The southeastern Canadian Cordillera: thrust faulting, tectonic wedging, and delamination of the lithosphere*

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(*Received* 1 *July* 1984; *accepted in revised form* 18 *March* 1985)

Abstract—Displacement of tectonic wedges, bounded above and below by zones of thrust faulting with opposing vergence, has produced tectonic delamination at various stratigraphic levels and times in the Rocky Mountain fold and thrust belt of Canada. The 'triangle zone', along the eastern edge of the belt, comprises an easterly tapering wedge of imbricate thrust-slices and delaminated Upper Cretaceous molasse deposits. The Porcupine Creek anticlinorium is a fan fold resulting from the insertion of a wedge of Proterozoic rocks along a zone of delamination at the base of the Lower Paleozoic shale succession. In the Selkirk fan structure, which involves the metamorphic infrastructure of the Cordillera, delamination has occurred as the result of the insertion of an apparently allochthonous mass (a 'suspect terrane') between the detached parautochthonous supracrustal rocks and the autochthonous basement complex.

The diagnostic feature of tectonic wedging and delamination is a reversal in vergence between the bottom and the top of the wedge. Conspicuous tectonic overprinting ('polyphase folding') characteristically occurs above the wedge, and is commonly described as 'backfolding' and ascribed to polyphase orogeny. Tectonic wedging and delamination are widepread in compressional fold belts of various ages. Examples occur in the Cordilleran tectonic collage of accreted terranes and in early Proterozoic (Wopmay Orogen), Paleozoic (Caledonide–Appalachian) and Cenozoic (Alps) mountain belts. Moreover, tectonic wedging and delamination occur over the whole spectrum of scales from the microscopic to the lithospheric. They are an inherent feature of 'flake tectonics' and of the development of large overthrusts such as crystalline basement sheets and obducted ophiolites, all of which comprise a strong upper layer that has been delaminated from the rest of one lithospheric plate, and has overlapped another lithospheric plate that has been wedged beneath it. Geometric and kinematic relationships discernible in well-documented natural prototypes of tectonic wedging and delamination on a small scale provide a basis for elucidating relationships that are more difficult to establish directly on a large scale.

INTRODUCTION

DISPLACEMENT of tectonic wedges, bounded above and below by shear zones or thrust faults of opposite vergence, has produced tectonic delamination at various stratigraphic levels, and at various times, in the Rocky Mountain fold and thrust belt of Canada. The basic phenomenon is a familiar feature of the experimental deformation of rocks under conditions favouring 'rigid–plastic' to brittle behaviour. Intersecting conjugate shear zones or shear fractures form mechanical wedges; which, if compression is subparallel with the layering in a layered anisotropic rock, will force the layers apart and delaminate the rock (Fig. 1). The objective of this paper is to outline the basic geometric and kinematic relationships of some well documented natural prototypes of tectonic wedging and delamination that occur in the external part of the Rocky Mountain foreland fold and thrust belt; and, using these relationships, to elucidate the geometry and kinematics of a series of enigmatic structures that occur in the interior of the Cordillera, including some that are associated with the collisional tectonic suturing of allochthonous crustal masses to North America.

CANADIAN CORDILLERA

The Canadian Cordillera is a collisional orogen (Davis *et al.* 1978, Monger & Price 1979). It consists of a tectonic collage of allochthonous and suspect terranes that have been swept against, and rotated anticlockwise relative to, North America, and a foreland thrust and fold belt that formed as North America 'collided' with these allochthonous and suspect terranes (Fig. 2). In the foreland thrust and fold belt the miogeoclinal (ancient 'passive margin' or continental terrace wedge) and parts of the platform cover and foreland basin deposits of Western North America have been detached from their basement and displaced over the flank of the craton (Price 1981). This deformation occurred during two main episodes that correspond with the accretion of two large composite masses of allochthonous and suspect terranes, during mid-Jurassic–Early Cretaceous time,

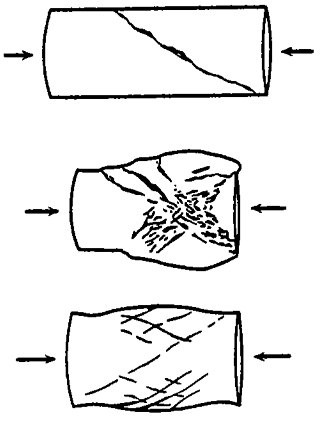


Fig. 1. Conjugate shear surfaces and tectonic wedging in experimentally deformed cylinders of limestone and marble (after Paterson 1958, Heard 1960).

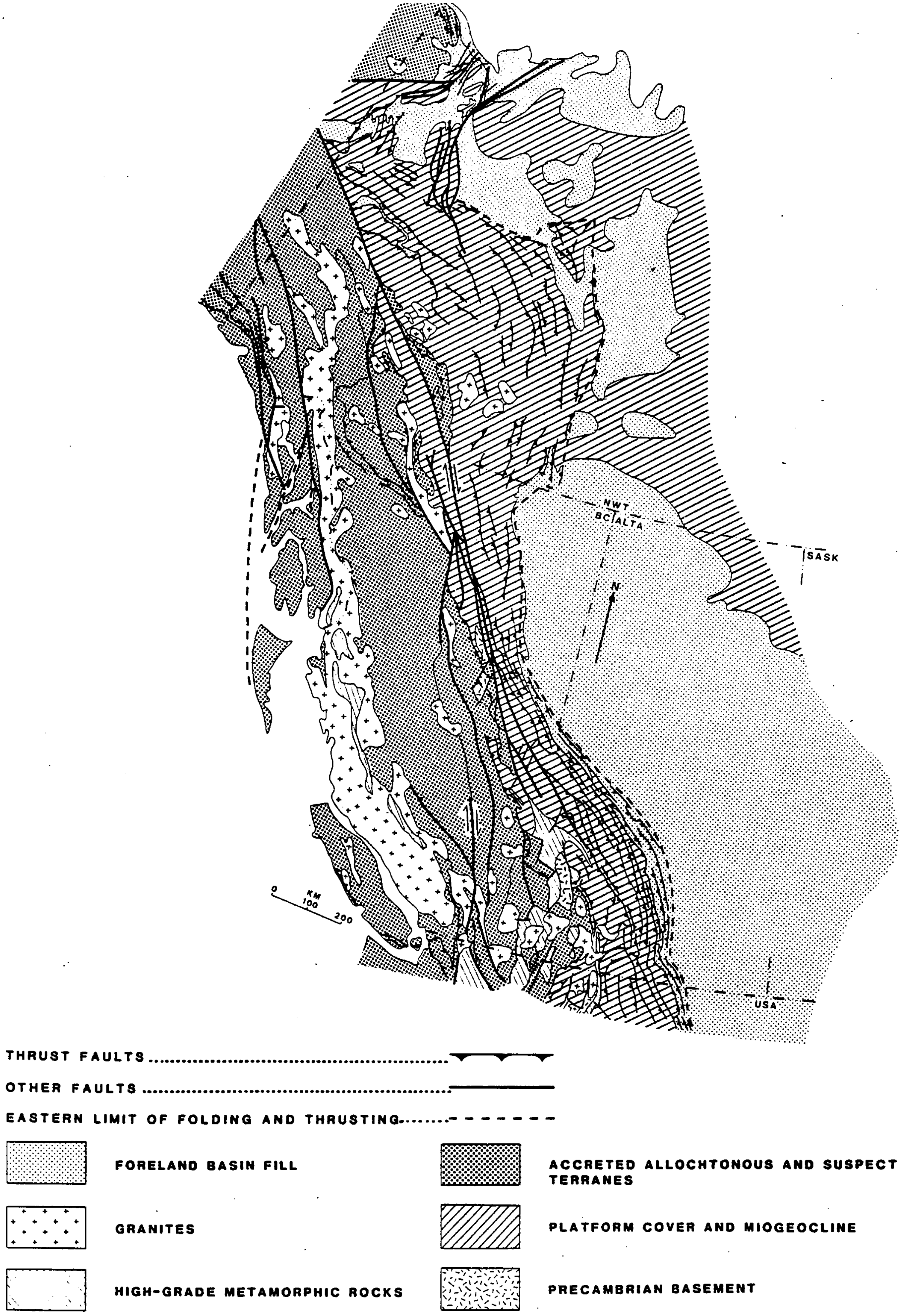


Fig. 2. Tectonic sketch map of Canadian Cordillera (modified after Douglas 1968).

