PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Western Canada Sedimentary Basin

J. W. Porter, R. A. Price and R. G. McCrossan

Phil. Trans. R. Soc. Lond. A 1982 **305**, 169-192
doi: 10.1098/rsta.1982.0032

Phil. Trans. R. Soc. Lond. A **305**, 169–192 (1982) [169]
Printed in Great Britain

The Western Canada Sedimentary Basin

By J. W. Porter†, R. A. Price‡[1] and R. G. McCrossan§

† *Canadian Superior Oil Limited*, 355 *Fourth Avenue S.W., Calgary, Alberta T2P* 0*J*3, *Canada*
‡ *Department of Geological Sciences, Queen's University, Kingston, Ontario K7L* 3*N*6, *Canada*
§ *Esso Resources Canada Limited*, 500 6*th Avenue S.W., Calgary, Alberta T2P* 0*S*1, *Canada*

The Western Canada Sedimentary Basin, a simple northeasterly tapering wedge of sedimentary rocks more than 6 km thick, extends southwest from the Canadian Shield into the Cordilleran foreland thrust belt. Its internal structure and the lateral variations in its shape reflect a long and complex history of development involving a foreland basin that was superimposed on a cratonic platform and continental terrace wedge. This history, which is inextricably linked to the evolution of the Canadian Cordillera, can be outlined succinctly with reference to the unconformity-bounded transgressive–regressive stratigraphic sequences established by Sloss (*Bull. geol. Soc. Am.* **74**, 93 (1963)), each of which has a distinctive character in Western Canada.

The continental terrace wedge was established with the deposition of the Proterozoic Purcell (1500–1350 Ma) and Windermere (850–600 Ma) sequences, but the first record of the platformal phase is the early Palaeozoic transgressive onlap of the early Proterozoic (> 1750 Ma) crystalline basement by the Sauk sequence. Early Palaeozoic subsidence of the margin of the craton may have been due to cooling of the lithosphere after renewed stretching at the ancient rifted western margin of the Precambrian craton, and to isostatic flexure of the lithosphere under the weight of the sediment that had accumulated at the margin in the oceanward prograding continental terrace wedge.

During a subsequent Middle Ordovician to Middle Jurassic phase, the cratonic platform became differentiated into an intersecting network of epeirogenic arches with intervening basins. Development of the basins was as much a result of erosion and uplift of the arches between transgressive–regressive cycles as it was a result of differential subsidence of the basins during the cycles. The cause of the long (> 300 Ma) episode of intermittent epeirogenic movements that produced the basins and arches is a major unsolved problem.

The foreland basin developed in two stages, in Middle Jurassic to early Cretaceous and late Cretaceous to Palaeocene time, as a result of collisions between North America and two pieces of a tectonic collage of oceanic terranes that were accreted to its western margin. During these two collisions, the continental terrace wedge, which had accumulated outboard from the rifted margin of the continental craton, was compressed and displaced over the western margin of the craton. Part of the supracrustal cover was scraped off the craton and accreted to the overriding mass to form a wedge of imbricate thrust fault slices that was tectonically prograded over the margin of the continental craton. Isostatic flexure of the continental lithosphere in response to the tectonic loading imposed on it by the displaced continental terrace wedge and the accretionary wedge of thrust slices produced the migrating moat in which the outwash of clastic detritus from the evolving thrust belt was trapped to form the foreland basin.

Introduction

The Western Canada Sedimentary Basin (figure 1) is basically a simple northeasterly tapering wedge of sedimentary rocks, more than 6 km thick, that extends southwards from the Canadian

[1] Present address: Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8, Canada.

Shield into the Cordilleran foreland thrust belt (figures 1 and 2). However, its internal structure and the lateral variations in its shape reflect a long and complex history of development that involved superposition of contrasting patterns of differential subsidence and uplift, the causes of which have yet to be explained adequately.

Two fundamentally different phases in the development of the basin coincide with the two different stages in the evolution of the eastern part of the Cordillera, which is the deformed counterpart of the sediments that fill the undeformed basin. An initial platformal phase involved transgressive onlap of the Precambrian crystalline basement of the North American Craton, and the development of a series of epeirogenic arches and basins on the cratonic platform. It coincided with the Proterozoic to Jurassic stage of oceanward progradation of a pre-Cordilleran continental terrace wedge along the ancient rifted western margin of the North American Precambrian craton. A subsequent foreland basin phase, involving cratonward progradation of synorogenic clastic detritus shed by the evolving Cordillera, coincided with the Jurassic to Palaeocene interval of collisional orogeny during which foreign terranes were

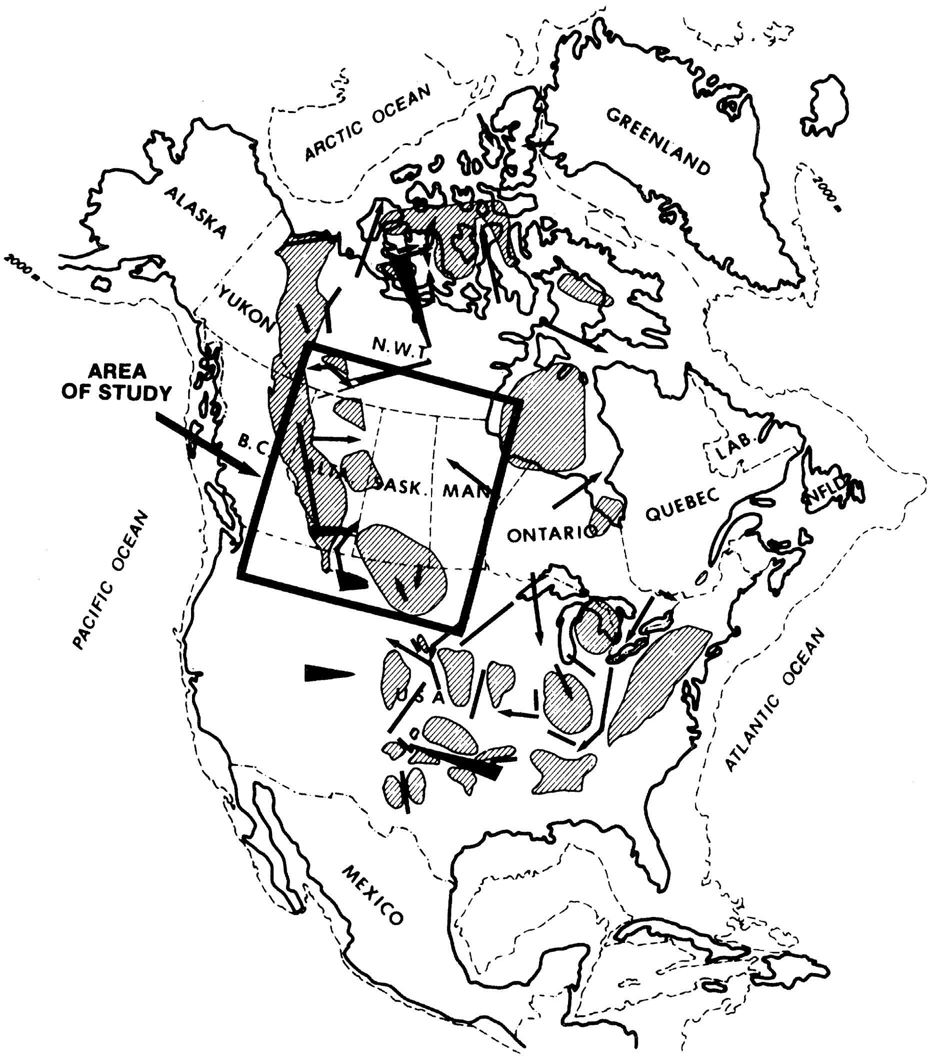

FIGURE 1. The Western Canadian Sedimentary Basin (area of study) in relation to the principal Palaeozoic cratonic basins (diagonal ruling) and arches (arrows) and Proterozoic aulacogens of North America.

accreted to the western margin of North America and the continental terrace wedge was compressed, detached from its basement, and displaced over the flank of the craton. The evolution of the Western Canada Sedimentary Basin is inextricably linked to the evolution of the Cordillera; to understand the one it is necessary to consider carefully the other.

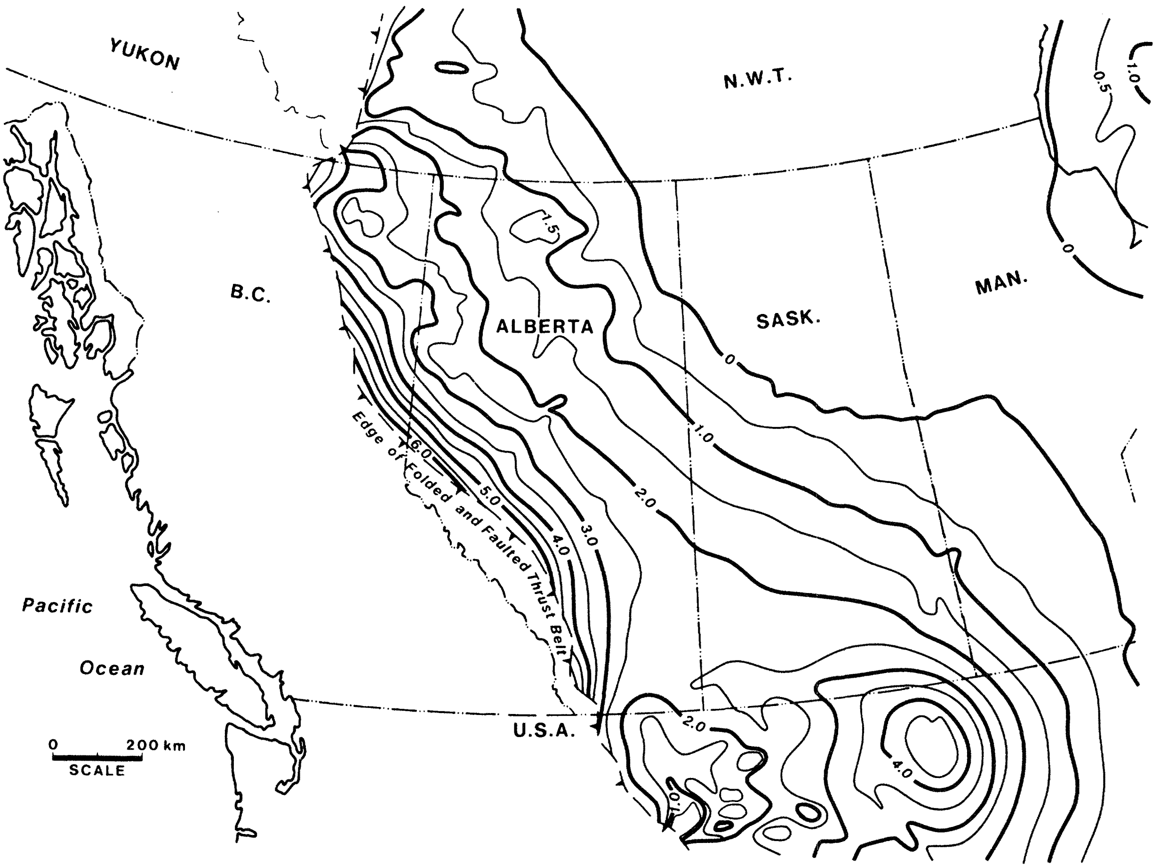

FIGURE 2. The Western Canada Sedimentary Basin. Total preserved thickness of Phanerozoic rocks east of the folded and faulted rocks of the Cordilleran foreland thrust belt. Contours in this and other figures are in kilometres.

This analysis of the stratigraphic record in the Western Canada Sedimentary Basin aims at elucidating the evolution of the basin, its relation to the evolution of the Cordillera, and its significance for models of basin development. The analysis involves a data base of 45000 exploratory wells within an area of 3×10^6 km^2 between the Cordilleran foreland thrust and fold belt and the Canadian shield, and published information from surface and subsurface studies of both the Cordillera and the cratonic platform. Porter and McCrossan are responsible for assembling and synthesizing the data from the undeformed basin fill; Price is responsible for the information on the Cordillera; the interpretations are a joint responsibility.

