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Obduction, backfolding and piggyback thrusting in the metamorphic hinterland of the southeastern Canadian Cordillera

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Abstract—The (paleo-)continental margin of the southeastern Canadian Cordillera was deformed and metamorphosed mainly in the Jurassic and Cretaceous, beginning with the obduction of a composite oceanic terrane, eastwards at least 60 km, onto the western part of the continental margin in the late Early Jurassic. In the Middle Jurassic, W-verging backthrusts and backfolds developed in this region, the folds becoming increasingly overturned and attenuated at deep structural levels. This deformation of the hinterland produced major crustal thickening and regional metamorphism, which peaked in the late Middle Jurassic.

The thickening mass of the hinterland curtailed westward vergence. The focus of crustal shortening stepped to the east in the form of E-verging piggyback thrusting, which carried the deformed hinterland eastwards. Displacements propagated from the hinterland into the foreland on major detachments and thrusts. The initial shear zone, the Monashee décollement, decoupled the cover from its basement and accounted for at least 80 km of shortening by the middle Late Jurassic. Continued thrusting on lower shear zones that rooted at the base of the crust, led to the development of a basement duplex and major uplift of the hinterland.

We present two balanced cross-sections; each based on available structural, petrologic, geophysical and geochronologic data. Both sections are internally consistent, and demonstrate that development of a basement duplex beneath the hinterland could have accommodated contemporaneous thin-skinned shortening of the Rocky Mountain Foreland.

INTRODUCTION

A BALANCED cross-section and palinspastic reconstruction of the North American Rocky Mountain Thrust and Fold Belt was first produced by Bally, Gordy and Stewart in 1966. Similar sections have since been drawn across the Canadian segments of the foreland region (Price & Mountjoy 1970, Dahlstrom 1970, Thompson 1979, Price 1981, Price & Fermor 1983). Reconstruction westward from the foreland into the hinterland (Omineca Belt) has been hindered by poor stratigraphic control (caused by complex deformation) and by uncertainties concerning the depth and nature of basement involvement. However, in recent years our understanding of the hinterland in the vicinity of the Shuswap Metamorphic Complex (Fig. 1) has approached the point where rigorous structural sections and at least partial palinspastic reconstructions may be drawn. Most recently a section of the southern Canadian Cordillera has been compiled for Transect B2 of the *Decade of North American Geology Program* (Monger *et al.*, in press). This section crosses the hinterland between latitudes 51°N and 52°N and extends eastward to the front of the Rocky Mountain Foreland.

The purpose of this paper is to document the Mesozoic and early Cenozoic structural history of the southern Omineca Belt, and present two composite cross-sections between latitudes 50°N and 53°N (Figs. 1 and 2). Geological constraints from surface data are combined with the principles of balancing cross-sections (Dahlstrom 1969) to produce as realistic a subsurface geometry as possible.

OBDUCTION

In the late Early to Middle Jurassic, a composite oceanic terrane, Terrane I of Monger *et al.* (1982), accreted to the North American (paleo-)continental margin. Terrane I consists of four smaller terranes, which were assembled by the end of the Triassic (Figs. 3 and 4). *Stikinia*, a dominantly volcanic terrane, was emplaced against *Quesnellia*, an upper Paleozoic to Lower Jurassic island arc terrane, in the latest Triassic (Fig. 4; Monger & Price 1979). The suture between them is marked by a Mississippian to Triassic subduction mélange, the *Cache Creek* terrane (Monger *et al.* 1982). From the Mississippian to the Early Jurassic, the *Eastern* terrane, probably a small oceanic basin, separated Quesnellia from the continental margin (see Monger 1977). Easterly directed thrusting began within this basin in the Early Jurassic (or earlier, see Klepacki & Wheeler 1985), leading to the obduction of the Eastern terrane and part of Quesnellia onto the continental margin, which is now represented by the Omineca Belt (Monger 1977; Fig. 3). The timing of the obduction is bracketed between the late Early Jurassic when the youngest marine sediments in Terrane I were deposited (see Monger 1984), and the Middle Jurassic when both Terrane I and the Omineca Belt suffered regional deformation, metamorphism and plutonism (Read & Wheeler 1976, Archibald *et al.* 1983).

The obducted Eastern terrane is generally composed of ophiolitic rocks throughout its length in southern British Columbia (Monger *et al.* 1972, Monger 1977). In one locality, serpentinized ultramafic cumulates, am-

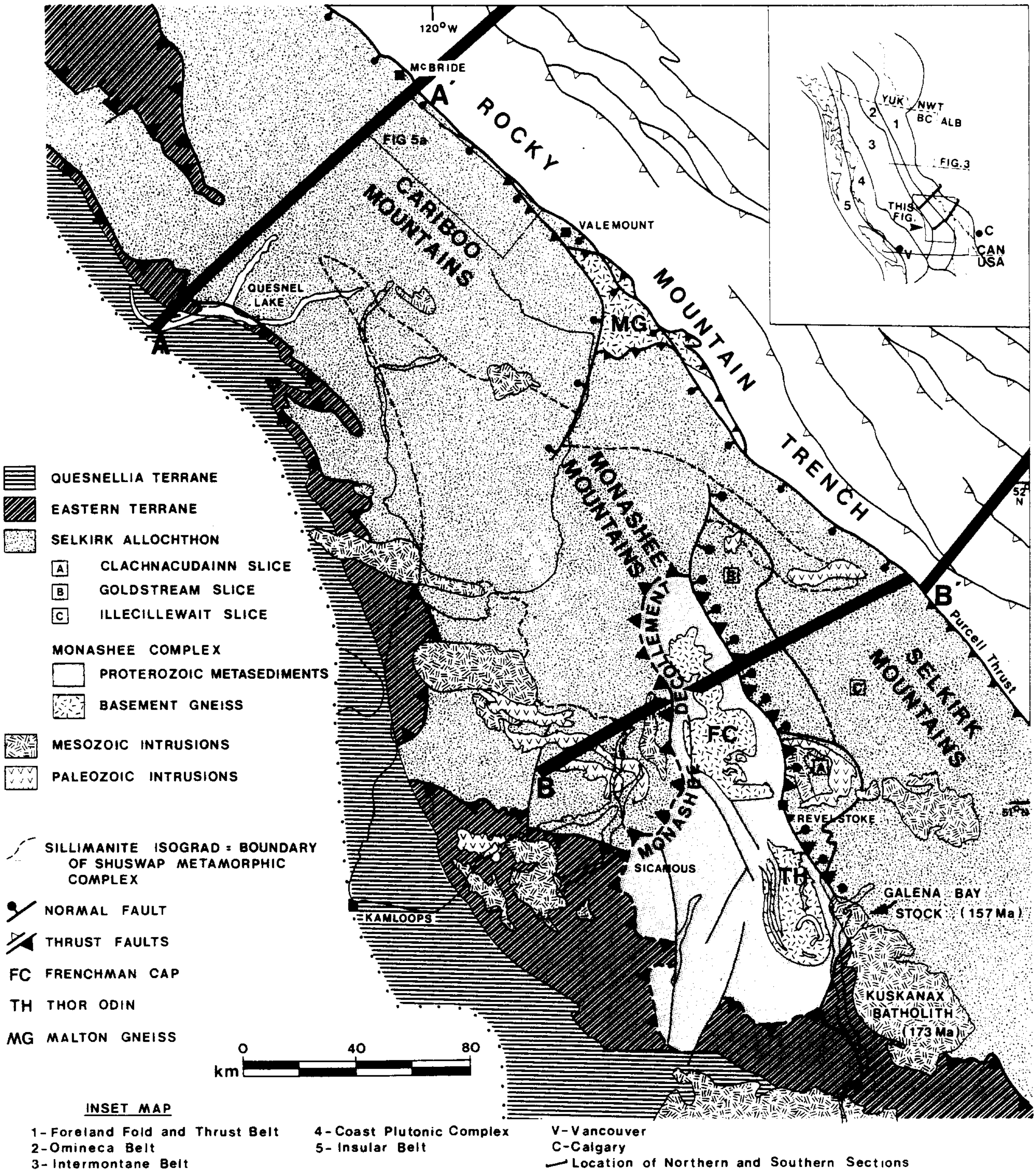


Fig. 1. Shuswap and Monashee metamorphic complexes and adjacent rocks, regionally important faults, major intrusions, and location of cross-sections in Fig. 2 (modified from Campbell 1972, and Read & Brown 1981).

