0–1.9 Ga) terrane accretion (Plint and Ross, 1993). Rb-Sr ages on muscovite (Henderson et al, 1990) and an $^{40}Ar/^{39}Ar$ plateau age of 1722 ± 11 Ma on muscovite from a quartzofeldspathic mylonite within the sliver of Archean gneiss immediately south of the subsurface magnetic expression of the Great Slave Lake Shear Zone were interpreted to record cooling associated with uplift and continental indentation (Plint and Ross, 1993).

The available data on the unexposed basement of northern Alberta represent a fraction of what is generally used in tectonic syntheses of exposed basement of similar extent. Consequently, the lateral accretion model in northern Alberta is highly hypothetical and the details are still tenuous. Conflicting interpretations exist for the nature and location of domain boundaries, such as the Buffalo Head–Taltson contact (Ross et al., 1994 vs. Burwash et al., 1994), and for the tectonic significance of isotopic data. The Nd, Pb and O isotope data indicate that the Taltson granitoids formed in response to crustal thickening, either in an intracontinental setting, well inboard from any plate margin (Chacko et al., 2000), or in a collisional zone (Ross, personal communication, 2001).

3.2 Syncollisional Transcrustal Discontinuities

The **Great Slave Lake Shear Zone (GSLSZ)** is a northeast-trending dextral mylonite zone across which the coeval north-trending Thelon and Taltson magmatic zones on the west margin of the Churchill Province are offset by 300 to 700 km (Hoffman, 1987). The GSLSZ acted as a continental transform during the oblique collisional indentation of the active margin of the Churchill Province by the microcontinental Slave Province between 2.03 and 1.95 Ga (Gibb, 1978; Hoffman, 1987, 1988). Where exposed, the GSLSZ comprises granulite to lower greenschist facies mylonite belts with an aggregate width of 25 km and a consistent dextral sense of transcurrent shear (Reinhardt, 1969; Hanmer and Lucas, 1985; Hanmer and Connelly, 1986). The subsurface trace of this shear zone has long been of interest because a collinear Devonian reef trend hosts the important Rainbow–Zama hydrocarbon occurrences of northwestern Alberta and the famous Pine Point Pb-Zn deposit near Great Slave Lake. The GSLSZ has been depicted by magnetotelluric investigations down to 100 km within the upper mantle (Alan Jones, personal communication, 2001).

The **McDonald–Hay River brittle fault zone**, along the northern margin of the GSLSZ, accommodated an additional 70 to 125 km of dextral slip after 1.86 Ga (Hoffman et al., 1977; Bowring et al., 1984). It is collinear in part with the GSLSZ, but extends further southwest into northern Alberta and British Columbia. The deflections of magnetic anomalies across individual faults of the en échelon McDonald Fault Zone are not as obvious as across the GSLSZ.

There are several **shear zones exposed in the Canadian Shield in northeastern Alberta.** From west to east, the north-trending sinistral Rutherford, Leland Lake, Warren and Allan shear zones occur near the transition zone between the Taltson magmatic zone and Archean Rae Province rocks of northeastern Alberta (e.g., Godfrey, 1958; Langenberg, 1983; Culshaw, 1984; Bostock et al., 1987). These major shear zones are interpreted to have partly accommodated southward escape of a crustal wedge during Early Proterozoic indentation (e.g., Hoffman, 1987, 1988). The southernmost exposures of these mylonite belts bend south-westward under the Devonian carbonate successions of the WCSB, suggesting that they cut obliquely through the Taltson magmatic zone in the approximate direction of the PRA–PRE. A detailed map of the Shield, including the above-mentioned shear zones, can be found in Langenberg (1983). Mineralization associated with the Allan and Leland Lake shear zones has been reviewed by Langenberg and Eccles (1996) and McDonough (1997).

The **Snowbird Tectonic Zone (STZ)** is an anastomosing, northeast-trending crustal break between the Archean Rae and Hearne provinces that extends almost 3000 km from the Hudson Strait to the Rocky Mountains (e.g., Hoffman, 1988). The STZ is associated with gravity and magnetic anomalies, and was initially interpreted as a possible suture zone (e.g., Gibb and Halliday, 1974). It cuts the Taltson magmatic zone in the subsurface of east central Alberta at a high angle, thus constraining the age of the suture to less than 1.92 Ga. The Grease River Shear Zone and the Black Lake–Virgin River segment of the STZ in Saskatchewan have been interpreted as intracontinental transcurrent shear zones that accommodated southward tectonic escape of the Tantato wedge of granulite facies crust from a convergence zone between the Archean Rae and Hearne provinces (e.g., Hoffman, 1988). The dextral Grease River Shear Zone projects along the southern side of Lake Athabasca and may intersect the Allan Shear Zone and the Black Bay Fault somewhere in the northwestern part of the Birch Mountains.

3.3 Postcollisional Tectonic Discontinuities

The **Kimiwan isotope anomaly (KIA)** is an elongate zone of depleted $\delta^{18}O$ values (<5‰) in basement rock that extends for 250 km along strike northwest of Edmonton (Muehlenbachs et al., 1993). The ^{18}O depletion is interpreted to have been caused by high-temperature interaction between basement rocks and meteoric waters in an extensional continental setting. Hence, the Kimiwan normal detachment zone, located in the southwestern part of northern Alberta, was postulated as a zone of southwestward dipping normal detachment overprinting the Chinchaga–Buffalo Head contact at about 1760 Ma (e.g., Chacko et al., 1995).

Hornblende and muscovite from amphibolite and micaceous gneiss, respectively, have yielded K-Ar and Rb-Sr dates of ca. 1760 Ma (Chacko et al., 1995), which record cooling through approximately 525° and 500°C, respectively, of older than 2.0 Ga basement rocks (Ross et al., 1991). Assuming that the anomalous oxygen isotope composition of hornblende resulted purely from diffusion processes, which require temperatures in excess of approximately 550 to 600°C, a point can be made that the K-Ar chronometer in hornblende (approx. 525°C) was set shortly after the depletion event (Chacko et al., 1995). By extrapolating the cooling history of the northern Buffalo Head Domain (below 350°C by 1882 Ma; cf. Plint and Ross, 1993) to the KIA zone, it is further speculated that the Kimiwan area has been thermally reactivated at 1760 Ma in connection with the ^{18}O depletion event (Chacko et al., 1995). The interpretation must be taken cautiously, as the 1760 Ma date may represent partial resetting of an older crystallization or cooling age by a much later depletion event. The postulated normal detachment zone that dips at a shallow angle to the west has not been confirmed by the Peace River Arch Industry Seismic Experiment (PRAISE), which depicts an easterly-dipping shear zone beneath KIA (e.g., Eaton et al., 1999).

The **Winagami Reflection Sequence (WRS),** recognized along seismic lines 12, 13, 14 and 20 of the PRAISE, is interpreted as intrusive sheets that record a ca. 1800 Ma magmatic event related to the indentation of the western Canadian Shield by the Slave Province (Ross and Eaton, 1997). The WRS sequence of discrete, subhorizontal, high-amplitude reflections of regional extent crosscuts the dipping middle and upper crust-reflection fabric inferred to have formed during terrane collision. The WRS achieves its greatest prominence beneath the central and eastern portions of the PRA, and may have modified the crust rheology by acting as strong beams, thus providig a possible mechanism for localization of anomalous stresses that ultimately controlled the vertical tectonic evolution of the PRA (Ross and Eaton, 1997).

3.4 Reactivation of Precambrian Tectonic Discontinuities

The Phanerozoic evolution of the WCSB in northern Alberta is largely related to inherited Precambrian zones of crustal weakness. Several lines of evidence suggest that at least segments of the major Early Proterozoic tectonic discontinuities may have been reactivated during the complex interaction between the irregular craton edge and the tectonically active pericratonic crust. These include Phanerozoic subsurface and surface lineaments that are coincident with segments of terrane boundaries or major Precambrian shear zones (*see* Chapter 8). Ross and Eaton (1999) differentiated two types of basement faults, based on differences in their magnetic and seismic expression. "Intrabasement" faults are *Precambrian* structures that have been reactivated during the Phanerozoic and are recognized by a close correlation of faults with basement magnetic and seismic data. "Suprabasement" faults, on the other hand, are *Phanerozoic* faults that show no correlation with basement magnetics and seismic reflection data.

Although no Phanerozoic mylonite texture has been isotopically documented on samples from basement rocks, existing evolutionary models for the northern Alberta PRA–PRE require reactivation of basement shear zones. In this context, it is worth noting that the Paleozoic PRA–PRE and Mesozoic crustal downwarping is more localized, but roughly collinear with the axis of the 'Athabasca Mobile Zone', which is characterized by basement shearing, chloritization, potassium metasomatism and low specific gravity, as observed in basement core samples (Burwash and Krupička, 1969; 1970; Burwash and Culbert, 1976). This spatial coincidence suggests causal relationships between basement shearing, retrogression and metasomatism, and structural and/or facies anomalies of the WCSB stratigraphic record along a Phanerozoic 'mobile belt' across the preconfigured north-trending Precambrian basement. The Devonian crustal arch (PRA) and its Carboniferous collapse and 'rifting' (PRE) involved the Ksituan, Chinchaga and western Buffalo Head basement rocks, whereas the Mesozoic crustal downwarping extended eastward into the Taltson Domain.

4 Late Proterozoic to Early Paleozoic Uplift of the Peace River Arch and Related Structures

4.1 Late Proterozoic to Ordovician Tectonostratigraphy

The subsurface stratigraphic record for the Early Paleozoic is largely missing in the vicinity of the PRA as a result of uplift and erosion prior to the Middle Devonian. Although there is no direct evidence of an arch configuration prior to the Devonian, subtle stratigraphic changes in the Middle Cambrian succession suggest that the time of initial uplift was Middle Cambrian or latest Proterozoic. Precursor Late Proterozoic deformation and the early uplift history of the PRA have been inferred from the stratigraphic record exposed in the Rocky Mountains (McMechan, 1990).

In the Rocky Mountains, directly on strike with the southern margin of the PRA, important facies and thickness changes in the Windermere Supergroup attest to crustal uplift north of latitude 54°N (McMechan, 1990) and outline a reentrant along the eastern edge of the Windermere basin that must have formed during Upper Proterozoic 'rifting' (ca. 730–760 Ma; Evenchick et al., 1984; Devlin et al., 1989). The abrupt north end of the reentrant would have been localized above major, south-side-down, basement-involved transverse structures (McMechan, 1990).

The first evidence for a two-sided 'arch' is from thickness and facies changes within the latest Proterozoic sub–Gog Group and Cambrian strata exposed in the Rocky Mountains. The change in nature of the Upper Proterozoic–Cambrian boundary from an abrupt disconformity south of latitude 56°N to a gradational one north of 56°N suggests differential subsidence and south-side-up tilting and/or uplift in the latest Proterozoic. This change coincides with the south margin of the Ordovician to Devonian Ospika Embayment, which projects eastward into the northern flank of the arch (Thompson, 1989). Along the south boundary of the arch, relatively abrupt thickening and facies changes in Lower and Middle Cambrian strata occur southward between Horseshoe Lake and Mt. Sir Alexander-Bastille Creek, and a significant number of faults and folds have east-west trends. The coincidence of anomalous structural trends and Cambrian thickness and facies changes suggests that the structural trends were influenced by the shape of the original (Cambrian) sedimentary basin, with the east-trending structures having formed along the south margin of the Cambrian PRA (McMechan, 1990).

The changes in thickness and facies that define the south margin of the PRA during the Lower and Middle Cambrian occur above the most significant transverse facies changes in the Windermere Supergroup found in the Canadian Rocky Mountains. The coincidence of Upper Proterozoic and Cambrian stratigraphic changes with the south margin of the Devonian (D3 reef) PRA suggests that Upper Proterozoic 'rift' structure(s) may have been reactivated during the rise and fall of the PRA.

