Introduction

This chapter provides an overview of the structural framework and overall architecture of the Western Canada Sedimentary Basin (WCSB), on a regional scale, using reflection seismic sections, geological sections, isochron maps and observed subsidence profiles (burial history curves or plots), and on a more local scale, highlighting distinct geological relations such as variations in facies, thickness, porosity and diagenetic characteristics as they relate to the boundaries of individual structural blocks.

The WCSB comprises the eastern Canadian Cordillera and two major sedimentary basins: a northwest-trending trough in front of the Cordilleran Fold and Thrust Belt (extending eastward to the Canadian Shield) called the Alberta Basin, and the cratonic Williston Basin, centered in North Dakota and extending into southern Saskatchewan and southwest Manitoba (Fig. 3.1). These two features are separated by a broad northeast-trending positive element, which includes the Bow Island Arch. The arch was a subtle, mildly positive structural element in the late Paleozoic, and became more clearly defined in the Mesozoic and Cenozoic. At the southwestern end of the Bow Island Arch is the Kevin-Sunburst Dome, a major northwest-trending Rocky Mountain intrusion.

The western boundary of the WCSB is here defined by the western limits of the exposed and deformed sediments of the ancestral North American margin, equaling to the eastern limits of the allochthonous terranes, and normally located near the boundary between the Omineca and the Intermontane belts of the Cordillera. The boundary between the Omineca Belt and the Rocky Mountain Foreland Fold and Thrust Belt is the Rocky Mountain Trench, which continues northward into the Tintina Fault. For mapping conventional, the southern limit of the WCSB in this chapter is normally taken to be at the Canada-U.S. border. The northern limit of the WCSB is defined by the Taltihna High in the Northwest Territories.

Strata of Middle Proterozoic to Cenozoic age thicken from an erosional zero edge in the northeast to more than 20 km within the Cordillera. Within this wedge, the Peace River Arch was a prominent east-northeast-trending topographic high in Cambrian to Late Devonian time that subsequently became, in part, the site of a limited basin (the Peace River Embayment) in Mississippian to Permian time.

The Middle Jurassic to Eocene compressive deformation of the western edge of the WCSB formed the Cordilleran structural elements—the Foreland Fold and Thrust Belt and the Omineca Belt—deforming Middle Proterozoic to Eocene strata. Compressive deformation was followed by regional extension, and consequent deformation of Oligocene strata in the Flathead Valley Graben (southeastern British Columbia). The loading of the North American craton and the creation of western source areas during formation of the Cordilleran Foreland Fold and Thrust Belt may have affected the Mesozoic and Cenozoic evolution of the entire WCSB.

Estimated post-mid-Jurassic shortening of 170 km across the Rocky Mountain Foreland Fold and Thrust Belt in southern British Columbia and Alberta includes 150 km since the mid-Cretaceous (Price and Fermor, 1984). Tectonic style and strain, thrust sheet thickness, and the nature of the displacement change all to the north in response to the following factors: changes in the tectological character of the deforming sedimentary prism; greater shortening of supercrustal rocks in the Bowser and Suastat basins of the Intermontane Belt (Evenshick, 1991); and increased lateral displacement along the Northern Rocky Mountain Trench fault system.

Structural features are, however, not restricted to the mountains. For example, in the Fort McLeod area of southwestern Alberta, there are a series of horsts and grabens. At the north end of the Alberta Basin, the Llrid Basin is a dramatic feature in northeastern British Columbia and the Northwest Territories, bounded on the east by the Rodeo Lake fault and fold complex. Also in the north, between the Peace River Arch and the Taltihna Arch, is the northwest-trending Hay River Fault and coincident Great Slave Lake Shear Zone (Fig. 3.1), which has up to 700 km of dextral displacement in Lower Proterozoic basement rocks. Vertical displacement and (possibly) horizontal offset are present in the Proterozoic strata near the Hay River Fault, but these are difficult to substantiate without geophysical data.

Apart from compaction and draping structures over reefs or other competent rock bodies, which are not discussed in any detail here, other "structural features" in the plains component of the WCSB include meteorite impact craters, and salt and carbonate dissolution structures. Several probable impact craters have been studied in the WCSB; all have faults or fractures near their sub-circular, raised perimeters and some have a central uplift. At Viewfield in Saskatchewan (Tp 7 R 7 WM), there is a probable impact location which is 6 km wide and contains fractured Mississippian carbonates (Swatkins, 1975). Other possible astroblemes are discussed in Burwash et al. and Norford et al. (Chapters 5 and 9, this volume).

A variety of solution features are present in the basin. For example, dissolution of Devonian Upper Elk Point salt has occurred around reefs of similar age. The timing of dissolution varies, but has been interpreted from seismic and subsurface well information. Dissolution of Devonian salt is also evident at the sub-Mesozoic unconformity, controlling to some extent the variation in the thickness of overlying Cretaceous strata as well as the relief on post-Cretaceous surfaces in the eastern and northeastern WCSB. Karst topography is present on several erosional surfaces.