phibolitized gabbro and greenschist form an assemblage that structurally overlies Omineca Belt metasediments (Montgomery 1978). Elsewhere, pillowed metabasalt of ocean floor tholeiite composition (Campbell 1971, Campbell *et al.* 1973, Hall-Beyer 1976), ribbon chert and argillite (Campbell & Tipper 1972, Struik 1981), and ultramafic rocks (Rees 1981, Klepacki 1983) together or individually characterize the Eastern terrane.

At the contact between the Eastern terrane and the Omineca Belt in the Quesnel Lake area (Fig. 1), mylonitic textures are well developed in Upper Paleozoic granitic orthogneiss and quartzofeldspathic metasediments of the Omineca Belt footwall (Campbell 1971, Rees 1981). In the hangingwall, Eastern terrane metabasalt is also strongly sheared and locally mylonitic. A kinematic study of the orthogneiss in the Omineca Belt by Rees & Ferri (1983) determined a west over east sense of shear, which was attributed to the obduction event because it is the oldest structural fabric in the rock. Potassium feldspar megacrysts have a preferred orientation produced by rigid body rotation in progressive simple shear. W-dipping flattening-plane foliation (*S* surfaces, cf.

Berthé *et al.* 1979) preserved in layers bounded by discrete planes of shear (*C*-surfaces, Berthé *et al.* 1979), and E-dipping shear-band foliation, both support a west over east sense of shear. The local trend of the shear displacement is 097° (Fig. 3). It is marked by the stretching lineation in the finite plane of flattening. Substantiating this displacement vector from other parts of the boundary is difficult because of the effects of later (Middle Jurassic) deformation and metamorphism, which re-oriented and recrystallized obduction-related kinematic indicators.

The width of the tectonic overlap of the Eastern terrane on the Omineca Belt is difficult to estimate because of later shortening, and the question of preservation. The original width was probably at least 60 km; it also depends on the identification of klippen, or of windows and re-entrants of the Omineca Belt. The preserved thickness of the Eastern terrane is about 1–3 km at or near its leading edge in the east (Struik 1980, Montgomery 1978). Farther west where the overthrust Terrane I consisted of Quesnellia, the thickness was probably at least 15 km. The greater thickness of the allochthon at the contact described above contributed to higher grade metamorphic conditions (greenschist) and mylonitization during the obduction.

Below the Terrane I allochthon, Omineca Belt rocks exhibit regional pre-Middle Jurassic foliation, and tight to isoclinal folds. These structures are interpreted to have developed during emplacement of Terrane I. Pre-Middle Jurassic E-verging folds with associated axial-planar foliation documented in the Cariboo Mountains farther east (Murphy & Journeay 1982, Murphy & Rees 1983), and in the Selkirk Mountains (Brown & Tippett 1978, Read & Thompson 1980), may also have formed during obduction. Farther south around latitude 50°N, the earliest structures are known to have formed in the Paleozoic (Read & Wheeler 1976), and the presence there of deformation fabrics related to Jurassic obduction remains to be demonstrated.

BACKFOLDING

E-directed obduction of the eastern edge of Terrane I onto the relatively thin distal portions of the North American continental margin sedimentary prism was followed by a cratonward transfer of the focus of strain to the thicker portion of the sedimentary prism. Subsequent shortening was accommodated by W-verging folds and faults (Monger 1977, Monger *et al.* 1978, Monger & Price 1979, Brown & Read 1983). These structures dominate the geometry of the supracrustal rocks of the hinterland from deep levels through to the overlying obducted sheet of Terrane I. Since the structures verge away from the Rocky Mountain Foreland towards the accreted terranes, they are termed 'backfolds' or 'backthrusts' (Monger & Price 1979). This important episode of deformation produced major crustal thickening, and induced regional metamorphism of the hinterland, but did not extend into the foreland (Brown 1978, 1981). These relationships are displayed in the Cariboo Mountains and Selkirk Mountains (Figs. 1 and 2), where excellent exposure and careful mapping permit construction of continuous, well constrained cross-sections to paleo-depths of up to 25 km.