The stratigraphic record of the evolution of the basin can be outlined succinctly with reference to six stratigraphic sequences, each representing a major transgressive–regressive megacycle, and bounded by inter-regional unconformities (Sloss 1963). The nature of each sequence, and the relations between sequences in the undeformed cratonic platform, can be illustrated with regional stratigraphic maps and sections based directly on data from exploratory wells and bedrock maps (figures 5–14), but to portray relations in the deformed rocks of the Cordilleran foreland thrust belt it is necessary to use palinspastic reconstructions of balanced structural cross sections (figures 4, 14 and 15).

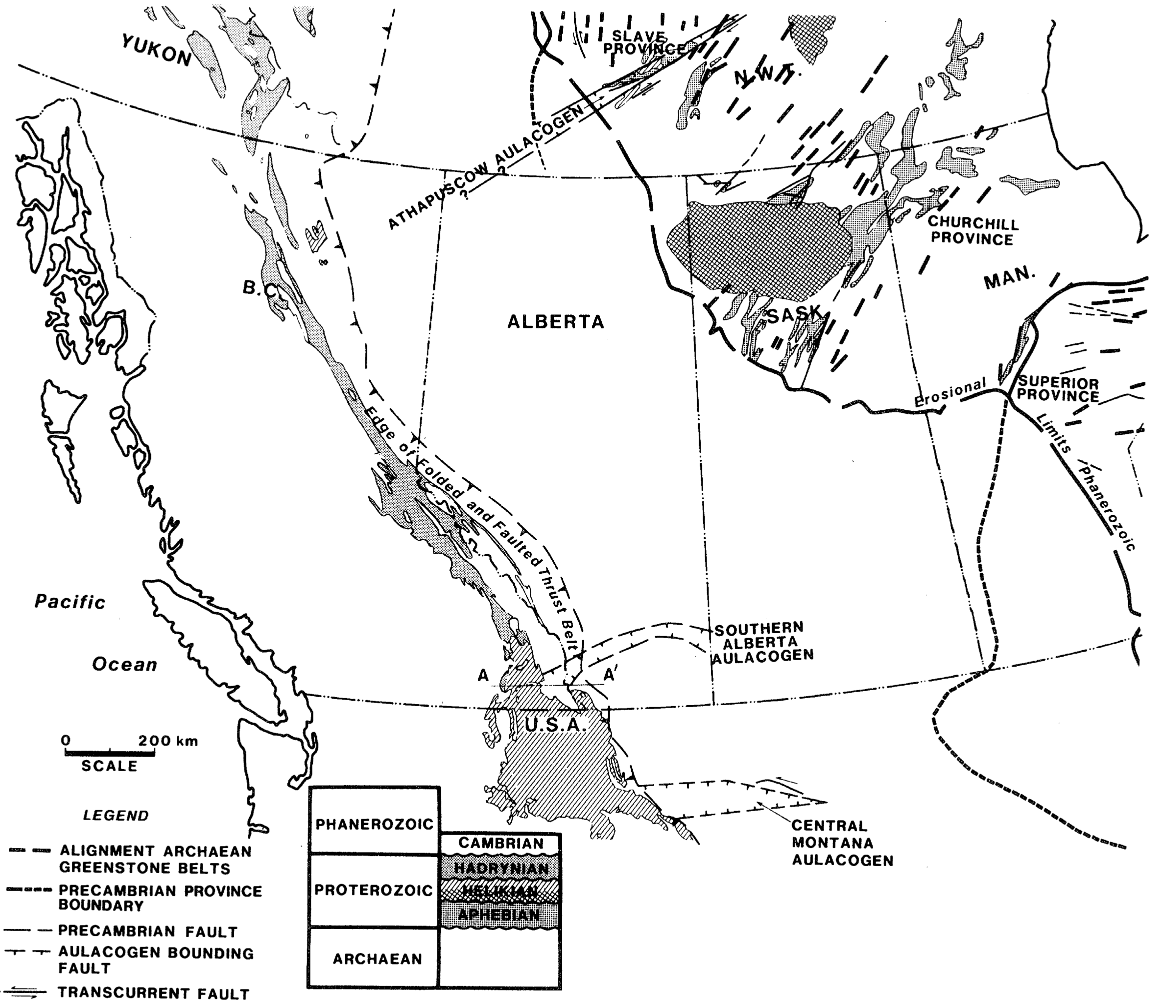

Figure 3. Precambrian geotectonic provinces and Proterozoic aulacogens (after Douglas (1969), Kanasevich *et al.*, (1969), Fraser *et al.* (1970) and Hoffman (1973).) Line A–A′ is the location of the section in figure 4.

The basement

The Precambrian continental craton, which forms the basement of the Western Canada Sedimentary Basin, consists mainly of Archaean crystalline rocks and Aphebian (2500–1750 Ma) supracrustal rocks that were modified by deformation, metamorphism and magmatism during the early Proterozoic (1750 Ma) Hudsonian orogeny, and are exposed in the Churchill Province of the Canadian Shield. It also includes large, unmodified, remnant Archaean cratons in the north (Slave Province) and the east (Superior Province), as well as smaller Archaean crustal remnants within the Churchill Province and its buried counterparts. Flat-lying, unmetamorphosed, early Helikian (1750–1500 Ma) platformal cover deposits that are preserved locally in the Churchill Province (figure 3) define an upper limit for the time at which the Churchill, Slave and Superior Provinces became established as a single stable continental craton (Fraser *et al.* 1970). The structures in Churchill Province trend northeastward, and can be traced on the basis of their distinctive magnetic anomaly signature, under the deformed Phanerozoic rocks of the foreland thrust belt (Price 1981). These northeast-trending structures were overlapped discordantly by the northwesterly trending prism of late Helikian (1550–1350 Ma) Belt–Purcell Supergroup sedimentary rocks that forms the lowest part of the continental terrace wedge.

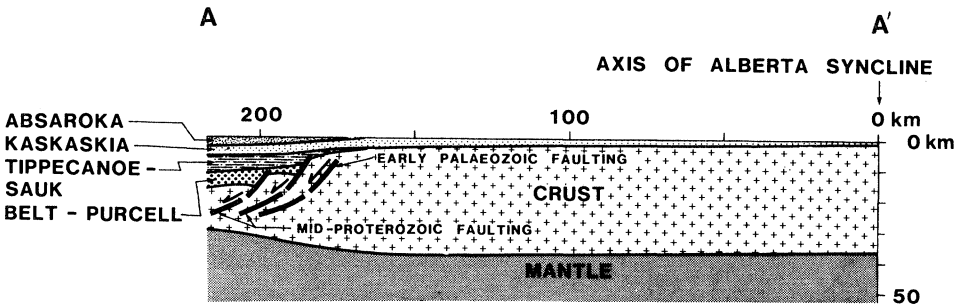

FIGURE 4. The continental terrace wedge: a palinspastically restored section through the Rocky Mountains along 49° 45′ N; line A–A′ of figure 3 (after Price 1981, Figure 2). No vertical exaggeration.

THE CONTINENTAL TERRACE WEDGE AND THE CRATONIC PLATFORM

Belt–Purcell sequence

The Purcell Supergroup in Canada and the Belt Supergroup of the United States consists mainly of fine-grained terrigenous clastic sediment that appears to be exclusively of North American provenance. In southern Canada the Belt–Purcell sequence (figures 3 and 4) forms a northeasterly tapering wedge up to 15 km thick (Price 1964). It appears to represent a continental terrace wedge that was prograded westward into the ocean basin formed by the rifting that extablished the western margin of the North American Precambrian craton (Sears & Price 1978). Thickness and facies variations indicate that rifting persisted during deposition of the Purcell Supergroup, and was influenced, at least locally, by the older northeasterly trending structures that characterize the Churchill Province of the Canadian Shield (McMechan 1979, 1980). Aulacogen-type rifts that project into the craton from this ancient rifted margin in southern Alberta and central Montana (figure 3) also may have been controlled by these older structures in the Precambrian basement. Deposition of the Belt–Purcell sequence appears to have terminated about 1350 Ma ago, with an episode of deformation that involved regional metamorphism, folding and granitic intrusion locally (McMechan 1979; McMechan & Price 1982), but only broad epeirogenic uplift on a regional scale.

Windermere sequence

A second major episode of faulting (rifting?) and oceanward progradation of the continental terrace wedge occurred during the deposition of the late Proterozoic (850–600 Ma) Windermere Supergroup, after a hiatus of about 500 Ma. It is recorded by the erosion of up to 4 km of the Purcell Supergroup and the deposition of up to 9 km of Windermere strata, before the early Cambrian regional transgression that initiated the overlying Sauk sequence (Lis & Price 1976).

The Windermere sequence is characterized by coarse clastic deposits ('grits') comprising detritus eroded from the granitic basement of the North American Craton, and by the occurrence of conglomeratic mudstones that may represent glacial deposits. It appears to comprise part of a suite of similar deposits of the same general age, marking an episode of rifting that extended almost continuously around the North American craton (Stewart 1976).

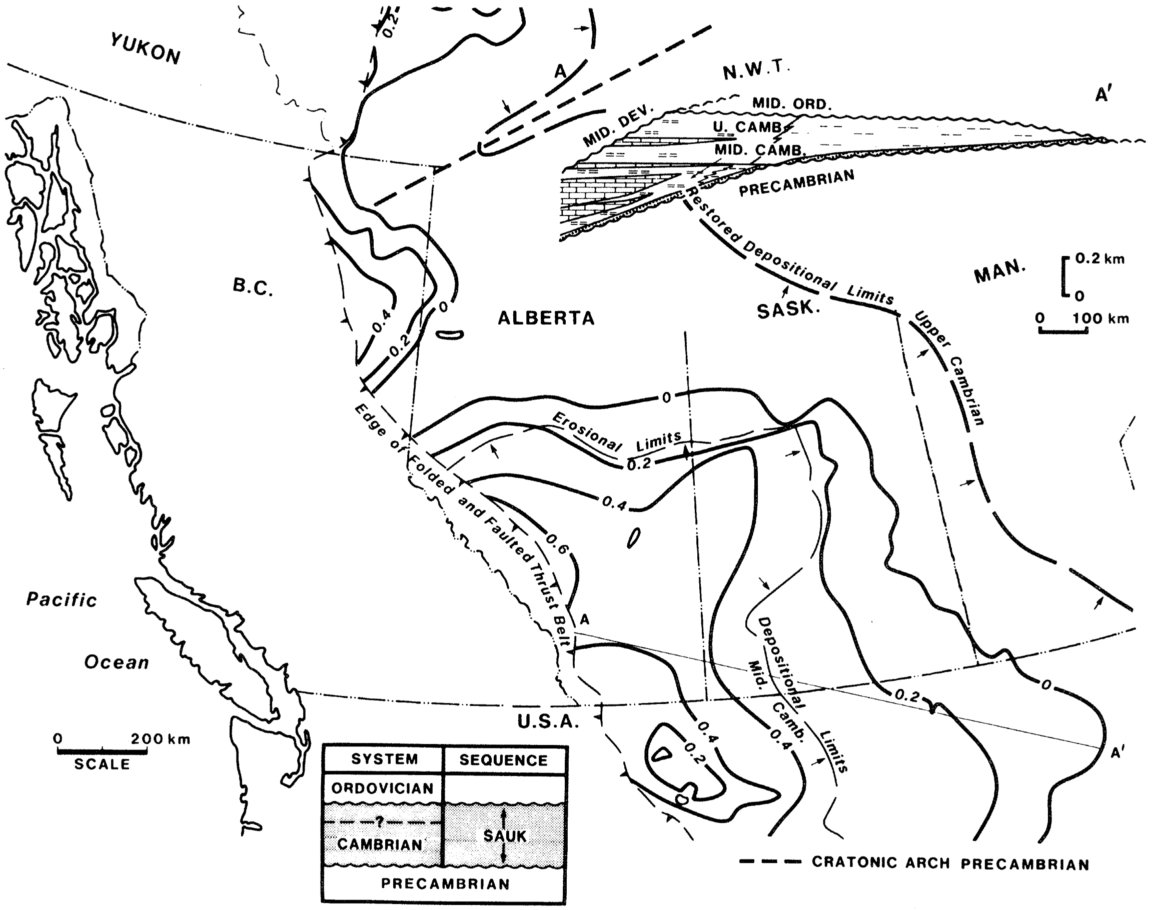

Figure 5. Sauk sequence, regional map and stratigraphic section A–A′ (modified after Fuller & Porter 1962, Figure 3).

