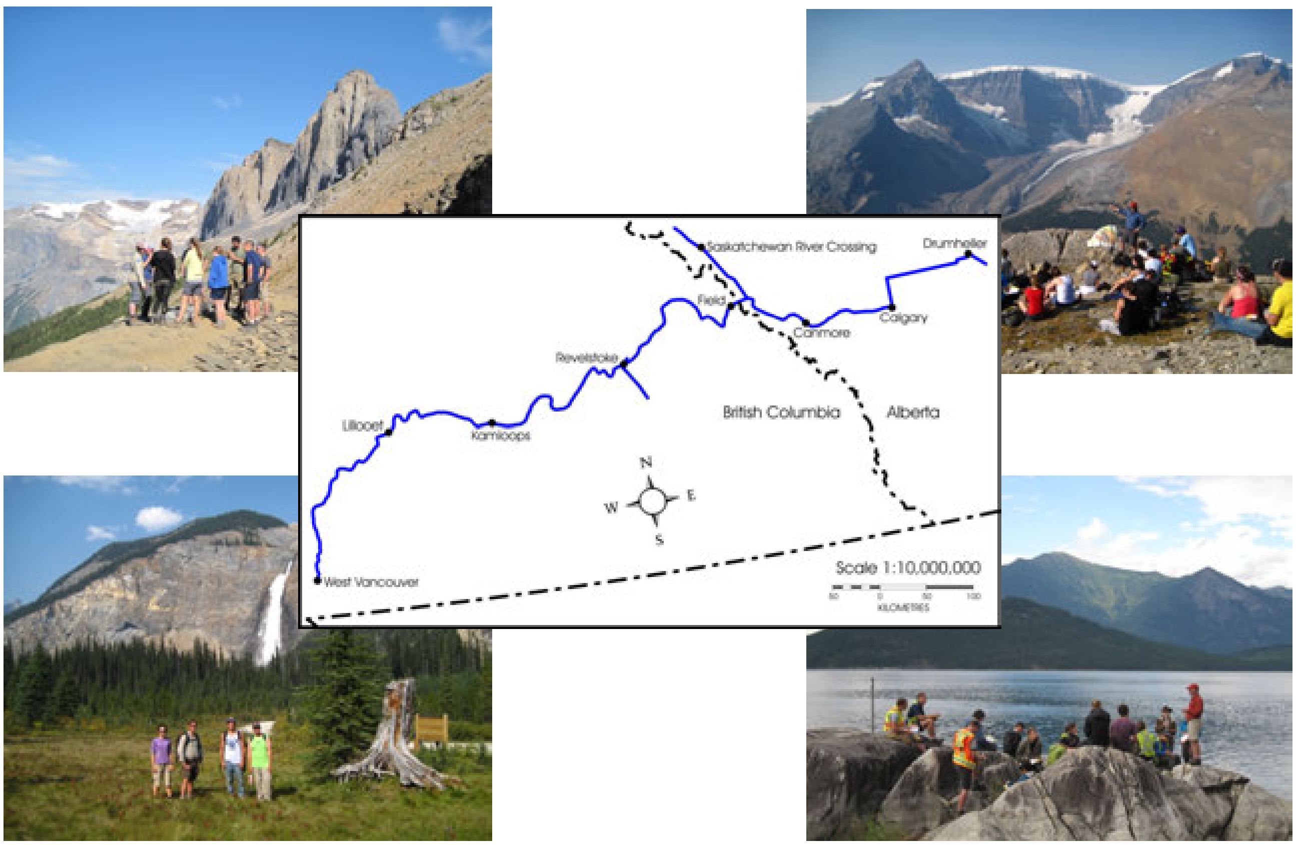
Advanced Field Geology
Western Canada
Cordilleran Transect

August 21st – 30th, 2013



School of Earth & Ocean Sciences
University of Victoria

Name: ______________________________

INTERNATIONAL STRATIGRAPHIC CHART

International Commission on Stratigraphy

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age (Ma)	GSSP
Phanerozoic	Cenozoic	Quaternary	Holocene		0.0117	GSSP
			Pleistocene	Upper	0.126	
				'Ionian'	0.781	
				Calabrian	1.806	GSSP
				Gelasian	2.588	GSSP
		Neogene	Pleiocene	Piacenzian	3.600	GSSP
				Zanclean	5.332	GSSP
			Miocene	Messinian	7.246	GSSP
				Tortonian	11.608	GSSP
				Serravallian	13.82	GSSP
				Langhian	15.97	
				Burdigalian	20.43	
				Aquitanian	23.03	GSSP
		Paleogene	Oligocene	Chattian	28.4 ±0.1	
				Rupelian	33.9 ±0.1	GSSP
			Eocene	Priabonian	37.2 ±0.1	
				Bartonian	40.4 ±0.2	
				Lutetian	48.6 ±0.2	
				Ypresian	55.8 ±0.2	GSSP
			Paleocene	Thanetian	58.7 ±0.2	GSSP
				Selandian	~61.1	GSSP
				Danian	65.5 ±0.3	GSSP
	Mesozoic	Cretaceous	Upper	Maastrichtian	70.6 ±0.6	GSSP
				Campanian	83.5 ±0.7	
				Santonian	85.8 ±0.7	
				Coniacian	~88.6	
				Turonian	93.6 ±0.8	GSSP
				Cenomanian	99.6 ±0.9	GSSP
			Lower	Albian	112 ±1.0	
				Aptian	125 ±1.0	
				Barremian	130 ±1.5	
				Hauterivian	~133.9	
				Valanginian	140.2 ±3	
				Berriasian	145.5 ±4	

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age (Ma)	GSSP
					145.5 ±4	
Phanerozoic	Mesozoic	Jurassic	Upper	Tithonian	150.8 ±4	
				Kimmeridgian	~155.6	
				Oxfordian	161.2 ±4	
			Middle	Callovian	164.7 ±4	
				Bathonian	167.7 ±3.5	GSSP
				Bajocian	171.6 ±3	GSSP
				Aalenian	175.6 ±3	GSSP
			Lower	Toarcian	183 ±1.5	
				Pliensbachian	189.6 ±1.5	GSSP
				Sinemurian	196.5 ±1	GSSP
				Hettangian	199.6 ±0.6	GSSP
		Triassic	Upper	Rhaetian	203.6 ±1.5	
				Norian	216.5 ±2	
				Carnian	~228.7	GSSP
			Middle	Ladinian	237 ±2.0	GSSP
				Anisian	~245.9	
			Lower	Olenekian	~249.5	
				Induan	251 ±0.4	GSSP
	Paleozoic	Permian	Lopingian	Changhsingian	253.8 ±0.7	GSSP
				Wuchiapingian	260.4 ±0.7	GSSP
			Guadalupian	Capitanian	265.8 ±0.7	GSSP
				Wordian	268 ±0.7	GSSP
				Roadian	270.6 ±07	GSSP
			Cisuralian	Kungurian	275.6 ±0.7	
				Artinskian	284.4 ±0.7	
				Sakmarian	294.6 ±0.8	
				Asselian	299 ±0.8	GSSP
		Carboniferous	Pennsylvanian Upper	Gzhelian	303.4 ±0.9	
				Kasimovian	307.2 ±1	
			Pennsylvanian Middle	Moscovian	311.7 ±1.1	
			Pennsylvanian Lower	Bashkirian	318.1 ±1.3	GSSP
			Mississippian Upper	Serpukhovian	328.3 ±1.6	
			Mississippian Middle	Visean	345.3 ±2.1	GSSP
			Mississippian Lower	Tournaisian	359.2 ±2.5	GSSP

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age (Ma)	GSSP
					359.2 ±2.5	
Phanerozoic	Paleozoic	Devonian	Upper	Famennian	374.5 ±2.6	GSSP
				Frasnian	385.3 ±2.6	GSSP
			Middle	Givetian	391.8 ±2.7	GSSP
				Eifelian	397.5 ±2.7	GSSP
			Lower	Emsian	407.0 ±2.8	GSSP
				Pragian	411.2 ±2.8	GSSP
				Lochkovian	416.0 ±2.8	GSSP
		Silurian	Pirdoli		418.7 ±2.7	GSSP
			Ludlow	Ludfordian	421.3 ±2.6	GSSP
				Gorstian	422.9 ±2.5	GSSP
			Wenlock	Homerian	426.2 ±2.4	GSSP
				Sheinwoodian	428.2 ±2.3	GSSP
			Llandovery	Telychian	436.0 ±1.9	GSSP
				Aeronian	439.0 ±1.8	GSSP
				Rhuddanian	443.7 ±1.5	GSSP
		Ordovician	Upper	Hirnantian	445.6 ±1.5	GSSP
				Katian	455.8 ±1.6	GSSP
				Sandbian	460.9 ±1.6	GSSP
			Middle	Darriwilian	468.1 ±1.6	GSSP
				Dapingian	471.8 ±1.6	GSSP
			Lower	Floian	478.6 ±1.7	GSSP
				Tremadocian	488.3 ±1.7	GSSP
		Cambrian	Furongian	Stage 10	~492*	
				Stage 9	~496*	
				Paibian	~499	GSSP
			Series 3	Guzhangian	~503	GSSP
				Drumian	~506.5	GSSP
				Stage 5	~510*	
			Series 2	Stage 4	~515*	
				Stage 3	~521*	
			Terreneuvian	Stage 2	~528*	
				Fortunian	542.0 ±1.0	GSSP

Intra-Cambrian unit ages with * are informal

Eonothem Eon		Erathem Era	System Period	Age (Ma)	GSSP
				542.0 ±1.0	
Precambrian	Proterozoic	Neo-proterozoic	Ediacaran	~635	GSSP
			Cryogenian	~850	
			Tonian	1000	
		Meso-proterozoic	Stenian	1200	
			Ectasian	1400	
			Calymmian	1600	
		Paleo-proterozoic	Statherian	1800	
			Orosirian	2050	
			Rhyacian	2300	
			Siderian	2500	
	Archean	Neoarchean		2800	
		Mesoarchean		3200	
		Paleoarchean		3600	
		Eoarchean		4000	
	Hadean (informal)			4600	

Subdivisions of the global geologic record are formally defined by their lower boundary. Each unit of the Phanerozoic and the base of the Ediacaran are defined by a basal Global Boundary Stratotype Section and Point (GSSP - http://www.stratigraphy.org/index.php) whereas Precambrian units are formally subdivided by absolute age. Numerical Ages are from 'A Geologic Time Scale 2004', by Gradstein, F.M., Ogg, J.G., Smith, A.G., et Al. (Cambridge University Press) and 'The Concise Geologic Time Scale' by Ogg, J.G., Ogg, G. and Gradstein, F.M. (2008), and are subject to revision. Most sub-Series boundaries (e.g., Middle and Upper Aptian) are not formally defined.

Advanced Field Geology (EOS 400) Syllabus

Instructor:	**Dr. Stephen Johnston**	Office:	**SCI A405 (SEOS Office)**
E-mail:	**stj@uvic.ca**	Tel:	**(250) 472–5133**

Required readings (to have been completed prior to departure)

Download compressed file from http://www.uvic.ca/science/seos/assets/docs/afgreadings13.pdf

Course Goals

- To provide you with the opportunity to synthesize the geological skills learned in the class room into a coherent framework, and to apply your geological knowledge to the analysis of an orogen.
- To give you the opportunity to ask BIG QUESTIONS (What is an orogen? What gave rise to the rocks underlying the mountains and plains? How can we relate plate tectonics to the growth and deformation of continents? What are terranes and how do they relate to plate boundaries?)
- To impress upon you how geological systems work on a lithospheric scale.
- To endeavour to understand the regional scale anatomy and evolution of an orogen.
- To improve you observational and data recording skills

Methodology

The course consists of a 10 day transect of an orogen, normally the southern Canadian Cordillera, and includes several hikes, as well as numerous road-side stops. The stops are designed to provide access to sections and rock exposures key to unravelling the evolution of the orogen. Students will maintain a field notebook in which they are to record geological observations and complete specific field-based studies (measured sections, structural analysis, etc.). Field notes should be legible and structured.

Each evening during the field trip, three to four students will each provide individual, 5 to 10 minute formal presentations on an aspect of the geology covered during that day. The presenters are required to discuss topics with one another in order to insure little or no overlap between presentations. Presentations will act as jumping off points for discussion of key points of interest and unresolved questions arising out of the day's field work. Presentations MUST address the relevant required readings, where applicable.

Participation, both in the field and during the evening discussion sessions, is essential and will count towards your final course grade. A final exam will be administered at the University on Tuesday, September 3rd (time/location TBD). Questions will address the required readings and material covered during the transect. Students can access their field notebook (but not the Field Guide or any other references) during the exam.

Grading

Final Exam	35%	Presentation	15%
Research Paper	35%	Participation	15%

Grade Assignment

A+	90 – 100%	B+	77 – 79%	C+	65 – 69%
A	85 – 89%	B	73 – 76%	C	60 – 64%
A–	80 – 84%	B–	70 – 72%	D	50 – 59%
				F	< 50%

Day	Date	Details
1	Wednesday, August 21st	Depart Lot 1 @ 6am for Canmore (~ETA: 9pm MDT). Note: we lose one hour just east of Rogers Pass. **No evening discussion**
2	Thursday, August 22nd	Depart hotel@ 8am for Calgary via Exshaw. **GRASSI LAKES** – A 2km (one way distance)/180m (elevation gain) hike up a well-marked trail to south side of the upper lake, with a view north to the cliff face. Hangingwall of the Rundle Thrust. Cliffs above us are part of the Paleozoic platform sequence, whereas rocks underlying Canmore (an old coal mining town) consist of Mesozoic clastic sequences. View to the northeast is of southwest dipping Mississippian and Triassic strata of the upper part of the McConnell thrust system. Drive into Canmore – grocery store stop (***next stop: 48 hours***). Drive east to Exshaw. **JURA CREEK** – 3.5km/225m hike up Jura Creek to a Devonian-Mississippian section exposed in the upper canyon. Bring sun screen, water, and your lunch. A second stop will be made ~half way back to the vans. Drive east to Calgary. **Evening Discussion:** Review of the Paleozoic passive margin stratigraphy/global paleogeography (where was North America during deposition of the sedimentary rocks observed today?). Preview of Mesozoic orogenic sedimentary rocks/foreland basin to be studied tomorrow.
3	Friday, August 23rd	Depart Calgary @ 8 am. Drive east to East Coulee, returning to Calgary via Drumheller. **EAST COULEE** – A short traverse up-section through the Bearpaw-Horseshoe Canyon transition. Drive west to Drumheller, stopping briefly at the Hoodoos Recreational Area for a bathroom break. **ROYAL TYRRELL MUSEUM** – A 'behind-the-scenes' tour of the research portion of the museum plus ~1 hour free time to explore the exhibits. Drive west to Horseshoe Canyon. **HORSESHOE CANYON** – A short traverse through the upper Horseshoe Canyon Formation across the canyon. Return to Calgary. **Evening Discussion** Review of origin, character and stratigraphy of the Foreland basin. Significance of the clay content of the rocks. What was the 'Western Interior Seaway'? Significance of the Carmacks Group for the foreland basin. Preview of structure of the Foreland belt (Foothills, Front , Eastern and Western Main & Western Ranges).
4	Saturday, August 24th	Depart Calgary @ 8 am. Drive west into the mountains, ending at Saskatchewan River Crossing. **SEEBE DAM/ MT. YAMNUSKA VIEWPOINT** – Observe the stratigraphy/structure of Cretaceous sediments exposed below the dam as well as the Foothills/Front Ranges transition, marked by the McConnell thrust. Drive into Canmore – grocery store stop (***next stop: 72 hours***). Drive west towards Banff. **BANFF TRAFFIC CIRCLE** – View (to the NW) of Cascade Mountain and (to the SE) Mt. Rundle. Note the Palliser-Banff-Rundle mountains profile/disharmonic folding on Cascade Mountain. **Panorama:** While traveling west towards Lake Louise, watch for each of the Rundle, Sulphur Mountain, Bourgeau and Sawback thrust sheets, as we pass from the platformal into the shelfal portion of the ancient passive margin of the continent. **LAKE LOUISE** – A 1km/100m hike along the southeast side of the lake. Lake Louise lies in the hangingwall of the Simpson Pass thrust fault. The fault carries a thick section of latest Neoproterozoic and younger strata. Drive north along the Icefields Parkway. **BOW SUMMIT VIEWPOINT (optional)** – This is the highest road pass in the four mountain parks at 2,088 metres above sea level. A short uphill walk from the parking area leads to a spectacular view of glacially fed and brilliantly turquoise Peyto Lake, formed in a valley of the Waputik Range, between Caldron Peak, Peyto Peak and Mount Jimmy Simpson. Continue north to Saskatchewan River Crossing. ***Continued…***

4	Saturday, August 24th (*cont.*)	**Evening Discussion** Geometry and development of the Foreland Fold and Thrust Belt. Changes in the passive margin stratigraphy as you move west (platform to shelf, the increase in preserved/exposed stratigraphy, and related changes in structural style). Tectonic setting of Lake Louise Strata. Preview of Wilcox Pass (Ordovician stratigraphy) – a not-so-passive, passive margin; Miette (Neoproterozoic stratigraphy); structural style – upper crustal *vs.* mid-crustal.
5	Sunday, August 25th	Depart Saskatchewan River Crossing @8 am heading north to Athabasca Glacier / Wilcox Pass before returning south and ending the day in Field. **WILCOX PASS** – A challenging 5+km/460m hike into the pass. View across to the continental divide triple point – rivers draining into three widely separated basins. **ATHABASCA GLACIER** – A short view stop. Note the rate of recession (global warming or not?) and the crevassed nature of the ice sheet and the nature of the glacier-related sedimentary sequences. Drive south along the Icefields Parkway towards Lake Louise. **HIGHWAY 1/93 INTERCHANGE** – Neoproterozoic Miette Group carried in the hangingwall of the Simpson Pass thrust. Drive west into Field. **Evening Discussion** Significance of the Neoproterozoic strata (rifting of Rodinia?). Ordovician stratigraphy of the Miogeocline; Upper crustal (Front Range) vs. mid-crustal (Main Range) deformation. Preview of Western Main Ranges and Burgess Shale.
6	Monday, August 26th	Depart Field @ 8 am from Yoho Bros. Trading Post (Burgess Pass trailhead). **BURGESS SHALE** – A demanding 8.5+km/1,100m hike to Walcott Quarry via Burgess Pass. The quarry is a UNESCO World Heritage Site, so collecting fossils is strictly prohibited (*i.e.* don't do it!). Hike down to Takkakaw Falls and drive ~15 kilometres west of Field. **KICKING HORSE RIVER VIEWPOINT** – Cambrian Chancellor Formation exposed in the core of the Porcupine Creek Anticlinorium. ***Please cross the highway to this outcrop as a group when traffic allows***. Return to Field **Evening Discussion** Significance of the Burgess Shale, structure of the Main Ranges; shelf to basin transition within the Miogeocline. Preview of the Omineca Crystalline Belt, and the nature of the Rocky Mountain Trench.
7	Tuesday, August 27th	Depart Field @ 8 am heading west for Revelstoke. Note: we gain one hour just east of Rogers Pass. **GOLDEN TIMMY'S** – The Rocky Mountain Trench and the transition from auto- to allochthonous sequences. **REDGRAVE REST AREA** – Ediacaran to Lower Cambrian Hamill Quartzite, that are considered correlative with the Gog Group. Note that the Hamill Group locally includes rhyolitic tuffs and basalt flows. Continue west to Revelstoke. **COAST HILLCREST RESORT** – Crystalline rocks of the Kootenay Terrane, the most inboard of the terranes currently distinguished from North America. Drive into Revelstoke – grocery store stop (***last one!***). Drive south to shelter Bay. **SHELTER BAY FERRY LANDING** – 162 Ma Galena Bay stock. Walk on the first available ferry for the 20 minute crossing to Galena Bay. **GALENA BAY FERRY LANDING** – A large-scale mapping exercise on a heterogeneous outcrop exposing complexly interrelated rocks near the core of the Galena Bay stock. Catch the ferry back to Shelter Bay and return to Revelstoke. **Evening Discussion** Nature of the Omineca Crystalline Belt; terranes – pericratonic Kootenay terrane; age of tectonism; links to Foreland Belt. What defines a 'terrane'? How do we explain magmatism, and what constraints to do magmatic rocks provide? Implications of available paleomagnetic data? Preview of the Intermontane Belt.

Day	Date	Details
8	Wednesday, August 28th	Depart Revelstoke @ 8 am heading west to Kamloops via the Revelstoke Dam. **REVELSTOKE DAM OVERLOOK** – High-grade metamorphic rocks assigned to the Lower Paleozoic Lardeau Group in the hanging wall of the Columbia River fault. **REVELSTOKE DAM** – You'll have approximately one hour to self-tour the dam. Security at the dam has been very tight since 9/11. Please take any questions asked of you seriously. Cameras/daypacks are not allowed inside the facility. Drive west towards Kamloops. **SHUSWAP LAKE** – Mississippian to Permian(?) Tsalkom Formation. Proceed down to the beach. Continue west towards Kamloops **HARPER RANCH HOUSE** – Harper Ranch Group exposed above the South Thompson River. Drive into Kamloops **Evening Discussion** Core Complex Formation; Eocene extension and its relationship to crustal thickening; the Intermontane Belt links to Omineca belt. Accreted terranes, and the relationship between accretion, deformation, metamorphism and foreland basin stratigraphy.
9	Thursday, August 29th	Depart Kamloops @ 8 am heading west to Lillooet. **KAMLOOPS LAKE OVERLOOK** – Nicola Group volcanics on the bluffs above the rest area. ***Be aware of the precipitous cliffs on the north side of this outcrop.*** **SAVONA VIEWPOINT** – Upper Triassic Nicola Group rocks. ***Please be careful when crossing the highway.*** Continue west toward Cache Creek **McABEE FOSSIL SITE** – Eocene-aged Tranquille sediments host an abundance of plant, insect and fish fossils at this locality. Note the hoodoo-like 'columns' above the road. Continue west into Cache Creek. Dairy Queen stop - caution should be exercised should you choose to consume a large-sized Blizzard! **CACHE CREEK** – The easternmost (of three) facies of the Cache Creek Complex: an early Mesozoic accretionary complex that likely accompanied the Nicola arc. These rocks are part of the Cache Creek terrane, along or close to its boundary with Quesnellia. Drive north and then west towards Lillooet. **HAT CREEK TURN-OFF** – Middle Permian to Late Triassic Marble Canyon Formation, which forms the central belt of the southern part of the Cache Creek Complex. ***Please be aware of the traffic, especially at the eastern end of the outcrop***. Continue west and then south towards Lillooet. **FRASER RIVER VIEWPOINT** – Middle to Late Eocene-aged, dextral strike-slip Fraser River/Straight Creek fault system. Note mid-Cretaceous Spences Bridge Group volcanics underlying the mountains to the south. Continue west and then south towards Lillooet. **Evening Discussion** Significance of the Cache Creek Terrane. Placing all of the terranes within a plate tectonic framework. Paleomagnetic data. How do we relate Intermontane terranes to the Rocky Mountain Foreland to the east?
10	Friday, August 30th	Depart Lillooet @ 7:30 am for Victoria via Pemberton and Tsawwassen (8 pm ferry) **JOFFRE LAKES RECREATION AREA** – Intrusive rocks of the Cretaceous Mt. Rohr Pluton(?). Continue south to Whistler. **WHISTLER MOUNTAIN** – Gambier Volcanic belt. We'll ride the gondola up to the Roundhouse and map while hiking to the peak. Time/weather permitting, we'll ride the Peak to Peak across to Blackcomb Mountain. Continue south through Vancouver to Tsawwassen via the Iron Workers Memorial Bridge. **Ferry terminal:** Please return all your equipment before we board the ferry

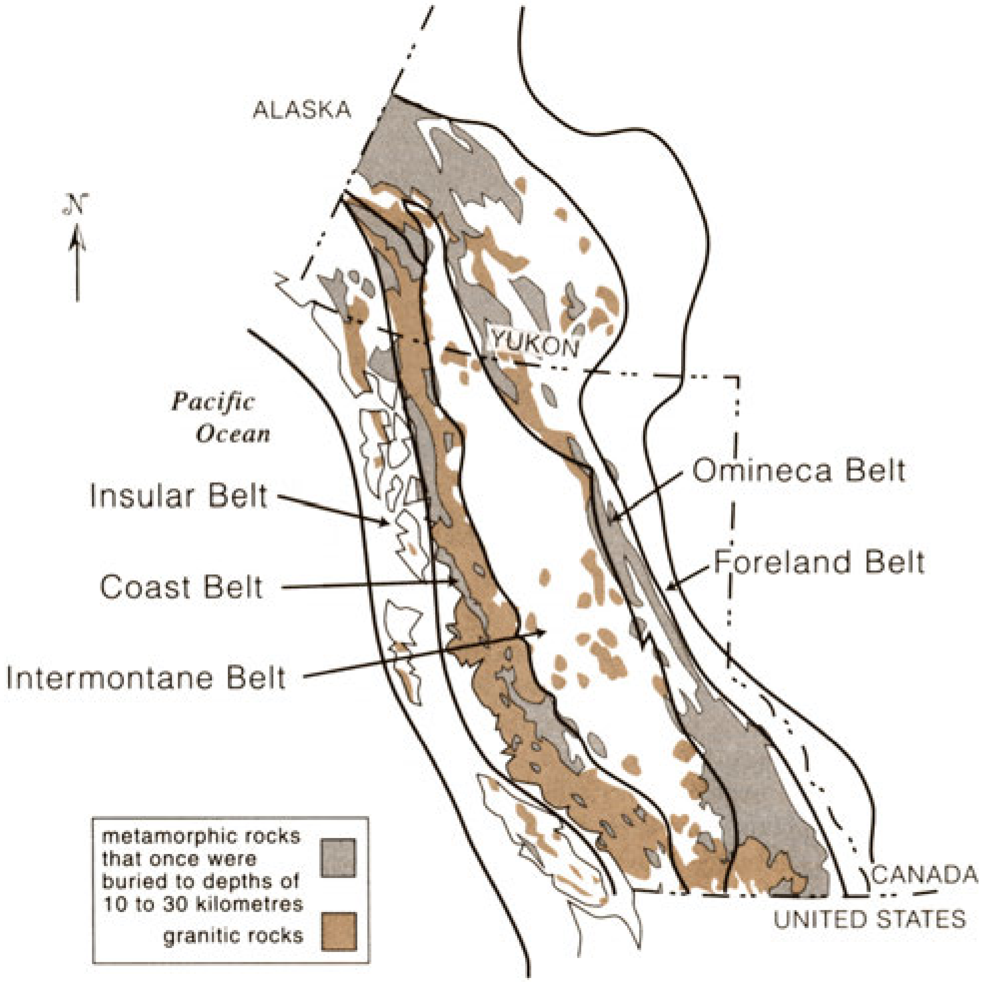
Introduction

The origins of the Canadian Cordillera extend back >540 Ma to the episode of rifting that marked the break-up of a continent that included what is now North America (Bond and Kominz, 1984). The earliest Cambrian break-up of the continent led to the opening of a new ocean basin that was the distant precursor of the present Pacific Ocean basin, and to the formation of a passive margin along the newly formed west coast of our continent. The identity of the continent that drifted away from North America remains unknown; the suspects include Australia, South China and Siberia.

What transpired between 540 Ma and the drowning of the passive west margin of the continent at 152 Ma, an event recorded by the inundation of the continent by distal turbidites and black shales of the Fernie Group, remains poorly understood. Cambrian and Ordovician carbonate strata provide a record of a tropical passive margin. A major 'sub-Devonian' unconformity removed most all Middle Devonian to Ordovician strata throughout much of the Canadian Cordilleran foreland, and was followed by what appears to be the re-establishment of a stable passive margin in the Upper Devonian. A major transgressive event marks the end of the Devonian followed by a final stratigraphic sequence that again appears to record passive margin sedimentation stretching from the Mississippian through into the Middle Jurassic. This last passive margin sequence was coeval with and represents the geological record of sedimentation along the west margin the Pangea supercontinent.

152 Ma marked the death of the passive margin and the beginning of orogenic sedimentation along the western margin of North America; the passive margin had been replaced by an active margin characterized by subduction, arc-magmatism and accretion. Black shales of the Upper Fernie Group record drowning of the continent, presumably in response to isostatic loading of the continents western margin by exotic thrust sheets. The presence of distal tuffs within the Fernie Group strata attests to active calc-alkaline magmatism. And while it is clear that active margin processes are in some way responsible for the subsequent deformation and imbrication of the passive margin strata the details remain obscure. The faults and folds responsible for giving us the Rocky Mountains of southern Alberta did not develop until the Late Cretaceous, between about 80 and 50 Ma. What transpired between the demise of the passive margin at 152 Ma, and the formation of the Rockies between 80 and 50 Ma, remains a matter of much debate.

By 50 Ma, the Canadian Cordillera had attained its present day geometry. There has been more or less constant eastward subduction of oceanic lithosphere underlying the Paleo-Pacific ocean basin beneath the west margin of the continent since that time. Magmatism and deformation attributable to the interaction of the continent with the subducting slabs have to some extent obscured the older record of orogeny, and rendered the chore of resolving the geological history of western North America that much more difficult. There remains much about the evolution of our Cordilleran orogen that we don't know and don't understand. Research opportunities are abundant, and the questions that remain to be addressed are fundamental.



Morphogeological Belts of British Columbia (Mathews & Monger, 2005)

INSULAR BELT (Vancouver Island, Strait of Georgia, modern continental shelf and slope)

Magmatic arcs and accretionary complexes welded to the continent about 95 million years ago; 90-million-year-old to present sediments eroded from uplifted Cordilleran mountains.

COAST BELT (Coast and Cascade Mountains)

Terranes accreted to the continent about 95 million years ago, including 170- to 110-million-year-old granitic rock of an island arc; granitic rock of the Coast Mountains belong to a continental arc that formed 95 to 45 million years ago; young volcanic rock of the Cascade continental arc.

INTERMONTANE BELT (Interior Plateaus)

Rocks of three terranes (Quesnel island arc, Cache Creek accretionary complex, and Slide Mountain ocean basin) were welded to the continent about 185 to 170 million years ago and intruded by granites of continental arcs; plateau basalts spread across the region 10 million years ago.

OMINECA BELT (Okanagan and Shuswap Highlands; Monashee, Purcell, Selkirk, and Cariboo Mountains, collectively called the Columbia Mountains)

Precambrian to Paleozoic sedimentary rocks deposited on or near the ancient North American continent and metamorphosed during Cordilleran mountain building between 180 and 60 million years ago; granitic rock formed in magmatic arcs; normal faulting during crustal stretching began 55 million years ago.

FORELAND BELT (Rocky Mountains)

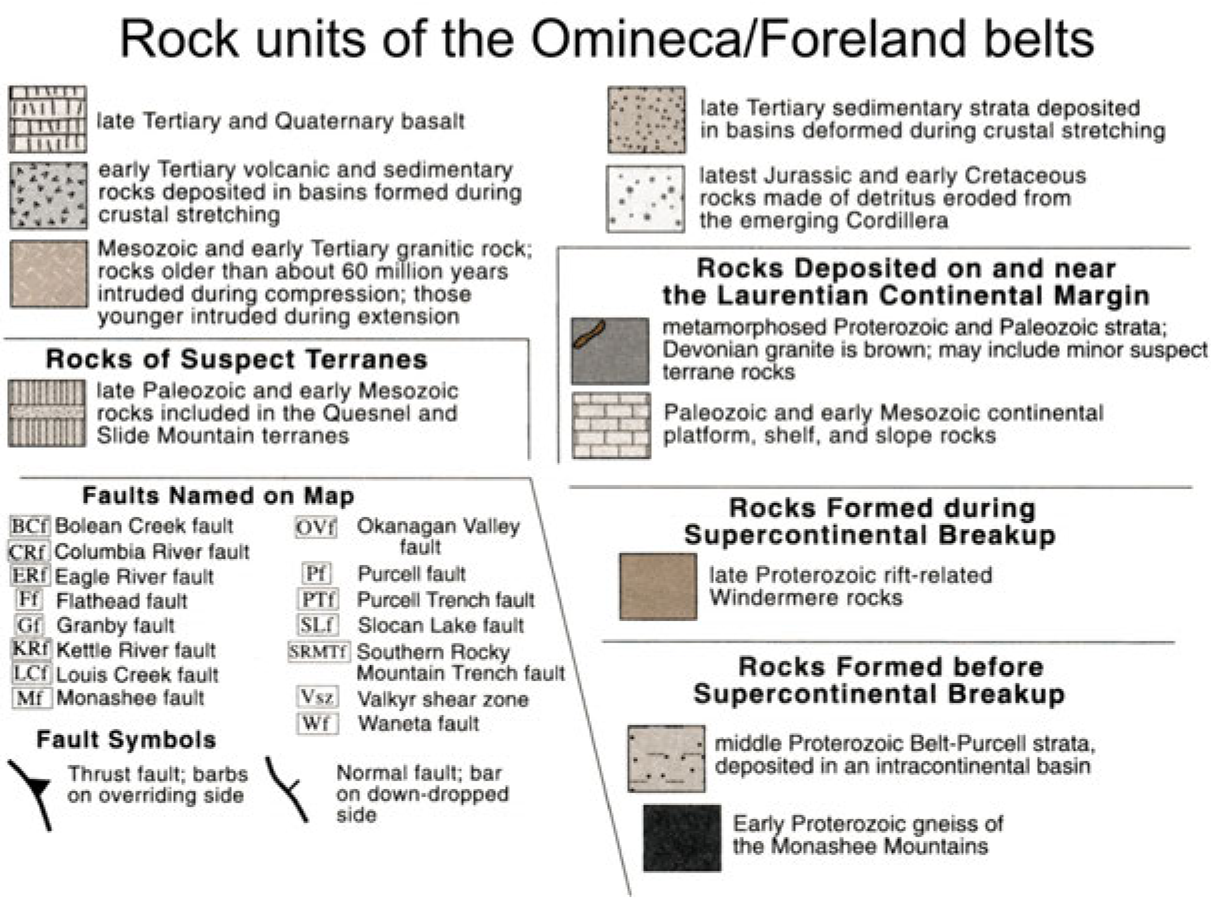
Precambrian through early Mesozoic rocks deposited on or near the margin of the ancient North American continent and thrust over the edge of the ancient continental platform during Cordilleran mountain building between 100 and 60 million years ago.