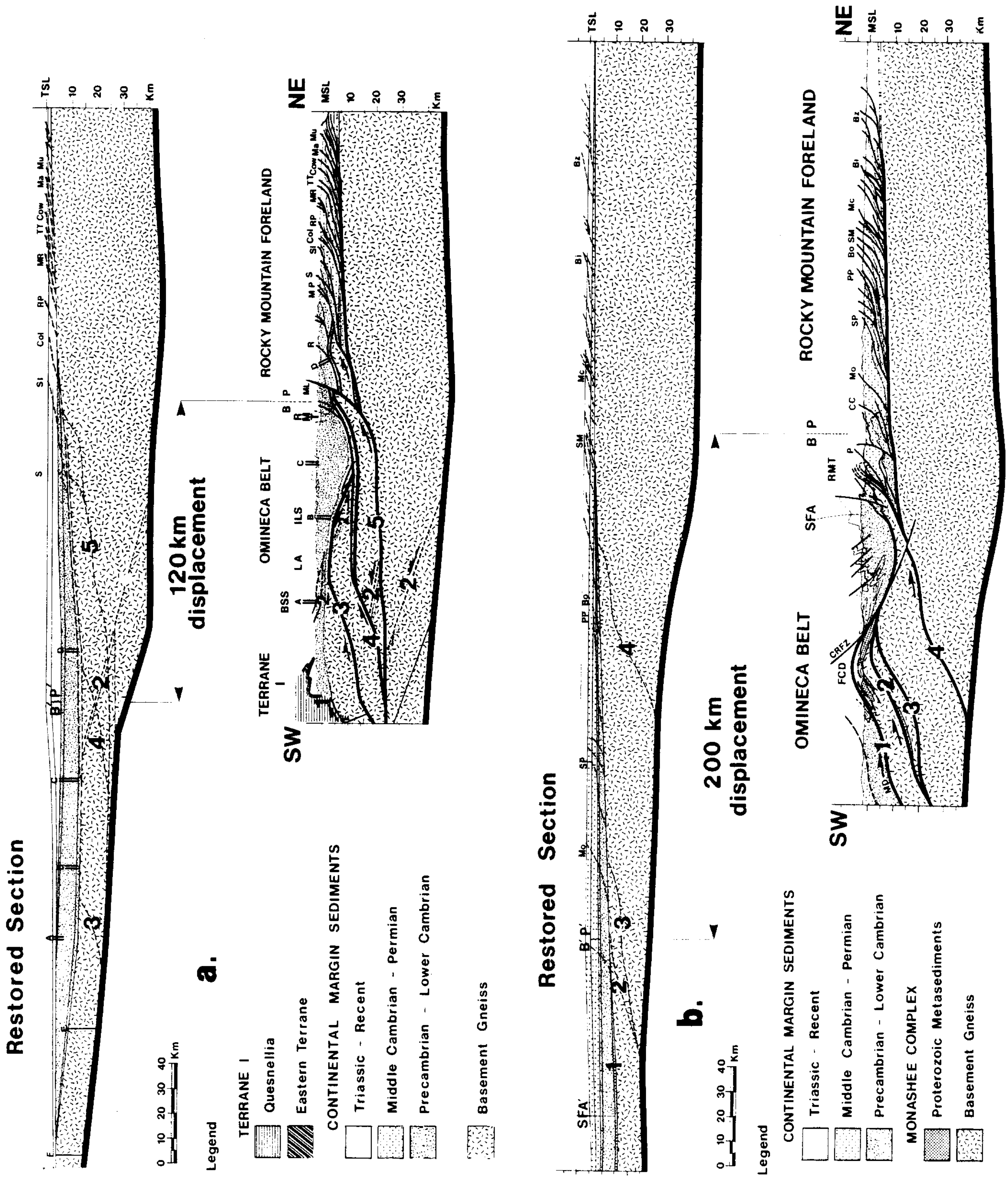
Cariboo Mountains

Figure 5(b) is a composite cross-section in the Cariboo Mountains illustrating the changes in structural style and geometry encountered in a 10 km thick structural sequence of Proterozoic meta-turbidites (Kaza Group). This section was compiled at 1:20,000 scale by projection of 28 serial vertical cross-sections into a single vertical plane of section. The locations of projected sections are controlled by structural and stratigraphic continuity and/or by the orientation of hinge lines of major folds. Structural and stratigraphic continuity is lacking in only two areas (across Raush River and across South Kiwa Creek, Fig. 5a) along a strike length of 65 km; in these areas, the location of the projected sections is controlled by hinge-line orientations exclusively.

In making these projections, we are aware of possible along-strike variations in structural geometry. As such, we only claim to be projecting structural styles and thicknesses. The original thickness of the Kaza Group was approximately 3.5 km (Pell & Simony 1984, Carey & Simony 1984). Approximately 7.5 km of uninvolved sediments lay above the structurally thickened sequence presented in Fig. 5(b) (Fig. 2a; Campbell *et al.* 1973). The base of the sequence in Fig. 5(b) would therefore have been under approximately 17 km of rock, roughly corresponding to a metamorphic pressure of 500 MPa. This pressure is compatible with assemblages of co-existing kyanite–staurolite–quartz–biotite–muscovite observed in pelitic rocks at the base of the sequence. In this regard, the 6 km of structural thickening present in the composite section is quite reasonable.

W-verging folds dominate the structural sequence at all levels in the Cariboo Mountains. At shallow structural levels, relatively open folds with steep, E-dipping axial surfaces accommodate 10–20% shortening (Campbell 1973, Murphy, in press). The axial surfaces of these folds progressively flatten with depth, merging at intermediate depths with a zone of tight to isoclinal, recumbent W-verging folds, implying an increase in the simple shear component of strain (Murphy 1983, in press). These isoclinal folds are parasitic on regional scale recumbent W-verging folds such as the Raush Nappe (Fig. 5b) which produced a large structural thickening of the middle Kaza Group.

Comparison of the Kaza Group structural sequence illustrated in Fig. 6 with stratigraphic thicknesses determined elsewhere (Carey & Simony 1984, Pell & Simony 1984) shows that the isoclinally folded middle unit of the Kaza Group is approximately four times thicker than its estimated stratigraphic thickness, representing a shortening of approximately 75%. In contrast, the deformed thickness of immediately overlying upper Kaza Group rocks is approximately the same as the estimated original


Restored Section
a.
120 km displacement
SW
NE
TERRANE I
OMINECA BELT
ROCKY MOUNTAIN FORELAND
BSS
LA
ILS
C
B P
TSL
MSL
10
20
30
Km
0 10 20 30 40 Km
Legend
TERRANE I
Quesnellia
Eastern Terrane
CONTINENTAL MARGIN SEDIMENTS
Triassic - Recent
Middle Cambrian - Permian
Precambrian - Lower Cambrian
Basement Gneiss
Restored Section
b.
200 km displacement
SW
NE
OMINECA BELT
SFA
RMT
B P
ROCKY MOUNTAIN FORELAND
FCD
CRFZ
MD
SFA
TSL
MSL
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Km
0 10 20 30 40 Km
Legend
CONTINENTAL MARGIN SEDIMENTS
Triassic - Recent
Middle Cambrian - Permian
Precambrian - Lower Cambrian
MONASHEE COMPLEX
Proterozoic Metasediments
Basement Gneiss

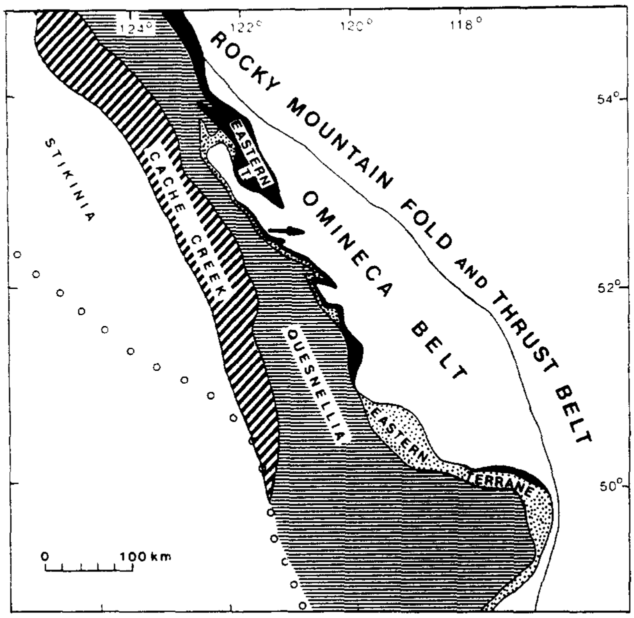

Fig. 3. Map showing the four terranes of Terrane I which accreted to the western margin of North America in the Early Jurassic. Arrow is direction of emplacement of Eastern terrane determined at this locality.

Terrane I	Stikinia	Dominantly Paleozoic to Middle Jurassic volcanic and sedimentary rocks
	Cache Creek	Mississipian to Upper Triassic mélange of chert, argillite, basalt, serpentinite, limestone
	Quesnellia	Upper Paleozoic to Lower Jurassic alkalic and calc-alkaline basaltic volcanics, sedimentary rocks
	Eastern	Upper Paleozoic (pillow) basalt, chert, serpentinite, gabbro, argillite (in black). Overlapped by Upper Triassic argillite and volcanics (stipple)
Continental North America	Omineca Belt	Mainly Proterozoic and Paleozoic miogeoclinal rocks deposited on North American craton or transitional crust
	Rocky Mountain Belt	Proterozoic to Upper Jurassic miogeoclinal and platformal sedimentary rocks deposited on craton and transitional crust

thickness. The difference in shortening between shallow (10–20% shortening) and immediately underlying deeper structural levels (75% shortening) requires that, to the west, shallow structural levels be detached from deeper levels (Fig. 6; Murphy, in press). North of Quesnel Lake, W-verging low-angle faults structurally imbricate the more distal portion of the continental margin sequence together with the obducted allochthon of Terrane I (Campbell *et al.* 1973, Struik 1980, 1981, 1982, 1983a, b, Klepacki 1981, Campbell *et al.* 1982). Struik (1981) reported 70% shortening of the hangingwall of the structurally lowest thrust, the Pleasant Valley fault. The structural topography of regional scale structures such as the Isaac Lake Synclinorium, the Lanezi Arch, and the Black Stuart Synclinorium, was used by us to infer the location of footwall cut-offs of the Pleasant Valley fault, yielding an estimate of 40–60 km of total displacement on this fault system. Such displacements could have been accommodated by thickening documented at deeper structural levels to the east (Murphy, in press).