Sauk sequence

The Sauk sequence (figure 5), which marks the beginning of the record of deposition on the cratonic platform, is a simple northeasterly tapering pericratonic wedge. It shows no signs of the influence of the cratonic arches and basins that dominated patterns of erosion and deposition during the subsequent evolution of the Western Canada Sedimentary Basin. The Sauk sequence began with a basal diachronous quartz sandstone that transgressed the entire western flank of the craton. The sandstone ranges in age from early Cambrian in the continental terrace wedge, where it overlaps the Helikian and Hadrynian (mid and late Proterozoic) rocks of the Purcell and Windermere sequences, to late early Ordovician (post-Tremadoc to pre-Arenig) in the east on the cratonic platform, where it overlies the deformed, Aphebian (early Proterozoic) and

Archaean rocks of the crystalline basement complex (figure 11). In the outboard, western part of the continental terrace wedge, the early Cambrian sandstone succession is more than 2 km thick, contains major intercalations of basic volcanic rocks (Wheeler 1963, 1965), and may have been deposited during an episode of crustal stretching. An overlying succession of younger onlapping units, showing progressively less eastward attenuation, advanced toward the centre of the craton until late Croixan time; and a regional regression began with the earliest Tremadocian deposits. Much of the centre of the craton remained emergent during the Sauk cycle; no Cambrian sediments are known to have been deposited in the Hudson Bay Basin and Moose River Basin, which lie east of the Western Canada Sedimentary Basin, in the centre of the Canadian shield.

The mid and late Cambrian and early Ordovician strata comprise a succession of grand sedimentary cycles, each of which begins with shales and grades upward into carbonate rocks. These cycles are superimposed upon, and reflect lateral shifts in the positions of, three broad facies belts (Aitken 1966). An inner detrital belt extends over the craton. It contains a higher proportion of shale, siltstone and sandstone, representing detritus eroded from the Precambrian Craton. A middle carbonate belt is characterized by thick carbonate bank deposits that are exposed in the thrust sheets of the Main Ranges of the Rocky Mountains. It separates the inner detrital belt from an outer detrital belt that is characterized by thick sequences of calcareous shales, most of which were deposited in relatively shallow water. Further outboard from the continent, in westernmost exposures of the continental terrace wedge deposits, homotaxial strata are black graphitic phyllites that contain intercalations of basic volcanic rocks, and may represent deposition in a continental slope and rise environment.

The carbonate bank margin that separates the middle carbonate and outer detrital facies belts persisted at essentially the same location from Middle Cambrian to Middle Ordovician time (Aitken 1971). Palinspastic reconstructions of the overthrust belt show that it was situated over the ancient rifted margin of the Precambrian continental craton (Price 1981), and suggest that there was intermittent 'down-to-the-basin' faulting along this zone from early Cambrian to Middle Devonian time (figure 4). In southern British Columbia and Alberta the southeastern edge of the basin in which the outer detrital facies accumulated coincided with the northwestern margin of a 'Montania', a large high-standing block that extended into the United States in central Montana (figure 5).

The northwestern margin of Montania was an important northeast-trending hinge zone from early Cambrian to late Devonian time (Norris & Price 1966). In southeastern British Columbia, within the continental terrace wedge, the net stratigraphic separation across this zone, along the unconformity at the base of the Upper Devonian rocks, is 8 km. This hinge zone was aligned with older northeast-trending structures that had controlled thickness and facies variations in underlying rocks of the Middle Proterozoic Purcell sequence (McMechan 1980) and in the late Proterozoic Windermere sequence (Lis & Price 1976); and these structures, in turn, were aligned with still older structures in the early Proterozoic crystalline basement complex of the craton (Kanasevich *et al.* 1969). The magnitude, nature and location of the differential movements across the hinge zone and the carbonate bank margin suggest that they were controlled by faulting in the basement beneath the continental terrace wedge (figure 3), and that this faulting followed the ancient rifted margin of the Precambrian craton southward to where it was deflected by some of the younger northeasterly trending structures that had formed when the Purcell and Windermere sequences were being deposited.

The pattern of variation of thickness of the Sauk sequence (figure 5) is a result of two episodes of erosional bevelling. A pre-Middle Ordovician (pre-Tippecanoe) episode affected the Sauk sequence over the entire Western Canada Sedimentary Basin. Within the Williston Basin, the pre-Tippecanoe erosional truncation of the Sauk sequence is approximately parallel with its depositional strike. This shows that the Williston Basin did not become established until later. The regional eastward bevelling marked a relatively uniform westward tilt of the craton that was associated with the westward progradation of the continental terrace wedge. A pre-Middle Devonian (pre-Kaskaskia) episode of erosion was more pronounced, but affected only those parts of the Sauk sequence not covered by Middle Ordovician strata. This second phase of erosion marked the inception of major cratonic arches, including the Central Montana Uplift, Peace River Arch, Western Alberta Arch and Tathlina Arch. Montania stood relatively high during deposition of the Sauk sequence; its northwestern margin was bevelled by pre-Kaskaskia erosion (Norris & Price 1966; Benvenuto & Price 1979). Along the axes of the Peace River Arch and Tathlina Arch, the entire Sauk sequence was eroded and the basement exposed before the Middle Devonian transgression (figure 7).

The only evidence of a cratonic arch during deposition of the Sauk sequence occurs across the locus of the northeast-trending, early Proterozoic Athapuscow Aulocogen (figures 3 and 5). Upper Cambrian rocks to the northwest comprise a red bed assemblage with numerous halite beds; but Upper Cambrian rocks to the southeast are marine clastics.

Tippecanoe sequence

The Tippecanoe sequence (figure 6) began with a transgressive basal sandstone that overlapped the eastward bevelled upper surface of the Sauk sequence from the part of the continental terrace wedge that is now exposed in the Western Ranges of the Rocky Mountains to the eastern limit of the Sauk sequence on the cratonic platform. The Williston Basin was established during the early stages of the deposition of the Tippecanoe sequence. It was circumscribed by the embryonic Western Alberta, Peace River, Severn, Transcontinental and Sioux cratonic arches. Montania may also have been relatively emergent and linked to the Western Alberta Arch during the deposition of the Tippecanoe sequence.

The pattern of variation in thickness of the Tippecanoe sequence in the Williston Basin is a result of both pre-Middle Devonian uplift and erosional truncation and the deposition of thinner condensed equivalents of the Tippecanoe sequence on the surrounding cratonic arches. The Middle Ordovician sandstone, which is thickest in the central and eastern parts of the Williston Basin (figure 6), was derived in part from Cambrian sandstones on the adjacent arches, as well as from Proterozoic sandstones on the Canadian Shield. A succeeding shallow-water carbonate shelf environment persisted until late Silurian time. Thinning of the carbonate deposits over the adjacent arches was a result of slower deposition rather than onlap. The carbonate platform deposits of the Tippecanoe sequence are the most widespread and of the longest duration of any of the Phanerozoic sequences. The maximum transgression probably occurred during late Ordovician time when most of the North American craton was inundated. Pre-Middle Devonian erosion has removed most of this sequence, leaving remnant small outliers of stratigraphically similar deposits at various sites on the interior of the craton, as well as the extensive deposits in cratonic basins such as the Williston, Hudson Bay, Moose River and Michigan basins (figure 7).

The carbonate facies that dominates the Ordovician in the Williston Basin is interrupted by some five sabkha evaporite cycles that are limited to the central and north-central part of the basin (Porter & Fuller 1959). Their development appears to be related to the initial growth of Central Montana and Western Alberta arches because the locus of the maximum sedimentary thickness during the interval in which they were deposited shifted some 60 km to the southeast. Subsequent shallow-water biogenetic carbonate deposits extended across the entire Western Canada Basin, and included biostromal reefs that were replaced in late Silurian time by micro-grained dolomites and anhydrite-bearing dolomites that are the counterparts of the Cayugan evaporites of the Michigan Basin.

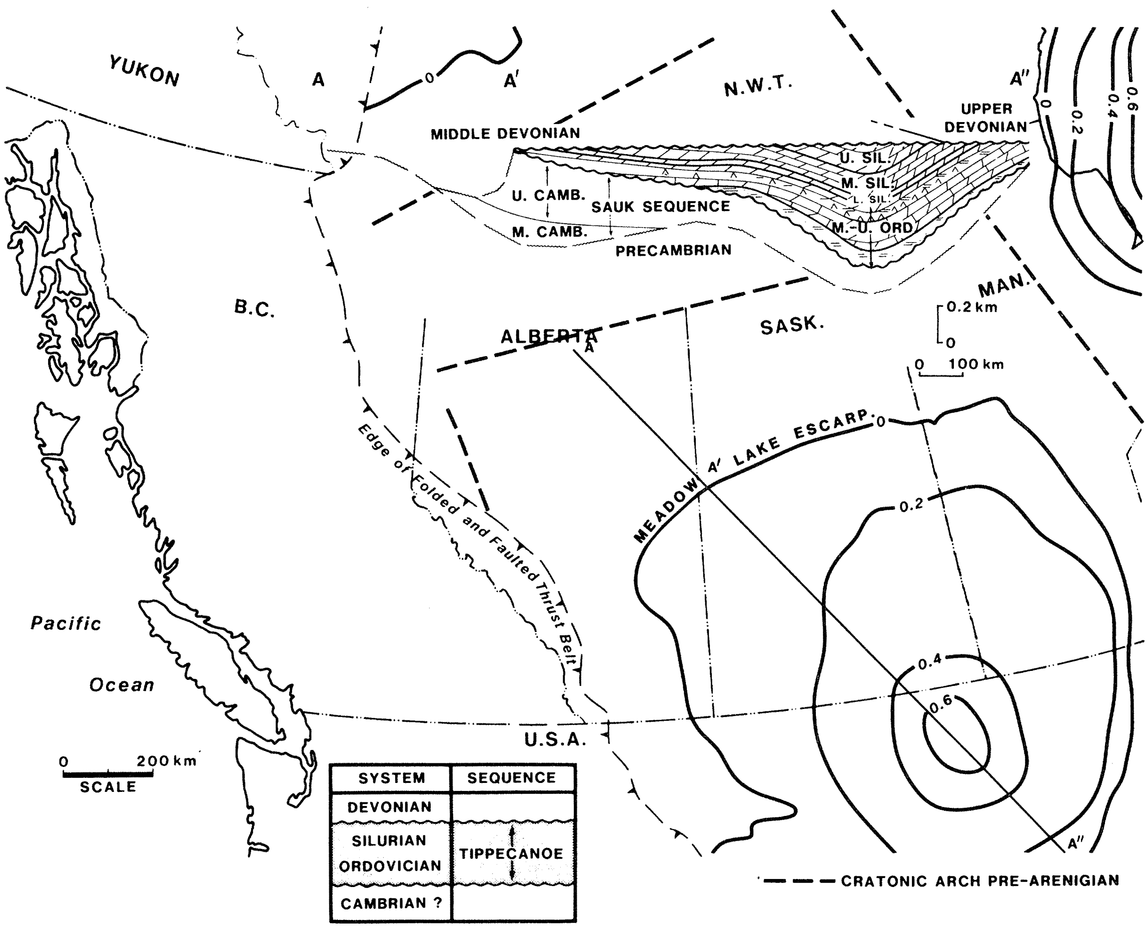

Figure 6. Tippecanoe sequence, regional map and stratigraphic section A–A′ (modified after Fuller & Porter 1962, Figure 7).

The restricted circulation reflected by these evaporite deposits can be attributed to the emergence of the cratonic arches that circumscribe the basin. A number of very thin, discrete synchronous sheets of sandstone that interrupt the massive carbonate strata of the Silurian system (Porter & Fuller 1959) probably result from periodic uplift of the central craton, which was the source of the sands.

