THE INFLUENCE OF CONCEPTUAL MODELS AND GEO-POETRY IN TECTONICS AND STRUCTURAL GEOLOGY

2012 Penrose Gold Medal lecture

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My fascination with the nature, origin, and evolution of mountains began during the summer of 1952, when, after only one course in geology, I had the good fortune to be employed on Geoffrey B. Leech's GSC (Geological Survey of Canada) field party in the Purcell Mountains of southeastern British Columbia. Having never before been in the mountains, I was enthralled and intrigued by their majesty, formidable beauty, and mystery. Fortunately for me, Geoff Leech was an amazing mentor and role model. He nurtured my fascination with the mountains and my latent interest in geology with the result that my scientific focus shifted from physics and chemistry to geology. My principal scientific quest became: "Whence the Mountains?" particularly the mountains of the southeastern Canadian Cordillera. Thanks to the GSC, I was able to launch my scientific career with a PhD thesis focused on that question, and also to spend ten years at the Geological Survey of Canada exploring the southern Canadian Rocky Mountains in a strip stretching 425 km northward from Glacier National Park in Montana to the Yellowhead Pass near Mount Robson and Jasper. Sixty years later, equipped with a wealth of new information and many new conceptual models, (some of my own making), I now can articulate comprehensible explanations for the nature, origin, and evolution of the southeastern Canadian Cordillera, and thereby for some other mountain belts elsewhere.

S. Warren Carey, Harry H. Hess, and Walter Bucher, three of my mid-twentieth century geotectonics heroes, have inspired me in my quest for insight on mountain building. In 1952 **S. Warren Carey** provided an elegant exposition on how **our thinking in tectonics and structural geology is done with models**, and how some of these models are empirical but not readily applicable very far beyond the scale of time and the scale of length of the observations with which they were formulated. In his geo-poetical "expanding earth" conceptual model for the origin of the ocean basins, Carey focused on structural evidence of continental rifting and divergence between conjugate continental fragments, and on

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conceptual models such as "megashears" that, like transform faults, linked "sphenochasms" and "rhombochasms" to explain the opening of ocean basins and the apparent "drift" between continents. **Harry H. Hess** presented a different more comprehensive, insightful and elegant conceptual model for "The History of the Ocean Basins" in his classic 1962 paper, which he himself called an **"essay in geo-poetry"**. In this paper, which is arguably the most innovative and influential global tectonics article of the 20th century, Hess suggested that **thermal convection within the mantle drives the continuous creation and destruction of ocean floors by the symmetrical generation of new ocean floor above divergent, gravity-driven buoyant upwellings of hot mantle, and by the reciprocal asymmetrical gravity-driven sinking of solid, older, colder, negatively buoyant ocean floor**. In this conceptual model, ocean basins are ephemeral; they open and close as divergent upwelling currents cause continents to split apart and carry the pieces away from each other; and as sinking currents give rise to oceanic trenches, magmatic arcs, the deformation of continental margins, terrane accretion, and continental collisions. **Walter H. Bucher**'s GSA presidential address, titled "Role of Gravity in Orogensis", was published in the October 1956 issue of the GSA Bulletin. This was the first issue of the GSA Bulletin that I received as a new GSA member! This paper was particularly inspirational for me because of Bucher's elaboration and elucidation of **conceptual models of gravitational lateral spreading for foreland thrust-and-fold belts and of intrusive fold-nappes that flow almost horizontally within the metamorphic core zones or orogenic belts** directly aided my quest for understanding of the origin and evolution of my small corner of the world --- the southeastern Canadian Cordillera, and thereby for some other mountain belt elsewhere.

The southern part of the Canadian Cordilleran foreland thrust-and-fold belt, which comprises the Southern Canadian Rockies and adjacent parts of the Purcell and Cariboo Mountains, consists of thrust slices of supracrustal strata have been detached from the under-riding edge and margin of Laurentia by an over-riding tectonic collage of allochthonous terranes that originated mainly as oceanic magmatic arcs. The detached sedimentary strata came from four different superimposed sedimentary basins: the Mesoproterozoic Belt-Purcell intracontinental rift basin, the late Neoproterozoic Windermere intracontinental rift basin, the Cambrian to Middle Jurassic Cordilleran miogeocline (a passive-margin, continental terrace-wedge basin), and the syn-orogenic Upper Jurassic to Paleocene Cordilleran foreland basin. The concept of tectonic heredity as expressed in the different configurations and locations of

the margins of these basins is important for the elucidation of mountain building. This complex, composite wedge of sedimentary rock was compressed horizontally and thickened (i.e. extended vertically) by imbricate thrust faulting and related folding as it was being displaced up to more than 200 km northeastward. Seismic reflection imaging and aeromagnetic anomaly maps show that the Paleoproterozoic crystalline basement of the Interior Plains extends under the Canadian Rockies without disruption. The deformation was 'thin-skinned'.

Bucher's gravitational spreading model involved pervasive flow from regions of higher elevation and higher pressure toward regions of lower elevation and lower pressure. In the area with higher surface elevations the deformation in the model involves vertical compression (surface subsidence) and horizontal extension; in the area with lower surface elevations it involves horizontal compression and vertical extension (surface uplift), but how does this happen and what happens in between?

Simple shear (laminar flow with no stretching or shortening in the direction of flow) **is the most popular geological conceptual model for flow in rocks**, and it has been used to analyze gravity-driven lateral flow in mountain belts. However, it is an inappropriate conceptual model because **simple shear is a special condition that marks the boundary between two quite different flow regimes: extending flow (extension in the direction of flow) and compressing flow (compression in the direction of flow).** The application of this more comprehensive conceptual model for gravity-driven flow in orogenic belts provides important tectonic insights that are not available with the simple shear model. The characteristics of extending flow in gravitational spreading are: horizontal stretching (stretching in the direction of flow), vertical thinning (vertical compression), boudinage and excision of less ductile layers, converging flow lines, and increasing displacement in the direction of flow. The characteristics of compressing flow in gravitational spreading are: horizontal shortening (compression in the direction of flow), vertical thickening (extension), diverging flow lines, and decreasing displacement in the direction of flow. **Deformation in the Cordilleran foreland thrust-and-fold belts bears the earmarks of compressing flow**. Whereas, **the deformation within mid-crustal metamorphic rocks that were exhumed as crustal-scale boudins in the interior of the southern Canadian Cordillera bear the earmarks of extending flow** that occurred before as well as during their tectonic exhumation by Eocene regional dextral transtension.

What we perceive of the deformation within the Cordilleran foreland thrust and fold belt depends upon the scale at which we observe it. Our conceptual models of the nature and evolution of the deformation must be adapted to meet the changes in our perceptions between one scale of observation and another. In the external part of the Southern Canadian Rockies foreland thrust-and-fold belt, pieces of rock that have undergone horizontal displacements of many tens of km together with associated large rotations generally provide little or no evidence of internal deformation at the scale of a thin section or hand specimen. Delicate intricate details of sedimentary and fossil structures are preserved without distortion. However, at the scale of an outcrop, or a larger scale, the supracrustal strata comprise stratified mosaics of meter-scale to centimeter-scale blocks of rock that are bounded by fractures. The 'fractures' are mainly parallel or perpendicular to the bedding. Some of the 'bedding-perpendicular' fractures are extension fractures that may or may not be filled or coated with carbonate minerals or quartz; some are stylolites that mark 'planes' along which there has been 'pressure solution'; some are polished or slicken-lined shear surfaces on which slicken lines commonly are parallel with bedding. Bedding surfaces may be stylolitic, but they commonly are polished or slicken-lined shear surfaces on which slicken lines are perpendicular to the hinge lines of adjacent folds. Some of the fractures are small faults that are commonly polished or slicken-lined shear surfaces. These small faults are inclined to the bedding, generally at ~30^0, if they are 'contraction faults', which produce bedding-parallel shortening, or at >60^0 if they are 'extension faults', which produce bedding-parallel stretching. At the outcrop scale and beyond, the fracture-controlled rheology of the deformed stratified rock mass can be geo-poetically described as "**cataclastic ductility**". Distortion of formations and of individual beds has been accomplished by the integration of opening, closing, and slipping along discrete fractures, including small faults that offset the bedding. Why do these small faults show preferred orientations with respect to the bedding surfaces, but not to gravity. Evidently, because the **bedding surfaces were surfaces of low shear strength, and slip along the bedding reduced the shear stress along the bedding, thus making the local orientation of the principal stresses within the beds parallel and perpendicular to the bedding**.

On the scale of a mountainside, compressing flow deformation within these un-metamorphosed supracrustal strata is expressed as **listric thrust faulting and thrust-related, flexural-slip, chevron-style and concentric-style folding**. **The tip lines of blind**

thrust faults that propagated along the axial zones of the kinematically elegant chevron folds form the centre-lines of the curvature within overlying concentric folds.

On a regional scale the thrust faults all 'die out' along strike. The northeastward tapering wedge-shaped mass of supracrustal strata as been shortened, thickened, and displaced northeastward by thrust-fault displacements that are distributed over a myriad array of discrete displacement discontinuities, all of which are embedded within an otherwise coherent mass of rock; they also are linked downward to a basal detachment zone close to the top of the underlying Paleoproterozoic basement. When viewed at a scale that is much larger than the largest thrust fault, the deformation involves large distortion with out loss of overall cohesion, and therefore is a type of flow.

There are large lateral gradients in the amount of displacement on the individual thrust faults. **Individual incremental displacements on the thrust faults must have propagated as "smeared out" dislocations at a maximum velocity that was small compared to the area of the fault that was affected by the incremental displacement, so that only part of this area was subject to displacement at any one time**. The so-called **"mechanical paradox of large overthrusts" is due to a fallacious assumption in a conceptual model that was used to analyze the mechanics of overthrusting, namely that thrust displacements occurred simultaneously over an entire fault**.

Viewed at the proper scale, the **flow within the Cordilleran foreland thrust-and-fold belt was analogous to the flow of the Pleistocene ice sheets** that covered most of the interior of Canada. However, because of the much greater specific gravity and thickness of the rocks, **the Cordilleran foreland thrust-and-fold belt created a much larger isostatic flexure in the continental lithosphere than was created by the ice sheets. This flexure, the foreland basin, subsided and trapped the Cordilleran detrital outwash <u>only</u> when the thrust-and-fold belt was rising and spreading laterally**. When the thrust-and-fold belt was not rising and spreading laterally there was no subsidence to trap sediment within foreland basin, and consequently the sediment eroded from the mountains then by-passed the foreland basin, as it does today. According to this conceptual model subsidence and sediment-accumulation in the foreland basin occurred only of times of thrusting and related folding, and therefore gaps in the sedimentary record in the foreland basin deposits are associated with times when thrusting and related folding were not occurring. This is contrary

to previous conceptual models, which did not recognize isostatically induced subsidence, and interpreted times of erosion as times of uplift and mountain building.

My **balanced (retro-deformable) structure sections are based on the concept that whatever occurs on one side of a fault must have a compatible counterpart on the other side**. Thus, what is discernible along the hanging wall of the thrust fault has been used to predict what exists out of view along the footwall; and likewise what is discernible along the footwall of a thrust fault has been used to reconstruct what has been eroded from the hanging wall. Retro-deformable structure sections have been used to construct **palinspastically restored structure sections** that portray the configuration and location of the remaining, uneroded deformed strata, but where they existed prior to thrusting, not where they are now. Sets of palinspastically restored retro-deformable structure sections have been used for the construction of **palinspastically restored maps** portraying the locations, configurations (isopachs), and structural relationships of the pre-existing Belt-Purcell, Windermere, and Cordilleran miogeocline sedimentary basins that have been incorporated into this part of the Cordilleran foreland thrust-and-fold belt.

Tectonic heredity (exemplified in the southern Canadian Rockies by sequential reactivation of structures aligned with the Vulcan structure, a major Paleoproterozoic crustal suture that has been identified along the northwest side of the Archean Medicine Hat block under southern Alberta) is responsible for a 225 km dextral offset in the eastern margin of the Cordilleran miogeocline from southeastern British Columbia to northeastern Washington. Reactivation of the Vulcan structure also influenced the configuration of the eastern margin of the late Neoproterozoic Windermere basin, and the evolution of the Mesoproterozoic Belt-Purcell basin. As a result of the tectonic inversion that occurred while the supracrustal strata in the Belt-Purcell, Windermere, and Cordilleran miogeocline basins were being detached and displaced upward and northeastward on to the flat surface of the craton, the thick sedimentary sequences filling the basins were transformed into very large tectonic culminations. **The orientations of the flanks of the culminations, which were inherited from the orientations of the basin margins from whence the displaced supracrustal strata came, controlled the topographic gradients and thus the directions of lateral gravitational spreading within the foreland thrust-and-fold belt.** The northwest trend of the thrust-and-fold belt in northern Montana and southern Canada is inherited from the orientation of the Belt-Purcell basin. The north-south trend of the thrust-and-fold belt in southern Alberta and

British Columbia is inherited from this part of the margin of the Cordilleran miogeocline, and the local northeast-trending, southeast-verging thrust-and-fold structures in southeastern British Columbia are inherited from the orientation of the dextral offset in the margin of the Cordilleran miogeocline that was, in turn, inherited from the Paleoproterozoic Vulcan structure.

Most of the northeastward tectonic displacement across the foreland thrust-and-fold belt of the southern Canadian Cordillera occurred during **a mid-Cretaceous to Late Paleocene interval of dextral transpression between Laurentia and the Cordilleran accreted terranes. During this interval much of the convergence and tectonic shortening across the southern part of the Canadian Rockies was transformed northward into dextral strike-slip along the Northern Rocky Mountain trench fault zone and related faults** to the west of it. The amount of tectonic shortening across the southern Canadian Rockies decreases substantially in the region north of the Athabasca River (~53^0 N). This northward decrease in tectonic shortening is reflected in a matching northward decrease in the thickness and extent of the Late Cretaceous-Paleocene sediment in the Cordilleran foreland basin.

A **transition from dextral transpression to dextral transtension at the end of the Paleocene terminated shortening across the southern Canadian Rockies and initiated a episode of early Eocene regional extension and crustal-scale boudinage in south-central British Columbia**. There, dextral strike slip was transferred, by crustal stretching across the central Cordillera, from the Tintina-Northern Rocky Mountain trench fault system in the north to the Yalakom-Ross Lake fault zone in the southern Coast Mountains and the northern Cascade Mountains. **The basal detachment zone of the foreland thrust-and-fold belt is at the surface or just below the surface in three en echelon, 35-km thick, crustal boudins (Monashee complex, Valhalla complex, and Priest River complex) that were tectonically exhumed as overlying supracrustal high-grade metamorphic rocks were displaced eastward into adjacent zones of crustal necking in which the crust is now ~15 km thick**. The zones of crustal necking are adjacent to the undeformed Paleoproterozoic continental crust that forms the basement of the foreland thrust-and-fold belt beneath the Southern Canadian Rockies and is ~35 km thick.

Lithoprobe geophysical investigations have demonstrated that the Moho under south-central British Columbia is relatively flat and at a depth of 30-35 km. In contrast, there are variations

in structural relief of up to 25 km or more between tectonically exhumed metamorphic core complexes (the crustal boudins) and adjacent supracrustal rocks. These are not accommodated by underlying variations in the depth to the Moho. Metamorphic mineral assemblages that are preserved in the crustal boudins, 35 km above the Moho, formed at depths of up to 20 km or more beneath supracrustal rocks that now reside within adjacent zones of crustal necking. At the beginning of the Eocene, prior to the dextral transpression, the crust was 55 – 60 km thick. **The present-day 35-km thick crustal section under south-central British Columbia is a result of reciprocal crustal stretching involving crustal boudins that were exhumed by stretching and removal of overlying supracrustal strata and zones of crustal stretching and necking that are overlain by the supracrustal strata that were removed from above the crustal boudins.**

This region, which is in the back-arc of the Cascadia subduction system, is now a region of shallow asthenosphere and abnormally high heat flow. **The sustained high heat flow in the back-arc region has been explained with a conceptual model involving retrograde thermal convection in the asthenosphere that is linked to the mantle corner flow that is associated with the downward movement of the subducting oceanic lithosphere in the Cascadia subduction zone**. This conceptual model may be applicable to the initial stages of Mesozoic terrane accretion to the western margin of Laurentia, which involved of the collapse of the Slide Mountain back-arc basin, the obduction of Slide Mountain terrane over the margin of the Cordilleran miogeocline, and then the juxtaposition of Quesnellia, as a tectonic flake, over the outboard margin of Laurentia.

Geological maps of fault surfaces are helpful in the elucidation of thrust faulting. A comparison of structure-contoured balanced geological maps of the both the hanging wall and footwall of the Hosmer thrust fault has been used to illustrate the three-dimensional pattern of displacement on a fault that involved complex patterns of superimposed thrust fault displacements associated with changes in the direction of lateral gravitational spreading during the lifetime of the fault. A **geo-poetic conceptual model of the effects of superposition of early Eocene dextral transtension on late Cretaceous-Paleocene dextral transpression is illustrated with a structure-contoured regional geological map of the footwall of the basal detachment fault of the entire foreland thrust-and-fold belt ,** extending northward from $\sim48^0$ to 54^0, and westward beyond the culminations of three crustal boudins that locally expose rocks that are below or very close to the basal detachment in the

Monashee metamorphic complex, the Valhalla metamorphic complex, and the Priest River complex.

Tectonic wedging and delamination occurs at all scales from the microscopic to the lithospheric. It is the compressing flow counterpart of the boudinage and excision that are associated with extending flow. It involves intrusive compressing flow and it occurs at various places in the Canadian Cordillera. At the 'blind' tip-line of the foreland thrust-and-fold belt, there is wedge-shaped thrust-duplex with a foreland-vergent floor thrust and a retro-vergent roof thrust, which is known locally as "the triangle zone". Growth and propagation of the thrust-duplex wedge involves coordinated slip on the floor thrust, the imbricate thrusts and the roof thrust, and it delaminates the stratigraphic succession within which it is propagating. **Tectonic wedging and delamination at a crustal- or lithospheric-scale, in combination the conceptual model of retrograde thermal convection in the asthenosphere that is linked to the mantle corner flow associated with the downward movement of the subducting oceanic lithosphere provides a simple explanation for the collapse of the Slide Mountain back-arc basin, the obduction of Slide Mountain terrane over the margin of the Cordilleran miogeocline, and the juxtaposition of Quesnellia, as a tectonic flake, over the outboard margin of Laurentia.**

It has been 56 years since I first read Walter H. Bucher inspiring paper on "Role of Gravity in Orogenesis". My appreciation of the topic has evolved significantly in that time. Therefore, I will conclude with a brief summary of my current (but never final) view of the:

ROLE OF GRAVITY IN OROGENESIS

Planet earth is a gravity-drive heat engine.

Gravity-driven thermal convection in the molten outer core generates the magnetic field and heats the base of the mantle.

Because of gravity, buoyant hot rock rises vertically through the mantle.

Because of gravity it diverges symmetrically as it approaches the surface and flows horizontally forming new oceanic crust and oceanic lithosphere that is itself constrained by gravity to flow parallel with earth's spherical surface.

Because of gravity, cooler, thicker, stiffer negatively buoyant spherical plates of oceanic lithosphere are bent as they sink below the spherical surface of the earth, thus forming an oceanic trench plus a magmatic belt within the over-riding plate.

Thickening of buoyant crust at convergent plate boundaries produces gravity-driven rock uplift and thus the topographical relief that drives lateral gravitational spreading, including both extending flow deep within the continental crust and compressing flow along the margins of mountain belts.

Thank you Walter Bucher, Harry Hess, and Sam Carey; and thank you GSA.

The Influence of Conceptual Models and Geo-poetry on Tectonics and Structural Geology

Penrose Gold Medal Lecture -- 05 November 2012

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THE SOUTHERN
CANADIAN CORDILLERA

ROCKY MTN TRENCH

SOUTHERN CANADIAN ROCKIES
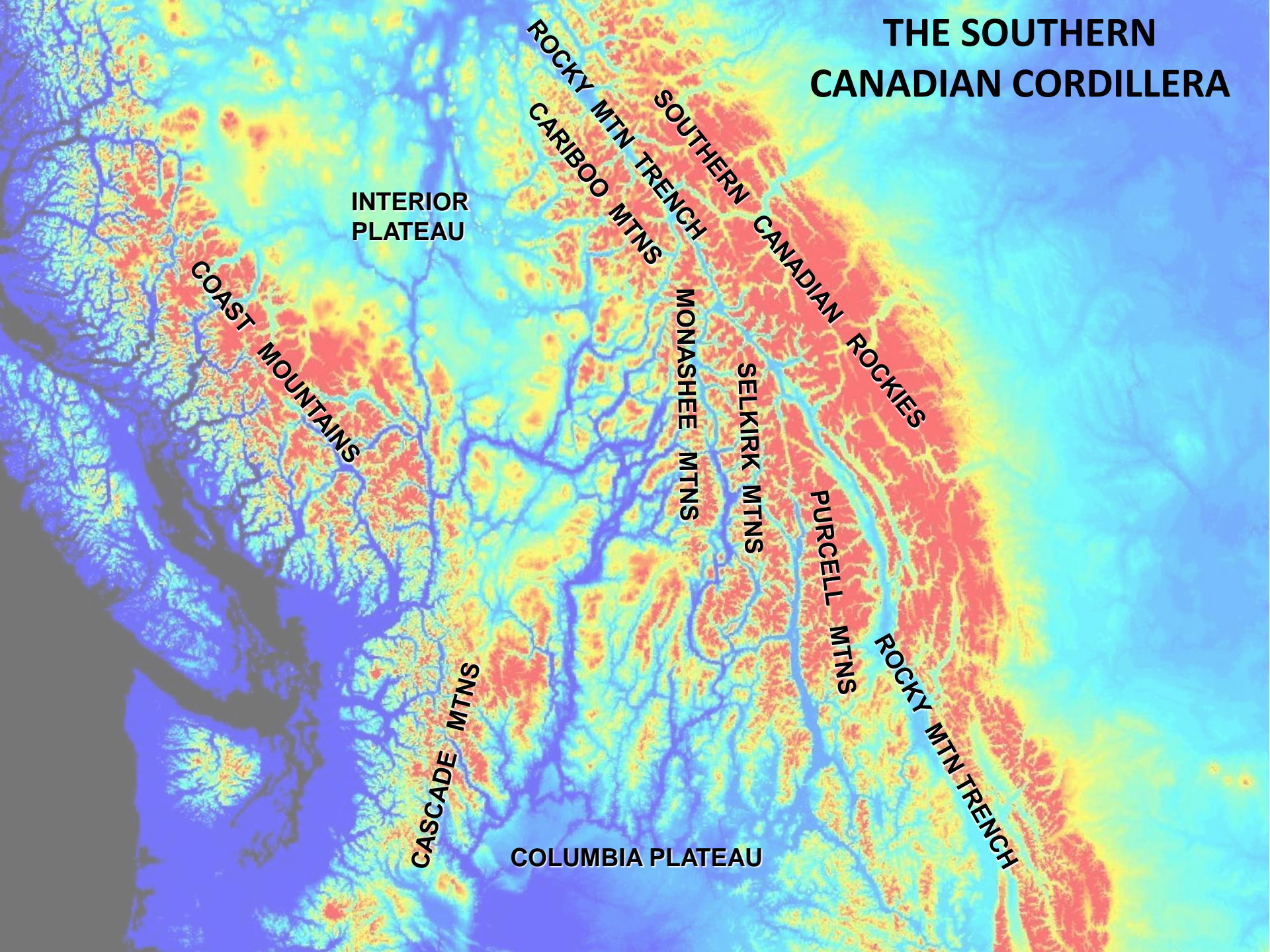
CARIBOO MTNS

INTERIOR
PLATEAU

COAST MOUNTAINS

MONASHEE MTNS

SELKIRK MTNS

PURCELL MTNS

ROCKY MTN TRENCH

CASCADE MTNS

COLUMBIA PLATEAU
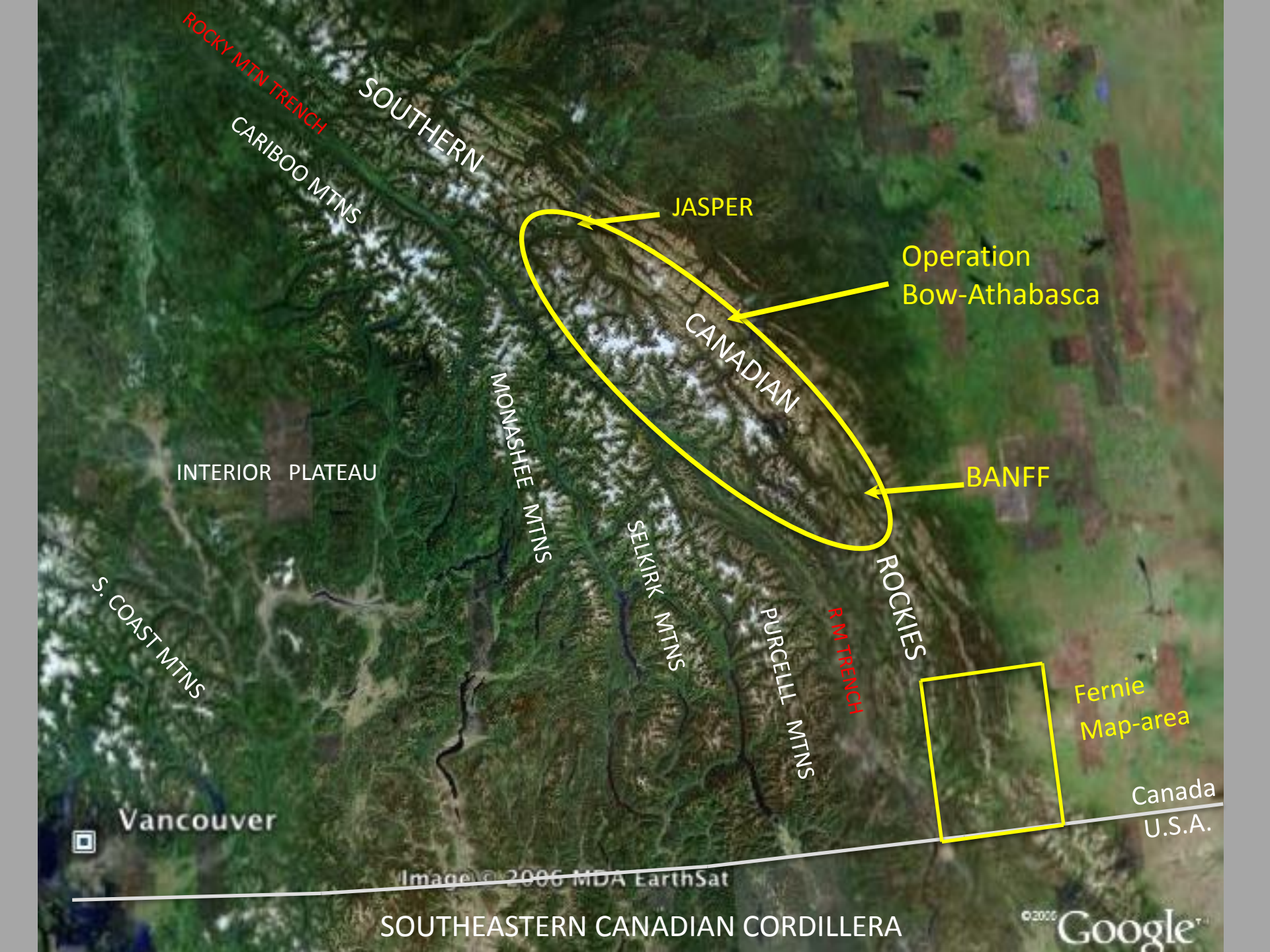
ROCKY MTN TRENCH

SOUTHERN

CARIBOO MTNS

JASPER

Operation
Bow-Athabasca

CANADIAN

MONASHEE MTNS

INTERIOR PLATEAU

BANFF

SELKIRK MTNS

ROCKIES

R M TRENCH

PURCELL MTNS

S. COAST MTNS

Fernie
Map-area

Vancouver

Canada
U.S.A.

