Chapter 9 – Middle Ordovician to Lower Devonian Strata of the Western Canada Sedimentary Basin

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Introduction

Although originally depositionally continuous, Middle Ordovician to Lower Devonian rocks are preserved only in isolated and separate areas within the Western Canada Sedimentary Basin: the Williston Basin and the mountain outcrops (Figs. 9.1 to 9.4). The stratigraphic package primarily corresponds to the Tippecanoe Sequence (Sims, 1961) but includes older (uppermost Sakia Sequence) and younger (lowest Kaskaskia Sequence) rocks in the mountains. Its present distribution is severely constrained by the effects of several later episodes of erosion. The entire succession is missing from virtually all of the basin north of the Meadow Lake Inercement, and Middle Devonian rocks rest directly on the Precambrian in much of this region. The base of the succession is a regional unconformity, except in the Rocky Mountains, where it is conformable within the basin facies and within the immediately adjacent platform facies. Several other unconformities are present within the Middle Ordovician to Lower Devonian succession.

The thick outcrop sequences (up to 2000 m) of British Columbia, Alberta and the District of Mackenzie disappear abruptly eastward and southward in the subsurface, below Devonian unconformities. Lower Silurian Nondius carbonates (up to 270 m) are the only part of these sequences with any significant extension into the subsurface. Preserved extensively in the subsurface of southern Saskatchewan and Manitoba and southeastern Alberta are strata that represent an early development of the Williston Basin. A basal clastic unit (up to 68 m) is restricted to Saskatchewan and Manitoba and a sequence of platform carbonates (up to 400 m) extends over the entire area of preservation. These rocks extend into outcrop in Manitoba and in eastern Saskatchewan. Their easternmost extent is marked by outcrops at Lake Winnipeg; the western feather-edge (basal Red River Formation, subsurface) is about 150 km west of the Alberta-Saskatchewan boundary.

Previous Work

By 1896, Silurian rocks had been recognized in outcrop in southern Manitoba and in the southern Rocky Mountains; these included strata subsequently designated as Ordovician. Reconnaissance studies later documented the presence of the stratigraphic interval in the northern Rocky Mountains, in the Yukon, in the District of Mackenzie and in northern Manitoba. Drilling led to its discovery in the subsurface of the southern plains. In the 1964 atlas (McCrossan and Glaister, 1964), Porter and Fuller presented an excellent synthesis of the subsurface development and Norford outlined the outcrop distribution in the Rocky Mountains as far north as the British Columbia-Yukon boundary. Lower Devonian rocks later were recognized in northern British Columbia. Since 1964, extensive drilling, stratigraphic tests and sedimentological studies have added much detail to the knowledge of the subsurface development of the plains. Knowledge of the outcrop regions of the Rocky Mountains and of the Territories has grown substantially through systematic mapping and of stratigraphic studies but virtually no sedimentological investigations have been attempted. East of the Rocky Mountains and south of the Mackenzie River, studies of the subsurface revealed that Middle Ordovician to Lower Devonian rocks extended only short distances into the subsurface from the outcrop regions. Recent syntheses of the stratigraphic interval include Cecile and Norford (in press), Osdetr and Haidl (1989), and Norford (1991) for the mountain regions. These, together with Norford (1964) and Porter and Fuller (1964), provide a comprehensive bibliography of the Middle Ordovician to Lower Devonian stratigraphic interval of the Western Canada Sedimentary Basin.

Geological Framework

During the early Paleozoic, a miogeocline lay next to the western margin of the North American craton. The transition between them (close to Q-Z) and to the boundary between southern Alberta and British Columbia in Fig. 9.1) was abrupt at most times and marked by slope environments that separated the shallow waters of the craton from the deep oceans. The western margin of the North American continent probably lay just beyond the Cenozoic Purcell platforms (Fig. 9.1). The North American continent straddled the equator and sediments accumulated in warm, tropical seas. The craton itself was low lying and sediments were mature in character with little argillaceous detritus, but there were some erosion highs, such as the Peace River Arch, which from time to time shed quartz sands into the nearby environments.

The Ordovician to Lower Devonian rocks that are now preserved in the Western Canada Sedimentary Basin are merely remnants of very extensive sheets of sediment that were deposited over much of the craton and its westward ocean margin. Later periods of erosion removed the entire stratigraphic interval from most of the region (Figs. 9.5 - 9.12, 9.15 - 9.19), but outliers are preserved in many places. Generally, the strata consist of shallow-water carbonates and minor clastics and evaporites on the craton, bordered to the west by basinal shales and limestones (Figs. 9.1, 9.6). The change of facies occurred at a fairly abrupt slope from the platform into deeper water. Outboard of this facies change, two highs hosted carbonate platforms (Purcell Platform and Cassiar Platform, Fig. 9.1), which themselves were bordered westward by further developments of basin facies. Volcanic complexes were developed near the platform margin in at least two occasions but seem to have had very limited lateral extents.

In the central part of the craton, subsidence of the ancestral Williston Basin began in Middle Ordovician time. The axis of this gently depressed shifted several times within the Tippecanoe interval but the areas of greatest subsidence were in northwestern North Dakota (Figs. 9.2, 9.3, 1964; Kent and Christofferson, this volume, Chapter 27). Depositional thickening southward mostly developed within the Winnipeg, Red River and Interlake units. Thickness variations and facies distributions within various stratigraphic units indicate that some intrabasinal structures affected depositional patterns during the Tippecanoe time (Osdetr and Haidl, 1989). The area of deposition at times extended well beyond the limits of the present-day structural Williston Basin, and many of the units were depositionally continuous with those of the Bow, Kakwa, MacDonald, Mackenzie, and Hudson platforms (Fig. 9.1). In the Canadian part of the Williston Basin, the subsurface development of these strata is thick (about 480 m) in southeastern Saskatchewan, adjacent to its maximum (more than 760 m, Gerhard and Anderson, 1980) in northwestern North Dakota. The preservation of these lower Paleozoic strata during Late Silurian and Early Devonian erosion was due to epigenetic tectonics creating a broad depression, and the Ordovician and Silurian rocks were preserved below the Middle Devonian rocks.