In terms of present-day structural features, adjustment along pre-existing fault planes is undoubtedly occurring and is expressed as geomorphological trends. Lineaments on the plains commonly reflect salt solution trends and deep faults. In the Cordillera, the amount of seismic (earthquake) activity recorded through this century is low—with between 54 and 60% (Müller et al., 1978).

Phanerzoic Summary

The Phanerzoic sedimentary wedge (Fig. 3.2) thickens southwestward from the exposed Canadian Shield to a preserved thickness of over 6 km east of the deformed belt in the Liard Basin, and southwestward to over 3 km in the Canadian portion of the Williston Basin. The latter was centered in North Dakota, but individual systems had different geographic depocenters, commonly within a circle of radius 110 km. In contrast to other intracratonic basins in North America, (Hudson Bay, Michigan and Illinois basins), the Williston Basin was periodically connected to the proto-Pacific ocean to the west through the northern United States, but became isolated in the Late Jurassic during the Cordilleran Orogeny. Anomalies in the Phanerzoic wedge include the Peace River Arch, the Swift Current Platform and the Bow Island Arch (Fig. 3.1). One of the less obvious tectonic anomalies is the thinning around Fort Nelson, in British Columbia, which was a tectonically positive element throughout the Phanerzoic (Fig. 3.2).

Periodically separating the Alberta and Williston basins (Fig. 3.1) was a positive area comprising the Bow Island Arch (Williams and Burb, 1964) and the Swift Current Platform, which formed the locus of intermittent, broad, low-relief topographic highs throughout the Phanerzoic (Kent, 1987). The northeast-trending Bow Island Arch is structurally distinct from the more complex Sweetgrass Arch of Montana, which has a northwest trend and consists of a South Arch and a North Arch (the Kevin-Sunburst Dome) separated by the possibly dextral northwest-trending Pen-droy Fault. The Sweetgrass Arch may have been contiguous with "Montania" of the early Paleozoic.

Deep well control becomes sparse toward the mountains, but in the Canadian Rockies the Cambrian to Cretaceous interval thickens to the west. Within the fold and thrust belt, much of the Phanerzoic section has been removed by uplift and erosion, yet Paleozoic strata attain thicknesses of over 8 km. West of the Rocky Mountain Trench, subsurface data are minimal but surface stratigraphic data suggest that there may have been a number of major sub-basins bordered by the North American Craton (see for example Struck, 1987).
Figure 3.2: Phanerozoic isopach of the Western Canada Sedimentary Basin. Represents 540 m.y. of deposition. Contouring is digitally smoothed on this and other regional maps in this chapter, manually smoothed at the eastern and western margins. In the west, contours reflect some seismic control. KB – Kelly Bushing of CG.
Figure 3.1 Cratonic Platform Isopach of the Western Canada Sedimentary Basin. Represents 334 m.y. of deposition (540 to 206 Ma). The cratonic platform is defined east of the thrust belt as the sub-Jurassic to Precambrian isopach. Note that there are few deep wells south and west of Edmonton, and that there are no contours west of the Bow Lake Fault, where isopach values exceed 3000 m.
Figure 3.4 Geological sections across the Western Canada Sedimentary Basin, east of the Cordilleran Fold and Thrust Belt (from Wright, 1984). Colours represent Atlas stratigraphic subdivisions. Vertical exaggeration is approximately 40 times. Note zone of overlap at the break in the A-A' section.
Figure 3.4 Continued
Cratonic Platform: Architecture – Cambrian to Middle Jurassic

The Paleozoic and earliest Mesozoic sequences (Fig. 3.3) were dominated by extensional tectonics and typified by the presence of an open ocean to the west. “Cratonic Platform” depositional sequences ended in Middle Jurassic time, about 138 million years ago. The cratonic platform succession can be described in terms of two divisions: the Sarn “Cambrian and older” sequence of Sloss (1965, 1968), and the remaining succession, encompassing three of Sloss’s Paleozoic sequences (Tippecanoe, Kasaskia and Ab- saroka). The preserved sub-Jurassic rocks (Fig. 3.3) are thickest north of 95°N, particularly north of the Peace River Arch (Figs. 3.1, 3.4). Although several systems are well represented throughout the WCSB, the Ordovician and Silurian strata of the plains are best preserved in the Williston Basin, and the Triassic is thickest in the north-west. The Cambrian to Jurassic platform sequences are interrupted by numerous widespread unconformities, which generally become less pronounced west of basin hinge-lines. Early Paleozoic sedimentation was affected by local high blocks, presently located within the Cordillera.