Subsurface facies mapping indicates that regionally extensive Middle Cambrian carbonate and shale units become sandy adjacent to the arch before being truncated northward by the sub-Devonian unconformity, thus suggesting a Middle Cambrian uplift or a shoal in the PRA area bounding a shallow Middle Cambrian cratonic embayment in central Alberta (Pugh, 1973, 1975; Aitken, 1989; Tawadros, 1990; Hein and Nowlan, 1998). During the Ordovician and Silurian, sedimentary deposits were stripped from virtually all of the emergent PRA landmass and preserved predominantly to the west and northwest (Norford, 1990). Along the PRAISE transect (Figure 1), seismic data show that the northern edge of the Cambrian–Ordovician units south of the PRA may be, at least in part, a depositional limit and not an erosional limit (Slind et al., 1994). These rocks appear to have been mildly deformed to produce a series of low-relief (approx. 60 m), long-wavelength (40 km) folds during a tectonic event that occurred sometime between the Early Ordovician and the Middle Devonian (Eaton et al., 1999).

4.2 Devonian Tectonostratigraphy

4.2.1 Granite Wash Lithozone

The Granite Wash Lithozone is a diachronous lithozone consisting of coarse siliciclastic material derived from erosion of the uplifted granite-gneiss basement in the area of the PRA. The thickness distribution of the Granite Wash provides an excellent indication of the early structural configuration of the uplift. Two distinct trends of thick Granite Wash deposits have been noted (Dec et al*.,* 1996). One trend strikes in an easterly direction within twp. 73, and defines an elongated area of subsidence in which the thickness of the formation exceeds 60 m. A second trend of thick Granite Wash deposits, up to 100 m, wraps around the PRA. Toward the eastern end of the arch, the Granite Wash forms narrow northeast- to north-northeast-trending sand bodies deposited in structurally controlled fluvial, estuarine and shallow-marine settings (Dec et al., 1996). The ages of Granite Wash sedimentary rocks are unknown except where they interfinger with Middle and Upper Devonian carbonate, shale and evaporite units away from the arch.

The Granite Wash has been interpreted to infill structural basins formed during extension prior to the onlap of the PRA (e.g., Cant, 1988; Trotter, 1989) or, alternatively, as a passive infill of paleotopographic features on the basement surface (Dec et al., 1996). Regional seismic sections reveal that, where abrupt Granite Wash thickness changes have been interpreted, overlying reflections exhibit distinctive drape patterns that are spatially separated from those associated with Carboniferous extensional faulting (Eaton et al., 1999). Moreover, the spatial sequence of drape features is not vertically aligned and, by progressively correlating drape patterns to higher stratigraphic levels, a dipping deformation plane can be delineated. Such a dipping plane is incompatible with differential compaction due to variable sediment infill over rough basement topography (Eaton et al., 1999) but rather with normal detachment.

A structural model of predominantly east-trending kilometre-scale horsts and grabens was developed as an extensional response to the uplift of the arch (Cant, 1988; Anderson et al., 1989; Trotter, 1989). East-northeast-trending bodies of Granite Wash deposits are noted along the crest of the arch (O'Connell, 1994). The seismic evidence suggests that Granite Wash sedimentation patterns near the crest of the PRA were probably controlled by active faults (Eaton et al., 1999). Linear bodies of coarse-grained clastic deposits up to 10 km long were interpreted to have accumulated in northeasterly-trending fault zones in the Red Earth and Utikuma areas at the eastern margin of the PRA (Dec et al., 1996). The easterly elongated depocentre south of the PRA partially coincides with the Cambrian–Ordovician zero edge. This may suggest an Early Paleozoic tectonically active lineament, which separated the northern uplands from the southern Cambrian–Ordovician basin and evolved into an easterly oriented zone of subsidence.

4.2.2 Elk Point Group

The Middle Devonian Elk Point Group comprises evaporitic, carbonate, and clastic sediments that onlapped much of the PRA (Figure 1). These rocks were deposited within a shallow, restricted, epicontinental seaway that was separated from the open ocean to the northwest and west by the PRA and the West Alberta Ridge. The sedimentary rocks of the Elk Point Group are up to 1000 m thick in the deepest parts of the basin and are absent on the crests of both the arch and the West Alberta Ridge due to nondeposition (Meijer Drees, 1994). In the southern part of the PRA, the total Elk Point isopach (30 m) falls at the lower limit of seismic resolution for the PRAISE data. During deposition of the Elk Point Group, the PRA was surrounded by an apron of siliciclastic sediments derived from the arch (e.g., Granite Wash, Gilwood strata).

4.2.3 Beaverhill Lake Group

Tectonic evolution of the Peace River Arch (PRA) during the late Middle and early Late Devonian is recorded by the depositional history of the Beaverhill Lake Group. The evaporitic rocks of the Fort Vermilion Formation and Slave Point Formation platform carbonate rocks were laid down during slow and even subsidence around a relatively stable arch (Keith, 1990). Carbonate buildups, equivalent to the reefs of the Swan Hills Formation of central Alberta (Fischbuch, 1968), form patch and fringing reefs around the eastern margin of the PRA landmass (Podruski et al., 1988; Moore 1989; Gosselin et al., 1989). Formation of the carbonate buildups is thought to have been initiated on fault-bounded highs in the underlying Precambrian and their development controlled by complex, small-scale, arch-related tectonics (Gosselin et al., 1989; Keith, 1990). North of the PRA, the Hotchkiss embayment marks a more than 400 km long east-northeast-trending zone of subsidence with an axial zone broadening eastward and encompassing the subsurface projections of the Leland, Warren, Allan and Grease River shear zones in the Lake Claire–Athabasca area. This coincidence suggests the development of the Devonian embayment is the result of basement reactivation along Late Proterozoic shear zones.

Both the carbonate platform and the reefs are sharply overlain by the predominantly basinal strata of the Waterways Formation, which onlap the arch. Northerly trending isopachs of the Firebag Member (Keith, 1990) indicate commencement of a period of tectonic instability, with differential subsidence of the basin to the east. Many units suggest a well-developed, west-facing clinoform geometry (Stoakes, 1988; Keith, 1990). The depositional pattern of the Lower Calumet limestone and the Middle Calumet shale suggests a north-trending trough, approximately 320 km long and 5 to 50 km wide, that was likely controlled by northerly-trending faults. It is important that, at the end of the Middle Devonian, the PRA did not extend eastward past 116ºW (Figure 1). Starting with the Christina shale, the Upper Waterways Formation units are more uniform in thickness and composition, thus marking a return to basin stability.

At the southern margin of the PRA, Swan Hills platform and subsequent reef growth (Ferry, 1989) are limited, to the north and east, to those areas underlain by thick Cambrian–Ordovician sedimentary rocks (Eaton et al., 1999). The reef buildup at the northern edge of the Swan Hills platform, near the Snipe Lake oil field (PRAISE line 14; Figure 1), has a subtle seismic expression that is interpreted as the crest of a broad antiform, with small positive relief that developed in the underlying Cambrian–Ordovician rocks. This superposition suggests that positive relief which resulted from the underlying folds, may have controlled the location of the reef edges.

4.2.4 Woodbend Group

At the base of the Woodbend Group in central Alberta, the Cooking Lake Formation consists of widespread and fairly uniform carbonate-platform deposits. The platform facies is succeeded by the carbonate platforms and reefs of the Leduc Formation, and the argillaceous carbonate and basinal shale of the Ireton and Fort Simpson formations. In the area of the PRA, carbonate rocks of the Leduc Formation onlap the Beaverhill Lake Group, the Granite Wash Formation and the Precambrian basement, forming a carbonate aureole around part of the PRA (Dix, 1990). Along the northern edge of the PRA, the Leduc platform is relatively narrow and has an approximate east-west orientation. It widens to the east and displays a northeast-southwest trend as it wraps around the southern margin of the arch. The increase in platform width to the south is believed to have resulted from the gentler dip of the Precambrian surface along the southern slope of the arch (O'Connell, 1994).

Evidence for arch-related syndepositional tectonic activity during Leduc sedimentation is provided by numerous examples of thickness variation and changes in carbonate and siliciclastic facies distribution (Dix, 1990). Many of these variations and changes can be spatially related to underlying Precambrian lineaments that appear to have been tectonically re-activated. Dix (1990) suggested that there was a regional differential tilting of the PRA during late Leduc deposition and this resulted in erosion and the progradation of Granite Wash siliciclastic rocks. Changes in regional sediment sources during late Leduc deposition also indicate possible modification of the basin away from the PRA (Geldsetzer, 1988; Dix, 1990). The Leduc PRA fringing reef has a very subdued seismic expression, but this may be an artifact due to the subparallel orientation of PRAISE seismic line 12 with respect to the Leduc fringing reef (Figure 1).

The boundary between the Lower and Upper Ireton is the so called Z-marker; this is a prominent well-log marker in the shale basin (Switzer et al., 1994) that is coeval with the terminal stage of Leduc reef growth (Dix, 1990). An important change in the direction of basin fill south of the PRA is recorded by a series of clinoform surfaces with an apparent dip toward the southwest (PRAISE lines 20A and 20B), exhibited above and onto the Z-marker (Eaton et al., 1999).

The enigmatic ***Rimbey–Leduc–Meadowbrook Reef Chain*** of central Alberta continues northward as the lower Leduc reefs into the area of the southern Birch Mountains (Switzer et al., 1994), where it projects into the area of the Legend kimberlite cluster. The long straight reef chain, which trends N20°E for more than 150 km from Sylvan Lake to Rimbey and Leduc, and its northern extension (trending N5°E) into the Morinville reefs may reflect fault-related antecedent topographic highs that were favourable for reef nucleation (e.g., Jones, 1980; Mountjoy, 1980). In contrast, others have proposed the presence of more subtle, low-angle, tectonic hinge lines underlying Leduc buildups or a purely depositional control by 'depositional highs' on the Cooking Lake Platform (Stoakes, 1992).

Most past studies have been well or core based and have provided little direct evidence to corroborate the tectonic control theory for the Rimbey-Leduc-Meadowbrook reef chain. The existence of faults is indicated by hydrothermal sphalerite that exists in places in Leduc cores (Bonnie Glen and Wizard Lake fields) and Pb-Zn sulphide minerals in the parallel Malmo–Duhamel reef chain (Haites, 1960). However, the presence of sphalerite in the overlying Ireton and Nisku formations may indicate that the mineralized faults are younger than the Leduc carbonate rocks or, alternatively, that the Leduc-age faults were reactivated. The influence of tectonic discontinuities on the formation of the 400 km long, straight and narrow (5 km wide) belt of dolomitized carbonate rocks stands out as a very attractive theory among other possible interpretations.

The possible influence of the basement on Leduc reef development, particularly in the form of topography inherited from the basement surface, was investigated using seismic and potential-field data in central and southern Alberta (Edwards and Brown, 1999). Two seismic lines, which are oriented east-west across the Homeglen–Rimbey reef chain in central Alberta, gave inconclusive results. An anomalously high amplitude event in the interval from the Precambrian to the Middle Cambrian Earlie Formation on the northern line was interpreted as a mineralized, diagenetically altered or fluid-enriched zone, and possibly also a structure that served to localize the overlying Leduc reefs (Eaton et al., 1995). Alternatively, this high-amplitude event may be the result of wavelet tuning due to a thin local stringer of Middle Cambrian Cathedral Formation limestone (Dietrich, 1999), or a method artifact resulting from lateral velocity differences in the Woodbend Group (Edwards and Brown, 1999).

The Rimbey–Leduc–Meadowbrook reef chain is oriented oblique to a series of north-northeast-trending magnetic anomalies that are believed to be related to deformation associated with the Snowbird Tectonic Zone (STZ; Eaton et al., 1999). It appears that no large-scale relationship exists between these two regional features. In contrast, there appears to be a regional relationship between the positive Bouguer gravity-defined STZ and this reef chain. However, since the edge of the gravity anomaly may be sourced in the middle crust, this coincidence does not necessarily imply that the initiation and development of the reef chain was controlled by a structure at the basement/cover interface.

Although no subtle inherited basement structure could be documented beneath the Homeglen–Rimbey reef, it is acknowledged that subtle fault displacements may be present but are beyond the resolution capabilities of the seismic data (about 20 m at the basement level). Considering the sparse sampling of the near base by drillholes and the low-relief nature of the basement in this area, potentially significant topographic features may have been overlooked on seismic data (Eaton et al., 1999).

4.2.5 Winterburn Group and Wabamun Formation

During deposition of the Winterburn Group, pre-existing topography on the PRA was bevelled and the area of the exposed PRA basement continued to decrease. The Winterburn consists of offlapping carbonate platforms of the Nisku and Blueridge formations, each with a gradual transition into basinal sedimentary rocks (Moore, 1988).