Image © 2006 MDA EarthSat

SOUTHEASTERN CANADIAN CORDILLERA

©2006 Google

THREE OF MY MID-TWENTIETH CENTURY GEOTECTONICS HEROES

S. Warren Carey, 1962: "Scale of Geotectonic Phenomena", Jour. Geol. Soc., India

"**Our thinking in tectonics and structural geology is done with models.**" The importance of gravity increases with the size of tectonic features.

Harry H. Hess, 1960: "Evolution of Ocean Basins". U.S. ONR report; 1962: "History of Ocean Basins", GSA book Honoring A.F. Buddington, Engel et al. eds.

Oceanic crust, created by gravity-driven, symmetrically divergent buoyant upward flow of hot mantle, is continuously re-cycled through the mantle by gravity-driven colder mantle asymmetrically sinking at oceanic trenches. Mountain building occurs above above sinking crust. Ocean basins are ephemeral.

Walter H. Bucher, 1956: "Role of Gravity in Orogenesis" (GSA Presidential Address), GSA Bulletin, Oct, 1956
(This was the first issue that I received after joining the GSA.)

Lateral gravitational spreading observed in analogue models of orogenic belts (and in ice sheets) provides a conceptual model for the elucidation of foreland thrust-and-fold belts.

THE SOUTHERN CANADIAN CORDILLERA

ACCRETED TERRANES | **NORTH AMERICAN ROCKS**

MIOGEOCLINE

Upper Devonian - Carboniferous
Fairholme, Palliser, Banff, and Rundle

Middle Cambrian - mid-Devonian
(shale ← carbonate)
(West)   (East)

Lower Cambrian
Hamill & Gog Groups
(sandstone)

Neoproterozoic
Windermere Supergroup
RIFT BASIN

Mesoproterozoic
Belt-Purcell Supergroup
RIFT BASIN

NORMAL FAULT
STRIKE-SLIP FAULT
THRUST FAULT
EASTERN EDGE OF ACCRETED TERRANES
(AN EARLY MESOZOIC TECTONIC SUTURE SEPARATING UNDERLYING NORTH AMERICAN ROCKS FROM OVERLYING SLIDE MTN. & QUESNEL TERRANES)

0   50   100   150
km
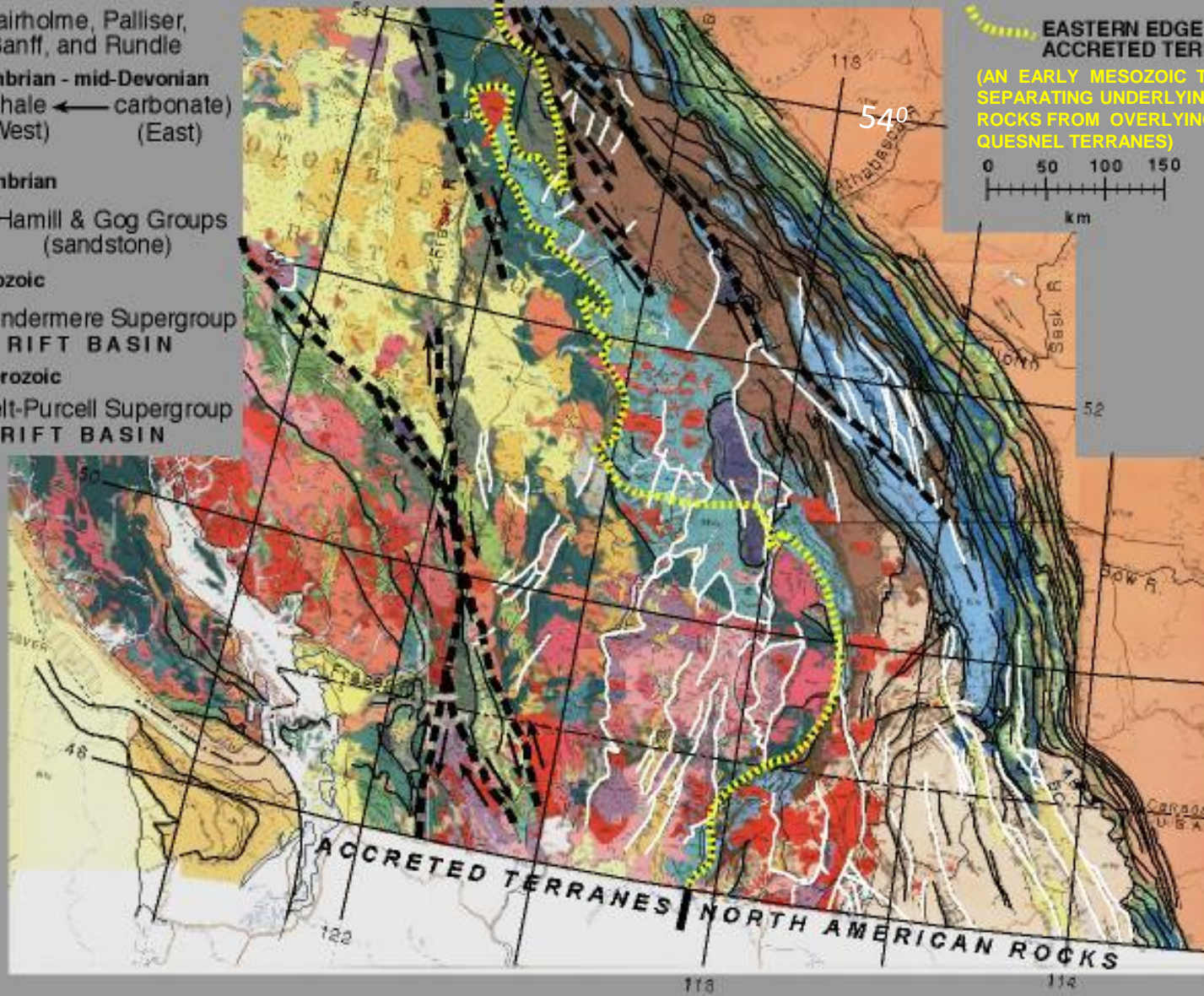
Canada
U.S.A.

Tectonostratigraphic Assemblage Map (Wheeler & McFeely, 1991 - GSC Map 1712A)

Tectonic domains in Paleoproterozoic basement after G.M. Ross et al., 1991, CJES v28, n 4.

TOTAL RESIDUAL MAGNETIC FIELD WITH ALL FAULTS

— NORMAL FAULT

⇒ STRIKE-SLIP FAULT

— THRUST FAULT

⟝⟝⟝ EASTERN EDGE OF ACCRETED TERRANES

Magnetic field data from Geological Survey of Canada
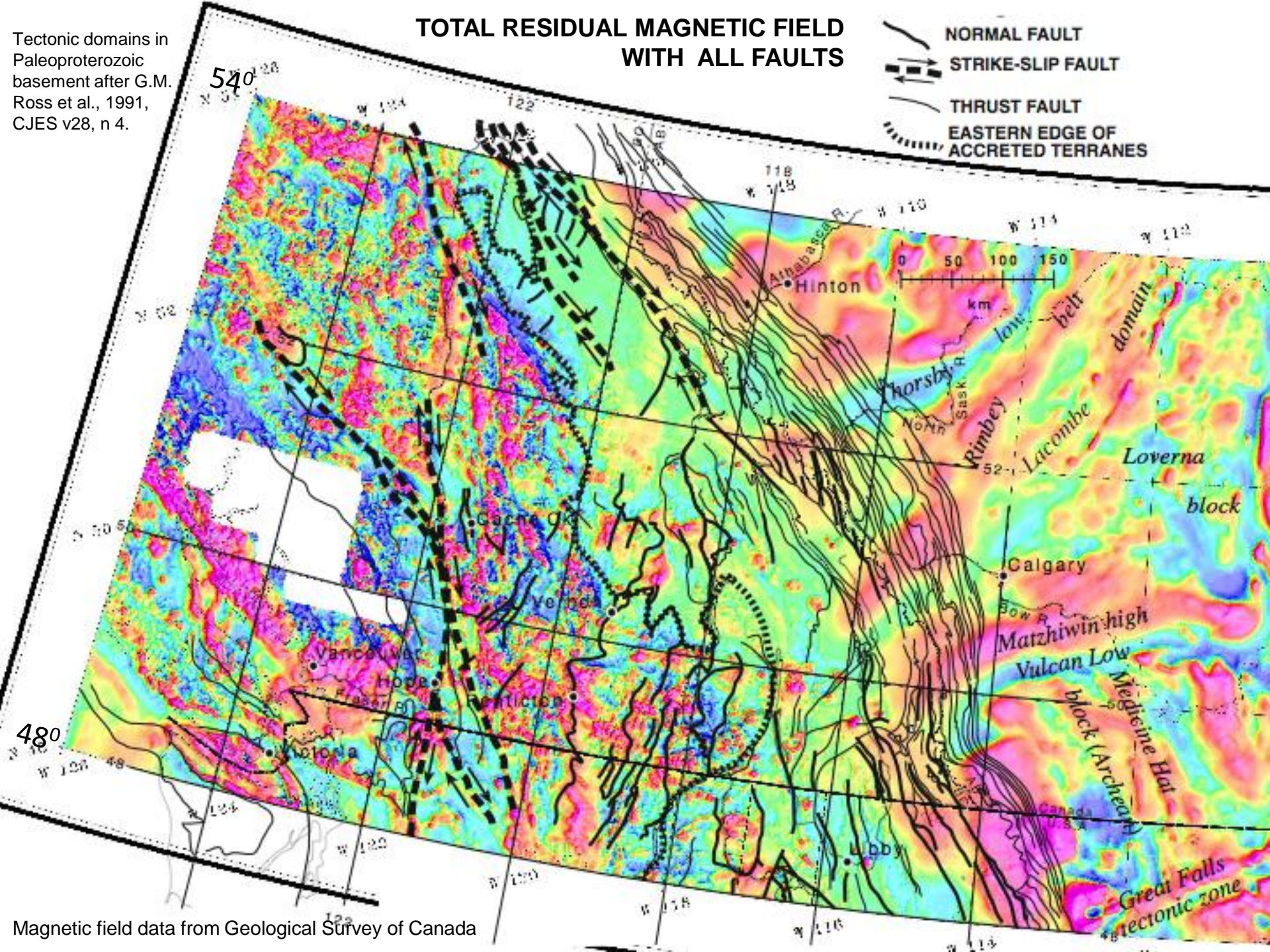
BUCHER'S 1956 LATERAL GRAVITATIONAL SPREADING MODEL

CLEAR 'STITCHING WAX'

clear wax

23°

LAYERS OF 'STITCHING WAX' AND GREASE

Structure produced by solid flow in layers of stitching wax with layers of grease, due to lateral spreading of a block of clear stitching wax (after Bucher, 1956, plate 1, figure 1.)
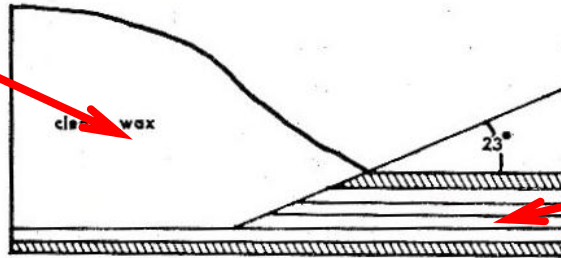
initial configuration
INITIAL CONFIGURATION

clear wax
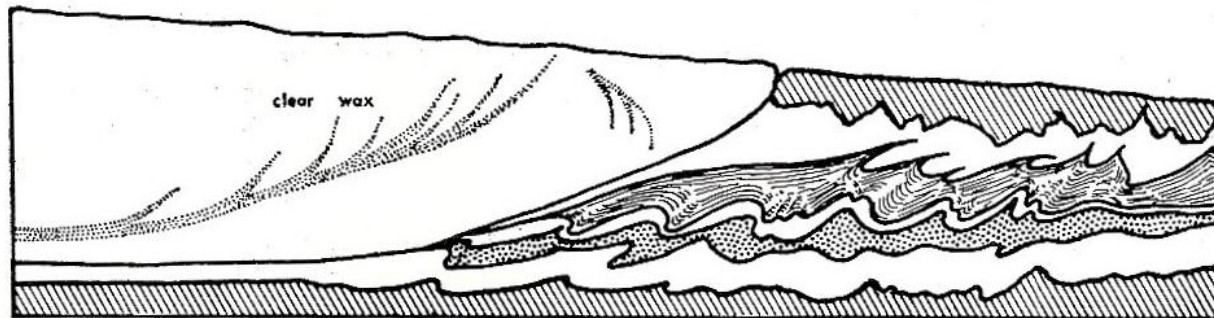
FIGURE 5 — The transition from extending flow to compressing flow in lateral gravitational spreading.

FINAL CONFIGURATION

24th IGC, 1972 — SECTION 3   549

From Price, 1972, Proc. 24th IGC (after Bucher, 1956, GSA Bulletin v.67, n.10 -- GSA presidential address)

BUCHER'S 1956 LATERAL GRAVITATIONAL SPREADING MODEL

INVOLVES CONCURRENT SIDE-BY-SIDE EXTENDING FLOW AND COMPRESSING FLOW

clear wax

23°
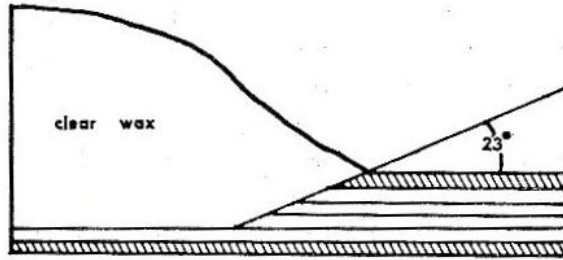
initial configuration

Structure produced by solid flow in layers of stitching wax with layers of grease, due to lateral spreading of a block of clear stitching wax (after Bucher, 1956, plate 1, figure 1.)

EXTENSION IN THE DIRECTION OF FLOW

COMPRESSION IN THE DIRECTION OF FLOW
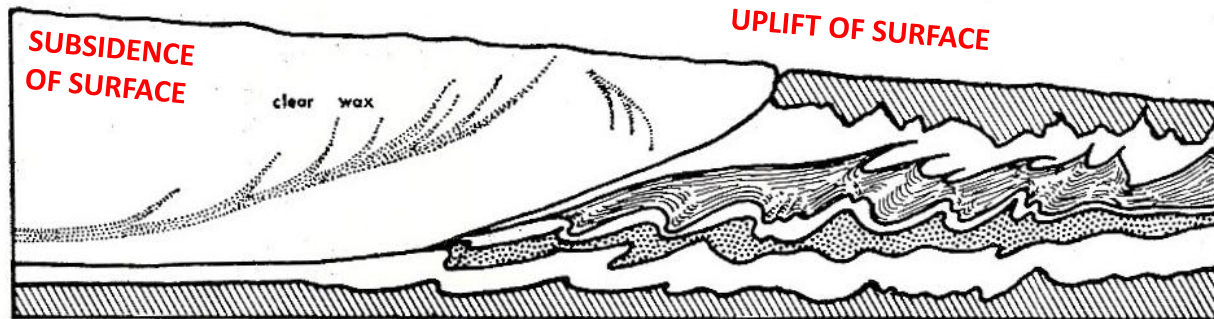
UPLIFT OF SURFACE

SUBSIDENCE OF SURFACE

clear wax

FIGURE 5 — The transition from extending flow to compressing flow in lateral gravitational spreading.

From Price, 1972, Proc. 24th IGC (after Bucher, 1956, GSA Bulletin v.67, n.10 -- GSA presidential address)

THE SIMPLE SHEAR CONCEPTUAL MODEL
(NO DISTORTION IN THE DIRECTION OF DISPLACEMENT)

IS THE MOST POPULAR CONCEPTUAL MODEL FOR FLOW IN ROCKS.

FOR EXAMPLE, IT IS COMMONLY USED IN THE ANALYSIS OF CHANNEL FLOW

(as illustrated below by Godin et al., 2006, Geol. Soc. London, SP #268)
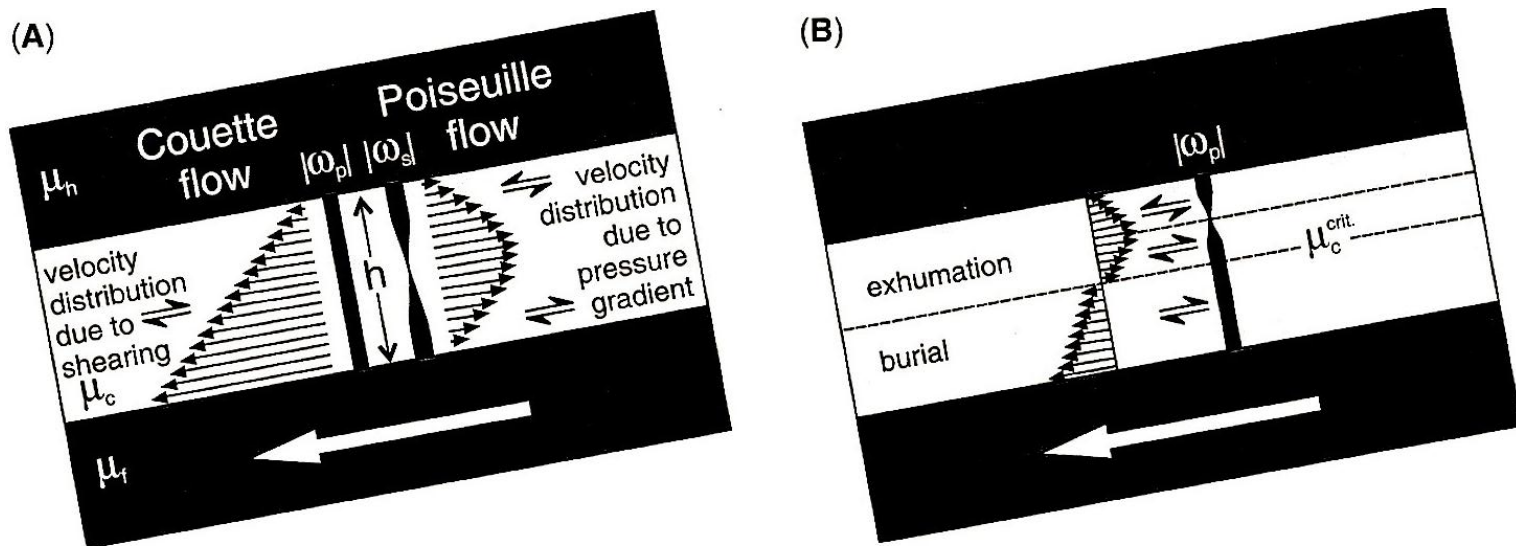
Figure 2 in "Channel Flow….An Introduction", GODIN, et al., 2006, GEOL. SOC. LONDON, S.P. #268

BUT SIMPLE SHEAR IS A SPECIAL CONDITION AT THE BOUNDARY BETWEEN:
1.) EXTENDING FLOW (EXTENSION IN THE DIRECTION OF FLOW) AND
2.) COMPRESSING FLOW (COMPRESSION ON THE DIRECTION OF FLOW)

NB   BECAUSE MATERIAL FLOWS ACROSS THIS BOUNDARY, IT IS DIACHRONOUS

EXTENDING FLOW

EXTENSION (STRETCHING) IN THE DIRECTION OF FLOW
FLOW LINES CONVERGE IN THE DIRECTION OF FLOW
DISPLACEMENT INCREASES IN THE DIRECTION OF FLOW
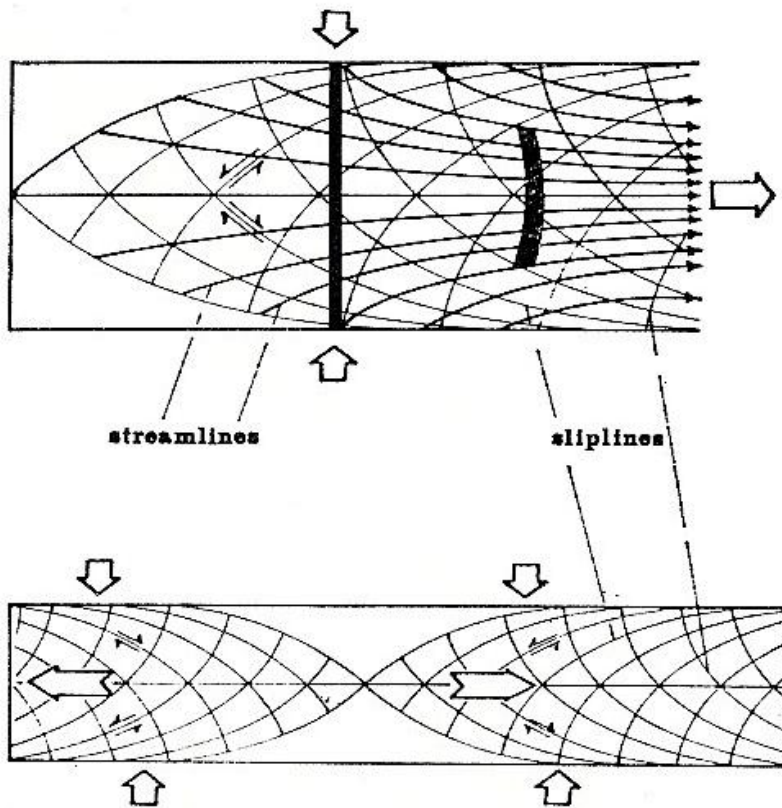
FIGURE 1 — (left) — Prandtl compressed cell (after Kanizay, 1962) for extending flow.

streamlines   sliplines
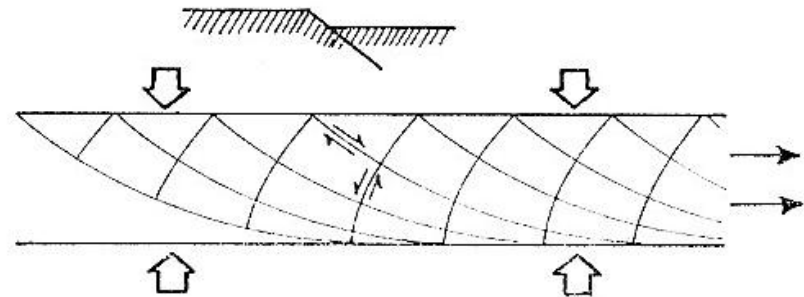
FIGURE 2 — Slip-line field for extending flow and normal faulting (active Rankine state of plastic equilibrium).

From Price: -

24th IGC, 1972 — SECTION 3   547

EXTENDING FLOW

BOUDINAGE WITH EXCISION OF AMPHIBOLITE LAYERS IN MIGMATITIC PARAGNEISS – Shuswap Metamorphic Complex, Three Valley Lake, B.C.