At the northern margin of their area of preservation, the lower Paleozoic rocks form an erosional escarpment (Meadow Lake) that limited a Middle Devonian sea within which the lower Elkh Point evaporites were deposited (Meijer Does, 1986). At the northeastern margin of the Williston Basin, erosion on the Severn Arch (a Devonian or later feature) removed Upper Ordovician and Silurian strata that apparently were continuous between the Williston Basin and the Hudson Bay Basin (Fig. 9.19). The elbow in the distribution pattern (Fig. 9.1), between the easterly trending feather-edge in the subsurface and the northerly trending Manitoba outcrops, coincides with the boundary between the Churchill and Superior provinces (Fig. 9.22) and may indicate the recessed effect of this Precambrian structural trend.

Figure 9.1. Distribution map showing platforms, troughs and areas from which the interval has been stripped by erosion, and locations of cross sections. Mountain areas without paleo-erostatic restoration. Subcrop limits in the United States of America are from Kier (1980).
Figure 9.2 Isopach map of the Middle Ordovician to Lower Devonian stratigraphic interval. Control points in the Cordillera are shown with palinspastic restoration. Most of these localities later were thrust to the northeast, but on the Cassiar Platform movement was primarily to the northwest along strike-slip faults.
Sea-level changes driven by eustatic and glacio-eustatic events are recorded by unconformities and depositional cycles in the Williston Basin and in the mountains. Successive transgression that began in the Middle Ordovician resulted in inundation of most of the Canadian part of the North American craton by Late Ordovician time, when carbonate deposition seemingly extended from the Mackenzie, Kaskwa and Bow platforms eastward to the Williston Basin and the Hudson Bay Basin and northward into the present Arctic Islands. Within the subsurface of the Western Canadian Sedimentary Basin, the present preservation of segments of these widespread carbonates is a function of subsequent erosion and the effects of episodes of uplift of the Peace, Sweetgrass-North Battleford and Severn arches, respectively in the northwest, southwest and northeast, and of the Transcontinental Arch (not shown within Fig. 9.1) in the south.

**Stratigraphy**

Figure 9.3 provides an overview of the stratigraphic nomenclature, but many of the units have been subdivided for local purposes, both formally and informally. Unconformities are prominent and there is a westward change from formations of the stratal platform into the Road River Group and the Glenogle Formation of the basinal facies. Figure 9.4 provides more detail for the Williston Basin. In the middle section, the top of the stratigraphic interval is drawn within the Kaskasia Sequence, at the base of the Bear Rock-Stone Assemblage of Moron and Goldeczter (1989), although the Stone Formation may include Lower Devonian (Emmian) strata. The base of the interval is drawn at the base (uppermost Arenig) of the Skoki Formation and its associated quartz sand beds (Monkmann and Tipperay quartzites) and the slightly older (about mid-Arenig) bases of the Glenogle and Road River units in the basinal facies. In the United States, the beginning of the Tippecanoe Sequence customarily is placed at the base of the Whitehorse Series, which corresponds approximately to the base of the Llanvirn Series (Fig. 9.3). In the Williston Basin, the base of the interval (Winnipeg Formation) is younger (Caradocian) than in the miogeoclone, and the top of the interval (Upper Interlake unit) is older (late Llandovery or Wenlock). The boundaries between the Tippecanoe and the Skokis and Kaskasia sequences are abrupt on the craton, where hiatuses between the sequences were at their maxima. In contrast, the boundaries are blurred in the miogeoclone, as the bounding unconformities lose their impacts.

**Mountain Region**

The Bow, Purcell, Kaskwa, MacDonald, Cassiar and Mackenzie platforms each have sequences of sediments, progradationally carbonates (e.g., Fig. 9.3), with unconformities that document transgressions at various horizons, many of which are common to most of the platforms and to the Williston Basin. The detailed stratigraphy is beyond the scope of this chapter and is available elsewhere (Norford, 1989; Norford et al., 1987; Taylor and MacKenzie, 1970; Norford and Macphee, 1975; Cecil and Norford, 1979; Pugh, 1983; Moron and Goldeczter, 1989; Ouzette and Haidl, 1989; Norford, 1991). From time to time, large amounts of clean, well-rounded quartz sand were transported westward, southwestward and southward from the Peace River Arch into and within the Bow, Kaskwa and MacDonald platforms (as Monkmann, Tipperary, Mount Wilson, “quartzite-dolomite unit” and Waggapah units and as components of the Beaverfoot, Nondra and Monkmann-McConnell formations) and sometimes into the ocean basin (Road River OBS unit and as turbidites within the Glenogle). Other than these sandstones, the rocks of these platforms are dominantly subtidal and intertidal limestones and dolomites (Skoki, Beaverfoot, Mount Kindle, Nondra). Some units indicate more saline conditions (Owen Creek, Munche-McConnell, Peel), but evaporites are very rare. Oololiths and pisoids are prominent at some horizons within the Skoki Formation. Limestonal horizons are common in the Beaverfoot, Mount Kindle and Nondra formations. Small bioherms are known within the Nondra and a small coral bioherm has been reported in the Beaverfoot (Jasoni, 1970). Stromatolite mounds are present in the Skoki of the MacDonald Platform (Cecile, 1989). Shaly intervals are rare in the platform environments except in the Tegart and in basal parts of the Beaverfoot and Mount Kindle. Carbonate slope breccias (Nondra) and carbonate and quartz-sand turbidites (from Skoki and Tipperary sources) are present at the western edges of the MacDonald and Bow platforms and on the adjacent slopes. Two small occurrences of volcanic rocks are known within the carbonates of the MacDonald and Kaskwa platforms, both close to the western edges of the platforms (lower Middle Ordovician Skoki; Lower Silurian Beaverfoot).
K-C (Fig. 9.7) shows the same pattern of facies change in the southern Rocky Mountains as E-E (Fig. 9.4) but with the sub-Upper Devonian unconformity truncating the sub-Middle Devonian unconformity west of the Alberta-British Columbia boundary. Documentation of the Middle Ordovician facies changes near Frigate Mountain from the White River Trough (Glenogle) to the Bow Platform (Outlaw-Skoki-Owen Creek) is impossible because of downslope by the sub-Upper Devonian unconformity. Further east, the same unconformity cuts down to the Upper Cambrian within the Front Ranges.