The Wabamun Formation forms a widespread, generally uniform carbonate ramp that onlaps the crest of the PRA, indicating near-complete inundation of the PRA landmass (Halbertsma and Meijer Drees, 1987). The end of Wabamun deposition represents the time at which the most elevated parts of the PRA were completely submerged. Its major tectonic significance justifies the choice of the shallow-water carbonate rocks of the Wabamun Group as a stratigraphic datum to remove tilting effects and other structural deformation that postdate deposition of this stratigraphic marker.

5 Carboniferous to Triassic Embayment Phase

The Carboniferous succession in the PRE is divided into three main stratigraphic units:

1. the lower to middle Tournaisian Banff Formation, consisting of a progradational, shallowing-upward succession of argillaceous shale, carbonate, and coarser siliciclastic rocks (Bamber et al., 1980; Chatellier, 1988)
2. the middle Tournaisian to upper Viséan Rundle Group, which forms a progradational shallowing-upward succession with deep-water carbonate and shale, passing upward into restricted shelf carbonate, siliciclastic and evaporitic rocks
3. the upper Viséan to Serpukhovian siliciclastic Stoddart Group

Regional isopach trends for the Carboniferous system indicate that the main areas of subsidence migrated over time, suggesting that the Carboniferous stratigraphy records two distinct tectonic phases that mark important changes in plate stresses and subsidence regime.

The first tectonic event was collapse of the PRA in the Late Devonian–Early Carboniferous and formation of the PRE along the northern margin of the Devonian PRA. The regional mechanism that led to this collapse may have been amplified in the area of the arch by a combination of transfer zone tectonics and local rheologic properties of the PRA crust (Eaton et al., 1999)

The second tectonic event was tectonic inversion along the axis of the Devonian PRA and development of the Dawson Creek Graben Complex (DCGC) in the late Early Carboniferous.

5.1 Early Carboniferous Development of the Peace River Embayment

5.1.1 Banff Formation

By the beginning of the Carboniferous, an arcuate zone of enhanced subsidence extended eastward into the area of the Devonian PRA from the narrow pericratonic Prophet Trough. This structure, known as the Peace River Embayment (PRE), opened to the west (Douglas, 1970).

The thickest accumulation of Banff Formation sedimentary rocks within the PRE (over 300 m) is located north of the axis of the Devonian PRA, reflecting a continuation of Devonian subsidence trends (Lavoie, 1958; O'Connell, 1990). Over the crest of the Devonian arch, Banff Formation sedimentary rocks thin to less than 180 m. The lower Banff succession consists mainly of basinal shale and carbonate ramp deposits and outlines the central axis of the PRE. By the end of lower Banff deposition, middle and upper Banff units with shallower water affinities prograded across the area with little variation in overall sediment thickness, indicating the cessation of differential subsidence throughout the PRA area (O'Connell, 1990). Subsidence patterns at the western edge of the PRE, in British Columbia, indicate the main structural elements that later dominated during Stoddart and Belloy deposition were initiated during deposition of the Banff Formation (Macauley et al., 1964; Barclay et al., 1990).

5.1.2 Rundle Group

The deposition of the Pekisko Formation (at the base of the Rundle Group) records renewed subsidence during a second phase of the PRE. The main depocentre of the upper Pekisko shale member partly overlaps the Banff depocentre north of the crest of the Devonian arch (O'Connell, 1990). During Upper Rundle Group deposition, the area of maximum differential subsidence was located to the south, directly overlying the crest of the arch.

The upper part of the Rundle Group and the Stoddart Group were deposited in the main graben basin, whose axis overlies the central region of the PRA (Macauley et al., 1964; Barclay et al.,1990).

5.2 Late Early Carboniferous Tectonic Inversion of the Devonian Peace River Arch

5.2.1 Stoddart Group

Starting in the lower Viséan, a series of linked grabens formed the central zone of a renewed PRE and controlled deposition of the Stoddart Group and the Permian Belloy Formation (e.g., Cant 1988). This system of normal faults is collectively referred to as the 'Dawson Creek Graben Complex' (DCGC). The origin of this tectonic inversion phase is unknown (Barclay et al., 1990; O'Connell et al., 1990). The DCGC comprises three main tectonic elements:

1. the asymmetrical Fort St. John Graben (FSJG) with a steep northern rim and a broad, gently sloping southern rim; the graben has an easterly trend with a southeasterly offset at its eastern end and is intensely segmented and block faulted;

2. the Hudson Hope Low, a prominent structural low at the western end of the Fort St. John Graben that is the earliest formed and the longest lived feature of the complex; and
3. three smaller, northeast-trending satellite grabens at the eastern end of the Fort St. John Graben.
4. These satellite grabens are named: the Hines Creek, Whitelaw and Cindy grabens

The Golata, Kiskatinaw and Taylor Flat formations of the Stoddart Group successively infilled the developing graben complex. The Golata and Kiskatinaw formations mark a change in sedimentation style from the carbonate sediments of the Rundle Group succession to siliciclastic sediments. Episodic differential syndepositional subsidence of horst and graben blocks controlled the thickness of the formations and produced both inter- and intraformational unconformities (Barclay et al., 1990).

5.3 Relationships Between Devonian and Carboniferous Structures

Although the PRA and the PRE are obviously linked, in that they formed at about the same site and along approximately the same trend, their origin remains enigmatic and no analogue has yet been identified. The arch may have constituted a zone of weakness that focused regional tectonic stresses during the Early Carboniferous, giving rise to the graben complex at that location (O'Connell, 1994). Crustal extension and development of the DCGC may be related to strike-slip motion and related compressional and rotational movement during the western Canadian Antler Orogeny (Barclay et al., 1990). Halbertsma (1990) suggested that the development of extension faulting during the Carboniferous is the result of thermal uplift. In contrast, O'Connell et al. (1990) suggested that the DCGC may have resulted from the development of an incipient rift because although shale and carbonate of the Banff Formation and Rundle Group cover a large proportion of the WCSB, the Stoddart Group is restricted to the Dawson Creek Graben Complex (DCGC) and comprises rift-related sedimentary rocks (Barclay et al., 1990).

Descriptions of PRA structures are generally based on well-log and sedimentological data to identify fault locations, trends, magnitudes and types of offset (e.g., DeMille, 1958; Lavoie, 1958; Williams, 1958; Sikabonyi and Rodgers, 1959; Cant, 1988; Barclay et al., 1990; Dix, 1990; O'Connell et al., 1990). The PRA faults appear to have been active over an extended period of time or reactivated episodically through time. Most of the fault displacement in the PRA–PRE region occurred during deposition of the Late Carboniferous Stoddart Group, but there is evidence for both Devonian and younger periods of fault activity. For some faults, there is evidence that folding affects all stratigraphic units below the glacial till layer, including the entire Upper Cretaceous section (Eaton et al., 1999).

In 1994, LITHOPROBE's Peace River Arch Industry Seismic Experiment (PRAISE) program acquired the first public-domain, regional, seismic-reflection profiles (with a total length of 432 km) across and adjacent to the PRA. This survey combined typical industry acquisition parameters with large shot-receiver offsets (>6 km) and long recording times (18 s) to image both bedding-scale and crustal-scale tectonic elements. The relatively large number of faults identified by this transect shed new light on the extent to which antecedent basement structures influenced the development of Phanerozoic tectonic elements, with particular focus on Carboniferous reactivation of basement fault zones. The PRAISE data have provided new evidence that older grabens containing Granite Wash sedimentary rocks may have been precursors to the Carboniferous normal faults of the DCGC. It is believed that Carboniferous faults nucleated preferentially within rheologically weaker basement domains rather than more massive basement units. The apparent correlation of the subcrop Dunvegan and Rycroft faults with a prominent basement reflection fabric suggests a relationship between Carboniferous faulting and basement tectonic domain boundaries.

Sedimentary rocks of the Devonian Granite Wash Formation and the Late Carboniferous Stoddart Group are preferentially preserved on the downthrown block of the Dunvegan fault, supporting the notion of a normal fault that is reactivated episodically though time (Eaton et al., 1999).

The seismic expressions of many normal faults in the PRA region show that offsets along the master normal fault in the brittle upper basement are accommodated by folding and subtle fracturing in the overlying, more ductile sedimentary cover. Movement apparently propagated upward within the fold hinge of the 'extensional forced folds' (Eaton et al., 1997). For example, along the Tangent Fault, Carboniferous strata of the Banff Formation and Rundle Group appear to drape across a deeper brittle fault. Diminishing displacement upward accompanied ductile deformation at the scale of seismic observation. Stoddart Group sedimentary rocks accumulated in a half graben in the hanging wall of the Tangent Fault. Permian and younger strata show evidence of movement of the Tangent Fault. Joints that developed in association with drape folds provide a potentially viable mechanism for creating fractures within otherwise tight reservoir units.

There is no compelling seismic evidence from these profiles, however, that discrete Early Proterozoic faults were reactivated during the Carboniferous (Eaton, et al., 1999). Alternatively, if Phanerozoic normal faults developed in the basement, steeply dipping brittle fault zones with moderate offsets would commonly be too steep to resolve with vertical incidence reflection techniques.

5.4 Permian and Triassic Tectonostratigraphy

The Permian stratigraphy indicates that the PRE was broader and more tectonically stable with no significant subsidence of the main body of the FSJG. Thickening of the mixed carbonate-siliciclastic Belloy Formation, suggesting local subsidence, is confined mainly to the deepest western end of the structure, in the Hudson Hope Low (Barclay et al., 1990).

The Triassic succession of the PRE records a major change in tectonostratigraphic style from carbonate to siliciclastic deposition (Davies, 1997). Throughout the PRE, the Triassic succession is punctuated by unconformities that may reflect both eustatic and/or tectonic influences, the most extensive of which is the Coplin Unconformity (Davies, 1997). The wide, low-relief embayment that developed during the Permian persisted throughout the Triassic, becoming broader in extent. The main subsidence in the basin continued to be centred on the axis of the DCGC, where the thickest Triassic section is deposited. Subtle, local movement along underlying Carboniferous horst and graben blocks caused variations in the Triassic isopach and facies trends (Gibson and Barclay, 1989; Gibson and Edwards, 1990). Westward thickening of Triassic strata beneath the Coplin Unconformity has been shown to be primarily the result of tilting and erosion, not differential sedimentation on the western side of extensional faults (Davies, 1997).

Along the PRAISE transect (Figure 1), the Triassic wedge thickens from a zero edge along line 13 to more than 750 m at the west end of line 11B, with greater thicknesses still farther west (Edwards et al., 1994). The Coplin Unconformity separates Lower to Middle Triassic rocks from Middle Triassic rocks (Davies, 1997). On the Alberta side of the PRE, the Upper Triassic forms a thin section above the Coplin Unconformity, and the bulk of the Triassic section consists of the weakly reflective Lower Triassic Montney Formation. A paleogeographic transition from prograding shoreface sands (inner shelf) to shallow-shelf mud (outer shelf) occurs within the Montney Formation along line 11A, near the Alberta–British Columbia border (Kent, 1994). The inner shelf facies of the Montney Formation is characterized in the reflection data by individual, west-dipping clinoforms, 50 to 100 km in length, suggesting regional tilting. Angular truncation of the Halfway and Doig formations is readily apparent and no seismic evidence is visible to support the presence of growth faults (Eaton et al., 1999).

6 Jurassic and Cretaceous Downwarping Phase

During the Early Jurassic pre-orogenic phase, minor thickness anomalies and the lateral variation of depositional environments may have been due to subsidence of underlying DCGC structures within the PRE (Poulton et al., 1990). Lower to Upper Jurassic pre-orogenic and orogenic Fernie Group sedimentary rocks increase in thickness where they overlie the central PRA structure. The orogenically-derived, sandstone-dominated sedimentary rocks of the Nikanassin / Minnes Group also thicken over the central PRA region (Poulton et al., 1990).

Enhanced subsidence occurred in the PRA/PRE region from the earliest Cretaceous, indicating an underlying local structural control on the basin configuration in this area. Facies distribution within the Lower Cretaceous Mannville Group and Peace River Formation appear to have been controlled by subsidence of the underlying DCGC structures.