COMPRESSING FLOW

COMPRESSSION (SHORTENING) IN THE DIRECTION OF FLOW
DISPLACEMENT DECREASES IN THE DIRECTION OF FLOW
FLOW LINES DIVERGE IN THE DIRECTION OF FLOW

streamlines   sliplines
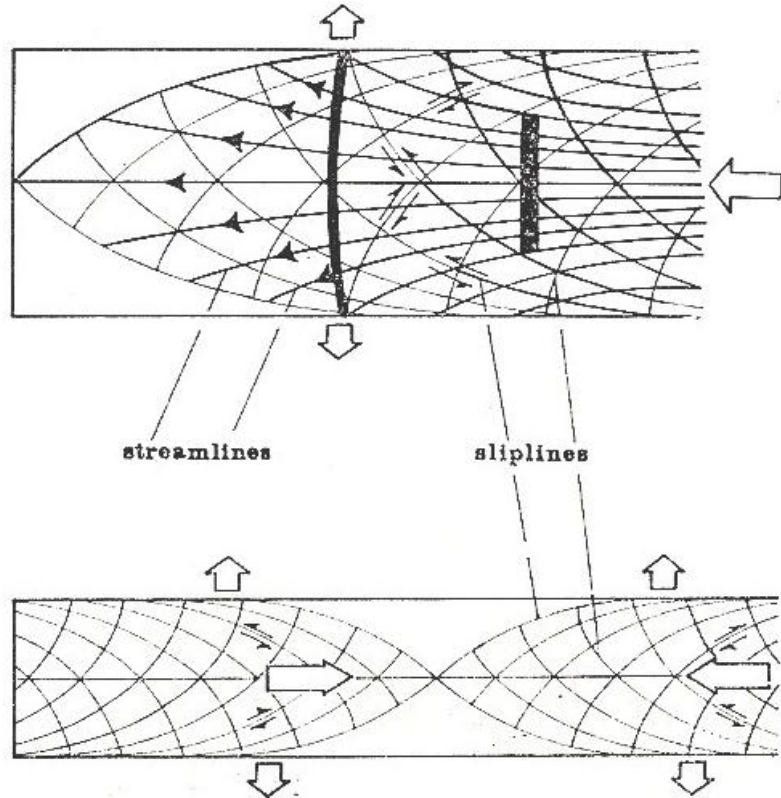
FIGURE 3 — (left) — Modification of Prandtl cell (after Kanizay, 1967) for compressing flow.
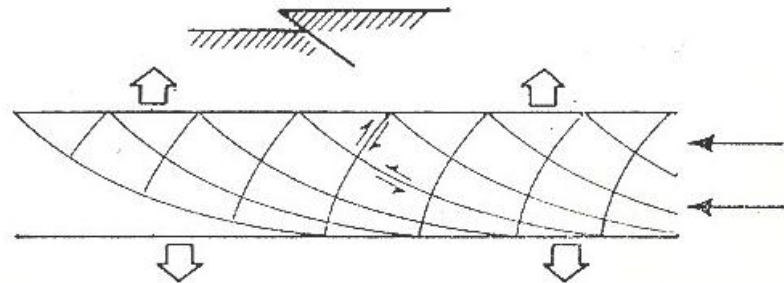
FIGURE 4 — Slip-line field for compressing flow and thrust faulting (passive Rankine state of plastic equilibrium).

548

From Price: -   24th IGC, 1972 — SECTION 3

COMPRESSING FLOW -- ALL THRUSTS DIE OUT ALONG STRIKE. DISPLACEMENT (SLIP) WAS DISTRIBUTED AMONG A MYRIAD ARRAY OF DISCRETE DISPLACEMENT DISCONTINUITIES ALL OF WHICH ARE EMBEDDED WITHIN A COHERENT ROCK MASS THAT HAS **FLOWED** NORTHEASTWARD.

Fissure Veins

Contraction Fault

Stylolitic Joints

Slickensided Bedding

Extension Faults

"Shear Joints"
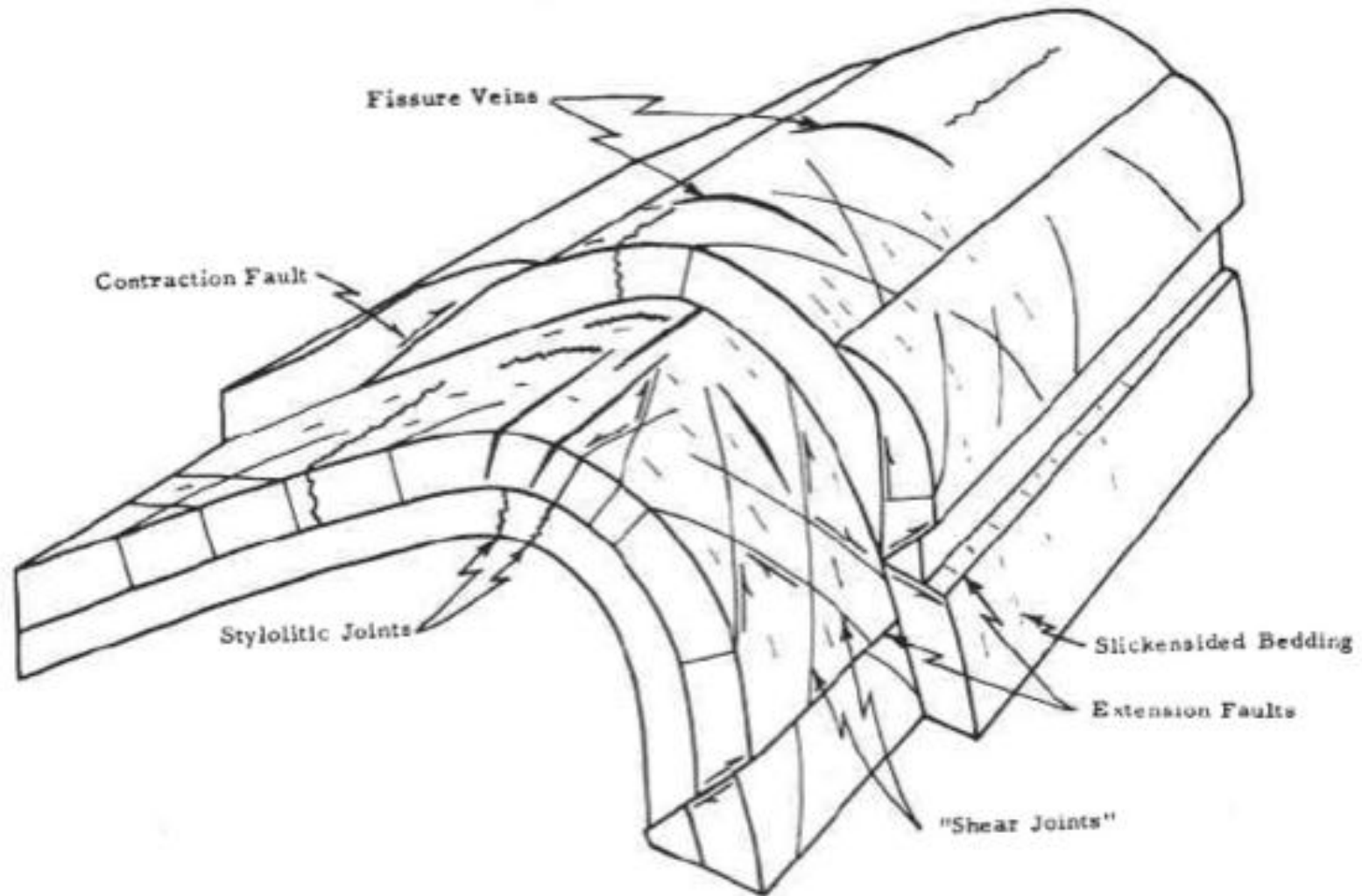
an outcrop-scale *CONCEPTUAL MODEL*
"CATACLASTIC DUCTILE DEFORMATION (FLOW) DURING FLEXURE OF SEDIMENTARY STRATA"

DISTORTION OF FOLDED STRATA IS ACCOMODATED BY INTERSTRATAL SLIP, SLIP ON JOINTS AND SMALL CONTRACTION AND/OR EXTENSION FAULTS, AND BY OPENING OF FISSURE VEINS AND CLOSING OF STYLOLITES BETWEEN BLOCKS OF SEDIMENTARY ROCK THAT ARE EFFECTIVELY UNSTRAINED.
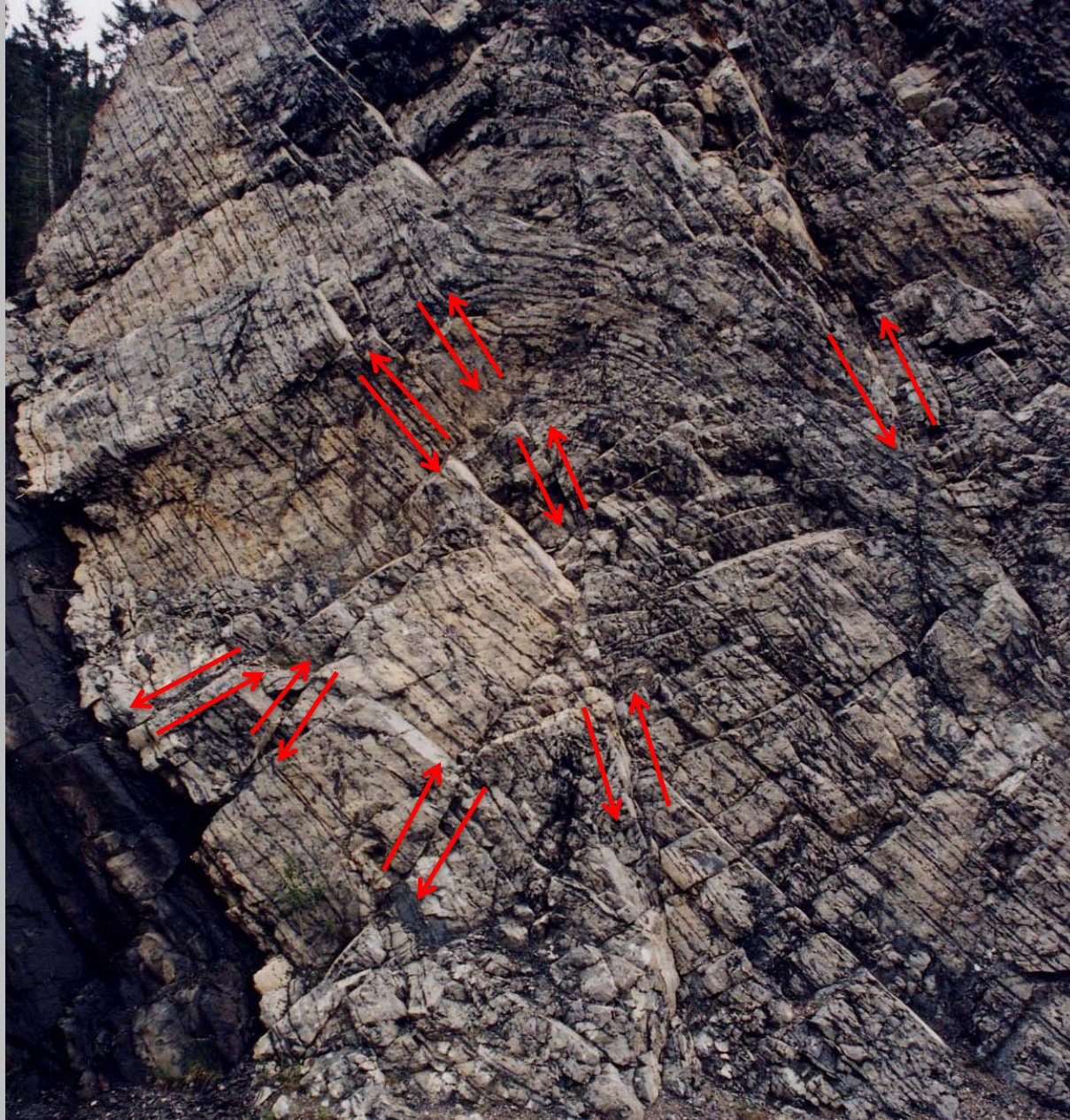
EXTENSION FAULTS (EXTENSION = GAP) INTERSECT BEDDING AT >60 degrees.
CONTRACTION FAULTS (COMPRESSION = OVERLAP) INTERSECT BEDDING AT ~30 degrees
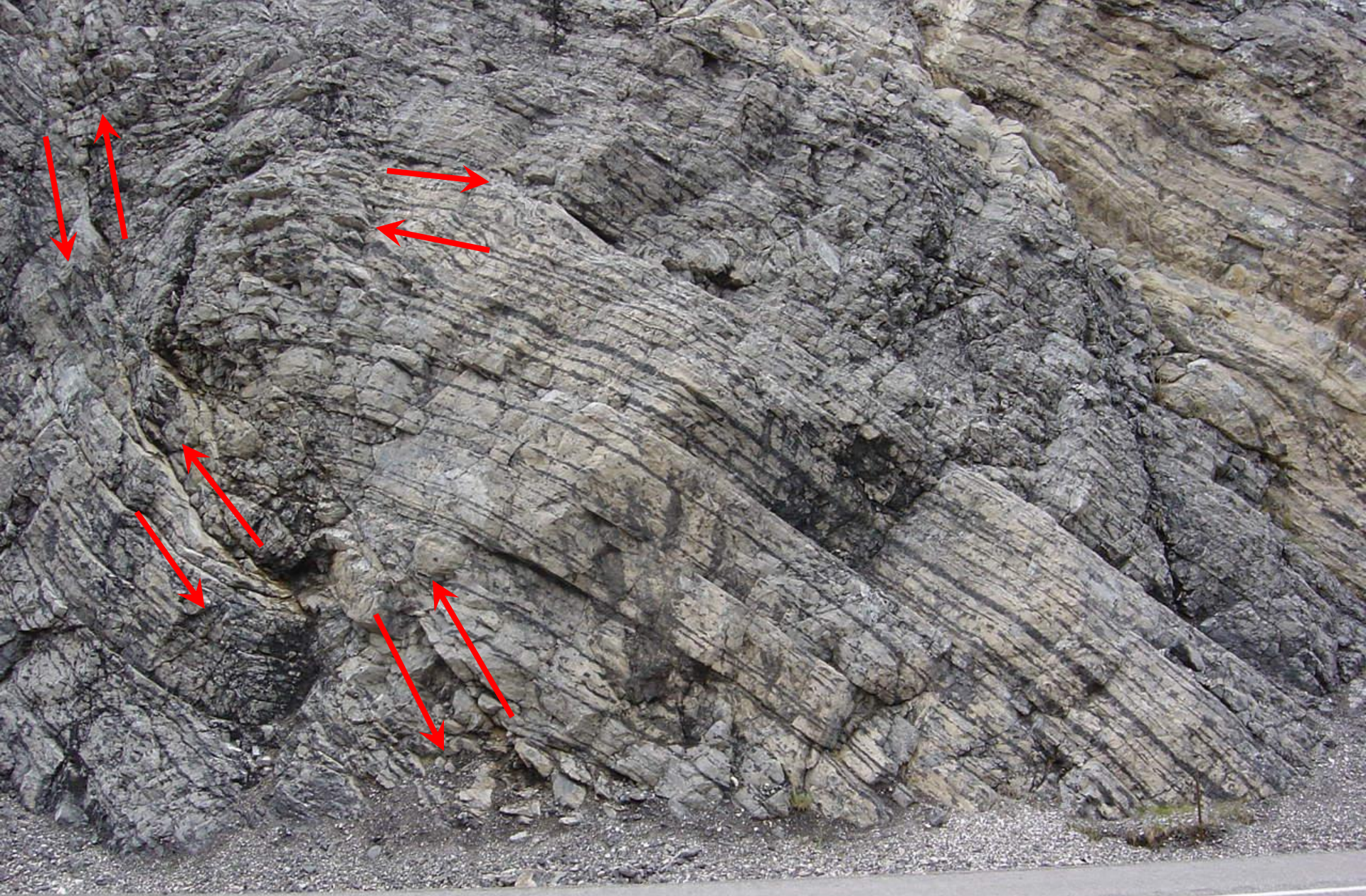
COMPRESSING FLOW --- SYNTHETIC AND ANTITHETIC CONTRACTION FAULTS ASSOCIATED WITH INTERSTRATAL FLEXURAL SLIP (SHEAR)

**Compressing Flow – Contraction Faults ---
Thrust duplex & Associated Interstratal Shear**

Livingstone range Anticlinorium
SW Alberta Foothills; view north

Livingstone Range

Pointer 49° 43'36.78"N 114° 21'58.91"W   elev 6677 ft   Streaming || || || || || 100%   Eye alt   40991 ft
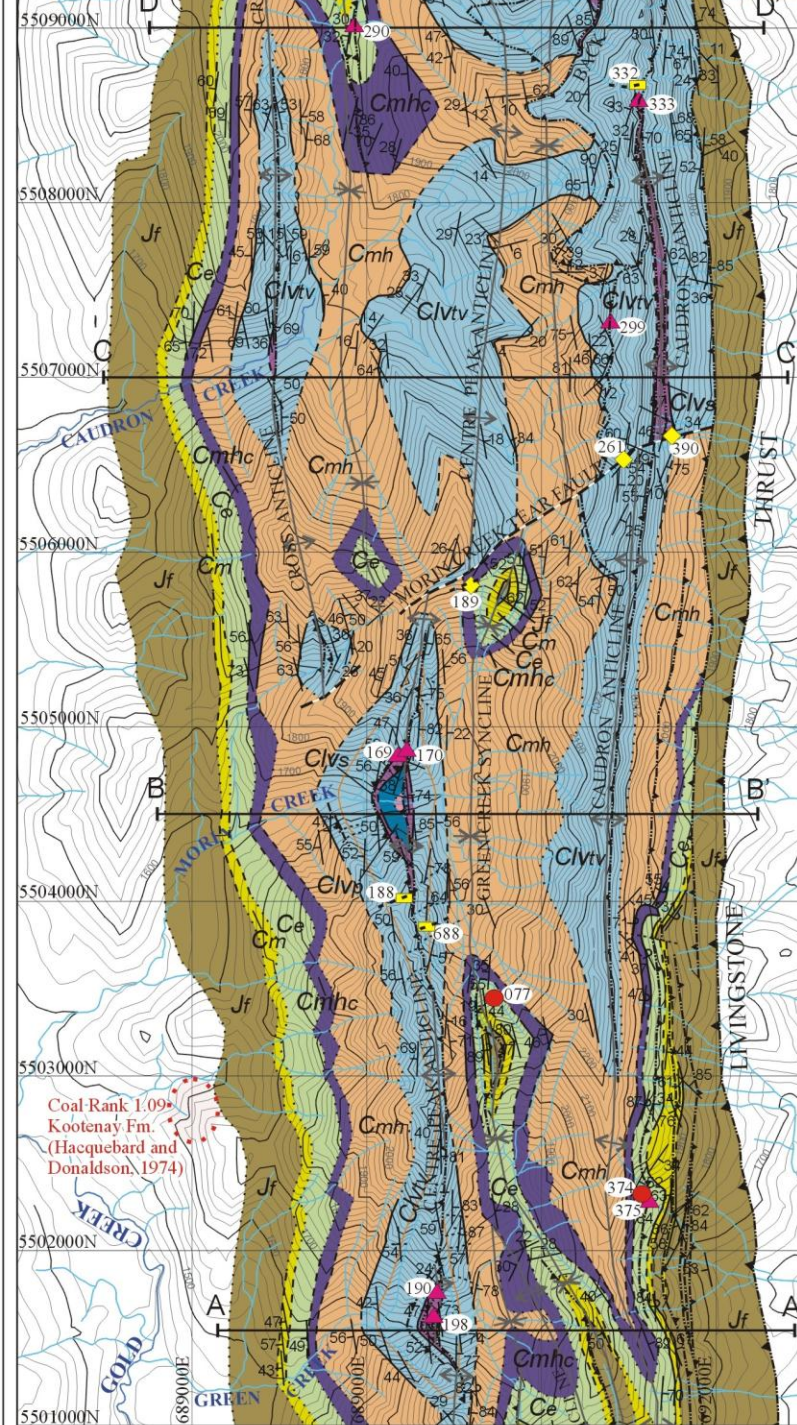
approximate
.... assumed

✳ Syncline

◄─► Anticline

▲─── Thrust Fault

┆┆┆ Transverse, intensely Fractured, Fault Zone

╲50 Bedding (inclined)

╲31 Bedding (overturned)

Geochem Samples

▲ Thrust Fault
☐ Transverse Fault
◆ Tear Fault
● Hydrothermal Vein

Map Units

Jf Fernie Formation shale + sandstone

Cm Misty Formation Arenite sandstone

Ce Etherington Formation dolomite, shale, siltstone and sandstone

Cmhc Mount Head Formation Carnarvon Member Dark grey limestone

Cmh Mount Head Formation undivided dolomite, shale, limestone

Clvtv Livingstone Formation Turner Valley Member crinoid lime packstone

Light brown weathering dolomitic cherty lime-mudstone, ~4m thick

Clvs Livingstone Formation Shunda Member dolomitic micrite + chert

Clvp Livingstone Formation Pekisko Member crinoidal lime grainstone

Cb Banff Formation Silty limestone + chert, siltstone

UTM coordinates in metres
NAD 83 Datum
Elevation in metres above sea level
Contour Interval 20 Metres

Coal Rank 1.09 Kootenay Fm. (Hacquebard and Donaldsson, 1974)

Cross Section 5507000N

Sample 299 projected 340m south

Cross Anticline · Centre Peak Anticline · Cauldron Anticline

Livingstone Fm. · Fernie Fm. · Etherington Fm. · Mt. Head Fm. · Shunda Mbr. · Banff Fm. · Palliser Fm. · Livingstone Thrust

Cross Section 5504500N

Samples 169, 170 projected 335m south

Centre Peak Anticline · Cauldron Anticline

Fernie Fm. · Etherington Fm. · Mt. Head Fm. · Livingstone Fm. · Shunda Mbr. · Banff Fm. · Palliser Fm. · Livingstone Thrust

Cross Section 5501500N

Sample 190 projected 268m south
Sample 198 projected 130m south
Sample 375 projected 853m south

Centre Peak Anticline · Bellevue Anticline · Cauldron Anticline

Fernie Fm. · Etherington Fm. · Misty Mbr. · Mt. Head Fm. · Livingstone Fm. · Shunda Mbr. · Banff Fm. · Palliser Fm. · Livingstone Thrust