L-C (Fig. 9.8) shows sub-Middle Devonian and sub-Upper Devonian unconformities in the central Rocky Mountains. These cut down eastward through the Silurian and Ordovician units so that the Devonian rests on Lower Ordovician Kekilka in the eastern outcrops.

M-M (Fig. 9.9) outlines changes of facies in the northern Rocky Mountains from the basin east into platformal facies but with a distinct Upper Ordovician quartz-sand rich unit (CRS) extending westward into the Kekilka Trough from the Peace River Arch (Norford, 1991). The sub-Ordovician unconformity trim Ordovician units and a sub-Middle Devonian unconformity cuts below the Ordovician in the subsurface adjacent to the mountains.

N-N’ (Fig. 9.10) is located farther north within the northern Rocky Mountains and shows that pre-Lower Silurian units are cut out eastward below the sub-Ordovician unconformity within the moun-
tains. However, both the Nonda itself and the Munro-McConnell extend eastward into the subsurface beyond the mountains, where they are ultimately cut out below the sub-Middle Devonian unconfor-
mity.

P-P (Fig. 9.11) illustrates that only a thin remnant (lower Mount Kendrick) of the Macdonald Platform sequence extends southward into the Atlas area (Meijer Drees, 1979). The sub-Middle Devonian unconformity cuts down into the Precambrian.

Q-Q’ (Fig. 9.12) is a lateral cross section within the platform in the northern and central Rocky Mountains. Unconformities have had substantial effects, both within the stratigraphic package itself and by the downsloping of the sub-Middle Devonian and sub-Upper Devonian unconformities. Lateral facies changes within the pack-
age mostly result from the local presence of significant bodies of quartz sandstone. The Moroka Quartzite is a thick unit equiva-
 lent to the lower Skoki. The “quartzite and dolomite unit” is equiva-
 lent to the lower Beverstock and similar quartz sandstone continues westward as the coeval CR 5 unit of the Road River. The Wokpknah Quartzite is laterally equivalent to some of the upper (Lower Devonian) part of the Munro-McConnell.

Williston Basin

Because of its extensive subsurface development, the succession in the Williston Basin area is outlined in much more detail than for the rest of the Atlas region (Fig. 9.4). A major unconformity separ-
rates the Tippecanoe Sequence from the underlying rocks. In most of the region these latter rocks are shales and argillaceous and glauconitic siltstones and sandstones of the Deadwood Formation (Upper Cambrian to Lower Ordovician; Blund et al., this volume, Chapter 8) but beyond the eastern erosional limit of the Dead-
wood, the Tippecanoe Sequence rests directly on Precambrian rocks. Tippecanoe sedimentation began with a Middle-Ordovician marine transgression from the southeast and deposition of the Winngporn Formation. The distribution of Winngporn lithofacies in-
dicates three phases of deposition of basin margin sands and ophiolite muds (Vigrass, 1972; Kessler, 1991). The top of the Win-
ngporn marks a transition with associated erosion (Piasen et al., 1977; Kessler, 1979) but the contact also has been interpreted as tran-
itional (Porter and Fuller, 1999; Vigrass, 1972; McCabe, 1978).

A widespread early Late Ordovician transgression followed, with deposition of burrow-mottled carbonates (Yoneman Formation; lower Red River; Fig. 9.4 shows subdivisions of these units). The transgression extended to the Hudson Platform to the east and northeast to New Mexico to the south but did not submerge the Bow, Kalwa, McDowell and Mackenzie platforms; these were not transgressed until later in the Late Ordovician (Early Silurian for the MacDonal Platform).

The overlying formations of the Williston Basin are characterized by cyclic sedimentation commencing with three carbonate-evap-
orative cycles in the Herald Formation (upper Red River; Fig. 9.4 shows subdivisions). Complete cycles consist of basal, thin, argi-
llaceous dolomites, commonly arenaceous, overlying by fossiliferous mudstones/weaklysten (commonly burrowed and dolomitized), laminated dolomites, and capping archeanites (Kendall, 1976, 1988; Haal, 1987). The evaporation of these and the later cycles are re-
stricted to the central parts of the Williston Basin (Fig. 9.13). Re-
versed transgression produced deeper water environments, documented by carbonates, argillaceous carbonates and calcare-
ous shales of the lower Stony Mountain Formation; this transgress-
ion also is documented on the Bow, Kalwa, and Mackenzie platforms. Next, sequences of carbonate-evaporite cycles, constit-
uting the upper Stony Mountain, Formantov and Lower Interlake units, were deposited. The evaporite portions of the Lower Inter-
lake cycles are restricted to North Dakota and thus are not shown in Figure 9.13. Noncyclic carbonate sedimentation followed and continued without any major interruption during much of the rest of the interval ("Middle Interlake" of Porter and Fuller, 1959, 1964; Cedar Lake of Stem, 1956). However, in the central part of the basin, the youngest part of the sequence ("Upper Inter-