Selkirk Mountains

Major pre- to syn-metamorphic W-verging folds are the dominant structures in the Selkirk Mountains west of the Selkirk fan axis (Brown & Tippett 1978, Brown *et al.* 1983). The importance of these structures and their change in style with structural depth may be observed by projection of surface information into cross-sections

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Fig. 2. (a) Structural section AA′ and palinspastic restoration of southern Omineca Belt and adjacent Rocky Mountain Thrust and Fold Belt (Fig. 1). Rocky Mountain Thrust and Fold Belt structural section is modified after Mountjoy (1980) and Campbell *et al.* (1982). Restored section portrays the inferred geometry of the miogeocline and its attenuated basement in the Late Triassic (fine dashed line). Also shown is the inferred configuration of basement in the Middle Jurassic, after backfolding and backthrusting but prior to shortening on easterly-directed shear zones. Ductile shear zones within the Omineca Belt are constructed to balance 125 km of shortening within the Rocky Mountain Foreland. Basement area is equal in both sections except for small wedge in lower left-hand corner of structure section. Ductile shear zones within the Omineca Belt: Quesnel Lake Shear Zone (1), Pleasant Valley fault and equivalent basement shear zones (2), (3), (4), (5). Thrust faults within the Rocky Mountain Foreland: Monarch (M), Pauline (P), Snaring (S), Resplendent (R), Snake Indian (SI), Collin (Col), Rocky Pass (RP), Mt. Russell (MR), Tip Top (TT), Cowlick (Cow), Mason (Ma), Muskeg (Mu), Moose Lake (ML). Other tectonic elements of importance include: Black Stuart Synclinorium (BSS), Lanezi Arch (LA), Isaac Lake Synclinorium (ILS), Rocky Mountain Trench (RMT), and lower Paleozoic Platform to Basin transition (B/P). Reference stratigraphic sections: (A) Mt. Kimball (Struik 1980); (B) Azure River–Thunder River (Pell 1984); (C) North-Central Cariboos (Campbell *et al.* 1973); (D) Cushing Creek (Carey & Simony 1984); (E) Restoration of basement above shear zone 5; (F) Restoration of E by removing displacement along shear zone 2; Triassic sea level (TSL); Mean sea level (MSL). (b) Structural section BB′ and palinspastic restoration (Fig. 1). Rocky Mountain Foreland structure section and its palinspastic restoration are taken from Price & Mountjoy (1970). Structure section for western Main Ranges, between SFA and Mo is taken from Simony (1979). Restored section portrays the inferred geometry of the miogeocline and its attenuated basement, prior to shortening along E-directed shear zones. Ductile shear zones within the Omineca Belt are constructed to balance 200 km of shortening within the Rocky Mountain Foreland, and to satisfy existing geometric and petrologic constraints (Journeay, in prep.). Area of basement is equal in both sections. Ductile shear zones within the Omineca Belt: Monashee décollement (MD) (1), (2), (3), Purcell thrust (4). Thrust faults within the Rocky Mountain Foreland: Purcell (P), Chatter Creek (CC), Mons (Mo), Simpson Pass (SP), Pipestone Pass (PP), Borgeau (Bo), Sulphur Mountain (SM), McConnell (Mc), Bighorn (Bi), Brazeau (Bz). Other tectonic elements of importance include Frenchman Cap dome (FCD), Columbia River fault zone (CRFZ), Selkirk Fan Axis (SFA), Rocky Mountain Trench (RMT) and lower Paleozoic Platform to Basin transition (B/P); Triassic sea level (TSL); Mean sea level (MSL).

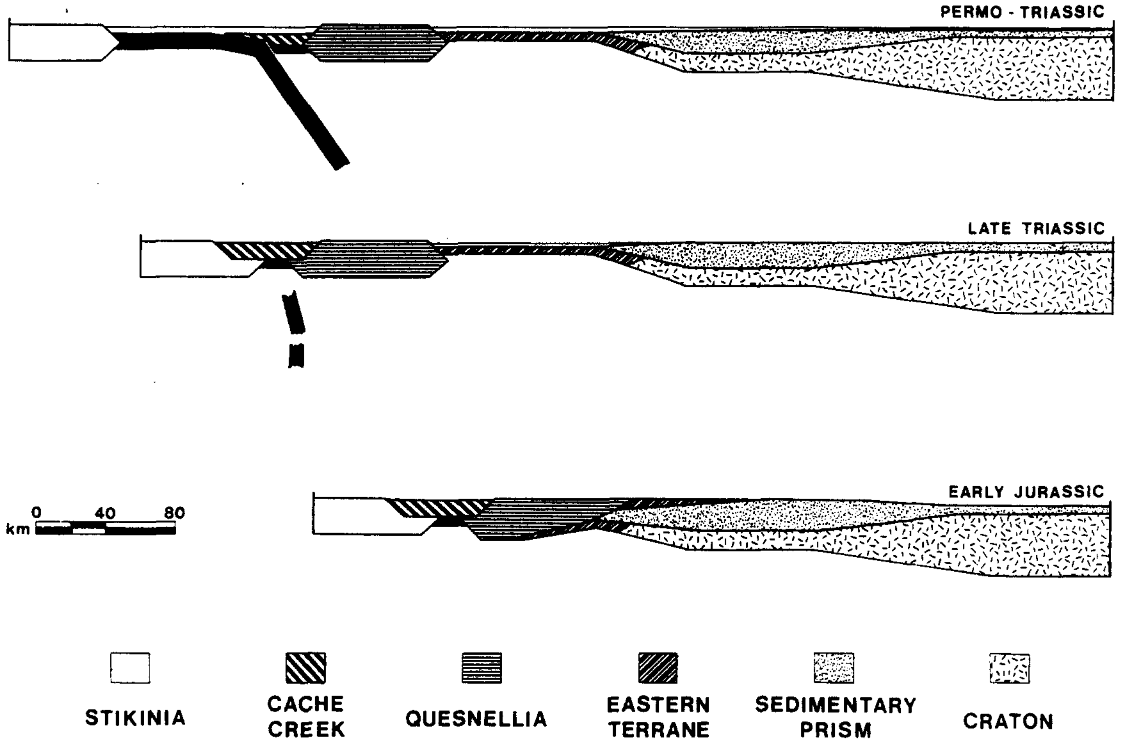

Fig. 4. Diagrammatic cross-sections showing the inferred development of the western North American margin in the early Mesozoic.

(Fig. 2b). W-verging folds have steeply E-dipping axial surfaces at high structural levels and become recumbent at deeper levels. Relations are more complex than in the Cariboo Mountains because both older and younger phases of folding are present on a regional scale. Despite the effects of refolding, it is clear that the significance of the W-verging structures increases with depth in a manner similar to that observed in the Cariboo Mountains.

The westerly vergence that dominates the structural style in the southwestern Selkirks gives way to dominantly E-verging folds in the northeast. This structural fan is in part the result of steepening and easterly overturning during a progressive phase of syn-metamorphic deformation (phase 2 of Franzen 1974, Simony *et al.* 1980, Perkins 1983), but its style to the east of the fan axis is primarily the result of superposition of E-verging syn- to post-metamorphic folds (phase 3 of Brown & Tippett 1978, Raeside & Simony 1983, Perkins 1983).

Scrip nappe is a W-verging structure with an overturned limb length of approximately 60 km (Simony *et al.* 1980, Raeside & Simony 1983) that has been mapped in the northern Monashee Mountains 40 km to the northeast of our southern section (see Figs. 1 and 2b). This structure appears to have originated at shallow levels during a pre-metamorphic phase of W-verging deformation, and to have been progressively buried by tectonic thickening as syn-metamorphic folds were superimposed. This tectonic thickening resulted in peak metamorphic conditions in the pressure range of 700 MPa (Ghent *et al.* 1979, 1981, 1982, 1983, Leatherbarrow 1981, Raeside & Simony 1983), equivalent to a depth of approximately 25 km. These peak conditions were attained in the Middle Jurassic at approximately 165 Ma (Read & Wheeler 1976, Archibald *et al.* 1983).