View is South

Figure 12 B

EAST

WEST

Cmh

Clvtv

X'
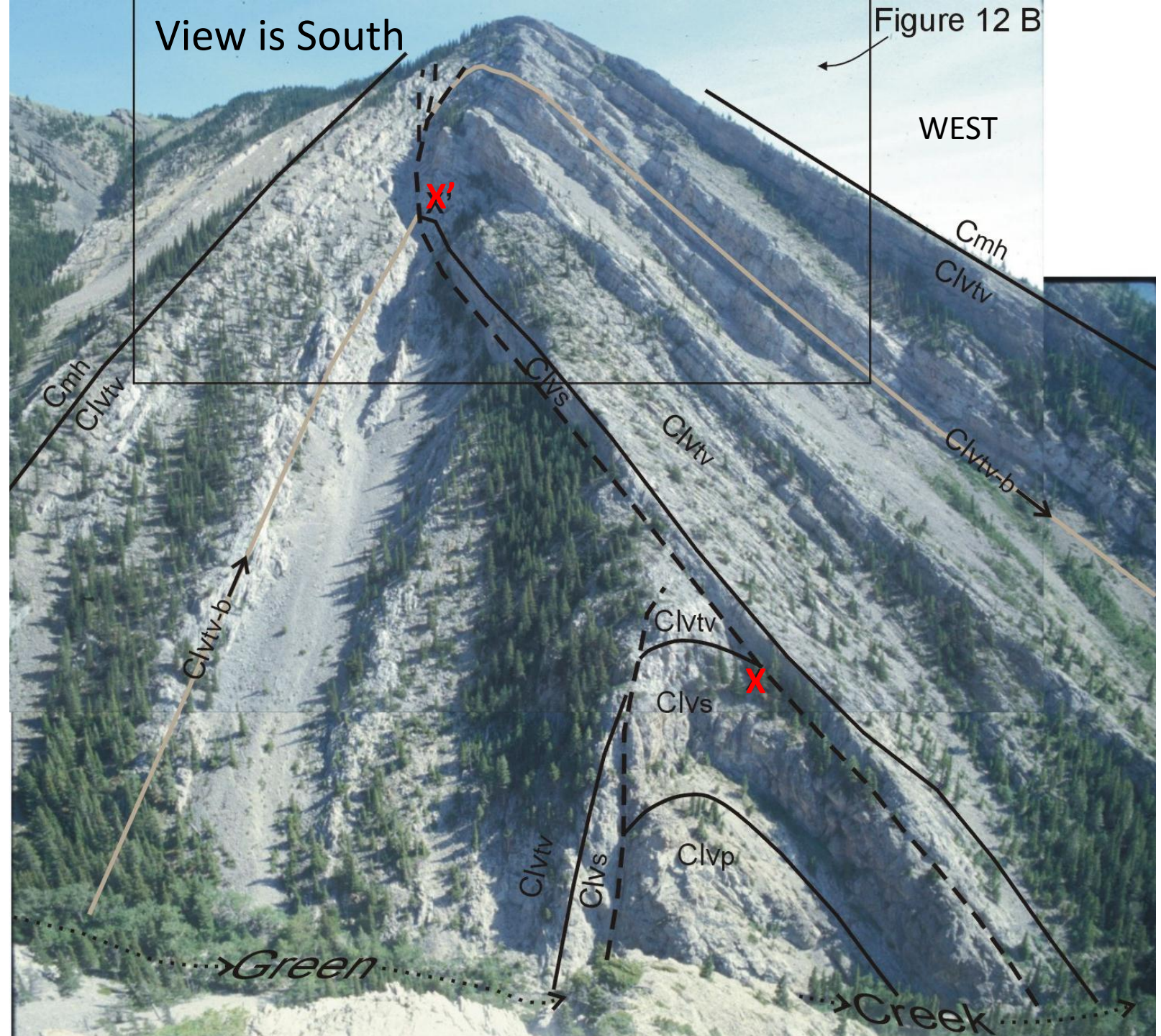
Cmh

Clvtv

Clvs

Clvtv

Clvtv-b

Clvtv-b

Clvtv

Clvs

X

Clvtv

Clvs

Clvp

Green

Creek
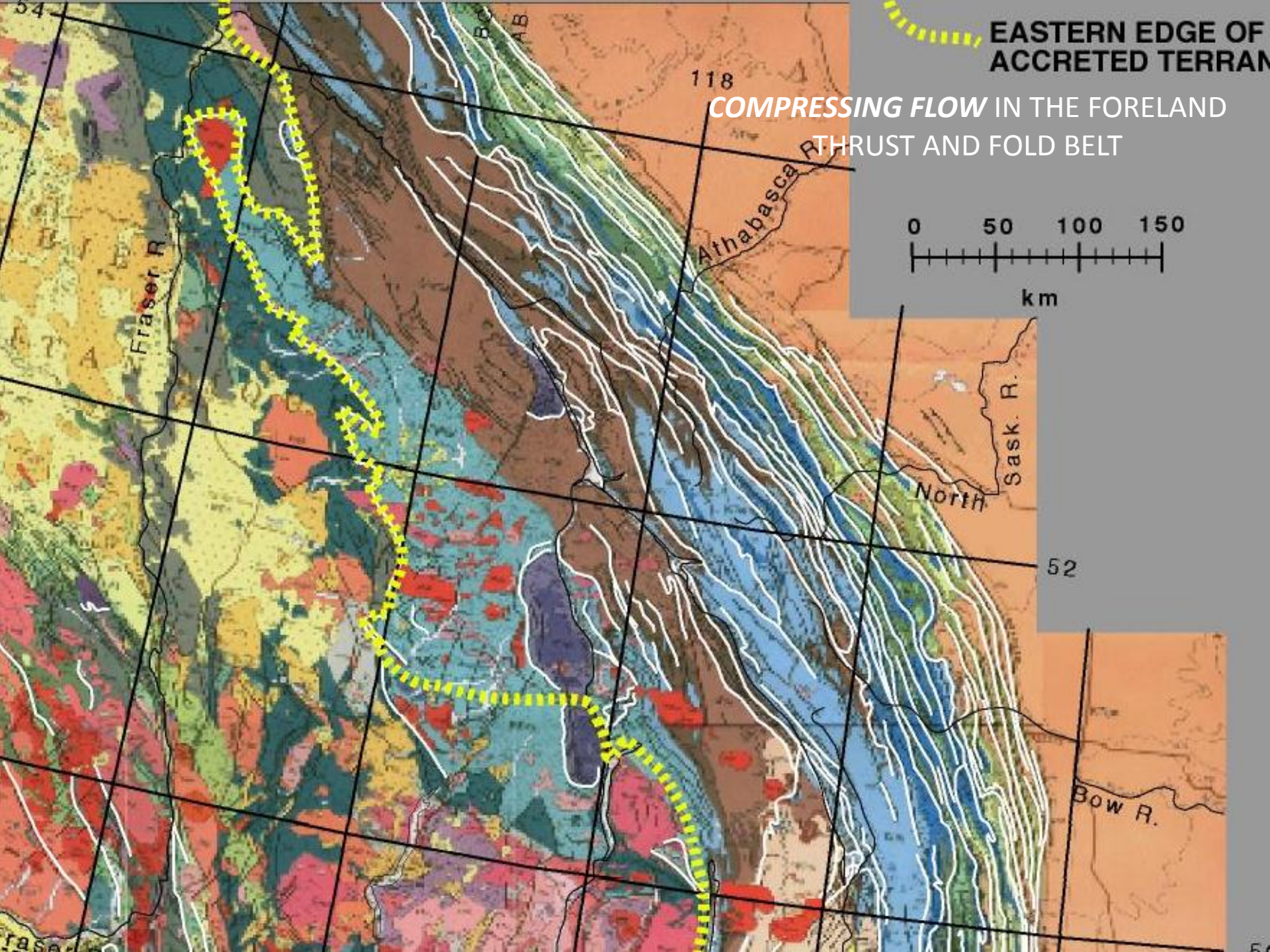
EASTERN EDGE OF
ACCRETED TERRAN[E]

COMPRESSING FLOW IN THE FORELAND
THRUST AND FOLD BELT

COMPRESSING FLOW COMPRISING SLIP DISTRIBUTED AMONG DISCRETE DISPLACEMENT DISCONTINUITIES THAT ARE EMBEDDED WITHIN THE FLOWING ROCK MASS
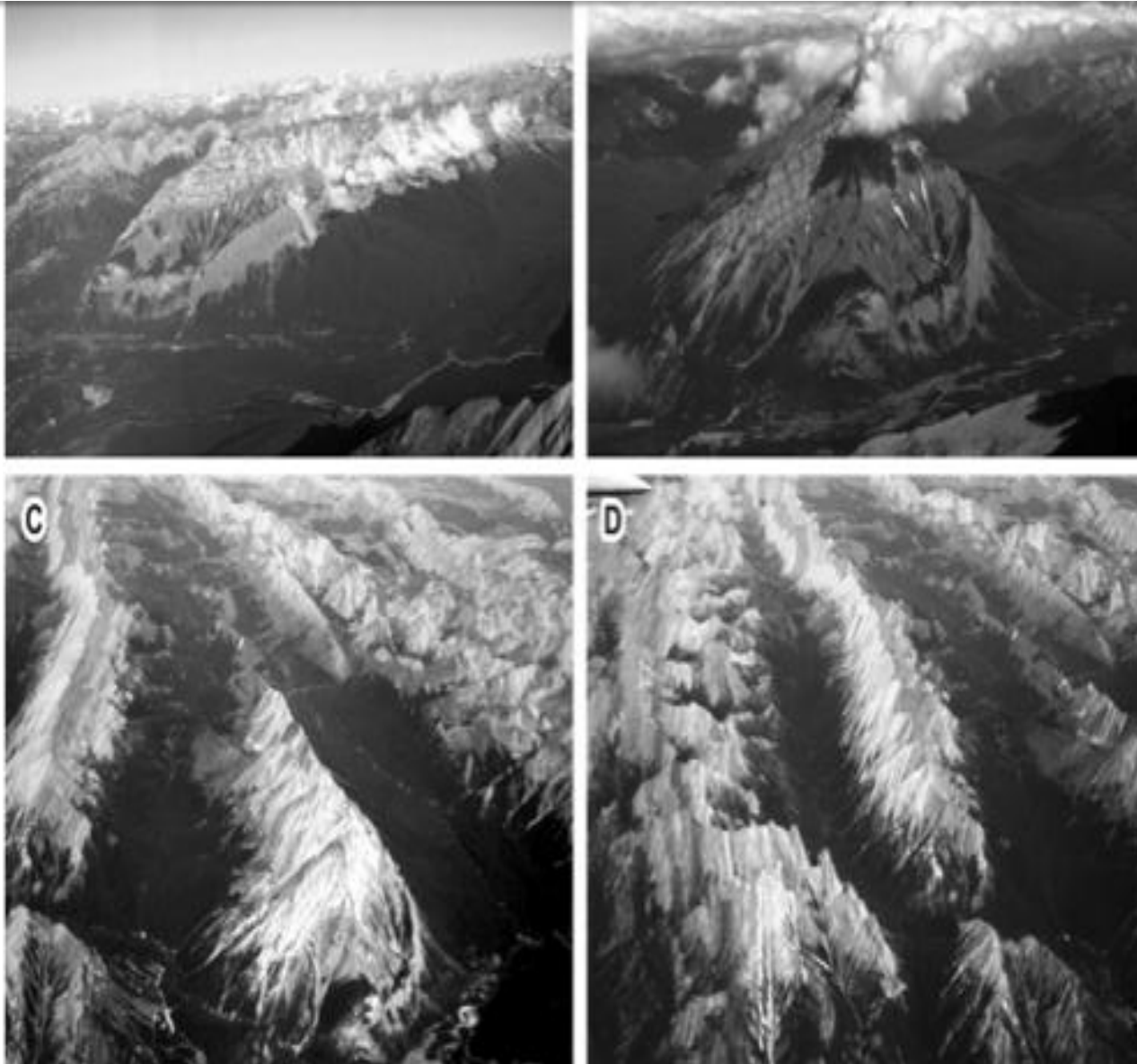
DISCRETE INTER-LEAVED IMBRICATE THRUST FAULTS 'DIE OUT' ALONG STRIKE

Monashee Mtns

Cariboo Mtns

Rocky Mtn trench

Rocky Mountains
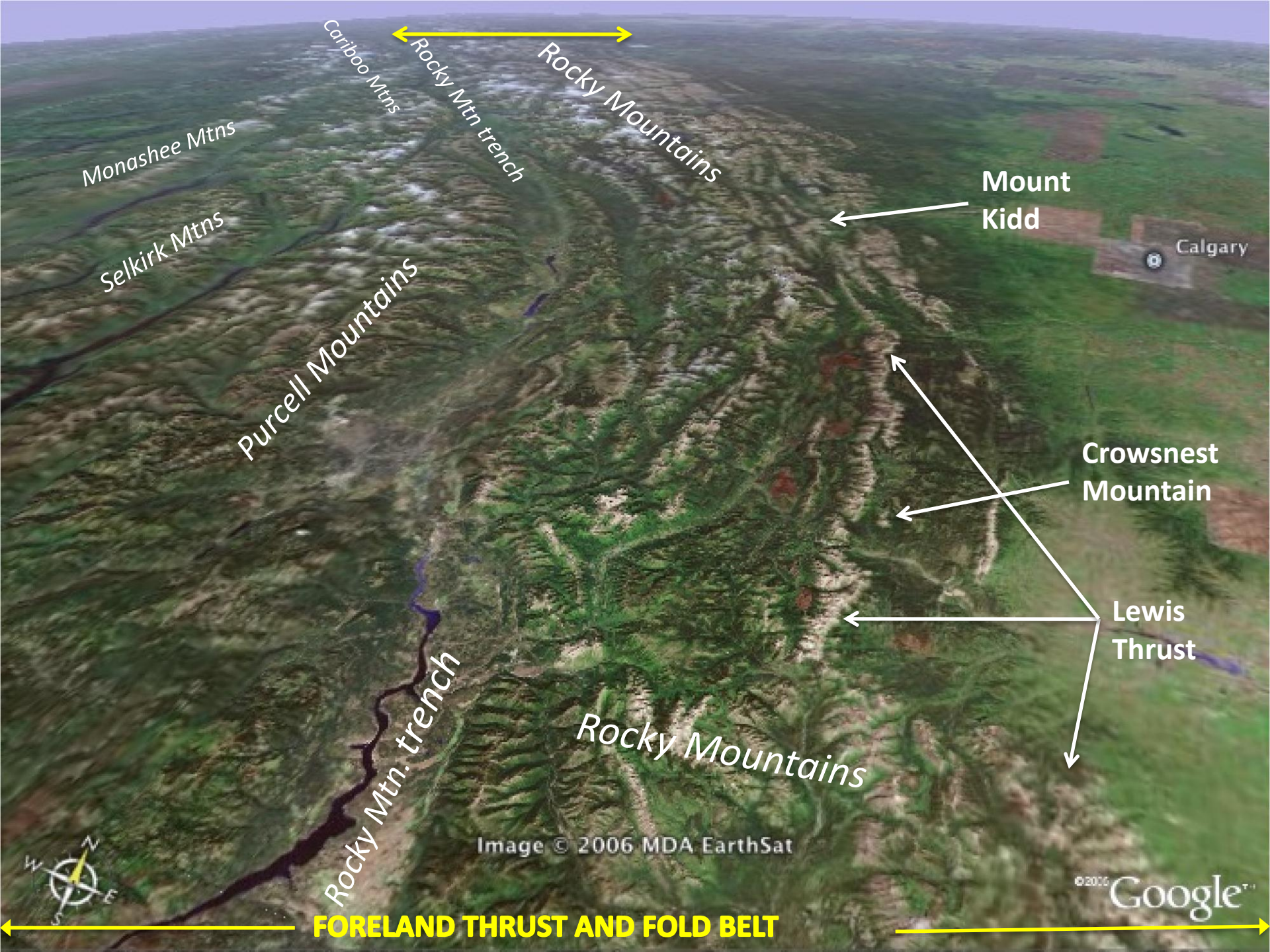
Mount Kidd

Selkirk Mtns

Calgary

Purcell Mountains

Crowsnest Mountain

Lewis Thrust

Rocky Mtn. trench

Rocky Mountains

Image © 2006 MDA EarthSat

©2006 Google™

FORELAND THRUST AND FOLD BELT
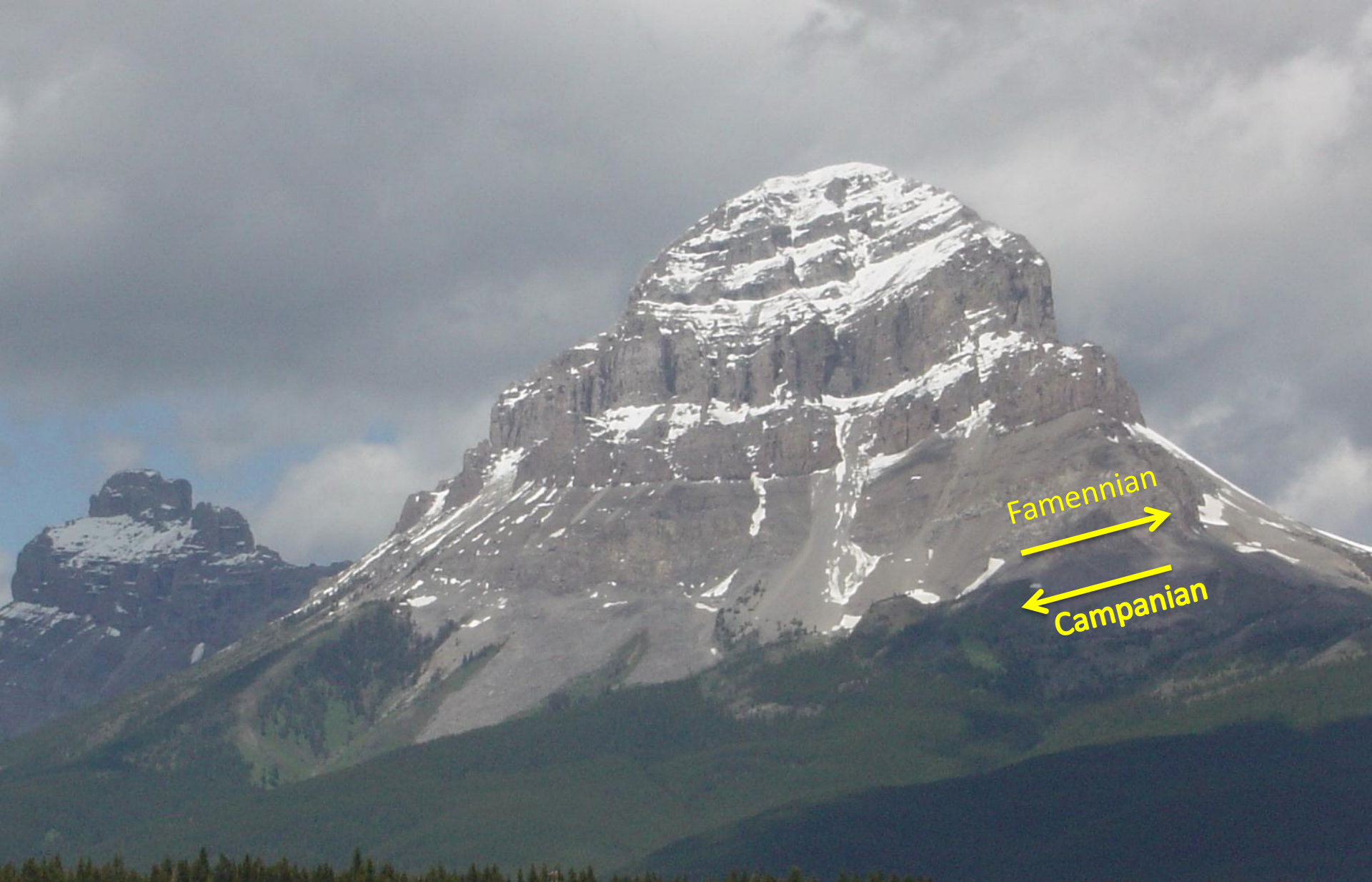
The Lewis Thrust at Crowsnest Mountain

***COMPRESSING FLOW* by thrust-related folding
at the northern tip-line of the Lewis Thrust fault**

MOUNT KIDD

$49^0\,45'$

Calgary

Image © 2006 MDA EarthSat

Google

Pointer 49° 39'13.16"N 115° 07'07.87"W elev 5778 ft   Streaming |||||||||| 100%   Eye alt 61.03 mi

EAST-WEST STRUCTURE SECTION & RESTORED SECTION AT 49^0 45'

THE HORIZONTAL UPPER JURASSSIC SEA-LEVEL DATUM IN THE RESTORED SECTION IS THE CONTACT BETWEEN UPPER JURASSIC MARINE AND NON-MARINE STRATA.
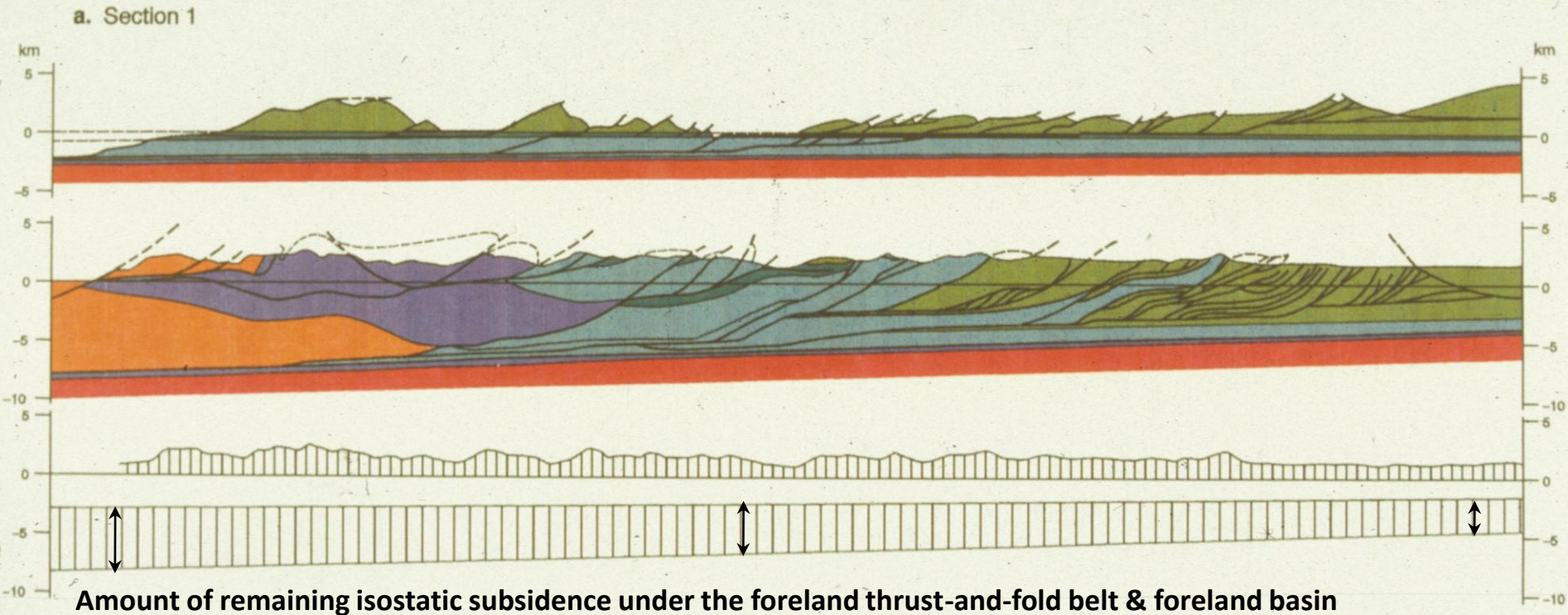
Amount of remaining isostatic subsidence under the foreland thrust-and-fold belt & foreland basin

Undeformed wedge of supracrustal rocks

Supracrustal rocks

Di

Sea level

Undeformed basement
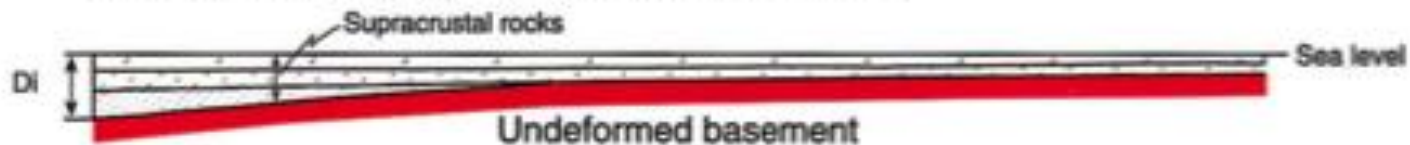
Tectonically thickened supracrustal rocks

Df=Di

Sea level

No isostatic compensation

Thrust and fold belt   Foreland basin   Forebulge

Sea level

Df>Di

Regional isostatic lithospheric flexure

Amount of subsidence,

Df-Di

Sea level

of the basement surface

Sea level

of the foreland basin
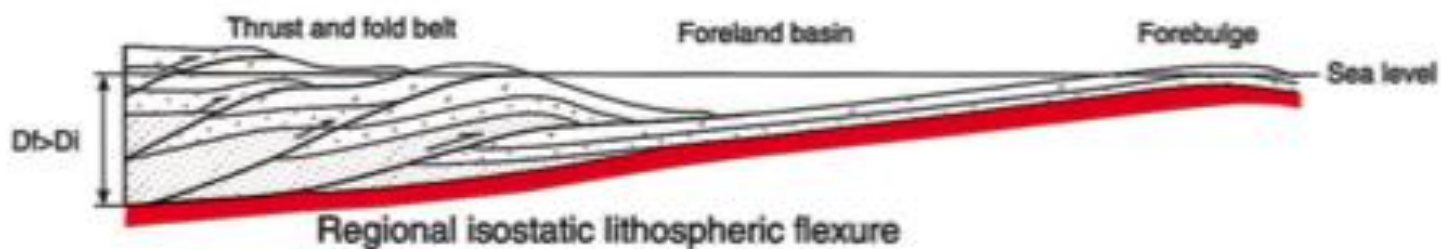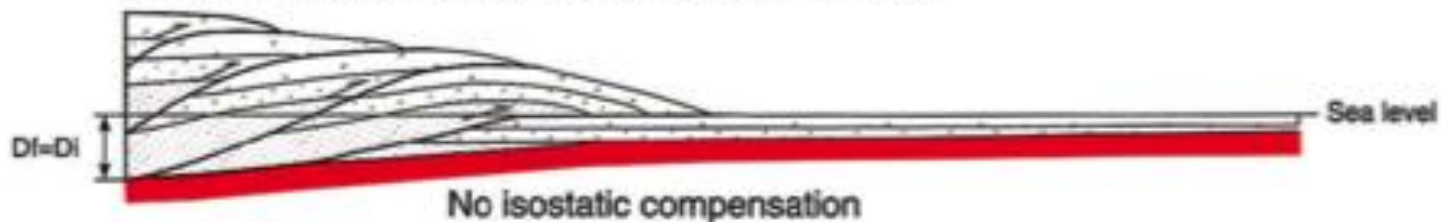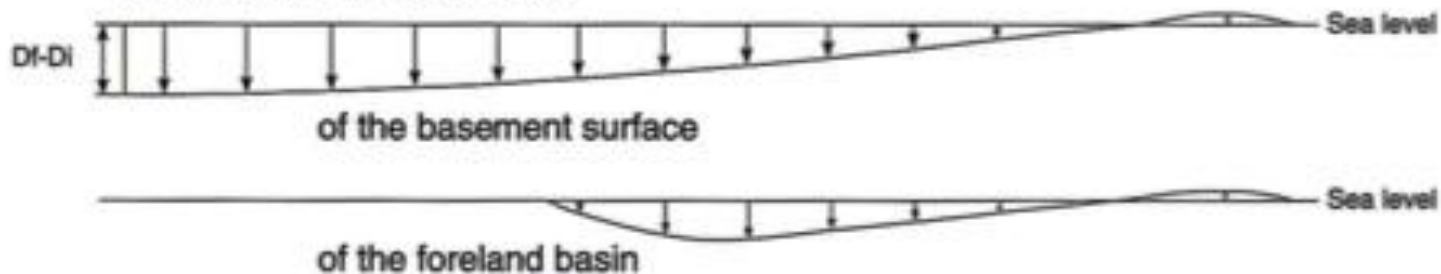
LOCATION OF RESTORED BALANCED STRUCTURE SECTION