There may be an unconformity between these rocks and the under-
lying parts of the Interlake (Porter and Fuller, 1964; Ouadetz and Haal, 1990). Regional uplift followed deposition of the Interlake and perhaps younger rocks (similar to those preserved in the Hudson Bay Basin, Fig. 9.13), and across the entire Williston Basin the Tippecanoe Sequence was transgressed by erosion associated with the sub-Devonian unconformity. At the northern erosional edge, differential erosion of the Ordovician carbonates and the cliffs below formed a relatively steep slope, the Meadow Lake Escarpment (Haal, 1989; Blund et al., this volume, Chapter 8). Later, the escarpment limited the areal distribution of the Middle De-
vonian sea in which the lower ER Point evaporites accumulated. The basal Devonian rocks are the Ashern Formation (probably Elladian), except in southwestern Saskatchewan and southwestern Alberta, where younger Devonian strata progressively onlap pa-
eteopelagic highs of Tippecanoe strata.

Reference Well

Figure 9.14 shows the geophysical log responses and lithologies for the Home Dome Torquay South 3-4-1-11W2 well in southwestern Saskatchewan. This well characterizes the Tippecanoe Sequence in an area where the depositional cycles seem to be most complete. Medium-to course-grained quartz sandstones of the lower part of the Winnipeg Formation unconformably overlie very fine-line-fine-
grained glauconitic sandstones of the uppermost Deadwood For-
mation. The upper 20 m of the Winnipeg Formation consists of dark greenish-gray, wavy-shales. These are overlain with apparent unconformity by burrow-mottled dolomitic limestone and dolo-
mites of the Yoneman Formation (lower Red River). Of particular interest in this well are four thin beds of organic-rich laminites (kuktainers) between 3182 and 3195 m in a core within the upper edge of the Yoneman. This interval with kuktainers beds can be correlated over a large part of the Williston Basin (Kendall, 1976; Haal, 1990) and is the source rock for oil produced from Ordovi-
cian reservoirs and also from some younger reservoirs in the Wil-
liston Basin (Ouadetz et al., 1992). The contact between the Herald and Yoneman formations is transitional but can be picked most consistently using the gamma-ray log to differentiate the clean
carbonates of the Yeoman from the more argillaceous beds of the Herald. The bases of the Stonewall and Stony Mountain formations and of each member of the Herald Formation are placed at the bases of argillaceous and locally arenaceous dolomite marker beds that give high gamma-ray responses (Kendall, 1976). In the Stony Mountain Formation, the Gunn Member has a greater argillaceous content than the underlying Hartven and overlying Gun-ton members and thus has a characteristic higher gamma-ray response. The top of the Stonewall Formation is picked at the top of a marker bed that commonly is less argillaceous and thicker than marker beds above and below. The Lake Alma, Coronach, and Gunton depositional cycles are capped by anhydrites as is the lower cycle of the Stonewall. Two informal interlakes, Lower and Upper, can be correlated with confidence on geophysical logs and are used in the regional cross sections. The top of the Lower Interlakе is picked at the uppermost root of a number of argillaceous marker beds (Fig. 9.14, gamma-ray log). The "v" marker of Porter and Fuller (1959, 1964) coincides with this marker in much of the area but locally seems to have been picked at a lower argillaceous marker. The top of the Lower Interlakе falls below the top of the East Arm Formation of the Manitoba outcrops (Fig. 9.4). The remainder of the Interlakе is difficult to subdivide with confidence using geophysical logs, and the Upper Interlakе of the present chapter combines both the "Middle Interlakе" and "Upper Interlakе" of Porter and Fuller (1959, 1964). It includes the Cedar Lake Formation of the outcrop region and the subsurface determinations of Cedar Lake and Taylorton used by King (1964), Jamieson (1979) and Haídałl (1987). The Cedar Lake-Taylorton contact can be picked only where core is available.

**Williston Basin Cross Sections**

Four cross sections (A-A', P-G, C-G, and H-F; Figs. 9.15 to 9.18) illustrate the "layer cake" stratigraphy characteristic of most of the Tippecanoe Sequence of the Williston Basin. The argillaceous marker beds that define the lithostratigraphic units on gamma-ray logs can be traced across the basin but precision of correlation diminishes away from the central part of the basin where the depositional cycles are most complete. The top of the Ashern Formation (and its equivalent in Alberta) is chosen as the datum for these cross sections because it is easily correlated by gamma-ray logs. However, the Ashern is absent on paleontological highs in the southwestern part of P-F and the top of the Tippecanoe Sequence is used as the datum. There are elsewhere, variations in Ashern thicknesses reflect the paleopography of the sub-Ashern erosion surface. Infiltration of Ashern sediments into cavities of the karsted erosion surface can cause changes (error) less than 0.5 m in picking the tops of the underlying Silurian or Ordovician carbonates. The local presence of anhydrites within the basal Ashern can lead to other difficulties in precisely picking the contact. Lithologies portrayed on the cross sections have been interpreted from examination of geophysical logs, supplemented by sample and core data from a few wells. Dolomite is the dominant lithology within the sequence. Regional pervasive dolomitization appears to have been controlled by the distribution of the argillaceous carbonates of the Gunn Member of the Stony Mountain Formation (Kendall, 1976, 1989). Strata above the Gunn are dolomitized as is the entire carbonate part of the sequence out the depositional limits of the Gunn (Figs. 9.14, 9.18, 9.23 - 9.26). Dolomitization is not pervasive in the carbonates that underlie the Gunn Member (Figs. 9.14, 9.18, 9.17, 9.18) and the complex pattern of dolomitization within these strata have been attributed to a number of factors during multiple phases of dolomitization (Kendall, 1976; Kohm and Louder, 1978; Haídałl, 1990).