Within the Gething Formation of Lower Mannville Group, an anomalous northeast-trending thickening coincides with the location and orientation of the underlying DCGC (Stott, 1973; Smith et al., 1984; Gibson, 1992; Cant and Abrahamson, 1996); this indicates possible renewed subsidence of underlying graben structures. A large northeast-trending sand body within the Bluesky Formation (at the top of the Lower Mannville) is contained within the structural boundaries of the DCGC, suggesting that renewed subsidence of the Carboniferous graben structures resulted in the preferential preservation of this sand unit (O'Connell et al., 1990; O'Connell, 1992). During Upper Mannville deposition, an area of enhanced subsidence developed parallel to the trend of the DCGC and overlies its southern margin. At the southern edge of the basin, a series of Upper Mannville shoreline units are stacked one on top of one another (Cant, 1984; Smith et al., 1984), suggesting rapid subsidence prohibited the northward progradation of these shorelines (Cant, 1984, 1988; Leckie, 1986).

Within the Cadotte Member of the Lower Cretaceous Peace River Formation, an abrupt transition from shoreline sandstone to offshore shale overlies the southern margin of the DCGC. This shoreline is paralleled by an incised fluvial-estuarine system at the base of the overlying Paddy Member (Leckie et al., 1990). In the PRA region, many minor structural offsets within units throughout the Cretaceous may have been caused by the reactivation of underlying PRA–DCGC structures (Cant, 1988; Hart and Plint, 1990).

During the Albian to Cenomanian, both Cordilleran tectonic loading, and uplift and subsidence of the PRA–PRE region were intermittent and appear to have influenced stratal depositional trends in its southern part (Chen and Bergman, 1999). The isopach patterns on maps of the lower Shaftesbury–Dunvegan and Cardium formations suggest deposition in a dynamic foredeep setting with elongate depositional zones, parallel to the Cordilleran tectonic front, migrating eastward away from the tectonic front. Differential subsidence patterns observed on isopach maps of the upper Dunvegan, Doe Creek and Pouce Coupe formations appear to reflect basement domain boundaries and faults (Chen and Bergman, 1999).

Detailed lithostratigraphic studies of the Lower Kaskapau Formation in the Saddle Hills area show that the PRA–PRE structural system was reactivated during the latest Cenomanian (Kiernan, 1996). Isopach maps show northerly trends prior to the K1 marker, consistent with the general foreland basin architecture. In contrast, the isopachs of the latest Cenomanian K1 to K2 interval and the K2 to yellow interval show easterly trends and northward thinning of strata, consistent with uplift along the edge of the Gordondale Fault. A tongue of coarser material (sandstone) within the Howard Creek Member trends approximately perpendicular to the Rycroft Fault, suggesting that the block behind it may have been slightly elevated and caused forebulge-related sand to spill out to the southwest. However, the interpretation of forebulge-related stratigraphic effects is tenuous (Cant, personal communication, 2001) At least the Carboniferous

Gordondale, Rycroft and Dunvegan faults appear to have been reactivated during Latest Cenomanian. Three erosional unconformities within the Lower Kaskapau Formation have been interpreted to record the three latest Cenomanian episodes of forebulge uplift, erosion and westward migration, corresponding to episodes of Cordilleran accretion and tectonic loading. The K1 erosional surface is marked by a trail of oolitic ironstone within the Lower Kaskapau, which is interpreted as the forebulge unconformity that migrated toward the orogenic zone (Kiernan, 1996).

7 Recent

The Alberta plains were glaciated during the Pleistocene and are today blanketed by drift. Much of the drainage system was formed in preglacial time, and the valleys are in many cases located along fracture zones. The valleys were deepened by ice action during glaciation and later modified by fluvial erosion (Misra et al., 1991). Some recent topographic features are therefore believed to be surface expressions of faults in the sedimentary cover, which may be in turn controlled by basement faults. Consequently, the orientation of lineaments appearing on aerial photographs and satellite images can serve as a guide to locate faults in the subsurface.

An early lineament study which used airphotos in northwestern Alberta, identified four principal lineament trends that form two orthogonal pairs intersecting at about 90° (Blanchet, 1957). It was inferred that the WCSB is crossed by a network of straight lineaments, each tens to hundreds of kilometres long. Many of these were believed to extend from the surface into the Precambrian basement and to have played a key role in the orientation of linear oil fields in this region.

A combination of Landsat MSS (Multispectral Scanner), TM (Thematic Mapper) and Seasat satellite radar images indicates the presence of two orthogonal sets of lineaments, one trending northeast and the other northwest, that are believed to represent nearly vertical tensional stress faults in Phanerozoic strata (Figure 7; Misra et al., 1991). The northwest lineament trend defines a southwest-facing arc, which is roughly parallel to the western edge of the Canadian Shield. The northeast lineament trend shows a peak trending N35°E. The lineaments are divided almost equally between the northeast (48%) and the northwest (52%) trends. The northeast set is composed of a larger number of shorter Iineaments (average length 14.3 km), while the northwest set has fewer but longer lineaments (average length 36.8 km). Although both lineament trends commonly occur together, either of them may predominate in a particular region. Many lineaments are segments of much longer composite structures, some of which extend for several hundreds of kilometres. A few lineaments with the northwest and northeast trends typical of the sedimentary basin appear in some Precambrian rocks close to the edge of the WCSB. Away from the basin margin, the simple orthogonal pattern is replaced by the complex of short, intersecting lineaments that characterizes the rocks of the Canadian Shield.

The PRA–PRE is represented by a marked increase in the density of long, northeast-trending lineaments that are believed to indicate increased stresses in the Precambrian basement rocks (Misra et al., 1991). This zone of lineaments is widest (500 km) at its southwestern extremity, close to the Rocky Mountains, and narrows to a width of 300 km where it approaches Lake Athabasca. Lineament densities are higher along the northern and southern margins of the arch, and the trend of the density contours suggests a northwestward periclinal closure (Misra et al., 1991).

A zone of east-northeast-trending lineaments, 150 km wide in the west and narrowing eastward, appears to be related to the McDonald Fault Zone, north of the magnetic anomaly corresponding to the Great Slave Lake shear zone (Misra et al., 1991). When traced westward into the plains region, the magnetic anomaly curves southward into northern Alberta and the mapped zone of lineaments maintains its west-southwest trend. A central fault zone, about 100 km wide, passes the full length of WCSB and has a magnetic expression that would indicate this structure originates in the basement (Misra et al., 1991).

Straight river courses and right-angle bends in rivers or other topographic features were primary criteria used for the recognition of surficial indicators of subsurface structure (Figure 7). Short topographic lineaments are currently mapped very conservatively in northern Alberta, consistent with the study objectives; more aggressive mapping would definitely result in a much higher lineament density and longer lineaments.

8 Reactivation of Precambrian Basement Structures

Collinearity of basement structures with Phanerozoic sedimentary and structural trends, and ultimately with Quaternary lineaments, may indicate tectonic reactivation of pre-existing zones of weakness. The spatial correspondence between these features does not prove that a direct cause-and-effect relation exists, but indicates the possibility that regionally significant Precambrian tectonic discontinuities were rejuvenated during the Phanerozoic. Projections along strike of major Precambrian shear zones in the Shield appear to have had topographic expressions throughout the Phanerozoic. They remained zones of crustal weakness and concentrated strain during the complex plate interaction between proto–North America and the Cordilleran front. The Laramide orogeny was, at least in part, accommodated by pre-existing tectonic discontinuities in the foreland. Some faults in the Cretaceous strata, which underlay the Pleistocene drift, are likely controlled by Carboniferous faults, whereas some others by older Precambrian basement discontinuities. This may explain the colinearity of topographic lineaments at the surface with basement faults and/or shear zones. Several examples are given here, but many others exist.

8.1 McDonald Fault Zone

In northwestern Alberta, Barss et al. (1970) recognized a pervasive northeasterly fault pattern in the Rainbow area, and speculated that the McDonald Fault Zone was intermittently active during the Phanerozoic. A Pb-Zn mineralized breccia from the Middle Devonian Keg River Formation was reported from well 16-34-118-21W5 (Turner and McPhee, 1994), which is located above the magnetic expression of the Great Slave Lake Shear Zone. The only isotope age that is related to the tectonic activity of the GSLSZ in the unexposed Alberta basement is an $^{40}Ar/^{39}Ar$ age of 1780 Ma (Plint and Ross, 1993); therefore, the Keg River breccia indicates Devonian or younger brittle reactivation, most likely as discrete faults overprinting the basement shear zone.

Although the drift thickness in the northwestern corner of Alberta is approximately 200 m, the drainage pattern is parallel to the inferred trend of the McDonald Fault Zone. Landsat data depict a zone of east-northeast-trending lineaments, 150 km wide in the west and narrowing eastward, which appears to be related to the McDonald Fault Zone (Misra et al., 1991). Based on an integration of linear hydrocarbon production trends, these authors suggest a strong correlation between basement features and oil and gas fields.

8.2 Peace River Structural Anomaly

In the PRA–PRE region, basement faults appear to have been active over an extended period of time or were reactivated episodically through time. Perhaps the most obvious and frequently cited example of collinearity of a Phanerozoic fault trace with a basement tectonic feature is the Dunvegan Fault, a normal fault with a Carboniferous and younger history of motion. The Dunvegan Fault is parallel to, and approximately coincident with, a segment of the Ksituan–Chinchaga domain boundary as defined on aeromagnetic maps. The Dunvegan Fault clearly offsets the basement-cover contact and is the central fault in a half-graben that is approximately 7 km wide (Hope et al., 1999). A prominent reflection-fabric depth within the Ksituan Domain projects toward a basement subcrop between the Dunvegan and Rycroft faults. It could have localized structural reactivation or influenced the orientation of these faults.

O'Connell et al. (1990) suggested a causal link between the northerly trending Ksituan–Chinchaga Precambrian basement contact in the Peace River area and several roughly parallel, structural-sedimentological features in the overlying Phanerozoic sedimentary cover. These features include:

1. a prominent line of north-trending grabens filled with Granite Wash sedimentary rocks;
2. a linear trend of dolomite within the Wabamun Formation, which may, in part, have been controlled by postdepositional fracturing (Stoakes, 1987; Churcher and Majid, 1989);
3. the southeasterly offset at the eastern end of the Fort St. John Graben, and
4. the Early Cretaceous erosional Fox Creek Escarpment

In contrast with the large-scale correlations described above, however, publicly available seismic images do not show any direct evidence for reactivation of directly underlying discrete basement faults. As well, a direct link between the Dunvegan Fault and reflective basement structures directly below, remains elusive. On the other hand, a fault-bounded synform in the upper crystalline basement that contains a thick accumulation of Granite Wash sediments, appears to correlate with the Dunvegan Fault (e.g., Eaton et al., 1999). Nonetheless, no clear basement reflection zone that projects into the Dunvegan fault and no basement reflection offsets that are aligned so as to suggest the presence of a seismically transparent fault, have been demonstrated (Eaton et al., 1999). A similar absence of obvious correlation with basement reflection patterns applies to all Carboniferous faults crossed by the PRAISE seismic profiles. If discrete, antecedent basement faults exist beneath these Carboniferous faults, they cannot be detected directly because they do not offset any basement reflector to any significant degree (Eaton et al., 1999). At a broad scale however, the Carboniferous Dunvegan, Rycroft and Tangent faults (with obvious normal components) can be correlated with an apparent eastward-dipping zone of ductile deformation in the basement that extends upward from about 20 km in the Ksituan Domain (Ross and Eaton, 1999)

In contrast to faults developed in response to a single tectonic event (which show constant thickness of the sedimentary units on either side of the fault), Late Carboniferous Stoddart Group sedimentary rocks constitute thickened reflection packages in the downthrown blocks of some faults (e.g., the Dunvegan and Tangent faults; cf. Eaton et al., 1999). Although this feature could result from an erosional event following the end of the Mississippian, the seismic data suggest that there has been infilling of fault bounded basins by Stoddart Group sedimentary rocks in this region. As well, the preferential preservation of older Granite Wash sedimentary rocks on the downthrown block along the Dunvegan Fault supports the notion of a normal fault that is reactivated episodically though time (Eaton et al., 1999).