Legend:

MIOGEOCLINE

Upper Devonian - Carboniferous
Fairholme, Palliser, Banff, and Rundle

Middle Cambrian - mid-Devonian
(shale ← carbonate)
(West)   (East)

Lower Cambrian
Hamill & Gog Groups (sandstone)

Neoproterozoic
Windermere Supergroup
RIFT BASIN

Mesoproterozoic
Belt-Purcell Supergroup
RIFT BASIN

NORMAL FAULT
STRIKE-SLIP FAULT
THRUST FAULT
EASTERN EDGE OF ACCRETED TERRANES
LINE OF SECTION
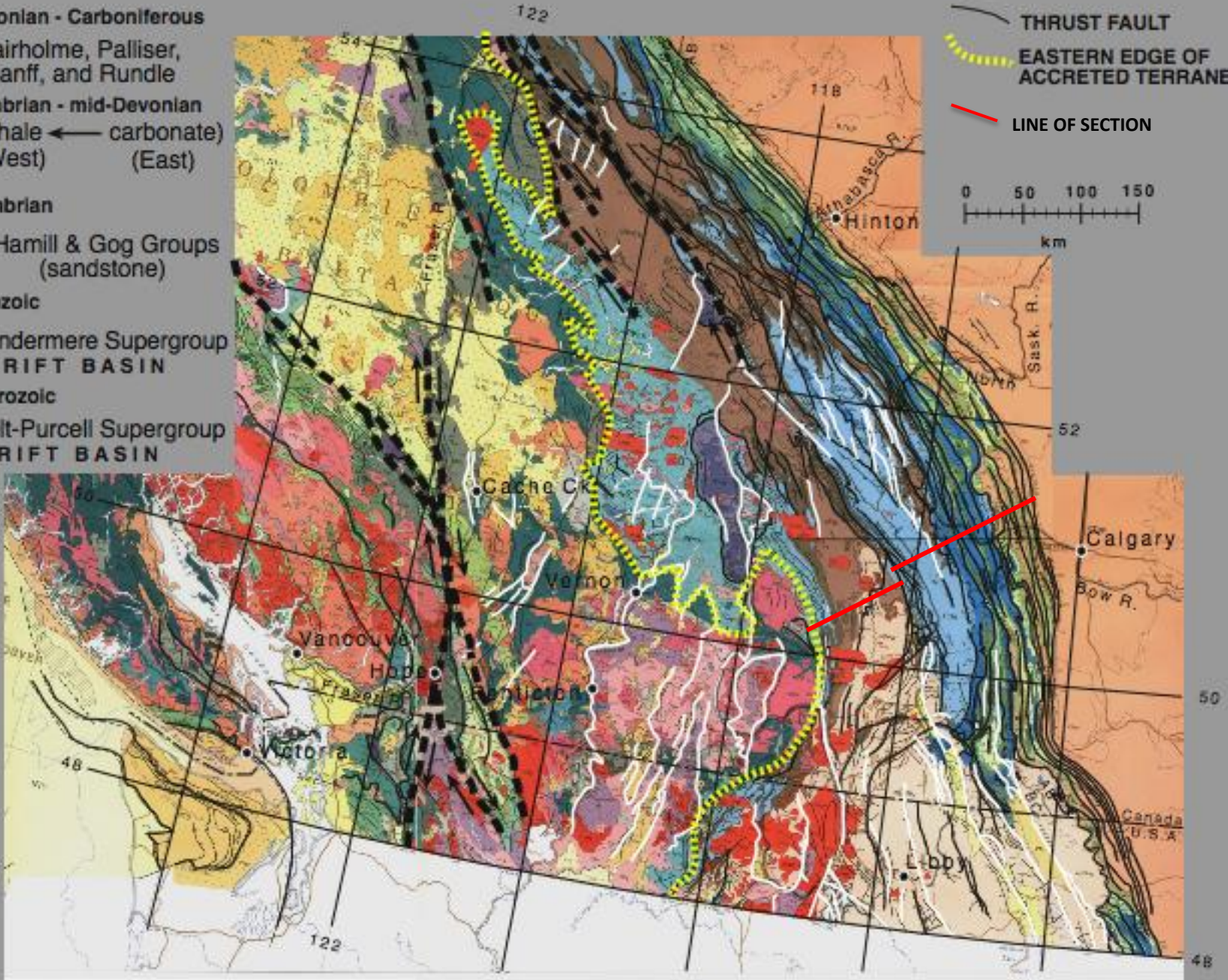
0   50   100   150
km

Section after Price and Fermor, 1985, Geological Survey of Canada Paper 84-14

LEGEND

Jurassic Granite
180 million years

Accreted Terranes

Up...
15...

Up...
38...

Ca...
54...

Ne...
78...

Mo...
15...
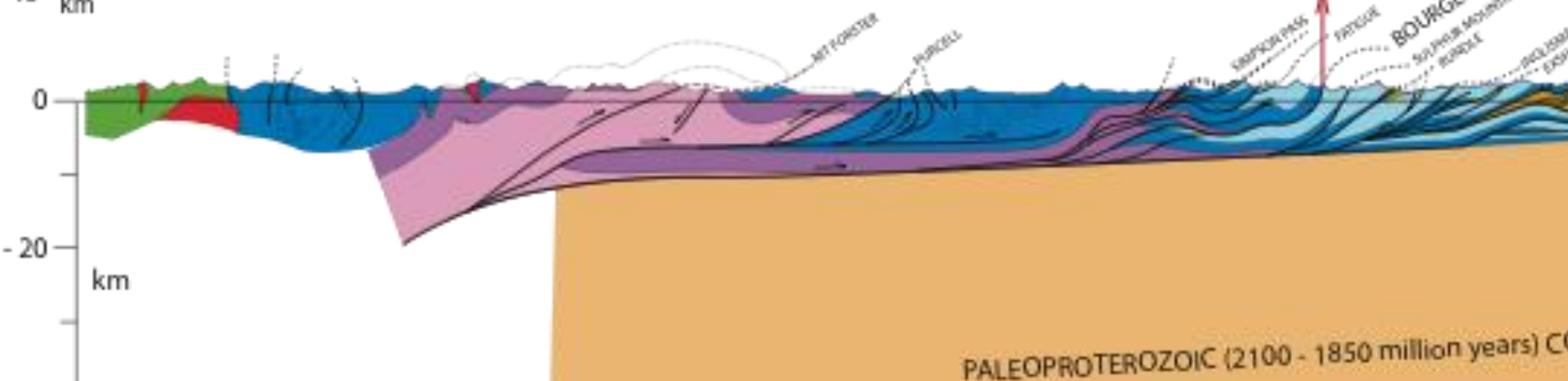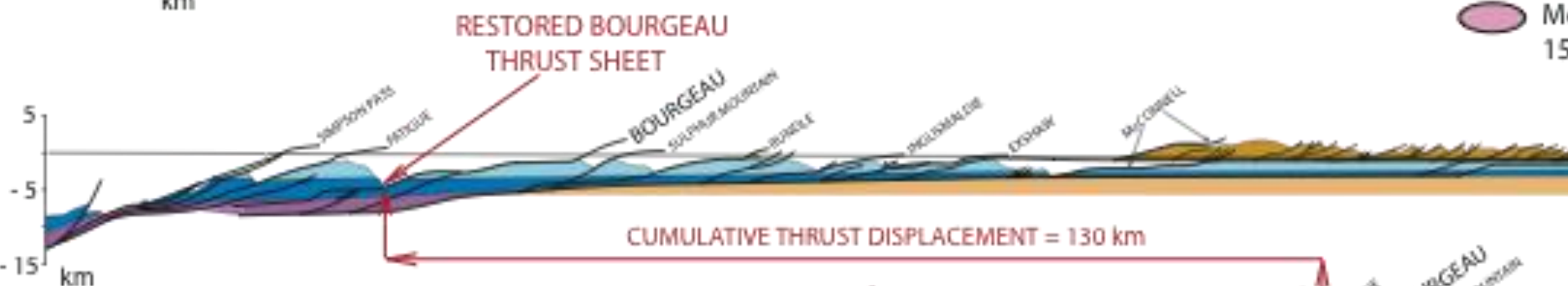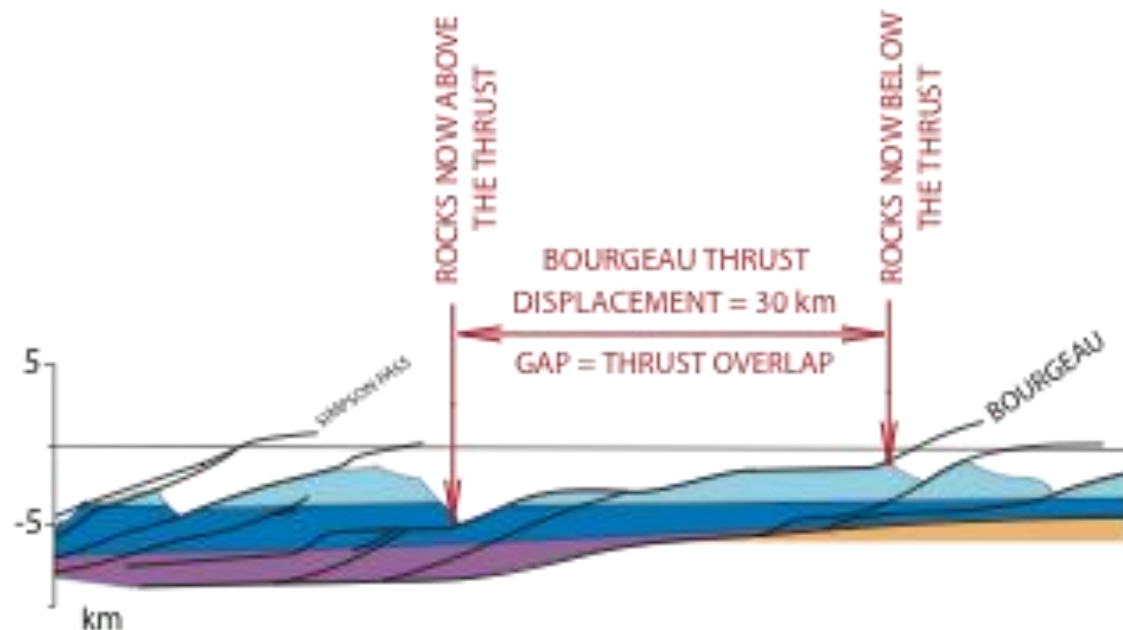
ROCKS NOW ABOVE THE THRUST

ROCKS NOW BELOW THE THRUST

BOURGEAU THRUST
DISPLACEMENT = 30 km

GAP = THRUST OVERLAP

SIMPSON PASS

BOURGEAU

RESTORED BOURGEAU
THRUST SHEET

SIMPSON PASS   FATIGUE

BOURGEAU   SULPHUR MOUNTAIN   RUNDLE   INGLISMALDIE   EXSHAW   McCONNELL

CUMULATIVE THRUST DISPLACEMENT = 130 km

MT FORSTER   PURCELL   SIMPSON PASS   FATIGUE   BOURGEAU   SULPHUR MOUNTAIN   RUNDLE   INGLISMALDIE   EXSHAW

PALEOPROTEROZOIC (2100 - 1850 million years) C...

MIOGEOCLINE

Upper Devonian - Carboniferous

Fairholme, Palliser, Banff, and Rundle

Middle Cambrian - mid-Devonian

(shale ← carbonate)
(West)   (East)

Lower Cambrian

Hamill & Gog Groups (sandstone)

Neoproterozoic

Windermere Supergroup
RIFT BASIN

Mesoproterozoic

Belt-Purcell Supergroup
RIFT BASIN
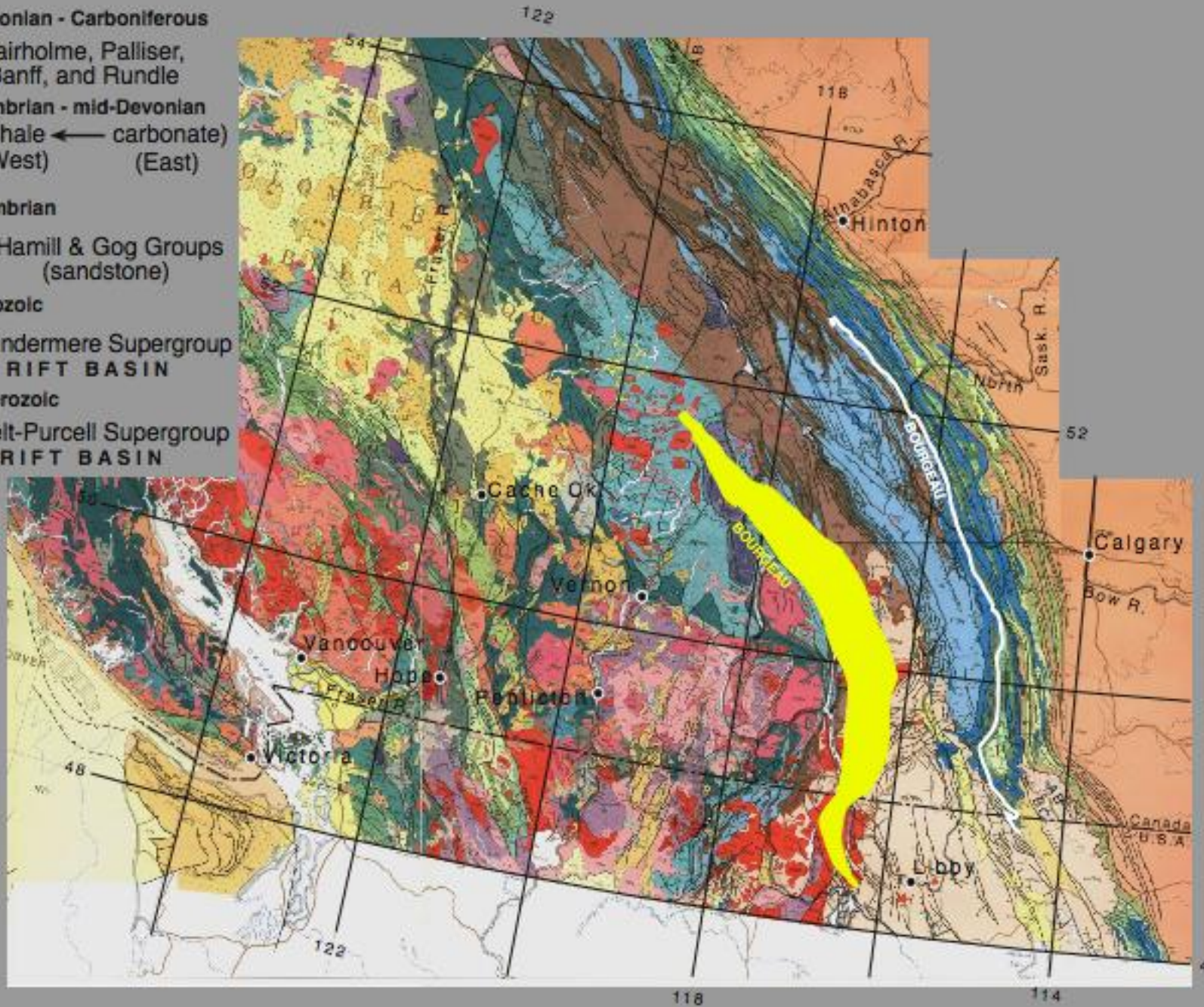
RESTORED CAMBRIAN TO MIDDLE DEVONIAN PALEOGEOGRAPHY

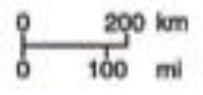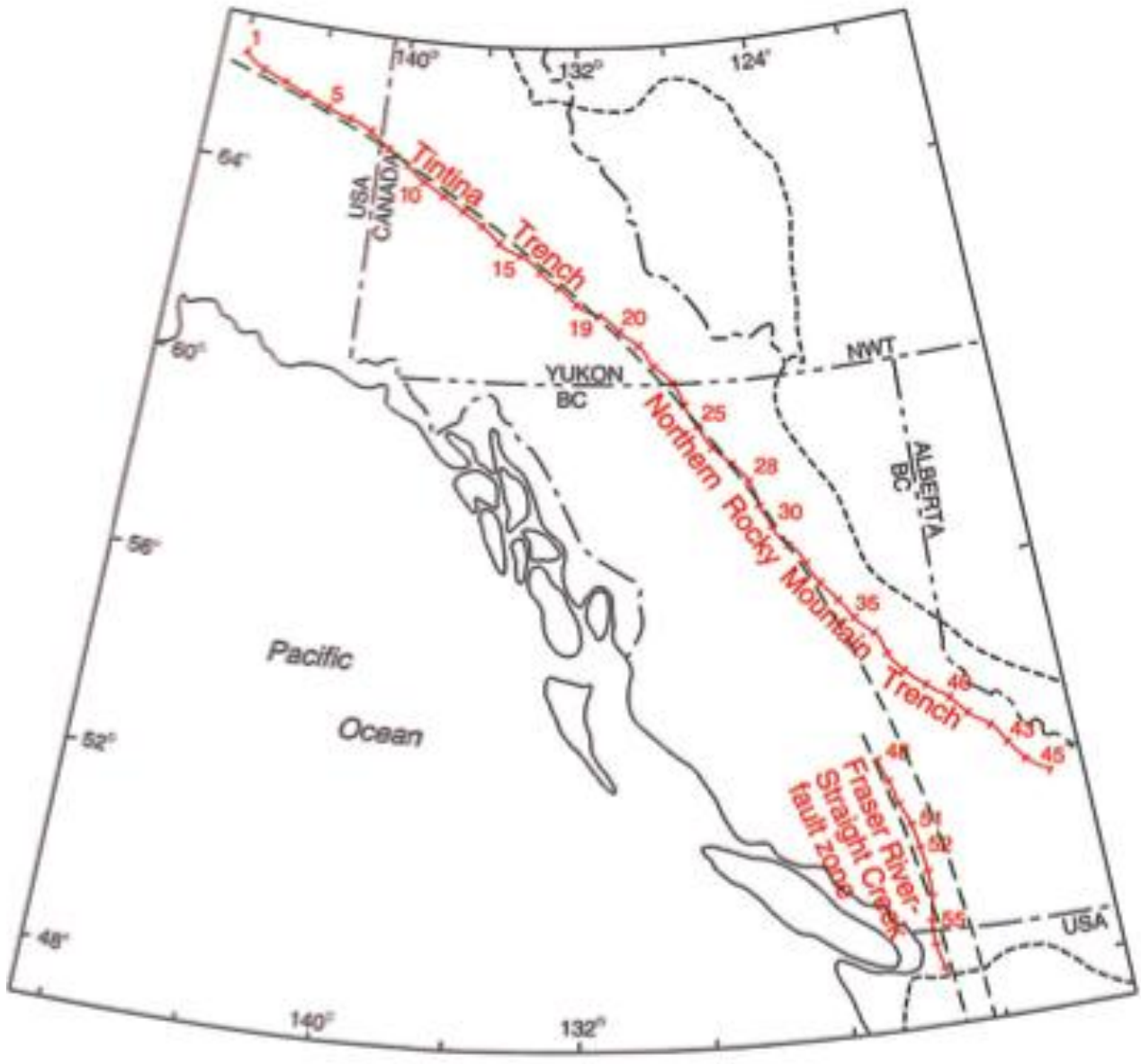Cratonic Platform
Miogeocline
Carbonate Shelf
Shale Basin

RESTORED STRATIGRAPHIC SECTIONS

Paleozoic

Upper Devonian to Triassic
Cambrian to Middle Devonian

Windermere
Belt-Purcell

Restored Thrusts

Present surface Trace
Restored Hanging Wall Trace

0   50   100   150
km
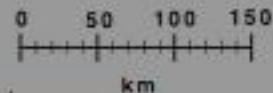
DH   Dogtooth DH High
WH   Windermere WH High
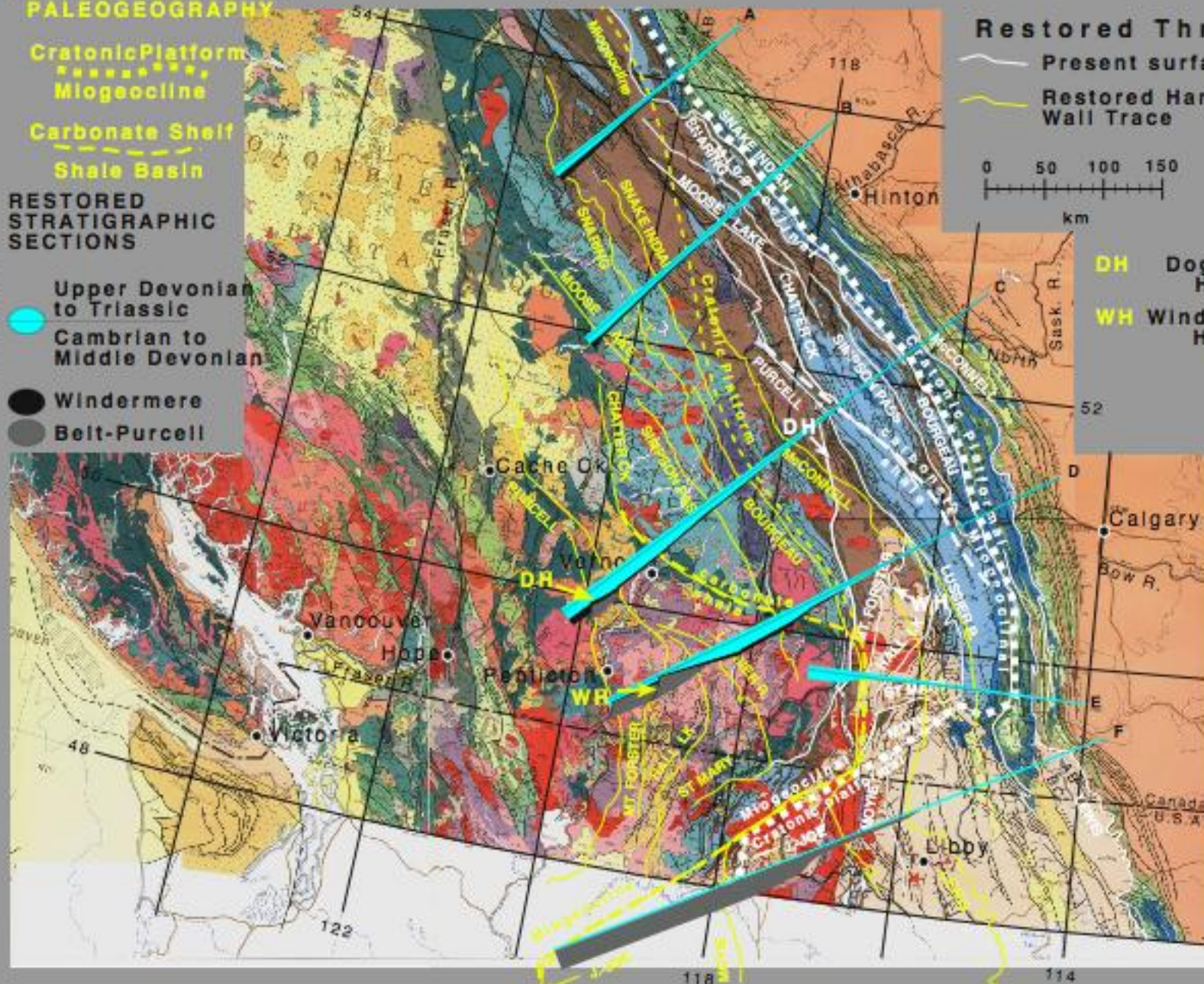
RESTORED ISOPACHS (km)
Cambrian-Middle Devonian (542-385 Ma)
Windermere (750-542 Ma)
Belt-Purcell (1500-1400Ma)

RESTORED ISOPACHS (km)
Cambrian-Middle Devonian (542-385 Ma)