Discussion of backfolding

The nature of deep crustal compensation of the W-directed structures documented within the upper 25 kilometres of the crust is speculative. It has been argued that W-verging backfolds and thrust faults, associated with initial shortening of the suprastructure, were produced by crustal delamination and the wedge-like emplacement of accreted terranes along a conjugate set of shear zones (Archibald *et al.* 1983, Price 1983). In this model, shortening of the suprastructure occurs within the upper plate of a W-verging shear zone, and is compensated at depth by the westward underthrusting of the lower crust of North America beneath Terrane I. For reasons discussed in detail elsewhere (Murphy, in press) and briefly below, we prefer a model in which the initial shortening of the supracrustal sediments, by W-verging folds and faults, is accommodated at depth by the eastward underthrusting of attenuated continental basement (Monger & Price 1979, Brown 1981, Price & Fermor 1981) beneath the adjacent North American craton (see Fig. 2a).

In seeking a dynamic justification for this interpretation, it is important to keep in mind the change in cross-sectional profile of the continental margin during progressive shortening. The earliest recognized structures are E-verging folds and faults, some of which are related to the obduction of Terrane I. The restored continental margin following the obduction of Terrane I is shown in Fig. 7. At this stage, further shortening may be accommodated either by the development of E- or W-dipping basement shear zones. We propose that the dynamic influences of the weight of obducted oceanic rocks (Terrane I) and the W-sloping, W-thinning conti-

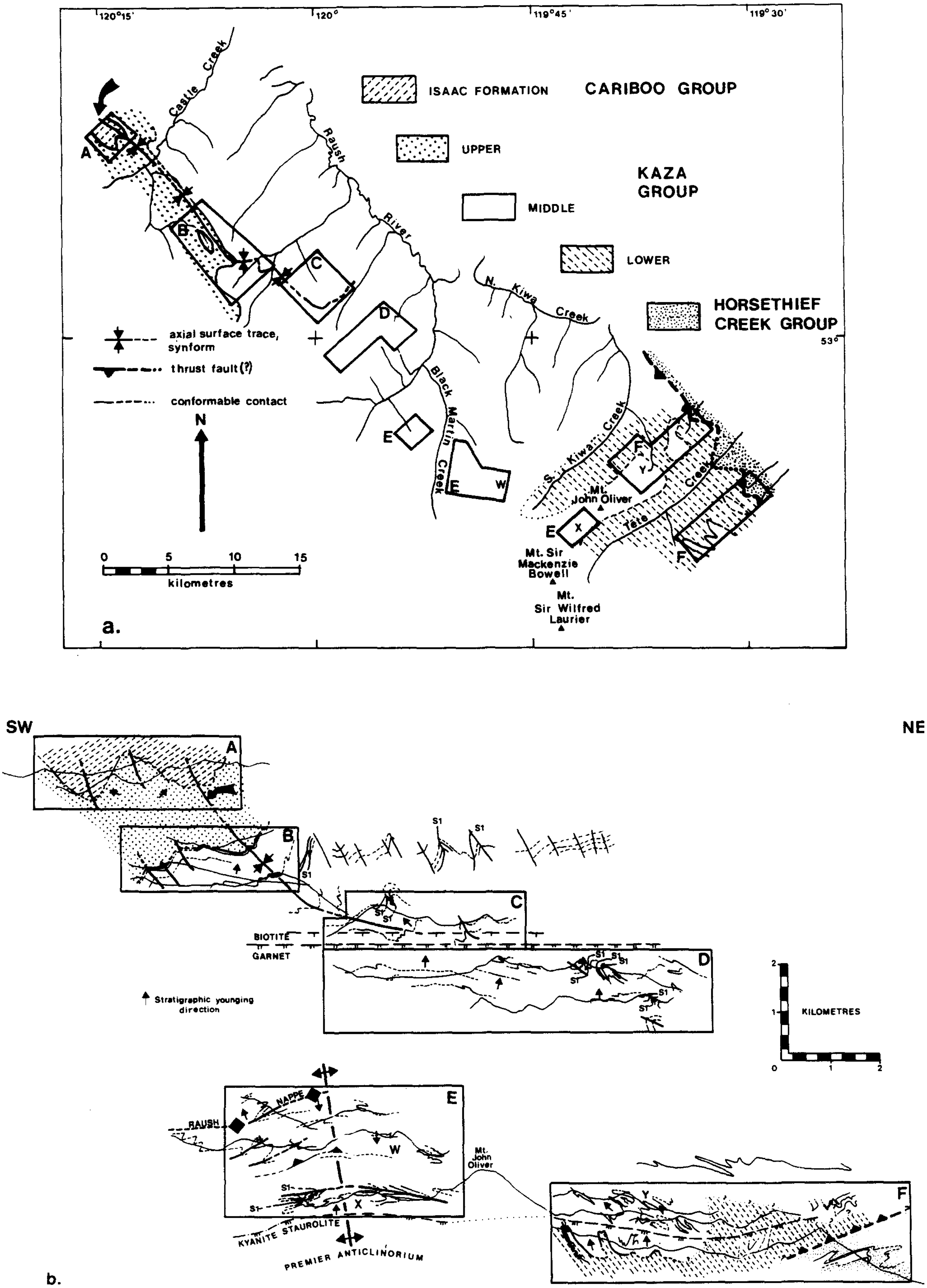

Fig. 5. (a) Simplified geological map, and (b) composite vertical cross-section of the east-central Cariboo Mountains (from Murphy, in press) illustrating the change in style with depth of the W-verging syn-metamorphic folds. See Fig. 1 for location of Fig. 5.