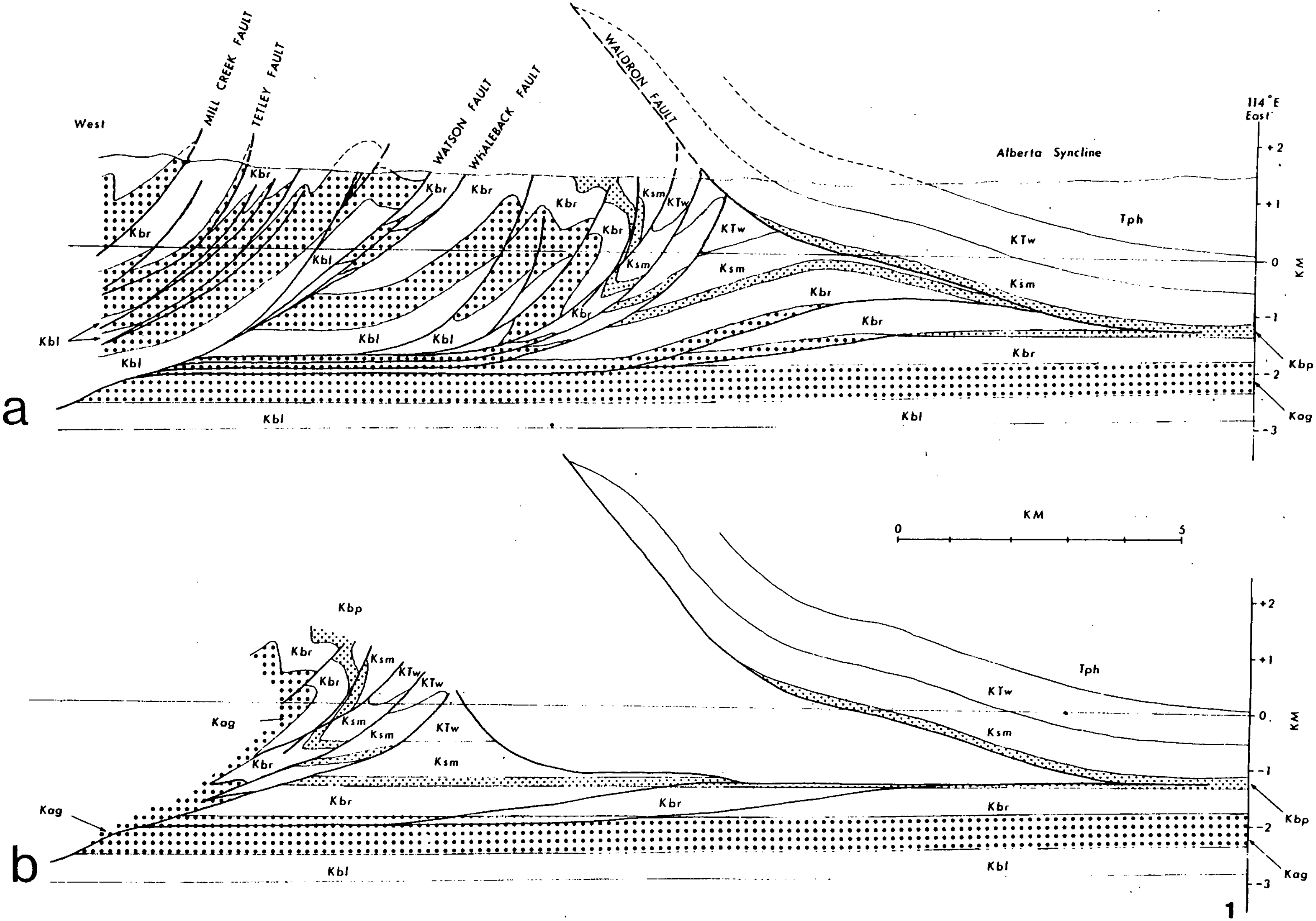


Fig. 3. Tectonic wedging and delamination along the eastern edge of Cordilleran foreland folding thrust belt at 49°, 45′ North latitude (after Price 1981). (a) Balanced structure section; (b) partial palinspastic restoration. For location of section see line 1 in Fig. 4. Stratigraphic units are identified as follows: Kbl, Blairmore Group; Kag, Alberta Group; Kbr, Belly River Formation; Kbp, Bearpaw Formation; Ksm, St. Mary River Formation; KTw, Willow Creek Formation; Tph, Porcupine Hills Formation.

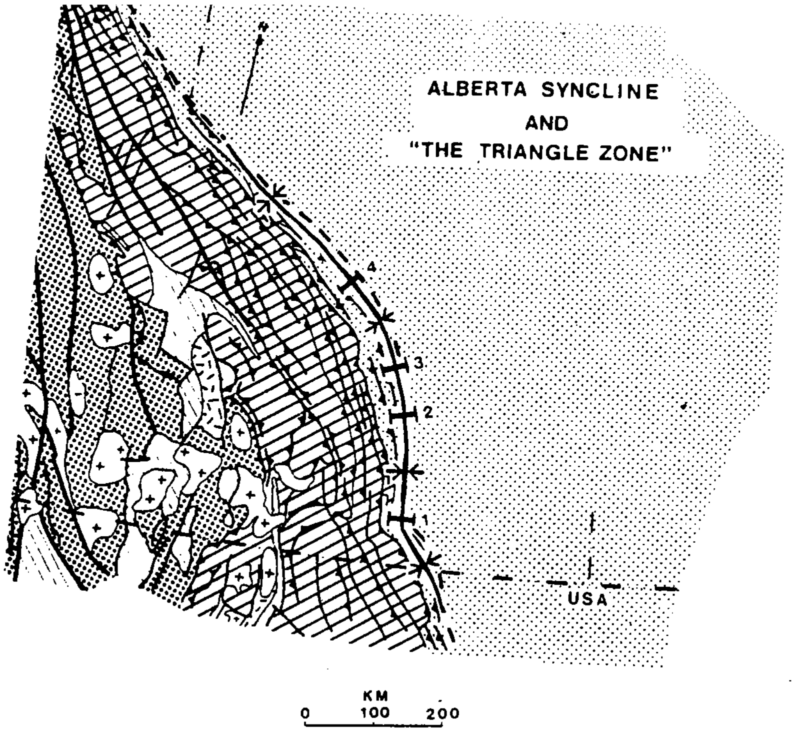


Fig. 4. Index map for structure sections of Figs. 3 and 5; same legend as Fig. 2.

and during Late Cretaceous and Paleocene time (Monger *et al.* 1982). The record of these collisions is preserved in the stratigraphy of the foreland basin, because subsidence of the foreland basin was an isostatic flexure of the lithosphere in response to the weight of the advancing thrust masses (Price 1973).

TRIANGLE ZONE

The structure of the foreland thrust and fold belt is dominated by E-verging listric thrust faults and associated décollement folds. In the southern Canadian Rockies, the thrust and fold structures terminate as an E-tapering wedge that forms a triangle zone within the edge of the autochthonous foreland basin deposits (Fig. 3). The structure within this triangle zone is well constrained by surface mapping and by borehole information and seismic reflection profiles acquired by the petroleum exploration industry (Gordy & Frey 1975, Price 1981, Jones 1982). A balanced vertical section through the wedge at 49°, 45′ North latitude (Fig. 3) provides a relatively complete illustration of the nature of the termination of the thrust and fold belt. The floor of the wedge is an unnamed sole fault that follows bedding-parallel detachment zones in the marine shales of the Upper Cretaceous Alberta Group (Kag) and Bearpaw (Kbp) Formations, and an intervening ramp through the non-marine deposits of the Belly River formation (Kbr). Imbricate, E-verging thrust faults, that splay from this sole fault, have shortened and tectonically thickened the Upper Cretaceous and Lower Tertiary succession. The Waldron fault, a W-verging listric thrust fault, forms the roof of the wedge. It arises out of a bedding-parallel detachment zone in the marine shales of the Upper Cretaceous Bearpaw Formation (Kbp), and cuts up through the overlying Upper Cretaceous and Paleocene rocks westward. Thus, the imbricate thrust slices form a tectonic wedge that has been driven eastward, into the foreland basin succession, along a bedding-parallel detachment zone in the Bearpaw shale. The result has been tectonic delamination of the foreland basin succession. The upper part has been wedged upward; and now forms the west limb of the Alberta syncline, a broad regional structure, the east limb of which conforms with the regional monoclinal westward dip of the platform and foreland basin deposits from the Canadian Shield into the deeper parts of the foreland basin. The lower part has remained aligned with the regional westward dip of the autochthonous platform and foreland basin deposits. This basic style of wedge structure persists, with some variations, along the margin of the foreland thrust and fold belt, over an interval of about 750 km, from northern Montana to northwestern Alberta (Fig. 4). Among the variations are the occurrence of imbricate splays from the W-verging roof thrust, and changes in the stratigraphic level of the main bedding-parallel detachment zone along the floor of the wedge (Fig. 5).

A simple model (Fig. 6) illustrates the basic geometric and kinematic features of this style of thrust wedging and tectonic delamination. The locus of thrust faulting is controlled by the mechanical anisotropy inherent in the stratigraphic layering. The sole thrust of the detached mass climbs up through the stratigraphic succession in the direction of relative displacement of the detached mass. The result is a tectonic thickening of the layered