The asymmetrical Williston Basin is well defined by thick Paleozoic sediments (Figs. 3.2, 3.3, 3.11 and Kent and Christopher, this volume, Chapter 27). Eastward transgression of the Cambrian sea is represented by the clastics-dominated Upper Cambrian Deadwood Formation; the latter shows thinning over Upper Cambrian positive elements such as the Nesson and Cedar Creek antiformal in the U.S.A. Across the Cedar Creek Antiformal, the entire Devonian section is missing, primarily because of erosion. The Swift Current Platform and Meadow Lake Escarpment (Fig. 3.1) were active during Silurian time. Porter and Fuller (1959) also recognized Silurian uplift on the eastern margins of the Williston Basin. Uplift of the Transcontinental Arch was synchronous with the establishment of the basin, the axes of which can be traced from the Northwest Territories and northeastern British Columbia, through the La Cret and Prairie Evaporite sub-basins into north-central North Dakota. The topographic highs of the Peace River Arch and the independent, 320 m high Meadow Lake Escarpment (Figs. 3.1, 3.4, 3.5), and the West Alberta Ridge, had profound effects on Devonian deposition, but the impact of basement features on Devonian reef growth varies from area to area. The Meadow Lake Escarpment lies above the Precambrian Hearne Province of the Canadian Shield and could be a purely topographic feature, although it may be associated with the Stanley Fault, mapped to the east on the exposed shield. This sub-Middle Devonian escarpment forms the northwest erosional limit of several lower Paleozoic units and provides the relief for the southern depositional limit of the Middle Devonian Lower Elk Point evaporites, Middle Devonian Upper Elk Point strata blanket the escarpment.

Coincident with the Late Devonian-Mississippian Antler Orogyny of the U.S.A., extensional tectonics produced the Liard Basin (Figs. 3.1, 3.2) and the east-west-oriented Peace River Embayment (Figs. 3.6, 3.7, 3.8) containing the similarly oriented Fort St. John graben (see Bardsey et al., 1998). Orthogonal faults are associated with the graben. Similar grabens and orthogonal faults are present within the thrust belt (Richards, 1989). The Dunvegan Fault (Figs. 3.6, 3.7, 3.8) near the eastern end of the Peace River Embayment was active primarily in Late Mississippian, Pennsylvania and possibly Pennsylvanian time. It provides an example of the reactivation of a boundary between two Precambrian elements, the Kootenay magnetic high and the Chinchaga magnetic low (Fig. 3.7). The 88 km long Dunvegan Fault has a northwest orientation and is parallel to many other lineations in northern Alberta and British Columbia, some of which are also identifiable as present-day topographic lineaments. The Carboniferous Prophet Trough of Western Canada (Richards, 1989) can be mapped from the Antler Foldzone of the western United States northwest to Alaska, and straddles the present-day Rocky Mountain Trench. Henderson (1989) showed that the Prophet Trough existed into the Permian (the Tashmoo Trough). Exposed in the Cordillera are several other features, such as the Sukansa High (Fig. 3.1) which extends from near Jasper to the Peace River area and was active from earliest Middle Permian on to earliest Permian (about 70 m.y.)
Depositional (or at least isopach) strike of Paleozoic strata in southern Alberta was east-west, changing to northeast and eventually north-northwest by early Mississippian time. The Mississippian has a particularly well defined depocentre in North Dakota but depositional centres for individual units of the Carboniferous Madison Group clearly vary. Within the Williston Basin, Permian-Pennsylvanian strata are preserved only in the deeper southern areas. The Bow Island Arch became an important barrier between the Alberta and Williston basins in Triassic to Late Jurassic time (Christopher, 1985), isolating the more evaporitic Williston Basin (Kent and Christopher, this volume, Chapter 27). Thin Mississippian strata beneath sub-Jurassic erosional surfaces indicate the positive axis within the Arch, which at that time plunged southward.

**Foreland Basin: Architecture – Middle Jurassic to Oligocene**

The foreland basin (Fig. 3.9) contains the Zuni and Tejas sequences (Sloss, 1988). Because ground elevation, or rather, Kelly bushing elevation, has been used in mapping, the isopach map includes Miocone and Pleocene strata as outliers, as well as glacial deposits. In the northeast parts of the foreland wedge, irregular thicknesses are due to present-day erosional outliers, such as the Swain Hills (Fig. 3.4), Caribou Mountains, and Cypress Hills. The foreland basin sequences form a thick (up to 4000 m) arcuate band of sediment that is best developed south of 56N (Tp 81) and west of the Bow Island Arch. The foreland basin formed as a consequence of deformation along the western edge of the North American Craton, which began in the late Early Jurassic with the accretion of exotic terranes from the Pacific. Marked subsidence of the foreland basin occurred in the Kimmeridgian more than 20 m.a. after the initial collision, deformation and metamorphism, suggesting that this early deformation occurred mainly subsea and well outboard from the thick North American craton (McMechan and Thompson, in press). Immobile loading of the North American craton as a consequence of structural thickening and overlap during compressive deformation caused the gradual depression and flexure of the craton and formed the foreland basin (Price, 1973; and this column, Chapter 2). Erosion of newly uplifted western source areas helped fill this trough with sediments. The orogenic events have west-east chronology and a peripheral bulge can be expected to have moved eastward with each major advance of the east-verging thrusts and folds. The bulge was possibly arrested periodically by anomalously underlaying structures.