THRUST FAULT

RESTORED CAMBRIAN TO MIDDLE DEVONIAN PALEOGEOGRAPHY

Cratonic Platform

Miogeocline

Carbonate Shelf

Shale Basin

DH -- Dogtooth High

WH -- Windermere High

TOTAL RESIDUAL MAGNETIC FIELD
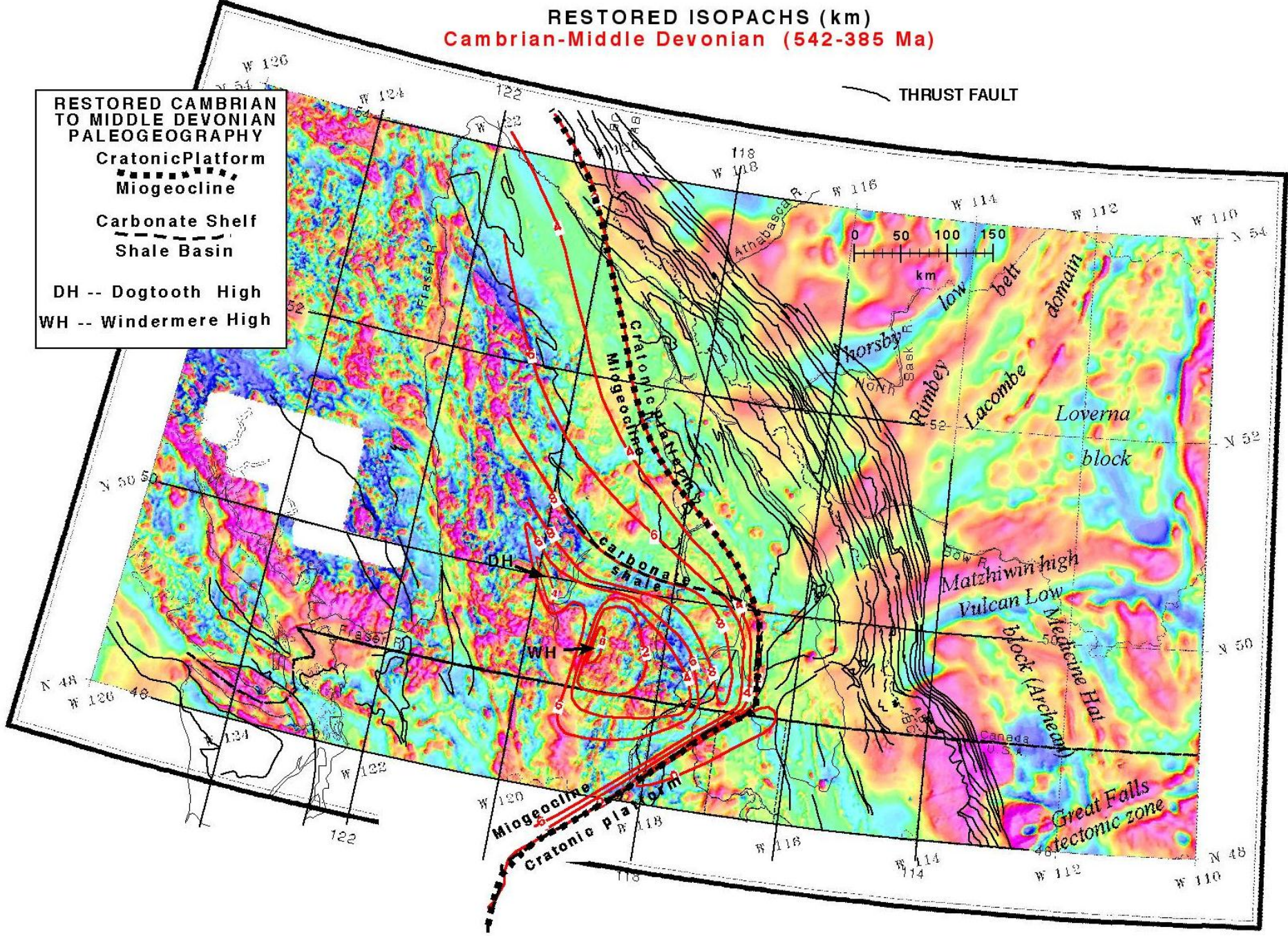
RESTORED CAMBRIAN
TO MIDDLE DEVONIAN
PALEOGEOGRAPHY

CratonicPlatform
Miogeocline
Carbonate Shelf
Shale Basin
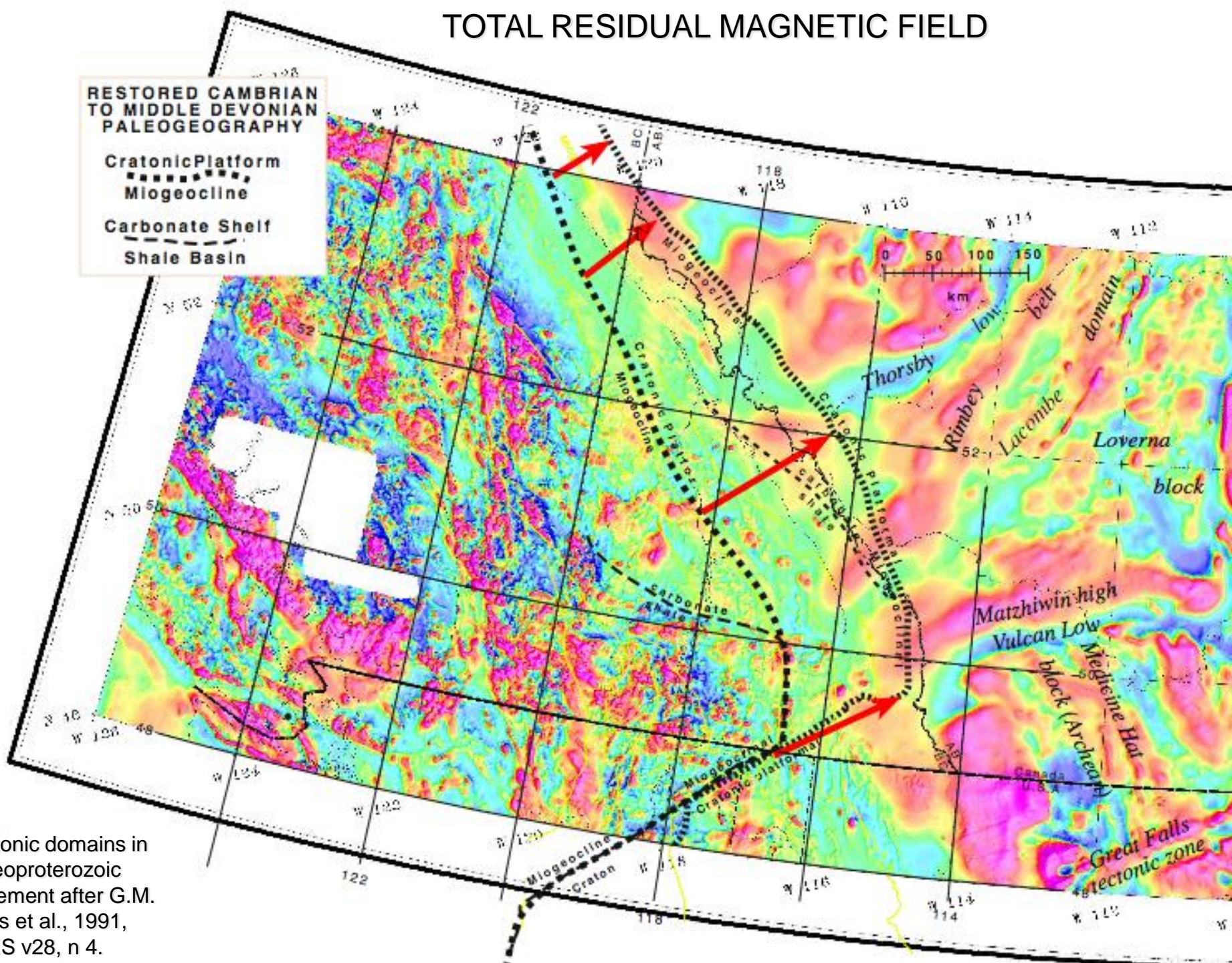
Tectonic domains in
Paleoproterozoic
basement after G.M.
Ross et al., 1991,
CJES v28, n 4.
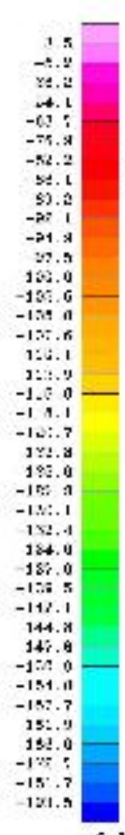
RESTORED CAMBRIAN
TO MIDDLE DEVONIAN
PALEOGEOGRAPHY

Cratonic Platform
Miogeocline

Carbonate Shelf
Shale Basin

Restored Thrusts
Present surface Trace
Restored Hanging
Wall Trace

mGal

Hinton

Cache Ck.

Vernon

Vancouver

Hope

Penticton

Victoria

Calgary

Libby

Fraser R.

Athabasca R.

McConnell

North Sask. R.

Bow R.

Fraser R.

SHAKE INDIAN
MOOSE LAKE
PURCELL
SIMPLON PASS
BOURGEAU
MT. FORSTER
LUSSIER R.
ST MARY
MOYIE
HALL LK.
LEWIS
ST. MARY
MT. FORSTER
J. JOE
SHAKE INDIAN
CHATTER CK.
SHARING

Miogeocline
Cratonic Platform
Carbonate
shale

BC AB

Canada
U.S.A.