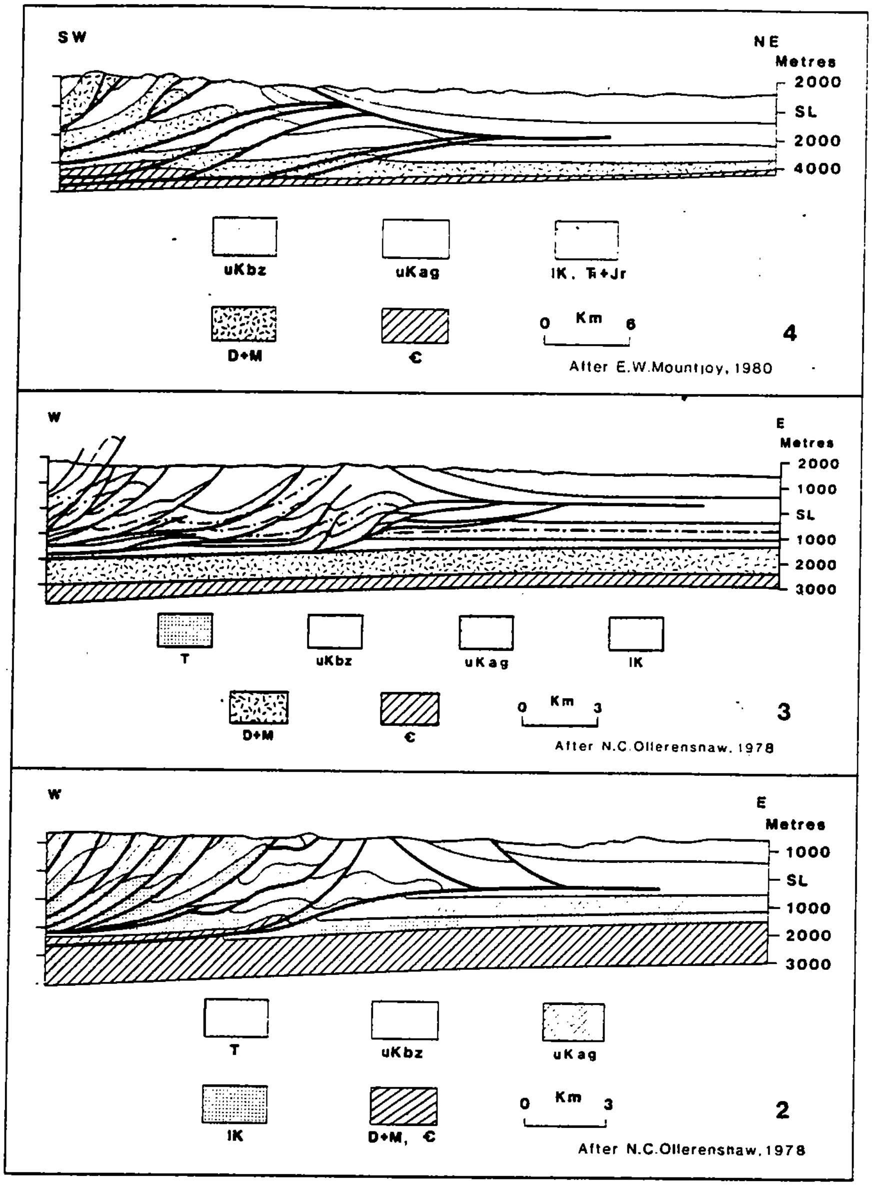


Fig. 5. Tectonic wedging and delamination along the eastern edge of the Cordilleran foreland thrust and fold belt in the southern Canadian Rockies. For location of sections see lines 2–4 in Fig. 4. Stratigraphic units are identified as follows. Section 2: T. Tertiary units. undivided: uKbz. Brazeau Formation: uKag. Alberta Group: lK. lower Cretaceous units undivided: D + M. Ꞓ. Devonian. Mississippian and Cambrian units. undivided. Section 3: T. Tertiary units. undivided: uKbz. Brazeau Formation: uKag. Alberta Group: lK. lower Cretaceous units. undivided: D + M. Devonian and Mississippian units. undivided: C, Cambrian units. undivided. Section 4: uKbz. Brazeau Formation: uKag. Alberta Group; lK. Tr + Jr. lower Cretaceous. Triassic and Jurassic units. undivided: D + M. Devonian and Mississippian units. undivided: Ꞓ. Cambrian units. undivided.

sequence by thrust duplication. Tectonic wedges form at the intersection of two conjugate, stair-step thrust systems. Displacement of the detached mass drives the tectonic wedge along the bedding-parallel detachment zone, prying the overlying strata upward; and the result is tectonic delamination of the 'stationary' block.

MACKENZIE AND FRANKLIN MOUNTAINS

Folds rather than thrust faults dominate the structural style of the Cordilleran foreland thrust and fold belt in the Mackenzie and Franklin Mountains of the northern Canadian Cordillera (Fig. 7): but thrust faults of relatively small displacement do occur along the flanks of the folds. Most of the folds and thrust faults are NE-verging, but conspicuous reversals in fold and fault vergence are common. Along the outer edge of the foreland thrust and fold belt, in the Franklin Mountains (Fig. 8), the relatively thin platform cover and foreland basin deposits are cut by two conjugate sets of relatively widely spaced listric thrust faults. The displacements on these faults are relatively small, and the result is a series of broad flat-bottomed synclines, separated by narrow thrust-faulted anticlines of variable vergence. In contrast with the situation in the triangle zone along the eastern margin of the southern Canadian Rockies, in this region tectonic wedging and delamination occur within as well as at the edge of the detached mass; and at least some of the tectonic wedges are not associated with footwall ramps along the floor thrust.

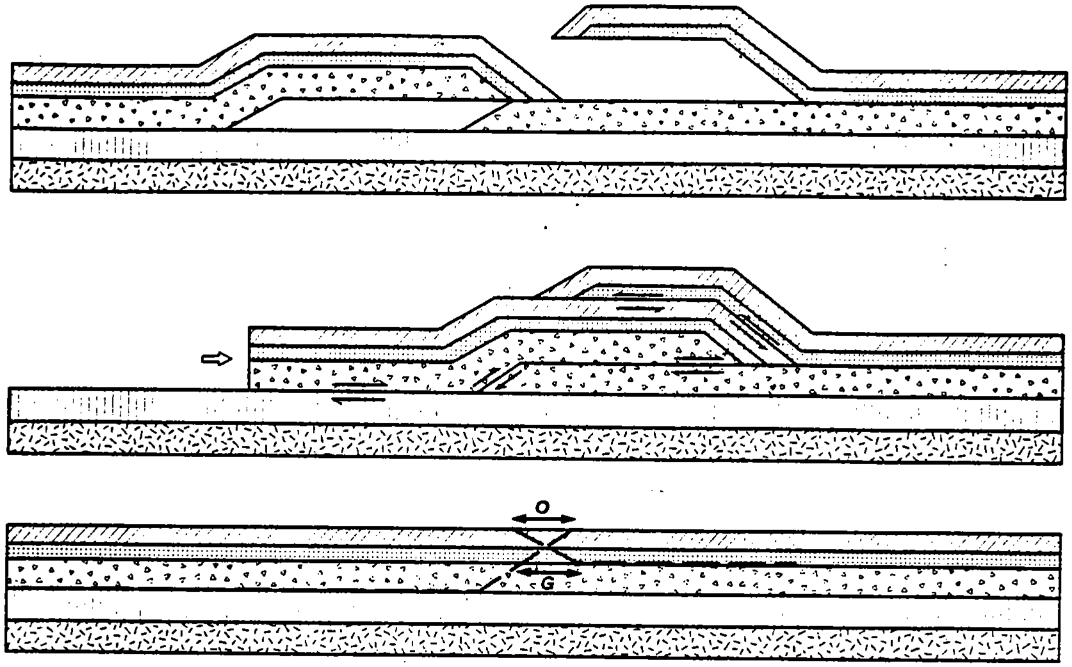


Fig. 6. Simplified geometric and kinematic model for tectonic wedging and delamination along the eastern edge of the Cordilleran thrust and fold belt. Gap (G) and overlap (O) in this palinspastic reconstruction, which is based on the assumption that bed length remains constant, can be accounted for by stretching and shortening in folds.