The following descriptions of the morphogeological belts have been modified after Mathews & Monger, 2005:

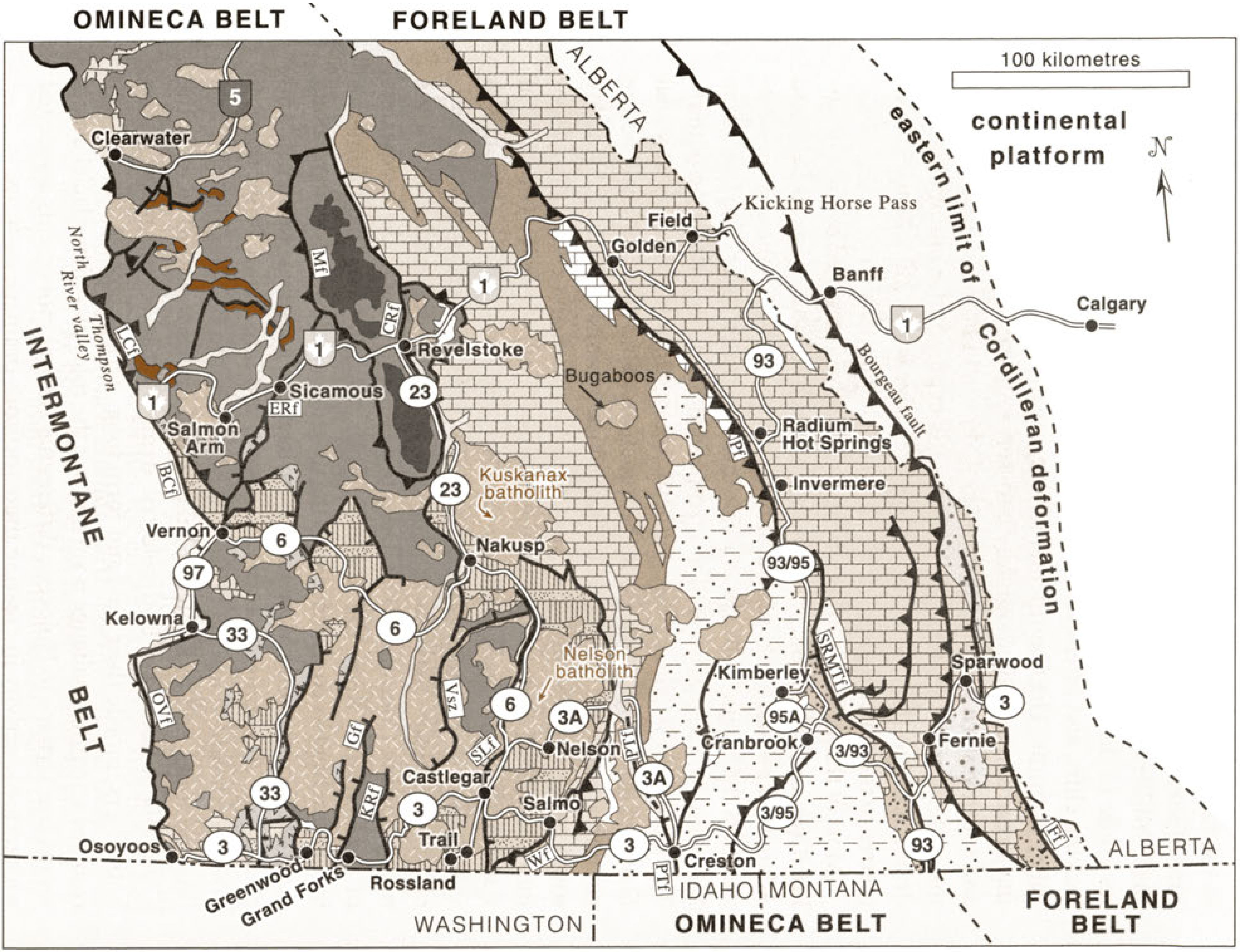
Omineca and Foreland Belts

The Omineca and Foreland Belts are names applied by geologists to the eastern part of the Canadian Cordillera, extending 2,500 kilometres from the Arctic Ocean at 70^{o} latitude to the international boundary at 49^{o} latitude. In the south, this mountainous region is up to 400 kilometres wide, with the easternmost section continuing for 50 to 100 kilometres into the province of Alberta. The great longitudinal valley called the Rocky Mountain Trench separates the two belts in British Columbia. The name 'Omineca' is taken from the Omineca Mountains, which lie west of the northern Rocky Mountain Trench between 54^{o} and 56^{o} latitude. The name 'Foreland' refers to the position of that belt in the easternmost Canadian Cordillera and to its structural style.

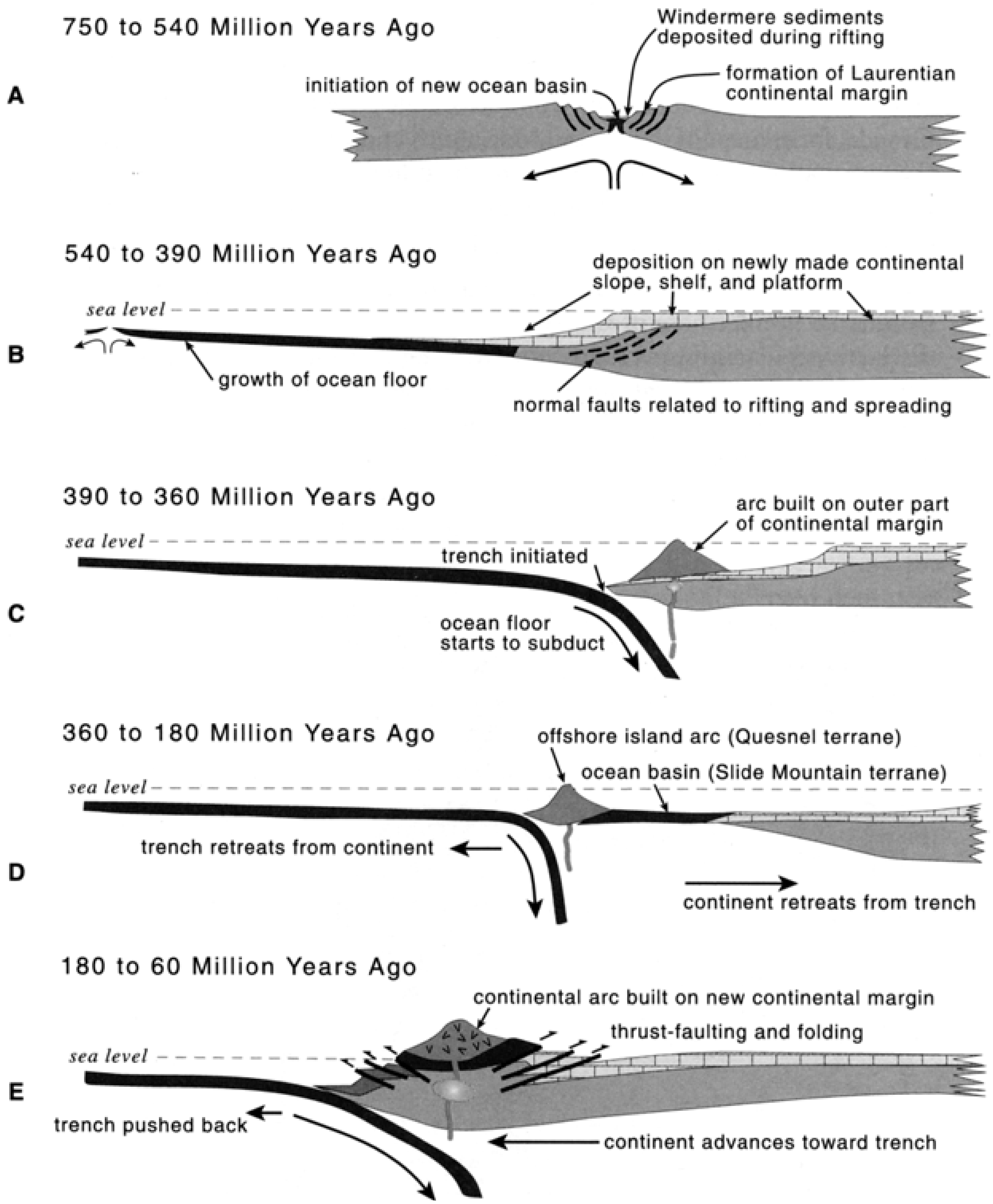
In most, but not all models of Cordilleran evolution it is assumed that the geological evolution of the Omineca and Foreland belts are linked. There are, however, major differences between the two belts. First, and perhaps most distinctively, the Omineca Belt contains extensive areas of high-grade metamorphic rock, whereas most rocks in the Foreland Belt have undergone little metamorphism. Second, granitic, and in places, volcanic rocks are widespread in the Omineca Belt, whereas the Foreland Belt is underlain largely by sedimentary rock. Third, the Omineca Belt is overthrust from the west by oceanic terranes of the Intermontane Belt, whereas the Foreland Belt consists largely of continental passive margin and younger orogenic sedimentary sequences.



(Mathews & Monger, 2005)



OMINECA BELT
FORELAND BELT
ALBERTA
100 kilometres
continental platform
eastern limit of Cordilleran deformation
Kicking Horse Pass
Field
Golden
Banff
Calgary
Bourgeau fault
Clearwater
Revelstoke
Sicamous
Salmon Arm
North Thompson River valley
LCf
Mf
CRf
ERf
BCf
Bugaboos
Radium Hot Springs
Invermere
Kuskanax batholith
Nelson batholith
INTERMONTANE BELT
Vernon
Nakusp
Kelowna
OVf
Gf
KRf
Vsz
SLf
PTf
SRMTf
Ff
Wf
Kimberley
Cranbrook
Sparwood
Fernie
Nelson
Castlegar
Salmo
Trail
Rossland
Osoyoos
Greenwood
Grand Forks
Creston
ALBERTA
IDAHO
MONTANA
WASHINGTON
OMINECA BELT
FORELAND BELT



Evolution of the southeastern Canadian Cordillera from the time of initial rifting of the super continent Rodinia to the later stages of crustal thickening and mountain building. **A.** ***In Late Proterozoic time, Rodinia rifted apart.*** **B.** ***From Late Proterozoic to Middle Paleozoic time, sediments were deposited on the Laurentian continental margin.*** **C.** ***In Devonian time, a convergent margin developed and a magmatic arc formed.*** **D.** ***In Late Paleozoic to early Mesozoic time, the Quesnel island arc was separated from the continental margin by a deep ocean basin, as the continents amalgamated into the supercontinent Pangea.*** **E.** ***From Middle Jurassic to Early Tertiary time, the North American continent advanced towards the trench, causing Cordilleran mountain building.*** **(Mathews & Monger, 2005)**

Intermontane Belt

The Intermontane Belt occupies the central part of the Canadian Cordillera between south-central Yukon and northernmost Washington state, a distance of 1,800 kilometres. The belt is 200 kilometres wide in the middle, near Prince George BC, but tapers and pinches out to the north and south. In contrast with the flanking, mostly mountainous Coast and Omineca Belts, the topography is subdued. High plateaus, rolling uplands, and deeply incised valleys are typical of the southern Intermontane Belt. The volcanic and sedimentary rocks that make up the Intermontane Belt are of very low metamorphic grade, again in contrast with the rocks in the flanking belts.

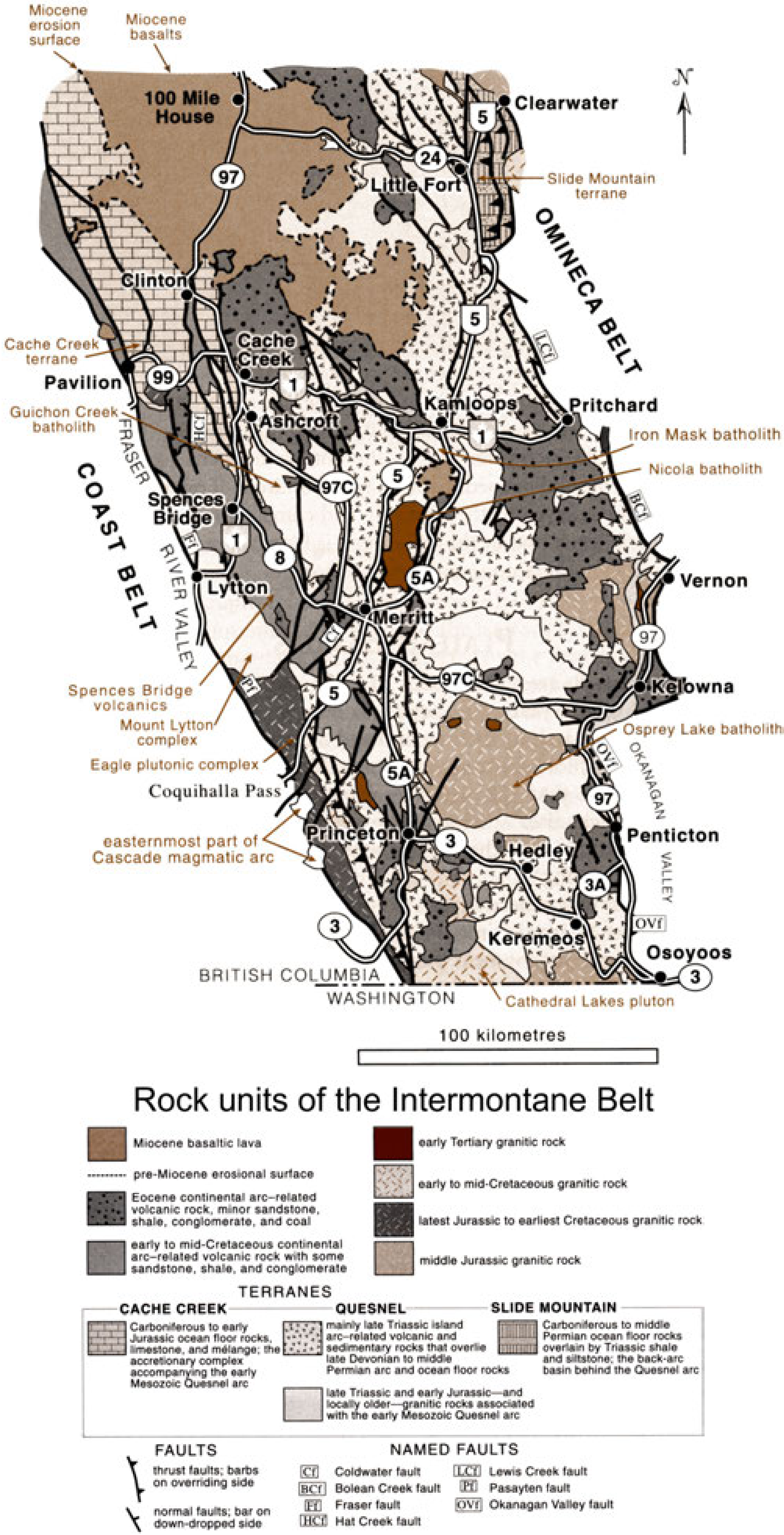
The Intermontane rocks are of Upper Devonian to Lower Jurassic age (about 360 to 180 million years old), and are divisible into several fault-bound terranes that include Stikinia, Quesnellia Cache Creek, and Slide Mountain. Their rock types, fauna and chemistry indicate an oceanic provenance for the Intermontane terranes. They accreted to and overthrust the continental strata of the Omineca belt in the Upper Triassic, thickening the Omineca belt crust, and explaining the widespread metamorphosed character of the Omineca belt.

Quesnel terrane. The Quesnel terrane, named for a town in central BC 300 kilometres NNW of Kamloops, is the dominant terrane in the southern Intermontane Belt. Much of the terrane consists of Late Triassic and minor Early Jurassic lava, volcanic breccia, and tuff interbedded with marine shale and minor limestone, with numerous coeval granitic intrusions. The granitic rocks host major copper-gold deposits, and copper mineralization is widespread in the volcanic rocks. Although Triassic volcanic rocks dominate the western part of the Quesnel terrane, east of Kamloops they grade laterally into marine shale, siltstone, and localized volcanic-rich sandstone and tuff. The volcanic and granitic rocks probably formed in an offshore volcanic island arc like the modern Japanese or Philippine island chains, with little or no continental crust below it at the time it formed. The Quesnel arc was proximal to a back-arc basin, containing mud and silt. Parts of the basin are preserved further to the east.

The early Mesozoic volcanic-arc rocks overlie two different Late Paleozoic rock units: (1) a Late Devonian through Permian unit of volcanic sandstone and tuff of arc origin with interbedded shale, limestone, and in places chert-pebble conglomerate; and (2) a unit of basalt, tuff, radiolarian chert, shale, sandstone, and minor ultramafic rocks of Carboniferous and Permian age that may represent ocean lithosphere of the Slide Mountain terrane.

Cache Creek terrane. The Carboniferous to earliest Jurassic Cache Creek terrane crops out west of the Quesnel terrane. It thus overlaps the age of the Quesnel terrane but is of different character. It consists of disrupted and broken radiolarian chert, argillite, volcanic rock including pillow basalt, large distinctive masses of limestone, and locally, serpentinite and gabbro. With the exception of the limestone, the other rock types are typical of those found on floors of deep ocean basins, and this, together with the jumbled, deformed nature of the Cache Creek terrane, suggests that it is material scraped off of an oceanic plate at a subduction zone – part of an ancient accretionary complex.

The presence of blueschist near Fort St. James in central BC is consistent with an accretionary complex interpretation. Blueschist, a rock containing the bluish sodium amphibole mineral glaucophane, forms during high pressure-low temperature metamorphism, conditions known to characterize subduction zones. The blueschist in central British Columbia is of Late Triassic age (220 to 210 Ma) indicating that subduction was active at this time. Blue amphibole is known in two places in the south, but no true blueschist.



(Mathews & Monger, 2005)

The original relationship between the Quesnel and Cache Creek terranes remains obscure, in part because they are now juxtaposed along younger faults. However, the geographic distribution and chemical composition of rock types in Quesnellia have been used to suggest that it originated as a west-facing island arc that formed above an east-dipping subduction zone. The Cache Creek terrane, lying to the west of Quesnellia, has the right characteristics, is the right age, and is in the right place to be the accretionary complex that formed within the forearc region of the Quesnel arc.

Slide Mountain terrane. The Slide Mountain terrane, named for a locality near Barkerville in the Cariboo Mountains, 300 kilometres north of Kamloops, is the easternmost of the accreted terranes and straddles the boundary between the Intermontane and Omineca belts. Rocks of the Slide Mountain terrane form a series of discrete thrust sheets that extend from near Kootenay Lake in SE BC north to Yukon. The terrane is ophiolitic and includes ocean floor rocks of Upper Devonian to Permian age. Because the Slide Mountain terrane is the same age as, and lies east of and behind the west-facing arc that comprises Quesnellia, it has been interpreted as a back-arc basin that formed in response to rollback of the slab subducting beneath Quesnellia. The Slide Mountain terrane is overlain by a blanket of Triassic shale and phyllite that probably extended from the Omineca belt across to the east side of Quesnellia.

Faunal data indicate that the terranes of the Intermontane belt did not form near their present position relative to the ancient North American continent. Limestone in the Cache Creek terrane contains shells of calcareous single-celled animals called fusulinids that are of Middle Permian age. Similar fossils of the same age are widespread in Asia, the Middle East, and the Mediterranean region but are unknown in autochthonous North American strata.

Limestone in Middle Permian strata of Quesnellia contain fusulinids unlike those in the Cache Creek terrane but similar to those found in the Slide Mountain terrane and Stikinia, and in coeval strata in California and Nevada.

The Cache Creek fossils with their Asian affinities probably lived in western parts of Panthalassa, the ancestor of the Pacific Ocean, which in Permian time occupied more than half of Earth's surface. How the Cache Creek rocks with their contained fossils came to cross Panthalassa remains unknown. The animals whose remains occur in the early Mesozoic Quesnel arc and its Paleozoic underpinnings, as well as in the Slide Mountain terrane, probably lived in central or eastern Panthalassa, but farther south than they are today relative to the old continental margin. Today, a distance of about 100 kilometres separates the different Cache Creek and Quesnel faunas, but in Middle Permian time, 265 million years ago, they were probably separated by many thousands of kilometers within the Panthalassa Ocean.

Continental Arcs of the Intermontane Belt. The thrusting and folding that accompanied accretion of the Cache Creek, Quesnel, and Slide Mountain terranes to the continental rocks of the Omineca belt occurred about 200 million years ago. Accretion thickened the crust and raised its surface above sea level. In the southern Intermontane Belt, sedimentary and volcanic rocks younger than Middle Jurassic age, less than about 160 million years old, are nonmarine. Middle Jurassic through Eocene granitic rocks represent deeper parts of continental arcs, whose volcanic edifices are preserved in many places. The granitic rocks are found east of the Intermontane Belt in the Omineca Belt, where they intrude continental rocks. Furthermore, the chemistry of Middle Jurassic and younger granitic rocks in the southern Intermontane Belt shows they were derived from crust that contained some old continental crust, unlike the early Mesozoic granitic rocks. This confirms that these rocks formed after the terranes had accreted to a continental terrane.

A Cretaceous, 105-million-year-old continental arc composed of andesitic and rhyolitic lava, tuff, and breccia is associated with sandstone, shale, and conglomerate deposited in lakes and rivers and is accompanied by granitic intrusions of similar age. These volcanic and sedimentary rocks belong to the Spences Bridge group and were deposited on top of both the Quesnel and Cache Creek terranes. Eocene continental arc volcanic rocks, about 50 million years old and belonging mostly to the Kamloops group, are interbedded with sandstone, shale, conglomerate, and minor coal beds, as well as small intrusions, and are widespread across the southern Intermontane Belt and flanking belts. The volcanic rocks include flows that range in composition from basalt to rhyolite and associated pyroclastic rocks.

Plateau Basalts. About 18 to 10 million years ago, in Miocene time, basaltic lava flowed out onto the surface of this part of southern British Columbia, blanketing the rolling landscape with flat-lying layers of hard rock. Later, erosion removed the Miocene basalt cover in many places, but elsewhere, mainly to the north, left extensive high-standing, relatively flat areas capped by the lava.

The plateau basalts are mostly about 10 million years old, but range in age from 20 to 1 million years old. They are akin in composition and age to the Columbia River basalt flows in central and eastern Washington, although the latter are far more extensive and much thicker. The stack of lava flows here is mostly less than 150 metres thick but in places reaches 350 metres. The greater thicknesses accumulated over topographically low areas, for example, in former river channels or where earlier flows had undergone gentle down-warping.

Coast Belt

The Coast Mountains are those mountains north and west of the Fraser River in southwestern British Columbia that extend from the city of Vancouver northwestward along the mainland coast of British Columbia and southeastern Alaska. South and east of the Fraser River the mountains are called the Cascade Mountains in British Columbia and the North Cascades in Washington. They continue south to where the older rocks disappear beneath the extensive cover of volcanic rocks of the Late Eocene to Holocene Cascade magmatic arc. Together, the Coast and Cascade Mountains make up the Coast Belt, a rugged mountainous region 2,000 kilometres long and 100 to 200 kilometres wide, whose most distinctive geologic feature is that it contains abundant granitic rock.

Granitic Rock of the Coast Mountains. Granitic rock makes up about 80 per cent of the Coast Belt. The most common variety of intrusive rock is quartz diorite, followed by granodiorite and diorite. Interestingly, granite is rare. Granitic rocks are so abundant in the Coast Belt that it has been called the Coast Plutonic Complex. Intrusive bodies have an enormous range in size and shape, some more than 50 kilometres long and nearly half that in width.

Contacts between Coast Range plutons and the surrounding country rocks are sharp in places, but elsewhere are indistinct, forming zones a kilometre or more wide. Contacts may also be narrow faults or broad zones of sheared granitic rock, and a few contacts are depositional, where volcanic rock or sediment was laid down on top of an older pluton that had been exposed by erosion.

Isotopic dating of the granitic rocks in the southwestern Coast Belt, west of Harrison Lake, shows that most of them range in age from about 170 to 95 million years old. Granitic rocks in the southeastern Coast Belt, east of Harrison Lake, and in the Cascade Mountains south and east of the Fraser River are mostly younger and range in age from 95 to 45 million years old and are associated with Cordilleran mountain building. Some even younger granitic rocks, about 26 to 18 million years old, straddle the Coast Belt, although they are concentrated in the eastern part, and represent older, deeper parts of the still-active Cascade magmatic arc.

Metamorphic Rocks between the Granites. Many (but not all) of the remaining rocks in the Coast Belt are metamorphosed, made by subjecting pre-existing volcanic, sedimentary, and in some cases granitic rock to high temperatures and pressures. The increased temperature and pressure caused metamorphic minerals to grow at the expense of the former minerals and in some cases completely changed the rock's nature. The metamorphic rocks may form bands or septa, which can be many kilometres long and a few kilometres wide, or small, isolated inclusions within the dominant granitic rocks.

Metamorphic rocks derived from volcanic rocks are common in the Coast Belt. Greenstone (resulting from the low-grade metamorphism of basaltic or andesitic volcanic) and greenschist (where deformation accompanied metamorphism and caused the mineral grains to grow in alignment) are common, as is amphibolite (indicating higher temperatures and pressures). With still greater heating, and especially in the presence of water, the rocks may partially melt, resulting in the segregated bands characteristic of migmatitic gneiss.

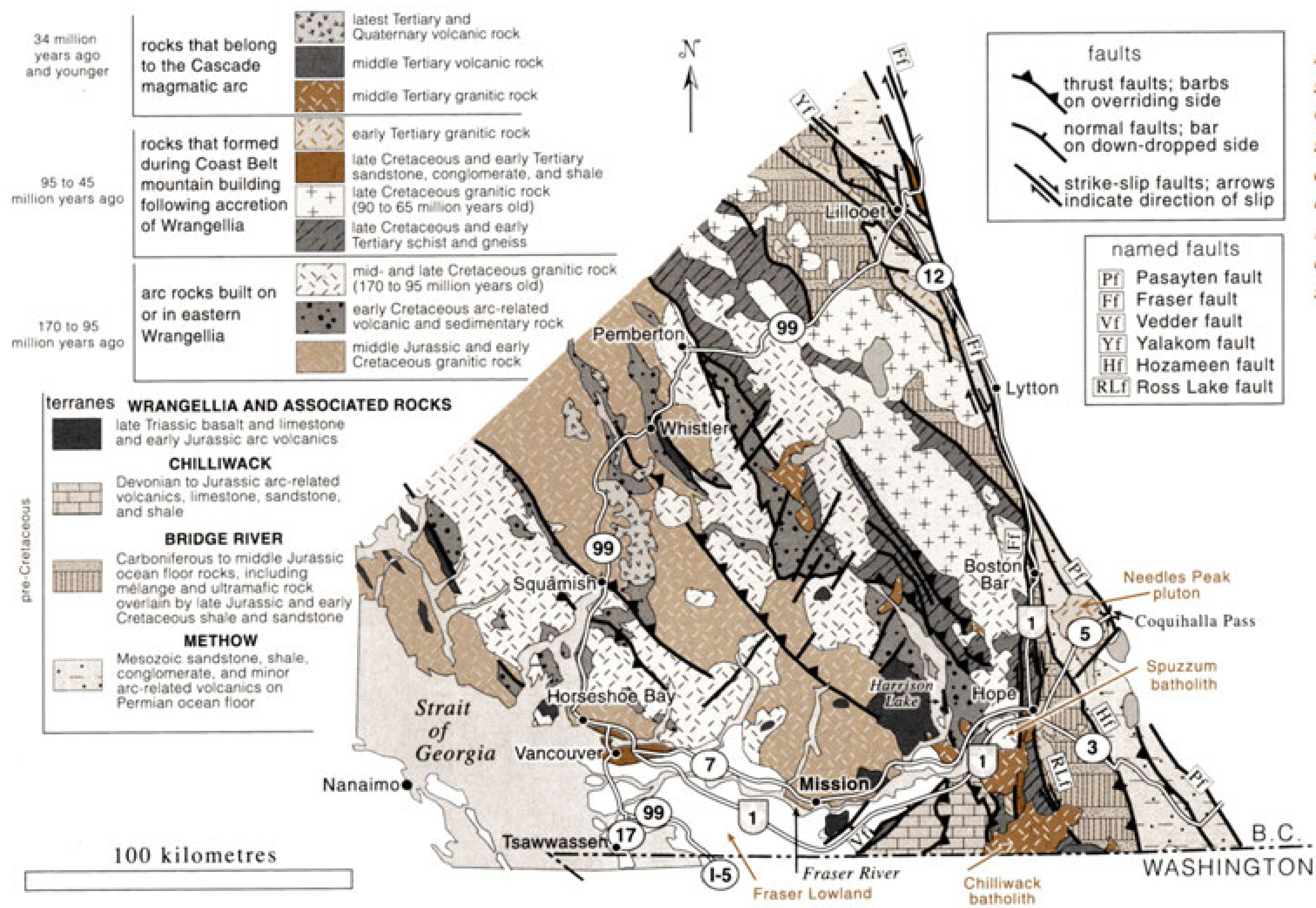
In the Coast Belt, metamorphic rocks derived from sedimentary rocks are less abundant than those derived from volcanic rocks. In the field, they commonly form bands, rusty-coloured when weathered, within the granitic rock, a characteristic that reflects their high pyrite content. At low metamorphic grades, shale or mudstone forms slate or phyllite, with its diagnostic sheen. At higher grades, the rock may form schist.

The temperatures and pressures indicated by metamorphic minerals vary considerably from place to place in the Coast Belt. In the southwestern Coast Belt, the former volcanic and sedimentary rocks appear to have been heated to high temperatures by the abundant granitic intrusions but were probably never buried very deeply. In places, such as on the western side of Harrison Lake and the east and west sides of the Cascade Mountains, the rocks are barely metamorphosed. However, about 10 kilometres east of Harrison Lake, the metamorphic grade is high, and the metamorphic minerals there, typically either staurolite or kyanite and sillimanite (aluminum silicates derived from clay-rich mud and muddy sandstone) require temperatures of up to 700^{o}C and pressures corresponding to burial depths between 15 and 30 kilometres.

Components of the Southern Coast Belt

Terranes. In places such as the flanks of the Cascades and immediately east of Harrison Lake, the rocks are little metamorphosed and we can identify different terranes. Wrangellia, the terrane that underlies much of Vancouver Island, can be traced eastward into the Coast Belt, where it occurs as disconnected shreds within granitic rock. Wrangellia and rocks linked to it in Jurassic time may extend from the western margin of the Coast Belt as far east as the valley containing Harrison Lake and Pemberton. East of this, and also south of the Fraser River and across the international border, are three other terranes. The Devonian to Jurassic Chilliwack terrane contains mainly arc-related rocks that are widespread in the western Cascades but only form a sliver in the Coast Mountains at the southeast end of Harrison Lake. The Carboniferous to Middle Jurassic Bridge River terrane appears to be remnants of an ocean basin floor incorporated in an accretionary complex in Mesozoic time and is overlain by Late Jurassic and Early Cretaceous marine sandstone and shale. The Permian to mid-Cretaceous Methow terrane consists of Permian oceanic crust, on which were deposited marine and mainly arc-derived shale, sandstone, and conglomerate of Mesozoic age. Its youngest sedimentary rocks contain detritus eroded from the Intermontane Belt to the east.

Rock units of the Coast Belt



Map of the southern Coast Belt, showing distribution of rock types, terranes, and geologic structures.

(Mathews & Monger, 2005)

170- to 95-million-year-old granitic rocks. Middle Jurassic to Early Cretaceous granitic rocks and marine volcanic and sedimentary rocks, all between about 170 and 95 million years old, are interpreted to represent the deeper parts of an island arc that formed on the eastern side of Wrangellia; higher parts of the arc are represented by variably metamorphosed volcanic rocks. The granitic rocks, exposed on Quadra and other islands at the north end of the Strait of Georgia and underlying the mainland Coast Mountains, define the western boundary of the Coast Belt. These rocks are rare in the southeastern Coast Belt or in the Cascade Mountains.

90- to 45-million-year-old granitic and metamorphic rocks. Granitic rocks intruded during the folding, faulting, metamorphism, and initial uplift of the Coast Belt are 90 to 45 million years old. The presence of granitic rocks about 95 million years old in both southwestern and southeastern parts of the Coast Belt provides the oldest firm evidence that all components of the Coast Belt were together by that time. Granitic rocks between 90 and 45 million years old are known only in the southeastern Coast Belt.

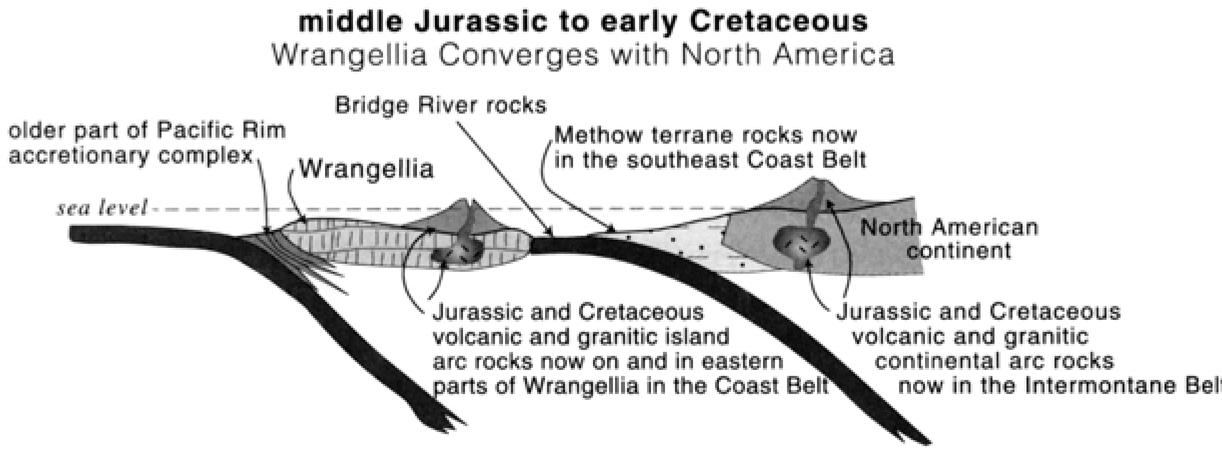
Cascade magmatic arc. Beginning about 40 million years ago, volcanic and granitic rocks of the Cascade magmatic arc were emplaced across all of the older rocks. The arc extends from southwestern BC to northern California above the subducting Juan de Fuca and Gorda Plates. The older part of the arc in Canada is represented by volcanic rocks ranging from about 34 to 14 million years old, and by granitic rocks ranging from about 26 to 18 million years old. The younger part of the arc is more restricted in extent and is represented by volcanoes, lava flows, and a few small granitic intrusions less than 8 million years old. The young volcanic centres in Canada are aligned in a roughly north-to-south direction and lie between 50 and 200 kilometres north of Vancouver.