The erosion that removed much of the Silurian and older strata of the Tippecanoe sequence before the deposition of the Middle Devonian was concentrated along the axial regions of the cratonic arches, which became high-standing topographic features and strongly influenced the depositional environment of the succeeding Kaskaskia sequence. The asymmetrical depositional profile of the Williston Basin was accentuated by deeper erosion along the east and south sides of the Severn, Transcontinental and Sioux arches. This shape and the lack of any deep water facies suggests that the geometry of the basin was controlled primarily by the growth of the arches.

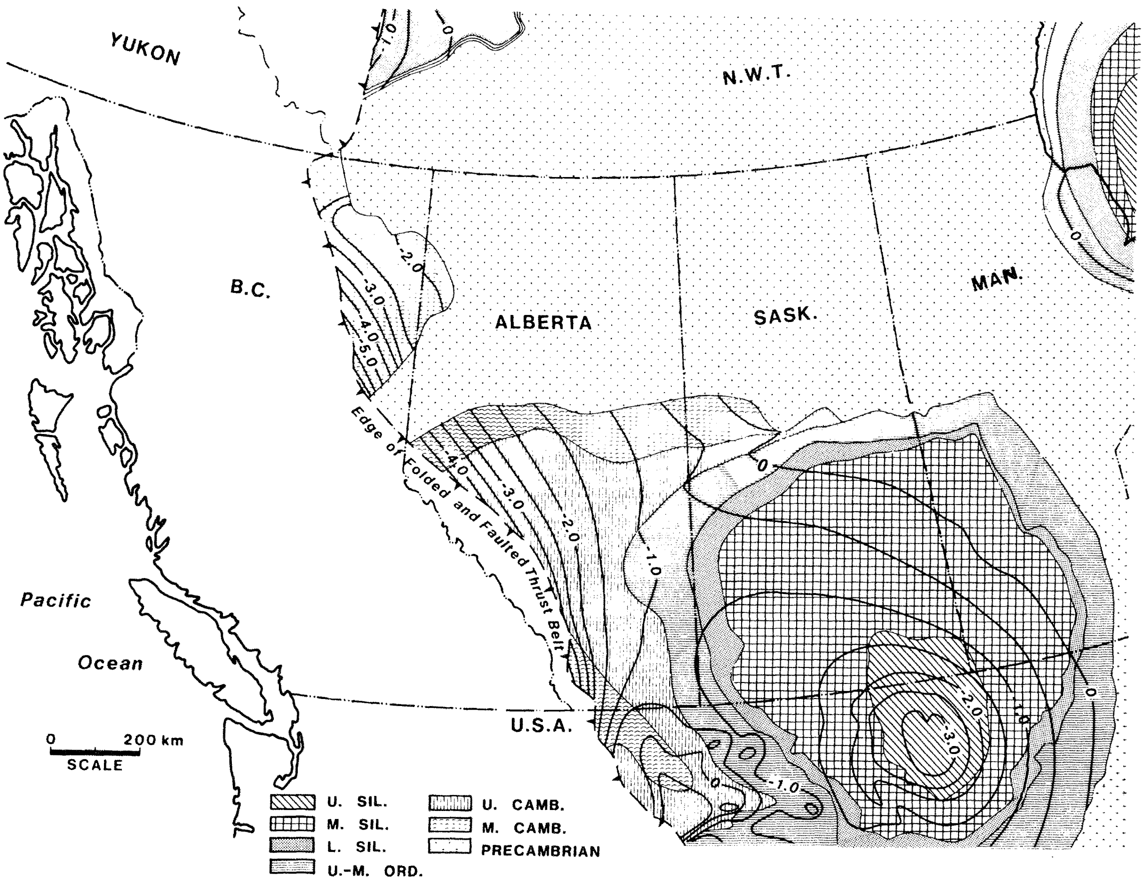

FIGURE 7. Structure and palaeogeology of the pre-Devonian erosion surface.

Kaskaskia sequence

The Kaskaskia sequence was preceded by the most profound episode of epeirogenic deformation in the history of the Western Canada Sedimentary Basin. The surface relief produced by early Devonian epeirogenic uplift of the cratonic arches and by the ensuing erosion of the Tippecanoe and Sauk sequences controlled the distribution, thickness and character of the initial deposits of the Kaskaskia sequence. This surface relief forced epeiric seas to transgress from northwest to southeast instead of from the previous westerly direction. The Tathlina, Western Alberta and Peace River arches were strongly emergent and shed sands into the transgressive basal Devonian deposits. The Williston Basin, where the Silurian and Ordovician strata were preserved, persisted as a regional depression with little topographic relief, bounded on the east by the Seven Arch and on the south by the Transcontinental and Sioux arches. In central Alberta and Saskatchewan, where the protective cover of resistant Ordovician carbonate rocks was breached, deep erosion of the less resistant clastic rocks of the underlying Sauk sequence created the northward-facing Meadow Lake Escarpment, which was about 250 m high (figure

6). The initial Middle Devonian (Eifelian) deposits, which consisted of massive halite beds, associated red mudstones and a basal sandstone, completely filled the topographic depressions that were enclosed on the west by a combination of cratonic arches (Western Alberta, Peace River and Tathlina), and on the north and south by inward facing Cambro-Ordovician escarpments (figure 10*a*). The three pods of Eifelian salt that remain are relics of a much more extensive evaporite deposit, the eastern parts of which have been removed by subsequent dissolution, and by erosion during Mesozoic time. The early Middle Devonian (Eifelian) northwest margin of the evaporite basin was controlled by a massive reef barrier (Manetoe) which was situated

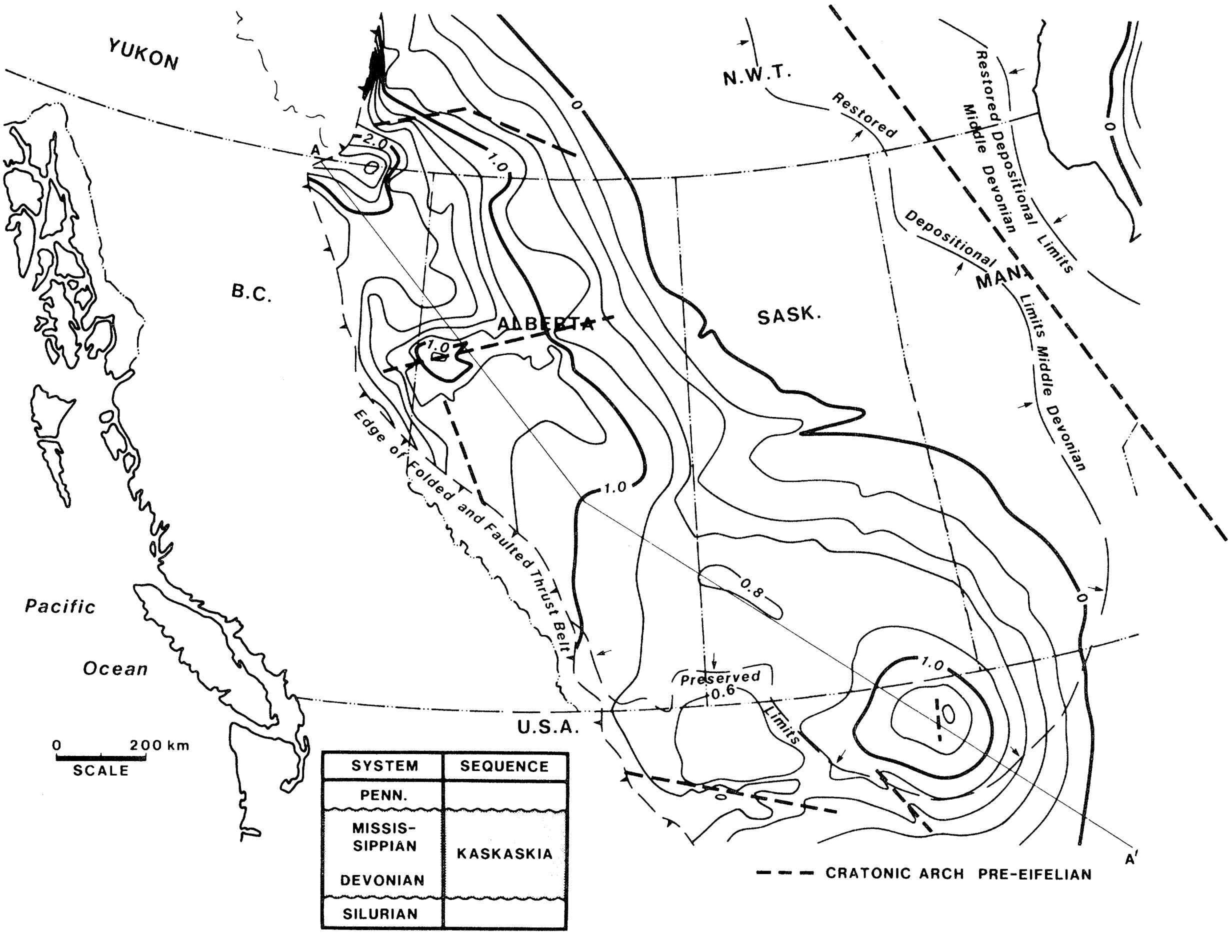

FIGURE 8. Kaskaskia sequence, regional map, showing line of section A–A′ of figure 9.

north of the map area, and which limited the southern encroachment of unrestricted marine deposition (figure 10*a*). Subsequent dissolution of thick halite deposits by meteoric water resulted in complex adiastrophic structures within the Western Canada Basin. The dissolution of the salt affected both the preservation and the facies and thickness of overlying beds.

The changing patterns of distribution of successively younger Devonian salt deposits (figure 10) involved a progressive southward shift into the central part of the Williston Basin, and was part of a regional pattern involving southward transgression of barrier reefs and unrestricted marine facies (figures 9 and 10). The Peace River Arch and Western Alberta Arch remained

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

emergent and supplied sand to transgressive Givetian deposits. A massive reef complex (Presqu'ile) that developed across the south flank of the Tathlina Arch formed the barrier behind which was formed an extensive (600 × 1600 km) Givetian evaporite basin, bounded by the Western Alberta, Severn, Transcontinental and Sioux arches (figure 10 *b*). Successively younger (Frasnian and Fammennian) barrier reefs enclosed progressively smaller salt basins (figure 10*c*,*d*). Frasnian deposits transgressed the Western Alberta Arch, reestablishing the marine connection between the cratonic platform and the adjacent continental shelf, and Famennian deposits transgressed the last inliers of the Precambrian basement complex on the crest of the Peace River Arch (figures 7 and 11). At the south end of the Williston Basin, the

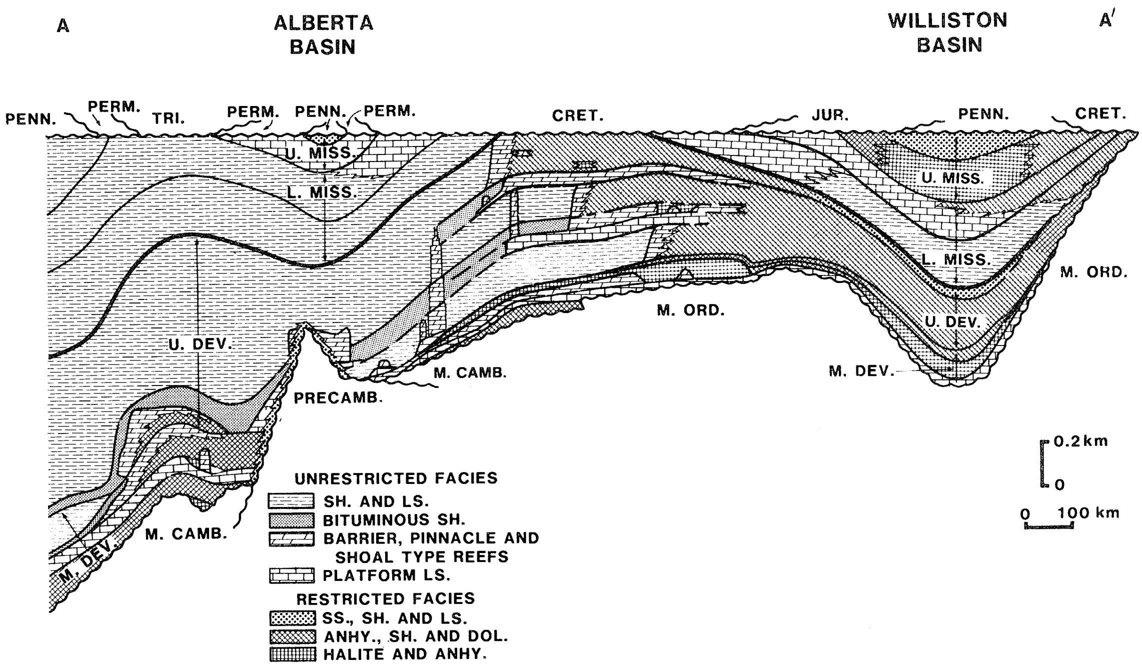

FIGURE 9. Kaskaskia sequence, regional stratigraphic section along line A–A′ of figure 8.