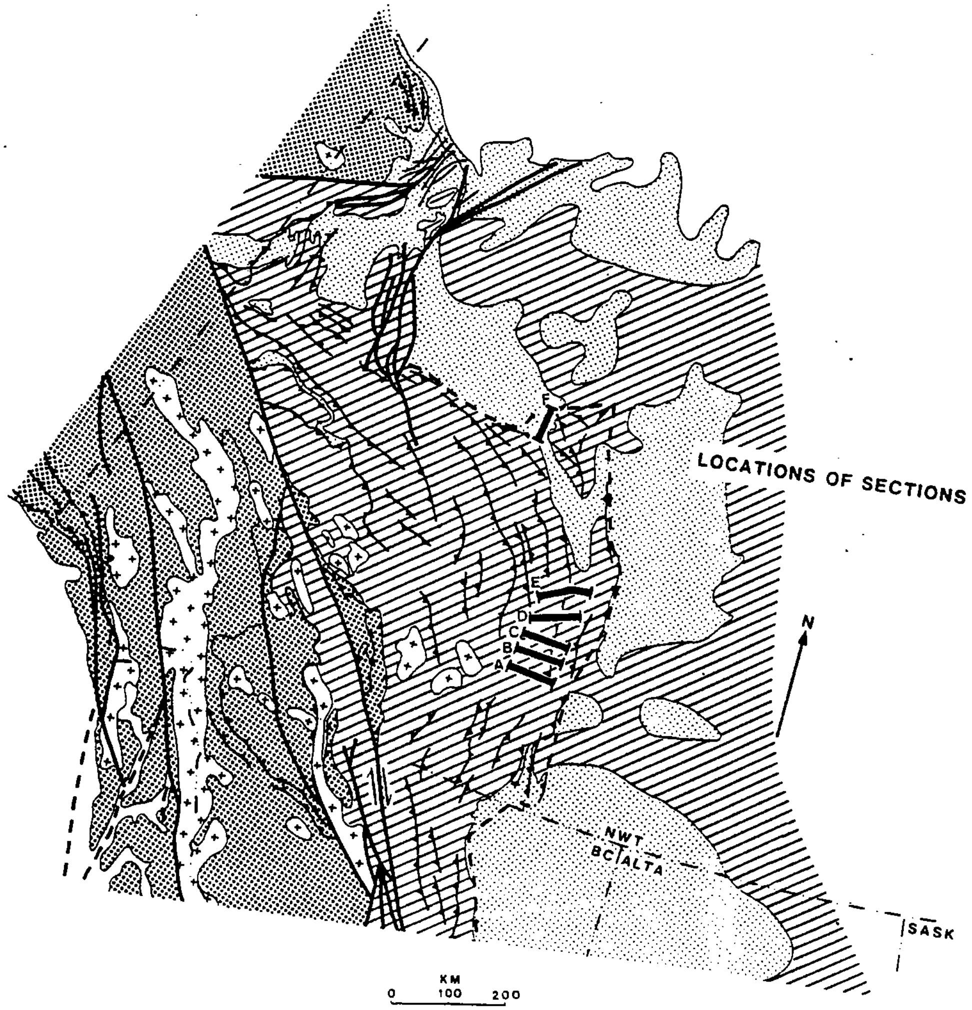
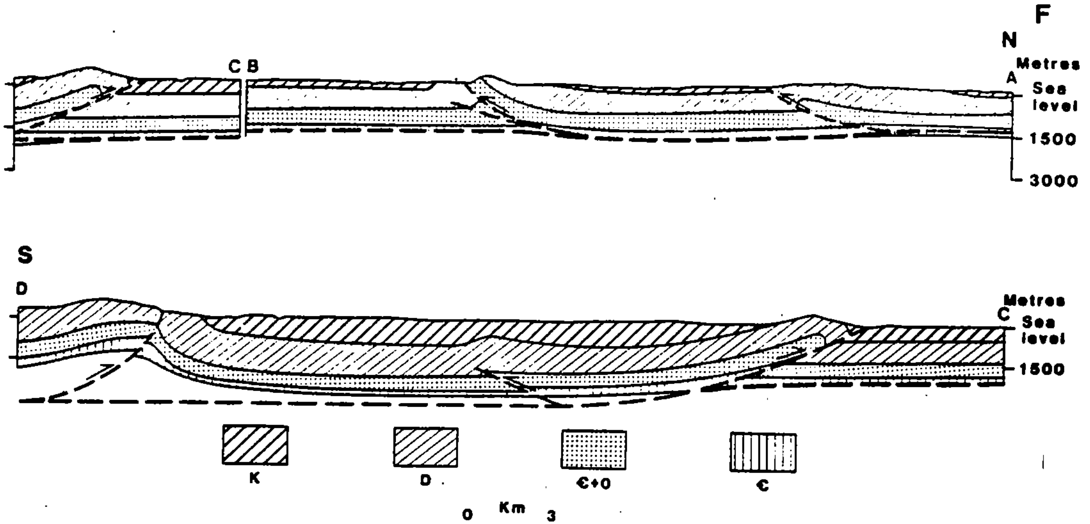


Fig. 7. Index map for sections of tectonic wedging in the Mackenzie and Franklin Mountains; same legend as Fig. 2.



After J.D.Aitken and D.G.Cook,1979

Fig. 8. Tectonic wedging and delamination. Cordilleran foreland thrust and fold belt. Franklin Mountains (after Aitken and Cook, 1979). For location of composite section, see line F in Fig. 7.

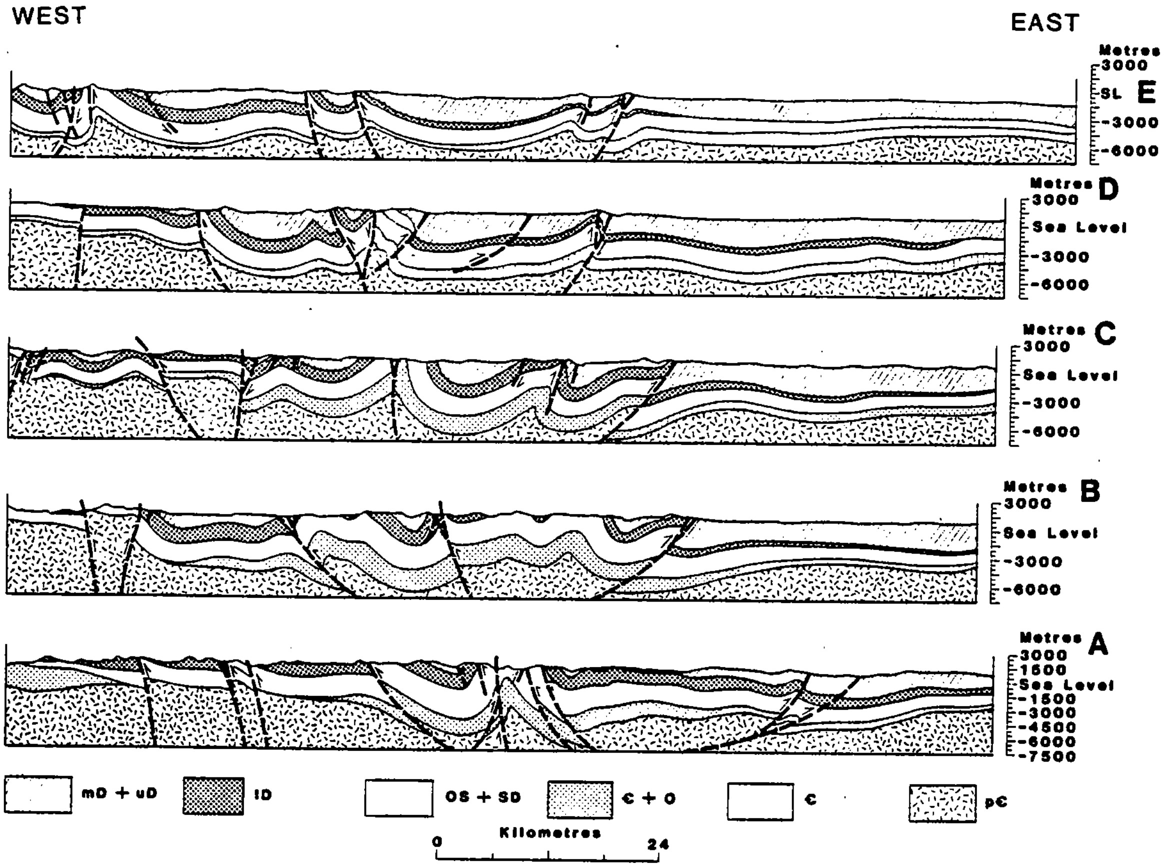


Fig. 9. Tectonic wedging in the Cordilleran foreland thrust and fold belt. Mackenzie Mountains (after Douglas 1974. Douglas & Norris 1976). For location of section-lines A, B, C, D and E, see Fig. 7. Stratigraphic units are identified as follows. mD + uD, middle and upper Devonian units, undivided; lD, lower Devonian units, undivided; OS–SD, Ordovidian–Silurian and Silurian–Devonian units, undivided; Є + O, Cambrian and Ordovician units, undivided; Є, Cambrian units, undivided; pЄ, Proterozoic units undivided.

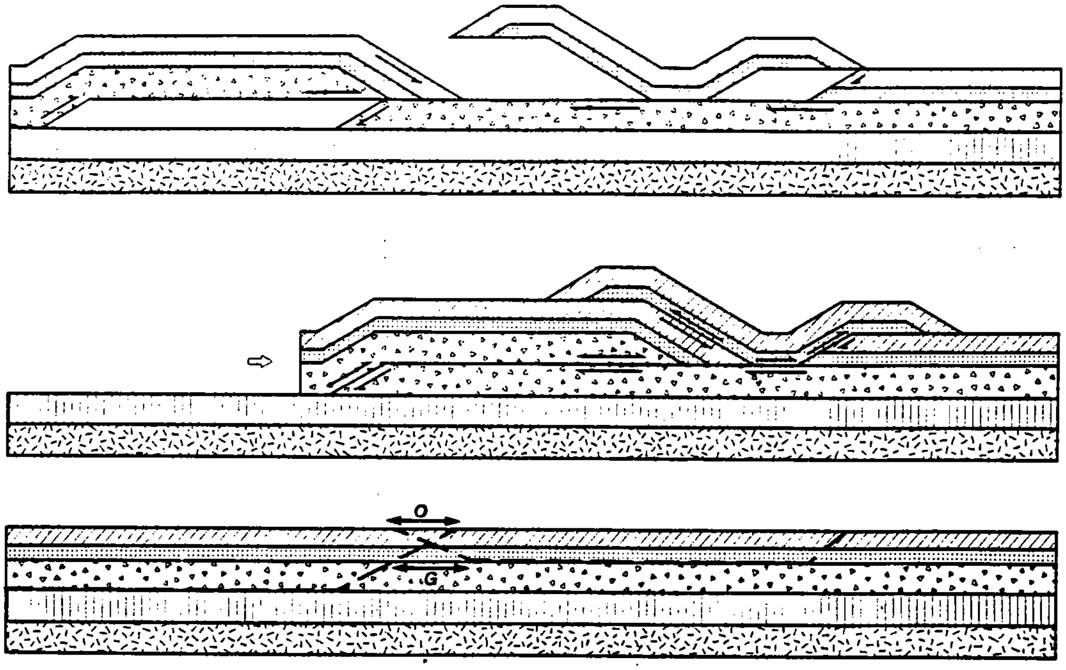


Fig. 10. Simplified geometric and kinematic model for tectonic wedging and delamination within displaced thrust nappes. Gap (G) and overlap (O) in this palinspastic reconstruction, which is based on the assumption that bed length remains constant, can be accounted for by stretching and shortening in folds.