Finally, in several places similar relationships between known and inferred lineaments/faults and thickened stratigraphic packages or hydrocarbon pool margins, have been reported both in detailed studies of adjacent areas and at the basin scale. Examples include, Jones (1980) described the linearity of various Cretaceous and Devonian oilfields and suggested an underlying structural control; Greggs and Greggs (1989) described the pervasive fault pattern and applied a basement tectonic model to the Devonian carbonate rocks of the WCSB; and Greggs and Hein (1999) presented the results of an airphoto study of northeastern Alberta, showing the strong correlation between basement features and oil and gas fields.

8.3 Leland Lake and Warren Shear Zones

The Leland Lake and Warren shear zones, which are exposed in the Shield of northeastern Alberta, consist of high- to low-grade mylonite. Displacement along the high-grade mylonite units of the Leland Lake Shear Zone ceased before 1933 Ma (i.e., the age of the Slave granite dike that intruded and truncated the western part of the shear zone; cf. McDonough et al., 1995). The eastern margin of the shear zone is not sealed by intrusions and consists of a 50 m to 500 m wide belt of lower amphibolite– to greenschist-grade mylonite derived from high-grade mylonite and Slave granite (McDonough et al., 1995). The age of the younger low-grade mylonite has never been documented. Examination of airphotos indicates that the Warren Shear Zone has a topographic expression in the Devonian strata on the west side of the Slave River that may reflect either post-Devonian movement or differential compaction on an irregular basement topography (Godfrey, 1958). In the same region, Devonian carbonate rocks of the Keg River, Muskeg, Fort Vermilion and Slave Point formations are characterized by a zone of 'karsting' (e.g., Turner and McPhee, 1994) that may, in fact, represent tectonically induced brecciation. Along strike, the Leland Lake and Warren shear zones project into the axis of the Middle Devonian Hotchkiss Embayment, suggesting Phanerozoic reactivation. The topographic expression of this axis during the deposition of the Beaverhill Lake Group is emphasized by the transition from the northern Alberta Hay River shelf, with shallow-marine carbonate rocks of the Slave Point Formation, to the central Alberta basinal shale and argillaceous carbonate rocks of the Waterways Formation. Segments of the Peace River and some of its tributaries line up along the southwestern projection of the Warren Shear Zone and may represent its present-day topographic expression (Ozoray, 1972).

8.4 Allan Shear Zone

The Allan Shear Zone is a north-trending, mainly granulite-grade mylonite belt near the transition zone between the Taltson magmatic zone and Archean Rae Province rocks of northeastern Alberta. The deformed Wylie Lake intrusion (1963 Ma) and the undeformed Charles Lake granite (1919–1932 Ma) constrain the timing of high-grade deformation (McDonough et al., 1995, 2000). However, high-grade mylonite is largely overprinted by younger, predominantly sinistral deformation, and the Charles Lake granite is deformed into greenschist mylonite. A splay of the Allan Shear Zone named the Bayonet Lake Shear Zone, consists largely of interlayered chlorite-biotite schist and quartzofeldspathic high-grade mylonite layers showing dextral S-C fabrics superposed on the older coplanar high-grade mylonite. Displacement on greenschist mylonite is demonstrated by the offset of pegmatite dykes that cut the high-grade mylonite. The $^{40}Ar/^{39}Ar$ data record slow regional isostatic uplift and cooling through hornblende, muscovite, biotite and K-feldspar closure temperatures (525–170°C) between ca. 1900 and 1700 Ma (Plint and McDonough, 1995). However, low-grade shear-zone activity may have continued and no direct isotope dates exist on the greenschist mylonite.

The southernmost exposure of the Allan Shear Zone main branch bends southwestward under the Devonian carbonate successions of the WCSB, suggesting that it cuts obliquely through the Taltson magmatic zone in the approximate direction of the PRA–PRE. Along strike, the Allan Shear Zone projects into the northern Birch Mountains, where a possible Jurassic south-facing scarp and several topographic lineaments point to Phanerozoic shear-zone reactivation.

9 Discussion

Successful exploration for many mineral deposits is critically dependent on knowledge of location, age and nature of faults and/or fault zones since they provide possible pathways and traps for mineralizing fluids, and may favour kimberlite emplacement. From a hydrocarbon exploration perspective, faults compartmentalize pools and create structural traps and migration pathways for hydrocarbons. Moreover, knowledge of the tectonic history of the region may help interpret changes in depositional, lithostratigraphic, and diagenetic facies, establish basin-wide correlations and determine correct reservoir-trap geometries. In spite of the obvious importance of faults for both energy and non-energy mineral exploration, no detailed and low cost, publicly available structural synthesis exists for northern Alberta, or the entire Alberta plains for that matter! The present report and the accompanying data on the CD-ROM includes information acquired to end of March 2001 and acknowledges the need for continuous updating and ranking of structural features reported in the Alberta basin.

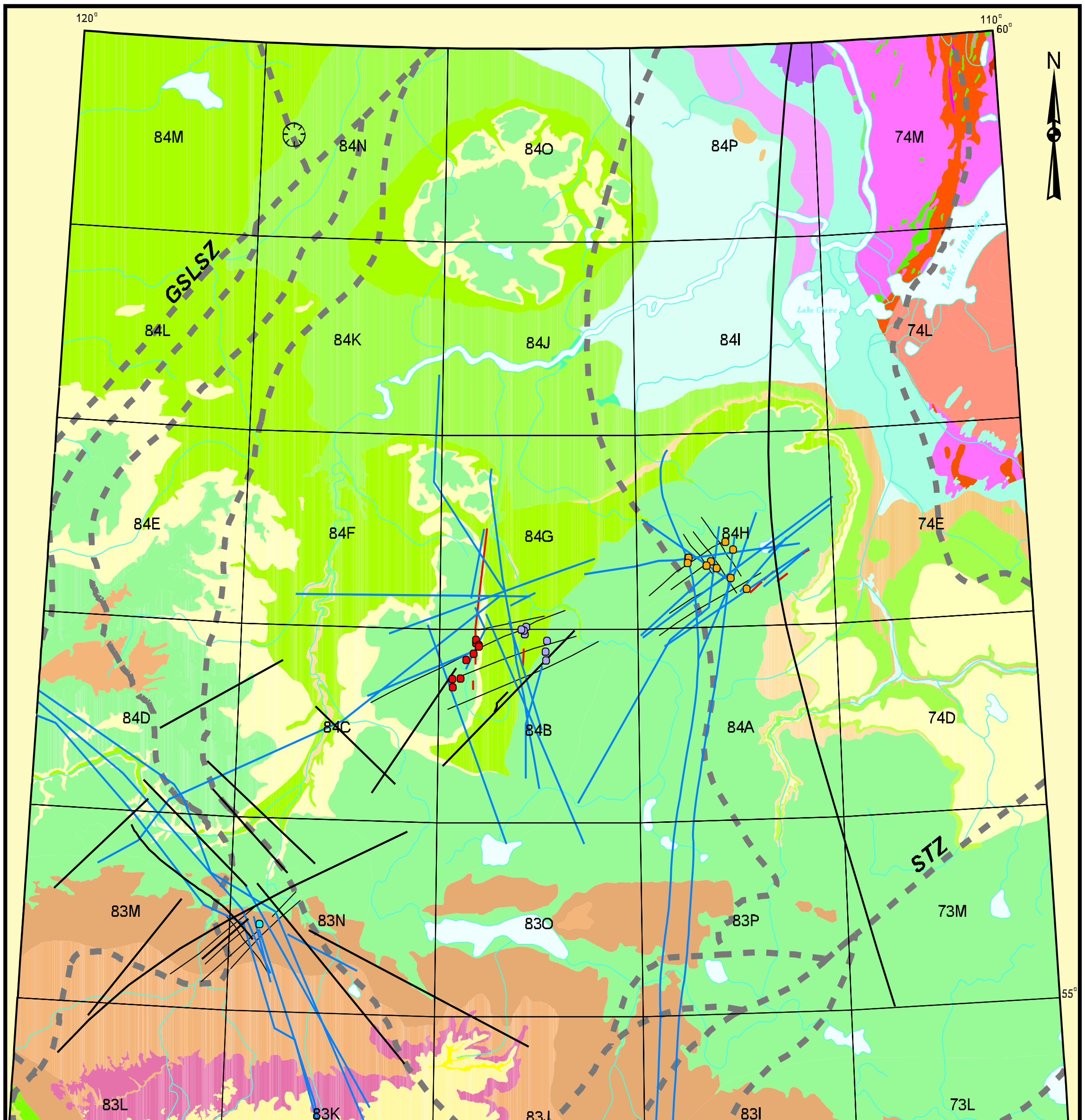
During the course of the compilation it became apparent that well constrained faults were inferred from more than one type of data. With the possible exception of the seismic method, no single method can provide compelling evidence for the location and timing of faults in northern Alberta, an area that is heavily covered by drift. For example, aeromagnetic and gravity maps assume gradation between differing contour values and there is no set minimum value difference across which one may postulate a fault. In fact, some faults do not have any gravity or magnetic signature. The limitations imposed by existing data at 1:1 000 000 scale and the current contouring conventions require that one not attempt to locate lineaments precisely, as it is unlikely that fractures coincide precisely with boundaries of potential field structures. Although a truism, it is worth mentioning in this context that remote-sensing lineament maps provide limited information on the timing of fault formation or reactivation. It must be realized that faults can be confidently identified only through the integration of various types of data, by identifying coincidental geological, geophysical and/or geomorphic boundaries of some linearity and length, across which there are substantial differences in values, thus suggesting the existence of a fault. Where possible, local and regional lineament data should also be integrated with seismic, stratigraphy and sedimentology data to determine the most likely lateral contact and stratigraphic relationships. Consequently, the digital product that accompanies this report includes, among the attributes for each fault identified, the main and the secondary criteria used by the original author of the source report in inferring the fault and a credibility rank, somewhat arbitrarily assigned by the compiler of this report.

9.1 Spatial Relationships Between Kimberlite Pipes and Compiled Structures

Recognition of faults formed or reactivated in the foreland during Laramide tectonism is of paramount importance to exploration for Late Cretaceous kimberlites in northern Alberta. The emplacement of kimberlites requires mantle-reaching tectonic discontinuities, most likely Precambrian shear zones reactivated during Late Cretaceous tectonism. As well in several places, some of the lineaments recognized in the Pleistocene drift are probably related to structures in the underlying Cretaceous bedrock.

No obvious structural pattern can yet be confidently related to known kimberlite clusters. Surface and subsurface lineaments spatially related to the Mountain Lake diatreme, and to the Buffalo Head and Birch Mountains kimberlite clusters are shown in Figure 8. Whether or not any of the lineaments corresponds to a significant tectonic discontinuity in the basement that may have favoured kimberlite emplacement needs to be investigated in greater detail. Once such a relationship is definitively demonstrated, major crustal discontinuities could be used as a prospective tool. However, several structural-stratigraphic lineaments that exist within a few kilometres of known kimberlite or kimberlite-like diatremes are highlighted below and represented in figures 9, 10, and 11.

The Late Cretaceous **Mountain Lake diatreme** appears to have been emplaced at the intersection of a Jurassic to Cretaceous zone of tectonic instability that is sub-parallel to the Cordilleran front, with the northeasterly fault zone bounding to the south the pre-Carboniferous PRA (Figure 9). The closest structural lineaments to the Mountain Lake diatreme that have been identified so far include:



- Selected faults recognized in subsurface in the vicinity of kimberlites
- Lineament of thickness and/or facies change
- DEM lineament
- Surface lineament, visible in satellite imagery (Misra, 1991)
- Precambrian basement terrane boundary (Ross et al., 1994)
- *GSLSZ* Great Slave Lake Shear Zone
- *STZ* Snowbird Tectonic Zone
- Steen River astrobleme

Kimberlites

- Legend
- Peerless Lake
- Buffalo Head Hills
- Mountain Lake

Note: Bedrock geology shown in background. See Geological Map of Alberta (Hamilton et al., 1999) for legend detail.