Tintina Trench

Northern Rocky Mountain Trench

Fraser River-
Straight Creek-
fault zone

Pacific

Ocean

USA
CANADA

YUKON
BC

NWT

ALBERTA
BC

USA

64°

60°

56°

52°

48°

140°

132°

124°

140°

132°

0   200 km

0   100 mi

Prior to
Late K-Paleocene
Dextral Transpression

Prior to
Early Eocene
Dextral Transtension

After
Early Eocene
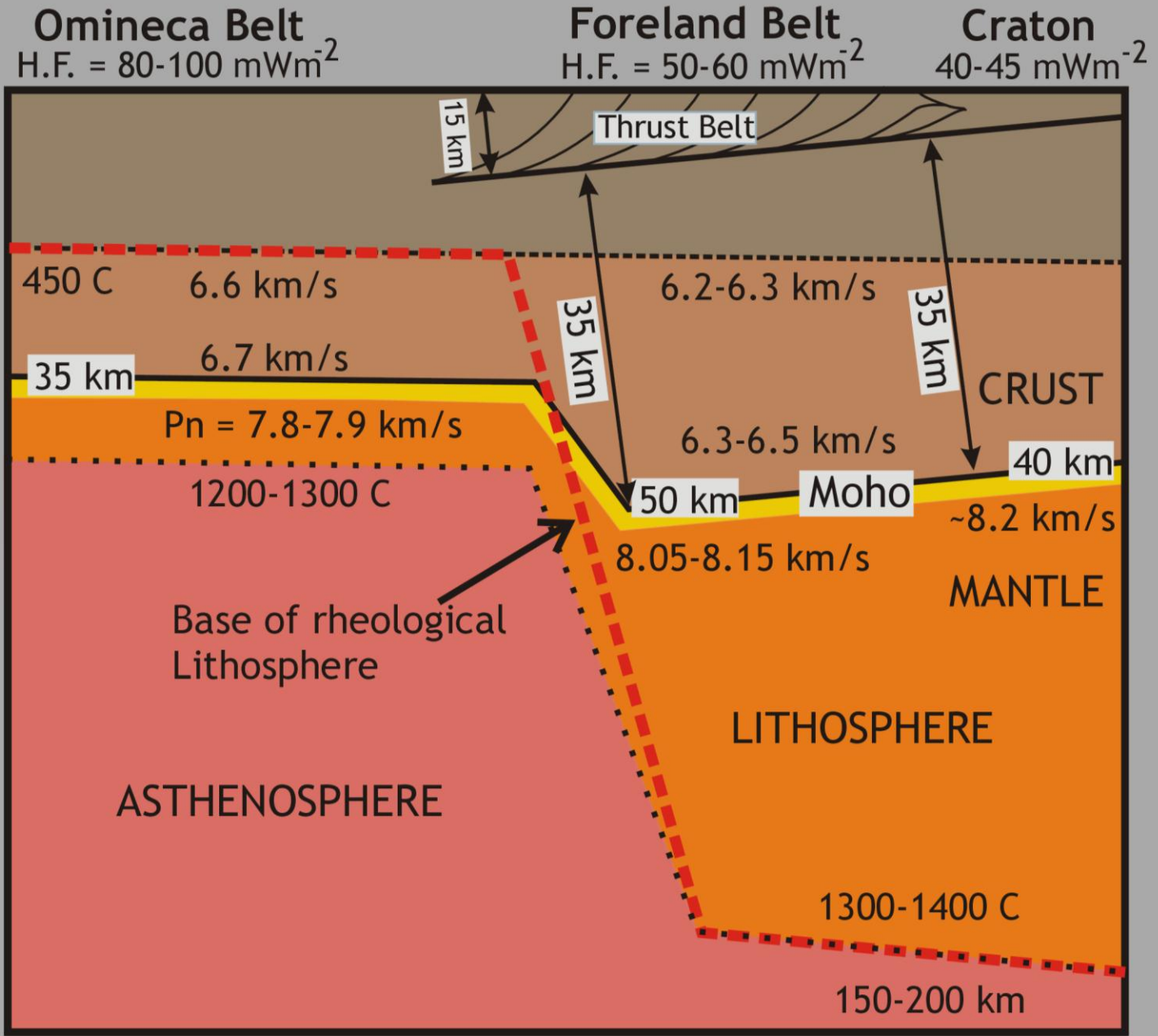Dextral Transtension

80 Ma
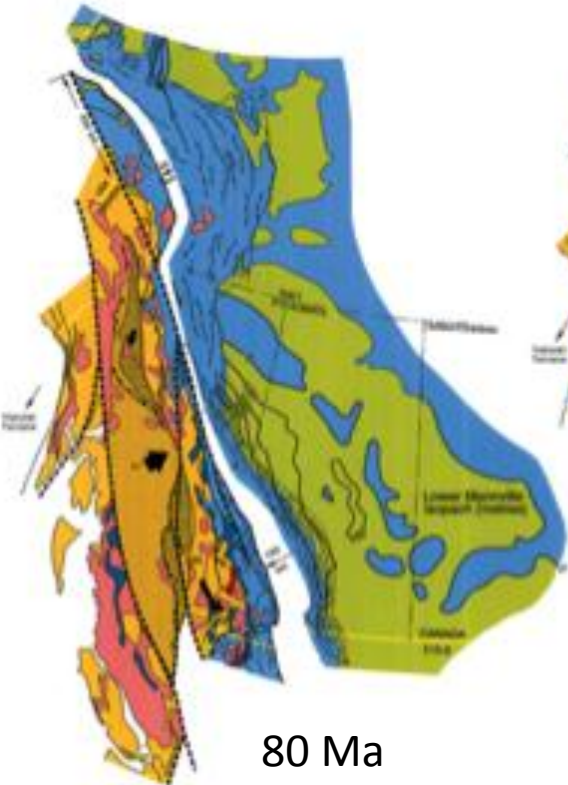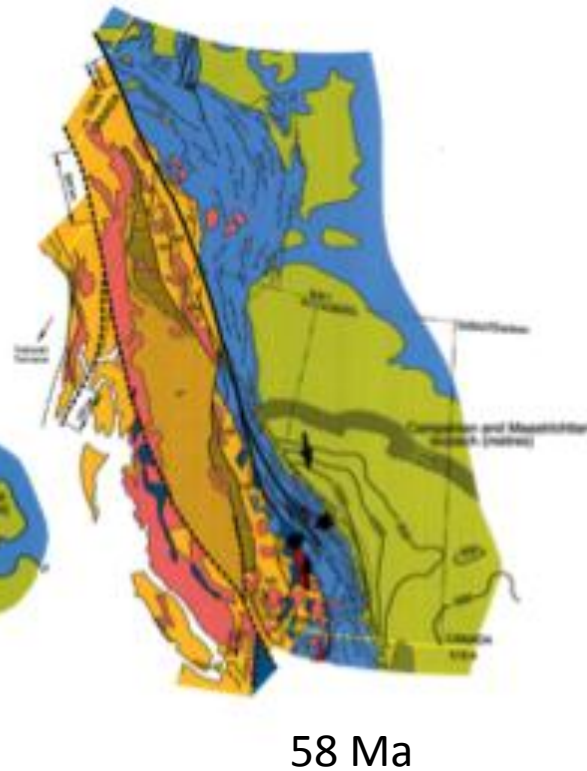
58 Ma

40 Ma
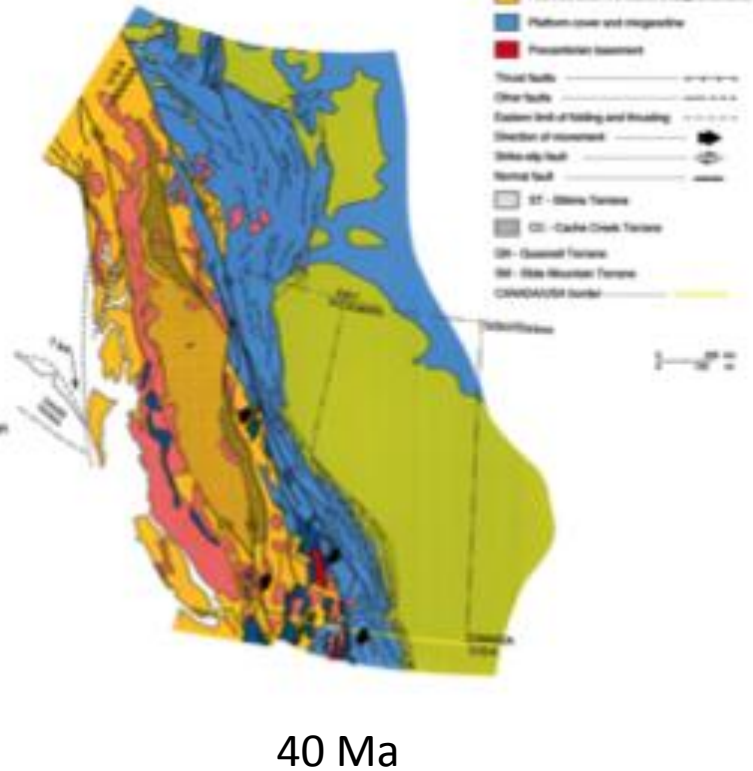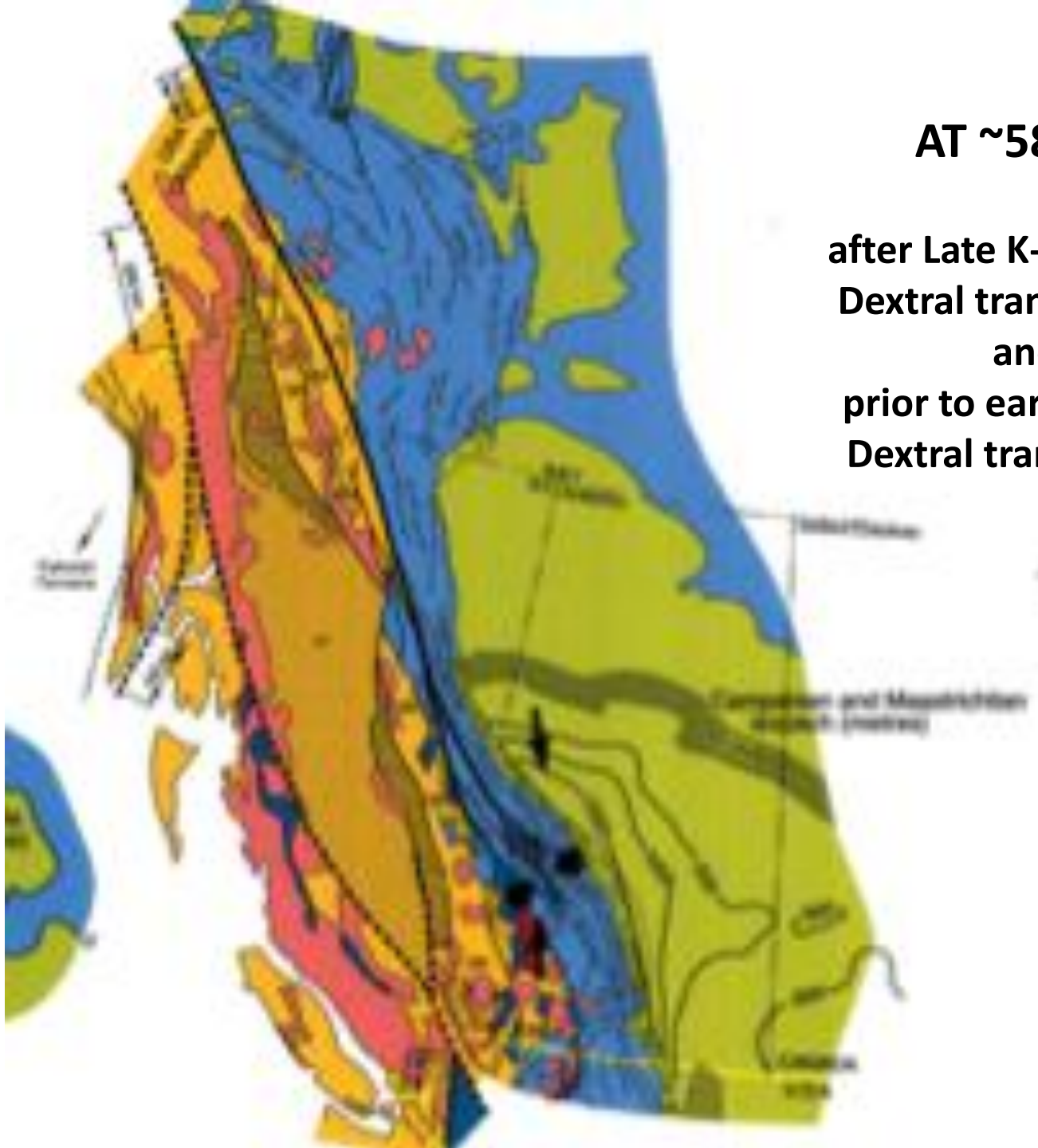
AT ~58 Ma

after Late K-Paleocene
Dextral transpression
and
prior to early Eocene
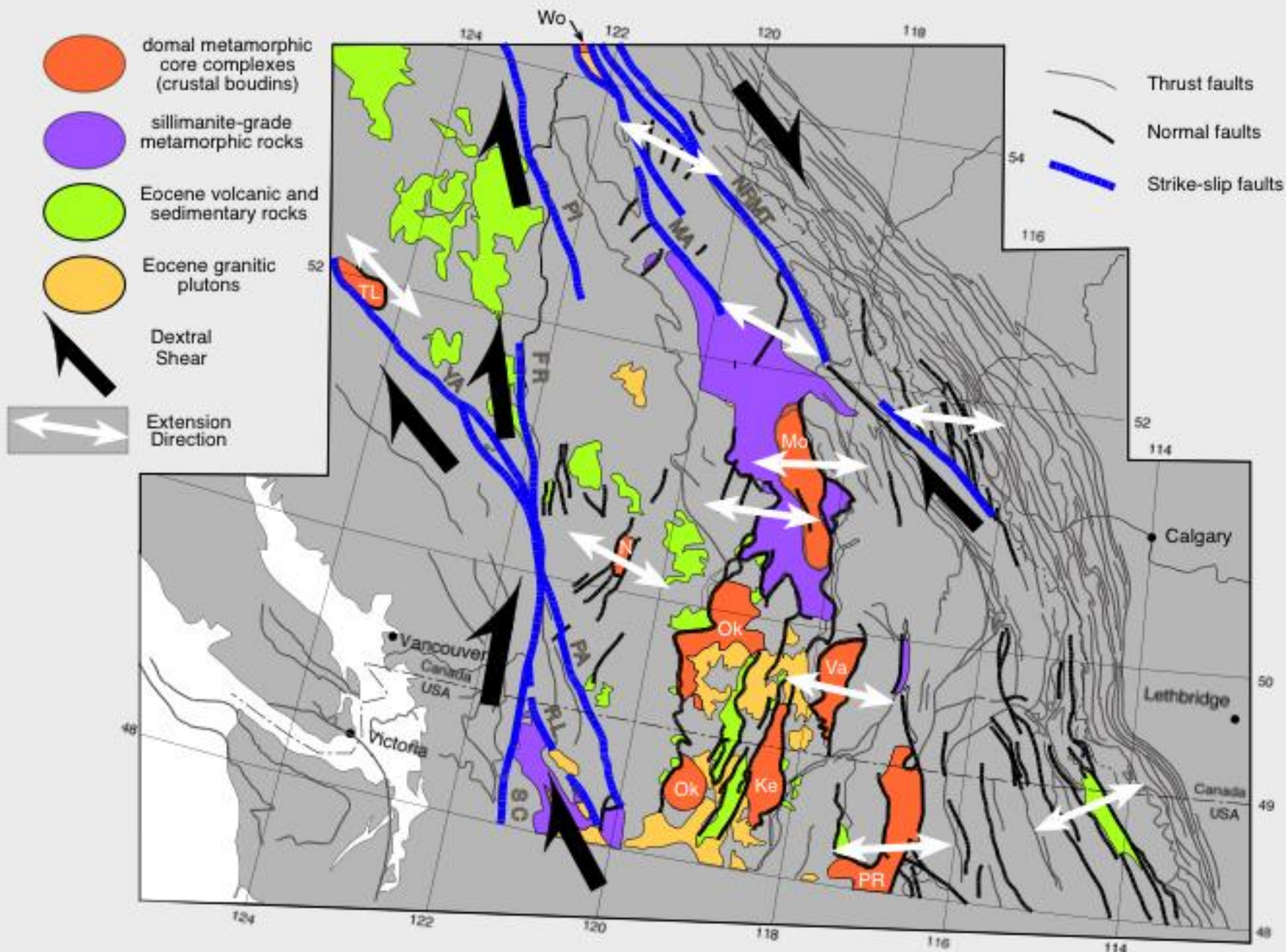Dextral transtension
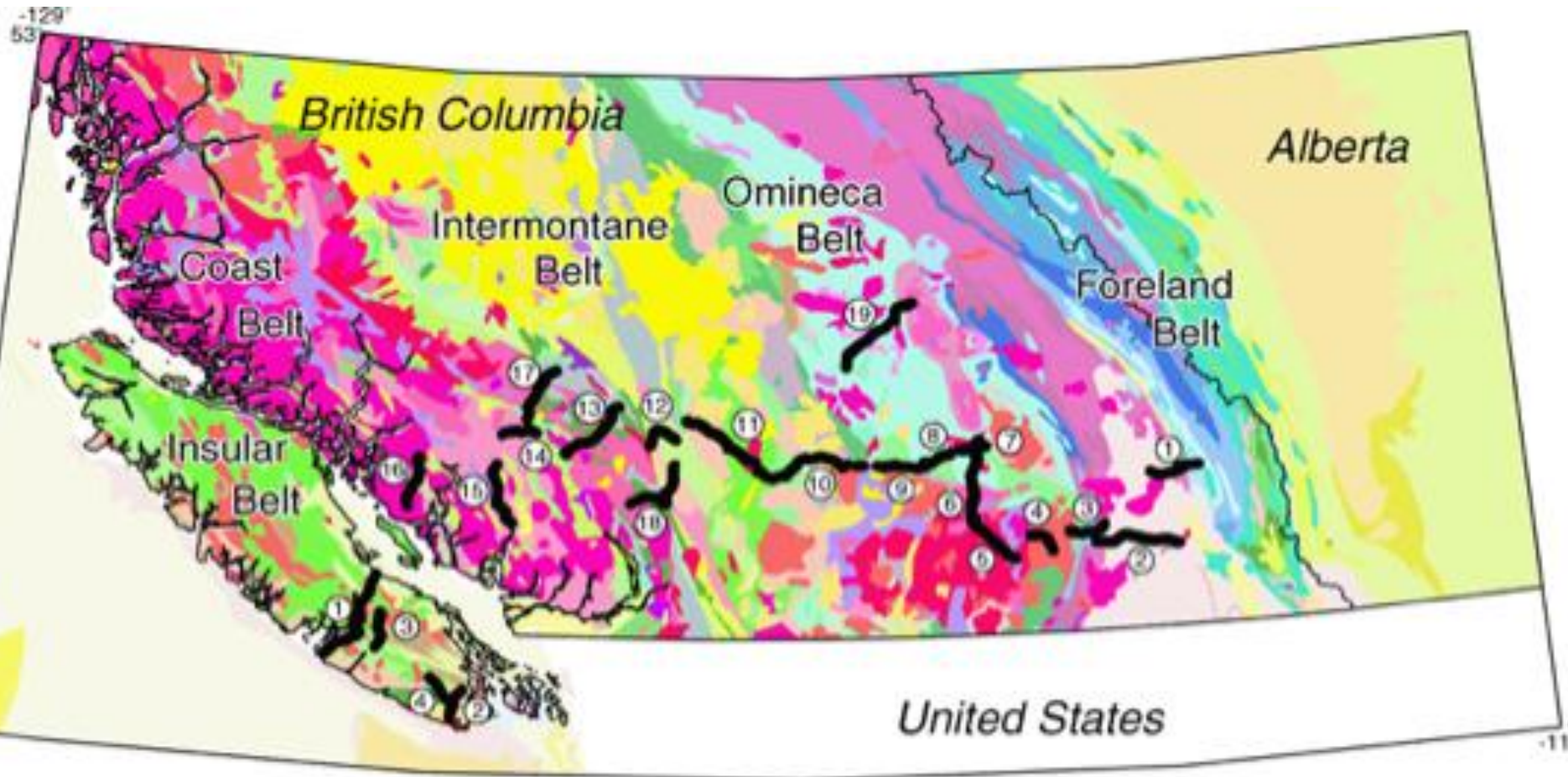
LITHOPROBE SOUTHERN CORDILLERA TRANSECT
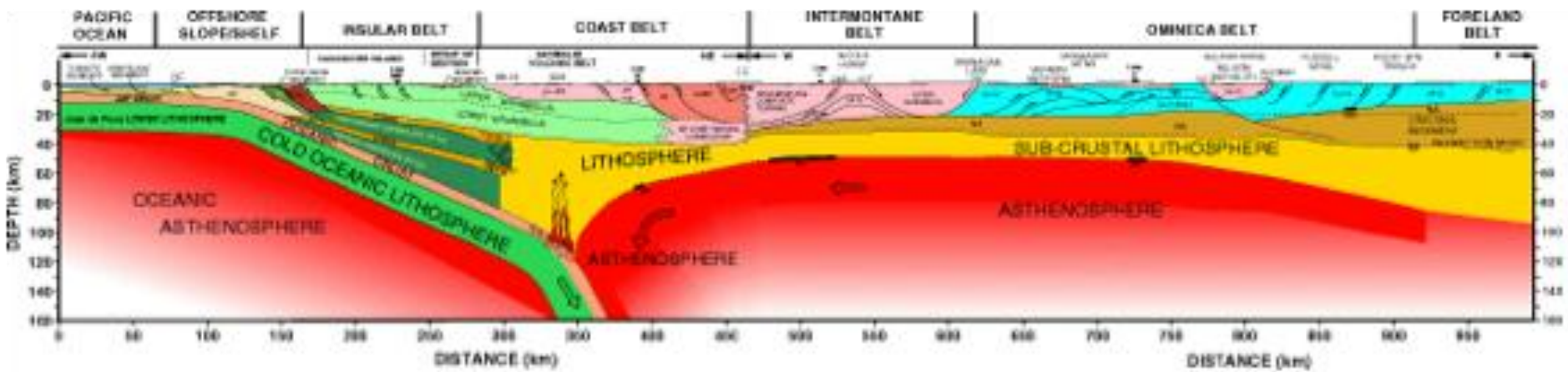
LITHOPROBE SOUTHERN CORDILLERA SIMPLIFIED COMPOSITE SECTION

Omineca Belt
H.F. = 80-100 mWm^{-2}

Foreland Belt
H.F. = 50-60 mWm^{-2}

Craton
40-45 mWm^{-2}

15 km

Thrust Belt

450 C   6.6 km/s   6.2-6.3 km/s   35 km

35 km   35 km   CRUST

6.7 km/s

Pn = 7.8-7.9 km/s   6.3-6.5 km/s   40 km

1200-1300 C   50 km   Moho   ~8.2 km/s

8.05-8.15 km/s   MANTLE

Base of rheological
Lithosphere

LITHOSPHERE

ASTHENOSPHERE
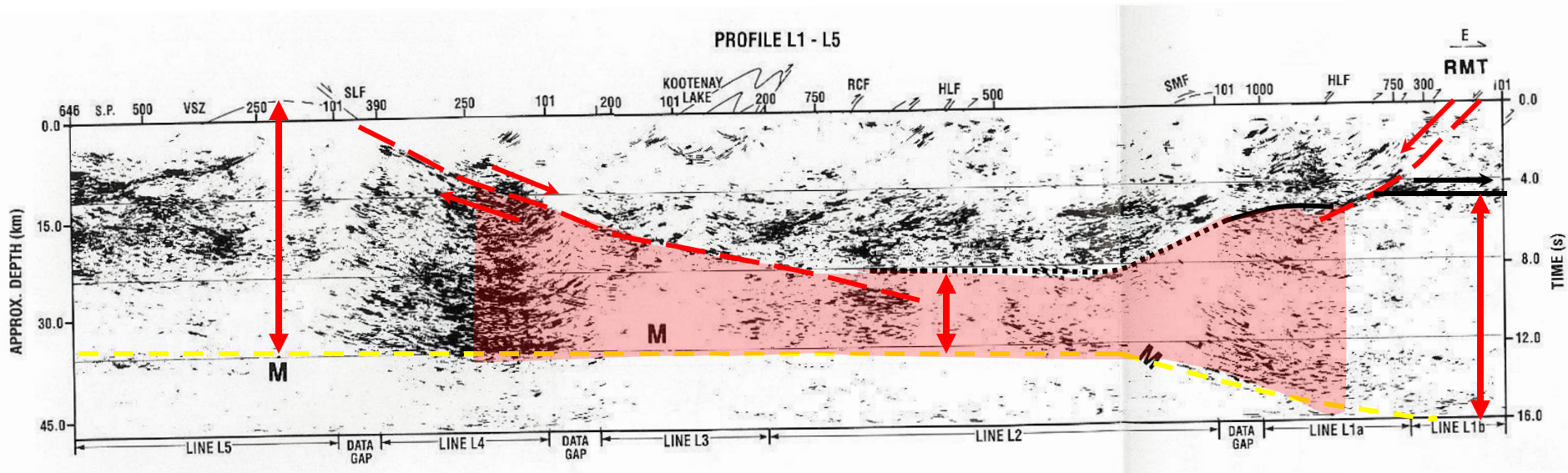
1300-1400 C

150-200 km

LITHOPROBE Pn VELOCITIES AND CRUSTAL THICKNESSES

(Modified after Hyndman and Lewis,1998;
Zelt and White, 1995; Burianyk et al., 1997)

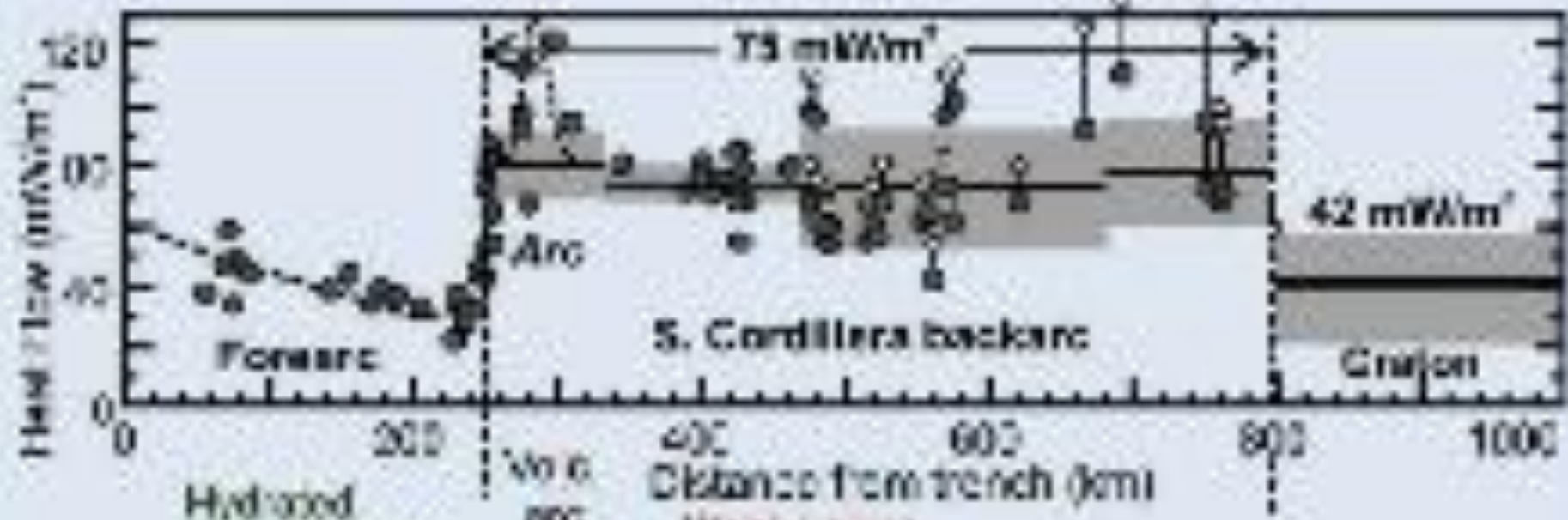**EOCENE DEXTRAL TRANSTENSION AND CRUSTAL-SCALE BOUDINAGE**

PROFILE L1 - L5

BOUDIN   NECK ZONE

Hyndman et al., 2005, GSAToday, v. 15
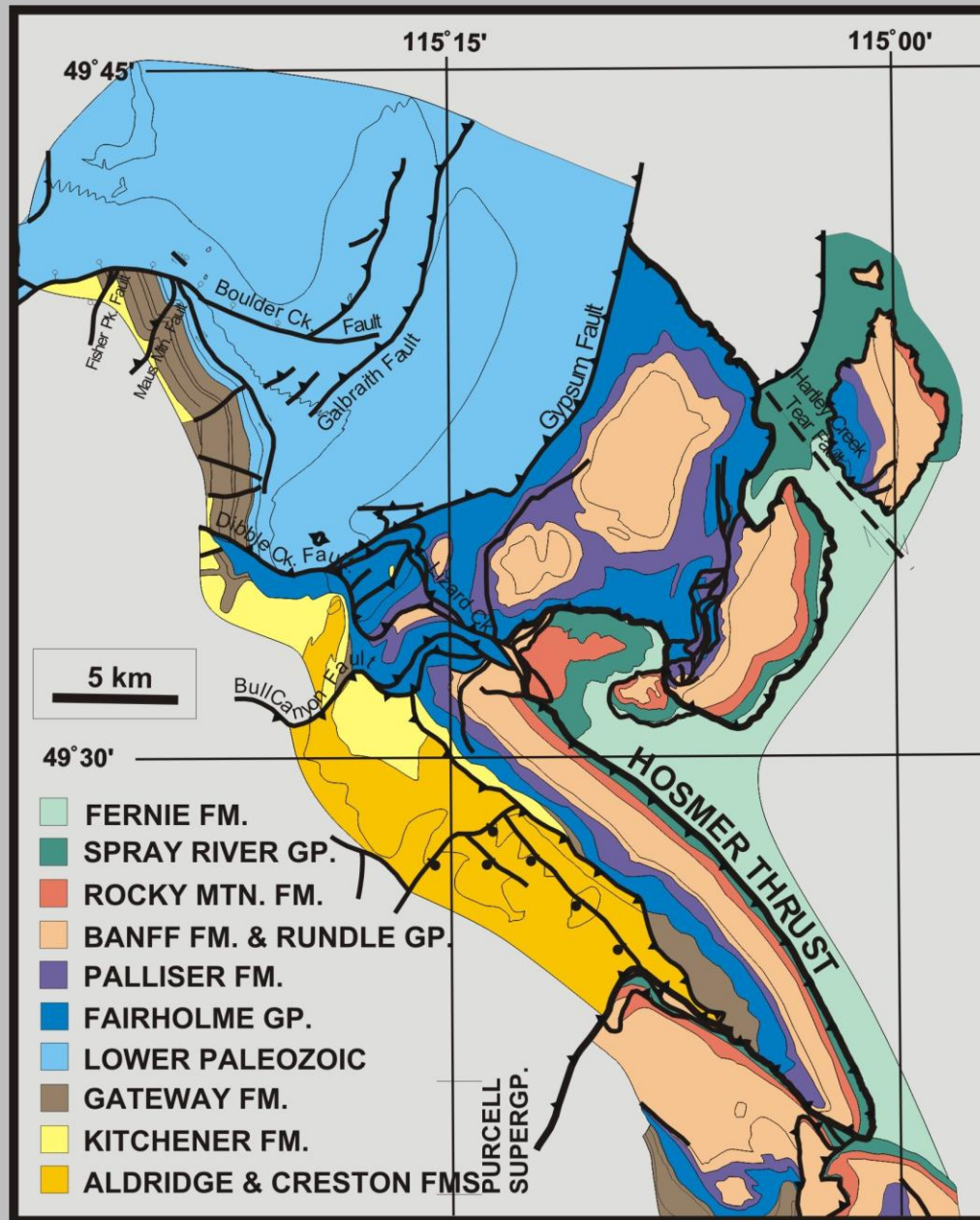
HANGING WALL AND FOOTWALL GEOLOGIAL MAPS OF THRUST FAULTS

WHATEVER OCCURS ON ONE SIDE OF A FAULT
MUST HAVE A MATCHING COUNTERPART ON THE OTHER SIDE.

A HANGING-WALL GEOLOGICAL MAP PROVIDES A TEMPLATE FOR RECONSTRUCTION OF
A GEOLOGICAL MAP OF THE DEEPLY BURIED FOOTWALL.

A FOOTWALL GEOLOGICAL MAP PROVIDES A TEMPLATE FOR RECONSTRUCTION OF
A MAP OF THE ERODED HANGING WALL.

MATCHING FOOTWALL & HANGING-WALL GEOLOGICAL MAPS OF A THRUST FAULT
PROVIDE A 3-D PALINSPASTIC RESTORATION OF VARIATIONS
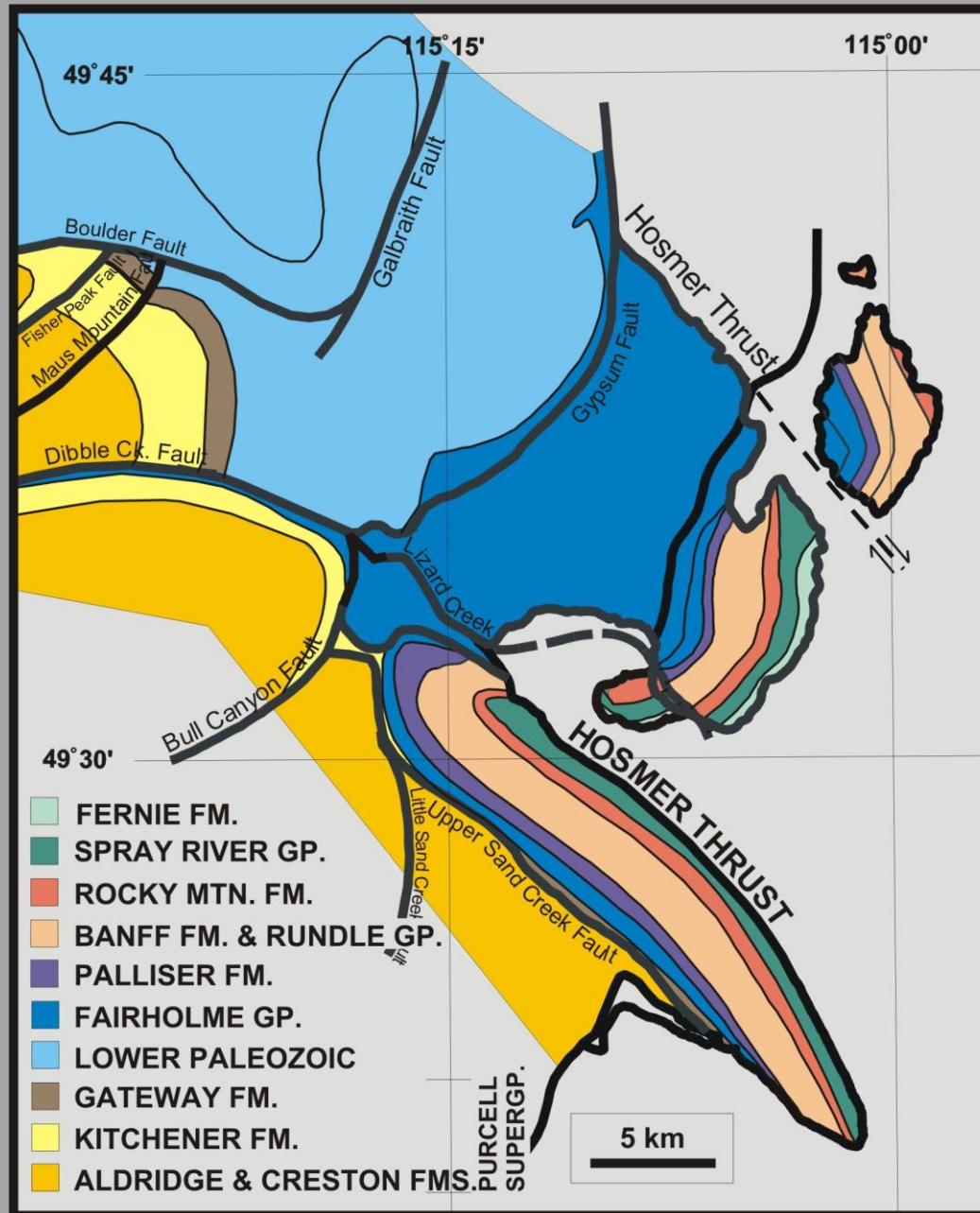IN THE DIRECTIONS AND MAGNITUDES OF DISPLACEMENT ON THE THRUST FAULT
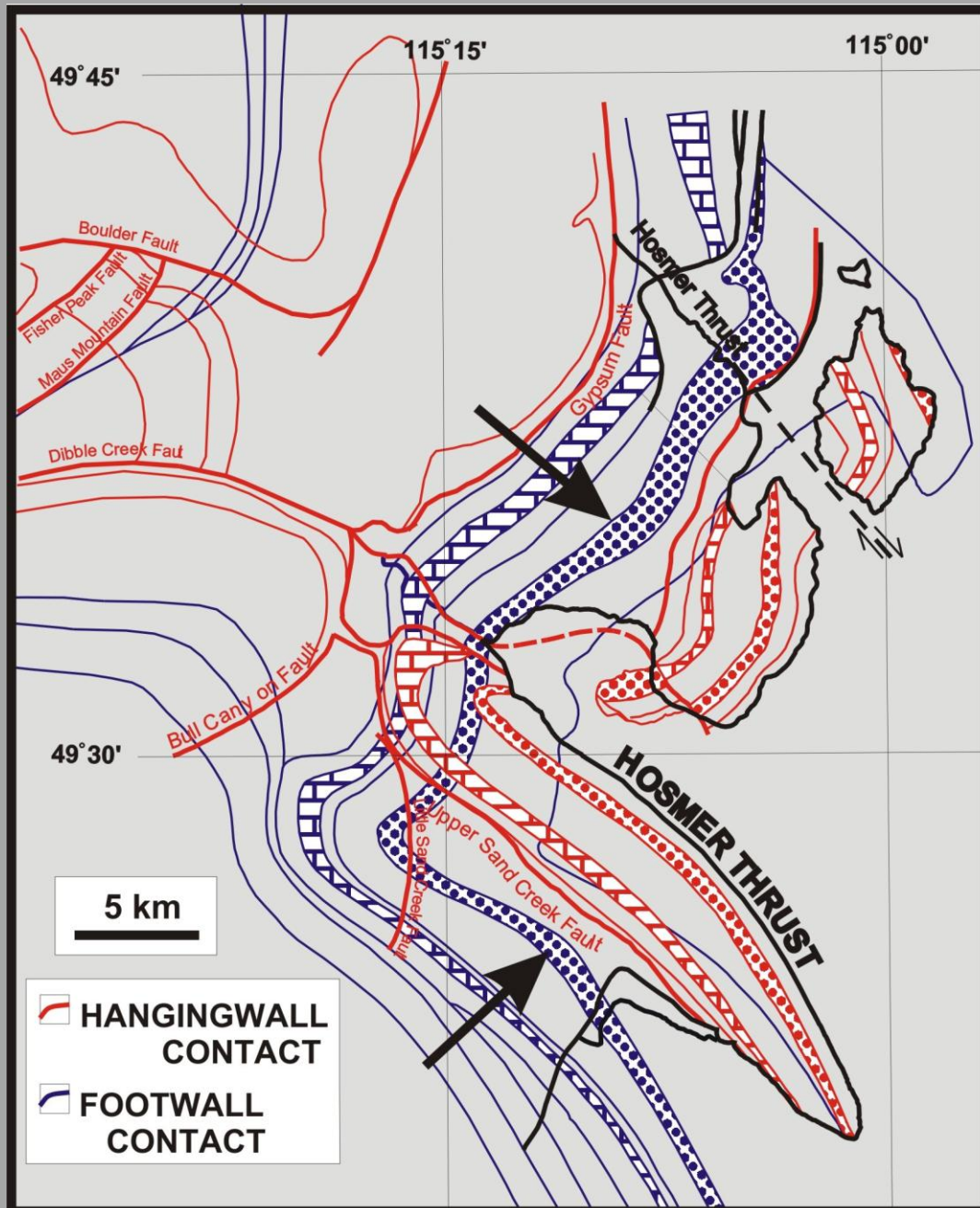
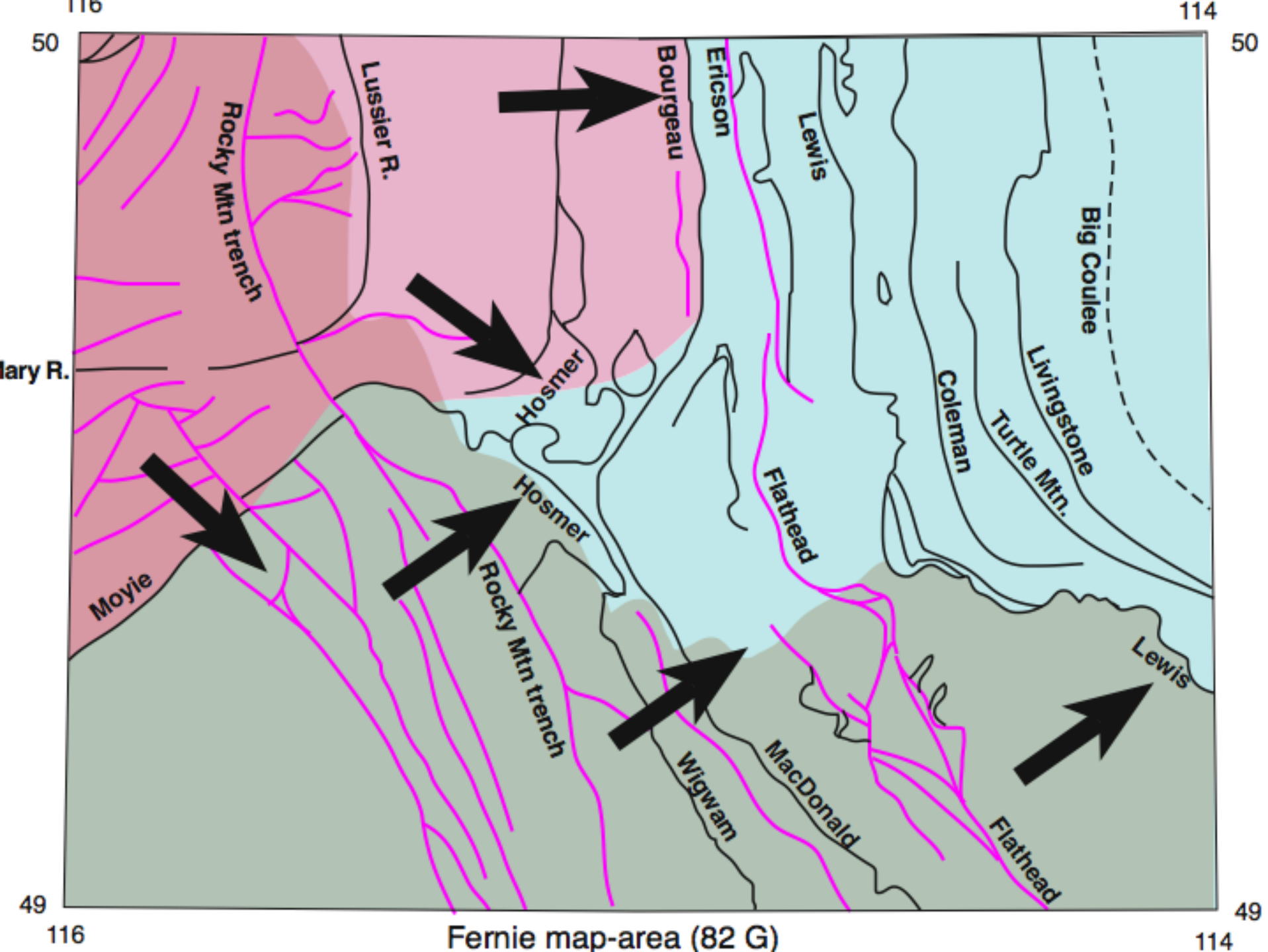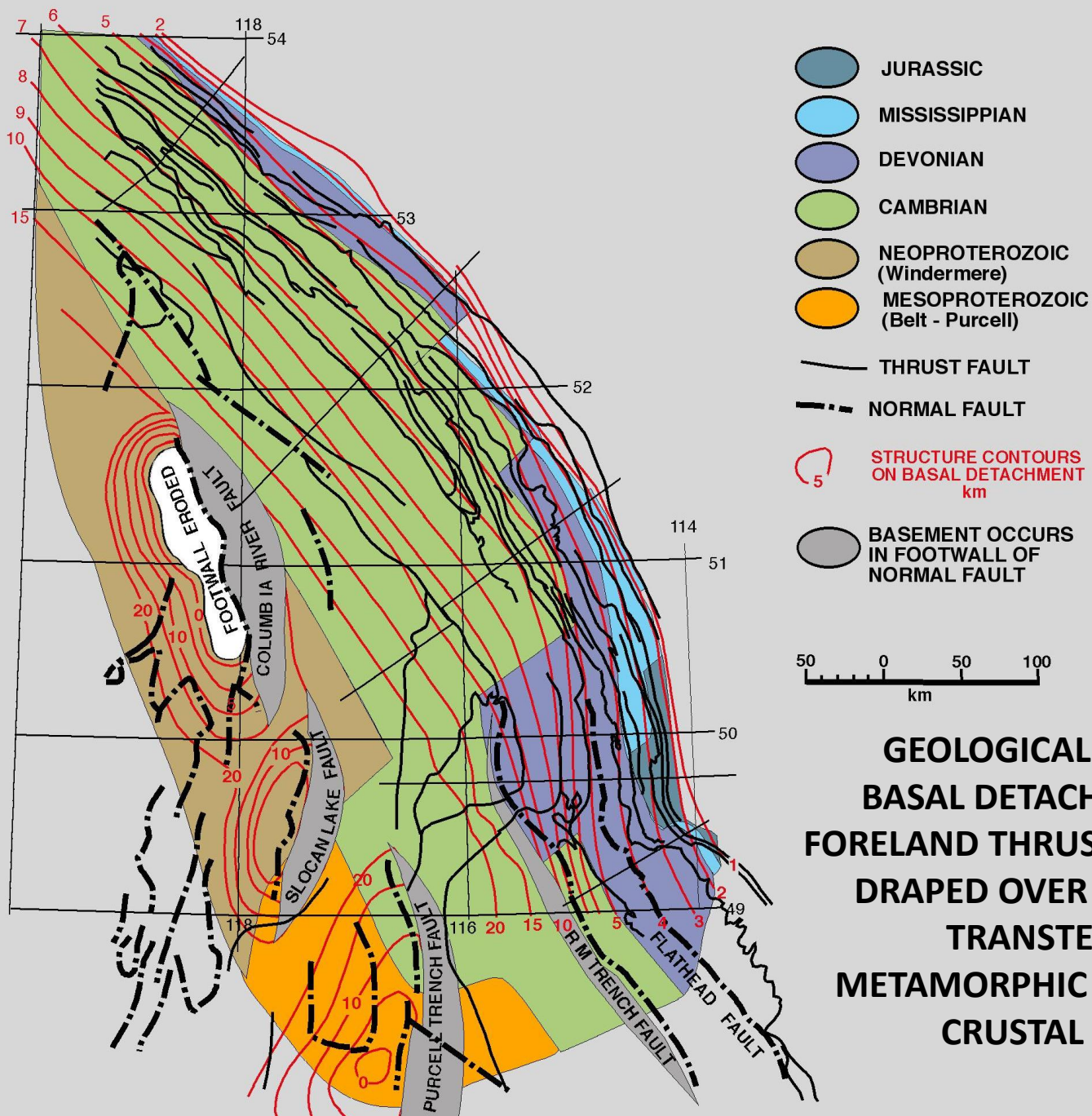# THE HOSMER NAPPE – Geological Map