Renewed uplift and consequent erosion immediately postdated the termination of compressive deformation in the Middle Eocene. Middle Tertiary uplift is displayed on the burial history curves (Fig. 3.10). Cool rock data suggest that this uplift increased from approximately 1 km in the east to over 2.5 km at the western edge of the undeformed basin near 54N (Kalkeuth and McMechan, 1984; Nukiowski, 1984, and Osadetz, pers.comm.), whereas the maximum erosion north of 56N was less than 1 km (Kalkeuth and McMechan, 1988). Within the Rocky Mountains, over 4 km of early to late Eocene Oligocene uplift and erosion are recorded by the changing provenance of clasts in the Oligocene Kisheninan Formation of the Flathead Valley group (McMechan, 1981). Thus the Eocene foreland basin was substantially deeper than, but similar in form to, the present foreland basin. For example, the foreland basin strata in southern Alberta (near Fort Macleod, Tp 8 R 23 W4M) still measure over 3000 m despite post-Tertiary erosion of 1900 m (Nukiowski, 1984 and pers. comm.).

**Figure 3.7** Dunvegan and Belloy gas fields. Structure map on the Mississippian Darlot Formation. The Dunvegan Fault is approximately coincident with the northeast limit of the Killanym magnetically positive arc. Tops are from a variety of sources and can be used only in a regional context.

**Figure 3.8** Dunvegan seismic section. The line is parallel to the Peace River and shows the Dunvegan Fault with displacement from well control over 77m down to the northeast, where the Pembina and uppermost Mississippian are thinner. Line courtesy of Source Levee Ltd. O.D.P. coverage 100% - migrated, 1985 vintage. Displacement of Devonian Wabamun is 60 ms.

The thick southern part of the foreland basin sequences of the Alberta Basin terminates (to the north) within the site of the earlier Peace River Embayment (Figs. 3.6, 3.7, and this column, Chapter 2). Marked changes in coal rank suggest that the area was structurally active in the Tertiary (Kalkeuth and McMechan, 1980). The contrast in depositional trends between the Lower Cretaceous beds (variable, but approximately north-south) and the post-base Fish Scale marker succession (east-west in British Columbia) is remarkable. The thickening of the Lower Cretaceous Upper Mannville Group is centred on the site of the Carboniferous Peace River Embayment, and the control may also have been exerted on the orientation of the younger Paddy and Cadotte members of the Cretaceous Peace River Formation (Leckie et al., 1990). Depositional trends in the Paddy-Cadotte sequences are subparallel to the axis of the late Devonian expression of the Peace River Arch, and indeed almost coincident with the crest of the high where the Devonian Wabamun Formation is absent (Figs. 3.5, 3.6, 3.10c). The Liard Basin also shows a thick section of Cretaceous strata that thins abruptly eastward at the Bowie Lake Fault (Figs. 3.4, 3.10a).

The Bow Island Arch (Figs. 3.1, 3.9, 3.10b) may, in part, provide an example of interference between the Alberta foreland basin peripherial bulge and the rim of the Williston Basin (Beaumec, 1981; Wu, 1991). The axis of the Bow Island Arch can be defined on the 1000 m contour of the foreland basin-fill isopach (Fig. 3.9). Circular intrusions are present in the northeast quadrant of the Kerwin-Sum- burn Dome (Foley, 1972) and provide some of the rare exposures of igneous intrusions into sediments of the WCBS. The intrusions occurred at a time of widespread extension and volcanism within the Cordillera which immediately postdated compressive deformation of the Omineca and Rocky Mountain Foreland Fold and Thrust belts. Intrusions in the Sweetgrass Hills of Montana, near the Alberta border, and the exposed dykes within Alberta (Wil- liams and Dyer, 1950) range in age from 74 to 59 Ma, according to Marvil et al. (1980), who also recalculated the age of the Miocene Dyke at Pinhorn Butte in Alberta to be 49.7 Ma.

The Williston Basin (Figs. 3.4, 3.10f, 3.11) continued to accumulate sediments in Mesozoic time. In Saskatchewan it has a significant east-west extension, not apparent in the basin's earlier history (Figs. 3.9, 3.32). The Punrock Arch and the Swift Current Platform emerged near the northern and western margins of the Williston Basin (Fig. 3.11) in Late Jurassic time. Within Saskatchewan, the Punrock Arch and the Bowdoin Dome (Fig. 3.11) were both posi- tive during the Cretaceous, and fault movement persisted over Pecosianian time. Significant dissolution of Devonian salt contin- ued throughout the WCBS (Fig. 3.11).