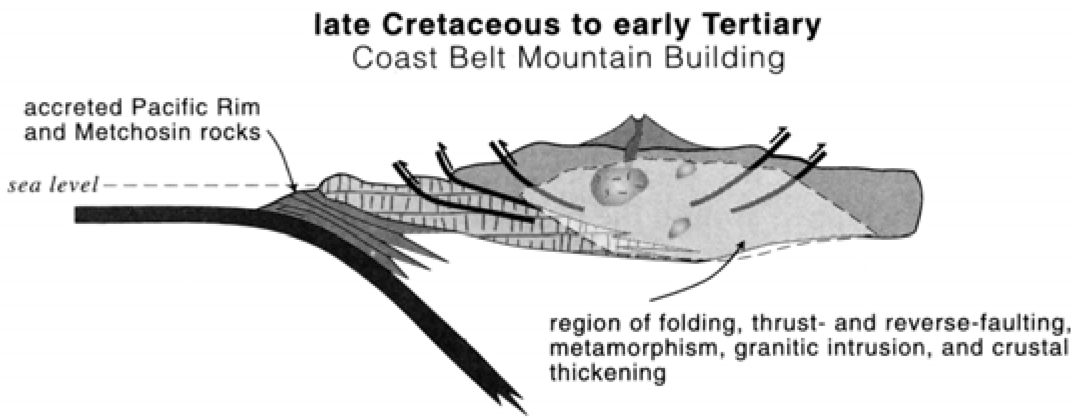
Origins and Uplift of the Coast Belt

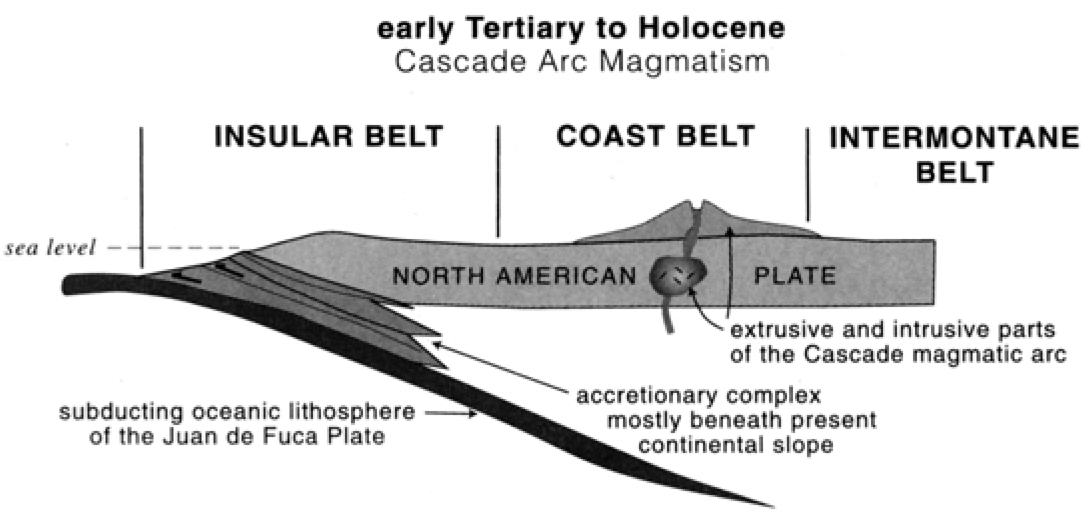
The first, and probably greatest, episode of uplift of the Coast Belt occurred 95 to 85 million years ago. East of Harrison Lake, granitic rocks that formed 95 million years ago are associated with metamorphic rocks formed at depths of nearly 30 kilometres. In the same area, granitic rock just 10 million years younger is associated with metamorphic rocks that formed at depths of about 15 kilometres. Geologists believe that the erosion that accompanied and followed crustal thickening and uplift thus removed a thickness of nearly 15 kilometres of rock from the area. The products of the erosion (sand, gravel, and mud) were carried westward by running water and deposited forming the sandstone, conglomerate, and shale of the Nanaimo group on Vancouver Island.

Erosion continued through Late Cretaceous and Early Tertiary time and reduced the first-formed big mountains to rolling hills by Miocene time. We deduce this from three lines of evidence. First, Miocene fossil plants and pollen characteristic of a wet climate are found in sedimentary beds beneath 8-million-year-old lava flows on the presently very dry east side of the Coast Mountains. If there were big coastal mountains in Miocene time, there would have been a rain shadow in the region as there is today, and the plant fossils would reflect a dry climate. The fact that big mountains exist today indicates that the region must have been uplifted again, this time geologically quite recently.

Second, on the eastern side of the Coast Mountains, 8-million-year-old lava flows have been gently tilted in places and are raised by as much as 1,800 metres above their flat-lying counterparts farther east in the Intermontane Belt. Signs of tilting are even seen in younger lava flows between 3 and 2 million years old.







(Mathews & Monger, 2005)

More evidence of uplift comes from the tilts of bedding layers in sedimentary rocks that occur in patches at the foot of the mountains along the mainland shore of the Strait of Georgia and on the north side of the Fraser Lowland east of Vancouver. There, sandstone, shale, and conglomerate, in part equivalent to the Late Cretaceous Nanaimo strata on Vancouver Island, and in part of Early Tertiary age, were deposited as nearly horizontal beds by southward- or southwestward-flowing streams that brought gravel, sand, and finer debris eroded from the original Coast Mountains. The beds now tilt about 10^{o} to 15^{o} to the southwest. The tilting resulted from uplift of the mountains and subsidence under the Strait of Georgia sometime after they were deposited.

Finally, geologists think that erosion has removed between 2 and 4 kilometres of rock from parts of the southern Coast Mountains in the past 10 million years. The evidence for this is provided by examination of fission tracks in crystals of apatite, a mineral that is present in small amounts in granitic rock. The tracks, microscopic scars produced by the radioactive decay of minor amounts of uranium, tell us that some rocks of the Coast Belt cooled below 100^{o}C about 10 million years ago. From boreholes and mines, we know this temperature generally occurs today at depths of 2 to 4 kilometres below the ground surface, depending on the local heat flow in the Earth.

It might be surmised that the divide separating streams flowing more or less directly to the coast from those draining to the interior was likely to develop at the site of greatest uplift, somewhere within the eastern part of the Coast Mountains. However, several streams now head near the eastern side of the mountains or on the Interior Plateaus east of it and flow westward right across the mountains in spectacular canyons. Examples include the Homathko River, its tributary Mosley Creek, and the Klinaklini River, all near Mount Waddington. These rivers may have originally crossed the site of the present mountains when they were little more than low hills and kept to their original courses as the mountains rose again at the end of Tertiary time. Such incised drainage patterns are called *antecedent drainage*.

GRASSI LAKES – SOUTH FAIRHOLME REEF COMPLEX

The cliffs above Grassi Lakes, in addition to being a local climbing mecca, also provide a section through the interior of a Devonian-age reef, known as the South Fairholme reef complex. The outcrop is located in the hanging wall of the Rundle thrust, which has carried rocks of Cambrian through Triassic-age to the surface along the west side of the Bow River corridor (**Figure 2-1**). The resistant, cliff-forming Mississippian and Devonian carbonates have been modified by subsequent erosion to form Mount Rundle (to the northwest) and Mount Lawrence Grassi and the Three Sisters (to the southeast).

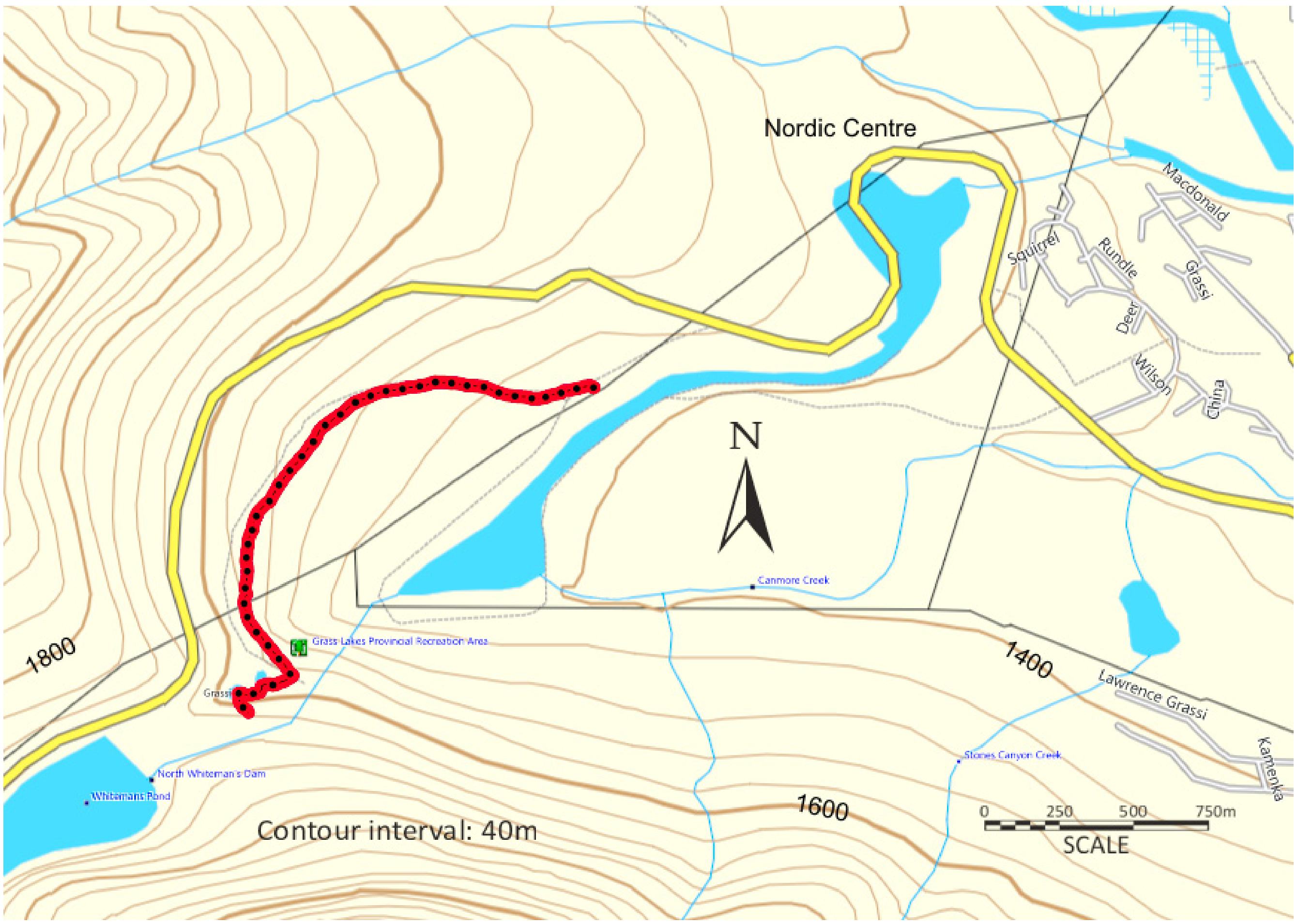


Figure 2-1 – Grassi Lakes hike

The reef complex at Grassi Lakes comprises cyclic successions, generated by changes in sea-level, which can be correlated throughout the basin. Typical reef building fauna are not particularly well preserved in the outcrop owing to the degree of dolomitization, dissolution and the initial sandy nature of the reef complex at this location.

The lower reef sequence (which you will sketch from the far side of the upper lake) was deposited in a subtidal to intertidal environment in the interior of an extensive carbonate platform and has been assigned to the Frasnian Cairn Formation, part of the Upper Devonian Fairholme Group. It is a thickly bedded, stromatoporoid-rich dolostone – stromatoporoids being the main reef-building organisms at that time (**Figure 2-2**).

A walk along the north side of the lake reveals places where the stromatoporoids built massive, wave-resistant structures with their shells, and places where the waves smashed the reef into fragments, which then cascaded down the reef front. In other places, shallow lagoonal deposits are revealed in thinly bedded and sparsely fossiliferous units.

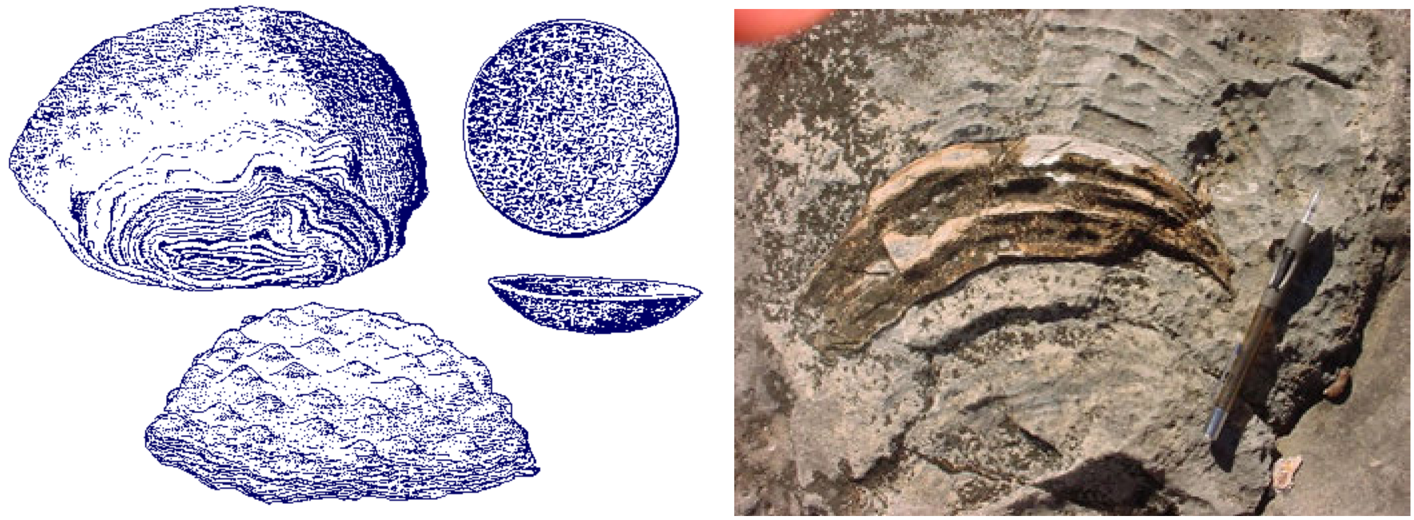


Figure 2-2 – Stromatoporoidea is an order of colonial aquatic invertebrates with either sheet-like or hemispherical skeletons that were important reef-formers throughout the Paleozoic. The group was previously thought to be related to corals (Cnidaria), but is now placed in the phylum Porifera (sponges).

As you begin to look at the section in detail, the ‘swiss cheese’ appearance of the rocks becomes obvious. These cavities represent the original bulbous stromatoporoids that formed the reef. Sometime after burial (and possibly contemporaneously with the dolomitization of the rocks) the stromatoporoids were leached out, leaving behind only ghost rims of the original structure and large ‘vugs’ or cavities. It is this vuggy porosity that, in the sub-surface, makes these reefs such excellent oil and gas reservoirs.

Follow along the base of the cliff and look for the smaller branching, 'spaghetti-like' stromatoporoid *Amphipora* (**Figure 2-3**). While subordinate to the various stromatoporoids, tabulate corals, gastropods and brachiopods can also be observed in this section.

Figure 2-3 – *Amphipora ramosa*

The Cairn Formation carbonates unconformably overlie the Upper Cambrian Lynx Group (the contact between which is mapped as passing between the upper and lower lakes) and are in turn overlain by the more recessive Southesk Formation, a fossiliferous dolostone dominated more by corals and *Amphipora* than by bulbous stromatoporoids (**Figure 2-4**).

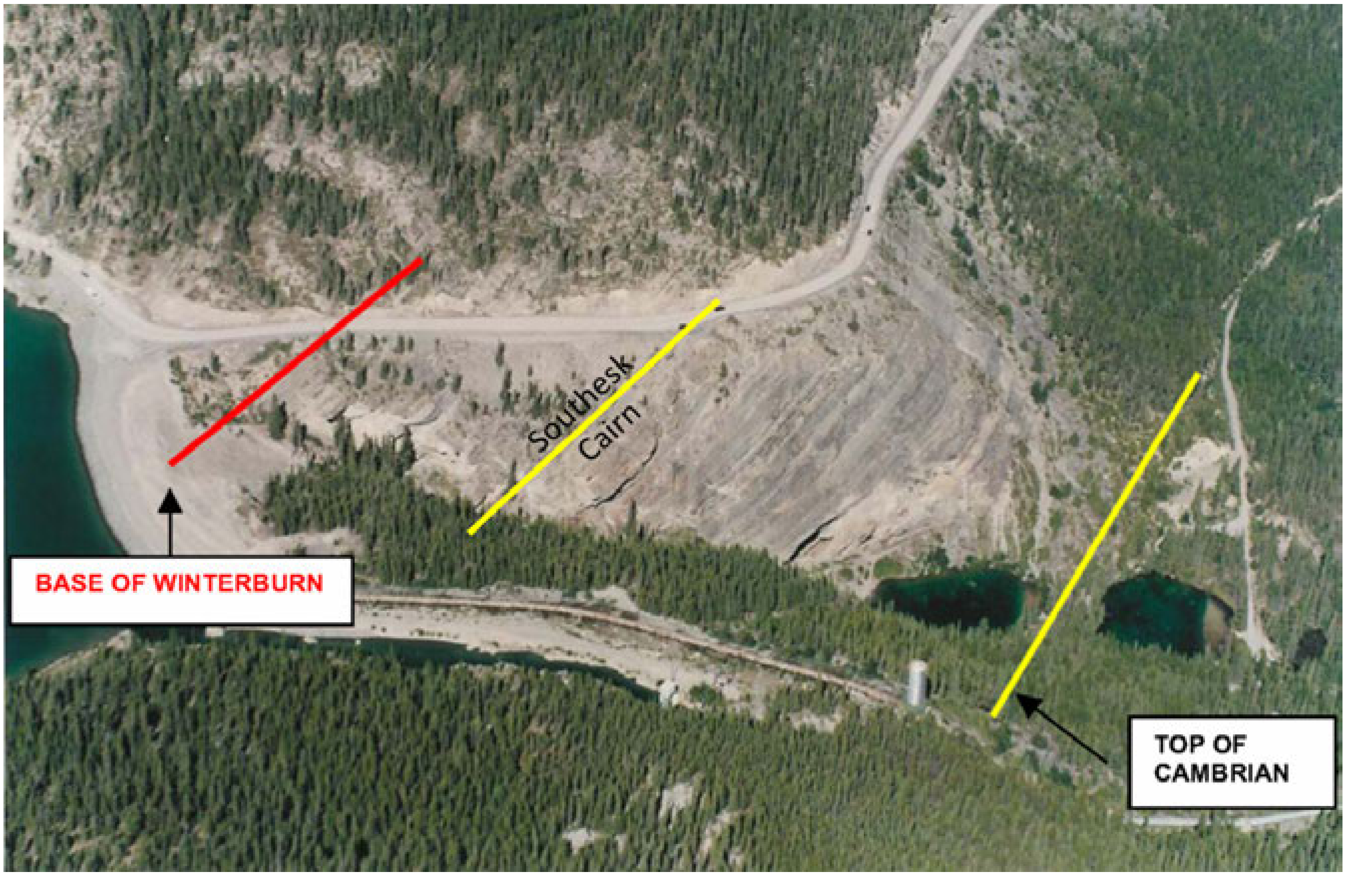


Figure 2-4 – Grassi Lakes reef complex section from Ha Link Peak

Time-equivalent Devonian reefs (including the Leduc and Nisku formations), in the adjacent subsurface have been important to the Alberta economy since the discovery of oil at Leduc in 1947 (**Figure 2-5**). Owing to their size, proximity to oil and gas source rocks and favourable reservoir characteristics, these reefs formed excellent reservoirs for oil and natural gas. While many pools are reaching the end of their productive capacity, they originally hosted some 3 billion cubic metres of crude oil (19 billion barrels) and 3.4 trillion cubic metres (119 trillion cubic feet) of natural gas.

Assignment 1: sketch the cliff face (landscape on one sheet of note paper) from the far side of Upper Grassi Lake. In particular, try to distinguish the geometry of the individual layers. This sketch will be the basis for examining and interpreting the rock face.

Cross over to the rock face around the west end of the lake. ***Be aware of any climbers above you.***

Assignment 2: describe and distinguish the individual layers depicted in your sketch. Your descriptions should include colour, grain size, support, reaction to acid, fossil content and porosity. Based on your sketch and lithological descriptions, construct a stratigraphic section depicting how the rock sequence varies through time. Draw a eustatic (relative) sea level curve (see p. 48 for an example) on the right side of the stratigraphic column. Answer the following:

Main questions: what was the environment of deposition for each of the layers, and how do they relate to one another? What diagenetic processes are recorded here? What is the source of the large cavities that characterize some of the layers? Why are the thicknesses of some of the layering inconsistent? Which direction is landward, and which is toward open ocean? What is the significance of this section for the paleogeography and tectonic setting of the ancient west margin of North America? What are the implications of this section for hydrocarbon exploration?

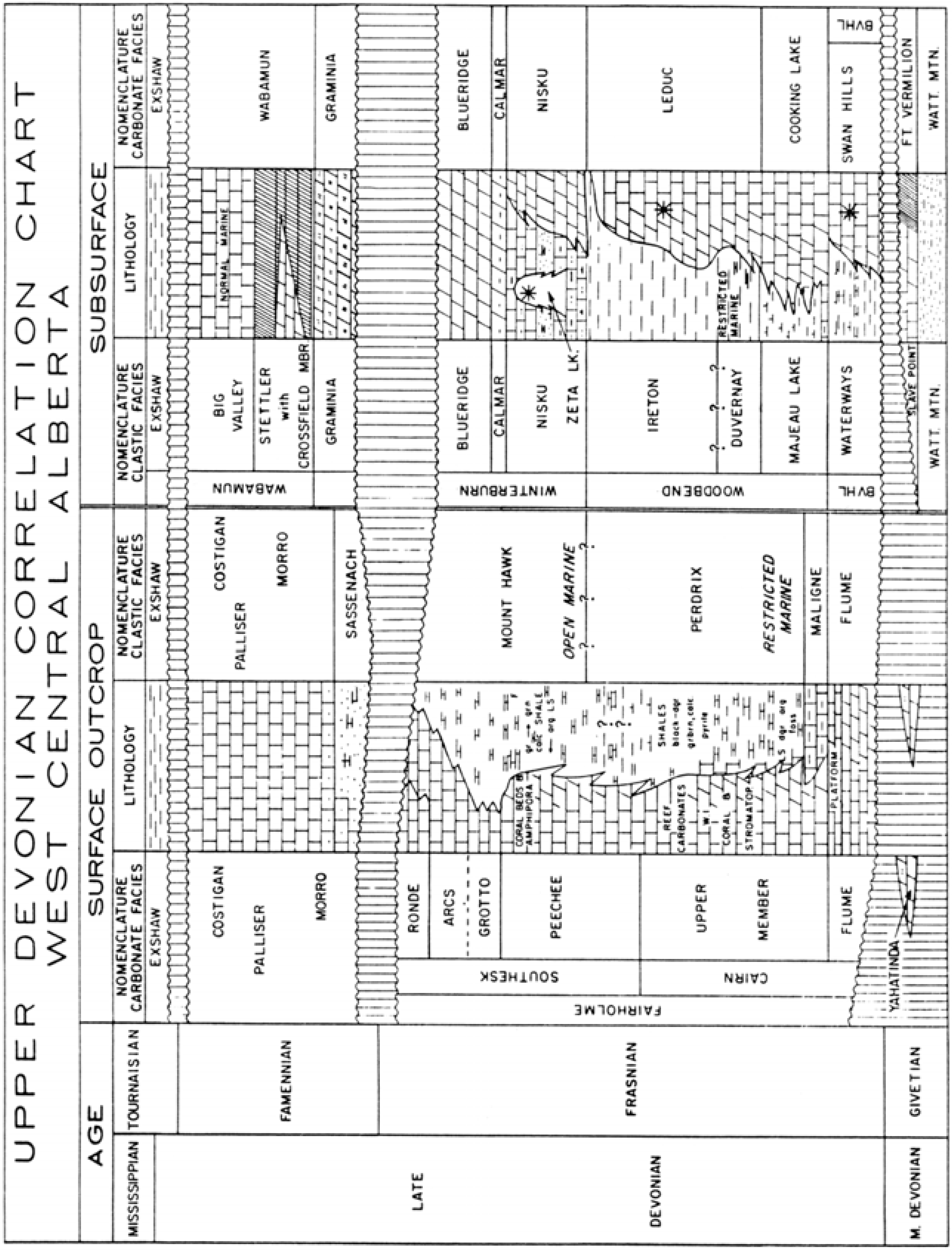


Figure 2-5 – Upper Devonian stratigraphy, west central Alberta

JURA CREEK – DEVONO-MISSISSIPPIAN BOUNDARY

The valley of Jura Creek, just north of the town of Exshaw (**Figure 2-6**), will provide an introduction to Front Range geology. Exposed formations include the Palliser (Devonian), Exshaw and Banff (Mississippian). Jura Creek, one of the classic geological field excursions in the Front Ranges, was named in error – from misidentified fossils which were actually Paleozoic, not Jurassic, in age.

Figure 2-6 – Jura Creek hike

The first prominent landmark of the route is the downstream end of the 'lower canyon'. Most of the year, the canyon is passable, although any rainy period will fill a few critical pools with enough water that you will be forced to take the upper trail, through the trees.

The canyon is cut down into the Morrow Member of the Palliser Formation. This Famennian cliff-forming unit is dominated by dolomitic limestone and has distinctively thick beds. Outcrops displaying distinct raised dolomitic bioturbation(?) traces resulting from differential weathering belong to the Morrow Member.

Above the lower canyon, the stream bed approximates regional strike, but wanders slightly, providing exposures of parts of the Banff Formation, which we'll discuss further on our way out (Stop 2).

The 'upper canyon' of Jura Creek (Stop 1, **Figure 2-7**) is not really a canyon, but a draw where the creek cascades down the Palliser-Exshaw contact. On the east side of the draw is the Famennian Costigan Member of the Palliser Formation. Although lithologically similar to the Morrow Member, the Costigan is more thinly-bedded, and locally bioclastic. It also hosts two types of nodules; the first, elongate, black and siliceous, the second, more rounded and composed of calcite-cemented yellowish-brown phosphorite oolites. Sharp eyes may also spot brachiopod, orthoconic (straight shelled) nautiloid and possibly trilobite fossils on the uppermost, water-worn surfaces of this member.

Figure 2-7 – 'Upper Canyon', Jura Creek (looking north)

On the west side of the draw is the Famennian/Tournaisian Exshaw Formation, which here includes approximately 10 metres of anoxic-dysaerobic black shale gradationally overlain by approximately 37 metres of pale yellowish-brown siltstone, whose abundant trace fossils indicate deposition under more oxygenated conditions. Many Phanerozoic system, epoch, and stage boundaries are marked by the deposition of black shale units, several of which are coincident with mass extinction events (see back cover).

Conodont species at this section indicate that the Devonian-Mississippian boundary (correlated with the Hangenberg mass extinction event from Europe) is restricted to an approximately 3 metre interval centred 2.4 metres from the top of the black shale member. The Re-Os age of this boundary has been determined to be 361.3 ± 2.4 Ma.

Assignment 1: working in pairs, define and describe the main geological units in the 'Upper Canyon'. Draw a quantitative cross-section (looking upstream) showing the thickness and orientation of, and the relationships between units (structural orientation data is required to determine the orientation of the line of section and the geometry of units depicted on the section). Construct a stratigraphic section and an accompanying eustatic (relative) sea level curve. Answer the following:

Main questions: what are the depositional settings of the various units, and the implications of these settings in regard to the nature of the North American margin at the time of deposition? What is the nature of contacts between the units (conformable vs. unconformable vs. tectonic)? What is the evidence for tectonic activity / change in tectonic setting (look for the recessive tuff layer in the black shale)? What is the significance of this section for oil & gas exploration? What is the relationship of your units to regionally established stratigraphy?

Once the group has completed this exercise, we'll head back downstream to Stop 2 (which will be flagged).

In traversing downstream, one moves up section into the Banff Formation, part of a westward-prograding and shallowing-upward Mississippian ramp succession (**Figure 2-8**). The lower and middle Banff members accumulated in dysaerobic, distal ramp to more oxygenated proximal ramp settings, with the late Early Tournaisian regressive trend culminating in deposition of restricted ramp (supratidal) lithofacies of the uppermost Banff Formation.

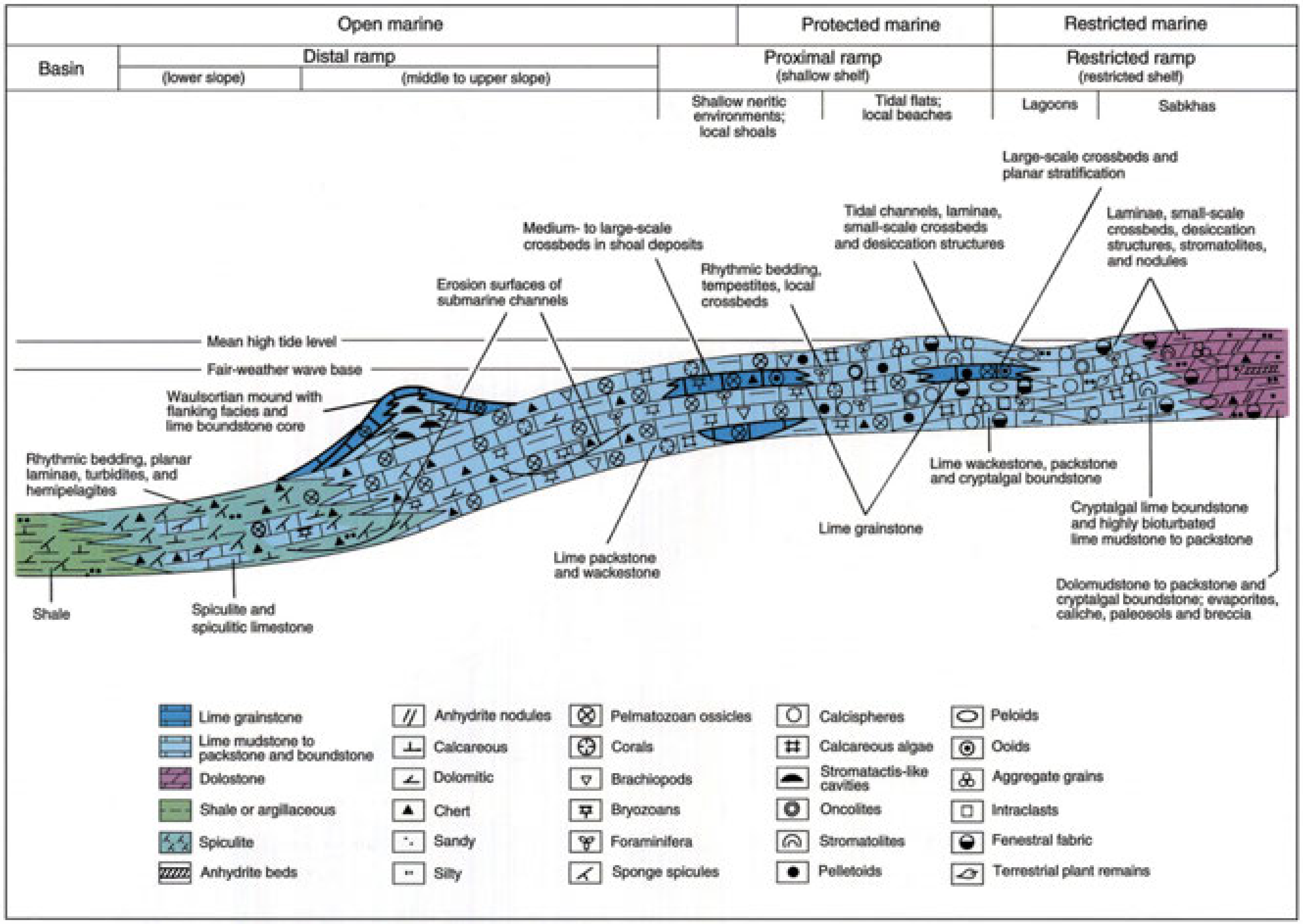


Figure 2-8 – Generalized model of a Carboniferous carbonate ramp

Assignment 2: examine the exposure for evidence of the tectonic setting and for the evolution of tectonic setting through time. Answer the following:

Main questions: what is the significance of the fine laminations and why are they so non-planar? What is the white mineral that forms large clots locally within the laminated rock? What process gave rise to the brecciation and when? What is 'sour gas', why is it economically important and what does it have to do with this outcrop?

[redacted]

East Coulee (Red Deer River Valley) – Bearpaw-Horseshoe Canyon Transition

Introduction

During the Late Cretaceous (about 76 to 65 Ma), southern Alberta was the center of a major regression with deposition of marine, deltaic and coastal plain sediments. The major sites of accumulation occurred along the margins of the Bearpaw Sea with the resultant progradation of the shoreline to the east. The deposits of the transition zone between the Bearpaw and Horseshoe Canyon formations in the area east of Drumheller formed part of one of the major delta build-ups along the sea margin. In this area, sequences of sediments can be recognized representing: the marine environments of prodelta and delta front; shoreline facies, including distributary channel, beach/barrier, tidal flat and inlet, interdistributary bay, lagoon and swamp; and continental sequences involving fluvial channels, floodplain and swamps.