**Figure 9.7 Regional cross section K-K' (Fig. 9.1) southeastern British Columbia (White River Trough) to southwestern Alberta (Front Ranges west of Red Deer).**

**Figure 9.8 Regional cross section L-L' (Fig. 9.1) east-central British Columbia to west-central Alberta.**

The southeastern segment (1134-7-2SW2 to 1636-1-1SW2) of A-A' and the southwestern part of C-G are within the Rocoroc High-Hummingbird Trough area where episodic Phanerotic movements of Precambrian structural blocks influenced patterns of sedimentation, erosion, dolomitization and salt dissolution (Haidal, 1990; Kent and Christopher, this volume, Chapter 2). An example of such influence is at the Mark et al. Minter 11-2-3-2SW2 well. Located on a small structural high, this well has anomalously thin Ashern and Upper Interlakе units and good intercrystalline porosity is developed within the Yeoman Formation. The Minter well has produced more than 20,000 m³ of oil from the Yeoman. Oil derived from Ordovician rocks also is produced from a reservoir within the Devonian Winnipegosis Formation.
Figure 9.9 Regional cross section M-M (Fig. 9.1), northeastern British Columbia (Kechika Trough) to northwestern Alberta. See Figure 9.3 for nomenclatural abbreviations (CIA, ORM, SL, SD and associated informal units).
Figure 5.12 Regional cross section O-Q (Fig. 5.1), northeastern British Columbia southeast to west-central Alberta.
Figure 9.13 Geographic limits of a. Lake Alma and Cronach anhydrites (Herald Formation), b. Gunton anhydrite (Saskatchewan Formation), and c. Stonewall anhydrite. Distribution shown in Saskatchewan is modified from Kerr (1980) and from Kendall (1976); correlations into Manitoba are tentative and based on interpretations of geophysical logs. Map scale 1:5,000,000.

Figure 9.14 Reference well, Home Dome Torquay S, 3-8-1-11 W2, southeastern Saskatchewan (Fig. 8.1 shows location). Winning through interlobe units, lithostratigraphic nomenclature of Ordovician strata follows Kendall (1976). Gamma-ray, density and sonic-sonics are illustrated. Lithologies interpreted from core (136/2011 ft), cuttings, and geophysical logs (primarily the compensated neutron–borehole log). Note that the vertical scale (1:2000) is much expanded from the Atlas standard (1:8000).
P'-F' (Fig. 9.16) crosses the northern part of the Williston Basin from a southwestern erosional foreland-edge of the Tippecanoe Sequence and continues into outcrop near Cumberlands Lake in the northeast. It lies beyond the depositional limits of the evaporite units (Fig. 9.13) and of the Gumm Member of the Stony Mountain, which thus cannot be subdivided into members. South-westward erosional thinning below the Devonian is shown. The Winnipeg is present only in the northeast as less than 10 m of shale with interbedded siltstones and sandstones overstepping the eastern limit of the Deadwood; it is itself overstepped by the Yeoman in west-central Saskatchewan. The Herald cannot be discriminated as a discrete unit west of 4-27-13-23W3. Stratigraphic correlation of lowermost Kazan and uppermost Tippecanoe strata in Saskatchewan wells west of 1-26-23-11W3 indicates that a shale previously placed in the Ashern should be assigned to the Winnepesaukee. This revision is based on studies of core and correlated biostratigraphic data (F.T. Uyeno, pers. comm.) from the B.A. Hatton 2-12-15-27W3 well.

G'-G" (Fig. 9.17) extends from the central Williston Basin to near the Manitoba outcrops and shows the eastern limit of the Deadwood, with the overlying Winnipeg overstepping onto Precambrian rocks. Variations in thickness of the Gumm Member of the Stony Mountain reflect the westerly and northerly facies changes of this unit into the less argillaceous carbonates of the Harkins Member, but the line of section is oblique to the directions of these changes of facies (Fig. 9.25). The anhydrites within the Herald, Stony Mountain and Stonewall disappear north-eastward away from the central part of the Williston Basin.

H-H" (Fig. 9.18) essentially follows the Manitoba-Saskatchewan boundary. The Deadwood is present only in the extreme south close to its erosional edge. The Winnipeg thickens southward and its shale component increases. The Yeoman also thickens southward toward its depocentre in North Dakota. Some similar depositional thickening also occurs within the Herald and Stonewall and may be present in the Upper Interlake, but the lack of marker beds in the Upper Interlake makes it difficult to differentiate any such thickening from the effects of erosional truncation of the unit (Kendall and Christopher, this volume, Chapter 27). Within the Stony Mountain, a facies change near 13-3-35-29W1 from argillaceous limestones and calcareous shales (Gumm Member) to non-siliciclastic limestones precludes subdivision of the Stony Mountain into members north of this well. The anhydrites within the Herald and the Stony Mountain are present only at the southern end of H-H". An anomalous sequence is present in the Cherokee et al. Westman 2-34-1-32W1 well, which is located on a Precambrian high. The Deadwood is absent and the Winnipeg is considerably thinned with loss of most of its lower sandstones. Core from this well shows faulting in strata below the Lake Alma Anhydrite (Herald Formation).