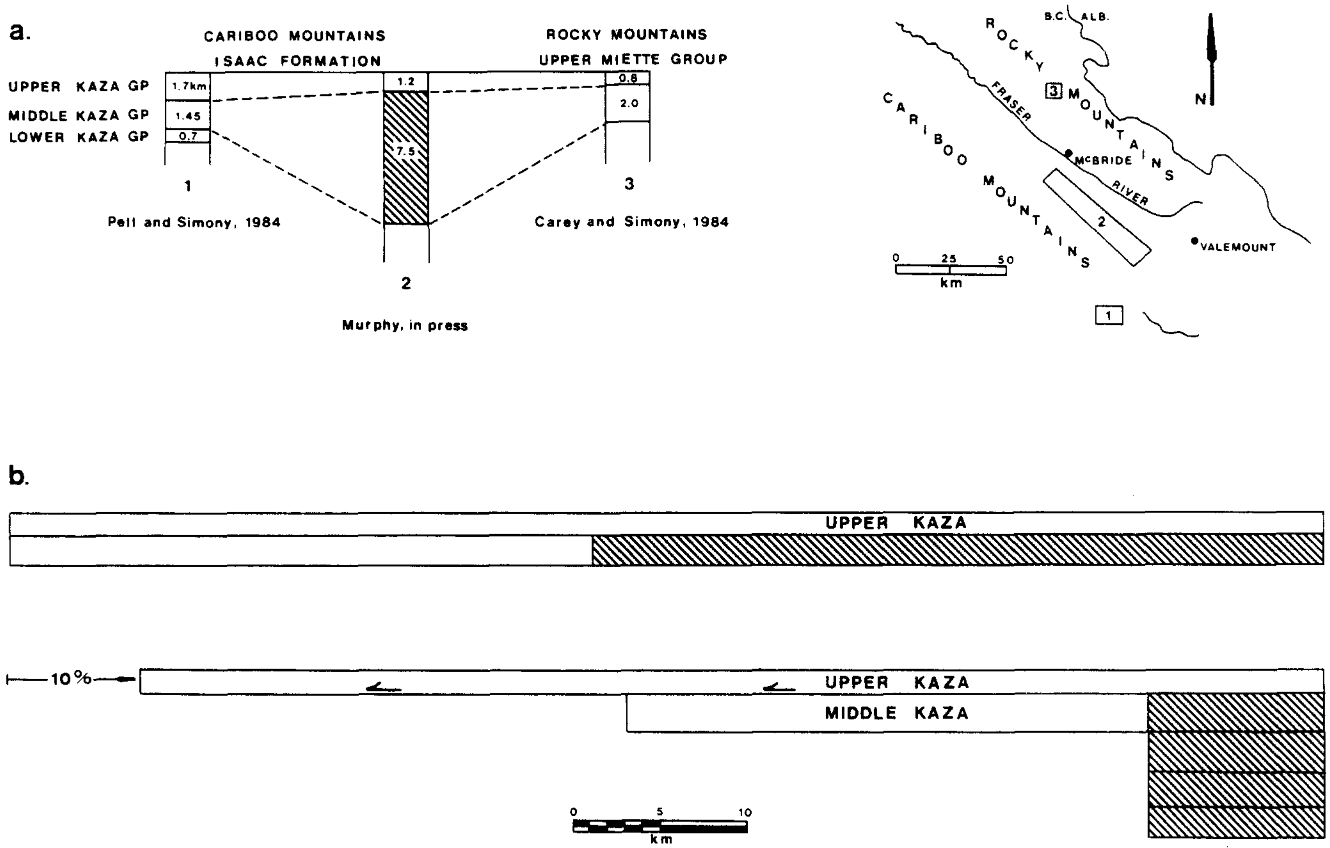

Fig. 6. (a) Comparison of the structurally thickened Proterozoic section (2), from Fig. 5, with (1) a less deformed Proterozoic section from the southern Cariboo Mountains and (3) a stratigraphic section of equivalent rocks from the western Main Ranges of the Rocky Mountains. (b) Model illustrating the relationship between structural thickening in the Cariboo Mountains and low-angle thrust faulting near Quesnel Lake (Fig. 1). The upper diagram is an idealized pre-kinematic configuration; the lower diagram illustrates how the distribution of structural thickening in the infrastructure requires detachment between structural levels to the southwest.

nental margin sequence favoured the formation of E-dipping basement shear zones.

Shortening and thickening of the outer part of the continental margin sequence during this W-verging phase of deformation led to a new dynamic configuration which focused stresses onto the W-dipping basement/cover contact (cf. Davis *et al.* 1983). Continued shortening is interpreted to have been accommodated by detachment and eastward displacement of the structural wedge of continental margin sediments along a basal décollement (Monashee décollement), and associated foreland-propagating piggyback thrust faults, as described below.

Because these vergence reversals occurred within the thickening North American plate, they need not imply changes in polarity of lithospheric subduction at the western boundary of the plate.

PIGGYBACK THRUSTING

In the Rocky Mountain Thrust and Fold Belt, it is established that thrust faulting migrated from west to east towards the foreland from the hinterland (Armstrong & Oriel 1965, Bally *et al.* 1966, Armstrong 1968, Price & Mountjoy 1970). The piggyback style of listric thrust faulting, by which the higher and earlier-emplaced thrust sheets are carried by progressively lower and younger thrust faults, was first documented in the Front Ranges where extensive drilling during oil exploration supplied the necessary subsurface control (see Bally *et al.* 1966, Dahlstrom 1970). This thin-skinned model of foreland shortening, requiring detachment faulting along a sole thrust above rigid crystalline basement of the North American craton, has been extrapolated westwards to the eastern edge of the hinterland. (Bally *et al.* 1966, Price & Mountjoy 1970).

The relationship between the tectonic history of the hinterland and foreland thrusting to the east has been a subject of considerable controversy. Gravitational upwelling and lateral spreading of the hinterland was thought by some to be the driving mechanism of foreland thrusting (Price & Mountjoy 1970, Elliott 1976, Price 1973). Others have proposed basement uplifts on high-angle reverse faults with thin-skinned shortening being restricted to the Foothills segment of the Rocky Mountains (Campbell 1973, Eisbacher *et al.* 1974). However, Brown & Tippett (1978) recognized that the hinterland was deformed and metamorphosed in the Middle Jurassic, before deformation of the foreland began. They pointed out that the dominant vergence within the hinterland during deformation was westerly, away from the foreland rather than toward it. Brown (1978) argued that the hinterland was not the cause of foreland shortening but instead should be considered an integral part of the thrust belt that differed from the foreland only by the

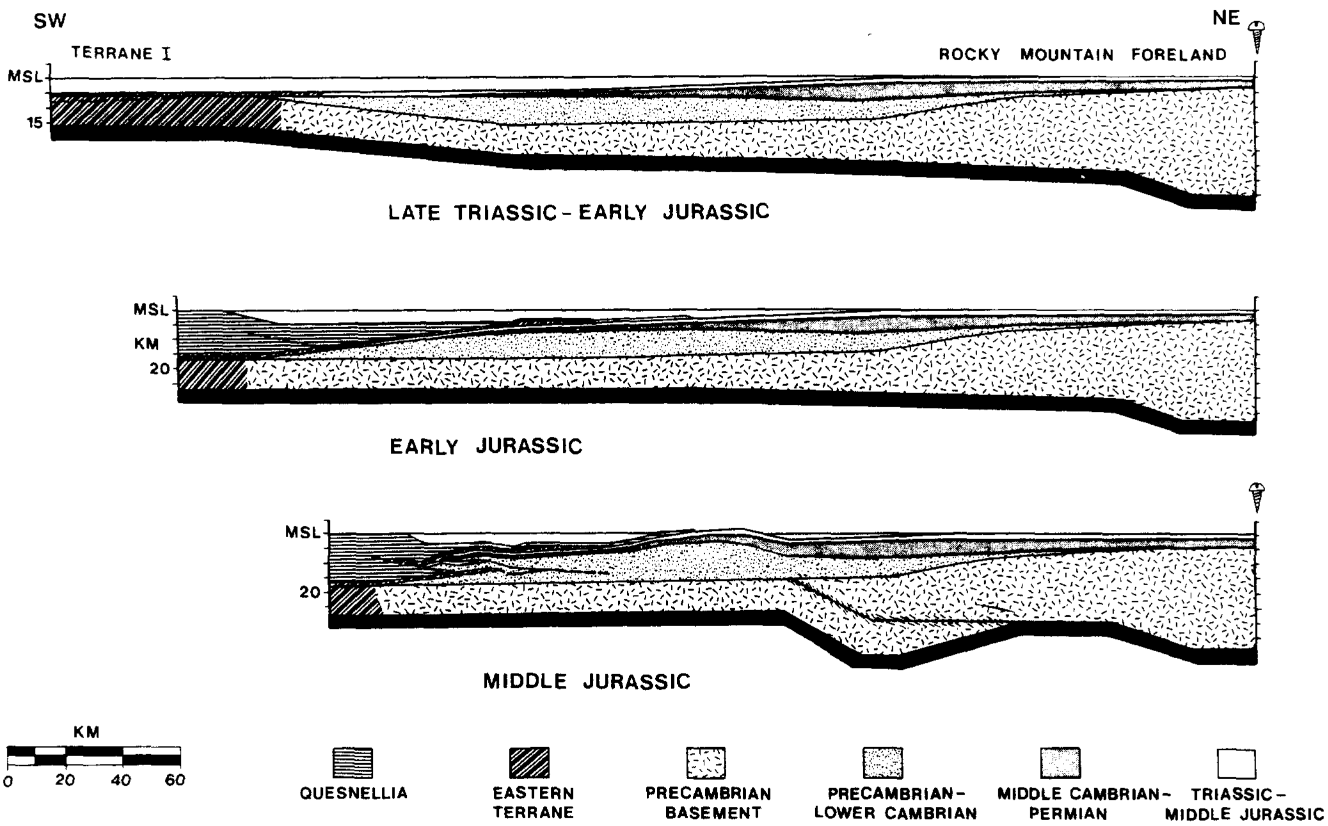

Fig. 7. Restored and partially deformed balanced section constructed from interpretation of geology of Cariboo Mountains. Terrane I is obducted onto the North American sedimentary prism in the Early Jurassic and deformed by W-verging thrusts and folds in the Middle Jurassic. Shortening of the cover is diagrammatically balanced by eastward underplating of the basement. Western thrust belt is modified after Struik (1982). See text for further explanation.