The transition from the fully marine strata of the Bearpaw Formation to the marginal marine strata of the Horseshoe Canyon Formation represents an overall basin-ward progradation of paralic facies punctuated by marine incursions and is easily recognized in outcrop. The dark gray-brown silty shales of the Bearpaw Formation contrast sharply with the light gray, kaolinitic, fine-grained sandstones of the overlying Horseshoe Canyon Formation. The boundary is typically abrupt, but in many places the contact is gradational, consisting of intertongueing fine- and coarse-grained sediments. Recognition of the boundary in the subsurface can be difficult because numerous coarsening-upward cycles of shale and siltstone to sandstone are present in close proximity to the Horseshoe Canyon/Bearpaw contact. In central Alberta, the lowest major sandstone of the Horseshoe Canyon Formation commonly is overlain by a thick coal, locally referred to as the Drumheller coal zone.

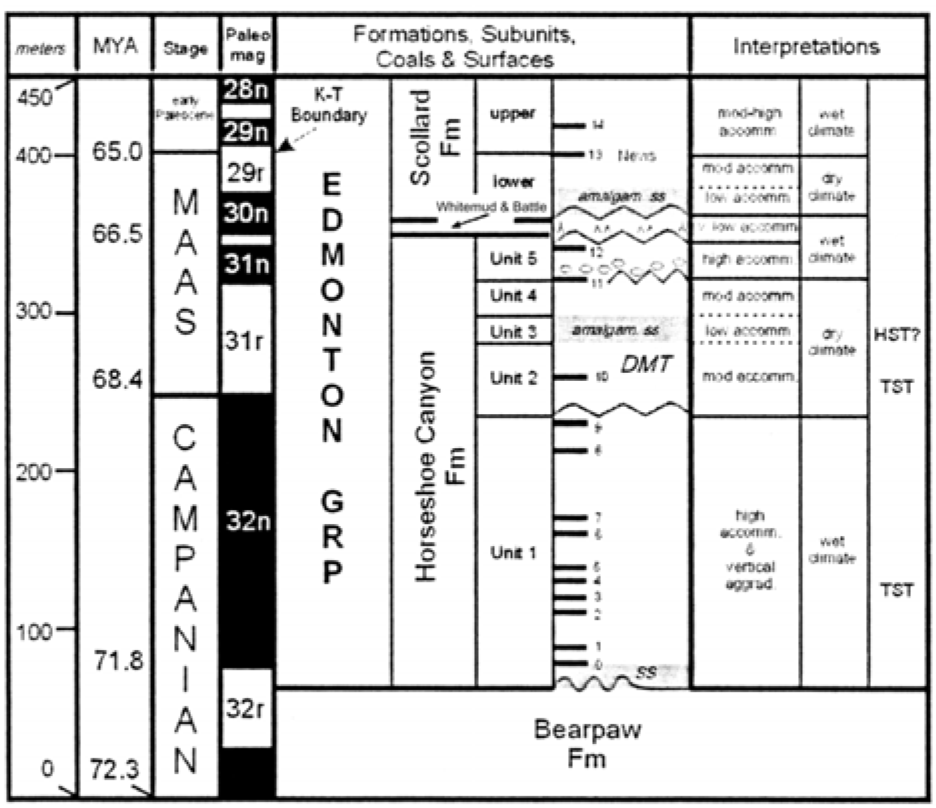


Figure 3-1 – Stratigraphic nomenclature and framework for the Edmonton Group (Eberth, unpublished)

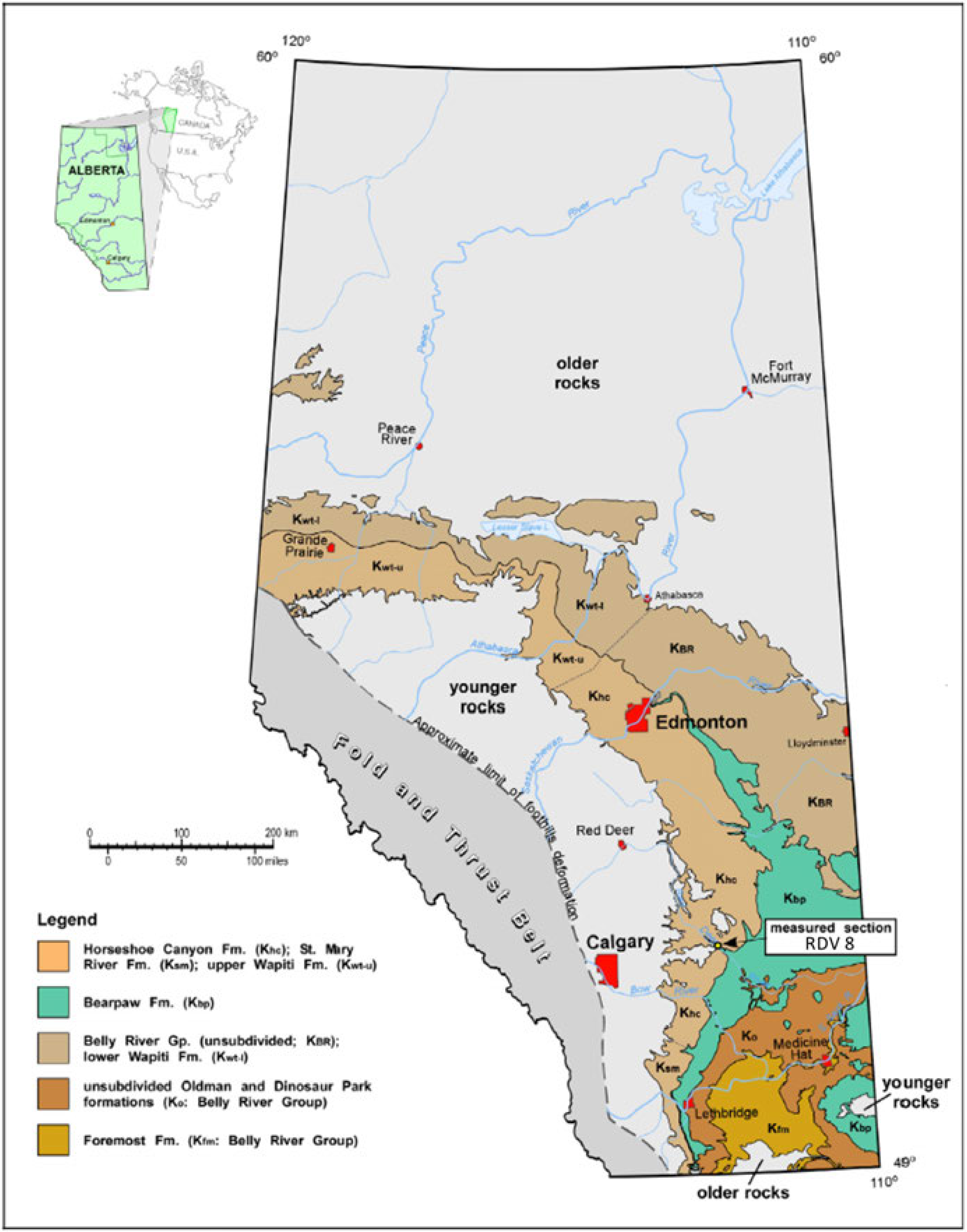


Figure 3-2 – Simplified geological map (modified from Hamilton et al., 1999) showing the distribution of Bearpaw and Horseshoe Canyon formations and surrounding rocks in Alberta and the location of measured section RDV 8.

Stop 1 – East Coulee

The base of this section (RDV 8), located near the town of East Coulee (**Figure 3-3**), comprises a thick sequence of prodeltaic mudstone variously interpreted as either the top of the Bearpaw Formation or a distal expression of deltaic lobes of the overlying Horseshoe Canyon Formation.

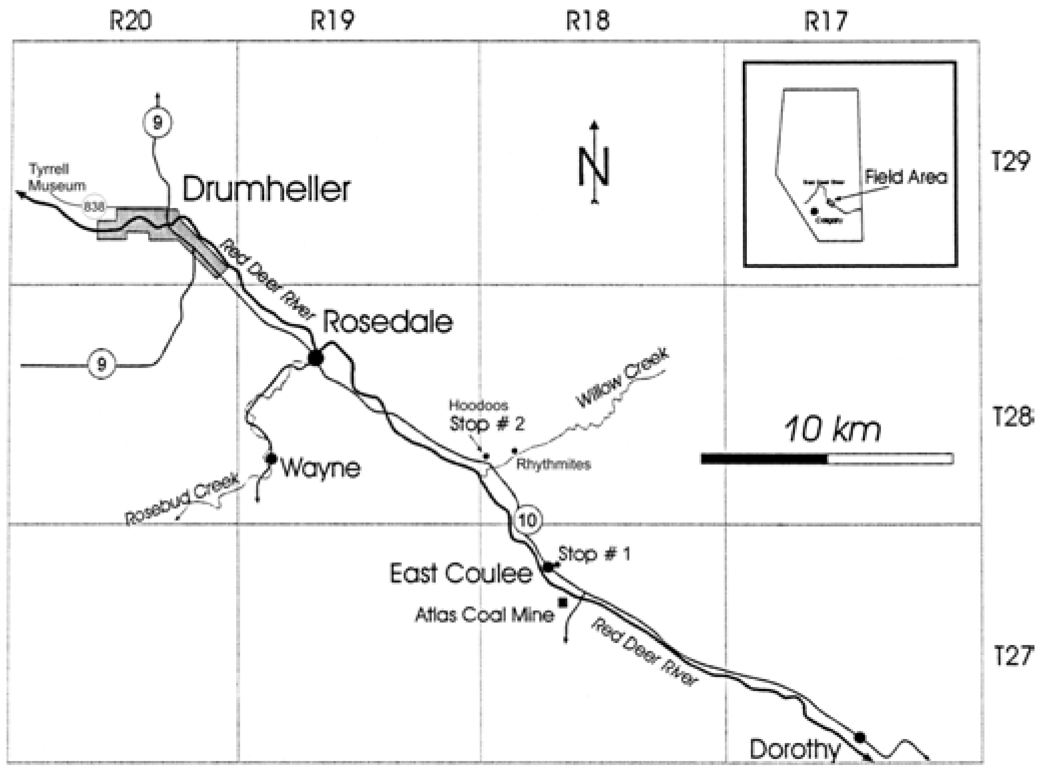


Figure 3-3 – Day 3 Stop locations, Red Deer River Valley

Up section, these mudstones are in sharp[*] contact with a course, shoaling-upwards succession of delta-front sandstones characterized by swaley cross-stratification and *Ophiomorpha* and *Macaronichnus*-dominated trace fossil assemblages. Approximately 15 metres above the prodelta/shoreface contact, the sandstones are succeeded by lagoonal/tidal flat facies capped by a <1 metre coal layer, the upper surface of which hosts *Teredolites* borings. Such coals have been interpreted as representing flooding surfaces, as they often overlie well-rooted lowstand surfaces of erosion.

The section above the coal consists of a series of tidal flat and channel sequences (locally characterized by herringbone cross-stratification) passing upwards into deeply rooted sandstones capped by coal. Of particular interest at this location is the occurrence of a mud-filled incised channel. The depth of the scour (up to 10 metres) may be indicative of a similar drop in relative sea-level and the fill (mud with a sandy heterolithic base) consistent with deposition in a lagoonal environment resulting from the subsequent drowning of the wave-dominated, barred coastline.

Continued transgression resulted in the deposition of a shoaling upward shoreface succession (hosting a diverse trace fossil assemblage) followed by an estuarine channel complex capped by yet another well-developed rooted surface. A petrified tree stump in what appears to be its living position can be observed at this interval in the section.


Petrified stump near top of section

* while sharp here, this contact is gradational regionally

Assignment: starting at road level, traverse up-section through Cretaceous foreland basin strata. Using the RDV 1 section (**Figure 3-4**, next page) from the Hoodoos Recreation Area (Stop 2, **Figure 3-3**) as an example, construct a stratigraphic section (suggested scale - 1:200) in your notebook, defining and distinguishing the successions observed. Specify the depositional setting of each and the nature of the boundaries between them. Draw a eustatic relative sea level curve next to your section. Answer the following:

Main questions: what is sequence stratigraphy? What is eustasy? What gives rise to the flooding surfaces? What was the depositional setting of the units? What was the source of the sediments? What was the source of the subsidence? Why were the Paleozoic carbonate sediments succeeded by Mesozoic clastic sediments? What is a foreland basin? What is the significance of bentonite layers in the Cretaceous strata? Can changes in the depositional setting of units in the foreland basin be linked to tectonism to the west? How do sequence boundaries vary across strike.

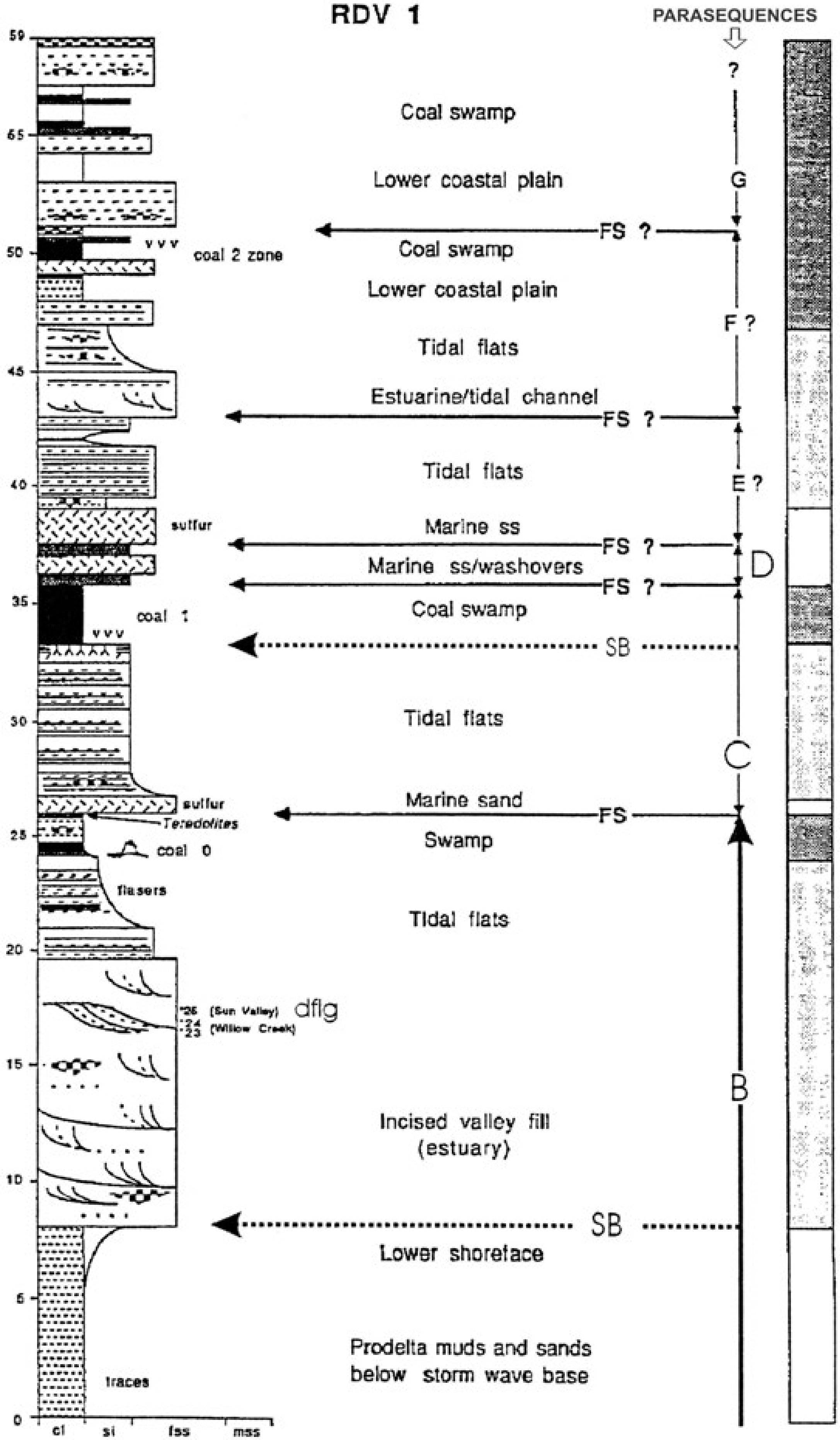


Figure 3-4 – Measured section RDV 1 – Hoodoos Recreation Area (Scale 1:250)
SB – sequence boundary, FS – flooding surface, dflg – dinoflagellates (Eberth & Lavigne, 2002)

Stop 2 – Hoodoos Recreational Area (RDV 1)

The sharp sequence boundary between the Horseshoe Canyon and Bearpaw formations is readily evident at the Hoodoos recreational area (**Figure 3-5**). This erosional(?) contact is characterized by ball and pillow structures resulting from the loading of sand onto unconsolidated mud (**Figure 3-6**). Striking mud-pebble conglomerate is also exposed at this outcrop.

Figure 3-5 – Bearpaw/Horseshoe Canyon transition at Hoodoos Recreation Area. Note the sharp sequence boundary.

Figure 3-6 – Ball & Pillow structures in upper prodelta sediments at Hoodoos Recreation Area

HORSESHOE CANYON – UPPER HORSESHOE CANYON FORMATION

Just west of Drumheller is a popular overlook into Horseshoe Canyon (**Figure 3-7**). The very gentle westerly regional dip on the plains means that we are now up-section from our stop at East Coulee. Here, the upper Horseshoe Canyon Formation comprises widely sideritized mudstone, sandstone and carbonaceous shales and includes two markers, the Drumheller Marine Tongue, identified by beds of molluscs, and the Kneehills Tuff, a thin reworked bed of volcanic ash (**Figure 3-8**). The distinctive light green-grey mudstone unit, about 4 meters thick, near the top of the canyon, marks the transition into the overlying Whitemud zone, which includes kaolinitic and bentonitic sandstone, siltstone and shale elsewhere across Alberta and Saskatchewan.

Figure 3-7 – Horseshoe Canyon/Whitemud transition at Horseshoe Canyon

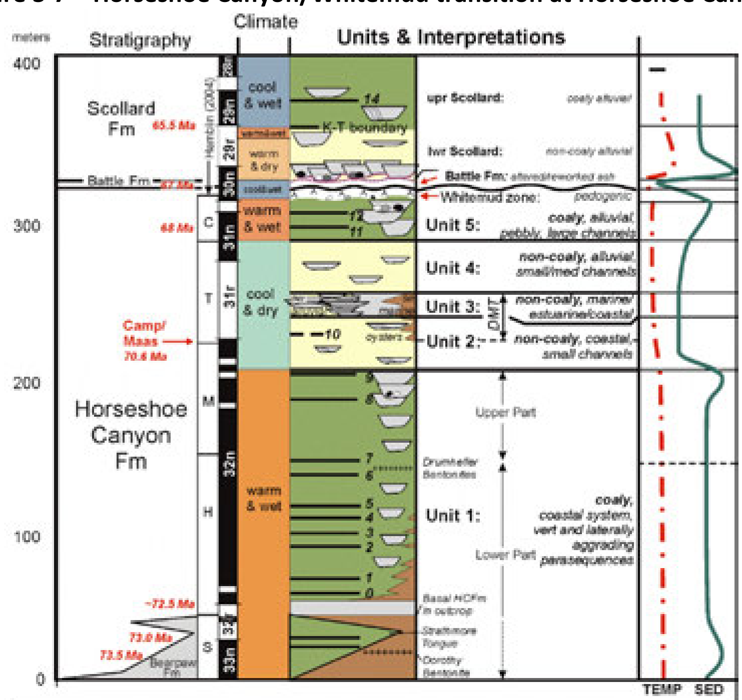
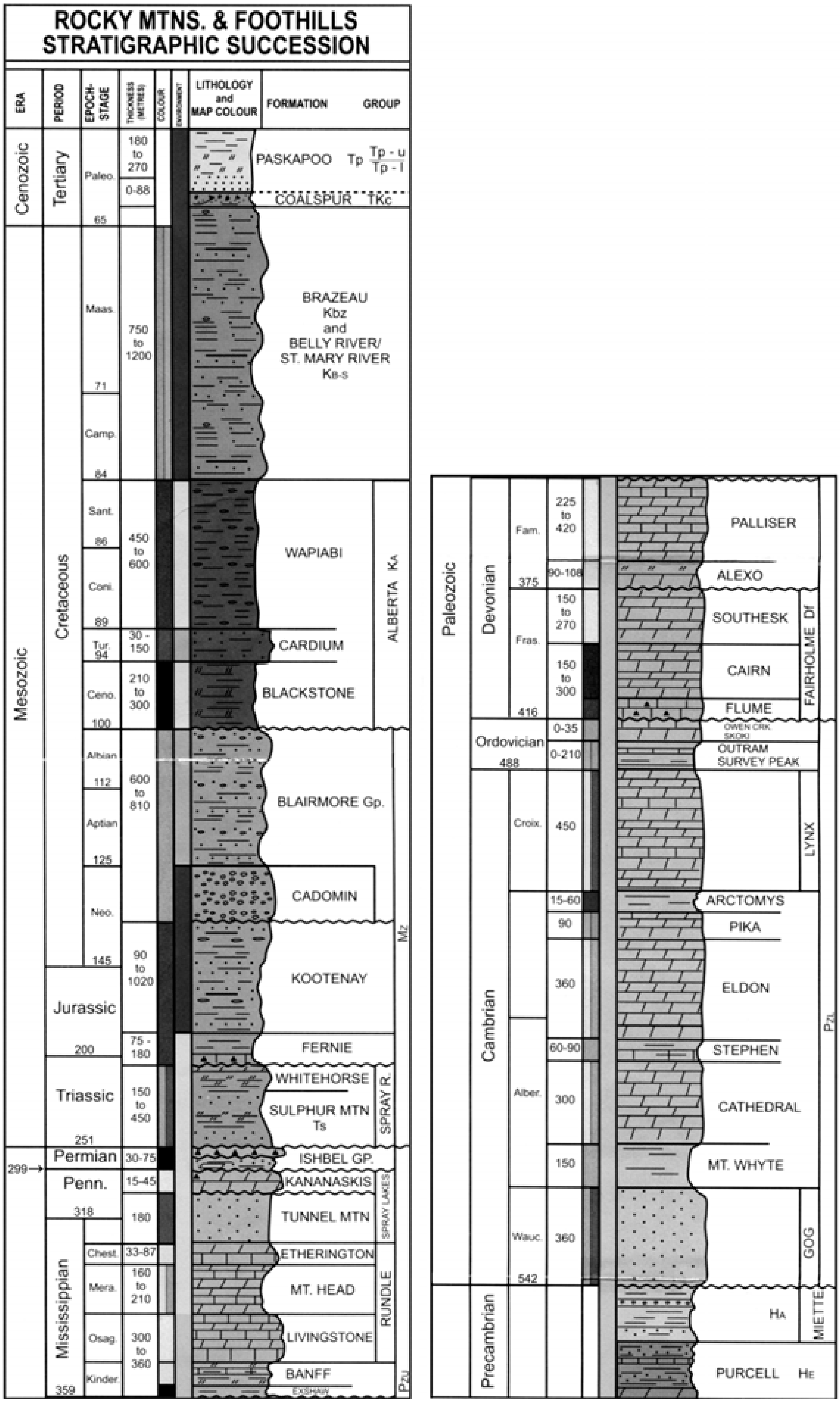


Figure 3-8 – Summary of the stratigraphic revision of the Horseshoe Canyon Formation (Eberth, 2010)

Assignment: produce a semi-quantitative measured stratigraphic section through the sequence, with an accompanying eustatic relative sea level curve. Answer the following:

Main questions: what is the depositional setting? How do these rocks differ from those observed at East Coulee? How are these two sections (here and East Coulee) related (i.e., where were the two stops relative to the paleoshoreline?)?


ROCKY MTNS. & FOOTHILLS STRATIGRAPHIC SUCCESSION
ERA
PERIOD
EPOCH-STAGE
THICKNESS (METRES)
COLOUR
ENVIRONMENT
LITHOLOGY and MAP COLOUR
FORMATION
GROUP
Cenozoic
Tertiary
Paleo.
65
180 to 270
0-88
PASKAPOO Tp Tp - u / Tp - l
COALSPUR TKc
Mesozoic
Cretaceous
Maas.
71
Camp.
84
750 to 1200
BRAZEAU Kbz and BELLY RIVER/ ST. MARY RIVER KB-S
Sant.
86
Coni.
89
450 to 600
WAPIABI
Tur.
94
30 - 150
CARDIUM
Ceno.
100
210 to 300
BLACKSTONE
ALBERTA KA
Albian
112
Aptian
125
600 to 810
BLAIRMORE Gp.
Neo.
CADOMIN
145
90 to 1020
KOOTENAY
Mz
Jurassic
200
75 - 180
FERNIE
Triassic
251
150 to 450
WHITEHORSE
SULPHUR MTN Ts
SPRAY R.
299→
Permian
30-75
ISHBEL GP.
Penn.
318
15-45
KANANASKIS
180
TUNNEL MTN
SPRAY LAKES
Mississippian
Chest.
33-87
ETHERINGTON
Mera.
160 to 210
MT. HEAD
Osag.
300 to 360
LIVINGSTONE
RUNDLE
Kinder.
359
BANFF
EXSHAW
PZU
Paleozoic
Devonian
Fam.
225 to 420
PALLISER
375
90-108
ALEXO
Fras.
150 to 270
SOUTHESK
150 to 300
CAIRN
416
FLUME
FAIRHOLME Df
Ordovician
488
0-35
OWEN CRK. SKOKI
0-210
OUTRAM SURVEY PEAK
Cambrian
Croix.
450
LYNX
15-60
ARCTOMYS
90
PIKA
360
ELDON
60-90
STEPHEN
Alber.
300
CATHEDRAL
150
MT. WHYTE
PZL
Wauc.
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HA
MIETTE
PURCELL HE

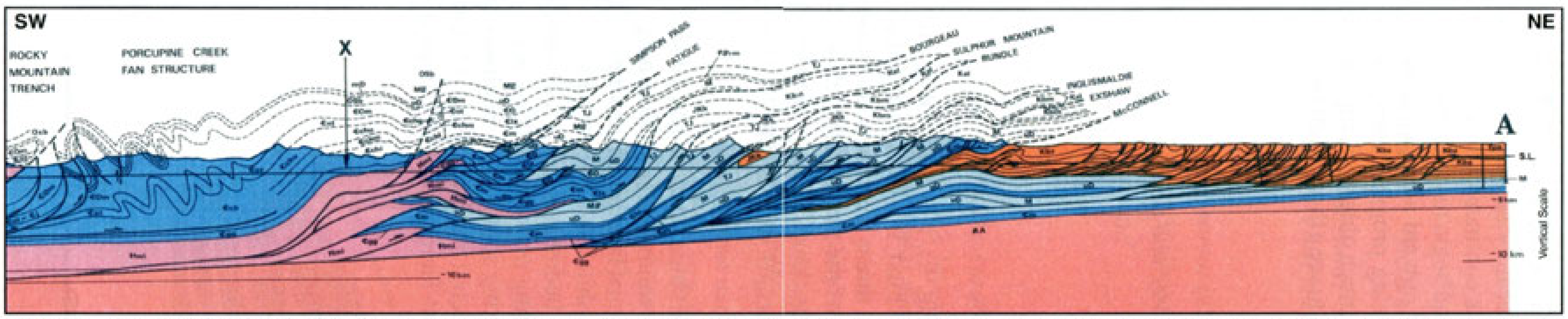


Figure 8. Geological cross-section of the Foothills and Rocky Mountains west and southwest of Calgary (modified from Price and Fermor, 1985). Note that the section is true to scale; ie. the vertical scale is the same as the horizontal scale. Illustrated rocks, from oldest to youngest are - Precambrian crystalline basement (tan coloured; not involved in thrusting); Proterozoic sedimentary rocks (pink; from the Windermere Gp. [see Figure 12]; thrusted); Paleozoic and Triassic strata of the Cratonic Platform succession ([see Figure 12] dark and light blue; thrusted); and Jurassic-Cretaceous strata of the Foreland Basin succession ([see Figure 12] orangy-brown; thrusted in the Foothills and locally preserved as inliers in the mountains). Strata traced up into what is now the air show the total thickness of rock removed by erosion (~10 km) during and since formation of the Rockies.. **A** marks the front of the Foothills, just west of Calgary. **X** marks the western limit of our traverse.

Day 4 – Foreland Belt

SEEBE DAM – ALBERTA GROUP

The Cardium Formation, which forms the middle part of the marine succession of the Alberta Group, comprises a terrigenous, muddy, sandy and locally conglomeratic clastic wedge that accumulated in Turonian/Coniacian (early Late Cretaceous) time along the western margin of the Alberta Foreland Basin. In the foothills, the formation has been brought to surface by multiple, juxtaposed, east-verging thrusts. It is of significant economic interest as it possesses 'colossal' hydrocarbon storage capacity, manifested in a series of stratigraphic traps, the largest of which is the productive Pembina Field.

Below the Seebe Dam, Cardium marine sandstones are stratigraphically overlain by a thick succession of black marine mudstones/shales assigned to the Campanian (late Late Cretaceous) Wapiabi Formation (**Figure 4-1**). This southwest-dipping succession sits in the southwest limb of one of a series of northwest plunging anticlines that form the northwest end of the northwest-plunging Moose Mountain Culmination. The sediments have been cut by northwest trending, steeply-dipping normal faults and shallowly-dipping thrust faults, locally placing the Cardium Formation structurally above the Wapiabi.

Figure 4-1 – Alberta Group rocks at Seebe Dam w/ Front Ranges in the background

Assignment: Construct a geological map of the area. Structural data and the nature of all contacts (both fault and stratigraphic) must be shown right on the map, which should include a legend in which you define the main lithological units. A detailed, quantitative cross-section (with a perspective similar to the photograph above) showing the relationship of the units to one another must accompany the map. Determine the regional structural plunge. Answer the following:

Main questions: are these strata part of the passive margin, or the foreland basin? What is the depositional setting of these rocks? What structures are evident (provide orientation data) and how do they relate to one another?

Walk back past the vans to Highway 1X, turn left, cross the bridge (across the Bow River) and stop at the gate to the Lafarge shale quarry.

MT. YAMNUSKA VIEWPOINT – MCCONNELL THRUST FAULT

Mt. Yamnuska (Laurie) marks the beginning of the Front Ranges of the Canadian Rockies (**Figure 4-2**). Movement on the McConnell thrust fault has placed resistant Middle Cambrian Eldon Formation carbonates structurally on top of softer Upper Cretaceous Brazeau (Belly River) Formation, a coarse clastic wedge representing the initial pulse of the Laramide Orogeny. While nearly horizontal beneath Mt. Yamnuska, the fault steepens to ~40^{o} beneath Loder Peak, to the southwest. This is an example of the classic 'ramp-flat' fault geometry typical of foreland fold and thrust belts.

Lafarge Concrete Inc. is presently mining thick exposures of Wapiabi shale in the quarry west of this viewpoint. These low permeability shales acted as a seal, or cap rock, impeding the escape of hydrocarbons trapped within the underlying Cardium Formation reservoirs in the Alberta subsurface.

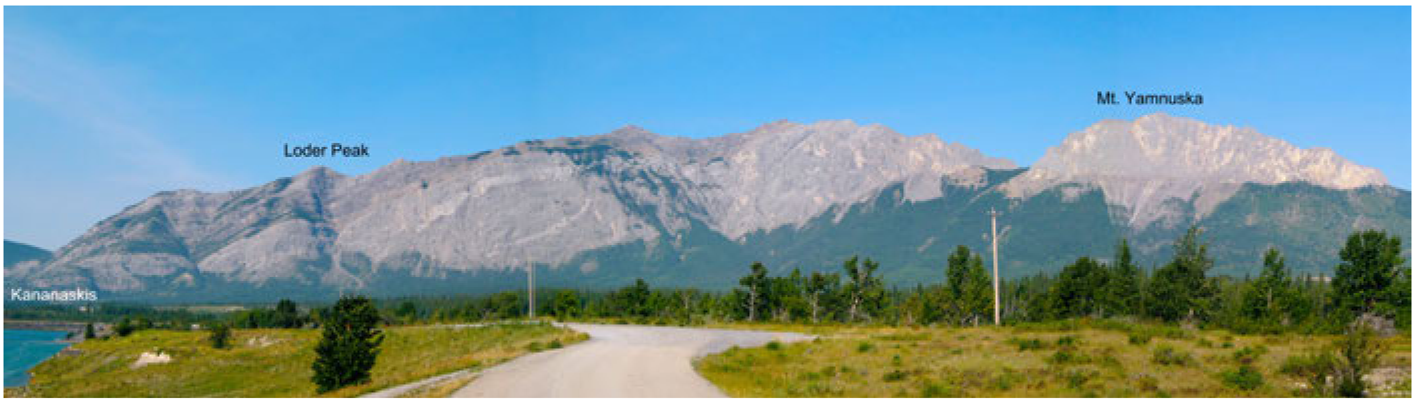


Figure 4-2 – McConnell thrust exposed on Mt. Yamnuska.

Assignment: Produce a labelled sketch cross-section from Mt. Yamnuska, south towards Kananaskis.. Using the regional geological map (**Figure 4-3**, next page), place geological labels on your sketch, indicating the likely units, and locating stratigraphic and structural contacts. Answer the following:

Main questions: what is the relationship of the Seebe Dam strata to strata and structures exposed on Mt. Yamnuska (think of the structural plunge)? Determine the amount of displacement on the McConnell fault. What is the relationship of the Jura Creek section to the Mt. Yamnuska section? What does Mt. Yamnuska tell us about the age of deformation?

GEOLOGY ON THE FLY: FRONT RANGE TOPOGRAPHY

As we cut through the first few thrust sheets of the Front Ranges heading west from Canmore, notice the recurring stratigraphic and structural pattern of long, linear ranges. Notice also that virtually all the visible bedding dips to the southwest. Each range has a thrust fault on its northeast side, with the hanging wall beds riding on and parallel to the rather steeply inclined ramp of the thrust fault below. The northeast (up-dip) side of each range has a characteristic steep and rugged slope, while the southwest (down-dip) slopes, because they are more bedding parallel, tend to be smooth and take on gentler gradients.