J-J" (Fig. 9.19) shows the close resemblance between the stratigraphic units in the Williston Basin and the Hudson Bay Basin, indicating that many of them were depositorially continuous. The Red River and the Bad Cache Rapids are broadly equivalent, as are the Stony Mountain and the Churchill River, the Stonewall and the interval designated Red Head Rapids, much of the Lower Interlake and the Seven River. In southern Manitoba, the Winnipeg is overlapped by the Red River northward and does not extend into the Hudson Bay Basin although basal sandstones are present within the Red Cache Rapids. There is no equivalent of the Upper Silurian and Lower Devonian components of the evaporitic Kernyam River in the Williston Basin. The Red River to Interlake interval is at least twice as thick in the Hudson Bay Basin as in the Williston Basin.
Systemic Boundaries
Precise location of the Ordovician-Silurian boundary is difficult in the mountain outcrops, because of the poorly fossiliferous strata of the boundary interval. In the southern Rocky Mountains, it can only be positioned within a 25 m interval of the Beaverfoot Formation (Norford, 1988). In the subsurface of the Williston Basin, the boundary traditionally has been picked at the t-marker within the upper part of the Stonewall Formation (Porter and Fuller, 1999; Brindley, 1963; McCabe, 1988). Using both corals and conodonts, recent biostratigraphic studies confirm this as an approximate placement, both in outcrop (Cormorant Hill roadcut) and in the subsurface (Easterly 3SWD well, 16-26-20-33W1, Haid, 1991; diamond drillhole at Warren near Stonewall; Borys, 1991).

Details of the Silurian-Devonian boundary are poorly known. Relevant strata are preserved only in the northwestern part of the Atlas area, where the boundary lies somewhere within the virtually unfossiliferous Munchow-McCormell Formation of the Macdonald Platform and within the SD Unit of the Road River Group of the Kechika Trough.

Structure
Figures 9.17 and 9.22 clearly show the limited subsurface extent of the stratigraphic package. The cross sections (Figs. 9.5 - 9.12, 9.15 - 9.19) demonstrate the edges of rock units where they are truncated beneath Devonian and younger unconformities. Similar relations are shown for several units below unconformities within the Middle Ordovician to Lower Devonian interval (Figs. 9.6, 9.7, 9.11, 9.12).

In the Williston Basin area, contours on the eroded top of the Tippecanoe Sequence (Fig. 9.21) show a general southwesterly dipping surface on which is imposed the somewhat asymmetrical influence of the structural Williston Basin (note the -1000 m contour in Fig. 9.21). The Sweetgrass-North Battleford Arch forms the west flank of the basin and trends north-northeast; the east flank is against the Severn Arch that trends north-northwest (Fig. 9.2). Some local structures affect the smoothness of the structural pattern. In southwestern Saskatchewan these include the Val Marie Arch (a northern extension of the Bowdoin Dome), the Battle Creek High, the Swift Current High, and the Eastend Syncline (Fig. 9.21). Kent and Christopher (this volume, Chapter 25). In Manitoba, the Tippecanoe strata are disrupted by three structures that possibly were caused by meteorite impacts: the Hartney Structure in the subsurface (McCabe, 1982) and the Lake St. Martin and High Rock Lake structures in the outcrop belt (Fig. 9.22; McCabe and Bannatyne, 1970; McCabe, 1982).

The paleogeology of the post-Tippecanoe erosion surface reflects the topographic patterns developed during the pre-Kaskaskia basin. Many of these patterns were inherited from Pre cambrian structural features that had persistent effects through much of Paleozoic time, such as the Peace River, Mackenzie, and Sweet grass-North Battleford arches. The Meadow Lake Escarpment was an Early Devonian erosional feature and forms much of the present northern limit of the Tippecanoe Sequence of the Williston Basin (Fig. 9.2). Near the feather-edge of the escarpment in southeastern Alberta, isopach patterns indicate that Early Devonian valleys cut into the Tippecanoe Sequence. Pre-Jurassic and pre-Cretaceous erosion locally affected Tippecanoe strata in parts of Manitoba and Saskatchewan; for example, south of Winnipeg, the "Dominion City Channel" was eroded into and through the Tippecanoe Sequence and later filled with Jurassic sediments, causing an area of east-west thinning shown by the isopach maps (Fig. 9.25 etc.). The course of the remainder of the eastern edge of outcrop
Figure 9.19 Regional cross section J-J', west central Manitoba to northeastern Manitoba and adjacent Ontario (Hudson Bay Lowlands). Datum, base of Innisfail and base of Severn River. J joins with H. 'J' connects with the southwest end of a published cross section that traverses the Hudson Bay Basin (A-A' of Fig. 5 of Sanford and Grant, 1990). These authors recognize the Bass River Formation (a petroleum source rock) between the Bad Cache Rapids and the Churchill River groups in the northeastern wells shown on Figure 9.19, but this unit is too thin (less than 10 m) to be shown in the cross section.
reflects erosional truncations that were associated with later epis-
eses of uplift of the Severn Arch and the Transcontinental Arch and
with movements along faults documented in Precambrian rocks
adjacent to the edge. Figure 9.19 indicates that the Tippecan-
eoe Sequence originally was continuous across the Severn Arch
from the Williston Basin to the Hudson Bay Basin.

In the Rocky Mountains and in the southern District of Mackenzie,
Middle Ordovician to Lower Devonian strata are restricted largely
to the disturbed belt, with Mesozoic and Cenozoic thrusts obscuring
any earlier structures. However, east of the Rocky Mountains,
numerous positive areas (Fort Nelson High, Peace River Arch)
strongly influenced Cambrian and Middle and Late Devonian
sedimentation on the craton. Doubtless such areas also had influence
during Middle Ordovician to Early Devonian time but very little
of the effects are preserved in the stratigraphic record (Nor-
ford, 1991; Cecile and Norford, in press).

Isopach Maps

The pre-Winnipeg part of the stratigraphic interval is preserved
only in the mountains (Fig. 9.20) because of erosion associated
with later unconformities. Westward the interval is represented by
the Glenogle and Road River units of basinal facies. The isopach pat-
tern in the Bow Platform probably results from later Ordovician
erosion, but a southern bulge reflects thickening caused by
the local presence of Tipperary sands. Similarly, Mokson sand lobes
locally thicken a interval in a part of the Kakwa Platform. The
intense thickening of the interval westward and southwest of the
Kakwa and MacDonald platforms seems to be due to substantial
thickening of the Skoki Formation at the outboard edges of the
platforms combined with the post-Skoki unconformity rising in
the same areas to allow preservation of younger Skoki rocks.