THE HOSMER NAPPE – Footwall Map
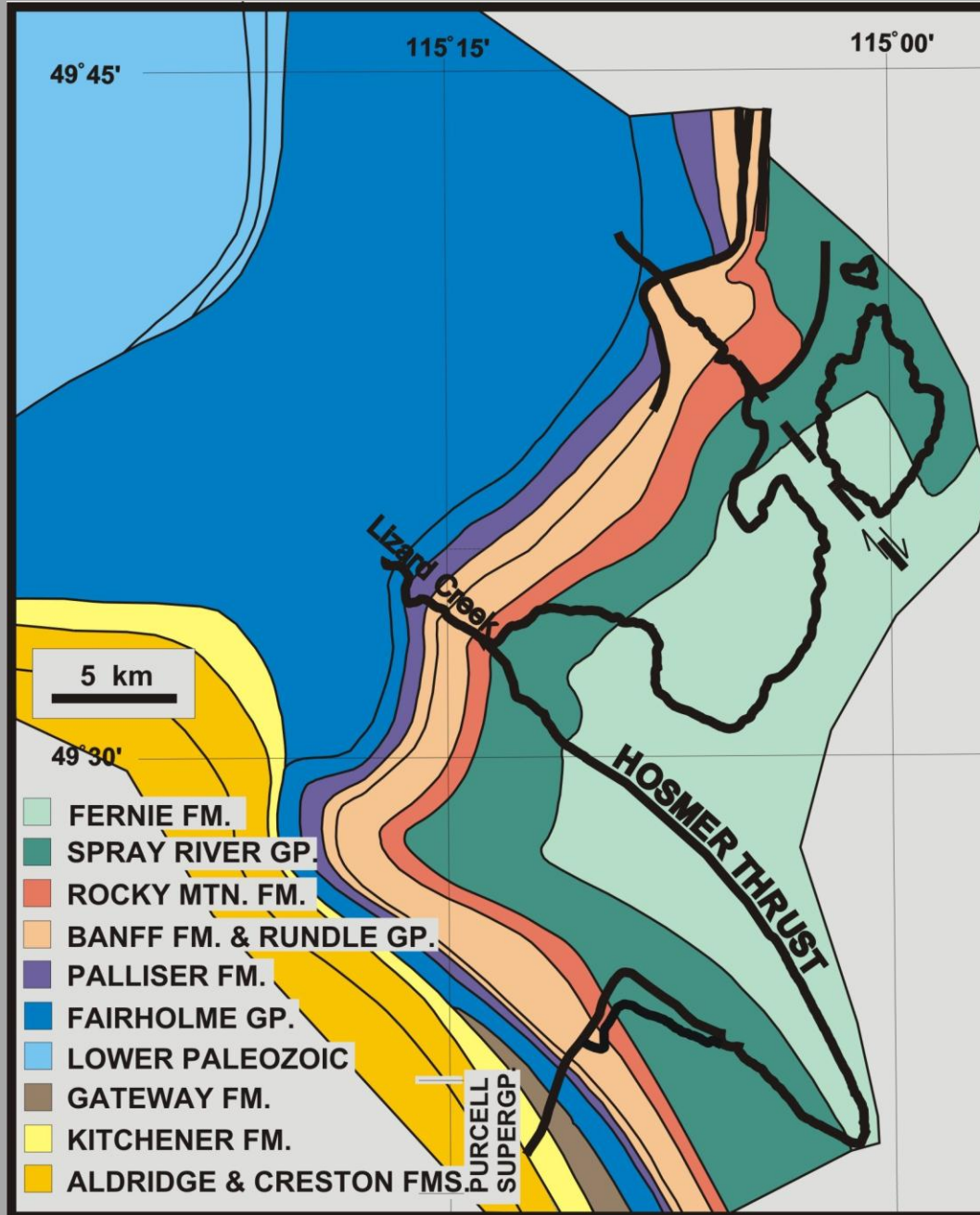
THE HOSMER NAPPE – Hanging wall map
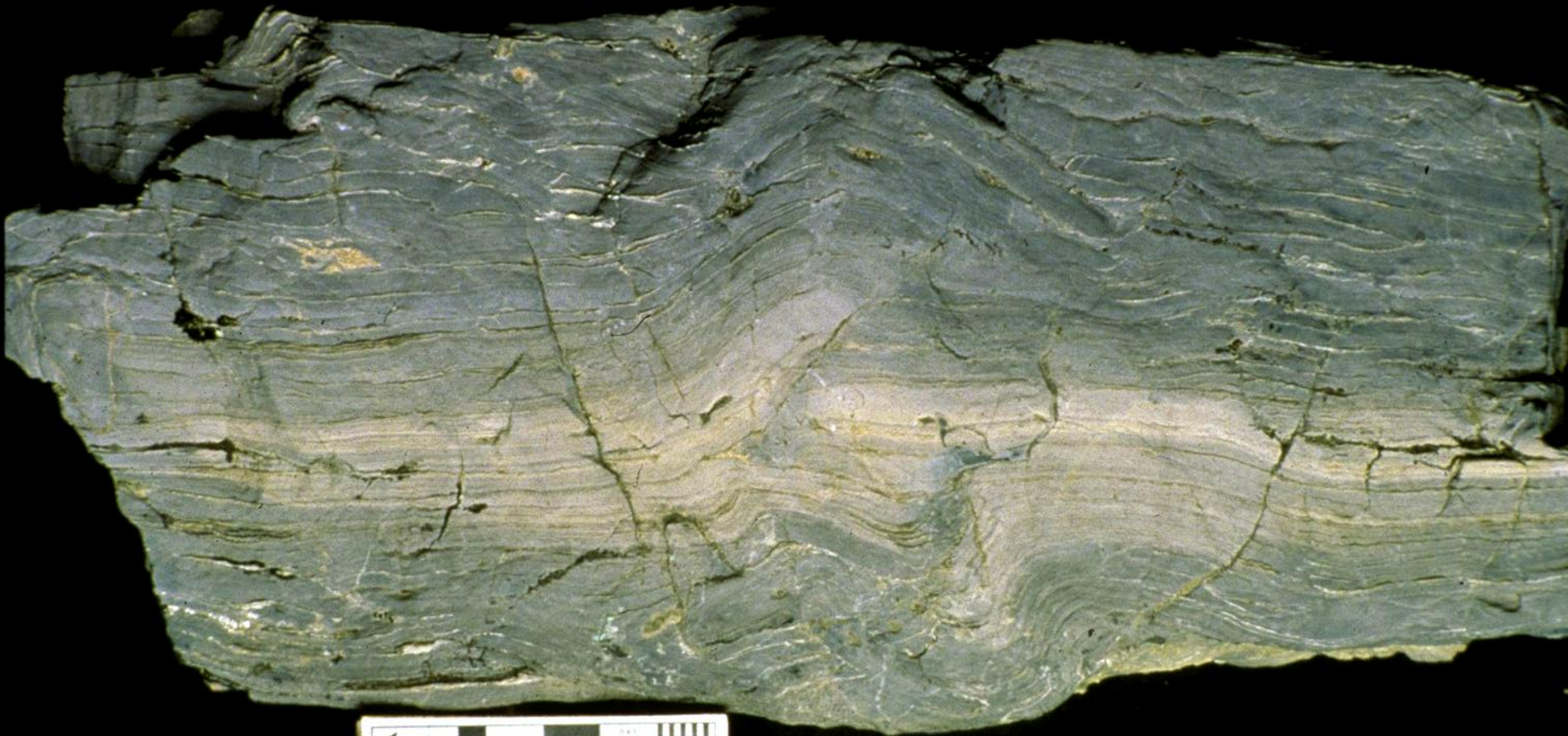
THE HOSMER NAPPE - Displacement

Fernie map-area (82 G)

GEOLOGICAL MAP OF THE BASAL DETACHMENT OF THE FORELAND THRUST-AND-FOLD BELT DRAPED OVER EARLY EOCENE TRANSTENSIONAL METAMORPHIC CORE COMPLEX CRUSTAL BOUDINS

Legend:
- JURASSIC
- MISSISSIPPIAN
- DEVONIAN
- CAMBRIAN
- NEOPROTEROZOIC (Windermere)
- MESOPROTEROZOIC (Belt - Purcell)
- THRUST FAULT
- NORMAL FAULT
- STRUCTURE CONTOURS ON BASAL DETACHMENT km
- BASEMENT OCCURS IN FOOTWALL OF NORMAL FAULT

Scale: 50 0 50 100 km

Labels on map: COLUMBIA RIVER FAULT, FOOTWALL ERODED, SLOCAN LAKE FAULT, PURCELL TRENCH FAULT, RM TRENCH FAULT, FLATHEAD FAULT

TECTONIC WEDGING

OCCURS AT ALL SCALES FROM MICROSCOPIC TO LITHOSPHERIC

Photo courtesy of M.E. McMechan

TECTONIC WEDGING AND DELAMINATION
are the compressing flow counterparts of extending flow
BOUDINAGE AND EXCISION
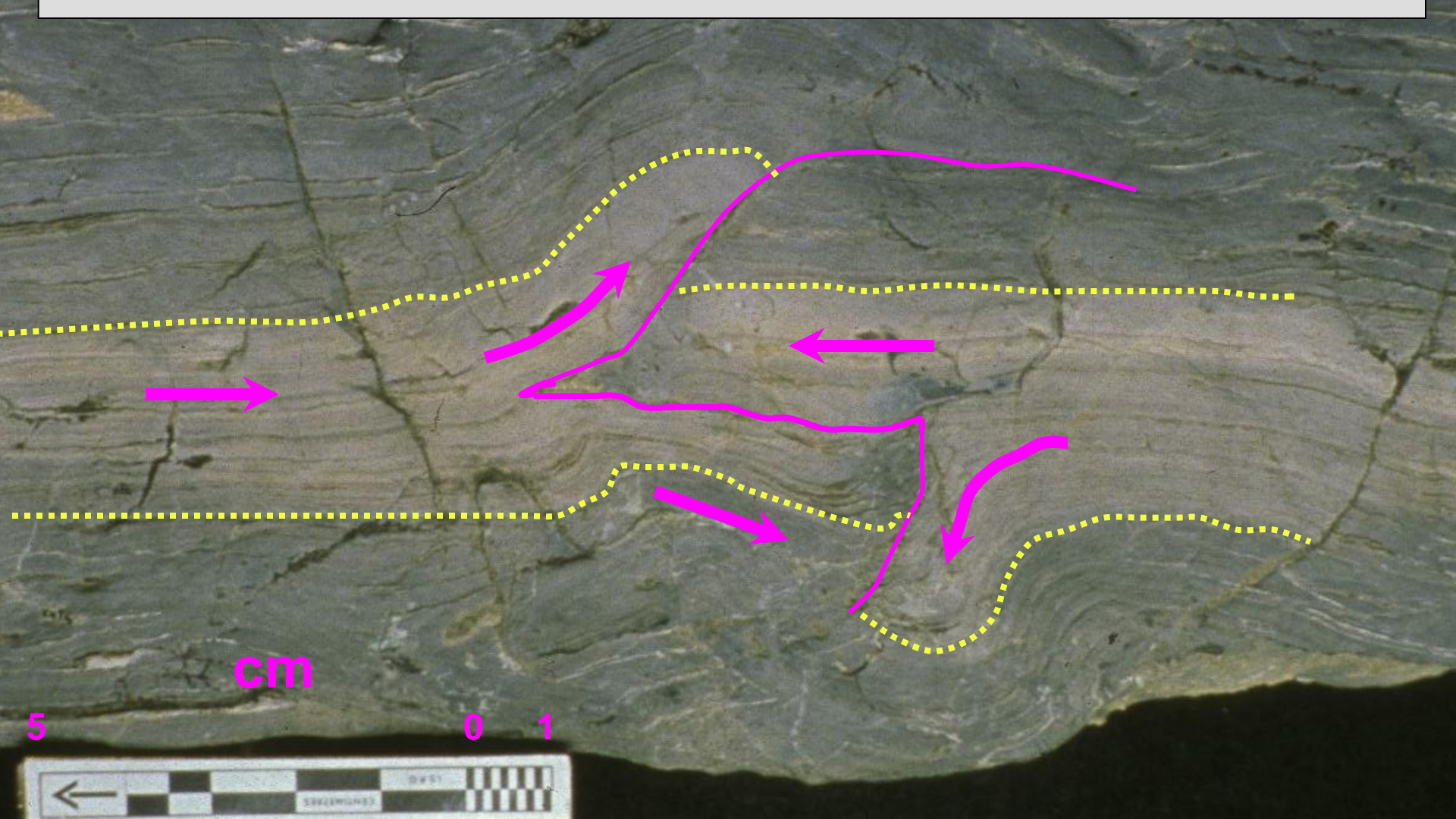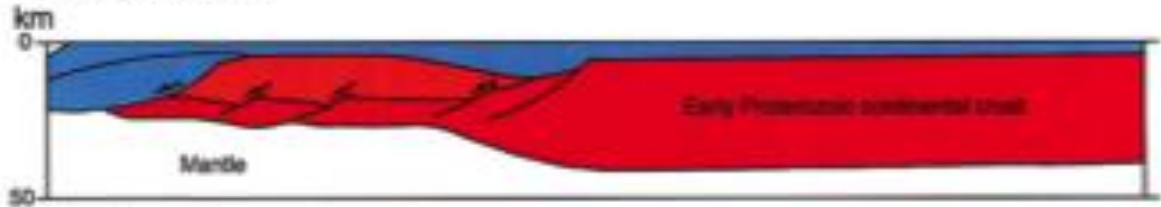
E-verging obduction

followed by

crustal-scale tectonic wedging with a W-verging roof thrust and then by detachment and

tectonic inversion of Mesoproterozoic and Neoproterozoic-Paleozoic basins

after Price, 1981, Jour. of Structural Geol.

a. Early Jurassic

km
0

Early Proterozoic continental crust

Mantle

50

b. Middle Jurassic

km
0

50

c. Early Cretaceous

km
0

50

d. Paleocene

km
0

50

Allochthonous terrane

Mid-Cretaceous granite

Middle Jurassic to Paleocene

Late Proterozoic to Middle Jurassic

Middle Proterozoic (Purcell-Belt)

Basement

0   50   km
0   25   mi

LITHOSPHERE-SCALE TECTONIC WEDGING

A – Onset of collapse of Slide Mtn. Basin;   **B** - Obduction of Slide Mountain terrane
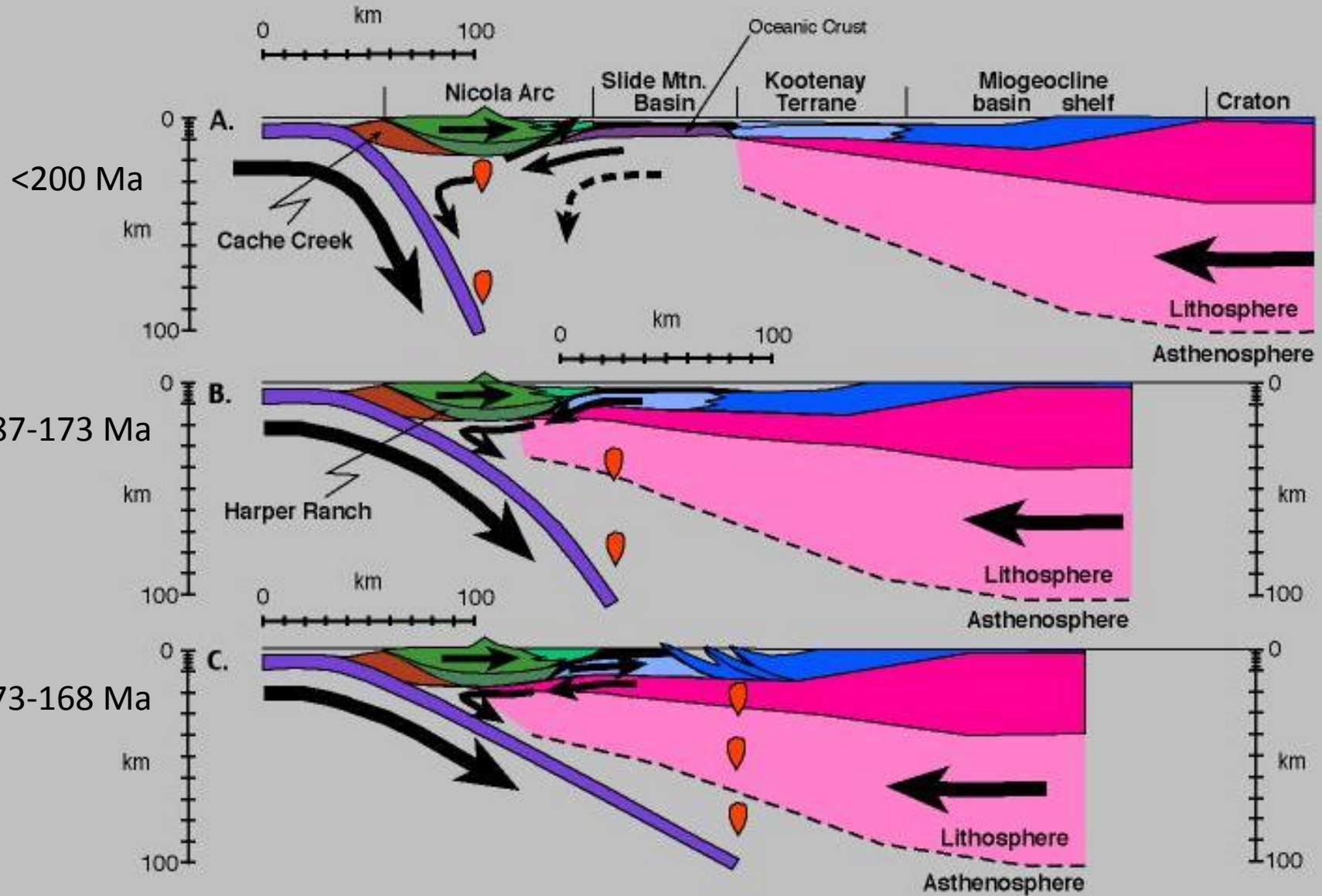
C - Tectonic Wedging of the continental margin by Quesnellia (Nicola Arc) & Kootenay terrane.

THE ROLE OF GRAVITY IN OROGENESIS

PLANET EARTH IS A GRAVITY-DRIVE HEAT ENGINE.

GRAVITY-DRIVEN THERMAL CONVECTION IN THE MOLTEN OUTER CORE GENERATES THE MAGNETIC FIELD AND HEATS THE BASE OF THE MANTLE.

BECAUSE OF GRAVITY, BUOYANT HOT ROCK RISES VERTICALLY THROUGH THE MANTLE.

BECAUSE OF GRAVITY IT DIVERGES SYMMETRICALLY AS IT APPROACHES THE SURFACE AND FLOWS HORIZONTALLY FORMING NEW OCEANIC CRUST AND OCEANIC LITHOSPHERE THAT IS ITSELF CONSTRAINED BY GRAVITY TO FLOW PARALLEL WITH EARTH'S SPHERICAL SURFACE.

BECAUSE OF GRAVITY, COOLER, THICKER, STIFFER NEGATIVELY BUOYANT SPHERICAL PLATES OF OCEANIC LITHOSPHERE ARE BENT AS THEY SINK BELOW THE SPHERICAL SURFACE OF THE EARTH, THUS FORMING AN OCEANIC TRENCH PLUS A MAGMATIC BELT IN THE OVERIDING PLATE.

THICKENING OF BUOYANT CRUST AT CONVERGENT PLATE BOUNDARIES PRODUCES ROCK UPLIFT AND THE TOPOGRAPHICAL RELIEF THAT DRIVES LATERAL GRAVITATIONAL SPREADING --- BOTH EXTENDING FLOW DEEP WITHIN THE CONTINENTAL CRUST AND COMPRESSING FLOW ALONG THE MARGINS OF MOUNTAIN BELTS.

THANK YOU
FOR
YOUR
ATTENTION