In the interior of the foreland thrust and fold belt, in the thicker miogeoclinal succession within the Mackenzie Mountains (Fig. 9), reversals in vergence are common, and tectonic wedging is widespread. The amount of horizontal shortening within the detached mass of supracrustal rocks is greater than in the Franklin Mountains, but substantially less than in the southern Canadian Rockies. The geometric and kinematic characteristics of this style of deformation are illustrated by a simple model (Fig. 10), involving development of two conjugate sets of listric thrust faults in a strongly anisotropic layered rock mass.

STRUCTURAL PROTOTYPE

Tectonic wedging and delamination due to thrust faulting is a relatively rare but widespread feature in foreland thrust and fold belts of various ages throughout the world. It has been well documented by seismic reflection profiling of the trench inner slopes of a currently active convergent plate margin (Seely 1977). It is a characteristic feature of the décollement folding and thrusting of the outer part of the Alpine foreland thrust and fold belt in the Jura Mountains (Laubscher 1965). It is widespread at the outcrop scale in the outer part of the

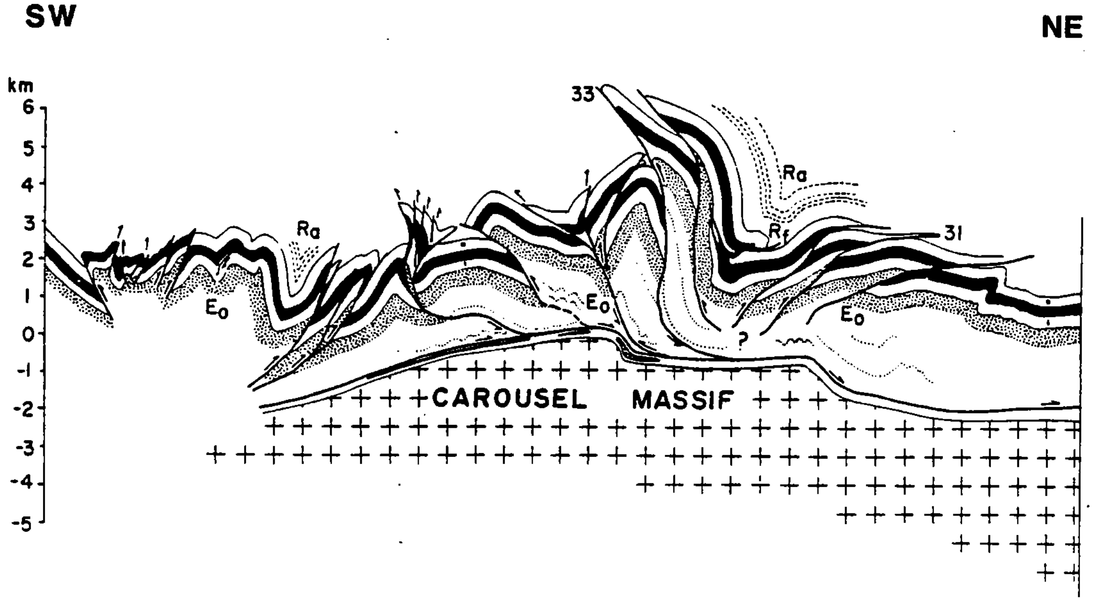


Fig. 11. Tectonic wedging within the Early Proterozoic Asiak foreland and fold belt, Wopmay orogen, northwestern Canadian shield (after Tirrul 1983).

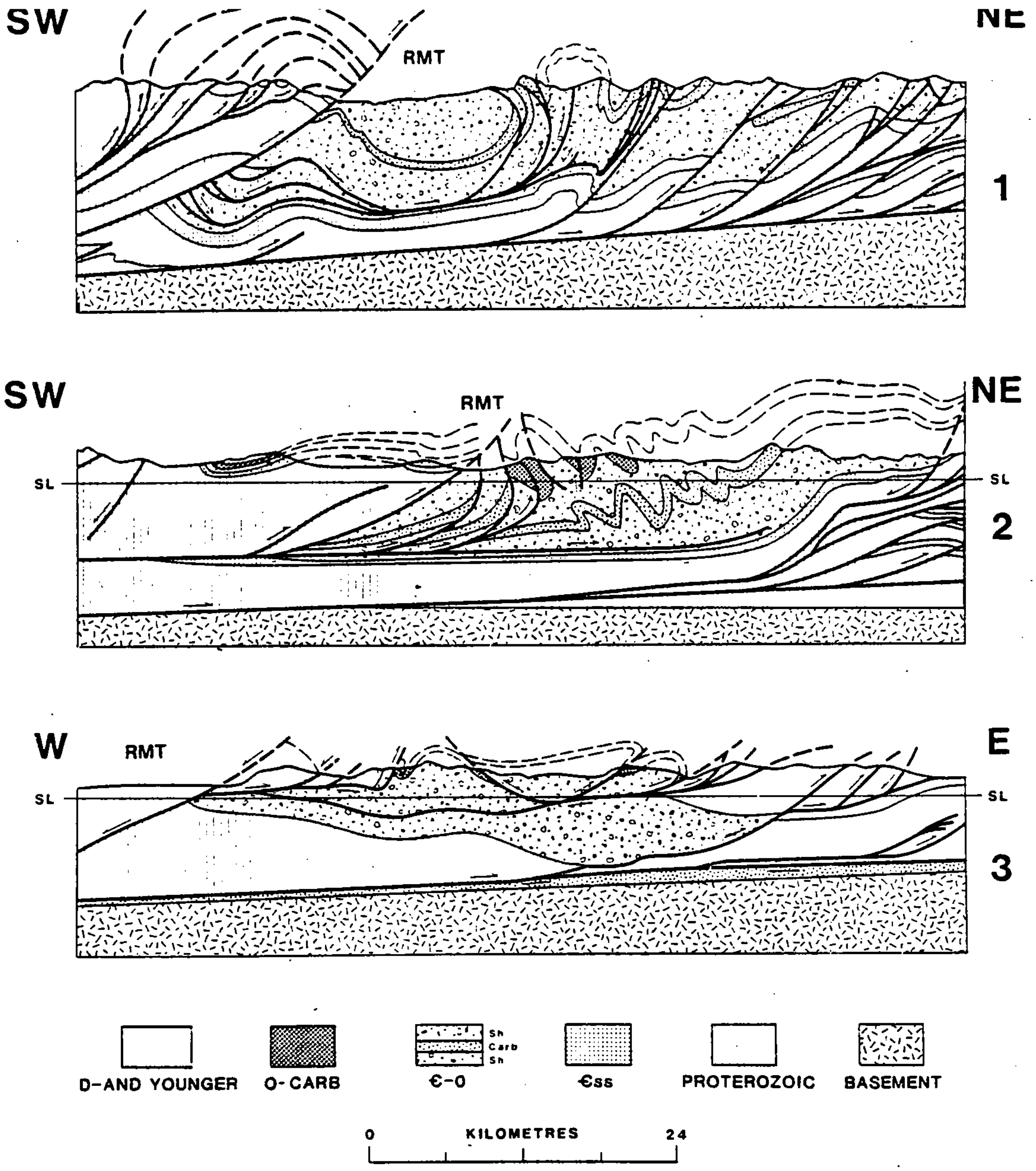


Fig. 12. Three sections through the Porcupine Creek fan structure, southern Canadian Rockies. RMT marks location of Rocky Mountain trench separating Rocky Mountains from Purcell Mountains. For location of lines of sections 1, 2 and 3, see Fig. 13. Stratigraphic units are identified as follows: Ꞓss, basal Cambrian sandstone; Ꞓ–O, Cambrian and Ordovician (sh, shale; carb, carbonate rocks); O–CARB, middle and upper Ordovician carbonate rocks; D, and younger, Devonian and younger units, undivided.

Upper Paleozoic Appalachian foreland thrust and fold belt in the United States (Harris & Milici 1977). However, some of the best documented examples of the phenomenon are a result of Early Proterozoic deformation in the Asiak foreland thrust and fold belt of the Wopmay orogen in the northwestern part of the Canadian Shield (Fig. 11). The geometric and kinematic relationships discernible in these well-documented natural examples of tectonic wedging and delamination from the outer part of foreland thrust and fold belts, are useful prototypes for the elucidation of relationships in the interior of mountain belts that are more difficult to establish directly.