Index Map

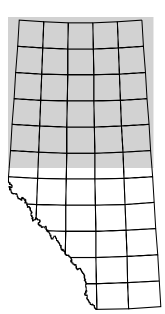


Figure 8

Selected Lineaments in the Vicinity of Known Kimberlites

50 0 50 100 km

1:3 500 000

March, 2001

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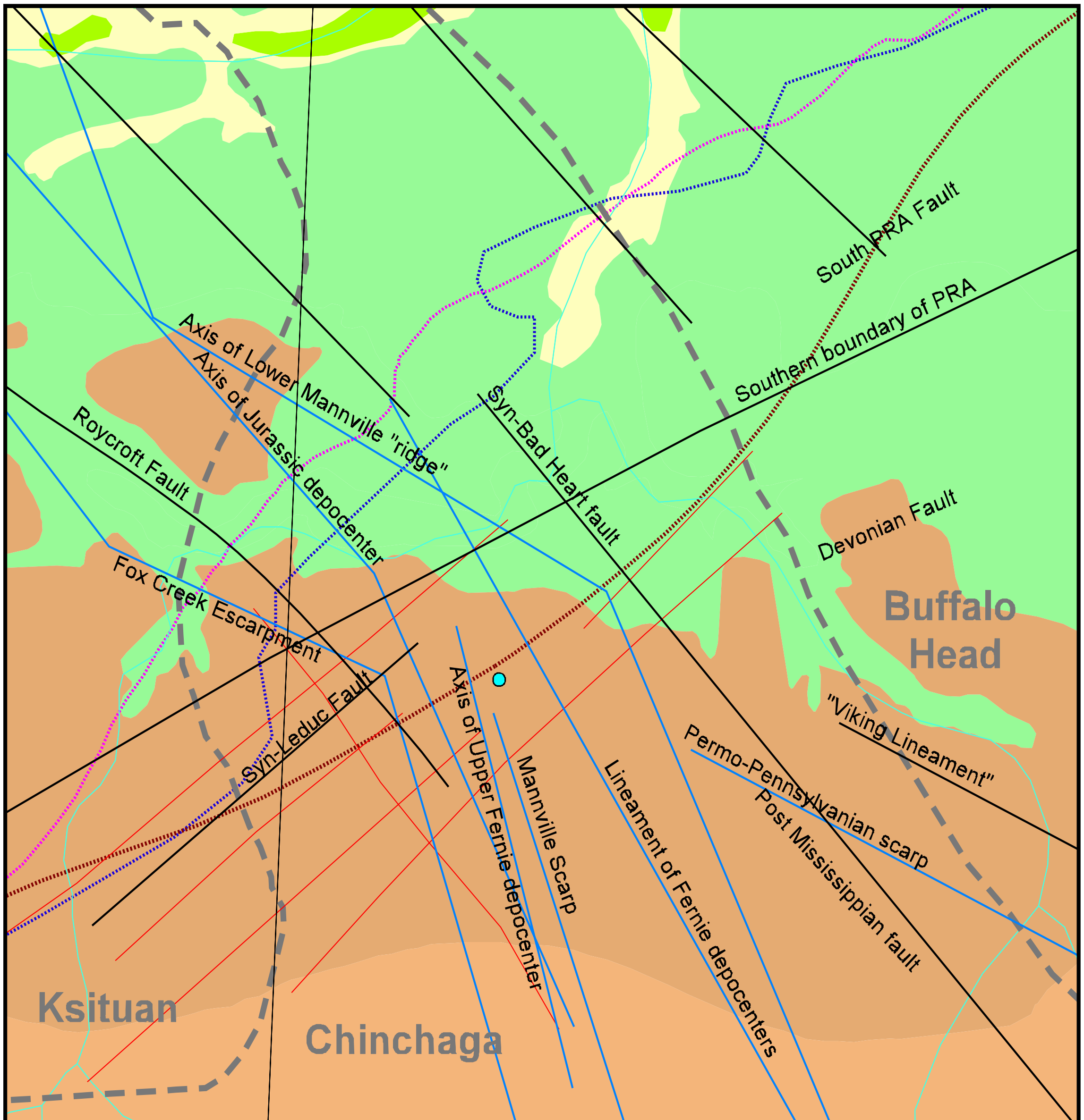
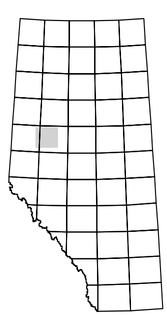
AGS Alberta Geological Survey



Elk Point Formation zero edge
Beaverhill Lake Formation zero edge
Leduc Formation zero edge
Selected faults recognized in subsurface in the vicinity of kimberlites
Lineament of thickness and/or facies change
Surface lineament, visible in satellite imagery (Misra, 1991)
Precambrian basement terrane boundary (Ross et al., 1994)
Mountain Lake diatreme

Index Map



Note: Bedrock geology shown in background.
See Geological Map of Alberta (Hamilton et al., 1999)
for legend detail.

Figure 9

Selected Lineaments in the Vicinity of Mountain Lake Diatreme

0 10 20 Km

1:500 000

March, 2001

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- the Aptian Fox Creek Escarpment and late Barremian to Early Albian depositional trends that define topographic lineaments within the Mannville basin (e.g., Hayes et al., 1994);
- a Santonian, syn-Badheart Formation fault (Donaldson et al., 1998)
- one of the 'Viking lineaments' formed or reactivated after the deposition of the Cenomanian-Santonian Colorado Group (Jones, 1980);
- several Jurassic Fernie Group elongated depositional centres (Poulton et al., 1994)
- Devonian and Carboniferous faults along and across the southern margin of the PRA (e.g., Sikabonyi and Rodgers, 1959; O'Connell, 1994);
- several structural lineaments visible in satellite imagery (Misra et al., 1991, Figure 7). These surface lineaments are subparallel to the southern margin of the PRA, suggesting some tectonic activity following the deposition of the late Campanian Wapiti Formation that constitutes the bedrock in this area.

The Buffalo Head Hills–Peerless kimberlite clusters (Figure 10) appear spatially related to:

- the southern margin of the Devonian PRA, an inferred lineament of long-lasting tectonism (e.g., Sikabonyi and Rodgers, 1959; O'Connell, 1994);
- a topographic lineament easily recognizable on the digital elevation model (DEM) along the eastern edge of the Buffalo Head Hills that suggests a northerly-trending fault (e.g., Eccles et al., 2001);
- four northeasterly-trending topographic lineaments visible in satellite imagery;
- a northeast-trending, mid-crustal, linear discontinuity depicted by magnetotelluric anomalies (Boerner et al., 1997, 2000);
- a northeast-trending Devonian to Mississippian fault zone recognized in the Leduc carbonate platform (Dix, 1990);
- several roughly northerly-trending lineaments of thickness and facies changes in the Devonian Duvernay, Woodbend, upper Leduc and Majeau Lake strata that may be structurally controlled; and
- axis of two northeast-trending Mannville depocenters.

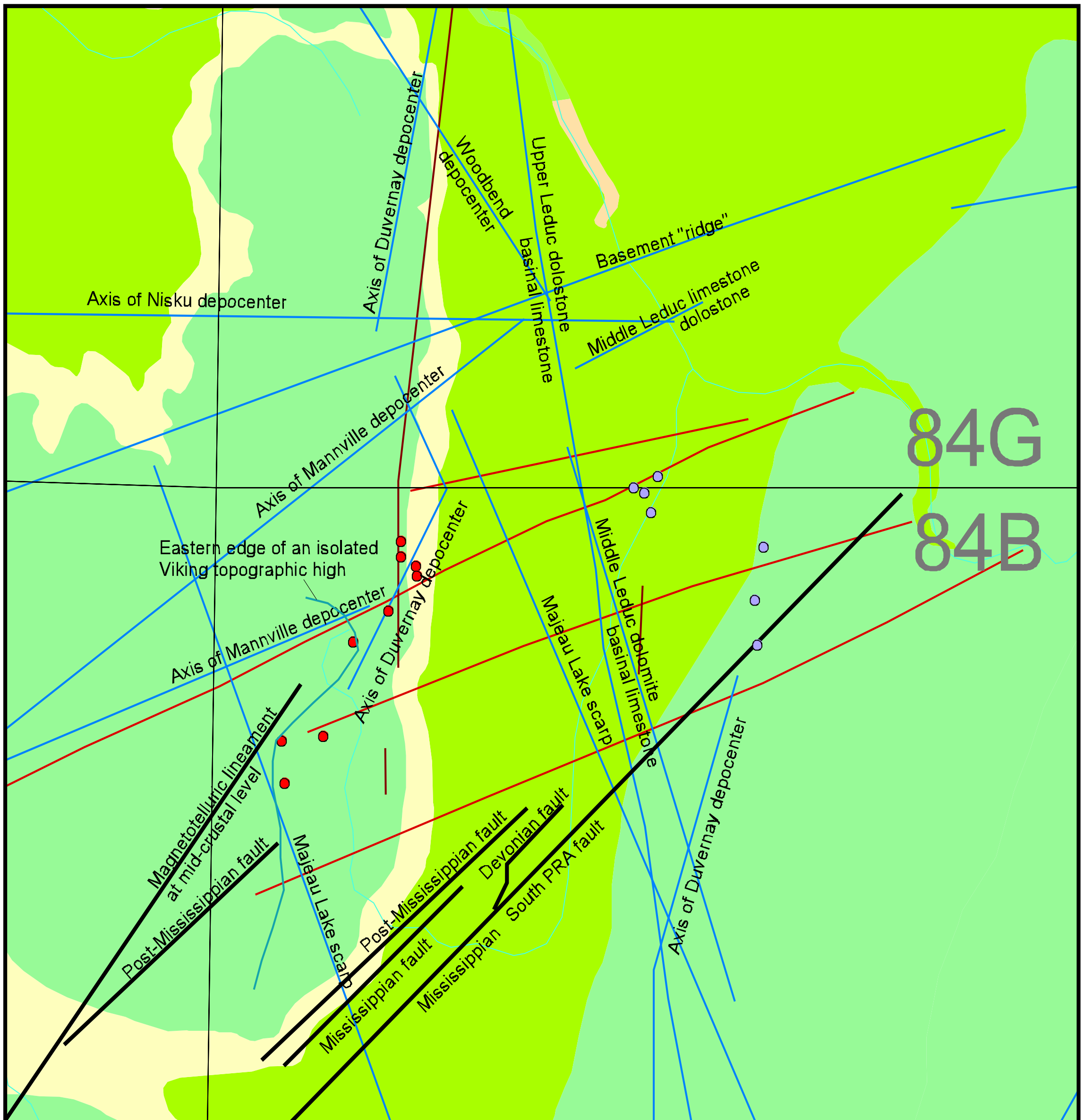
Similarly, a series of lineaments recognized in **the Birch Mountains kimberlite field** (Figure 11) require further investigation in order to establish their relationships to the Legend kimberlite cluster. The most significant appear to be:

- the northern extension of the Rimbey–Leduc–Meadowbrook reef chain, possibly related to a subtle seismically unresolved basement feature (Switzer et al., 1994);
- several Devonian lineaments of facies change within the Woodbend basin;
- several Cretaceous topographic lineaments inferred from isopachs of the Viking and Mannville strata; and
- east-northeast-trending topographic lineaments along the southern slope of the Birch Mountains.

9.2 Structural-Stratigraphic Constraints for Systematic Evaluation of Potential for Sediment-Hosted Ore Deposits in Northern Alberta

9.2.1 Evaluation of Potential for Sedimentary Exhalative (SEDEX) Deposits

The Banff Formation, and parts of the Rundle and Stoddart groups in the PRA–PRE area include the tectonic and stratigraphic prerequisites for the formation of typical SEDEX deposits (e.g., Evans, 1993). The Lower Carboniferous Exshaw and Banff formations consist of black shale and fine-grained carbonate rocks, with the Exshaw black shale deposited in a typical euxinic basin. The Carboniferous to Permian basin evolution in northwestern Alberta corresponds to an epicratonic embayment on the North American



Selected faults recognized in subsurface in the vicinity of kimberlites

Lineament of thickness and/or facies change

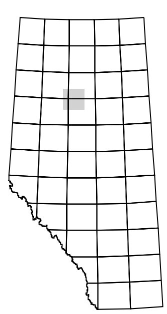
DEM lineament

Surface lineament, visible in satellite imagery (Misra, 1991)

Peerless Lake kimberlites

Buffalo Head Hills kimberlites

Index Map



Note: Bedrock geology shown in background.
See Geological Map of Alberta (Hamilton et al., 1999)
for legend detail.