In the Canadian part of the Williston Basin the Tippecanoe Se-
quence reaches a maximum thickness of 478 m (Fig. 9.2) almost
half of which consists of the Stonewall and Interlake units. The
dominant influence of these two units on the isopach is decreases
away from the central part of the basin as they are truncated by
the sub-Kaskaskia unconformity. However, the depositional basin
doubtless extended much farther eastward and connected with the
Hudson Bay Basin. The major paleotopographic feature on the
pre-Kaskaskia surface was the Mosow Lake Escarpment, which
was formed by differential erosion of the resistant Ordovician
carbonates and the underlying clastics of the Sauk Sequence.
South of the escarpment, the surface was essentially flat with the
exception of paleotopographic elevations associated with the Swift
Current Platform and the Sweetgrass Arch and local elevations
and depressions related to Precambrian structures.

The Winnipeg Formation (Fig. 9.23) reaches a thickness of 105 m
(Kessler, 1993) at its depositive in North Dakota but its maximum
thickness in Canada is 68 m. Paleotopography and syndepositional
tectonic activity related to Precambrian basement features such as
the Churchill-Superior Boundary Zone (Fig. 9.22) and local highs
(e.g., at 2-34-1-32W1), Fig. 9.18) and differential compaction of
mud relative to sands contributed to local variations in Winnipeg
The distribution of the Winnipeg and variations in its thicknesses
near its western limit have been attributed to sub-Yoemian erosion
(Peterson, 1971), depositional thinning (Vigars, 1972) and assign-
ment to the Winnipeg Formation of sands reworked from Win-
ipeg supracks into the basal Yoemian Formation (Kendall, 1976).
The complete absence of the Winnipeg in the Imperial Lightning
Creek 16-7-32W1 well is an anomaly that has been explained by
faulting (Kendall, 1976). The eastern limit of the Winnipeg is a

feature of post-Tippecanoe erosion and the northeastern edge
of the Winnipeg Formation is due to overlap by the Red River Forma-
tion.

The distribution of lithologies within the Winnipeg Formation
(Fig. 9.23) shows a decrease in the sandstone/shale ratio toward
the basin centre from Facies 2 to Facies 1. Facies of Carbonatite
data do not allow definition on this lithology map of the east-west
fingering sand body, the "Carmen Sand", outlined by the 50 m
isopach south on the City of Winnipeg (see Kessler, 1993, for
cussion of the deposition of this and other elongate sand bodies
within the Winnipeg).

Because of the limits of refined picks in the database, the Red River
isopach map (Fig. 9.24) combines both the Herald and the Yoeman,
although Kendall (1976) gave separate maps for part of the region.
The Yoeman is much thicker than the Herald and thus has stronger
influence on the isopach map of the total Red River. The map
shows depositional thinning away from the centre of the Williston
Basin and erosional truncation near the outcrop edge and the
outcrop edge. The northwestem edge of the Red River is at
the Mosow Lake Escarpment. Local thinning is evident southwest of
Winnipeg (closed 150 m isopach) and reflects a paleotopographic
high caused by differential compaction of the underlying Carmen
Sand of the Winnipeg Formation compared to the surrounding
shelves. Local depositional thinning also occurs in the Swift Cur-
rent area, associated with a Precambrian structure that also influ-
enced sedimentation at other times during the Phanerocenic (Kerr
and Christopher, this volume, Chapter 27). Two anomalies that
control the regional distribution are indicated in Figure 9.24.
The Red River, Stormy Mountain and Stonewall are absent in the
Dome Provost 11-8-36-3W4 well (C. en Fig. 9.24) and paucity of
data northwest of the locality prevents decision on whether this
an isolated anomaly or whether it is part of a narrow northwest
trending Devonian paleovalley that cut through the Ordovician
succession. The Red River is anomalously thick (215+ m) in the
Imperial Lightning Creek 16-7-32W1 well (B. Fig. 9.24) where
Kendall (1976) suggested repetition by faulting.

The boundary between the two lithological domains within the
Red River (Fig. 9.24) reflects the amount of diagenesis within the
Yoemian Formation. This in turn appears to have been control-
ed by the distribution of the Gunn Member of the Stormy Mountain,
which, where present, shelters the underlying Yoeman from My-
rich fluids (Kendall, 1976, 1989; Figs. 9.24, 9.25). Anhydrites re-
ported in the sampled cuttings are from the Lake Alma and
Coronach anhydrite beds within the Herald Formation (Figs. 9.13).
In general, thicknesses of the Stormy Mountain Formation range
between 25 and 45 m, except for the erosional truncations close to
to its outcrop and outcrop edges (Fig. 9.25) and the absence of the
Stormy Mountain from the Dome Provost 11-8-36-3W4 well (see
earlier discussion of absence of the Red River). The distribution of
the lithological domains is controlled primarily by the thicknesses
of argillaceous carbonates and shales of the Gunn Member, al-
though the boundary shown between the two domains lies par-
tally to the outcrop of the Gunn. The thinnest development
(45 m) of the Stormy Mountain Formation in southern Manitoba
coincides with the area of highest shale content within its Gunn
Member, and the actual amount of thickening of the formation
width the centre of the basin may have been subdued by the
degree of compaction of these shales. Anhydrites reported in the
sampled cuttings are from a thin anhydrite bed at the top of the
Stormy Mountain (Figs. 9.13, 9.25).