nature of its earlier deformation history. This interpretation is now supported by the recognition that after W-verging deformation (backfolding and backthrusting) induced thickening of the hinterland, an E-verging décollement (Monashee décollement) carried the cover rocks of the hinterland eastwards toward the foreland (Brown & Murphy 1982, Brown & Read 1983).

Basement deformation in the hinterland

The Monashee Complex (Read & Brown 1981) is well exposed in a tectonic window through the Monashee décollement (Fig. 1). It includes an Aphebian basement terrane (2.2 Ga; Armstrong 1983) of granitic orthogneiss and migmatitic paragneiss that is unconformably overlain by shallow marine clastic and calcareous metasedimentary cover rocks of probable upper Proterozoic age. Basement and cover sequences of the Monashee Complex share a Mesozoic history of intense penetrative strain and high-grade regional metamorphism (bathozone 5–6, Journeay 1983), and are herein interpreted to be the shortened and thickened equivalents of attenuated continental crust that initially extended westwards beneath continental margin sediments of the rifted North American craton (Monger & Price 1979, Brown 1981, Price & Fermor 1981, Price 1981, Monger *et al.* in press). We propose that the Monashee Complex is an antiformal duplex system of basement-cored horses that was assembled in the Mesozoic and unroofed sometime in the Late Cretaceous to Early Tertiary (Fig. 2b). This interpretation is based on the internal strain and metamorphic history of the uppermost basement horse (Frenchman Cap–Thor–Odin domes, Journeay 1983, in prep., Brown & Read 1983, Duncan 1984). The section compiled by Monger *et al.* (in press) shows the Monashee Complex cut by thrust faults that root at the base of the crust and that feed into the basal décollement of the Rocky Mountain Foreland. Our section (Fig. 2b) varies in detail, but we are in essential agreement concerning the style of crustal thickening. In the following sections, we summarize our geological evidence for the strain and metamorphic history of the Monashee Complex and overlying Monashee décollement. We relate this history to that in the upper plate (Selkirk Allochthon) of the Monashee décollement and to displacement along the décollement. This interpretation is the basis of our structural cross-sections and palinspastic reconstructions of the continental margin.

Style of basement deformation

The inferred geometry of the hinterland duplex is based on the results of regional mapping along major detachment faults within the southern Omineca Belt (Brown 1981, Read & Brown 1981, Journeay, in prep.), and on the configuration of the M-discontinuity presented in Monger & Price (1979) and based on the work of Chandra & Cumming (1972), Berry & Forsythe

(1975), Cumming (1977), Mereu *et al.* (1977) and Spence *et al.* (1977). The style of basement deformation within the duplex is documented by detailed mapping in exposed horses of the Monashee Complex (McMillan 1970, Fyles 1970, Reesor & Moore 1971, Psutka 1978, Höy 1979, Brown 1980, Read & Klepacki 1981, Journeay 1981 and in prep.), and in thick-skinned thrust sheets adjacent to the Rocky Mountain Trench (Fig. 1; Simony *et al.* 1980, Morrison 1982).

The internal geometry of the Monashee Complex is characterized by an early set of isoclinal folds and associated low-angle thrust faults that predate the peak of regional prograde metamorphism in the footwall of the Monashee décollement. The largest and most prominent of these N-trending pre-metamorphic structures is a recumbent, E-verging anticline–syncline pair whose shared upright limb underlies the eastern half of Thor–Odin Nappe and the elongate core zone of Frenchman Cap Dome (Figs. 1 and 2b). These early structures contain a well developed axial-planar foliation, and are refolded by two distinct sets of regional syn-metamorphic structures that developed during E-directed overthrusting of the Selkirk Allochthon along the Monashee décollement in the Middle Jurassic.

These syn-metamorphic structures include E-verging sheath folds and NE-verging asymmetric buckle folds that are typically reclined in the high strain zone of the Monashee décollement, and whose hinge lines have been rotated towards a regionally developed E–W-trending stretching lineation. This penetrative stretching lineation and associated flattening foliations are well developed at all observed structural levels of the Monashee Complex, but are most intense within mylonitic rocks of the Monashee décollement. NE-verging reclined buckle folds are truncated by the Monashee décollement, and can be traced into deeper structural levels of the lower plate where they are shallow plunging and nearly cylindrical in geometry. These NE-verging buckle folds appear to be kinematically linked to low-angle imbricate thrust faults along the southwest flank of the Monashee Complex (Duncan 1984), and are interpreted to have been generated by a component of NE-directed shortening during Middle Jurassic overthrusting of the Selkirk Allochthon (Journeay 1983, in prep.).

Pressure-sensitive mineral assemblages in the high strain zone of the Monashee décollement indicate that mylonitic foliations and associated E-verging syn-metamorphic folds in the lower plate of the fault zone were generated at depths in excess of 25 km, and continued to evolve by progressive deformation (rotation and flattening) during the uplift and differential displacement of the Monashee Complex and overlying Selkirk Allochthon (Journeay 1983, in prep.). E-verging post-metamorphic folds are well developed in both upper and lower plates of the Monashee décollement. These structures are interpreted to have been generated during the uplift and imbricate stacking of tectonic slivers within the basement duplex, and its subsequent detachment and eastward displacement onto the rigid basement of the adjacent Rocky Mountain Foreland.

Magnitude of displacement between basement and cover

The absence of matching stratigraphic cut-offs along the exposed length of the Monashee décollement requires a minimum displacement of 80 km (Read & Brown 1981). Restoring the motion on the Monashee décollement should result in the juxtaposition of pre-existing structures of similar style. Of particular significance is the transition from W-verging to E-verging syn-metamorphic folds in the Selkirk Allochthon (see Fig. 2b and section on Backfolding) above the Monashee décollement. In the underlying Monashee Complex, only E-verging structures are observed. The fan axis of the Selkirk Allochthon must therefore have originated west of the exposed Monashee Complex, a distance of at least 100 km to the west along the Monashee décollement.

Major eastward displacement on the Monashee décollement apparently ended prior to 157 Ma (Galena Bay Stock, Armstrong 1983, Fig. 1), yet at least 100 km of shortening within the Rocky Mountain Foreland is known to have occurred between the Late Cretaceous and Paleocene (Price 1981). These observations led Read & Brown (1981) and Brown & Read (1983) to propose a sole thrust at the base of the Monashee Complex to accommodate the remaining amount of post-Middle Jurassic shortening. We propose that the Omineca Belt culmination is underlain by a number of penetratively deformed basement slices separated by ductile shear zones. The foreland-ward dip of the structurally highest shear zone, the Monashee décollement, was inferred by Read & Brown (1981), Journeay (1983, in prep.), Simony (pers. comm.) and Monger *et al.* (in press) to be a result of motion on underlying faults in the style of a foreland belt duplex (Dahlstrom 1970, Elliott & Johnson 1980, Boyer & Elliott 1982).