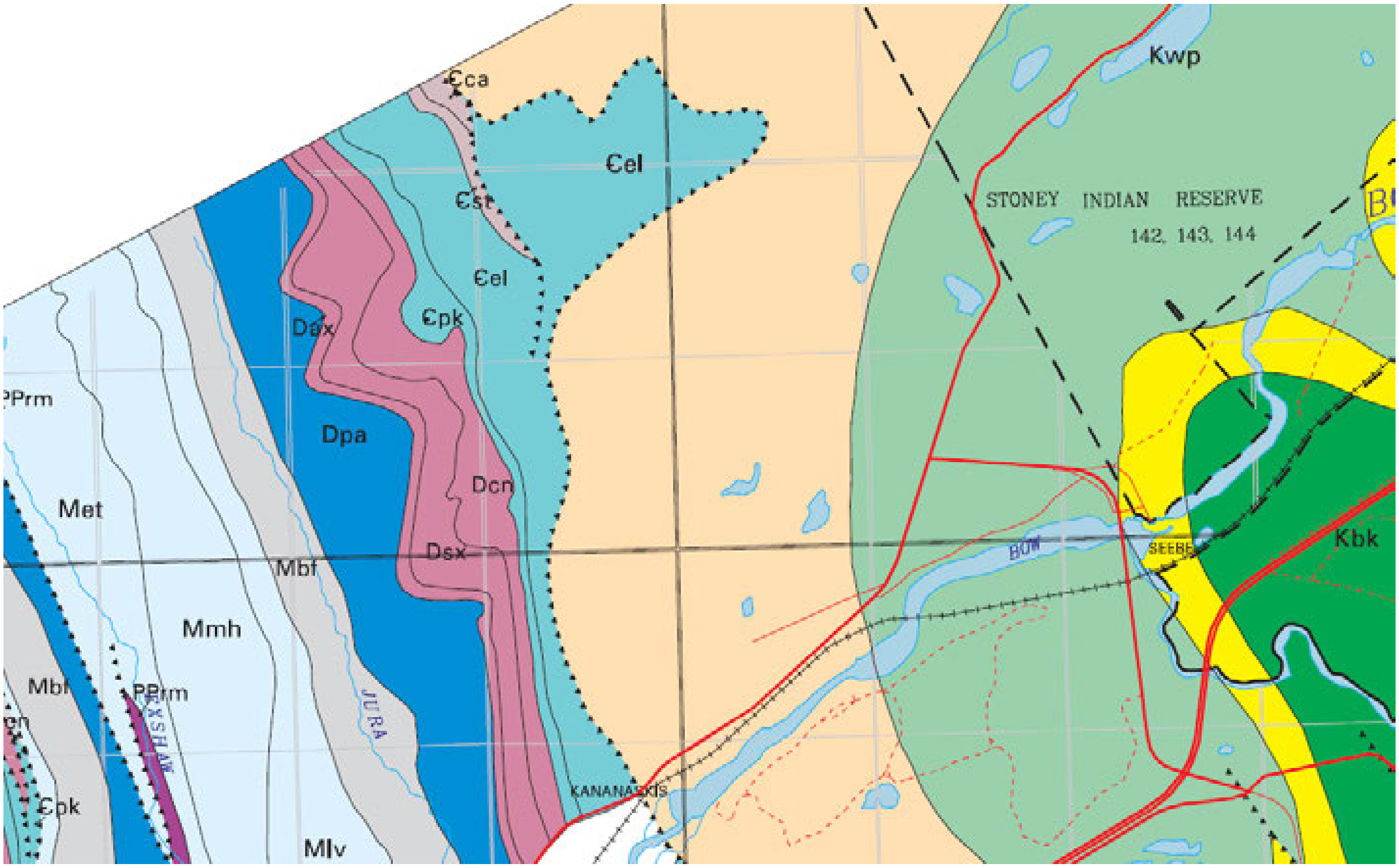


Figure 4-3 – Shaded relief map of the Kananaskis area, Alberta (Scale 1~50,000)
Ꞓel – Eldon, Ꞓpk – Pika, Dcn – Cairn, Dsx – Southesk, Dax – Alexo, Dpa – Palliser, Mbf – Banff, Mlv - Livingston

BANFF TRAFFIC CIRCLE (CASCADE MOUNTAIN VIEWPOINT) – FERNIE-KOOTENAY TRANSITION)

Highway cuts just east of the former Banff Traffic Circle expose transitional-marine sandstones of the Upper Jurassic-Lower Cretaceous Kootenay Group sitting *structurally* below marine shales of the Upper Jurassic Fernie Group, all in the footwall of the Rundle Thrust. Together, these sediments form the southwest limb of the Mt. Allan syncline (**Figure 4-4**) and represent the first real coarsening-upward sequence in the Foreland Basin. Sedimentary structures such as cross-stratification, bioturbation and the occasional coalified tree stump/trunk provide clues as to the changing depositional environments.

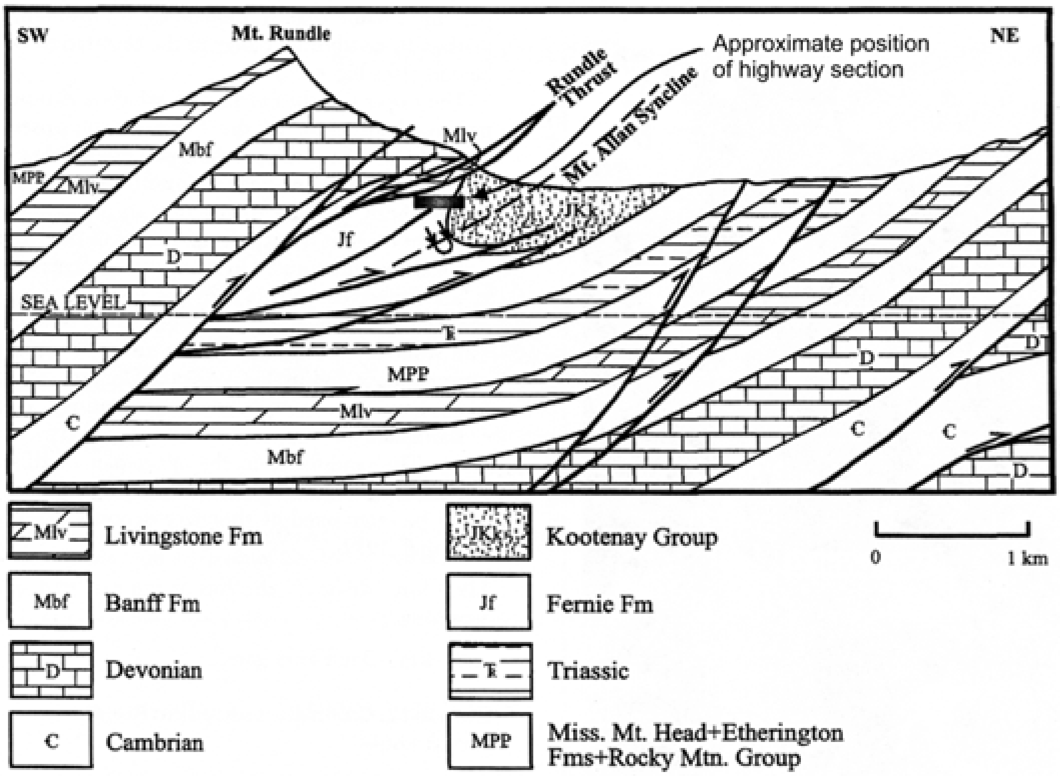


Figure 4-4 – Cross section of the Rundle thrust sheet and Mt. Allan syncline (Price & Monger, 2003)

Assignment: define the main lithological units exposed along the side of the highway and determine their relationship to one another and to any structural features. Answer the following:

Main questions: are these strata part of the passive margin, or the foreland basin? What is the depositional setting of these rocks? What structures are evident (provide orientation data)? What geopetal features are present and what do they say about the geometry of this succession? Relate the structural setting of the succession to this geometry. What is the greater tectonic significance of this sequence of rocks?

On Cascade Mountain (**Figure 4-5**), to the northwest, south-westerly dipping Upper Devonian Southesk Formation rocks (which immediately overlie the Cairn Formation carbonates seen at Grassi Lakes) have been thrust on top of overturned and steeply dipping Triassic Spray River and Fernie Group rocks. The distinctive Palliser and Banff formations and Rundle Group rocks make up the bulk of the mountain above the Rundle thrust.

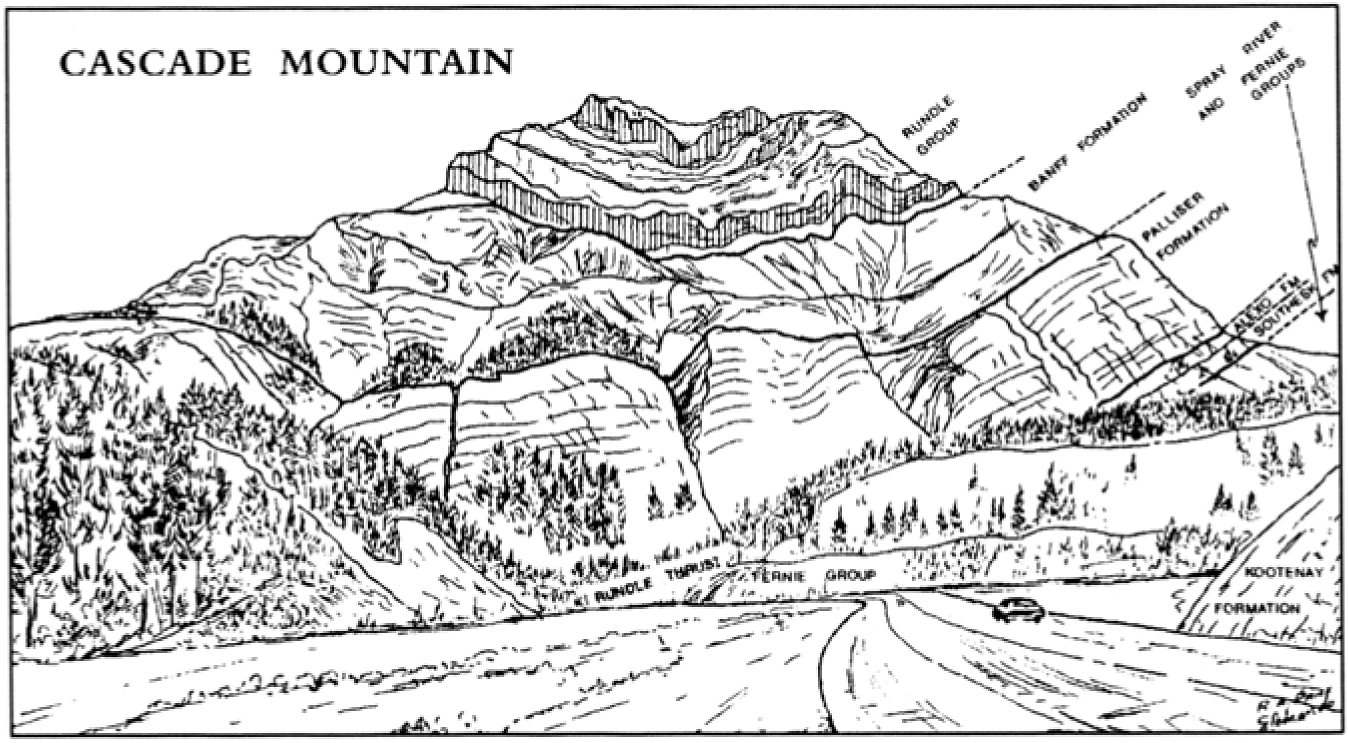


Figure 4-5 – Cascade Mountain looking northwest (Price & Monger, 2003)

LAKE LOUISE – GOG GROUP

The Lower Cambrian Gog Group in the Lake Louise area is an approximately 1,000 metre-thick, linear siliciclastic deposit consisting of alternating zones of thickly bedded quartzites and thinly interbedded quartzites and metapelites with minor carbonate lenses (**Figure 4-7**). This clastic package unconformably overlies the Miette Group of the Neoproterozoic Windermere supergroup (which we'll look at in greater detail on Day 5) and is overlain by Middle Cambrian carbonate strata. The Gog Group was deposited along the western edge of the North American craton in a prograding shallow, shelf-sea environment.

Although the Gog Group is generally impoverished with respect to index fossils, rocks in the Lake Louise area host a diverse and well-preserved suite of ichnofossils. This suite includes *Cruziana semiplicata*, *Cruziana goldfussi*, *Cruziana rugosa* and *Cruziana furcifera* (**Figure 4-6**).

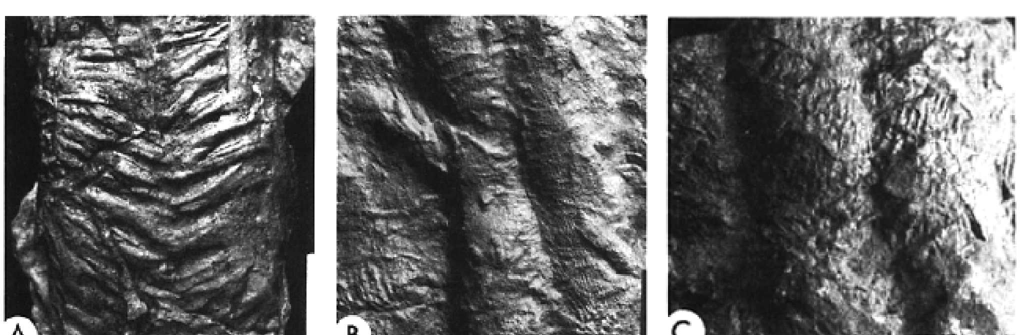


Figure 4-6 – Cruziana ichnospecies from the Lower Cambrian Gog Group near Lake Louise. Scale bars: 2 cm.

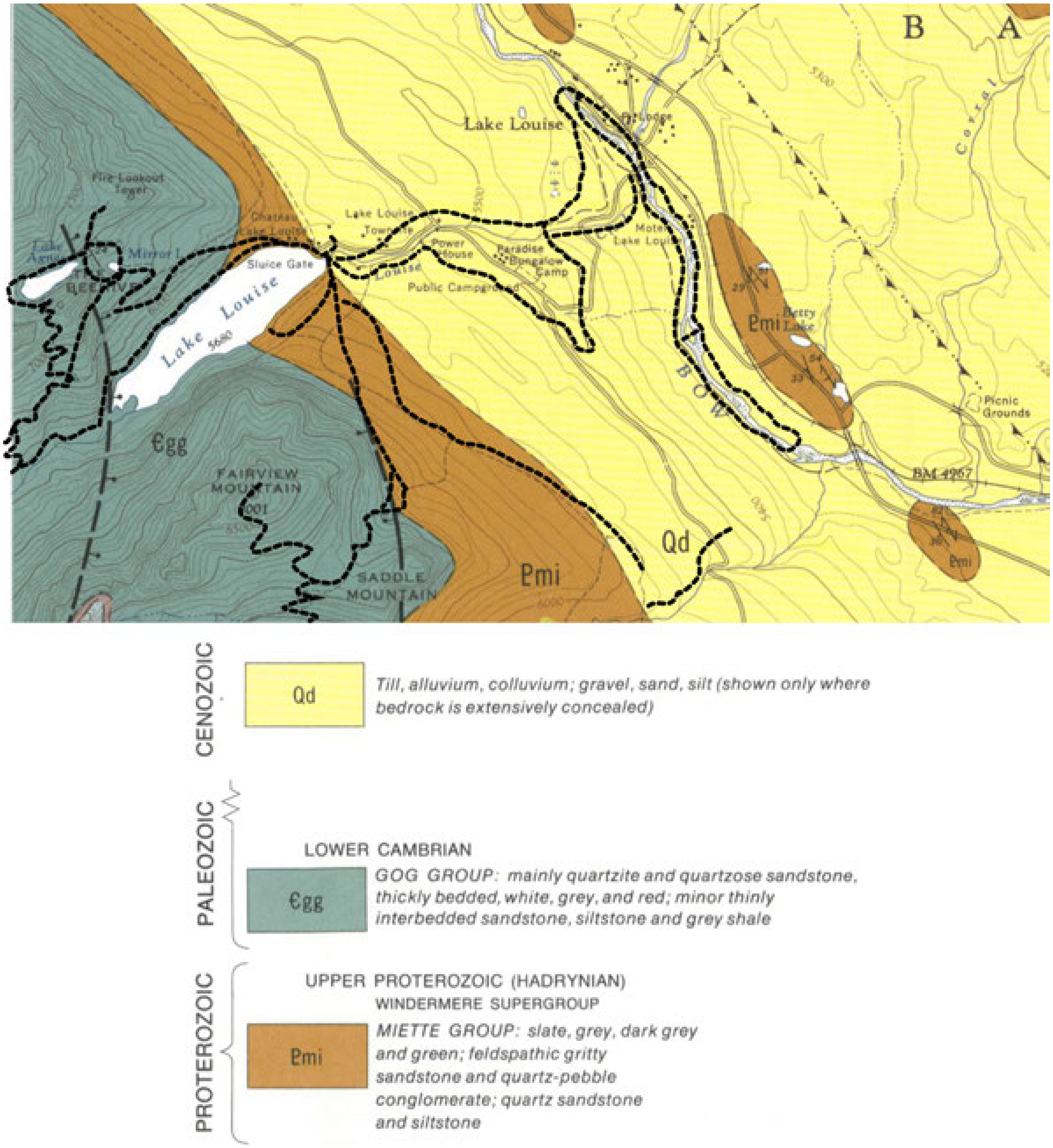


Figure 4-7 – Geology of the Lake Louise area. Scale 1~50,000

Assignment: examine the strata, noting its structural geometry (strike and dip; style of deformation). Construct a schematic cross-section extending from Lake Louise to Mt. Yamnuska. Answer the following:

Main questions: what lithologies are present? What was the tectonic setting that gave rise to these rocks? What are the implications for the tectonic and paleogeographic evolution of western North America? What does the structural geometry of the strata say about the nature of the Simpson Pass Thrust Fault?

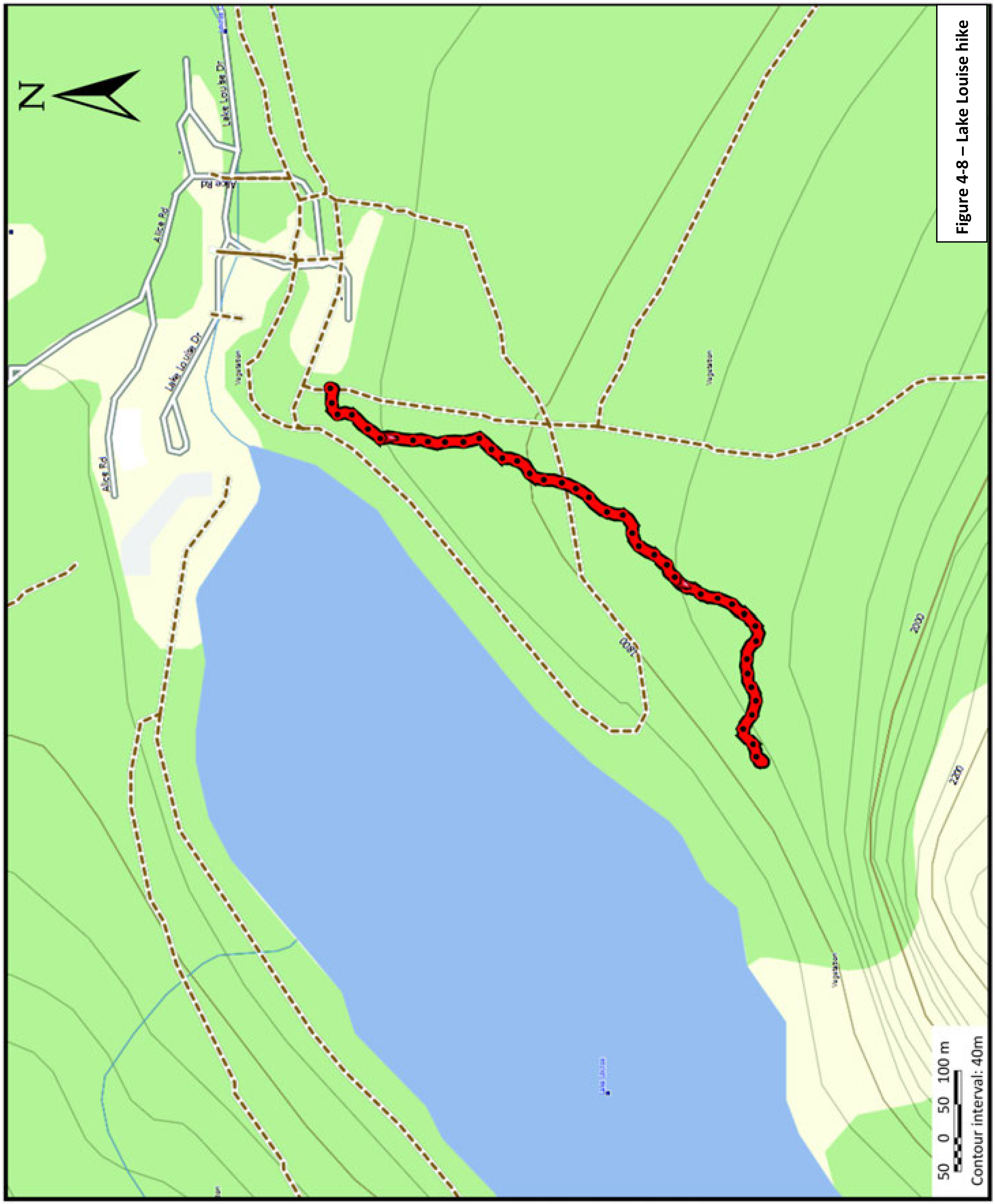


Figure 4-8 – Lake Louise hike

GEOLOGY ON THE FLY: CASTLE MOUNTAIN; SAWBACK RANGE

Geologists separate the Canadian Rocky Mountains into four different zones which relate to the style and degree of their structural deformation. In the Foothills area, the rock layers have been folded and faulted but not uplifted to any great extent. Farther west, the Front Ranges appear, their eastern edge forming a very distinct boundary where older limestones have been exposed. These ranges are composed of a series of thrust faults that underlie panels of rock which overlap like the shingles on a roof. They are almost always tilted down to the west. West of the Front Ranges lie the Main Ranges of the Rockies, in which the sedimentary layers remain relatively undisturbed although they have been uplifted significantly and moved eastward. Farther west, the layers of the Western Ranges are severely broken, faulted, and folded. The western boundary of the Rockies is the Rocky Mountain Trench, containing major rivers such as the Columbia.

Castle Mountain (also known as Mt. Eisenhower for a short period during the Second World War), the eastern-most mountain of the Main Ranges in the Bow Valley, comprises relatively horizontal strata of Precambrian and Cambrian age, whose resistance to erosion apparently varies widely (**Figure 4-9**). The upper two cliff-forming units (Cathedral and Eldon formations) are limestone, while the more gently-sloping, intermediary unit (Stephen Formation) is shale. These strata have been thrust north-eastward along a relatively flat portion of the Castle Mountain thrust. All of the Cambrian formations underlying Castle Mountain are substantially thicker than their lateral equivalents in the Front Ranges. The changes in structural style and physiographic expression from the Front Ranges Subprovince reflect the lateral changes in the supracrustal succession, from the relatively thin platformal facies to the thick miogeoclinal facies of the Lower Paleozoic succession.

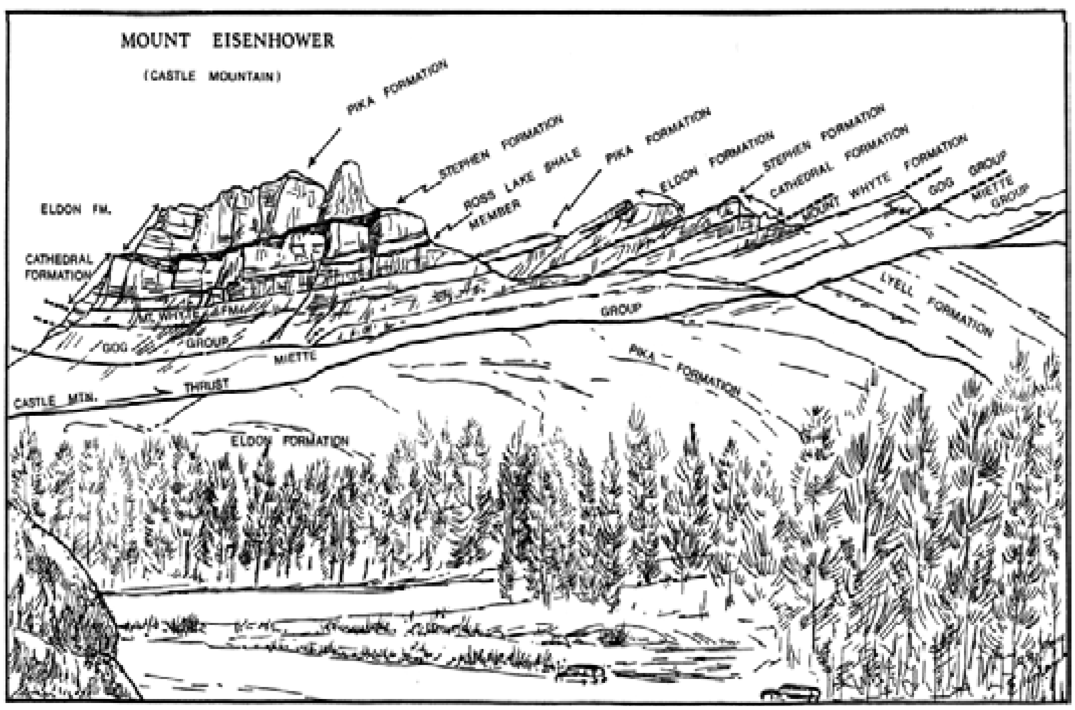
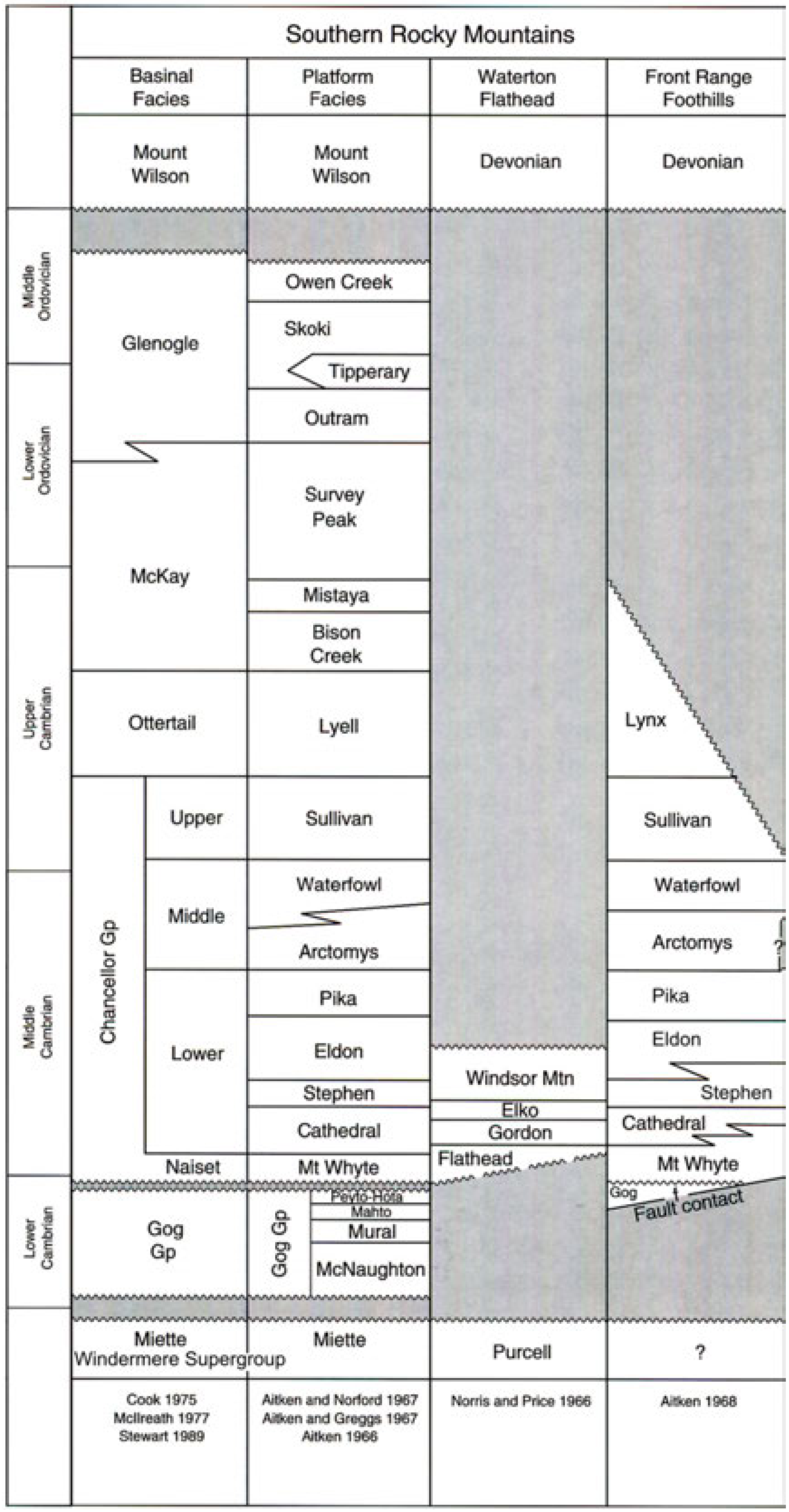


Figure 4-9 – Castle Mountain above the Castle Mountain fault (Price & Monger, 2003)

While Castle Mountain is the easternmost of the Main Ranges, the Sawback Range, with its serrated peaks, is the westernmost of the Front Ranges. The antithesis of Castle Mountain, the thin strata in this range have been tilted to near vertical and eroded by cross gullies to resemble the teeth of a saw.



Correlation chart of Cambrian and Lower-Middle Ordovician formations, Southern Rocky Mountains, Alberta

Day 5 – Foreland Belt

WILCOX PASS – ORDOVICIAN STRATA

The Wilcox Pass section in Jasper National Park, Alberta (**Figures 5-1**) exposes over 1,000 metres of Lower to Middle Ordovician strata, which provide a standard stratigraphic section for the southern Canadian Rocky Mountains. The lithostratigraphic units in ascending order are the Survey Peak, Outram, Skoki and Owen Creek formations, which together represent an upward shallowing, carbonate platform succession. This sequence is underlain by massive stromatolitic carbonates of the Upper Cambrian Mistaya Formation and overlain by siliciclastics assigned to the Middle and/or Upper Ordovician Mount Wilson Formation.

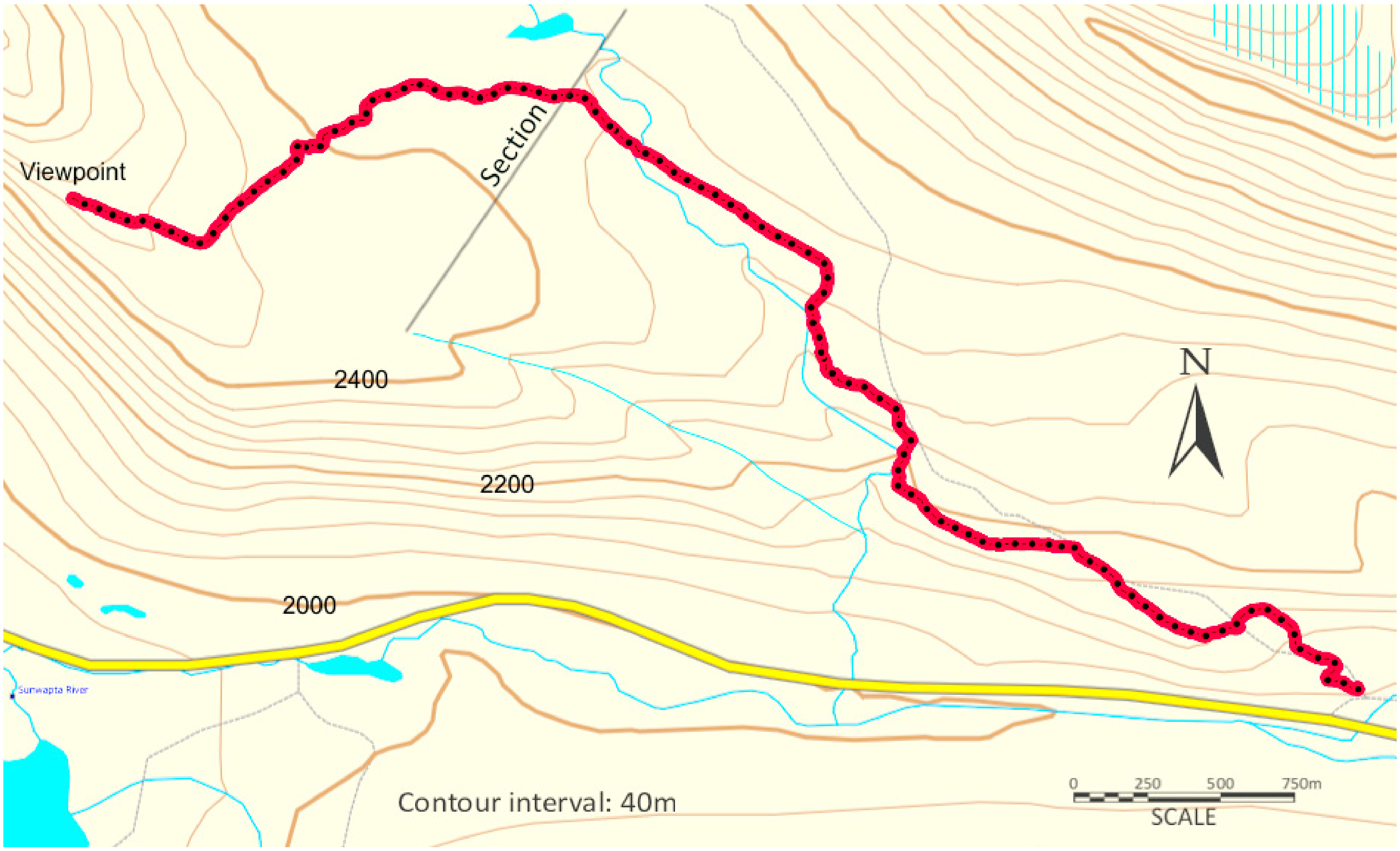


Figure 5-1 – Wilcox Pass hike/section

Spiral(?) flat pebble conglomerates (left) and stromatolites (right) of the Upper Cambrian Mistaya Formation.