**Cordillera**

**Summary**

The western margin of the WCBS, now preserved in the Cordillera, has had a long tectonic history dominated by major episodes of extension. To what degree compressive tectonic events affected the western edge of the WCBS prior to Jurassic Cordilleran deformation is a subject of debate. Two thick (up to 20 and 9 km) Protorezo- sic sequences in the Cordilleran Fold and Thrust Belt are generally absent in the undeformed WCBS to the east. The older, Middle Protorezoic Belt-Purcell sequence marks the beginning of the filling of the basin and provides evidence of continental rifting and extension around 1500 to 1400 Ma which, at least locally, formed extremely attenuated continental or oceanic crust. How- ever, it was continental rifting and separation associated with deposition of the Upper Protorezoic Windermere Supergroup that established the general position and trend of the proto-Pacific North American margin and the western edge of the WCBS. U-Pb zircon dates suggest extension was initiated between 770 and 730 Ma (see Hein and McMechan, this column, Chapter 6). A major latest Protorezoic extensional (rifting) and thermal event (Broom and Komirzi, 1984) controlled sedimentation in the up to 7 km
Figure 3.9 Foreland Basin isopach of the Western Canada Sedimentary Basin, representing the section preserved above the base of the Jurassic (208 Ma) to surface (KB – Kelly Bushing.)
Figure 3.10 Burial history curves and Phanerozoic isopach map. No profile is decompacted. Locations are indicated by letters on the accompanying Phanerozoic map. Curves are estimated in part from vitrinite reflectance data, and also from flexion track analysis, reported in Isak et al. (1990), Kukulnowski (1985), and Osadetz et al. (1990). Coefficients vary in meaning.
Williston Basin: Phanerzoic Isopach and Structural Elements

 STRUCTURE AND ARCHITECTURE

Figure 3.11 Williston Basin Phanerzoic isopach and structural elements. Isopach data in the U.S.A. portion of the basin are from Jernsien (1972).

K.B. TO BASE OF FISH SCALES ISOPACH

Illustrating post-95 Ma crustal shortening and sedimentary fill

Figure 3.12 Isopach map, surface (Kelly Bushing) to Cretaceous Base of Fish Scales.

approximately this change in direction (Figs. 3.5, 3.6) and this suggests significant north-side-up reactivation of structures associated with earlier arch and embayment tectonic controls. This reactivation of pre-existing transverse structures had a more pronounced effect on the along-strike basin form than the gradual northward decrease in the amount of time-equivalent shortening in the immediately adjacent fold and thrust belt (Fig. 3.12).

Structural Styles

The structural style of the fold and thrust belt was largely controlled by the lithological character of the deformed stratigraphic sequences. Thick, competent carbonate and/or sandstone successions favoured the development of thick thrust sheets. On the other hand, less competent interstratified shale and sandstone, or shale and carbonate successions, favoured the formation of folds between detachments. Locally, earlier-formed normal faults or basement ramps influenced Cordilleran structural development and trends.

A northward change in structural style from thrust-dominated in the south to fold-dominated in the north reflects facies changes within the Phanerzoic section and a general northward decrease in competency of almost the entire section. A broad transition zone, with folds more common at the surface and thrust faults more common in the subsurface, occurs between Athabasca River and Williston Lake-Piceau River. Structural cross-sections (Fig. 3.13) illustrate structural styles for the eastern foothills part of the fold and thrust belt, where most of the deformed belt hydrocarbon exploration has been and will continue to be over the next decade. Significant variations in structural style across and along the western part of the fold and thrust belt were recently reviewed in McMechan and Thompson (1989) and are not discussed here.

Northeast-verging thrust faults in Mesozoic and Paleozoic strata characterize the southern foothills. The Highwood River section (Cordy and Frey, 1975; Fig. 3.13) is typical of the foothills south of Bow River (51%), where Mesozoic clastic strata are cut by numerous thrust faults and Paleozoic strata by fewer. North of the Bow River, imbrication of the Mesozoic section is less intense. Strata near the leading edges of single thrust sheets or in thrust sheet stack-ups are targets for petroleum exploration (Fig. 3.13). A triangle zone or zone of underthrusting occurs at the eastern limit of deformation along most of the southern foothills (Jones, 1982). The resulting deformation of the overlying para-autochthonous strata produced the east-dipping west limb of the Alberta Syncline along the western edge of the essentially undeformed Alberta Basin (Figs. 3.4, 3.13).

Large-amplitude box and chevron folds in upper Paleozoic and Mesozoic strata characterize the surface structural expression of the northern foothills, a marked contrast to the complex array of faults found in the southern foothills (Fig. 3.13). Seismic data show that small-displacement reverse faults with both east and west dips underlie some of the surface anticlines, even though none are shown in Gabrielse and Taylor’s (1982) Tuchodi-Muskwa section (Fig. 3.13). Low-amplitude folds, developed in upper Paleozoic to Lower Cretaceous strata beneath nearly flat-lying Upper Cretaceous sandstone and shale, occur up to 20 km east of the physiographic northern foothills. Some of these structures result from the
Figure 3.13 Structural styles of the fold and thrust belt, eastern part. The fold-dominated northern Rockies (Tuchodi-Muskeg section) are separated from the thrust-dominated southern Rockies (Highwood River section) by a broad transition zone (Sukunka River section). Lines of section are shown in Figure 3.12. Colours vary in meaning.
reactivation and partial inversion of grabens, filled mainly with upper Paleozoic sediments. Partial inversion of grabens oriented subparallel to the compressive oxygen-forming stress field commonly occurs east of "regular" fold and thrust belt structures. The Bovie Lake Fault complexes on the eastern side of the Liard Basin (Figs. 3.4, 3.14, 3.15) may be related to this phenomenon.

Northern foothills folds formed above a regional detachment developed in a thick Upper Devonian and Mississippian shale succession. Underlying Devonian and older carbonates remained essentially undeformed across the eastern part of the subprovince. A few simple thrust faults are thought to deform these strata under the western part of the foothills (Fig. 3.13).