Upper Devonian strata onlapped the Middle Devonian against the Transcontinental and Sioux arches, which supplied clastic detritus for the diachronous inshore sand facies associated with both the Upper and Middle Devonian. By the end of the Devonian the present distribution of supracrustal rocks on the Precambrian basement complex, and most of the major epeirogenic structures on the cratonic platform, had been established (figure 11). Progressively younger deposits had onlapped eastwards over the Precambrian basement complex in the southern part of the area; but in the northern part the Upper Devonian had onlapped the Middle Devonian westward over the Peace River Arch, which had been stripped of its cover of Sauk and Tippecanoe sequences by erosion during early Devonian uplift.

On the cratonic platform much of the stratigraphic record of the Absaroka sequence and the Mississippian and Upper Devonian parts of the Kaskaskia sequence was destroyed by the Pennsylvanian to Middle Jurassic emergence and erosion of the Sweetgrass Arch, and by the regional northeastward erosional truncation that preceded the deposition of the foreland basin (Zuni) sequence (figure 12).

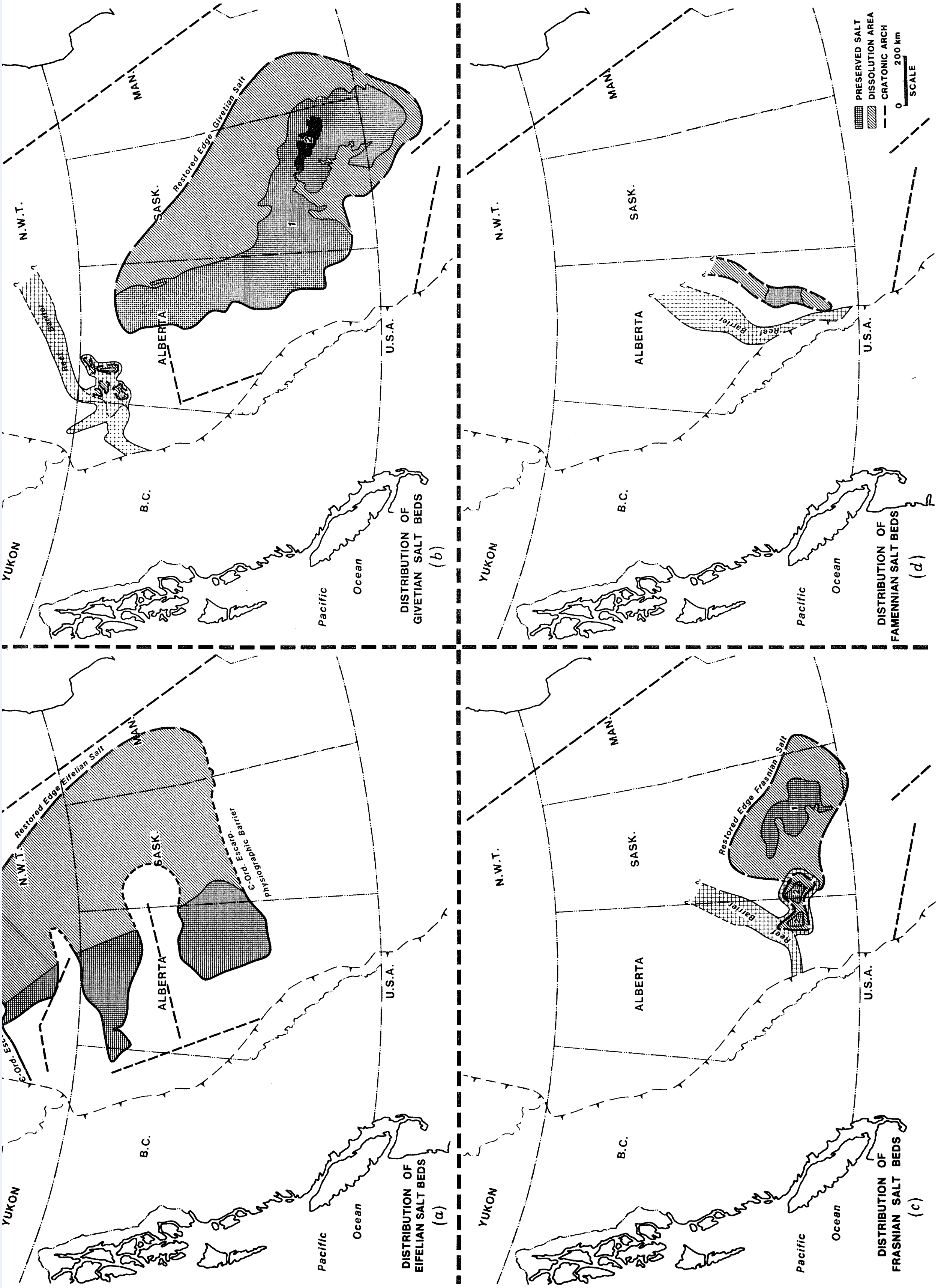

FIGURE 10. Devonian salt deposits.

Mississippian deposition began with an abrupt transgression marked by a thin but widespread veneer of dark organic shale. The associated fine clastic detritus may have been eroded from the Severn, Transcontinental and Sioux arches. There followed a gradual transition from Kinderhookean restricted euxinic conditions to an Osagean transgressive stage of open marine calcareous shales and limestones, and to lower Meramecian deposition of crinoidal sands representing the culmination of the transgression. The latter are gradational, on the eastern margin of the Williston Basin, into sabkha anhydrites and dolomites. They are succeeded by

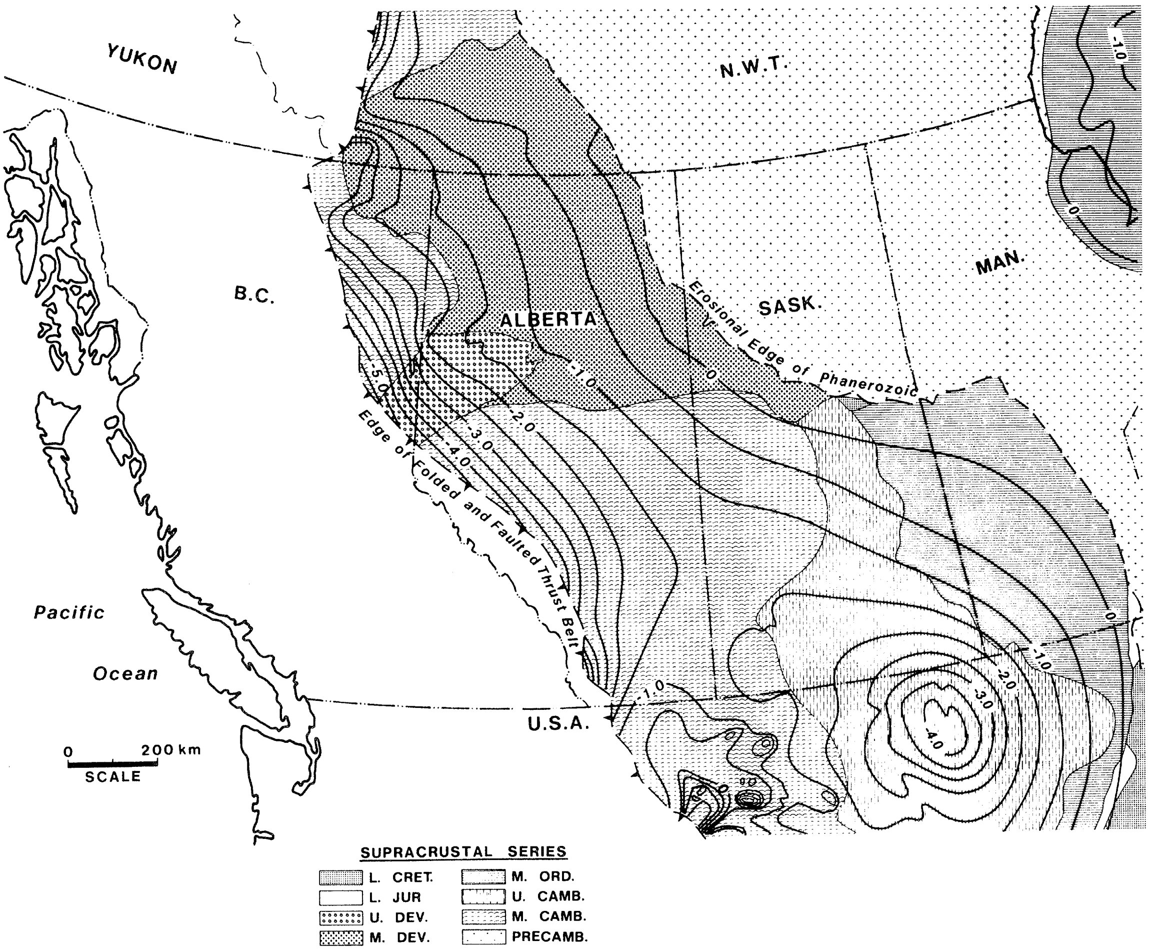

FIGURE 11. Structure of the Precambrian basement surface, and ages of overlying supracrustal rocks.

upper Meramecian regressive halite and anhydrite cycles, which formed in the centre of the Williston Basin, behind the barrier created by the emergence of the Central Montana Uplift. These general conditions also obtained in Alberta but were much less restricted and evaporitic since the arches in Alberta were inactive. Here the carbonate cycles pass northwestward into a deep-water fine clastic facies that is continuous from the Devonian (figure 9). The whole of the Kaskaskia sequence eventually becomes shale to the northwest. Uppermost Mississippian (Chesterian) deposits are characterized by silts and sands that record a reactivation of the cratonic arches, and signal a regional regression that preceded the deposition of the Absaroka sequence. The conspicuous lateral variations in thickness of the Kaskaskia sequence reflect a

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

combined influence of pre-Kaskaskia erosional relief, lateral variation in the amount of subsidence during deposition of the Kaskaskia sequence, and differential preservation due to lateral variations in the amount of uplift and erosion after the deposition of the Kaskaskia sequence.