The Survey Peak Formation has been subdivided into four successive informal members, with a total thickness of approximately 350 metres at Wilcox Pass. The base of the formation is defined by the cessation of massive thrombolitic (similar to stromatolitic, only with a clotted rather than laminated internal texture) and dolomitic limestones of the underlying the Upper Cambrian Mistaya Formation. This transition appears to represent a local or regional flooding surface marking the onset of a major transgressive phase.

The successive members of the Survey Peak include: the Basal Silty Member (38 metres thick at Wilcox Pass), the Putty Shale Member (36 metres), the Middle Carbonate Member (190 metres) and the resistant to cliff-forming Upper Carbonate Member (86 metres), whose contact with the overlying Outram Formation is gradational.

The Outram Formation has a total thickness of approximately 270 metres at Wilcox Pass, with its base marked by a change to darker weathering strata. The formation is recessive overall and corresponds to the base of a grand cycle. Its upper contact with the Skoki Formation is gradational and, at Wilcox Pass, contains alternations of the dominant lithologies of each formation.

The Skoki Formation is approximately 250 metres thick at Wilcox Pass and comprises two lithologically distinct members, with the transition from the lower Sikanni Chief member (126 metres) to the upper Keily member (124 metres) marked by a lithologic change to dark grey to yellow-grey weathering strata.

Macluritid gastropods (left) and up to 2 centimetre oncoids (right) in the upper part of the Sikanni Chief Member.

The Owen Creek Formation is 205 metres thick at Wilcox Pass and its contact with the underlying Skoki Formation is thought to be paraconformable. Its upper contact with light grey to white, thin to thick-bedded, partly cross-stratified quartz arenites of the Mount Wilson Formation is conformable, but erosional surfaces between the two formations are locally developed.

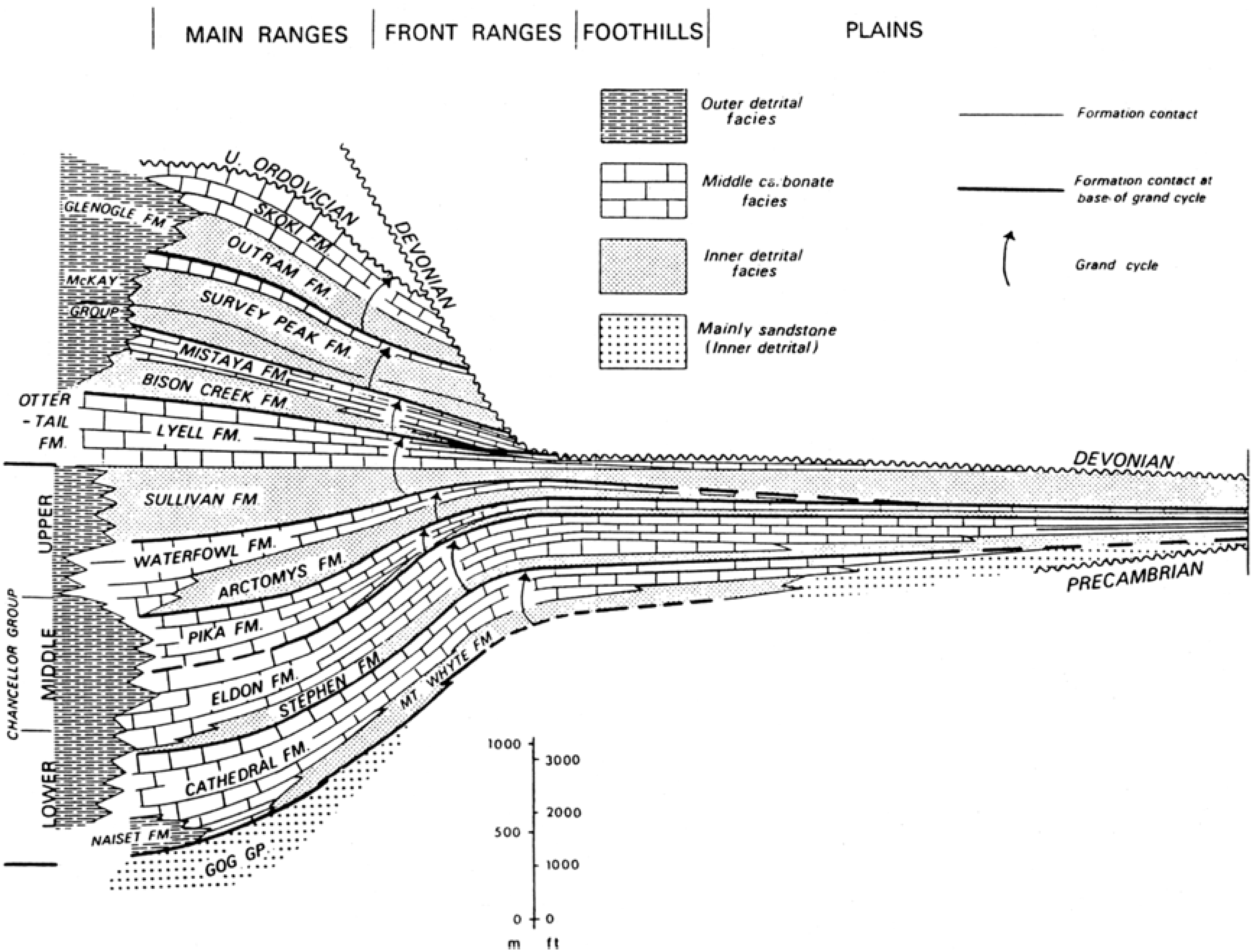


Figure 5-2 – Schematic, palinspastically restored stratigraphic section of Cambrian and Ordovician grand cycles between the Western Main Ranges shaly succession and the thin, cratonic platform succession of the interior plains, southern Rocky Mountains

Observe the mountains southwest of our viewpoint. The highest point is called the Snow Dome, which is one of only two hydrological apexes in North America (the other is Triple Divide Peak in Glacier National Park, Montana) and three in the world (the third is located in Siberia). Melt water from ice flowing away from the Snow Dome down the Athabasca Glacier eventually ends up in the Arctic Ocean, while that flowing to the southeast, down the Saskatchewan Glacier, ends up in the Atlantic Ocean and that flowing west and southwest eventually ends up in the Pacific. Answer the following:

Main questions: regarding the topography and drainages, what is the fate of sediment being shed from these mountains? What problem do you see in our use of sediment as a record of orogeny? What are the implications for the sedimentary record of the current mountainous topography? After >50 Ma of erosion, why are the Rockies still here?

Assignment 1: Examine the outcrops immediately below our viewpoint, noting the dominant lithology and any key fossils present. These rocks represent the upper-most part of the Cambrian Mistaya Formation. Walk along strike to the southeast and note any changes to the outward appearance of the sediments. Answer the following:

Main questions: how did these rocks (structures) form and in what depositional setting? Why are they so restricted in their occurrence today? What key fossils are present? What is a tempestite? What is a tsunamite? Locate and describe units which may provide examples of each of these deposit types.

Assignment 2: Complete, in teams of three, the stratigraphic column template (after Pyle, et al.) on the next page, depicting/describing, in as much detail as is practical, the features (lithologies, sedimentary structures, etc.) observed which differentiate the formations/members of the Ordovician succession exposed in Wilcox Pass. To accomplish this, you will need to account for the dip of the strata. Once complete, draw a eustatic relative sea level curve using the right-hand columns. Answer the following:

Main questions: what are the relationships between units and formations? What are the depositional environments and how do they change through the section? What is a 'grand cycle'? Comment on significance of the absence of Ordovician strata within the Front Ranges.

ATHABASCA GLACIER VIEWPOINT

The massive Columbia Icefield covers 325 km^2, reaches depths (once?) estimated at 365 metres and feeds eight major glaciers, including the Athabasca, Columbia and Saskatchewan.

The Athabasca Glacier is currently moving 125 metres/year at the headwall, but only a paltry 15 metres/year at the toe. Beginning in the latter half of the 19th century, the glacier has receded back approximately 1.5 kilometres. The annual rate of retreat has varied up to 30 metres. In years when the rate of advance and retreat were about equal, rock and mud debris were deposited in a series of moraines which can now be seen between the toe of the glacier and the highway. If the current warming trend continues, much of the glacier will melt over the next century, resulting in the loss of about half of the world's glacial ice.

Stage	Formation	Member	CLAY / SILT / SAND (FINE, MEDIUM, COARSE) / PEBBLE / COBBLE / BOULDER	Sedimentary Structures	Description (Legend on back; Scale ~1:5,000)	Sea Level Curve (High Stand Low): Basin / Shelf / Barrier / Lagoon / Supratidal
Middle Ordovician	Mount Wilson					
	1075					
	Owen Creek					
	870					
	Skoki	Keily				
		Sikanni Chief				
	620					
Lower Ordovician	Outram					
	350					
	Survey Peak	Upper				
		Middle				
		Putty Shale				
Cambrian		Basal Silty				
	0					
	Mistaya					

ICEFIELDS PARKWAY INTERCHANGE – MIETTE GROUP

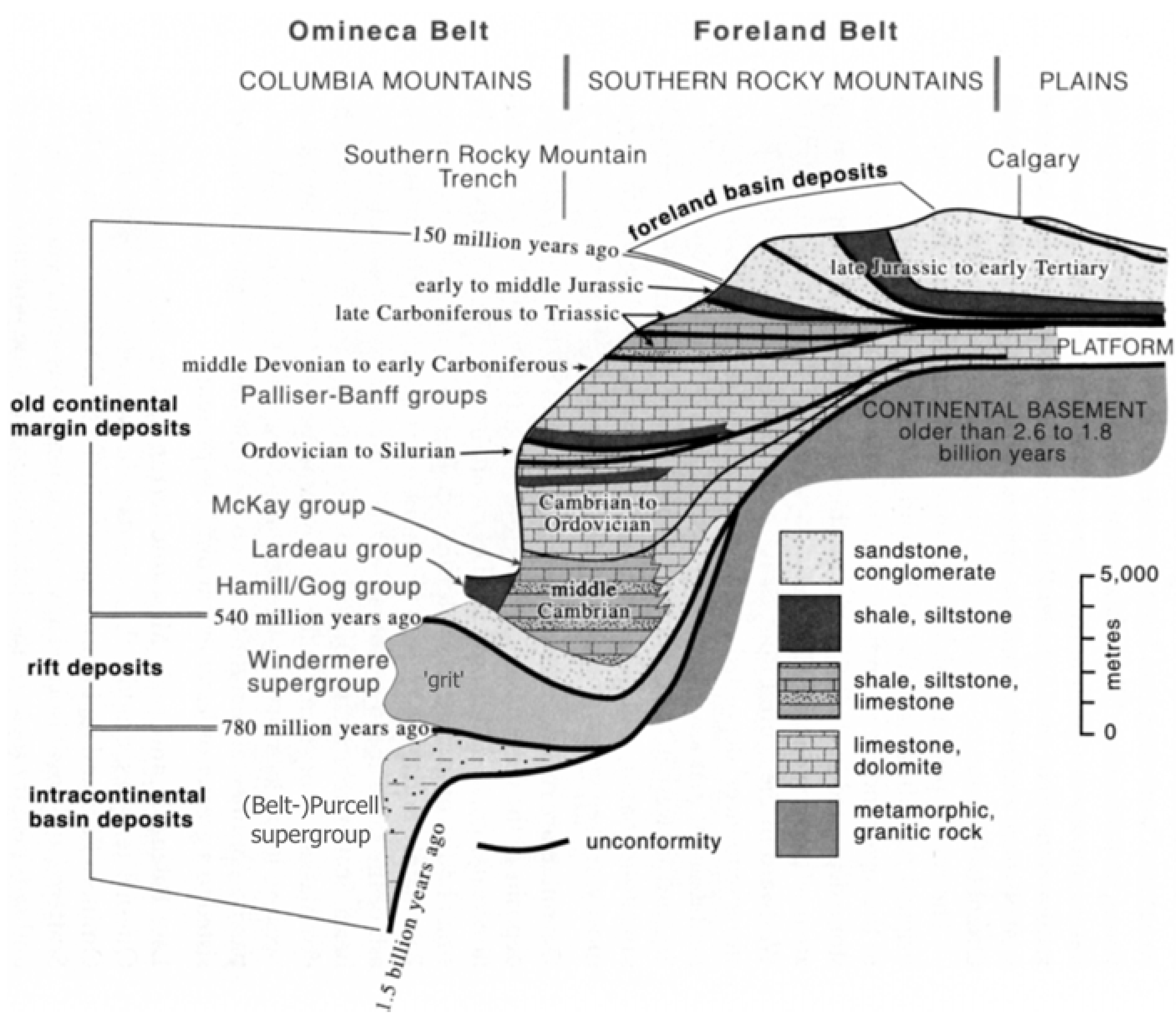
Deformed, turbiditic metasediments of the Neoproterozoic Miette Group (Windermere Supergroup) which accumulated adjacent to the margin of the Laurentia craton (**Figure 5-3**).

During the Rocky Mountain orogeny, Miette strata were tightly folded and faulted. The folds, which are associated with various types of axial-planar cleavage, appear to die out in the upper part of the formation and those in the overlying and conformable Gog Group are generally much more open and widely spaced. The bulk of the Miette Group belongs to the quartz-albite-chlorite-muscovite sub-facies of the greenschist metamorphic facies. The major metamorphic reactions were the conversion of illite to muscovite, chlorite, and quartz, and the breakdown of potassic and calcic feldspars into albite. The upper part of the Miette Group and the whole of the Gog Group show fewer metamorphic effects. Quartz-calcite-chlorite veins are common in the Miette Group. Radiometric potassium-argon ages range between 1,770 and 69 Ma and are intermediate between the age of the source rocks and the age of orogenesis.

Figure 5-3 – Miette Group, Icefields Parkway Interchange, looking east

Assignment: describe and characterize the rock type; identify and describe all the planar structures; provide a quantitative analysis of the structural evolution of the rocks (this requires the collection of orientation data and the plotting of this data on a stereonet). Answer the following:

Main questions: what is the nature and depositional environment of these rocks? What are the implications of these rocks for interpretation of the Gog quartzites, and for the paleogeographic and paleotectonic evolution of western North America? Have these rocks been metamorphosed? How many deformation events are recorded in these rocks and what is the relationship of the structures to deformation observed in the Front Ranges?



Major rock packages, sedimentary rock types, and thickness changes from west to east in the continental margin deposits of Precambrian through Jurassic time.

Figure 5-4 – Major rock packages, sedimentary rock types and thickness changes from west to east in the continental margin deposits of Precambrian through Jurassic time (Mathews & Monger, 2005)

WALCOTT QUARRY – BURGESS FORMATION (SHALE)

The History of the Burgess Shale

The story of the Burgess Shale began more than a half billion years ago, shortly after an evolutionary 'Big-Bang' called the Cambrian Explosion. After nearly two billion years of only simple, unicellular life forms on earth, a full spectrum of complex animal forms appeared in the oceans over a period of just 10-20 million years.

The Burgess Shale fauna are thought to have lived on a massive carbonate platform, sloping gently westward from the shores of ancestral North America, which at this time straddled the Equator. It is at the base of the submarine cliff, now known as the Cathedral Escarpment (**Figure 6-1**), which formed the eastern edge of this platform, that the remains of these animals came to be fossilized. How they got there and why they were so exquisitely preserved, is the subject of considerable debate. Some have suggested that turbidity currents

The animals were eventually either transported to or colonized the base of the escarpment, where they were buried and died. Over the course of many millions of years, the animals were buried by sediments, and their delicate remains turned into fossils. The fossils were at one time covered by up to 10 kilometres of overlying rock, and would have been subjected to great heat and pressure at those depths. Beginning about 175 Ma, mountain-building forces bulldozed and transported the fossils from their ocean burial-ground many kilometres eastward on faults, to their current position high on a mountain ridge in Yoho National Park.

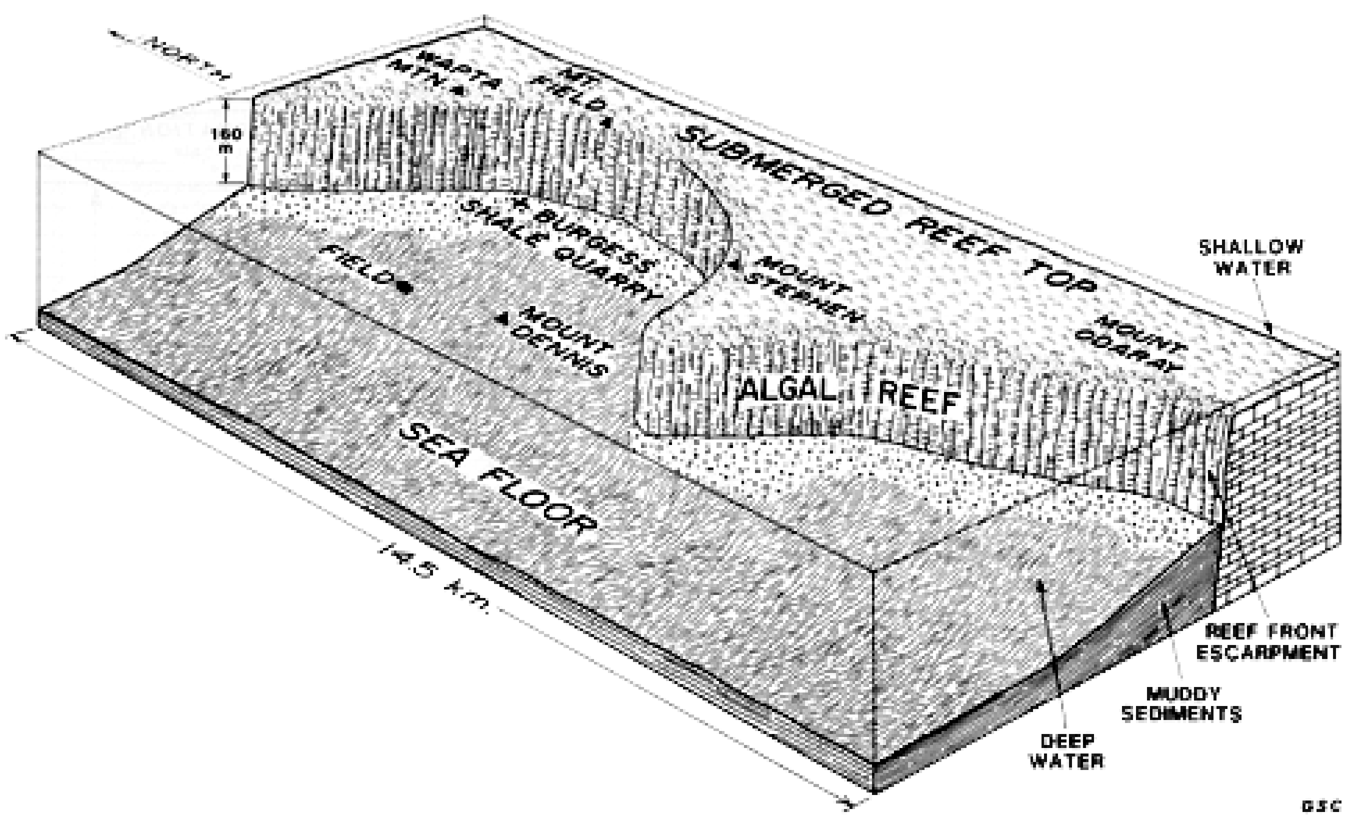


Figure 6-1 – Artist's impression of the Cathedral Escarpment

Since then, the ancient mudstones (shales) containing the fossils have been subject to the erosional powers of glaciers, wind, water, landslides and avalanches. The fossils' preservation for 505 million years is a miracle, indeed!

Summary of Research

The first geologist to visit the Mt. Stephen Trilobite Beds was R.G. McConnell of the Geological Survey of Canada (GSC), in 1886. He collected a number of trilobites, as well as fossils that he identified as the body of a shrimp, and named Anomalocaris canadensis, or 'odd shrimp'. In fact, the fossils were the moulted claws of the giant predator, Anomalocaris, and it took 96 years for scientists to piece together what the ancient animal really looked like.
Collections from the Trilobite Beds had also been made by Canadian Pacific railway workers. Charles Walcott of the Smithsonian Institute, the leading expert on Cambrian-age fossils at that time, heard about their reports of 'stone bugs' and first visited the site on Mt. Stephen in July, 1907. He published a comprehensive account of the fossils from that location in 1908.

Walcott discovered the first fossils from the more famous Burgess Shale site along the horse trail near Burgess Pass on Aug 30, 1909. The following season, he located the source of the fossils higher up on Fossil Ridge, and began excavating. The fossils, with their exquisite preservation, were unlike anything he had seen before. He named the site the Burgess Shale, after nearby Mt. Burgess. That specific site is now known as the Walcott Quarry.

Walcott spent the summers between 1910-1917 excavating the quarry with the help of his family. He collected more than 65,000 specimens that were sent to the Smithsonian Institute in Washington, D.C. Walcott classified the various fossils within our modern classification system, interpreting the fossils to be ancestors of animals alive today. He carefully documented his specimens with retouched photographs.

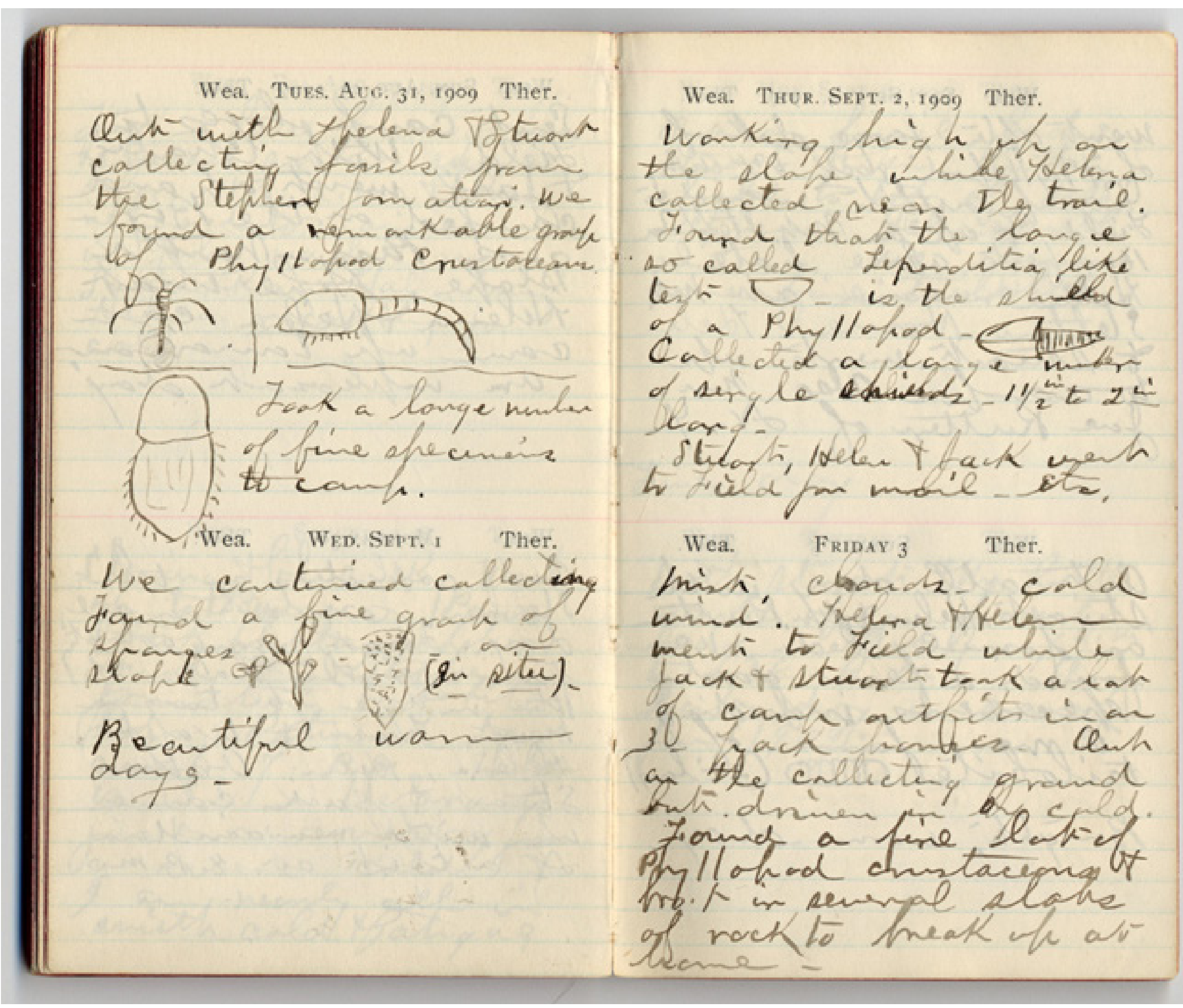


Figure 6-2 – Walcott's notes

The next work to be done on the Walcott quarry site was by Percy Raymond of Harvard. In 1930, he collected from Walcott's quarry, and then opened up another smaller quarry 20 metres above, which is now referred to as the Raymond Quarry. The two quarries differ somewhat in their fossil assemblages, and the specimens in Raymond's quarry tend to be a little larger.

The quarries were reopened by the GSC in 1966-67, and fossil collections were made. Many new, unknown specimens were recovered, which instigated a restudy of the Burgess Shale fossils led by Dr. Harry Whittington of Cambridge, along with his graduate students, Derek Briggs and Simon Conway-Morris. Walcott's notes (**Figure 6-2**) and photos had lain in drawers alongside his fossil specimens for nearly half a century, until 1973, when the Cambridge scientists dusted them off to have another look. Between 1971 and 1985, Whittington *et al.* published papers describing in great detail most of the soft-bodied fossils. To their surprise, they were unable to classify many of them within our modern classification system, listing them instead as members of unknown phyla, implying that there had been a greater diversity of basic animal forms half a billion years ago than today. Our understanding of evolution was turned on its head!

Recognition of the significance of the Burgess Shale led to its declaration as the 86th UNESCO World Heritage Site in 1981. The fossils were made famous with Stephen J. Gould's best-selling book, Wonderful Life in 1989. Based on the work of Whittington *et al.*, Gould concluded that more than half of the major animal groups present in the Cambrian seas are extinct. He attributed this to the effects of contingency (or mass extinction) being more drastic than previously thought. Indeed, there have been five great periods of extinction in Earth's history. The one we are most familiar with is the extinction of the dinosaurs at the end of the Cretaceous period, 65 Ma, that allowed mammals to diversify, ultimately leading to the rise of Man.

One of the world's leading experts on the fossils today is Dr. Desmond Collins of the Royal Ontario Museum (ROM) in Toronto. The ROM first collected from the quarries on Fossil Ridge in 1975. They returned in 1981, seeking new localities of the fossils by following the ancient reef front mapped previously. This proved very successful, and more than a dozen new localities were found in a 20 km vicinity of the original (Walcott) quarry. Since then, the ROM has collected from these new sites, finding a number of new and rare fossil forms.

Continuing work by paleontologists around the world has led to a reinterpretation of some of the previously unclassifiable forms such that they can now be classified in our modern system. However, there are just as many new unclassifiable forms from recent discoveries that have been made, maintaining the case for greater biodiversity in the Cambrian seas than in our modern oceans. Debate on the implications of the Burgess Shale fossils with regard to the evolutionary process rage on, and the saga continues.

Main questions: what is the depositional setting of the Burgess Shale? What is the relationship between the shale and the boundary between the Eastern and Western Main Ranges? Consider the enigma of the preservation of the fossils at this site (the lack of penetrative deformation and apparent lack of significant metamorphism). What is its significance for our understanding of the evolution of life on earth? What is its tectonic setting (Rodinia break up, post-Snow Ball earth)?

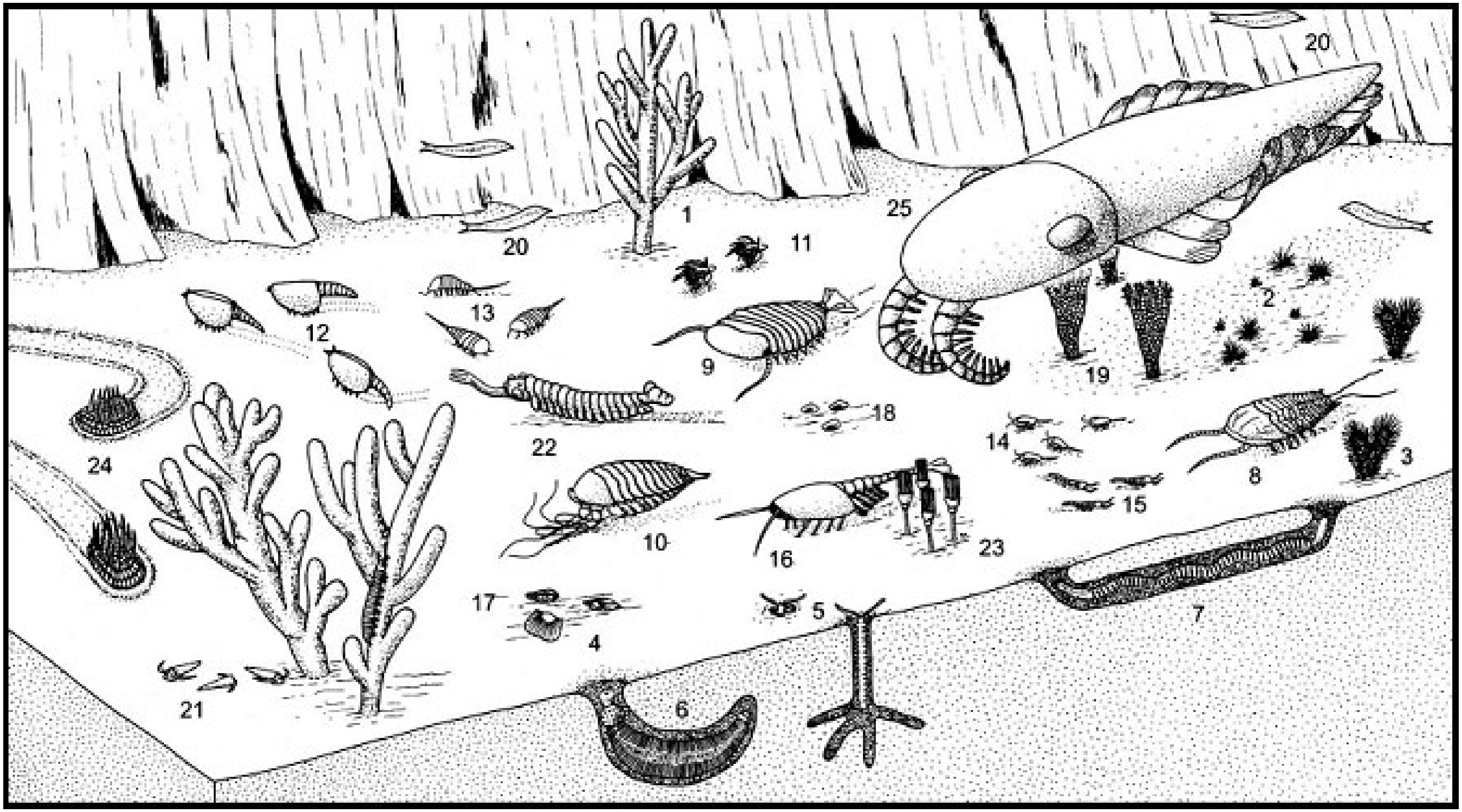
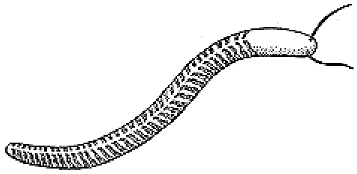
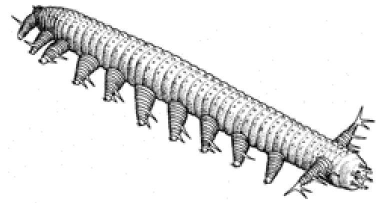
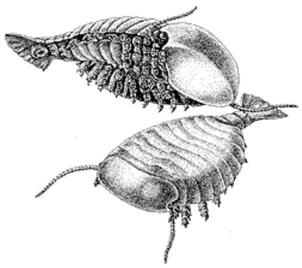
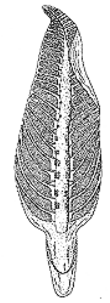
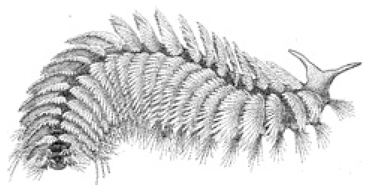
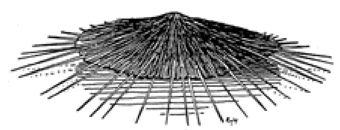
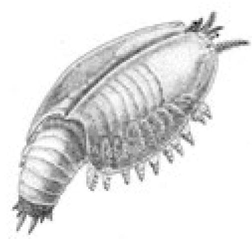
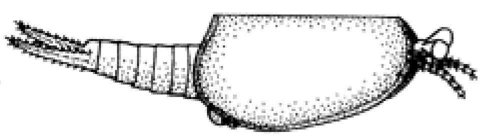
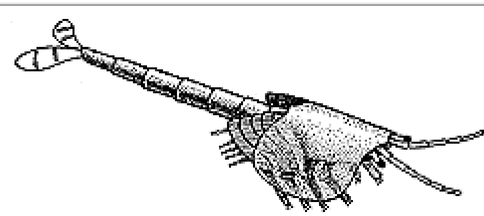
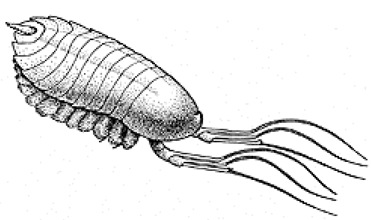
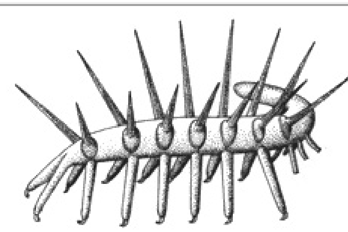
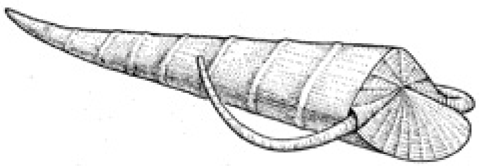
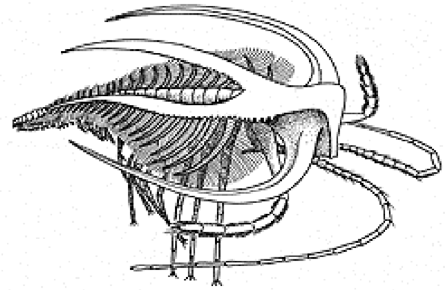
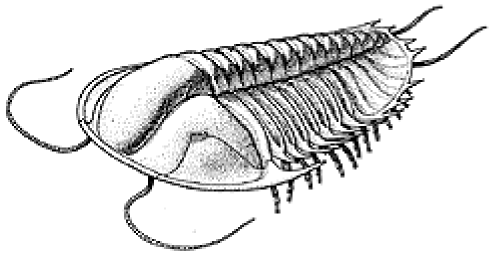
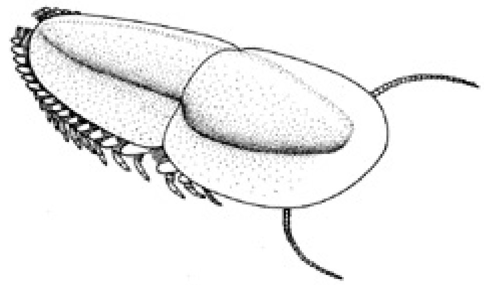
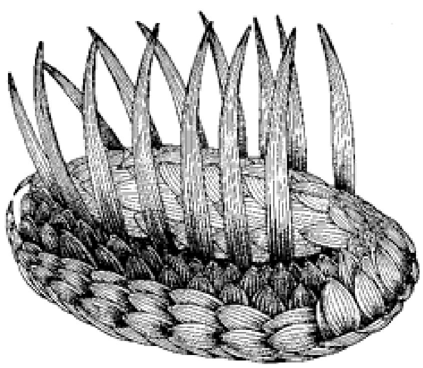
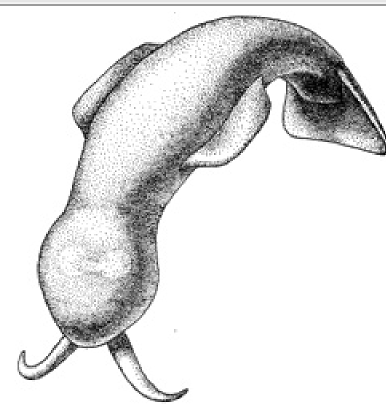
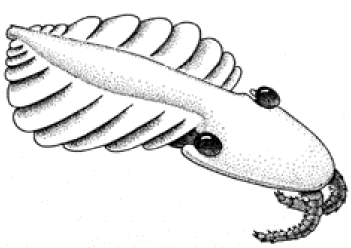
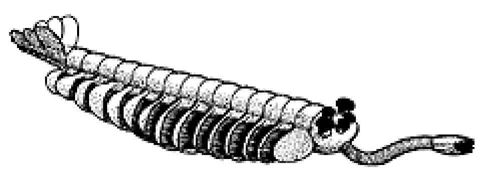


Figure 6-3 – In the image above (from the book *The Fossils of the Burgess Shales*, by Briggs, Erwin and Collier, 1994), trilobites (8) live among many species of arthropods and other invertebrates not normally preserved. A more typical Cambrian outcrop might have included only trilobites, brachiopods (4), mollusks (18), and crinoids (19). That is a tiny fraction of the full Cambrian biota.
The more typical roster of the Cambrian *Konservat-Lagerstatten* includes sponges *Vanuxia* (1), *Choia* (2), *Pirania* (3); brachiopods *Nisusia* (4); polychaetes *Burgessochaeta* (5); priapulid worms *Ottia* (6), *Louisella* (7); trilobites *Olenoides* (8); other arthropods *Sidneyia* (9), *Leanchoilia* (10), *Marella* (11), *Canadaspis* (12), *Molaria* (13), *Burgessia* (14), *Yohoia* (15), *Waptia* (16), *Aysheaia* (17); mollusks *Scenella* (18); echinoderms *Echmatocrinus* (19); chordates *Pikaia* (20); among others, including *Haplophrentis* (21), *Opabinia* (22), *Dinomischus* (23), *Wiwaxia* (24), and *Laggania* (an Anomalocaridid 25).