The transition zone between the thrust-dominated south and the fold-dominated north contains a variety of structural styles. To a large degree these reflect changes in structural competency of the deformed stratigraphic sequences. At Sukunka River (Fig. 3.13), the Front Ranges comprise complex, narrow folds formed in the interlayered competent and incompetent Upper Devonian to Triassic succession. These folds formed above a detachment in thick Upper Devonian shales. The underlying thick, competent Middle Devonian to Cambrian succession is mainly thrust faulted. In the western foothills, folded Lower Cretaceous strata at surface are separated by a detachment in the Jurassic and Cretaceous Fernie-Mines succession from Triassic strata with a very different structural style of faulted folds and local imbricate thrust (dipslips) complexes. Underlying Mississippian strata occur in relatively simple fault structures. The complex nature of the folded and faulted Upper Triassic reservoirs was described by Carswell and Monand (1981). A markedly different structural style occurs under the eastern foothills (Fig. 3.13). Barely deformed Upper Cretaceous Second White Specks and younger strata at the surface are underlain by broad, low-amplitude box folds formed by footwall folding and fault displacement transfer. Seismic data show that relatively small-displacement, northeast-verging reverse faults climb out of a detachment near the base of the Triassic and into an upper detachment in Upper Cretaceous Kaskapau shales. Small east-dipping anticlinal reverse faults that commonly die out upward as folds are relatively common. The Cretaceous Mines Group does not form an important detachment zone here, presumably because of eastward truncation and facies changes to more structurally competent strata in the upper part of the Mines Group.

**Basin Architecture**

**Structural Framework**

Some of the structural elements of the WCSB (Fig. 3.1) are associated with movements of the underlying basement. The texture and orientation of aeromagnetic data, integrated with age and lithological information, allow the basement east of the Cordillera to be subdivided into five broad, Precambrian units (Fig. 3.1) ranging in age from 1.8 Ga to 2.8 Ga. From southeast to northwest they are as follows: the Superior Province, the Trans-Hudson Orogen, the
Heorne Province (including the Cree Lake Zone), the Rae or Northwest churchill Province, and the Slave Province (Ross, 1989). The Snowbird Tectonic Zone separates the Heorne and Rae provinces, and the Great Slave Lake-Shear Zone separates the Rae and Slave provinces (see Ross et al., this volume, Chapter 6; Burwash et al., this volume, Chapter 9).

Beneath the eastern Williston Basin, the relatively young, north-south-trending Trans-Hudson orogenic belt (about 1.9 Ga) has been mapped utilizing aeromagnetic surveys (Fig. 3.11). Within the belt is the North American Central Plains (NACP) conductivity anomaly (Cantfield and Gough, 1977). This anomalous electrical conductivity zone in the crystalline crust extends from the Black Hills Uplift of South Dakota northward into Saskatchewan (Fig. 3.11). Several salt dissolution features, including the Hummingford Trough (Holter, 1969), appear to be related to the zone of anomalous conductivity. Parallel to the NACP anomaly and coincident with the north-south-striking Nosson Anticline of North Dakota is a broad salt anomaly (Majowicz et al., 1988) associated with elevated thermal maturity of Paleozoic hydrocarbon source rocks (Osadetz et al., 1990).

Locally there is evidence of Phanerozoic geology being influenced by basement structures. The Great Slave Lake-Shear Zone contains the Hay River Fault (Fig. 3.5) which affected Cretaceous strata and possibly influenced the deposition of the Devonian Elk Point Formation within the Rainbow oil field (38°00′N 109°W) and the Northwest Territories. According to Hoffman (1987), large-scale dextral transform movement of 300 to 700 km occurred until 1.9 Ga along the 25 km wide shear zone, which extends some 1300 km from northeastern British Columbia through Alberta and into the Northwest Territories (Fig. 3.11). This shear zone is clearly visible on aeromagnetic maps and to a lesser extent on gravity maps. At its southwestern end, where magnetic changes are less obvious, it may be a composite of several smaller faults, this may also be true for the southwestern end of the Snowbird Tectonic Zone (Fig. 3.1).

There is little evidence of Mesozoic and Cenozoic transcurrent movement east of the Cordillera, but dextral movements have occurred throughout British Columbia, related to the oblique convergence of the Pacific plate with the North American plate. Gabrielse (1985) suggested that lower Paleozoic units along the western edge of the basin have moved northwestward 750 km or more along the Northern Rocky Mountain Trench and Tintina faults, between the Middle Jurassic and early Cenozoic. Motogi (1989) stated that there could have been as much as 1000 to 2500 km of northern transportation involving the western allochthonous parts of the Cordillera since mid-Cretaceous times.

The epibathic Taltah formation forms the northern limit of the study area and can be defined from isopachs of "Middle Devonian" strata (Fig. 3.5). A Devonian Lower Elk Point Formation isopach map suggests a concave (to the south) ridge, but well control is sparse and the data therefore are potentially misleading.