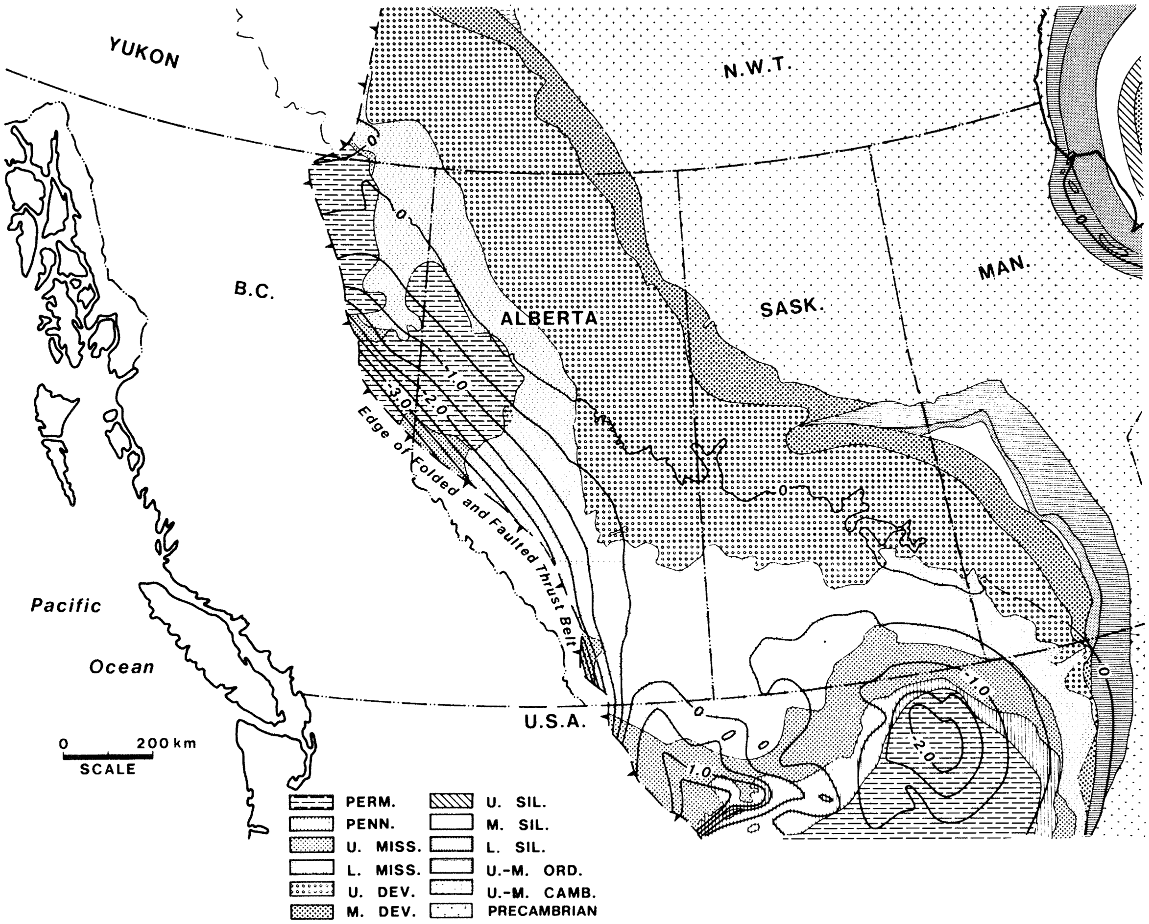

FIGURE 12. Structure and palaeogeology of the pre-Mesozoic erosional surface.

Absaroka sequence

The Absaroka sequence (figure 13) is characterized by a conspicuous westward shift in the limits of sediment accumulation, which records an emergence and westward tilt of the craton. This regional long-term regression is a continuation of a pattern established during deposition of the upper part of the Kaskaskia sequence, and is accompanied by an upward increase in the amount of terrigenous clastic detritus. The abrupt eastward thinning and termination of the Pennsylvanian, Permian and Triassic strata is a combined result of depositional attenuation and intermittent erosional bevelling.

The Absaroka sequence (figure 13) was separated into two contrasting facies domains by the early Pennsylvanian (Morrowan) to Middle Jurassic emergence of the northeast-trending Sweetgrass Arch. Southeast of the Sweetgrass Arch, in the Williston Basin, non-marine deposition was important, and during the Pennsylvanian and Permian deposition was influenced by the northward dispersal of sands and silts from the uplift of the ancestral Rocky Mountains (Mallory

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

1972; Rascoe & Baars 1972). During the Permian (Leonardian), Triassic and early Middle Jurassic, uplift of the bordering cratonic arches isolated the Williston Basin and it become a locus of evaporite (halite) and red bed deposition. This is in sharp contrast with the unrestricted marine deposits that characterize almost all of the Absaroka sequence northwest of the Sweetgrass Arch, on the cratonic platform and the continental terrace wedge. One particularly noteworthy feature of the Absaroka Sequence in this domain is the inversion and profound subsidence over the former site of the Peace River Arch. This foundering, which began early in the Mississippian and continued into the Permian, but not into the Triassic, is responsible for the preservation of Pennsylvanian and Permian rocks over the former site of the Peace River Arch (figure 12). The Triassic deposits, which were bevelled northeastwards by Jurassic erosion, appear to have been prograded westwards over the continental terrace wedge as a series of shallow-water continental shelf deposits.

The foreland basin

Zuni sequence

The Zuni sequence (figure 14) records the transformation of the Western Canada Sedimentary Basin from a cratonic platform containing a network of epeirogenic arches and basins, and

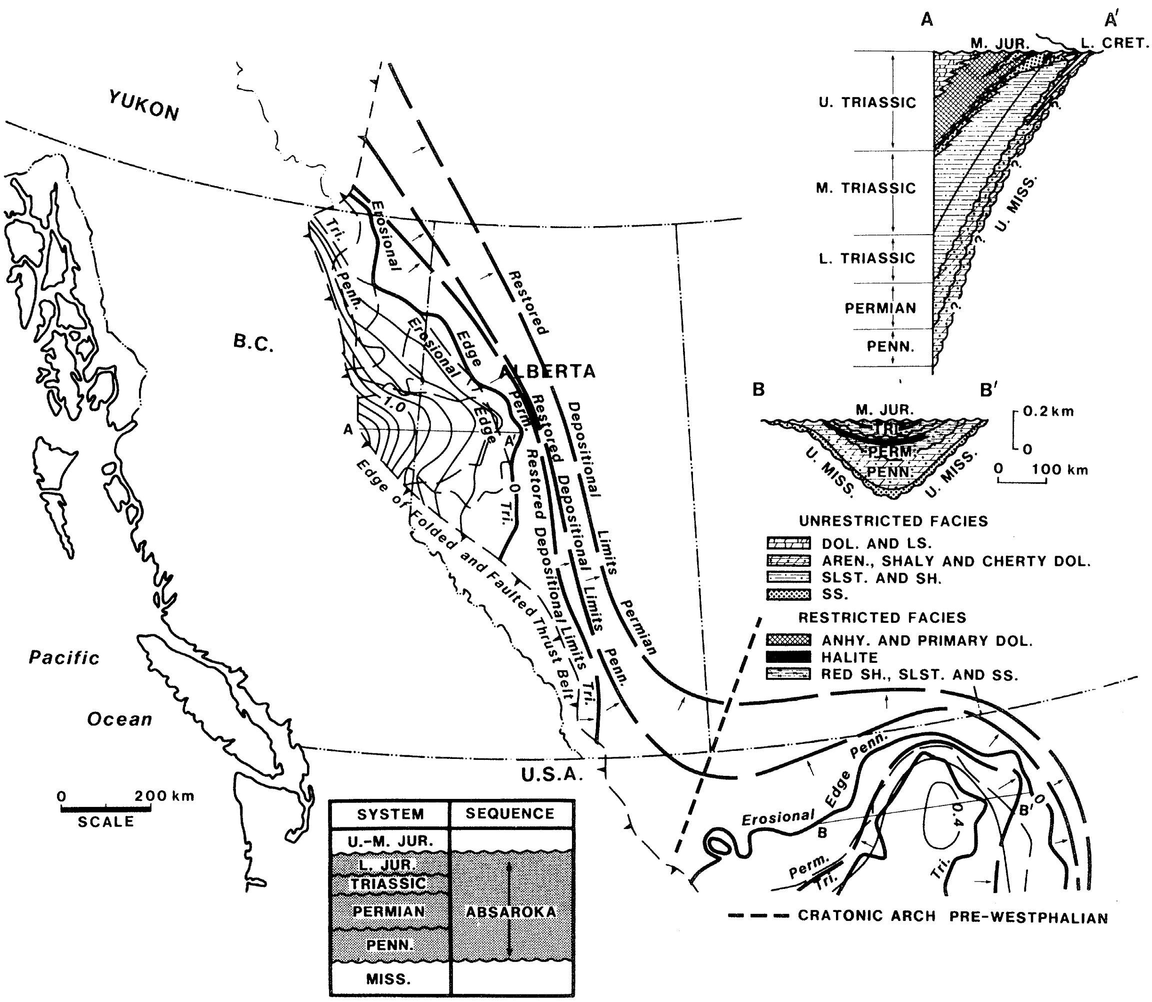

Figure 13. Absaroka sequence, regional map and stratigraphic sections A–A′ and B–B′.

bordered by a continental terrace wedge that was prograded into an adjacent ocean basin, into a foreland basin containing stacked northeastward tapering wedges of synorogenic clastic detritus that were prograded toward the interior of the craton. The Middle Jurassic deposits that initiated the Zuni sequence reflect the same pattern of tectonic controls on erosion and deposition that had characterized the Absaroka Sequence: deposition of a restricted facies within the lowermost Bajocian southeast of the Sweetgrass Arch in the Williston Basin, and of normal shallow-water marine facies on the craton and the continental shelf northwest of the Sweetgrass Arch. However, during the late Jurassic (Kimmeridgian and Portlandian) there

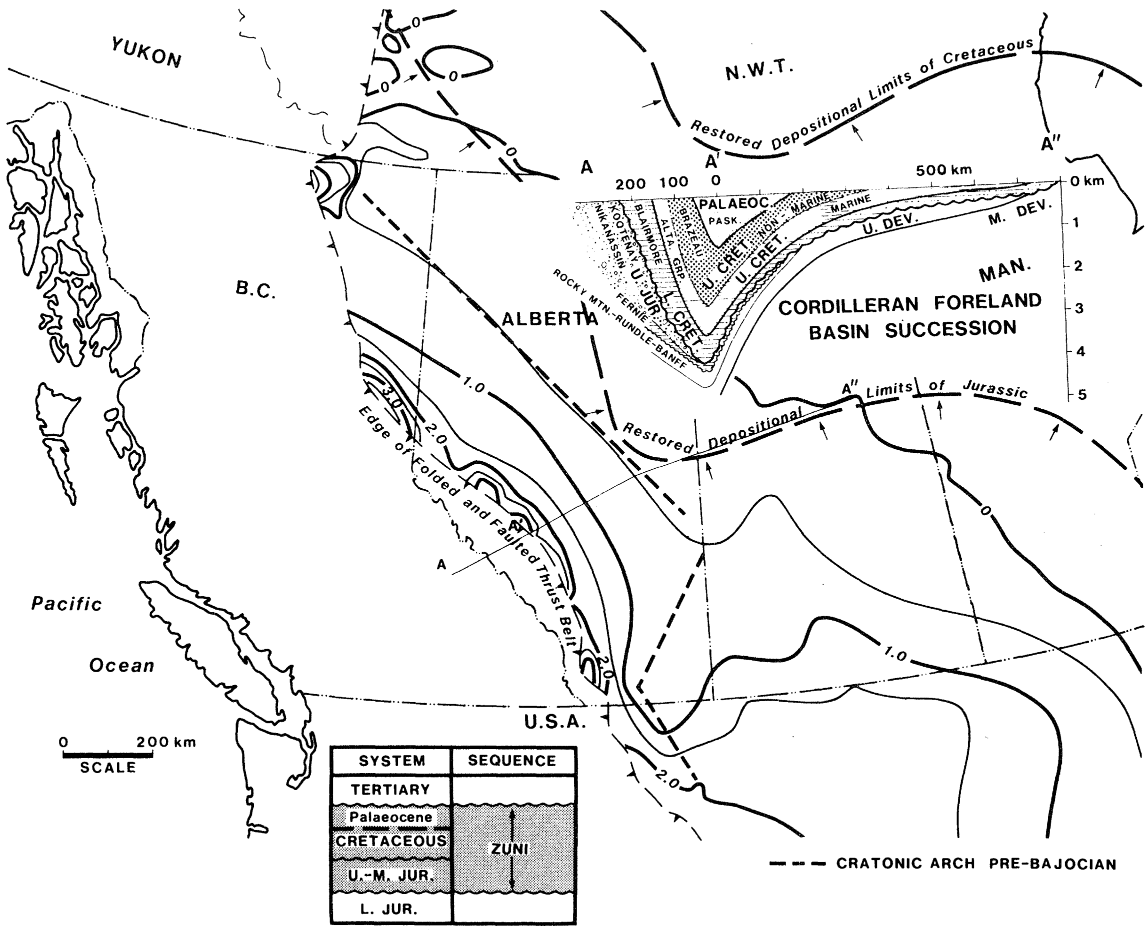

FIGURE 14. Zuni sequence, regional map and structure section. The segment A–A′ of the stratigraphic section is a palinspastic reconstruction through the foreland thrust belt, based on a structure section by Price & Mountjoy (1970, Figures 2 and 3), and the segment A′–A″ on a regional stratigraphic section edited by Gussow (1962).

was a reversal in the direction of sediment transport and an abrupt influx of clastic detritus from the emerging Cordilleran foreland thrust belt. Within the thrust belt, the latest Jurassic and earliest Cretaceous synorogenic clastic wedge, comprising the non-marine Kootenay and Nikannassin Formations, consists of sedimentary detritus eroded from the continental terrace wedge, and locally is more than 1 km thick. The succeeding early Cretaceous synorogenic clastic wedge, comprising the Blairmore Group, is mainly non-marine, contains metamorphic and igneous, as well as sedimentary detritus, and is locally more than 2 km thick. It spread out across the basin unconformably overlapping the Palaeozoic and older Mesozoic deposits, finally onlapping the crystalline basement (figure 12). An extensive marine transgression, which had been encroaching during the earlier Cretaceous from both the north and south, covered by Albian to Cenomanian time most of the Western Canada Basin and appears to coincide with a lull in the development of the Cordilleran orogenic belt. The late Cretaceous and Palaeocene synorogenic clastic wedge deposits, which are also of mixed provenance, comprise a major regressive cycle, up to 4 km thick, and record the final stages of the evolution of the foreland basin.