PORCUPINE CREEK ANTICLINORIUM

A major regional reversal in structural vergence in the southern Canadian Rockies is associated with the Porcupine Creek anticlinorium, a complex fan fold, some 25 km wide and several hundred km long (Figs 12 and 13). The Porcupine Creek anticlinorium involves a thick sequence of relatively weak calcareous shales of early Paleozoic age that accumulated in the Cordilleran miogeocline outboard from a long-lived carbonate bank margin. The Porcupine Creek anticlinorium coincides with a downward converging cleavage fan across which there is a progressive southwestward change from SW-

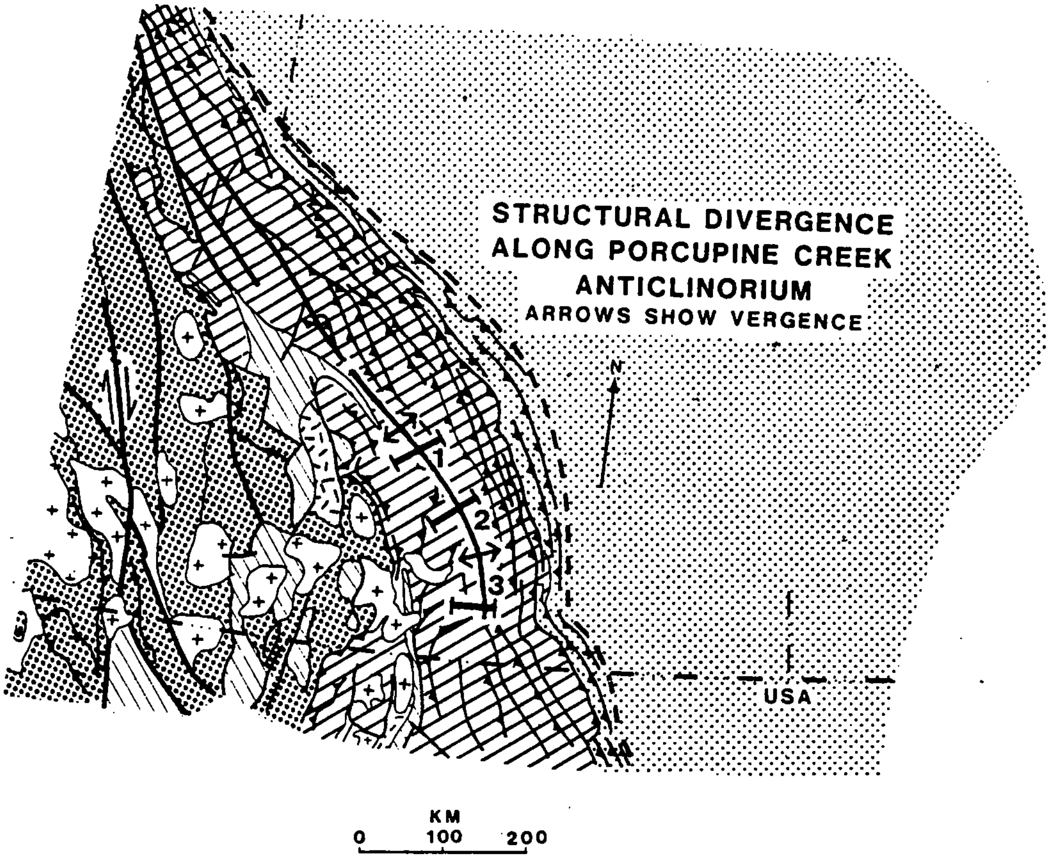


Fig. 13. Index map showing location of structure sections of porcupine Creek anticlinorium.

dipping to NE-dipping folds and faults. It coincides with the Cambro-Ordovician shale facies of the Cordilleran miogeocline, abuts the more competent coeval rocks of the carbonate bank margin to the northeast, and is overlapped by the more competent older rocks of the Purcell thrust sheet to the southwest (Price & Mountjoy 1970, Balkwill 1972, Gardner & Price 1979). The form of the anticlinorium varies from a tight elasticas fold (Fig. 12, top section), to a broad flat-topped fan fold (Fig. 12, bottom section), and to a broad, rather vague, fan structure (Fig. 12, middle section). At the south end, where the structures are N-plunging, it can be seen that the fan structure terminates downward across a broad décollement zone above the more competent Early Cambrian clastic rocks that underlie it (Benvenuto & Price, 1979). From these relationships, it is obvious that the shortening of the Cambro-Ordovician shale sequence above the décollement must be balanced further west by overlap of Early Cambrian and Proterozoic rocks across that same décollement, as shown in Fig. 12.

The Porcupine Creek anticlinorium represents another variation on the basic theme of tectonic wedging and delamination associated with thrust faulting. The E-verging floor of the thrust wedge is the décollement zone at the bottom of the Cambro-Ordovician shale sequence. The W-verging roof thrust is the zone of ductile deformation marked by W-verging cleavage folds and thrusts that comprise the west flank of the Porcupine Creek fan structure. The wedge itself comprises the mass of Proterozoic and older Cambrian rocks that locally have subsequently ridden up over the western part of the Porcupine Creek anticlinorium. These basic geometric and kinematic relationships are well illustrated by the simple model of an ideal conjugate kink band structure illustrated in Fig. 14. The flat-topped anticlinorium, bounded on either side by folds and opposing vergence, is a manifestation of tectonic delamination, and a consequence of tectonic wedging along its left side.

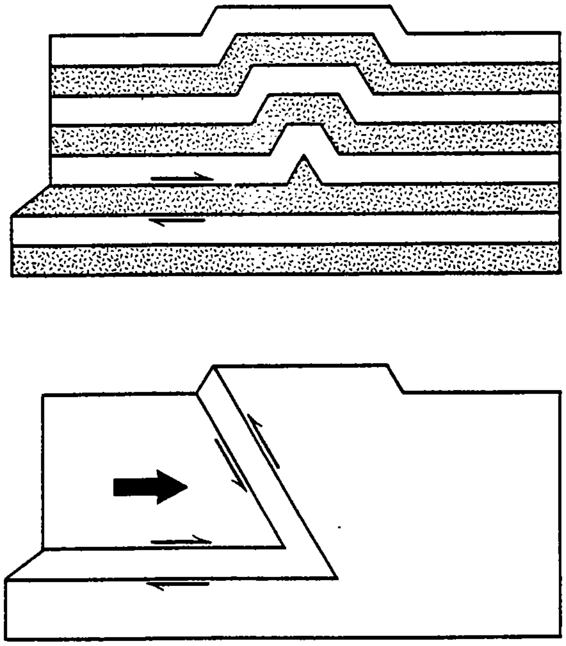


Fig. 14. Kink-band model of tectonic wedging.

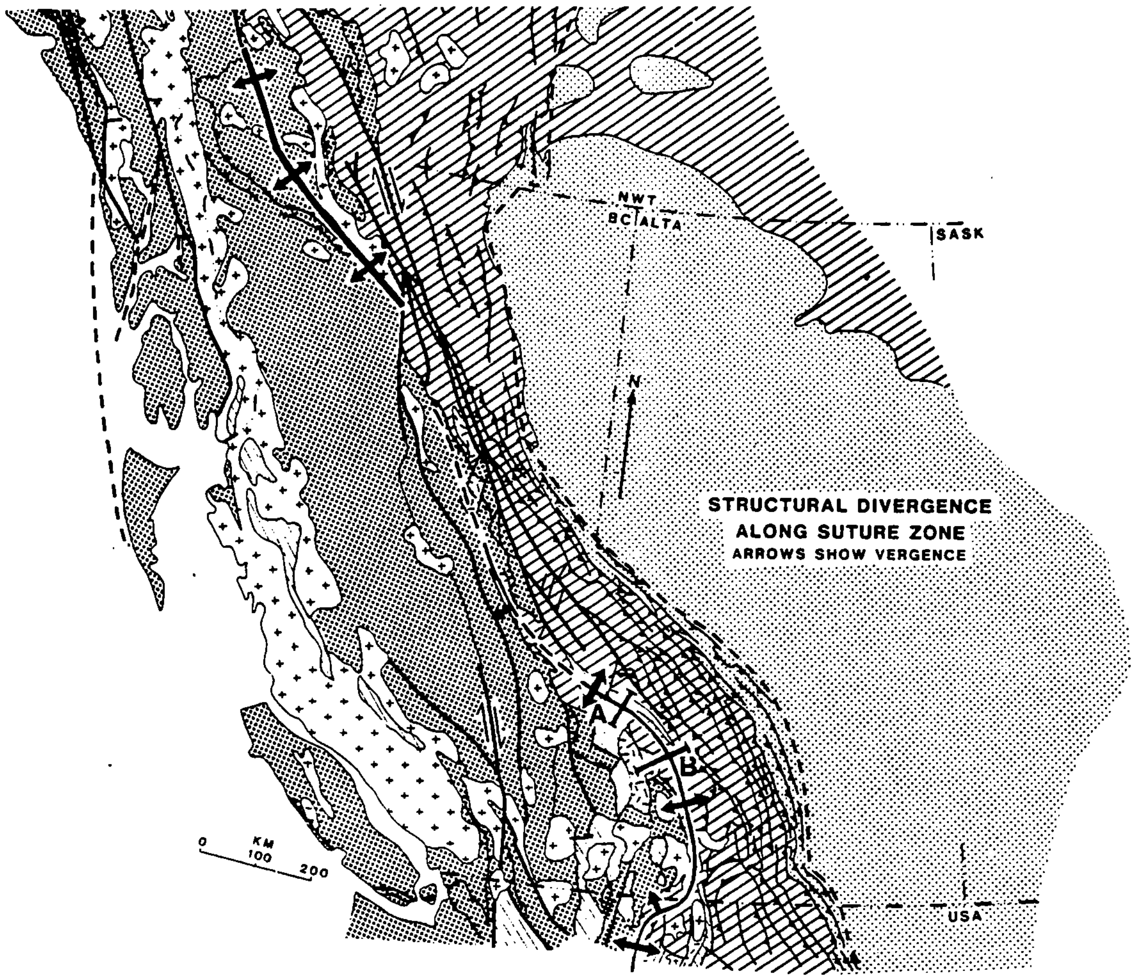


Fig. 15. Index map for structural divergence along the suture zone between the North American and the allochthonous and suspect terranes.