For the combined interval, Stonewall Formation and Interlake
Group, the isopach map reflects both depositional thickening to
ward the centre of the Williston Basin and erosional truncation
associated with the sub-Kaskaskia unconformity. Maximum thick-
nesses are almost 250 m in southeastern Saskatchewan and about

Figure 9.20 Isopach map, pre-Winnipeg interval in the Cordillera (uppermost Lower Ordovician and lower Middle Ordovician), Tippecanoe, Menokin, Skoki and Owen Creek units, Central provinces are geologically examined. Most of the localities later were thrust to the northeast, but the localities in the Wilcox Platform primarily moved to the northwest along strike-slip faults.
Figure 9.21 Structure contour and palaeogeological map, Williston Basin, upper surface of the Middle Ordovician to Silurian stratigraphic interval.
Figure 9.22 Subcrop-outcrop map, Middle Ordovician to Silurian, Williston Basin, showing Precambrian trends and post-Silurian erosional features and impact structures.

Figure 9.23 Isopach map, Winnipeg Formation, with overprinted lithological domains.
Figure 9.24 Isopach map, Red River Formation, with overprinted lithological domains.

Figure 9.25 Isopach map, Stony Mountain Formation, showing the distribution of the Gunm Member (following Kendall, 1976, in Saskatchewan; distribution in Manitoba is approximate because of limited subsurface control), with overprinted lithological domains.
INTERLAKE/STONEWALL ISOPACH AND LITHOFACIES

Contour interval – 10 metres

- Control well: A Horns Dome well
- Well with control coverage: DGC
- Stony Mountain outcrop: C CR, DCR, ECR, FCR, GCR, HCR

- Facies 1
  - Dominates, brown and brown-dull, very finely crystalline, with very minor argillaceous zones in the lower part, locally very slightly sandy and silty; extensively minor amygdaloidal bed in the lower part in the south.
- Facies 2
  - Dominates, brown and brown-dull, very finely crystalline, with minor argillaceous zones, locally very slightly sandy and silty and amygdaloidal bed in the lower part in the south.
- Facies 3
  - Dominates, brown and grey-red, very finely crystalline, with minor interbedded clastic units and minor zones, locally very slightly argillaceous, extensively minor amygdaloidal bed in the lower part in the south coastal portion.
- Amygdaloidal, trace to 2%.

Figure 9.27 Isopach map, Upper Silurian and Lower Devonian rocks (post-interlake) in northeastern British Columbia (details of Muncho-McConnell and Wabakinnick formations). Contour outcrop sections and wells indicated by dots; data from McMechan (1987), Taylor and MacKenzie (1970), Thompson (1969), Pugh (1976), and Norford (unpublished data). Palaeo-eustatic reductions as for Figure 9.2.

Figure 9.26 Isopach map, Stonewall and Interlake units, with overprinted lithological domains.
MIDDLE ORDOVICIAN TO LOWER DEVONIAN

Thermal Maturity and Resources

Thermal maturities are too high throughout the Rocky Mountains for preservation of petroleum or gas (Fig. 9.29). They are lower in the southern part of the Mackenzie Platform but the footwall edge of the Mount Kindle Formation only just reaches the Atlas area (Fig. 9.31). Dolomites and quartz sandstones of the Nipoda Formation extend some distance east from the northern Rocky Mountains within the subsurface of northern British Columbia (Fig. 9.9) but thermal maturities are high in the adjacent outcrops.

Thermal maturities are much lower in the Manitoba outcrops and in the subsurface of the southern Plains (Fig. 9.28) with some of the Ordovician and Silurian formations locally being within the wet gas and oil windows (Osadetz and Hadd, 1999). Development has been at a critically low temperature for the special character of the source rocks, kerogen. Minor oil shows have been known for many years in the lower Paleozoic rocks of Manitoba, and petroleum has been produced in small amounts from the Red River Formation of southern Saskatchewan. Extensive production has been achieved from locations in Montana and North Dakota where the exploration parameters are very similar, but structures have had a larger effect and burial seems to have been greater than in Saskatchewan (Longman et al., 1992). Recent exploration in the Minto area of southeastern Saskatchewan has resulted in significant discoveries (Pottier and St. Onge, 1991). These and other wells elsewhere in Saskatchewan have yielded cumulative production of 140,000,000 bbls of Red River-sourced oil in Red River and Winnipegosis (Devonian) reservoirs to the end of June, 1991. The oil may have migrated northward from more mature Red River rocks in the adjacent United States.

The carbonate rocks in the Manitoba outcrops have been extensively used as a source for crushed stone. Major operations quarry the Stonewall and Stony Mountain formations north of Winnipeg and quarries in the Interlake Group (south) are intermittently. Because the rocks are dominantly dolomites and argillaceous dolomite, there has been no production for cement. Interlake dolomites at Hiltre (20 km north of Winnipeg) have been used as a source of dolomitic lime for agriculture. For nearly a hundred years, rock of the Red River Formation (Selkirk Member) has been used as an ornamental building stone (Tyndall Stone, Fig. 9.29). Tyndall Stone graces several provincial legislatures, the Parliament Buildings in Ottawa, the Museum of Civilization in Hull, and many other public and commercial buildings across Canada. The prime source is the Gillis Quarry at Gason (40 km northeast of Winnipeg).

Silica sand from the Winnipeg Formation is extracted at Black Island (Lake Winnipeg) and used as a foundry sand. It has been used for glass manufacture and has the potential to be a source for silicon metal. In the Rocky Mountains (Fig. 9.30), the Mount Wilson Quartzite is quarried as a glass sand, for other industrial uses that include the manufacture of silicon, and for lining bunkers on golf courses. Production from the two active quartzes totalled 126,000 tonnes in 1990 (Butenczuk, 1991). Base metal mineralization is present in the Muncho-McConnell Formation (Thompson, 1969).

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References