A – Burgess Shale species assigned to commonly recognized groups.	
 Chordate - *Pikaia* ~4 cm in length	 Velvet worm - *Aysheaia* 5+ cm in length
 Arthropod - *Sidneyia* 5 to 13 cm in length	 Sea pen - *Thaumaptilon* up to 20 cm in length
 Annelid - *Canadia* ~3 to 5 cm in length	 Sponge - *Choia* ~3 cm in diameter
 Priapulid - *Ottoia* ~3 to 15 cm in length	 Crab - *Canadapsis*
 Crab – *Perspicaris* ~3 cm long	 Crab - *Waptia* ~8 cm long
 Arthropod - *Leanchoilia* ~5 cm long	 Anychophoran (velvet worm) - *Hallucigenia* ~3 cm long

B - Other “recognized” Burgess Shale species with no currently living examples:	
 Hyolith - *Haplophrentis* ¼ to 3 cm long	 Arthropod - *Marrella* ¼ to ¾ cm long
 Trilobite - *Olenoides* up to 10 cm in length	 Trilobite - *Naraoia* up to 4 cm long

C - Unassigned Burgess Shale forms with no clear signs of ancestral linkage to any surviving group:	
 *Wiwaxia* up to 5 cm long	 *Amiskwia* up to 2.5 cm long
 Proto-arthropod(?) - *Anomalocaris* ~50 cm in length	 *Opabinia* up to 10 cm including proboscis

Source: National Museum of Natural History's Paleobiology Website (http://nmnhgoph.si.edu/paleo/shale/index.html).

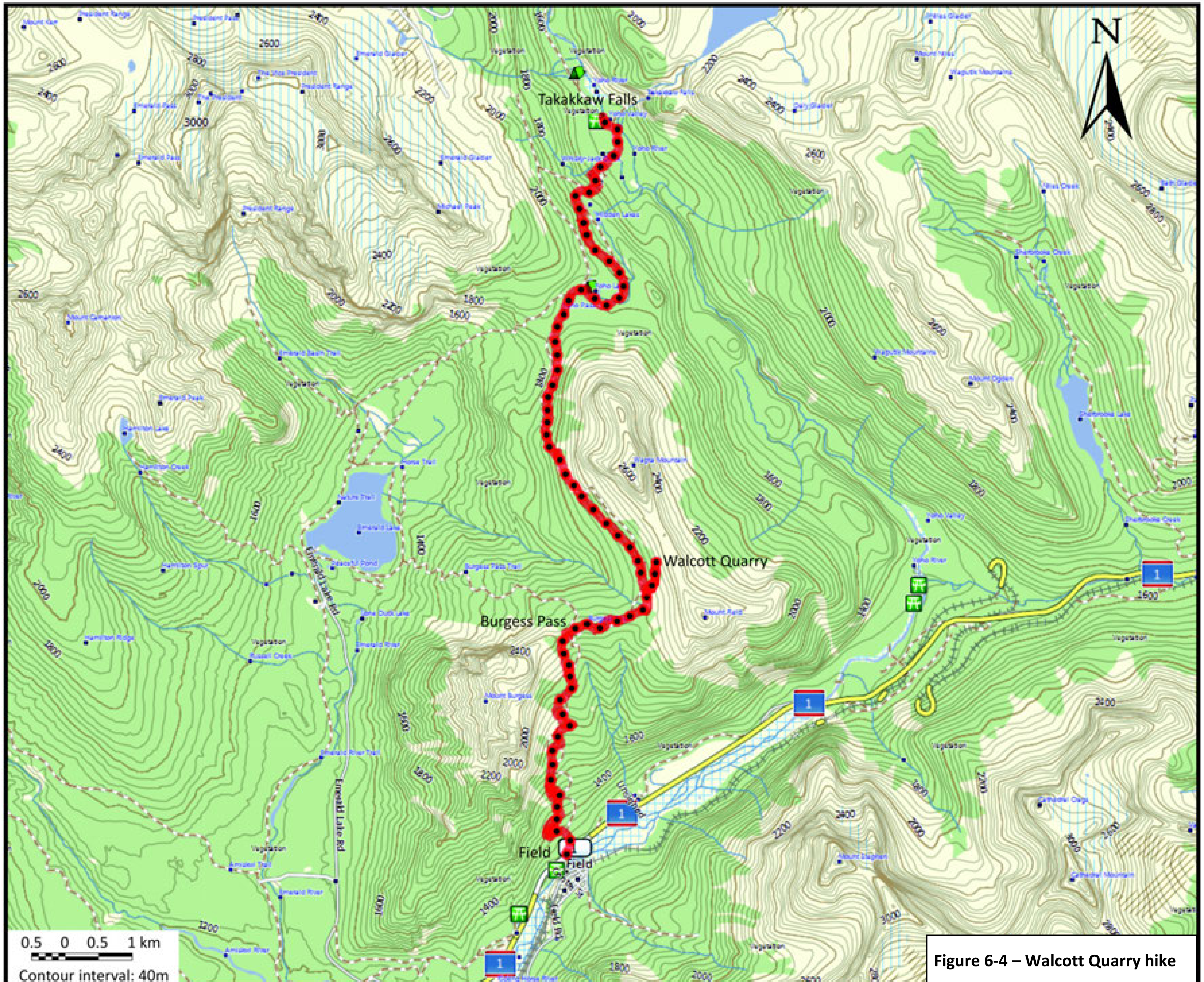


Figure 6-4 – Walcott Quarry hike

KICKING HORSE RIVER VIEWPOINT – CHANCELLOR FORMATION

Gently folded and strongly boudinaged alkalic dykes intrude ductile, highly strained sediments of the Middle Cambrian Chancellor Formation (**Figure 6-5**). The dykes are associated with the Devonian Ice River Complex (368 ± 4 Ma), a funnel-shaped, composite alkaline igneous complex that occurs within the core of the Porcupine Creek anticlinorium west of this location.

Figure 6-5 – Chancellor Formation hosting boudinaged dykes (D) with coarse-crystalline calcite and quartz in-fillings (after Price & Monger, 2003)

Assignment: describe the rock types and tectonic fabric elements (provide orientation data). Undertake a structural analysis using hand-drawn stereonets. Draw a sketch showing all of the planar fabric elements and indicating their relationships (order of development – S_0, S_1, S_2 ...). Answer the following:

Main questions: how do these rocks differ from all the previously observed rocks? Are we on the east or west limb of the anticlinorium? What is the vergence of the structures here? What is the significance of the dykes? What has happened to them?

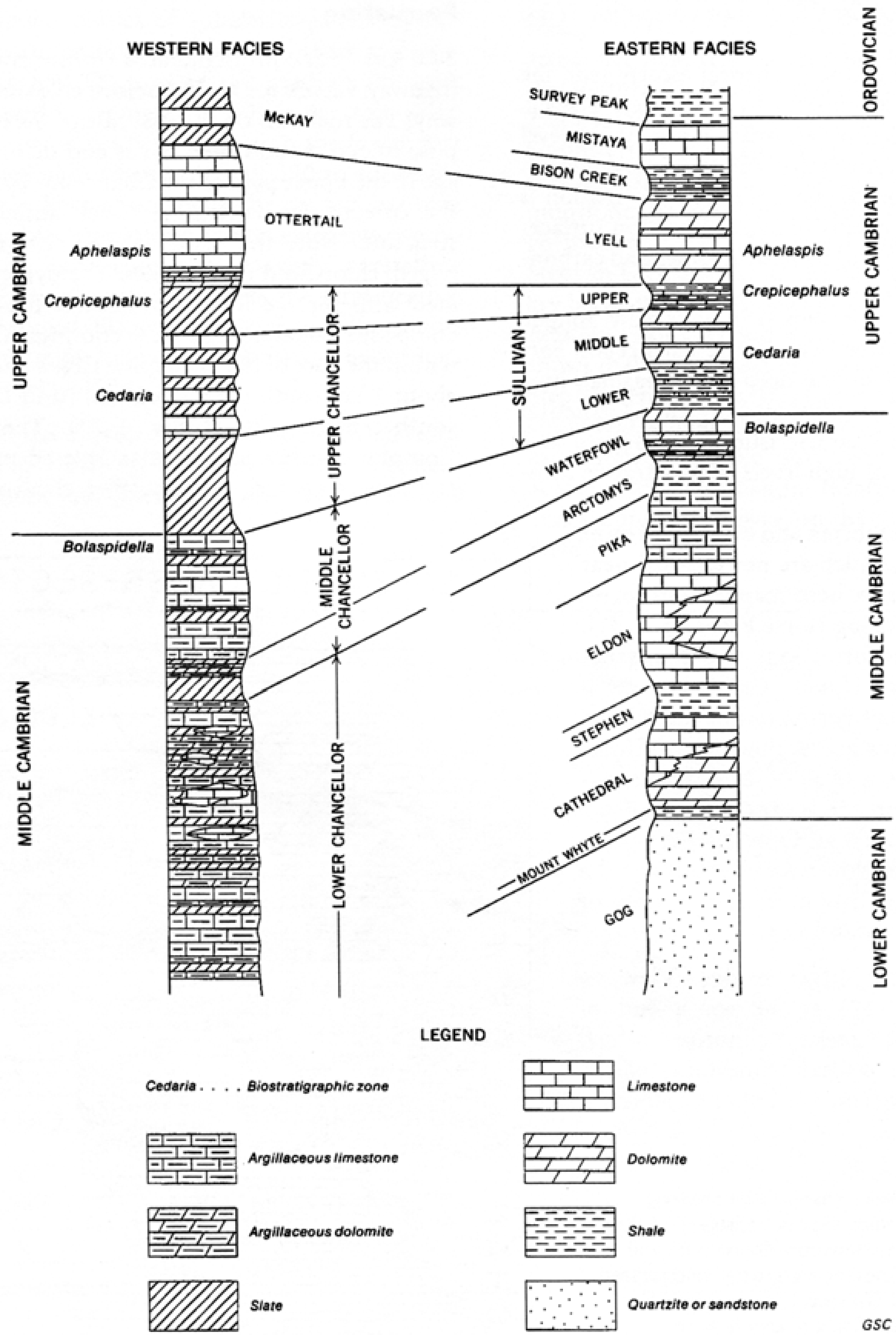


Figure 6-6 – Cambrian-Lower Ordovician correlations across the Kicking Horse Rim (Cook, 1975)

Day 7 – Omineca Belt

GOLDEN TIMMY'S (ROCKY MOUNTAIN TRENCH VIEWPOINT)

Extending for some 1,600 kilometres from northern Montana to the southern Yukon (where it is aligned with the Tintina Trench which extends a further 1,000 kilometres into east-central Alaska), the Rocky Mountain Trench is, in the Golden area, situated in the footwall of the Purcell thrust fault (**Figure 7-1**). It is bound on the northeast by resistant carbonate rocks of the Upper Ordovician-Lower Silurian Beaverfoot Formation and quartz arenites of the Mount Wilson Formation and to the southwest by siliciclastic rocks of the Lower Cambrian Hamill Group and the Neoproterozoic Horsethief Creek Group that occur in the hanging wall of the fault.

While an obvious topographic lineament, the trench is *not* thought to be coincident with any one major, through-going fault structure, is *not* a terrane boundary, does *not* mark the southwestern limit of the foreland thrust and fold belt and does *not* define the northeastern limit of metamorphic and magmatic rocks in the Canadian Cordillera.

The southern Rocky Mountain Trench *is* a half graben that follows the hanging wall of a southwest dipping, listric normal fault, while to the northern section follows a strike-slip fault system that has seen at least 450 kilometres of dextral displacement since the mid-Cretaceous.

The Purcell thrust (**Figure 7-1**) is a major, regional, northeast-verging, pre-mid-Cretaceous thrust fault following the western side of the Rocky Mountain Trench west of Golden. Further west, it truncates underlying southwest-verging structures and the older, back-rotated northeast-verging thrusts and folds that form the southwest flank of the porcupine Creek fan structure. Along its hanging wall, it also truncates the overlying, northeast-verging Dogtooth thrust duplex.

Figure 7-1 – Rocky Mountain Trench looking west-northwest towards the Dogtooth Mountains
Approximate location of the Purcell thrust shown

<u>REDGRAVE QUARRY – HAMILL GROUP</u>

Buff- to pink-coloured massive quartzite of the Upper Neoproterozoic-Lower Cambrian Hamill Group (equivalent to Gog, east of the Purcell thrust) in the hanging wall of the Purcell thrust. These rocks form many of the peaks surrounding Rogers Pass.

Gog and Hamill group strata are exposed in thrust sheets of the Main Ranges to the west and eastern Omineca belt, respectively (**Figure 7-2**). They overlie the sequence of immature, coarse-grained, arkosic grit and pelitic and calcareous (meta)sedimentary rocks of the Windermere Supergroup, locally with apparent conformity. The distribution of facies (shallow-marine to fluvial) and thickness variations within the lower part of the Hamill/Gog Group suggest that these rocks were deposited in a series of restricted, north-trending, fault-bounded basins. The middle part of the Hamill Group locally contains volcanic rocks that accumulated during crustal extension in proximity to inferred normal fault(s). A concordant U–Pb zircon age of 569.6 ± 5.3 Ma from synrift volcanic rocks within the group west of this locality provided the first direct U–Pb geochronologic constraint on timing of latest Neoproterozoic rifting and establishment of a passive margin along western Laurentia. The regional unconformity at the base of the upper Hamill–Gog Group formed as a consequence of continental breakup leading to thermal subsidence and deposition of lower Paleozoic miogeoclinal strata along the western margin of Laurentia.

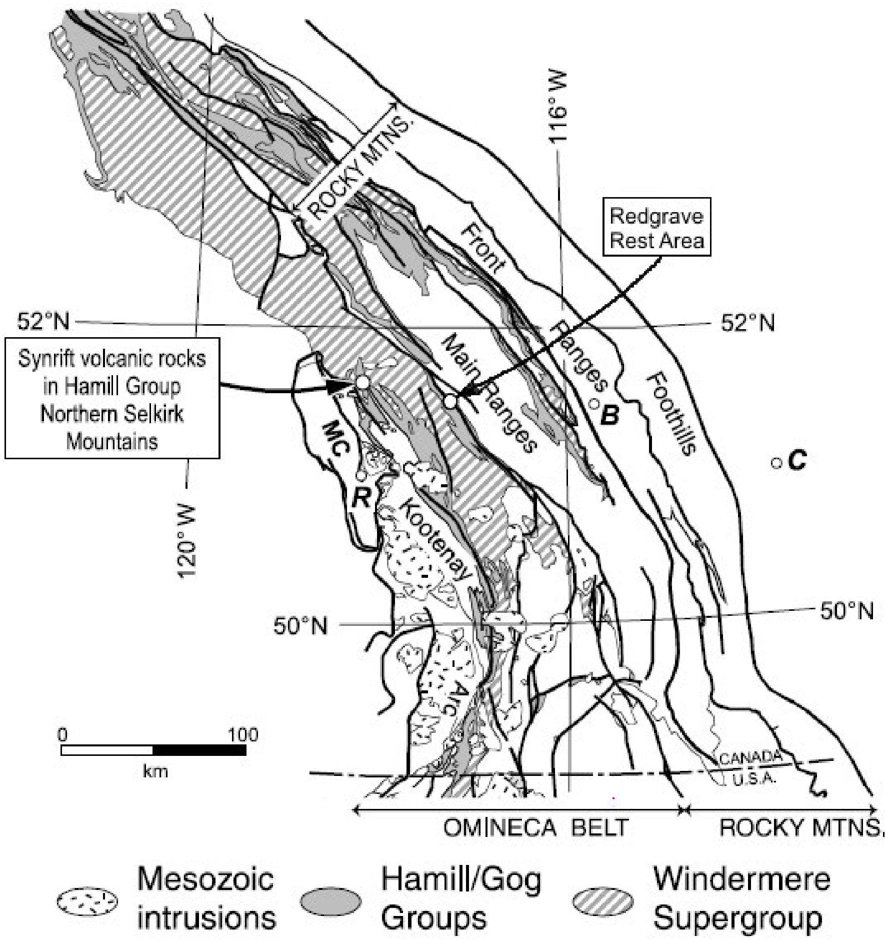


Figure 7-2 – Distribution of Neoproterozoic synrift deposits in the southeastern Canadian Cordillera. Sampling area for intermediate volcanic rocks of the Hamill Group. C – Calgary, B – Banff, R – Revelstoke, MC – Monashee Complex (Colpron, *et al.*, 2002)

Assignment: Describe the rock, and provide evidence for the depositional setting (sedimentary facies). Answer the following:

Main questions: why not maintain the name Gog? What is problematic about the depositional setting of these rocks (consider the implications of the Burgess Shale / Kicking Horse Rim)? What is the significance of the correlation with the Gog Group (your answer should address the paleomagnetic data and the origin of the Rocky Mountain Trench)?

The Windermere and Dogtooth 'highs', located in the central and northern (Dogtooth Range) Purcell Mountains, respectively, are interpreted as areas of erosion or non-deposition of the latest Proterozoic - Early Cambrian Hamill Group above a regionally recognized 'sub-Cambrian' unconformity (**Figure 7-3**). This unconformity places Hamill Group rocks on different stratigraphic units of the Late Proterozoic (Hadrynian) Horsethief Creek Group in these locations. Both 'highs' are interpreted to be uplifted/tilted and (in part) subaerially exposed crustal blocks that formed during the Eocambrian rifting that preceded the Early Cambrian seafloor spreading that marked the initiation of deposition of the Cordilleran miogeocline along the passive continental margin of Laurentia.

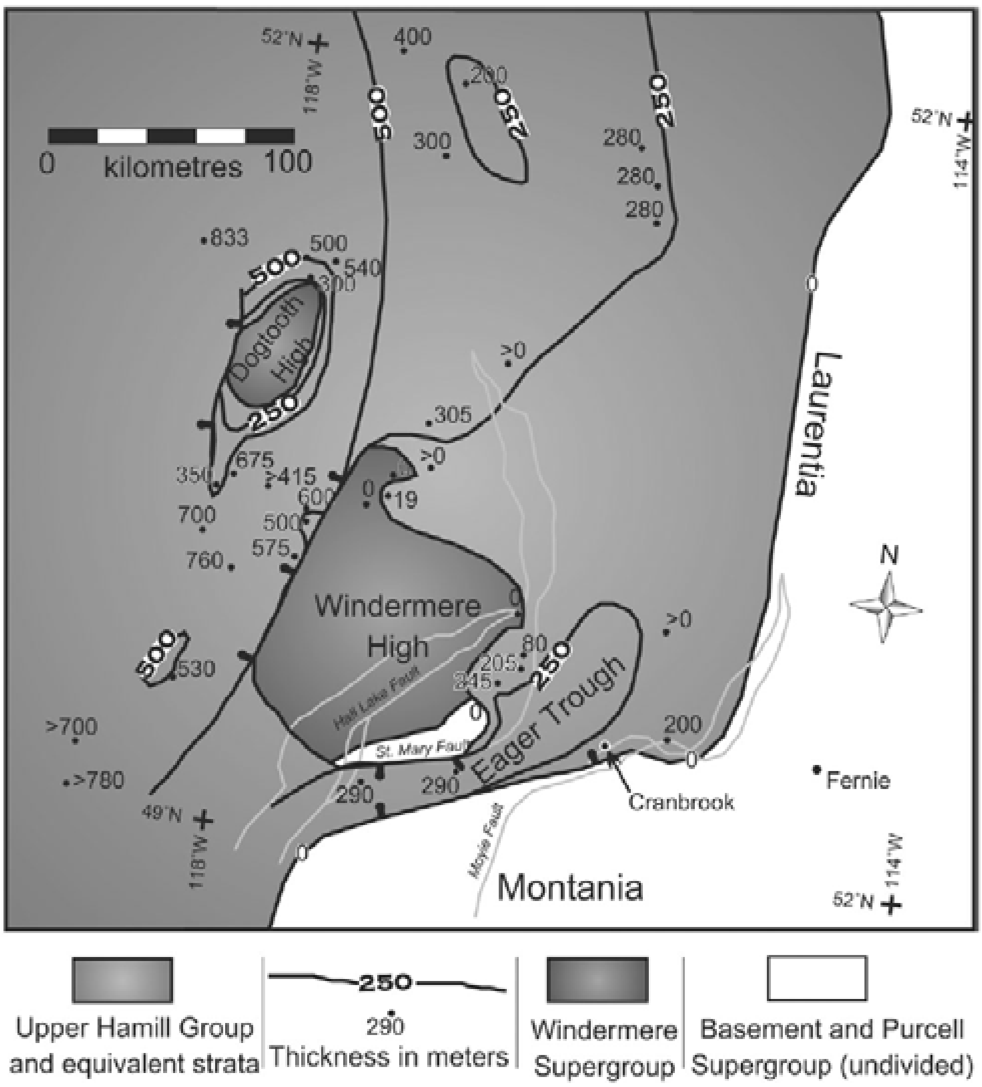


Figure 7-3 – Simplified paleogeographic map of the palinspastically restored, early Cambrian Cordilleran miogeocline in southern Canada, illustrating relationships between the Windermere and Dogtooth 'highs' and the Eager Trough. Isopachs (in m) are of the Lower Cambrian Hamill Group quartz arenite unit and correlatives (Larson & Price, 2006).

GEOLOGY ON THE FLY: SELKIRK FAN

The highway to the west of the trench transects a sequence of mostly low-grade, metamorphosed sedimentary rocks that have been folded, thrust-faulted and reverse-faulted into an enormous structure called the Selkirk fan. The term 'fan' is used because most of the rocks west of Rogers Pass are folded and thrust westward along west-verging faults, while those east of the pass are folded and thrust eastward along east-verging faults, forming a fan-like array of structures (**Figure 7-4**).

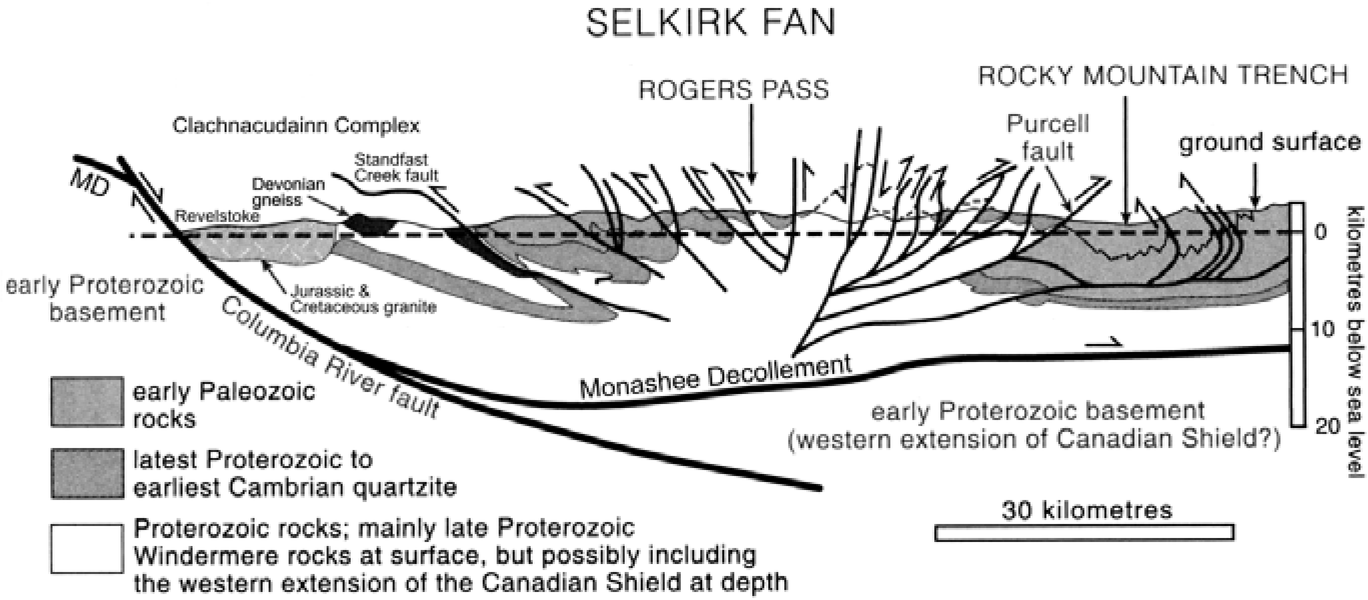


Figure 7-4 – Regional structure section across the Selkirk Fan from Revelstoke to the Porcupine Creek Anticlinorium

HILLCREST RESORT – CLACHNACUDAINN COMPLEX

The area north and east of Revelstoke is underlain by rocks assigned to the Clachnacudainn complex (CC), a local structural and metamorphic culmination comprising an assemblage of metamorphic and plutonic rocks that represents the lowest structural level in the west flank of the Selkirk fan structure (**Figure 7-4**). The complex sits above the east-dipping Columbia River fault and the Monashee décollement, forming a tectonic wedge that is bound above by the southwest-verging Standfast Creek thrust fault. The Monashee décollement is a major crustal-scale ductile thrust zone that has been identified as the basal décollement of the Rocky Mountain foreland fold-and-thrust belt to the east.

The southern part of the CC is dominated by a sequence of highly deformed, kyanite- and sillimanite-grade metasedimentary and metavolcanic rocks which have been variously correlated with Lower Paleozoic rocks to the east (Lardeau, Hamill and Horsethief Creek groups and Badshot Formation) as well as those occurring on the west side of the Shuswap metamorphic complex and assigned to the Kootenay terrane (Eagle Bay and Silver Creek assemblages and Tsalkom and Sicamous formations).

To the north, the CC comprises various granitoid bodies of Early Mississippian, Jurassic–Cretaceous (?), mid-Cretaceous, and Late Cretaceous (and younger) ages. The oldest of these, a granodioritic gneiss known as the Clachnacudainn gneiss (356 ± 6 Ma U–Pb zircon – interestingly about the same age as plutons intruding rocks of the Kootenay terrane west of the Shuswap metamorphic complex), forms a broadly folded, semi-concordant sheet approximately half a kilometre thick sandwiched between metasediments. Mid-Cretaceous plutons in the northern part of the CC are generally undeformed and include quartz diorite, quartz monzonite, granodiorite, two-mica granite and, locally, K-feldspar megacrystic granite. The youngest intrusive suite comprises Late Cretaceous leucogranite and pegmatites. The leucogranite typically occurs as sheets several tens of metres thick that intrude both older igneous and metasedimentary rocks.

Assignment: describe the main rock types. By documenting cross-cutting relationships and relationship of units to deformation, develop a geological history for this sequence of rocks. Show the relationship between the various units in a schematic sketch. Answer the following:

Main questions: what tectonic environment explains the magmatism? Are these rocks metamorphosed, and if so what were the protoliths of these rocks? How are we to determine the ages of the protoliths, metamorphism and deformation? How do these rocks differ from those previously observed (*i.e.*, what is it about these rocks that justify including them in a terrane distinct from North America?)? What is the significance of the age of these rocks? What is the tectonic significance of the mid-Cretaceous (120 to 100 Ma) rocks? What is the Omineca Magmatic Belt, and how did it form? What are the implications for the foreland basin?

UPPER ARROW LAKE – GALENA BAY STOCK

Upper Arrow Lake (**Figure 7-5**) is coincident with the southern portion of the Columbia River Fault Zone, a 250 kilometre long, major Eocene crustal-scale detachment having tens of kilometres of east-side-down displacement. It separates high-grade metamorphic rocks of the Monashee complex to the west from supracrustal rocks of the Selkirk allochthon to the east.

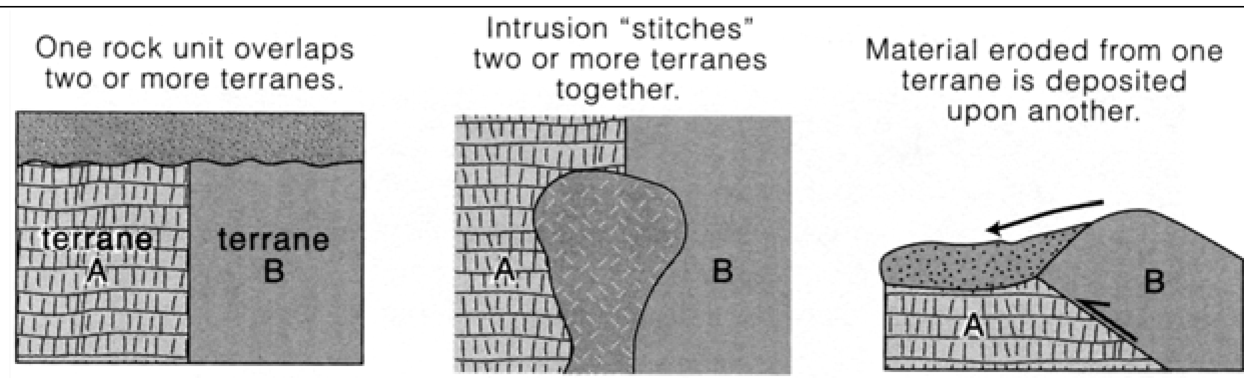
S-type granitoid rocks of the Jurassic Galena Bay stock intrude these rocks in the Shelter/Galena Bay area. The stock is a light-coloured, garnet-bearing, two-mica granite, locally hosting xenoliths of country rock. In thin section, these rocks are hypidiomorphic, granular and contain abundant quartz, plagioclase and significant amounts orthoclase and microcline. Biotite is an accessory mineral and occurs randomly or in clusters with minor ferromagnesian minerals and crosscutting muscovite laths. Determination of the normative mineralogy from major oxide chemical analysis of a typical sample of the granite yielded 27% quartz, 69% feldspar and 4% ferromagnesian minerals.

Shelter Bay Assignment: time permitting (we may have to run for a ferry), systematically describe the intrusive rock along either side of the ferry ramp. Answer the following:

Main questions: is there anything unusual about the mineralogy of this rock? What processes gave rise to this rock? How was its age of crystallization (cooling age) determined? What tectonic fabrics are present in this rock?