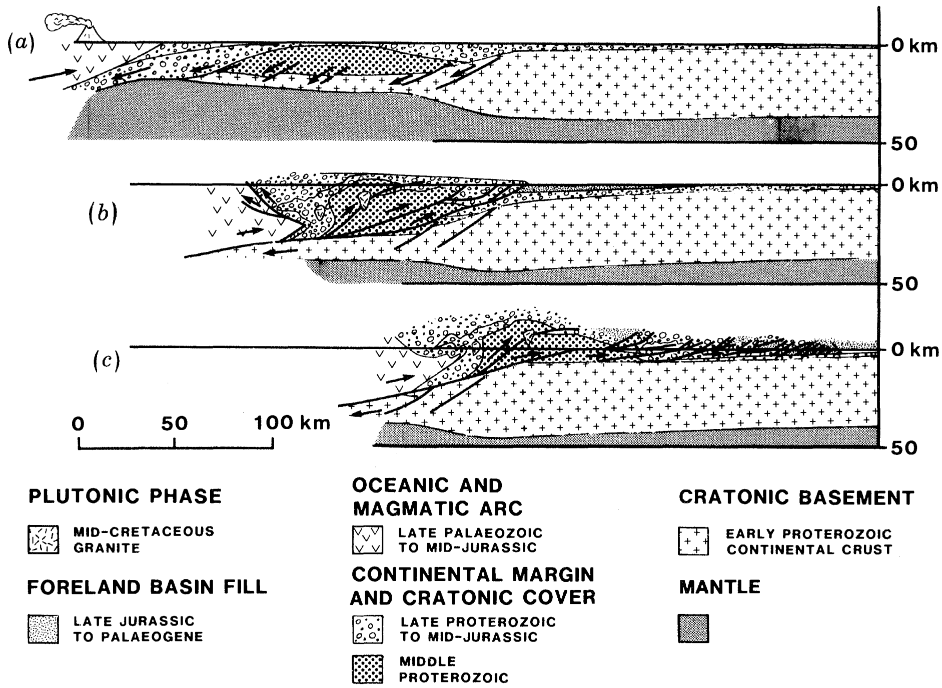

FIGURE 15. Three stages in the evolution of the foreland thrust belt in the southeastern Canadian Cordillera, based on a palinspastic reconstruction of a balanced structure section along 49° 45′ N (Price 1981). (*a*) Mid-Jurassic; (*b*) mid-Cretaceous; (*c*) mid-Tertiary.

The Cordilleran foreland thrust belt formed in the zone of convergence between the North America craton and the tectonic collage of oceanic terranes that were accreted to its western margin and now compose the main part of the Cordillera (Davis *et al.* 1978; Monger & Price 1979; Coney *et al.* 1980; Price 1981). The pre-Cordilleran continental terrace wedge, which had been deposited outboard from the Proterozoic rifted margin of the North American craton on a basement of oceanic or tectonically attenuated continental crust, was compressed, tectonically thickened, detached from its basement, and juxtaposed over the western margin of the continental craton (figure 15). Part of the supracrustal cover of platformal and foreland basin deposits was scraped off the craton and accreted to the overriding mass to form a wedge of imbricate thrust fault slices. This accretionary wedge was tectonically prograded over the margin of the continental craton. The foreland basin formed as a cratonward migrating moat because of isostatic flexure of the lithosphere in response to the tectonic loads imposed on it by the overriding continental terrace wedge and by the growing wedge of imbricate thrust fault slices. The sediments that filled the foreland basin comprise the clastic outwash that was eroded from the emerging thrust slices, and was trapped in this moat (Price 1973; Beaumont 1981). Thus the history of development of the foreland thrust belt and the lithospheric plate movements that gave rise to the foreland thrust belt is recorded by the sediments deposited in the foreland basin.

Three general stages in the evolution of the foreland thrust belt can be identified on the basis of structural relations within it (Price 1981), and these coincide with three general phases in the evolution of the foreland basin (figure 15). The long history of growth of the continental terrace wedge ended in a mid-Jurassic (Bajocian?) 'collision' with a 'foreign' terrane comprising an oceanic volcanic arc assemblage that accumulated on a basement of Triassic and Upper Palaeozoic rocks, quite unlike those in the continental terrace wedge (Monger & Price 1979). During the late Jurassic and early Cretaceous Columbian Orogeny, while the continental terrace wedge was still situated outboard from the craton, it was compressed between the 'foreign' terrane and the North American craton, was tectonically thickened, and was thrust over both. The load imposed on the lithosphere by the tectonic thickening and overthrusting of the continental terrace wedge was responsible for the isostatic flexure and the subsidence of the foreland basin that is recorded by the late Jurassic – early Cretaceous non-marine to brackish deposits of the Kootenay – Nikannasin clastic wedge, and the early to mid-Cretaceous mainly non-marine deposits of the much more extensive Blairmore clastic wedge (figure 14). Mid-Cretaceous granitic plutons that cut the thrust faults along the west side and in the central part of the deformed continental terrace wedge define the upper limit for the time of deformation there. The granitic intrusions are part of a regional episode that coincided with the widespread mid-Cretaceous marine transgression over the foreland basin. They appear to be associated with a lull in the convergence between the accreted 'foreign' terrane and the North American craton. The final stage in the evolution of the foreland thrust belt, during the late Cretaceous and Palaeocene Laramide orogeny, involved renewed convergence during which: (1) the deformed continental terrace wedge was detached from its basement and was displaced over the margin of the craton, (2) the supracrustal rocks scraped off the continental craton were incorporated into the eastward prograding accretionary wedge of imbricate fault slices, and (3) the foreland basin subsided rapidly and expanded eastward as it was filled with the thick regressive sequence of clastic wedge deposits that mark the terminal stage in the evolution of the foreland basin.

Tejas sequence

The record of the Tejas sequence is fragmentary. It is limited to a few small erosional outliers on the craton and to local basin-fill deposits in the eastern Cordillera. It is a record of intermittent crustal extension and listric normal faulting during which thin sheets of gravel were spread across the Western Canada Sedimentary Basin.

Summary

The Palaeohelikian flat-lying unmetamorphosed basin remnants high on the craton show that the craton was established long before the commencement of the Phanerozoic cycle of basin development examined in this paper. The first significant event in this history was the development, over attenuated crust, of an Atlantic type down-to-ocean faulted margin in the Neohelikian, upon which was deposited a great wedge of clastic sediments across the structural grain of the Archaean platform, followed after a gap of 500 Ma by renewed faulting and subsidence and further loading in Hadrynian time. The subsidence of the continental margin as a result of this imposed load and thermal contraction extended far into the craton and set the stage for the first cycle of deposition represented by the Sauk sequence.

Sauk sequence. The Sauk sequence records progressive onlap with the Upper Cambrian strata extending high on the western side of the craton and the depositional strike running northwesterly, parallel to the probable old continental margin. There is a notable lack of arches or isolated basins. This initial sequence is dominated by clastic sediments from the shield.

Tippecanoe sequence. Arches interrupted the linear depositional pattern. Marked sedimentary attenuation over highs created a relative thickening in the area of the Williston Basin. This sequence shows thin seams of fine sand and silt suggesting episodic uplift of the burgeoning arches, but the dominance of carbonate rock indicates that they were for the most part covered. The lack of an onlapping relation, and widespread inundation of the craton indicate a very rapid transgression. Like the Cambrian seas, those of the Ordovician and Silurian transgressed from the western margin.

Kaskaskia sequence. The strongly developed pre-Devonian arches surrounding and segmenting the Devonian depositional area resulted in a transgression of over 3000 km from the northwest, rather than the west, over a tectonically disturbed and eroded surface, resulting in complex facies patterns.

The Mississippian seas covered almost as large an area as those of the Ordovician, onlapping completely the Western Alberta and Peace River arches. Arches in the southern and western part of the Williston Basin continued to grow into late Kaskaskia time, creating sills with salt deposits in the regressive part of the sequence that culminated with a clastic assemblage derived from the flanking arches.

Absaroka sequence. The Sweetgrass Arch isolated the Alberta Basin from the Williston Basin for the first time. These opened to the southwest and west respectively. The Williston Basin had a dominant red bed-evaporite assemblage, the Alberta Basin a marine clastic assemblage.

This interval is characterized by periods of non-deposition and erosion, with depositional limits of each system indicating much less encroachment on to the craton, which appears to have progressively increased its rate of dip to the west. The progressively increased rate of westward thickening from the Sauk to Kaskaskia to Absaroka in the undisturbed part of the basin also suggests an increasing westward tilt or subsidence of the basin margin.

Zuni sequence. The Zuni reflects the late Jurassic orogenic activity in the west. The convergence of allochthonous terranes with the continental margin resulted in the thrusting of the marginal deposits eastward, tectonically loading the lithosphere and providing the provenance for the continental clastic sediment that filled the foredeep which formed in response to the loading. The continental sediment spread across the basin with marine seaways to the north and south that gradually advanced to join together to form a seaway extending from the Arctic to the Gulf of Mexico in mid-Cretaceous time. A second plate convergence resulted in further tectonic thickening with thrusting extending further east, cannibalizing previously formed deposits and generating a second sequence of terrestrial sediments that covered the entire basin again in the late Cretaceous and Palaeocene.

Notably absent during the Zuni was the influence of arches that had previously segmented the basin. Also absent are carbonates and evaporites. Instead the basin fill was entirely of clastic sediments. The present structural configuration of the basin was established during this period as the foredeep encroached onto the craton.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Discussion

The evolution of the Western Canada Sedimentary Basin involves a long history of recurrent regional or inter-regional vertical movements that controlled the transgressive–regressive mega-cycles recorded by the regional stratigraphic sequences. These cyclic movements appear to be part of a larger cycle involving gradual overall transgression and the expansion of realms of marine deposition from late Proterozoic to late Devonian to early Mississippian time, and then gradual overall regression and the retraction of realms of marine deposition until mid-Jurassic time. The rate of eastward thinning in the undisturbed portion of the Alberta Basin, expressed as sedimentary condensation as well as erosional truncation, increases with each successive sequence (figures 5, 8 and 13), indicating a progressive increase in westward tilt. Superimposed upon these regional or inter-regional movements are the recurrent local or intra-regional variations in amount of subsidence and uplift that controlled the protracted history of growth of the basins and arches. There is an obvious synchronism, on a regional scale, in the uplift of some of the arches and subsidence of some of the basins. This may also hold on an inter-regional scale. It is a fact that must be accommodated in any comprehensive models for the development of the basins and arches.

The obvious correlations between the history of development of the Western Canada Sedimentary Basin and that of the Cordillera leads to convincing explanations for some aspects of the development of the Western Canada Sedimentary Basin, but the explanations for some other fundamental aspects remain elusive. The subsidence of the basin during the final stage of its development can be attributed to isostatic flexure of the lithosphere in response to the tectonic loading imposed on it by the development of the foreland thrust belt, and to the ensuing loads imposed by the sediments that were trapped by the subsidence; on the other hand, the subsidence of the basin during the initial stage in its evolution, when the Sauk sequence was deposited as a simple pericratonic wedge that onlapped the crystalline basement, can be attributed to thermal contraction following late Proterozoic rifting and lithospheric stretching, and to isostatic flexure of the lithosphere in response to the load imposed on it by the accumulation of a thick wedge of clastic sediment in the continental terrace wedge. However, the development of cratonic arches and basins, which occurred during the intervening stages, remains enigmatic, because it does not appear to fit any of the popular contemporary models for the origin of sedimentary basins (Bally 1980).