Alberta Basin

The Alberta Basin is defined here as that part of the WCSB north and northwest of the Row Island Arch (Figs. 3.1, 3.9), extending up to the suba Taltahna High (Fig. 3.5). Since Cambrian time there have been two major high areas in the Alberta Basin: the Peace River Arch and the West Alberta Ridge (see Meijer Drees, this volume, Chapter 11). Central Alberta (Fig. 3.10A) shows little evidence of significant tectonic activity until Tertiary time.
To the northeast of the Dunvegan Fault (or fault), the Mississippian is downthrown by at least 77 m (Figs. 3.7, 3.8) preserving additional Mississippian Stoddart strata. This is shown by the Permian Belloy to Mississippian Deboit isopach, which thickness from the Dunvegan gas field into the depression to the northeast. Earlier evidence of the positive nature of the northeast boundary of the Keewatin block is the coincidence of the northwestward part of the Dunvegan Fault and the landmass existing during Frasnian (Ladinian) time suggested by the 200 m contour in Figure 3.5 (see Dix, 1960). Although here the coincidence of the Precambrian boundary and the Paleozoic fault is remarkable just 60 km to the northeast, at the fault-associated Tangent oil field, which produces mainly from the Devonian Waterbury Formation, there is no obvious aeromagnetic anomaly.

The Liard Basin of northeast British Columbia and the southern Northwest Territories is a striking feature of the WCSB east of the loading edge of the thrust belt (Figs. 3.1, 3.4, 3.14, 3.15). This 80 km by 200 km unexplored trough is bounded on the east by the Bovye Lake Fault, which is primarily post-Mississippian in age. The fault south of 1200 m of west-side-down vertical displacement of the Middle Devonian, over a horizontal distance of 500 m. The Bovye Lake Fault complex contains normal faults but shows some attributes of later and thrust movement. It was reactivated during Cordillerean deformation, which also produced folding within the Liard basin. The western boundary of the trough is less easily defined, but may be considered to coincide with the eastern edge of the physiographic Rocky Mountain Foothills. The burial history curve (Fig. 3.13a) shows the high depletion rates that have occurred periodically from Mississippian to Tertiary time. A short distance to the east of the Bovye Lake Fault, at about 60°N, 122°W, is the elliptical Colbath High, which may have been formed early in the Cretaceous (Fig. 3.9).

Faults present in deeper strata may be represented by fractures higher in the section; neither are necessarily parallel to the strike of the beds. Near Fort Macleod (Tp 9 R 2 W 4 M), reflection seismic data indicate that faults with strikes of 120 to 128° clearly affect Devonian and Cambrian strata (Figs. 3.14, 3.17), and are associated with fracturing of Mississippian Banff to mid-Cretaceous base of the Fish Scale zone rocks as determined from borehole data. Bell and Babcock (1986) reported similar borehole breakout azimuths in the area (121-135°). The 260' basin dip direction (Eq. 3.16) is clearly different from the direction of current maximum horizontal stress (211-241° as derived from Bell and Babcock's data).

East of the fold and thrust belt, some normally impermeable Devonian to Cretaceous strata have open fractures containing commercial oil and gas pools. One particularly prolific well was drilled in 1968 near Clarksburg (50 km northwest of Fort Macleod) by Dome Petroleum, at 66-12-24 $W$, and as of September 1991 had produced 2104 m$^3$ of oil from perforations into the fractured, oil-rich Cretaceous “Second White Sparks” zone. The same zone contains fractured reservoirs in central Alberta at the Pine Creek field (Tp 56 R 19 $W$M) where the fractures could be due to a combination of factors such as thrusts, "down to the basin" faults, or differential compaction around underlying reefs. The open fracture system (strike 142°) at Pine Creek is oriented approximately perpendicular to the current direction of maximum horizontal stress (228-229°; Bell and Babcock, 1986). At Edson (Tp 51 R 18 $W$M), fractures in Cretaceous shales are associated with minor northeast-directed thrust faulting and the development of passive roof duplexes some 30 km east of the eastern margin of the fold and thrust belt (Skue et al., 1992).

**Williston Basin**

The Williston Basin (Figs. 3.1, 3.10, 3.11) is a Late Cambrian to Tertiary intracratonic basin centred in Williams and McKenzie counties, North Dakota, where total sediment thickness reaches 4900 m. The basin is bounded on the west by the Central Montana Uplift and on the east by Precambrian exposures (Fig. 3.11). The southern margin of Williston Basin is defined (using a 2500 m Phanerozoic contour) by the northwest-trending Black Hills Uplift. At the southeastern margin of Williston Basin is the Sioux Uplift (part of the Transcontinental Arch of South Dakota), which is capped by Precambrian basement. In simple terms the basin is a sacral-shaped depression with three main structural elements: the northwest-trending Cedar Creek Anticline, and the Nelson Anticline and Bowdoin Dome; all of which have an approximately north-south orientation (Gerhard et al., 1990, and Clement, 1987). On the Cedar Creek Anticline a thin Cretaceous section rests on Silurian strata, indicating significant vertical movement. The 25 km wide Bowdoin Dome, with up to 200 m of closure, extends from just north of the Canadian border, southeast for 100 km into Montana. It contains an estimated 13 x 10$^9$ m$^3$ of recoverable Upper Cretaceous gas (Rice et al., 1991). Late Cretaceous and Early Tertiary uplift is recorded by erosion across the dome. In Williston Basin other distinct structural elements with 50 to 60 m of relief are oriented along northwest and northeast trends, and contribute significantly to the localization of hydrocarbon reserves. Shifting axes of deposition throughout Phanerozoic time are well documented, suggesting intrabasinal basement control as well as influence from the surrounding tectonic elements especially those to the southwest.