Figure 10
Selected Lineaments in the Vicinity of Known Kimberlites in the Bufallo Head Hills-Peerless Lake Area

0 10 20 Km

1:500 000

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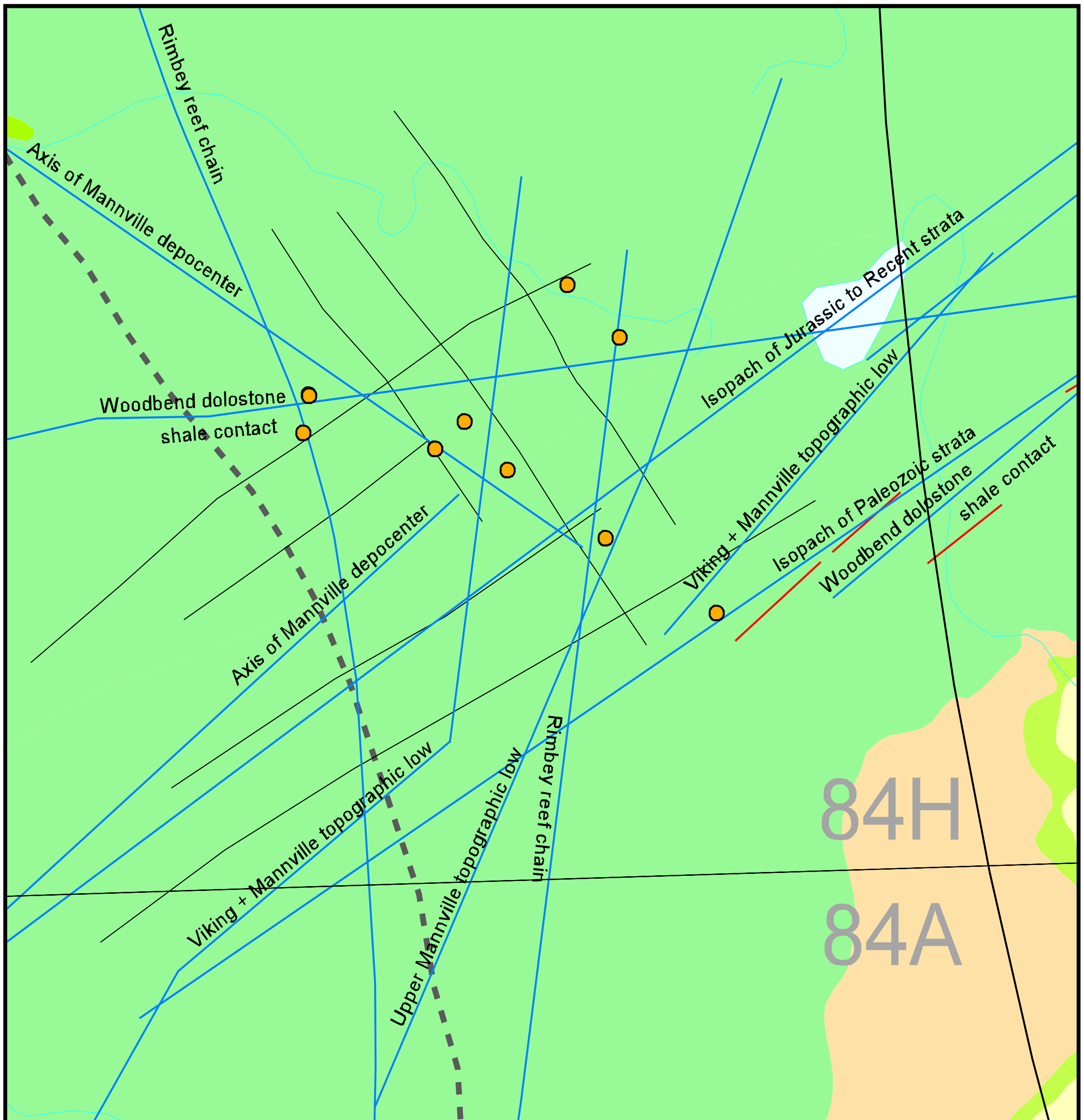

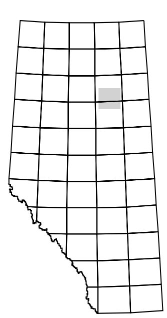

Legend kimberlites
Selected faults recognized in subsurface in the vicinity of kimberlites
Lineament of thickness and/or facies change
DEM lineament
Surface lineament, visible in satellite imagery (Misra, 1991)
Buffalo Head / Taltson basement terrane boundary (Ross et al., 1994)

Note: Bedrock geology shown in background.
See Geological Map of Alberta (Hamilton et al., 1999) for legend detail.

Figure 11
Selected Lineaments in the Vicinity of Known Kimberlites in the Birch Mountains

0 10 20 Km

1:500 000

March, 2001

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AGS Alberta Geological Survey

continental margin. Syntectonic infill of the Fort St. John Graben by the Stoddart Group sedimentary rocks suggests incipient continental rifting. Rapid changes in sedimentary thickness and the development of debris-flow breccia in the Late Carboniferous indicate synsedimentary faulting. Depositional centres and associated faults that may have served as possible feeder zones, allowing hydrothermal venting, should be prime targets for detailed geochemical and petrographic studies of existing drill-core material.

9.2.2 Evaluation of Potential for Carbonate-Hosted Pb-Zn Deposits

Occurrences of Pb and/or Zn minerals have been documented in cores from 18 wells in northern Alberta (Dubord, 1987) and in a sample collected near Whitemud Falls on Clearwater River in northeastern Alberta (Olson et al., 1994). The occurrences are all hosted by Devonian carbonate strata except for one occurrence of Zn that was reported at the Campanian Belly River–Spray River contact.

9.2.2.1 Northwestern Alberta

Seven of the eighteen wells with Pb and/or Zn minerals are located in northwestern Alberta, an area of intense fracturing of the basement along the southwesterly projection of the GSLSZ (i.e., the Hay River - McDonald Fault). In one well, approximately 10% Zn was reported in a carbonate breccia within the Middle Devonian Keg River Formation at a depth of approximately 1280 m. This high grade Zn occurrence is in well 16-34-118-21W5 and is located above the magnetic trace of the GSLSZ in the subsurface. To the northeast, along the GSLSZ, 87 individual Pb-Zn orebodies, which with two exceptions are hosted in the paleokarsted, epigenetic Presqu'ile dolostone, constitute the famous Pine Point series of Mississippi Valley type deposits (e.g., Rhodes et al., 1984; Quing and Mountjoy, 1992, 1994). Both the paleokarst and the Presqu'ile dolostone at Pine Point are believed to have formed due to the presence of faults and fractures that were the result of structural displacement of large fault blocks along the McDonald Fault Zone (Kyle, 1981; Krebs and Macqueen 1984). The timing of the Pine Point mineralization event has not been unequivocally resolved; various direct and indirect dating techniques have given ages ranging from Late Devonian (Nakai et al., 1993; Nesbitt and Muehlenbachs, 1994) to Pennsylvanian-Permian (Kyle, 1981; Beales and Jackson, 1982; Cumming et al., 1990) or even Cretaceous to Early Tertiary (Garven, 1985; Arne, 1991; Symons et al., 1993, Adams et al., 2000). Whatever the age of mineralization, any metallogenic model would require metal-bearing brines channelled along zones of extensive porosity and permeability, represented by the karsted and / or brecciated, variable dolomitic limestone, coupled with a reductant fluid.

The mineralized breccia from northwestern Alberta may indicate post–Middle Devonian tectonism and metallogenesis along the GSLSZ. Barss et al. (1970) recognized the pervasive fault pattern in the Rainbow area and speculated that tectonic activity had likely recurred on the McDonald Fault Zone. The only dated mylonite in the Alberta subsurface indicated Early Proterozoic tectonism (e.g., Plint and Ross, 1996), but unequivocal geological evidence indicates Phanerozoic tectonic reactivation on discrete low-grade shear zones and faults not yet subjected to isotope dating (*see* Chapter 8). Finally, although the depth to the Pb-Zn mineralised zone that was intersected by well 16-34-118-21W5 in northwestern Alberta prevents any mineral exploration and development in that area, the occurrence indicates detailed investigation is warranted along the GSLSZ to the northeast where the carbonate successions are shallower.

9.2.2.2 Northeastern Alberta

Several Pb-Zn geochemical anomalies were reported by Turner and McPhee (1994) from analysis of drill cores of the carbonate successions in the area of the Prairie Evaporite salt scarp near Fort McMurray. Although the reported concentrations of Pb/Zn are modest, ranging up to 120 ppm Pb and up to 2816 ppm

Zn, it must be realized the geochemical survey was of a reconnaissance nature and that a more detailed study of core from areas of inferred reactivated basement faults may lead to more significant findings.

As is the case with the GSLSZ, the major shear zones that have been mapped on the Shield in northeastern Alberta (e.g., Allan Shear Zone, Black Bay Fault, and the Grease River Shear Zone, a splay of the Snowbird Tectonic Zone) extend to the southwest into the WCSB basement and apparently merge in an area north of the Birch Mountains. Detailed exploration may be warranted in such areas where tectonostratigraphic conditions are favourable for carbonate-hosted mineralized zones: the structural control may be provided by reactivated major shear zones (*see* chapter 8) and the lithological control may be represented by variously dolomitic carbonate successions, partly equivalent with the Keg River Formation (e.g., the Winnipegosis Formation).

10 Conclusion

Spatial relationships between identified structures and kimberlites may constitute the basis for understanding the tectonic setting of the Alberta kimberlites.

- Fault locations combined with detailed stratigraphy may help constrain prospective areas for sediment-hosted ore deposits.
- Faults ranging in age from Precambrian to Recent have been identified and catalogued.
- The density of faults affecting strata of the WCSB is strikingly higher above major basement structural distortions, suggesting either long-lasting or reactivated tectonic activity. The PRA–PRE and the Great Slave Lake Shear Zone–McDonald Fault Zone appear to be the most tectonized regions of northern Alberta. The density of faults affecting the stratigraphy of the WCSB appears much lower in northeastern Alberta, but this is likely due to the complete lack of well data in Wood Buffalo Park and very little subsurface data in the northern Birch Mountains and Caribou Mountains. Hence, there is practically no information on the possible continuation of shear zones mapped in the Canadian Shield beneath the sedimentary cover of the WCSB.
- There is a distinct possibility that regionally significant Precambrian tectonic discontinuities in northern Alberta were rejuvenated throughout the Phanerozoic. However, it must be realized that the kinematics during Phanerozoic phases of reactivation was different from the original kinematics inferred for the major shear zones, and that the displacement along Phanerozoic faults was most likely orders of magnitude smaller than that inferred for the shear zones developed during the Hudsonian terrane accretion.
- Some of the faults identified in the Phanerozoic cover appear to be unrelated to old shear zones in the Precambrian basement.
- The origin of the PRA–PRE zone of structural disturbance remains enigmatic. The stratigraphic record indicates that the arch phase lasted from the latest Proterozoic to the latest Devonian. Its early evolution is inferred from thickness and facies changes of Late Proterozoic to Early Paleozoic strata in the Rocky Mountains, and its late evolution from the Devonian stratigraphic record in the Alberta subsurface. Areas of increased thickness of the Granite Wash lithozone are interpreted as graben infills in the west-central part of the PRA (Cant, 1988, O'Connell, 1994) and as narrow northeast- to north-northeast-trending sand bodies deposited in structurally controlled fluvial, estuarine and shallow-marine settings at the eastern termination of the PRA (Dec et al., 1996).
- Although the initial region of structural disturbance which is inferred from the distribution of the Granite Wash, extended eastward to longitude 114°W, the Devonian emergent arch configuration, as defined by the sedimentological characteristics of the Elk Point, Beaverhill Lake and Woodbend groups, did not extend eastward beyond longitude 116°W.

- The seismic expression of normal faulting in the PRA area features brittle faulting at depth, overlain by folded and fractured strata in a broad zone of deformation. This has important implications for the possible distribution of hydrothermal fluids in the affected zone (Hope et al., 1999). As well, faults may have played an active role in the local dolomitization of carbonate rocks and compartmentalization of reservoir rocks (e.g., Stoakes, 1987; Davies, 1996).
- Development of a comprehensive theory for the evolution of the PRA–PRE depends on the acquisition and integration of new data, particularly that dealing with basement structure (e.g., aeromagnetic data, direct isotope dating of low-grade textures), and the identification of specific structural styles throughout the Phanerozoic (e.g., high resolution seismic data).