TECTONIC SUTURE ZONE

Some of the most conspicuous major regional reversals in tectonic vergence in the Canadian Cordilleran occur in the general vicinity of the suture zone linking the allochthonous and suspect terranes to the rocks that were deposited on or adjacent to North America (Fig. 15). This zone of overlap between the Cordilleran miogeocline and the tectonic collage of allochthonous and suspect terranes coincides in general with the Omineca crystalline belt, a major regional tectonic belt in the eastern Canadian Cordillera that is a principal locus of regional metamorphism, granitic magmatism, intense deformation, profound uplift and deep erosion, all of which can be attributed to the tectonic overlap and/or compressional thickening of these crustal rocks during collisions between North America and the allochthonous and suspect terranes that were accreted to its western margin (Monger *et al.* 1982). The zone of structural divergence (Eisbacher *et al.* 1974) locally coincides with the actual boundary between the North American rocks and the allochthonous and suspect terranes. This is true, for example, adjacent to the International Boundary with the United States. Here, early Paleozoic rocks of the Cordilleran miogeocline, in which the dominant structures are E-verging, have been thrust westwards over Triassic and Jurassic volcanic and related deposits (Fyles & Hewlett 1959) that comprise part of the suspect terrane Quesnellia (Monger *et al.* 1982). Elsewhere, the zone of structural divergence lies wholly within the allochthonous terranes, as for example along the northern boundary of British Columbia (B.C. in Fig. 15). Here, the Teslin suture separates the E-verging thrust nappes of ophiolite, cataclasite and granodiorite, which have overridden the North American miogeoclinal rocks, from the W-verging structures along which the Cache Creek terrane has overridden the Stikine terrane (Tempelman-Kluit 1979). Over an interval extending some 500 km northward from the International Boundary with the United States, the zone of structural divergence lies wholly within the deformed miogeoclinal rocks in the Omineca crystalline belt. Close to the International Boundary the zone of structural divergence corresponds to a zone across which there is a change from the E-verging structures, characteristic of the foreland thrust and fold belt, to complex coaxially folded W-verging fold nappes (Fyles 1964, Höy 1977, 1980). Further north, in the vicinity of the structure section shown in Fig. 16 (for location see Fig. 15), the zone of structural divergence coincides with the Selkirk

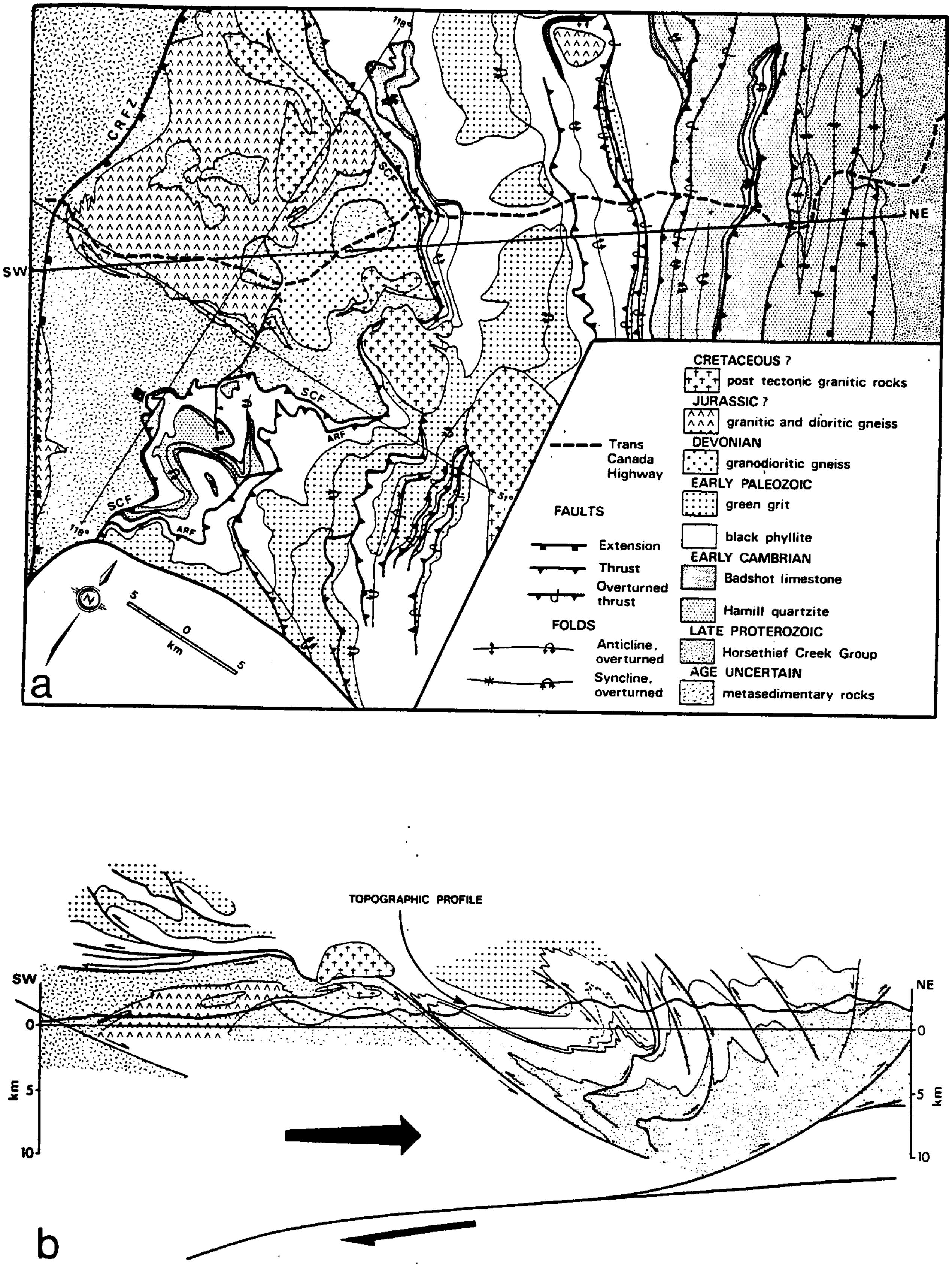


Fig. 16. (a) The west flank of the Selkirk fan structure along the Trans-Canada Highway, southern British Columbia (after Price *et al.* 1981). Structures shown above the topographic profile in the cross-section (b) are based on projections along plunge, mainly after Thompson (1978) and Sears (1979). ARF, Akolkolex River Fault; CRFZ, Columbia River Fault zone; SCF, Standfast Creek Fault. For regional location of line of section, see line B, in Fig. 15.

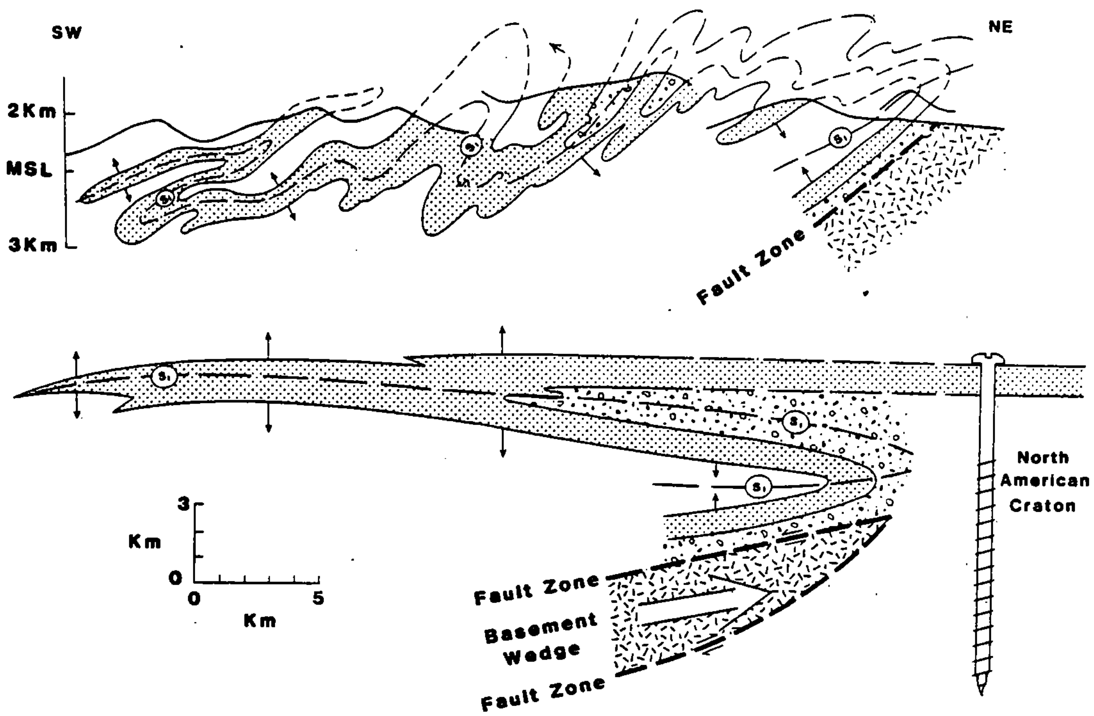


Fig. 17. The Scrip nappe as a product of thrust wedging and tectonic delamination. Upper section after Simony *et al.* (1980). Lower section schematic partial palinspastic reconstruction illustrating the effects of thrust wedging and ductile tectonic delamination of Late Proterozoic supracrustal rocks which remained attached to the North American cratonic basement in the northeast. For location of line of section, see line A, in Fig. 15.

axis, or Selkirk fan structure (Wheeler 1966, Brown & Tippett 1978, Price *et al.* 1979), across which there is a change from a region dominated by NE-verging thrust nappes and folds to a region dominated by large, near recumbent SW-verging fold nappes. The SW-verging structures overprint older NE-verging folds, and locally are themselves extensively overprinted by younger NE-verging folds (Fig. 17). The otherwise enigmatic SW-verging structures find a ready explanation as a product of tectonic wedging and delamination at middle to lower crustal levels within the metamorphic infrastructure of the evolving suture zone.