Direct evidence of basement faulting in the Williston Basin comes from both well and seismic data. Kent (1974) and others have suggested that surface lineaments provide indirect indications of a dominant northwest-southeast and a subordinate northwest-southwest fault system. The dominant lineation direction may vary geographically and stratigraphically. Based upon a regional analysis of structural elements, Thomas (1974) concluded that simple shear basement coupling along zones of basement weakness created large rectilinear basement blocks and the present configuration of faults in the Williston Basin. Brown and Brown (1987) proposed that pure shear along a wrench-fault system with both vertical and horizontal displacement created normal faults, grabens, etc., along block boundaries. They explained rotation of basement blocks adjacent to wrench faults by scissor-type faulting in response to adjustment from compressional stress. With the exception of Devonian and early Mississippian strata, Paleozoic strata have a preferential northeast-southwest direction of shear with left lateral movement in response to an estimated azimuth of maximum horizontal stress trending 012°. Within the Mississippian strata, recent work by R.A. Clark (pers. comm.) indicates a common borehole breakout direction of 105°, which coincides with an 015° azimuth of maximum stress, although breakout directions also occur. Extensive studies by Thomas (1974) indicate that in the southern portion of Williston Basin, in Montana and North Dakota, structural features such as the northeast-southwest Brookton-Froid Fault Zone and the Weldon Block are reflected by surface lineaments (Fig. 3.11). Gerhard et al. (1990) proposed that left-lateral shearing of the Precambrian craton along the well-defined northeast-southwest-trending Brookton-Froid Fault Zone and on the Transcontinental margin created the conjugate shear pattern throughout the basin. Secondary elements include the "Divide Re-entrant" (Kissling and Ehrets, 1980), which is on a northeastern extension of the Brookton-Froid Zone that trends perpendicularly to the Devonian Winnipegosis shelf margin in North Dakota into a deep, pinnacle-bearing sub-basin in southwestern Saskatchewan.

The Panunich Arch (Fig. 3.11) trends east-west and defines a structural "lip" in the northern portion of Williston Basin. The arch extends to the southwest to join the Virden-Whitewater Lake erosional high of Manitoba. Movement on the Panunich Arch may be traced back to Silurian time (Paterson, 1975) with dramatic post-Mississippian erosion that produced relief of up to 300 m. It was re-activated in Early Cretaceous time and also during the Late Albian. Late Albian erosion bevilled the arch and opened up the Late Cretaceous seaway into the Williston Basin (Christopher, 1980, 1984).
Clearly some oil and gas pools in the Williston Basin are associated with fault complexes. Reactivated deep structures are reflected, in part, by erosional or subcrop patterns, and carbonate diapirism or deformation of the basement. The Mississippian oil pool in Saskatchewan is an example of a local, fault-bounded basement structure where 40 m of relief at the Orleodou level extends over a 3.5 km (2.5 miles) distance. Pre-historic high (Potter and St. Omer, 1991). Near the North Dakota/Saskatchewan border, on a similar high, oil is produced at the Norpylt Field from Cambrian and the weathering basins. Preliminary subsidence at evaporated salt basins in the Mississippian Mission Canyon Formation (Sherwood Zone) in the Carcass and Elmore pools of southeastern Saskatchewan are analogous with "limbs" 25 to 30 km long, suggesting basement fault controls.

**Summary**

1. The Western Canada Sedimentary Basin consists of the Ottine and Cordilleran Fold and Thrust belts in the west and the loosely defined Alberta and Williston basins to the east.

2. Trace fossils appear to be present at various levels throughout the Williston Basin. The Cambrian to Devonian interval is characterized by the presence of various trace fossils, indicating that the Williston Basin was a marine environment during this time period.

3. Pre-Cambrian boundary faults have affected the Phanerozoic sedimentary rocks in the western parts of the basin. These faults have produced significant structural and stratigraphic changes, including the development of the Great Slave Lake Basin.

4. The Cordilleran Fold and Thrust Belt formed during the Jurassic to Cretaceous collision of the North American plate with the Laurentian craton. This collision resulted in the development of the Rocky Mountains and the formation of the Great Divide Fault System.

5. The Bow Island Arch, described by Williams and Burd (1946), is the southern end of the Williston Basin and contains a major oil province. The arch is characterized by a series of fault-bounded basins that trap massive oil and gas deposits.

6. Salt dissolution has profoundly influenced the depositional and structural patterns of the western parts of the basin. The dissolution of evaporite units has created numerous structural features, including the development of the Great Slave Lake Basin.

**References**