Geometry of basement duplex

The geometry of ductile shear zones within the Monashee Complex is not accurately known. However, a reasonable and internally consistent geometry can be constructed by combining the principles of balancing cross-sections with available geological and petrologic constraints. By starting with the easternmost fault involving basement (Purcell Fault and Pauline–Monarch system, as interpreted by D. Murphy) and using observed or inferred cross-section shapes of basement slices (Simony *et al.* 1980), a trajectory may be constructed for the fault beneath the structurally lowest basement sheet. The remaining fault trajectories are constructed by determining the shape of basement horses whose hangingwall and footwall cutoffs yield a total displacement that matches the post-Middle Jurassic displacement in the Rocky Mountain Foreland. Determination of horse shape is constrained by the empirical 'rule' that thrust faults either stay at the same level or cut up section in their direction of transport (Elliott & Johnson 1980). Ramp geometry in the southern section is further constrained by metamorphic data from the

Monashee décollement and underlying Monashee Complex (Journeay, in prep.).

ROLE OF CRUSTAL EXTENSION AND STRIKE-SLIP FAULTING

The Monashee Complex and structurally overlying rocks of the Shuswap Metamorphic Complex display evidence of limited Tertiary extension. Brittle reactivation along the eastern segment of the Monashee décollement gave rise to the Columbia River Fault (Read & Brown 1981, Lane 1984b, Fig. 2b). Evidence for more significant extension is documented to the south in allochthonous cover rocks adjacent to Late Cretaceous and Tertiary plutons (Monger 1968, Harms & Price 1983, Parrish & Ryan 1983, Parrish 1984, Parrish *et al.* 1985, Carr 1985), and to the southwest in the Intermontane Belt (Church 1975, Matthews 1981) where major detachment faulting induced by crustal extension has been suggested (Tempelman-Kluit, pers. comm. 1984, Bardoux 1985). Listric normal faults in the vicinity of the Rocky Mountain Trench root in older thrust faults at depths of 2–5 km and indicate significant Eocene to Miocene extension at high levels in the crust (Bally *et al.* 1966, Dahlstrom 1970). Lower crustal accommodation of these high level extensions is represented by the emplacement of dykes (e.g. Wheeler 1965, Monger 1968, Fyles 1970, Ross 1974) and more substantial plutonic bodies (e.g. Rice 1941, Jones 1959, Tipper *et al.* 1981, Harms & Price 1983), both of which are associated with abundant volcanic rocks of Early Tertiary age (e.g. Tipper *et al.* 1981, Matthews 1981). Significant plutonism and high heat flow in the Early Tertiary (Medford 1975, Mathews 1981, 1983) imply that ductile deformation mechanisms were operative up to high levels in the crust, and that ductile thinning probably has occurred in the Intermontane Belt. Early Tertiary heating is suggested for parts of the Omineca Belt, but not to the extent recorded farther west (Mathews 1983).

In our reconstruction of the Omineca Belt (Fig. 2), we considered the possibility that Tertiary crustal thinning has affected the basement rocks exposed in the structural culmination of the Monashee Complex (see also Coney & Harms 1984). The exposed basement is at present approximately 45 km above the M-discontinuity (Berry & Forsythe 1975). The ductile strain within these exposures is attributed primarily to Mesozoic or older deformation (Read & Brown 1981, Duncan 1984, Lane 1984a). Local N–S-trending vertical dykes and low-angle brittle extension faults of Eocene or younger age in the Monashee Complex probably account for no more than 10 km (10%) horizontal extension of the complex (Fyles 1970, Lane 1984b, Journeay, in prep.). The possibility of deep crustal extension beneath the exposed Monashee Complex cannot be ruled out entirely but seems unlikely to have occurred on a significant scale without accompanying major brittle extension of the overlying exposed part of the complex. It appears that the basement rocks exposed in the structural culmination of the Omineca Belt attained their present thickness during crustal shortening in the Mesozoic and have been little affected by the regional crustal extension in the Tertiary.

Our interpretation is based on a direct and balanced kinematic link between supracrustal shortening within the Rocky Mountain Thrust and Fold Belt and shortening of the basement within the hinterland of the southern Omineca Belt at their present geographic locations. This interpretation assumes minimal strike-slip faulting and strain normal to the plane of section. Major strike-slip faulting has not been documented, but cannot be ruled out. If future work should identify syn- to post-shortening strike-slip faults or major deviations from plane strain, the sections in Fig. 2 would have to be rebalanced. However, the qualitative arguments for the structural style of basement involvement and the deformation history would not be invalidated.

SUMMARY OF STRUCTURAL HISTORY AND CONCLUSIONS

(1) The hinterland of the southern Canadian Cordillera evolved in response to convergence between western oceanic terranes and the North American continental margin (Monger 1977, Monger & Price 1979, Monger *et al.* 1982). The deformation essentially began in the Early Jurassic when the eastern edge of the innermost oceanic terrane (Terrane I) was obducted eastwards onto the continental margin (Omineca Belt) (Monger 1977, Montgomery 1978, Struik 1981, Monger *et al.* 1982, Rees & Ferri 1983).

(2) This terrane and the more western part of the underlying continental margin were subsequently backthrusted (Monger 1977, Monger *et al.* 1978, Struik 1981) and backfolded (Struik 1981, Rees & Ferri 1983) during the Middle Jurassic.

(3) Backthrusts in the western Omineca Belt are kinematically linked with backfolding and crustal thickening within the central Omineca Belt. W-verging supracrustal shear strain was compensated by eastward underthrusting of transitional or attenuated continental crust (Monger & Price 1979, Brown 1981, Price 1981, Price & Fermor 1981) that formed the basement to the sedimentary prism (Brown 1978, 1981). This phase of deformation induced major crustal thickening and regional metamorphism, but ceased before the regional metamorphic peak which occurred at approximately 165 Ma (late Middle Jurassic).

(4) The wedge shape of the thickened crust, with its surface slope to the east, caused a reversal in regional structural vergence in the hinterland from westwards to eastwards. The thickened cover rocks of the hinterland were carried eastwards towards the foreland by piggyback transport on shear zones that root to the west (Read & Brown 1981, Monger *et al.* in press). The oldest and highest of these shear zones, the Monashee décollement, originated at a depth of at least 25 km. At least 80 and probably 100 km of movement on this décollement occurred before the intrusion of a middle Late Jurassic

granitic stock (Armstrong 1983) which plugs the shear zone (Read & Brown 1981).

(5) Post-Late Jurassic crustal shortening continued by the stacking of sheets of basement below the Monashee décollement along an interlocking array of thrust faults that transmitted displacements into the Rocky Mountain Foreland in the style of a foreland belt duplex (Read & Brown 1981, Brown & Read 1983, Monger *et al.* in press).

(6) A reasonable and internally consistent duplex geometry for the Monashee Complex can be constructed by determining the shapes of basement horses whose hangingwall and footwall cutoffs yield a total displacement that matches the post-middle Late Jurassic displacement within the Rocky Mountain Thrust and Fold Belt. Shortening of supracrustal rocks in the foreland is balanced by basement thickening in the hinterland. Basement thrusting induced uplift and arching of the Monashee Complex.

(7) Eocene extension of the uplifted hinterland resulted in dyke emplacement and normal-sense reactivation of old shear zones, but induced only minor crustal thinning (Brown & Read 1983, Lane 1984b).

(8) Major strike-slip faults or strain normal to the plane of our cross-sections have not been documented in the southern Omineca Belt. If future work should identify syn- to post-shortening strike-slip faults, the sections in Fig. 2 would have to be rebalanced. However, the qualitative arguments for the style of basement involvement and the deformation history would not be invalidated.

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