11 Recommendations

In order to understand the structural framework of Alberta and its implications for mineral exploration, the only valid approach is considered to be an integrated study of indirect (geophysical, remote sensing) and direct (field and drill-core) data. Significant faults inferred in the subsurface and confirmed by structural features in outcrop and/or topographic expressions should be included in the next edition of the Geological Map of Alberta, regardless of the thickness of the Pleistocene-Quaternary deposits. It is thus recommended that further work should include:

1. Completion of the GIS compilation of faults and other structural lineaments in northern Alberta;
2. An integrated study of basement–sedimentary cover interactions, resulting in a structural synthesis for Northern Alberta;
3. Expansion of the compilation / structural synthesis to the scale of the entire province.

A detailed scenario for an Integrated Study of Basement–Sedimentary Cover Interactions in Northern Alberta is provided in Appendix 2.

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13 Appendix 1 – Lineament Georeferencing Process

Table A1 summarizes information relating to the georeferencing of structural elements for the compilation. The table lists the source data type for each of the georeferenced figures (as discussed in Section 1.4): type 1 are ASCII coordinate data, type 2 are digital graphics files (.wmf), and type 3 are scanned and digitized maps from journal articles (type 3b are scanned, with the elements sketched in by eye). For reference, the table lists the original scale of the published map, which contributes to the overall accuracy of each figure's elements. Based on scale, the ground width of a 0.5 mm line on the map is calculated.

ArcInfo® software was used to perform the georeferencing, using the Arc TRANSFORM command. This is a six-parameter affine transformation that converts figures from one coordinate system (i.e., page) to another (i.e., map); if more than three registration ticks (fiducial marks) are used, a root mean square (RMS) error is reported by the software (Arc/Info ArcDoc on-line documentation, ver. 7.2, Environmental Systems Research Institute, Redlands, CA, 1999). The RMS error is essentially a measure of the average error associated with the registration and transformation process. All type 2 and most type 3 data have an RMS error listed in the table.

Each figure has been assigned an estimated margin of error for the georeferencing process, largely based on the reported RMS error. Type 1 data have very little associated error; their error stems from the number of decimal places carried in the coordinate data files; this has been calculated to be less than ±1 m on the ground. The margin of error for types 2 and 3 figures is simply the RMS error, which was deemed to be a reasonable error margin when fiducial marks in the resulting figures were compared with digital files containing their true positions. In only one case was the margin of error revised. Figure 1B in Donaldson et al. (1998) was deemed to have a ±500 m error, based on an examination of the resulting file. The RMS happens to average out to a small number for this figure, but the registration marks deviate by approximately 500 m from their true position.

Margins of error for the resulting lineaments span four orders of magnitude. Not surprisingly, those of type 1 suffered almost no degradation in positional accuracy. Figures of type 2 are located within the same order of magnitude as they were originally published. Type 3 figures may have incurred more significant degradation of positional accuracy. For example, whereas the width of a 0.5 mm line in Figure 2 in Burwash et al. (2000) is 159 m on the ground, the estimated margin of error is ±1601 m, a full order of magnitude greater. Higher margins of error for type 3 data are almost certainly due to differential shrinkage of the original paper map, and possibly also to distortion during the scanning process. We have generalized the error for the line elements in the ArcView® shapefile compilation into three categories, based on Table A1: ± < 1 m; ± < 1 km; and ± 1–2 km.

In conclusion, the largest margin of error associated with digitizing and georeferencing of structural elements in the Peace River Arch digital compilation is ±2 km. This is over and above any positional inaccuracy in the original documents.

Table A1: Summary statistics from the lineament georeferencing process.

Reference Figure	Type	Published Scale (Approx.)	Ground width of line 0.5 mm on map (m)	RMS (TRANSFORM) Error (m)	Estimated Margin of Error (+/- m)	Error Category
Ross et al., 1994, Figure 4.1	2	1:10,000,000	5000	336	336	< 1 km
Burwash et al., 1994, Figure 5.1	1	1:5,000,000	2500	Not Applicable	1	< 1 m
Burwash et al., 1994, Figure 5.12	2	1:10,000,000	5000	280	280	< 1 km
O'Connell, 1994, Figure 28.4	2	1:357,000	179	278	278	< 1 km
O'Connell, 1994, Figure 28.5	3b	1:192,000	96	Not Applicable	400	> 1 km, < 2 km
O'Connell, 1994, Figure 28.8	2	1:357,000	179	905	905	< 1 km
O'Connell, 1994, Figure 28.9	2	1:357,000	179	321	321	< 1 km
O'Connell, 1994, Figure 28.10	2	1:357,000	179	325	325	< 1 km
O'Connell, 1994, Figure 28.12	2	1:357,000	179	321	321	< 1 km
O'Connell, 1994, Figure 28.13	2	1:357,000	179	405	405	< 1 km
O'Connell, 1994, Figure 28.14	2	1:465,000	233	448	448	< 1 km
O'Connell, 1994, Figure 28.17	2	1:476,000	238	444	444	< 1 km
O'Connell, 1994, Figure 28.18	2	1:476,000	238	444	444	< 1 km
O'Connell, 1994, Figure 28.19	2	1:476,000	238	392	392	< 1 km
Sikabonyi, 1959, Figure 4	3	1:531,000	267	1146	1146	> 1 km, < 2 km
Sikabonyi, 1959, Figure 6	3	1:531,000	267	1123	1123	> 1 km, < 2 km
Sikabonyi, 1959, Figure 10	3	1:531,000	267	1129	1129	> 1 km, < 2 km
Sikabonyi, 1959, Figure 13	3	1:531,000	267	1146	1146	> 1 km, < 2 km
Sikabonyi, 1959, Figure 14	3	1:531,000	267	1176	1176	> 1 km, < 2 km
Sikabonyi, 1959, Figure 15	3	1:531,000	267	1123	1123	> 1 km, < 2 km
Sikabonyi, 1959, Figure 16	3	1:531,000	267	1129	1129	> 1 km, < 2 km
Sikabonyi, 1959, Figure 20	3	1:531,000	267	1017	1017	> 1 km, < 2 km
Sikabonyi, 1959, Figure 22	3	1:531,000	267	1231	1231	> 1 km, < 2 km
Donaldson et al., 1998, Figure 1B	3	1:526,000	263	81	500	< 1 km
Burwash et al., 2000, Figure 2	3	1:317,000	159	1601	1601	> 1 km, < 2 km
Boerner et al., 1997, Figure 1	3	1:8,696,000	4348	539	539	< 1 km
Barss et al., 1970, Figure 2	3	1:4,580,000	2290	294	294	< 1 km
Jones, 1980	3b	1:185,000	93	Not Applicable	Not Applicable	> 1 km, < 2 km
Cant, 1988, Figure 9	3	1:5,000,000	2500	324	324	< 1 km
Cant, 1988, Figure 11	3	1:5,000,000	2500	873	873	< 1 km
Cant, 1988, Figure 15	3	1:5,000,000	2500	211	211	< 1 km
Richards et al., 1994, Figure 14.5	2	1:1,136,000	568	53	53	< 1 km
Henderson et al., 1994, Figure 15.1	1	1:5,000,000	2500	Not Applicable	1	< 1 m
Dec et al., 1996, Figure 6	3b	1:200,000	100	Not Applicable	Not Applicable	> 1 km, < 2 km
Dec et al., 1996, Figure 10A	3b	1:333,300	167	Not Applicable	Not Applicable	> 1 km, < 2 km

14 Appendix 2 – Proposed Scenario for an Integrated Study of Basement-Sedimentary Cover Interactions in Northern Alberta

1 Compilation of Subsurface Faults

The compilation of faults documented in the geological literature must be completed and supplemented with structural-stratigraphic studies in areas of interest and/or inconclusive data. Detailed cross-sections should integrate stratigraphic, sedimentological and seismic data, where possible, to determine the most likely extension and geometry of previously inferred faults.

2 Core Study

A systematic study of existing core should focus on often-overlooked information such as:

2.1 Tectonic Deformation

Deformation should be documented by recording the tectonic features (syndepositional, pre- and postlithification) observed in core. These 'small-scale' effects are easily seen in core and are frequently the main unequivocal source of structural information in subsurface rocks. Pure or simple shear involves horizontal and vertical movement, and results in a variety of structures at different scales. Identification of these features in core, commonly not as well understood as the classic sedimentological analysis, requires:

1. core logging for macroscopic deformation characteristics as part of the overall core assessment (care should be taken to differentiate natural from artificially-induced fractures);
2. thin-section examination for mineralogy and detailed assessment of microgouge and microshearing (e.g., strained quartz, calcite grains); and
3. finding a causal mechanism for tectonic deformation features observed in core.

2.2 Hydrothermal Alteration

Optical identification of products of hydrothermal activity and, possibly, associated sulphide minerals, may indicate the proximity of an ore deposit. Complemented with geochemical, isotope and fluid inclusion analyses these observations may constrain prospective areas with nearby faults representing primary targets for further investigation.

3 Surficial Lineament Mapping

Airphotos and satellite images interpretation may represent the only means of structural mapping in the poorly exposed, highly vegetated terrains of Northern Alberta. Although the Alberta plains are blanketed by Pleistocene drift, the present-day drainage system appears to be, to a certain degree, structurally controlled. The explanation may be that preglacial river valleys preferentially occur along or within more recessive and / or tectonized rocks and were deepened by ice action during glaciation. As well, ice melting and recent fluvial erosion may have been concentrated along topographic lows inherited from the preglacial time. However, a large number of glacial lineaments do not show any direct bedrock control and, consequently, discrimination of tectonic from glaciotectonic lineaments is essential in an attempt to map faults in the Alberta subcrop.

3.1 Mapping of Lineaments on Airphotos and Digital-Elevation Models

Analysis of digital elevation models (DEM) and airphotos is a very economical and accurate tool for identifying lineaments at a variety of scales. Georeferenced, orthorectified airphotos should be examined for photolineaments. Recognition of geologically significant surficial lineaments may be challenging in heavily glaciated or forested regions, and in areas of heavy agricultural usage or dense cultural features (particularly roads and railways, buried pipelines or seismic lines), hence integration with satellite imagery is required. Nonetheless, our preliminary data indicates that many surface lineaments reflect control from an underlying bedrock fault or fracture zone.

3.2 Mapping Lineaments by Remote Sensing Techniques

The use of RADARSAT data in geological and geomorphological mapping is steadily increasing. Surface roughness, soil dielectric properties, slope attitude and vegetation coverage affect the radar backscattering and determine the tone, contrast and texture variation in radar images. The standard beam S1 with incidence angles of 20-27.4° appears to be the most effective in northern Alberta, an area characterised by low relief with slopes generally shallower than 30°. The analysis of the four principal components and the integration of lineaments extracted from each of the four data set may prove efficient in identifying structures, soil and bedrock lithological / geochemical characteristics. For example, the contrast in shadowing is induced by topographic variations or drainage patterns and thus may outline structures whilst textural variations are induced by dielectric properties of surface materials and may be related to lithological variation in soil and/or, to a lesser extent, bedrock. Better resolution of the fine beam images may be required in areas of maximum interest. The integration of RADARSAT principal components with the DEM, bedrock lithology and structural data will contribute to the understanding of the upper crust geometry. Fusion of these data with aeromagnetic and gravity data will add the geophysical characteristics of the deep crust and upper mantle to a more complete picture of the northern Alberta geology.

4 Integration with Aeromagnetic, Gravity, and Lightning Strike Density Data

To further document the bedrock structural framework, lineaments derived from geological data and remote sensing should be integrated with boundaries and trends depicted by gravity, and aeromagnetic anomaly maps, and with maps of lightning strike density. Aeromagnetic and gravity boundaries or trends should be integrated with a DEM in order to identify a 'coincidence of change'. Similarly, the lineaments defined by higher density and/or intensity of lightning strikes, once corrected for relief and distance to receivers should be draped on the geological map in an attempt to identify anomalously conductive lineaments, possible mineralised faults.

5 Fieldwork

Coincidence of steep geophysical gradients and/or significant faults inferred in the subsurface with geomorphic boundaries of some linearity and length requires 'ground-truthing'. Structural data from existing outcrops have to be thoroughly examined and their possible relationships with inferred lineaments analysed. According to Babcock (1975), "If lineaments are to be of value in structural studies, a geometric correlation between lineament orientation and joints/cleavages must be demonstrated"