In the vicinity of the Trans-Canada Highway (Fig. 16), the SW-verging structures are underlain across a prominent fault zone by a suspect terrane comprising a sequence of deformed and metamorphosed metasedimentary rocks, of uncertain stratigraphic affinities, with which are associated sheets of deformed granodioritic gneiss. This suspect terrane has been displaced relatively northeastwards beneath the SW-verging structures in the overlying rocks that form part of the Cordilleran miogeocline, and were therefore deposited on or adjacent to the North American craton and comprise part of North America. Palinspastic reconstructions of the Cordilleran foreland thrust and fold belt east of this region (Price & Mountjoy 1970, Price 1981), show that the basement upon which the thinner part of the Cordilleran miogeocline was deposited, now represented as imbricate thrust sheets in the central part of the Canadian Rockies, underlies the displaced miogeoclinal rocks in this part of the Cordillera. Accordingly, the suspect terrane has been displaced northeastwards relative to

overlying miogeoclinal rocks which were deposited above that basement. It is a tectonic wedge that has been inserted by northeastward thrust displacements between part of the Cordilleran miogeocline and its basement. This structure represents an example of tectonic wedging and delamination that occurred during ductile deformation at mid-crustal levels.

The Scrip nappe (Fig. 17) which is located immediately southwest of the zone of structural divergence about 150 km north of the Trans-Canada Highway, provides an even more dramatic example of a major SW-verging structure that can be attributed to tectonic wedging and delamination during ductile deformation at mid-crustal levels. The Scrip nappe has an inverted limb some 50 km in length across strike, and formed prior to the climax in regional metamorphism which accompanied the development of the superposed NE-verging structures at depths of burial of about 30 km (760 MPa) and temperatures of about 750°C (Ghent *et al.* 1982, Raeside & Simony 1983). The basement slices which are in fault contact beneath the Scrip nappe (Simony *et al.* 1980) probably represent tectonic wedges that were driven into the outboard part of the Cordilleran miogeocline at a relatively early stage in the collision with the allochthonous and suspect terranes that were accreted to it.

The record of tectonic wedging and delamination in the suture zone linking the allochthonous and suspect terranes to North America is complex and varies from one locality to another, but in general the polyphase deformation can be attributed to changes between episodes of northeasterly overriding of allochthonous

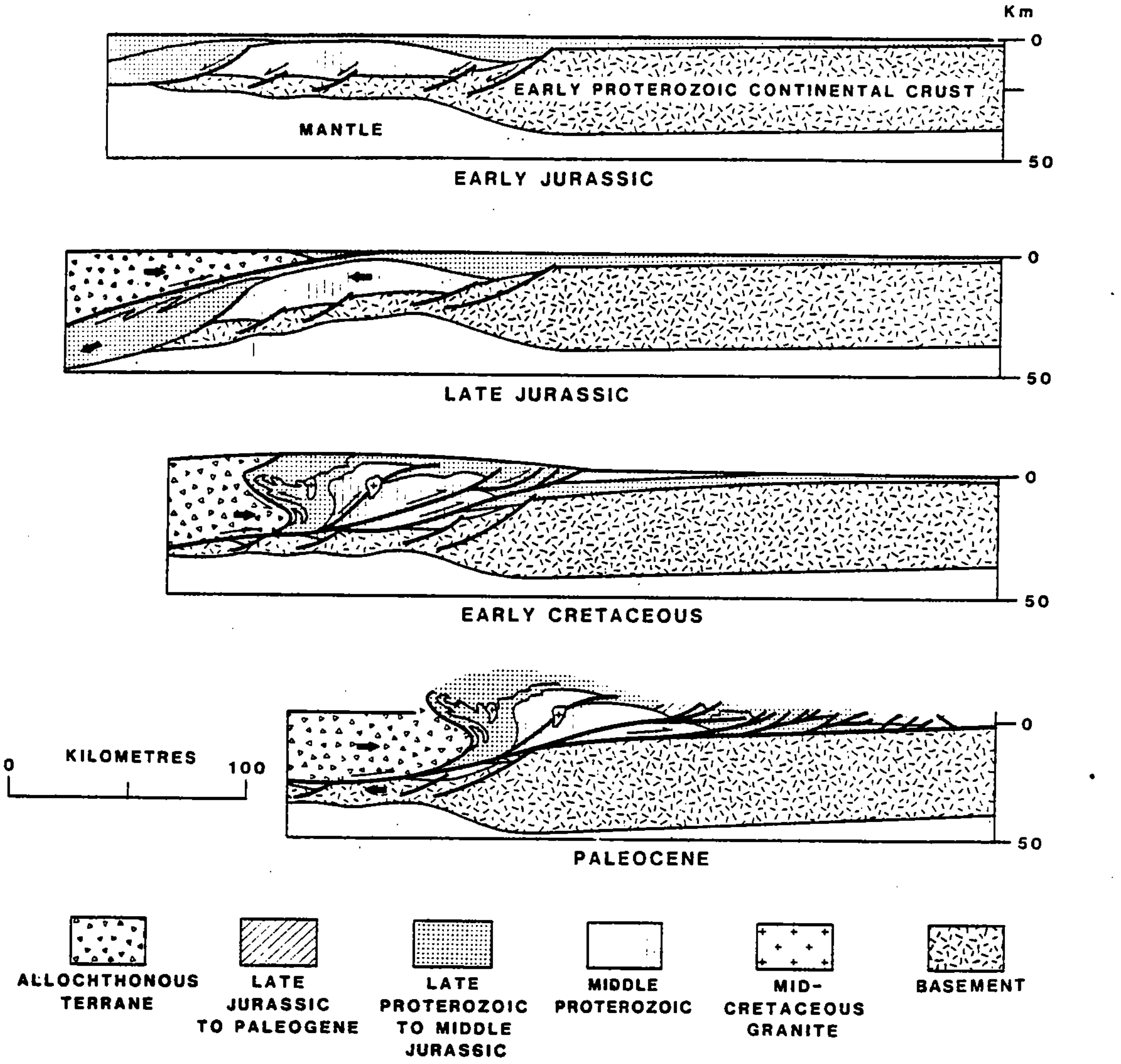


Fig. 18. Stages in the evolution of southeastern Canadian Cordillera in a section along 49°, 45′ North latitude (after Price 1981).

miogeocline, and episodes of tectonic wedging of allochthonous and suspect terranes between parts of the North American miogeocline and its basement. For example, in the vicinity of the Scrip nappe (Simony *et al.* 1980) concluded that the large W-verging structures, which I attribute to tectonic wedging by allochthonous or suspect terranes, occurred prior to deep tectonic burial of the outboard part of the miogeocline, during which it was overprinted by superposed NE-verging folds while buried at mid- to lower-crustal levels. In contrast, along the Trans-Canada Highway, and southward to the International Boundary, E-verging structures which formed at middle to lower crustal levels, predate W-verging structures that carry the North American rocks over the allochthonous and suspect terranes. These latter relationships are illustrated in a simple model (Fig. 18) based on a regional palinspastic reconstruction (Price 1981): Middle to Late Jurassic E-verging folds formed in the outboard part of the Cordilleran miogeocline as it moved beneath the allochthonous terranes; but by mid-Cretaceous time, the allochthonous terranes had been wedged beneath

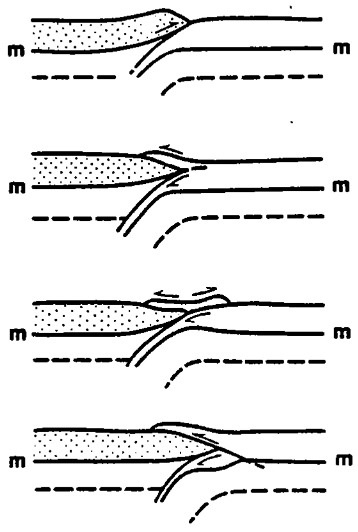


Fig. 19. Examples of tectonic wedging and delamination of the lithosphere (after Oxburgh 1974). Dashed lines mark the base of the litho-

thereafter, the allochthonous terranes and the miogeocline were displaced as a unit onto the flank of the North American continental craton.

CONCLUSIONS

Tectonic wedging and delamination occur over a whole spectrum of scales from the microscopic to the lithospheric. 'Flake tectonics' (Oxburgh 1972) and obduction in general, probably represent the upper end of the spectrum in that they involve delamination of the entire lithosphere such that the strong upper layer has been separated from the rest of one lithospheric plate and has overlapped another lithospheric plate that has been wedged beneath it. The simple models presented by Oxburgh (1974), to illustrate the ways in which the accommodation may occur between opposing continents during collision (Fig. 19), cover the spectrum of phenomena encountered in this brief review. The geometric and kinematic relationships discernible in these natural prototypes provide a basis for elucidating relationships that are more difficult to establish directly on a larger scale.

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