A satisfactory model for the origin and development of the epeirogenic arches and basins on the craton will have to accommodate several important facts about their nature and evolution.

1. The Williston Basin and most of the cratonic arches originated after the Sauk sequence had been deposited as a relatively uniform northeasterly tapering wedge that covered the flank of the craton. They were superimposed on this simple pericratonic wedge, and it was deformed as they developed; but this deformation has not provided any evidence of significant crustal stretching when the Williston Basin began to form, nor is there any obvious indication of crustal heating or igneous intrusions preceding the initial subsidence of the basin.

2. The cratonic basins occupy the spaces within a network of intersecting linear arches (figure 1), and the development of the basins is as much a result of uplift and erosion of the cratonic arches between the transgressive–regressive depositional cycles as it is a result of differential subsidence of the basins during the cycles. The individual arches can be assigned to one of several groups that have similar histories of protracted intermittent uplift and erosion (figure 16).

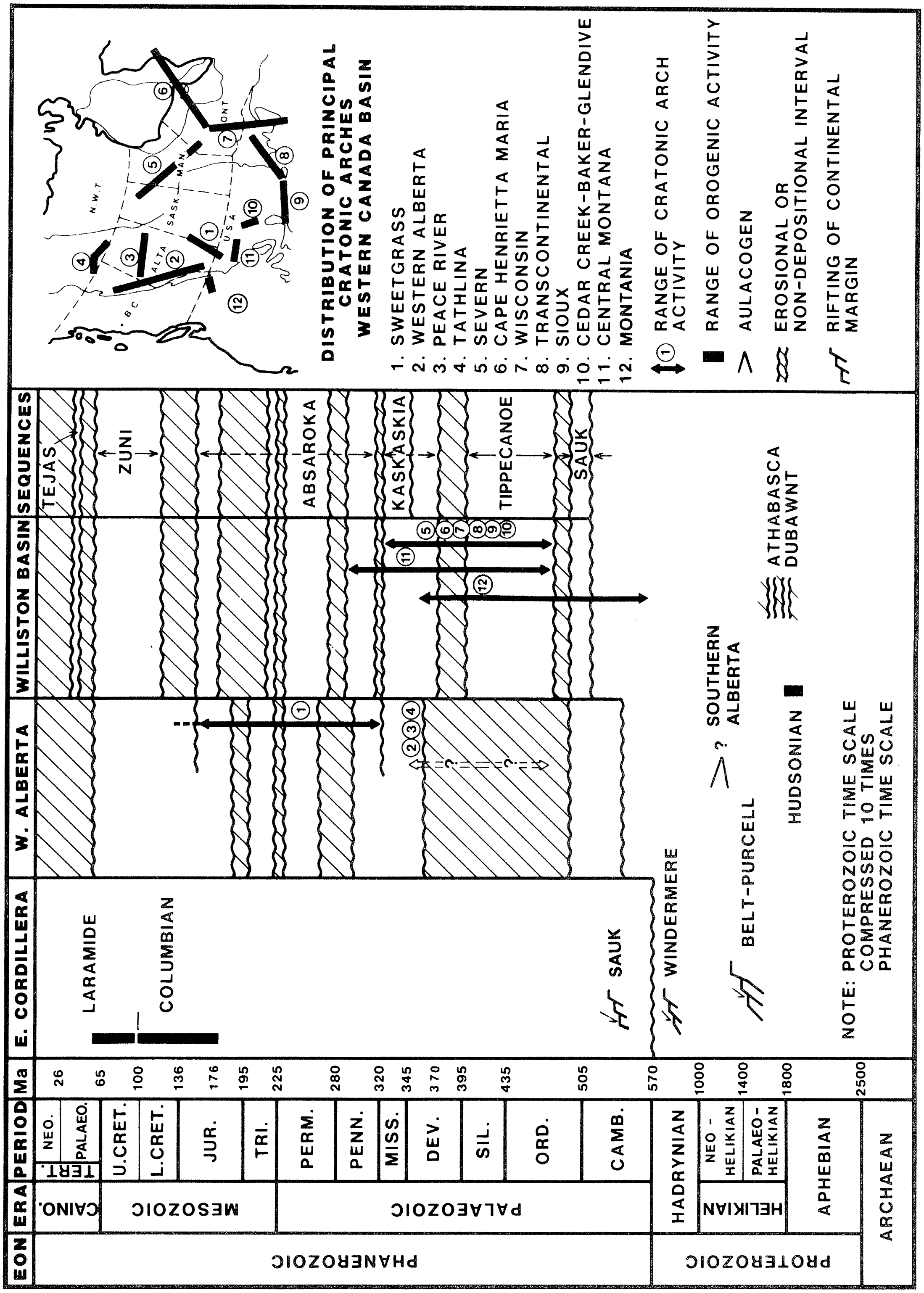

FIGURE 16. Tectonic history of the Western Canada Sedimentary Basin.

The Western Alberta, Peace River and Tathlina arches were uplifted and eroded mainly in early Devonian time, but they show some evidence of a previous history of Ordovician and Silurian uplift. These times of uplift coincide with the episodes of emergence of the continental terrace wedge. Uplift of these arches appears to have been related to deformation that was localized along zones of inherent structural weakness that follow the ancient rifted margin of the continent and the older northeasterly structural grain of the basement complex. Most of the other cratonic arches underwent synchronous intermittent uplift throughout the interval from Middle Ordovician to latest Mississippian time, and perhaps beyond; but uplift of the Sweetgrass River Arch did not begin until the Pennsylvanian, and it definitely persisted until the Middle Jurassic, isolating the Williston Basin from the continental terrace wedge. Mississippian and Pennsylvanian uplift of the Central Montana Arch was also important in isolating the Williston Basin. All of the arches were dormant during the compressive régime of the foreland basin (Zuni) deposition, although the Sweetgrass Arch appears to have been reactivated by Laramide compression in the Palaeogene.

3. The long history of intermittent differential subsidence of the Williston Basin spans more than 300 Ma from the Middle Ordovician to the Middle Jurassic. Although the geochronometric calibrations are quite imprecise, the average rates of accumulation in the basin during the various depositional episodes from the Middle Ordovician to the Mississippian appear to have been about the same, and to have been about an order of magnitude greater than during later episodes. We are not aware of any satisfactory explanation for the origin and development of these kinds of cratonic arches and basins; we consider this problem to be one of the major contemporary challenges in the study of the continents.

References (Porter *et al.*)

Aitken, J. D. 1966 *Bull. Can. Petrol. Geol.* **14**, 405–441.
Aitken, J. D. 1971 *Bull. Can. Petrol. Geol.* **19**, 557–569.
Bally, A. W. 1980 In *Dynamics of plate interiors* (ed. A. W. Bally *et al.*) (*Geodynamics Series*, vol. 1), pp. 5–20.
Beaumont, C. 1981 *Geophys. Jl R. astr. Soc.* **65**, 291–329.
Benvenuto, G. L. & Price, R. A. 1979 *Bull Can. Petrol. Geol.* **27**, 360–394.
Coney, P. L., Jones, D. L. & Monger, J. W. H. 1980 *Nature, Lond.* **288**, 329–333.
Davis, G. A., Monger, J. W. H. & Burchfiel, B. C. 1978 In *Mesozoic paleography of the western United States* (Society of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium) (ed. D. G. Howell & K. A. McDougall), pp. 481–502.
Douglas, R. J. W. 1969 *Geological map of Canada*. Geological Survey of Canada Map no. 1250A.
Fraser, J. A., Donaldson, J. A., Fahrig, W. F. & Tremblay, L. P. 1970 In *Symposium on Basins and Geosynclines of the Canadian Shield* (*Geol. Surv. Can. Pap.* no. 70–40) (ed. A. J. Baer), pp. 213–238.
Fuller, J. G. C. M. & Porter, J. W. 1962 *J. Alberta Soc. Petrol. Geol.* **10**, 455–481.
Gussow, W. C. (ed.) 1962 *Regional geological cross-sections of Western Canada Sedimentary cover*. Alberta Society of Petroleum Geologists and Geological Association of Canada.
Hoffman, P. F. 1973 *Phil. Trans. R. Soc. Lond.* A **273**, 547–581.
Kanasevich, E. R., Clowes, R. M. & McCloughan, C. H. 1969 *Tectonophysics* **8**, 513–527.
Lis, M. G. & Price, R. A. 1976 *Geol. Surv. Can. Pap.* no. 76–1A, pp. 135–136.
Mallory, W. W. 1972 In *Geological atlas of the Rocky Mountain Region* (ed. W. W. Mallory), pp. 111–127. Denver: Rocky Mountain Association of Geologists.
McMechan, M. E. 1979 *Geol. Soc. Am. Abstr. Programs* **17** (7), 477.
McMechan, M. E. 1980 Ph.D. thesis, Queen's University, Kingston, Canada.
McMechan, M. E. & Price, R. A. 1982 *Can. J. Earth Sci.* **19**. (In the press.)
Monger, J. W. H. & Price, R. A. 1979 *Can. J. Earth Sci.* **16**, 770–791.
Norris, D. K. & Price, R. A. 1966 *Bull. Can. Petrol. Geol.* **14**, 385–404.
Porter, J. W. & Fuller, J. G. C. M. 1959 *Bull. Am. Ass. Petrol. Geol.* **43**, 124–189.
Price, R. A. 1964 *Bull. Can. Petrol. Geol.* **12**, 399–426.
Price, R. A. 1973 In *Gravity and tectonics* (ed. K. A. De Jong & R. Scholten), pp. 491–502. New York: Wiley.

Price, R. A. 1981 In *Thrust and nappe tectonics* (ed. K. McClay & N. J. Price) (*Geol. Soc. Lond. spec. Pap.* no. 9), pp. 427–448.
Price, R. A. & Mountjoy, E. W. 1970 In *Structures of the southeastern Canadian Cordillera.* (ed. J. Wheeler) (*Geol. Ass. Can. spec. Pap.* no. 6), pp. 7–25.
Rascoe, B., Jr & Baars, D. L. 1972 In *Geological atlas of the Rocky Mountain Region* (ed. W. W. Mallory), pp. 143–165. Denver: Rocky Mountain Association of Geologists.
Sears, J. W. & Price, R. A. 1978 *Geology* **6**, 267–270.
Sloss, L. L. 1963 *Bull. geol. Soc. Am.* **74**, 93–113.
Stewart, J. H. 1976 *Geology* **4**, 11–15.
Wheeler, J. O. 1963 *Geol. Surv. Can. Pap.* no. 62–32.
Wheeler, J. O. 1965 *Geol. Surv. Can. Pap.* no. 64–32.

Bibliography

Apart from those specific references cited throughout the text, general information bearing on the tectonic elements and on the surface and subsurface distribution, thickness and lithology of systems comprising the sequences have been gleaned from the following sources.

Douglas, R. J. W. (ed.) 1968 *Geology and economic minerals of Canada.* Geological Survey of Canada.
King, P. B. 1969 *Tectonic map of North America* 1969, scale 1:5000000. U.S. Geological Survey.
Mallory, W. W. (ed.) 1972 *Geological history of the Rocky Mountain Region.* Rocky Mountain Association of Petroleum Geologists.
McCrossan, R. G. & Glaister, R. P. (eds) 1964 *Geological history of western Canada.* Alberta Society of Petroleum Geologists.
McCrossan, R. G. (ed.) 1973 *Future petroleum provinces of Canada.* Memoir no. 1, Canadian Society of Petroleum Geologists.
Muehlberger, W. B. 1967 *Basement map of North America*, scale 1:5000000. American Association of Petroleum Geologists.
Stockwell, C. H. 1969 *Tectonic map of Canada* 1969, scale 1:5000000. Geological Survey of Canada.