Galena Bay Assignment: produce a detailed geological map of the outcrop immediately south of the ferry landing. Describe (quantitatively) the deformation. Compare the fabric orientation recorded here with the regional geological map of the area (next page). Provide a point-form geological history to account for all the features observed here. Answer the following:

Main questions: what distinguishes the Galena Bay stock at this site? What is the origin of the additional rock types found here? What were the protoliths of these rocks? Describe (quantitatively) the deformation. Compare the fabric orientation recorded here with the regional geological map of the area. What constraints does this provide regarding interpretation of these rocks? Provide a point-form geological history to account for all the features observed here (consult regional geological map in field guide). How could one relate the Galena Bay stock to the foreland basin?



Spatial relationships between rocks can show how and when terranes came together

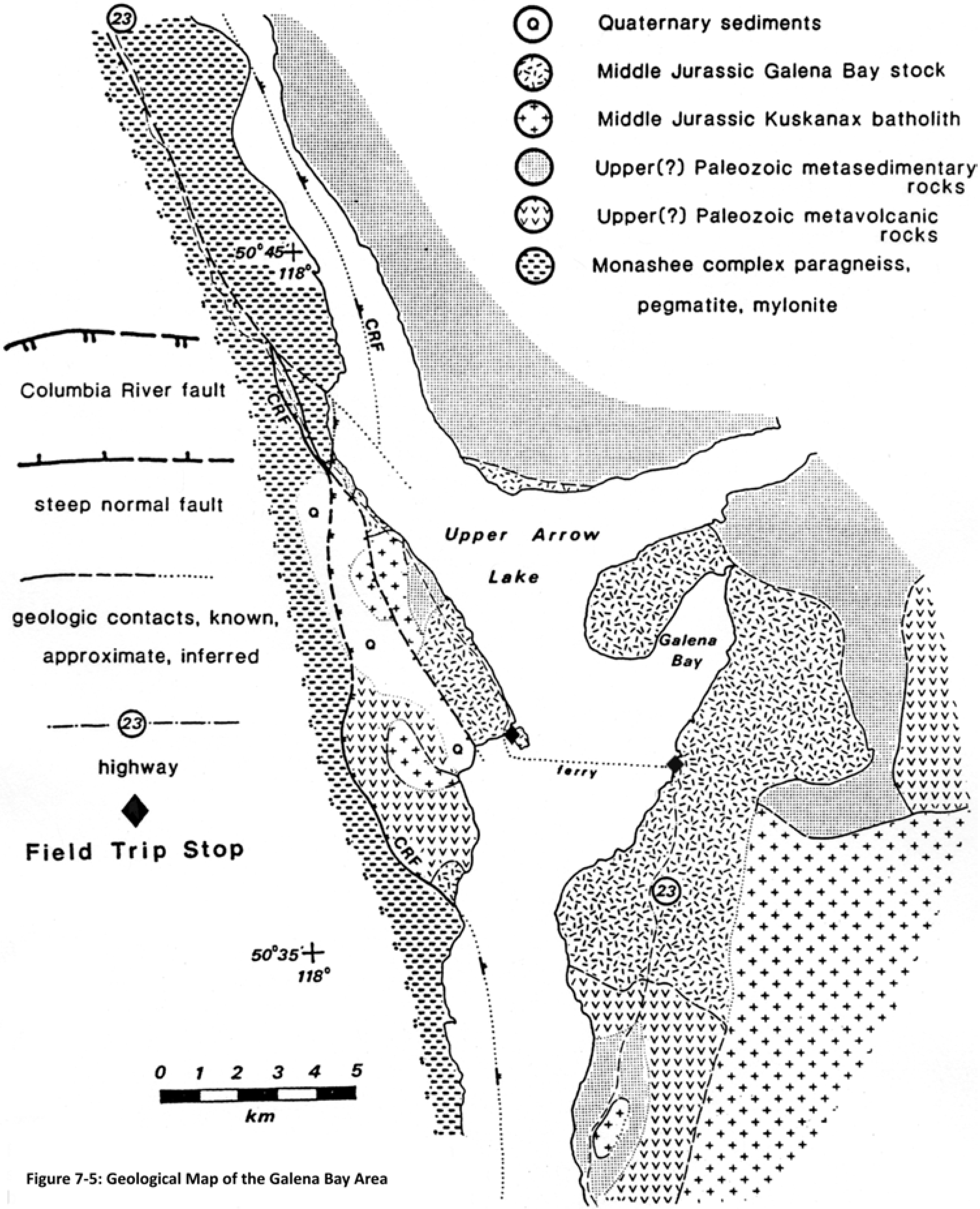


Figure 7-5: Geological Map of the Galena Bay Area

Day 8 – Omineca/Intermontane Belts

Revelstoke Dam Viewpoint – Lardeau Group(?)

The east abutment of the Revelstoke dam sits in the immediate hanging wall of the Columbia River fault, an Early to Middle Eocene, eastward dipping, crustal-scale extensional detachment fault which, north of Revelstoke, juxtaposes middle to lower crustal rocks of the Proterozoic Monashee complex (to the west) against Jurassic and younger granitoid plutons of the Clachnacudainn complex (to the east). The heavily buttressed, migmatitic rocks on the slopes above are representative of the latter complex's metasedimentary/metavolcanic component (Paleozoic Lardeau Group(?) – see Hillcrest Resort stop), here on the periphery of a large leucogranite (71 ± 1 Ma) pluton underlying Mt. Revelstoke.

Assignment: Describe the main rock types and indicate their relationship to one another. Answer the following:

Main questions: what is the evidence for metamorphism (include, based on the metamorphic mineral paragenesis, estimates of the P and T of metamorphism)? Draw a P-T diagram with the relevant reaction curves showing the stability region represented by these rocks? What were the protoliths, and what are their paleogeographic implications? These rocks are characterized by pre-170 Ma cooling ages: reconcile this data with the foreland basin sedimentary record. Deformation – how many deformational events are recorded in these rocks? Relationship to metamorphism? Location in the crust? Significance for the construction of the dam? Relationship of these rocks to basement gneisses of the Monashee Complex exposed west of the Columbia River?

Revelstoke Dam

Revelstoke Dam (**Figure 8-1**) is one of two major Canadian generating projects on the Columbia River (the other being the Mica Dam). With an installed capacity of 1,980 MW, the facility recently commissioned a fifth generating unit, increasing the capacity to 2,480 MW. An as yet to be developed unit has the potential to increase this capacity by an additional 500 MW.

The hydroelectric complex comprises a 175 metre high concrete gravity dam in Little Dalles Canyon, a 122 metre high earth-fill dam on the west bank of the river, and a powerhouse in the riverbed, immediately downstream from the concrete dam.

The reservoir created by the dam extends 130 km back to the tail-waters of the Mica Dam and has a surface area of 11,534 hectares.

Figure 8-1 – Revelstoke Dam looking north

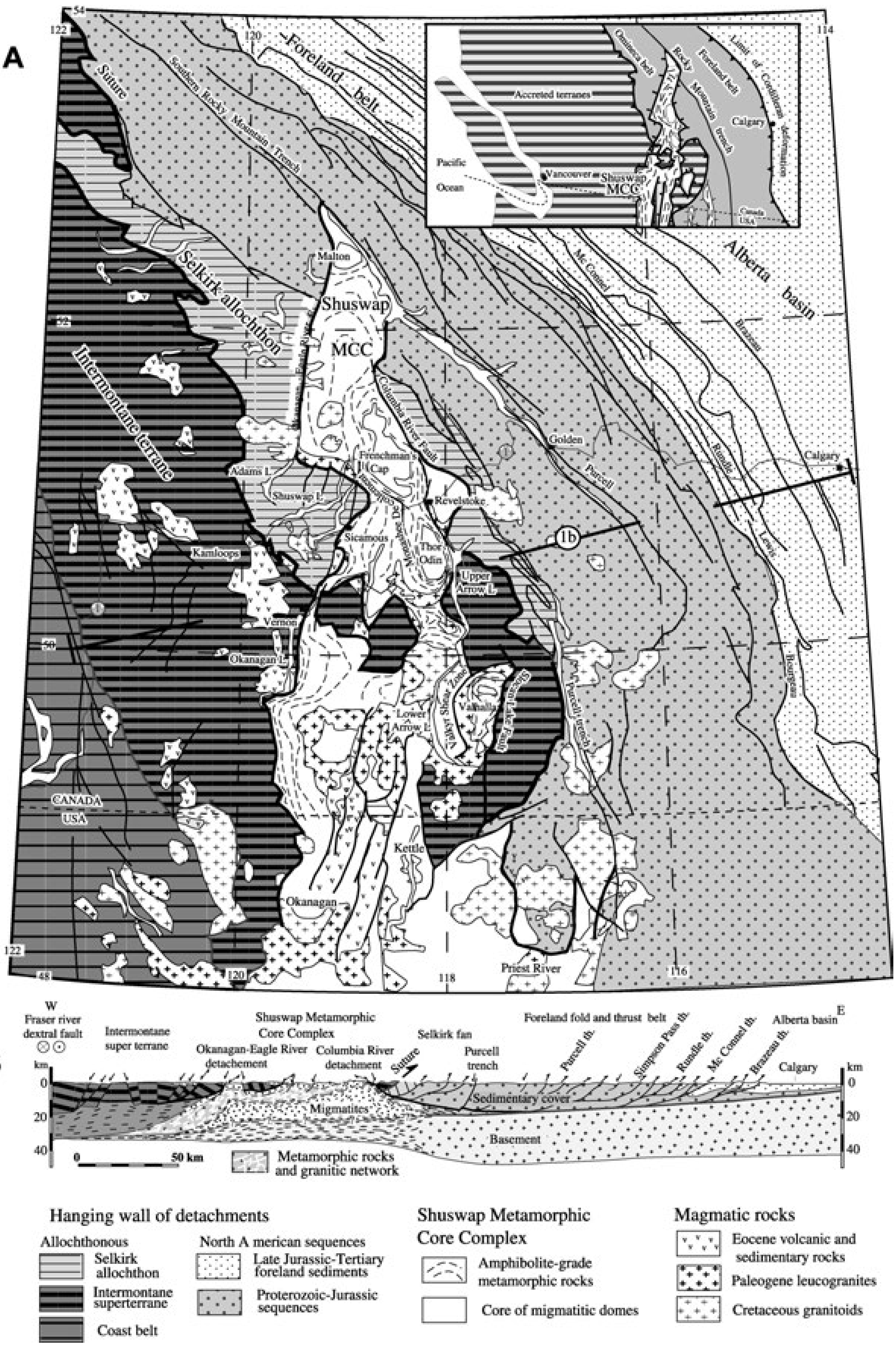


Figure 8-2 - Shuswap Metamorphic Core Complex (Vanderhaeghe et al., 2003)

GEOLOGY ON THE FLY: SHUSWAP METAMORPHIC CORE COMPLEX

Outcrops along the Trans-Canada Highway between Revelstoke and Sicamous expose rocks of the Shuswap metamorphic core complex (SMCC – **Figure 8-2**). The SMCC is a fault-bound, metamorphic-plutonic assemblage comprising Proterozoic to Paleozoic rocks exhumed along normal fault systems following a period of contraction and orogenic thickening of the Cordillera linked to the accretion of arc and oceanic terranes to the western margin of North America from Early Jurassic to Early Tertiary time.

The SMCC is bound, on the east and west respectively, by the east-side-down Columbia River–Slocan Lake and west-side-down Okanagan Valley normal fault systems, which separate remnants of a dismembered upper assemblage (rocks of the Selkirk allochthon) from the exhumed metamorphic core. But while predominantly Mesozoic cooling ages are preserved in the hanging wall rocks, rapid cooling of the SMCC from temperatures above 500°C is thought to have occurred as late as Early to Middle Eocene time.

The SMCC includes high-grade (amphibolite-facies) structural culminations that expose Paleoproterozoic North American basement (including orthogneiss, paragneiss, and migmatite) overlain and infolded with a Proterozoic to Paleozoic-aged cover assemblage (including quartzite, schist, marble, and gneiss). Together, these rocks represent the most deeply exhumed part of the southern Omineca belt, the metamorphic-plutonic hinterland to the Rocky Mountain foreland fold-and-thrust belt. The Monashee Complex (MC – **Figure 8-3**) is one such culmination, situated in the footwall of a northeast-directed thrust-sense shear zone, the Monashee décollement. The MC is further subdivided into two structural domes west of Revelstoke: the Frenchman Cap to the north and Thor-Odin to the south.

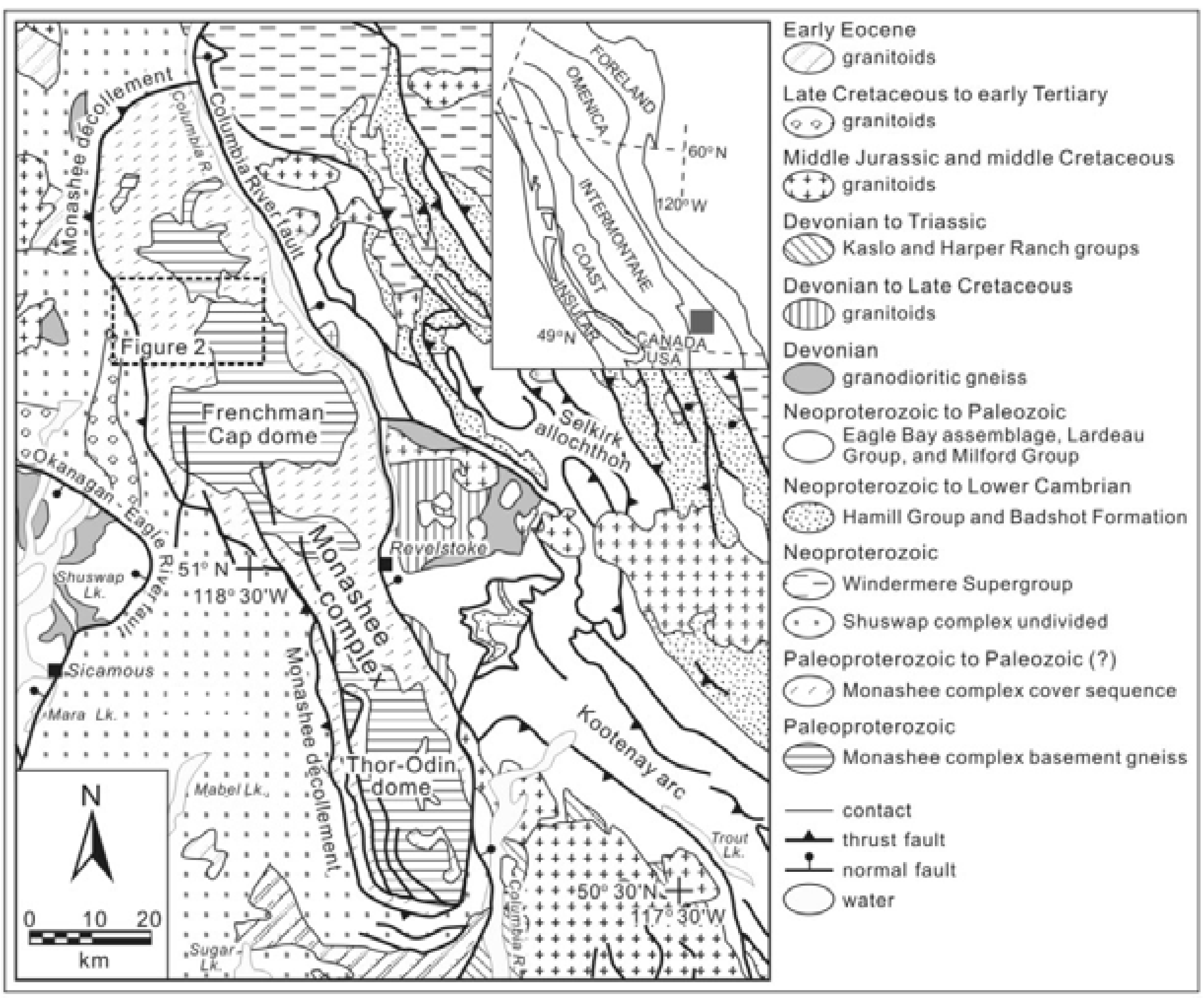


Figure 8-3 – Tectonic assemblage map in the vicinity of the Monashee Complex (Crowley, *et al.*, 2008)

The upper part of the SMCC, between the MC and the west-bounding Eocene normal-fault systems, consists of upper amphibolite facies metamorphic rocks and Cretaceous to Tertiary-aged granitic intrusions. The former are, at least in part, believed to be correlative with pericratonic basinal strata of the Neoproterozoic Windermere Supergroup.

The hanging wall of the detachments consist of pericratonic strata of Mesoproterozoic to Late Paleozoic age (Kootenay terrane) and Devonian to Jurassic rocks of accreted terranes, all emplaced at a high structural level in Cretaceous time. These rocks are typically metamorphosed to greenschist facies and lower grade, although they locally reach amphibolite facies. They are intruded by Mesozoic plutons and are overlain unconformably by Tertiary volcanic and sedimentary rocks.

Subsequent extension has led to the formation of pull-apart and extensional basins filled by Eocene sedimentary sequences and volcanic rocks. A second set of high-angle faults affecting all units trends dominantly north-south and is associated with dip-slip or slightly oblique-slip normal movement. These faults, in turn, are connected by east-west–trending steep strike-slip transfer faults.

SHUSWAP LAKE – TSALKOM FORMATION

Greenschist facies mafic metavolcanics of the Lower Paleozoic Tsalkom Formation (Mt. Ida Group) cut by buff-weathering intrusions that likely represent feeders to stratigraphically overlying volcanics of the Eocene Kamloops Group. The Tsalkom Formation, which regionally comprises greenstone and chloritic phyllite, is lithologically similar to the Permian Kaslo Formation (Kootenay Arc) and Late Paleozoic Fennell Formation (north of Barrière), both of which have been included in the Slide Mountain terrane, the easternmost accreted terrane.

Assignment: describe the two main rock types and ascertain their relationship. Answer the following:

Main questions: in what tectonic environment did each of these rock types originate? How do these rocks compare with those of the Revelstoke region? What are the ‘terrane’ and tectonic implications of these two separate rock types?

Harper Ranch House – Harper Ranch Group

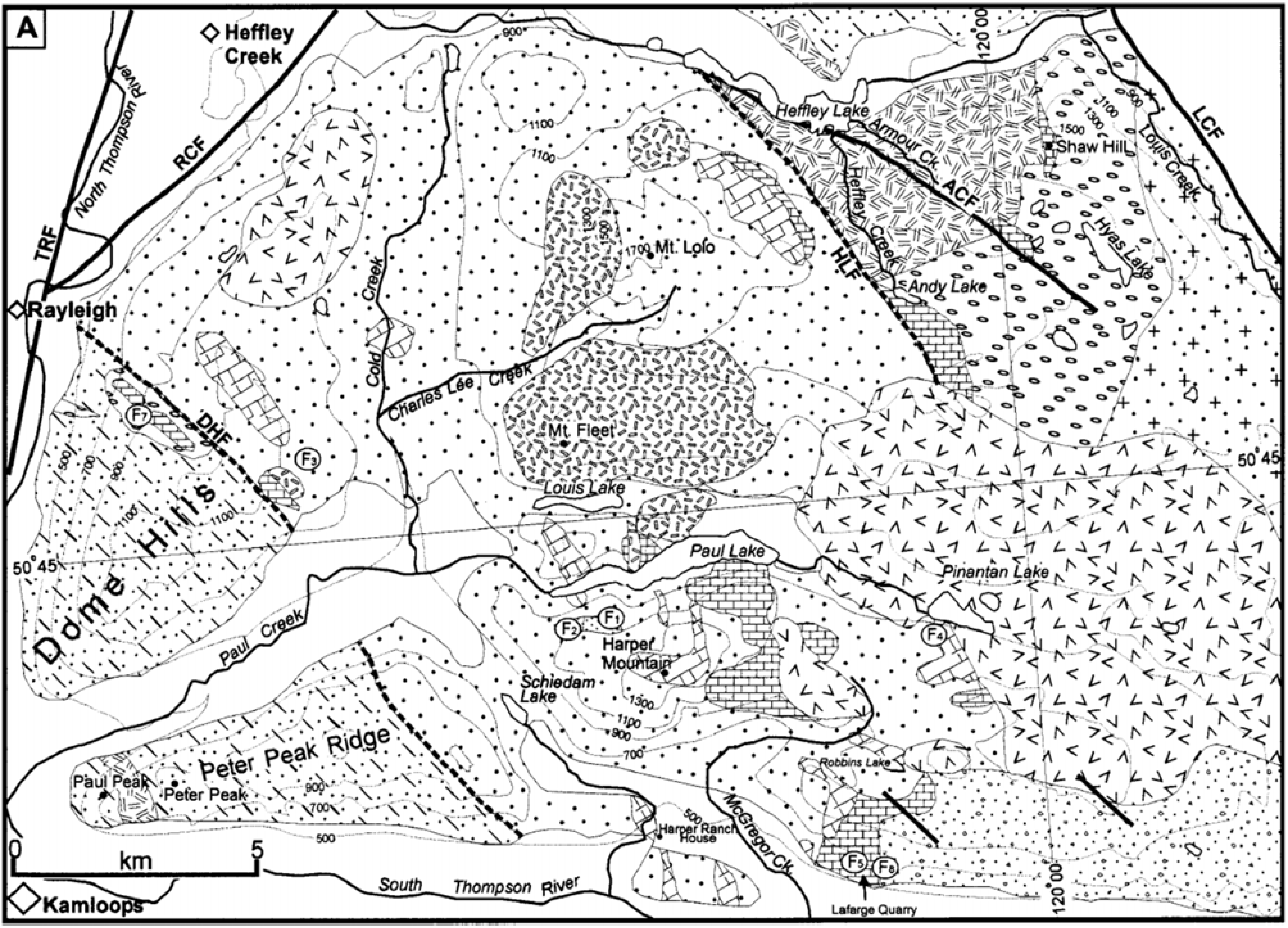
The uppermost Devonian to Permian Harper Ranch Group is a >3 kilometre thick sedimentary succession of marine volcaniclastics, epiclastics and carbonates that represent the stratigraphic base of the Quesnel Terrane (Quesnellia). Quesnellia is a mixed assemblage of Upper Paleozoic and Lower Mesozoic volcanic and sedimentary strata of oceanic and island-arc origin. It is comprised of the Upper Triassic to Lower Jurassic island-arc rocks of the Nicola and Rossland groups, which unconformably overlie the arc-related rocks of the Harper Ranch Subterrane and oceanic and marginal basin rocks of the Paleozoic Okanagan Subterrane. The accretion of Quesnellia, one component of the Intermontane Superterrane, onto the continental margin of North America took place in Early to Middle Jurassic time. The resulting compression, metamorphism, crustal thickening and plutonism formed the Omineca Belt.

The Harper Ranch Group actually comprises two distinct successions, one of interpreted island arc affinity spanning Late Devonian (Famennian) to Late Mississippian time (**Figure 8-4**), and an unconformably overlying Permian succession interpreted as a carbonate platform. Clastic rocks, occurring predominantly within the lower part of the Group, are volumetrically the most significant component.

Figure 8-4 – lower succession rocks of the Harper Ranch Group exposed near Harper Ranch House

The oldest rocks, the Upper Devonian to Mississippian Tk'emlups Formation, comprise a 2,600+ metre succession of interbedded hemipelagic mudstone and siltstone (interpreted as distal turbidites), interstratified with and overlain by volcaniclastic sandstone and conglomerate/breccias (thought to be deposited by more proximal sediment-gravity flows). These rocks interfinger with and are conformably overlain by the ~300 metre-thick Upper Mississippian to Lower Pennsylvanian South Thompson Formation which consists, primarily, of bioclastic limestone interbedded with volcaniclastic sandstone and limestone cobble conglomerate. The Early to Middle Permian McGregor Creek Formation paraconformably overlies these rocks and includes at least 500 metres of relatively pure, massive to interbedded crinoidal wackestone and packstone in a generally fining upwards succession. These limestones host secondary chert, both as nodules and beds and are currently being quarried by the Lafarge Cement Company to the east.

Strata in the area of Harper Ranch House, north of the South Thompson River (**Figure 8-5**), are oriented in a steeply east-northeast dipping homocline, although mesoscopic folds and apparent structural repetition of the units indicates greater structural complexity.


A
Heffley Creek
Rayleigh
Kamloops
TRF
RCF
North Thompson River
LCF
ACF
HLF
DHF
Heffley Lake
Armour Ck.
Heffley Creek
Andy Lake
Shaw Hill
Hyas Lake
Louis Creek
Mt. Lolo
Mt. Fleet
Louis Lake
Cold Creek
Charles Lee Creek
Paul Lake
Pinantan Lake
Harper Mountain
Schiedam Lake
Paul Creek
Dome Hills
Peter Peak Ridge
Paul Peak
Peter Peak
Robbins Lake
McGregor Ck.
Harper Ranch House
Lafarge Quarry
South Thompson River
F1
F2
F3
F4
F5
F6
F7
120°00'
50°45'
0
km
5

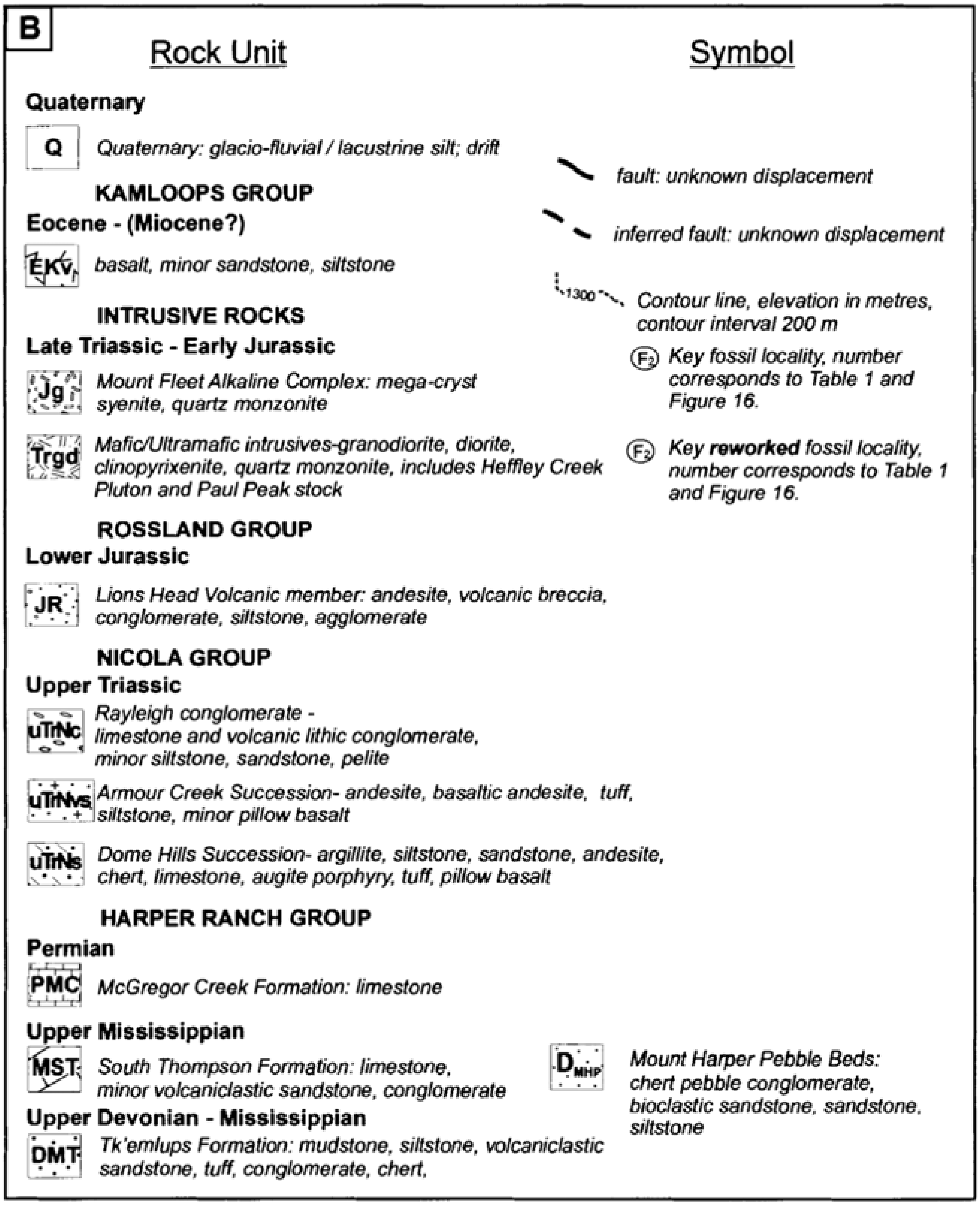


Figure 8-5 – Simplified Geologic Map of the Kamloops Area (Beatty, 2003)

The stratigraphic succession of the Harper Ranch Group records the early stages and eventual filling of an island arc marginal basin and the subsequent establishment of a carbonate platform. The Tk'emlups Formation embodies the early history of magmatism during the Mississippian, although, due to the absence of volcanic flows, represents only the distal part of the deposystem. The abrupt transition to the overlying South Thompson Formation suggests the cessation of volcanism together with basinal shallowing (through either infilling, eustacy or tectonism) during the Pennsylvanian, resulting in the consequent establishment of environments favouring carbonate deposition. The McGregor Creek Formation represents deposition in an open marine environment (middle shelf) on a stable, slowly subsiding carbonate platform during the Permian.

Rocks of the McGregor Creek Formation are thought to be related to those found in the 'McCloud belt', named for the Lower Permian McCloud Limestone of the eastern Klamath Terrane. The McCloud Limestone and members of the McCloud belt are unique in the Cordillera because they possess faunal elements of mixed North American and apparently exotic affinity. This mixed faunal signature is the basis for proposed longitudinal separation of terranes belonging to the McCloud belt from North America during the Upper Paleozoic. More recent estimates of the separation of the McCloud belt from the west coast of North America have ranged between 2,000 and 3,000 kilometres.

Assignment: describe the two main rock types and ascertain their relationship to one another. Answer the following:

Main questions: in what type of tectonic environment would you expect such a combination of rock types? How are these rocks distinguishable from those of the Omenica Crystalline Belt and the Foreland Belt (look at the metamorphic grade, as well as rock type)?

GEOLOGY ON THE FLY: KAMLOOPS WHITE SILT

The buff-coloured, incised benches observable along both sides of the valley of the South Thompson River east of Kamloops (**Figure 8-6**) are what's left of approximately 300 metres of glaciolacustrine silt that settled out of Glacial Lake Thompson approximately 10,000 years ago. The lake is thought to have formed behind a mass of ice that dammed the valley for approximately 1,000 years. The silt comprises a high proportion of quartz and feldspar with lesser lithics (including sericite).

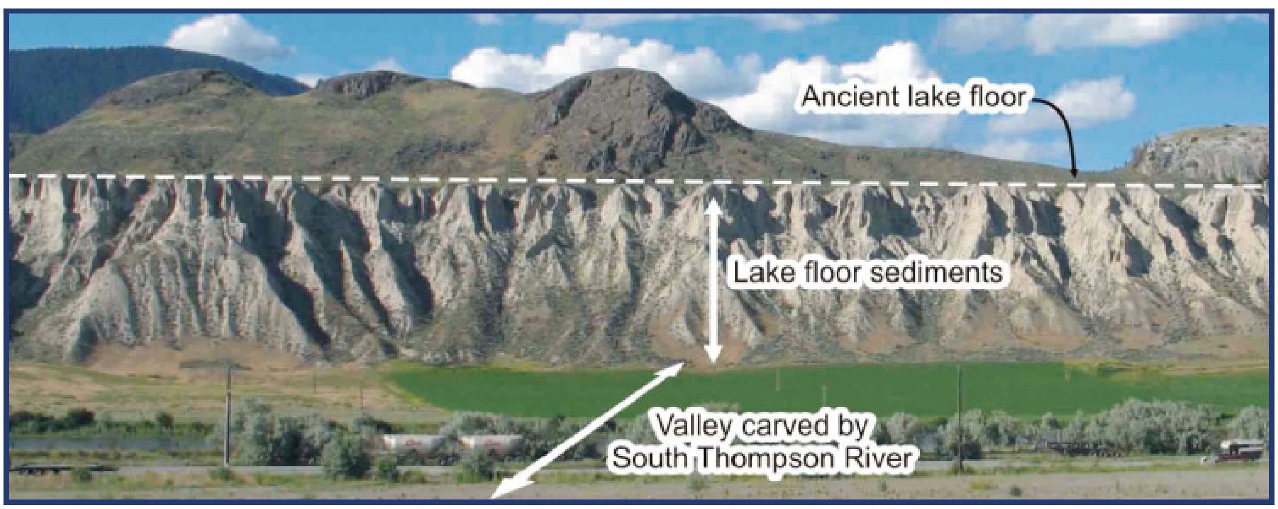


Figure 8-6 – Kamloops White Silt

Day 9 – Intermontane Belt

Kamloops Lake Viewpoint – Nicola Group (Eastern Volcanic Belt)

The principal unit making up Quesnellia in this region is the Upper Triassic Nicola Group, a predominantly subaqueous island arc assemblage composed of volcanic and sedimentary rocks that have been intruded by Late Triassic-Early Jurassic alkalic and calcalkalic plutons and batholiths (*e.g.*, Guichon Creek, Iron Mask, Wild Horse batholiths) forming a west-facing magmatic arc. The Nicola Group has been divided up into four lithologic assemblages: a steeply dipping, east-facing 'western volcanic belt' consisting predominantly of subaqueous felsic, intermediate and mafic volcanics of calcalkalic affinity that grade upward into volcaniclastic rocks; a 'central volcanic belt' composed of both subaqueous and subaerial basalt and andesite flows, volcanic breccias and lahars of both alkalic and calcalkalic (both plagioclase and augite-phyric) affinities; an overlying, westerly dipping 'eastern volcanic belt' composed of predominantly subaqueous and subaerial alkalic (both augite and hornblende-phyric; shoshonites and ankaramites) intermediate and mafic volcanic flow, fragmental and epiclastic rocks; and an 'eastern sedimentary assemblage' that is overlapped by the eastern volcanic belt and is composed predominantly of greywackes, siltites, argillites, alkalic intermediate tuffs and reefal limestones.

The Nicola Group is broken into three blocks by two sub-parallel fault systems (the eastern one partly defined by the Cherry Creek Fault and Kamloops Graben; the western one partly defined by the Guichon Creek and Deadman River faults). Many of these faults were active during volcanism and sedimentation and appear to have controlled the locus and shape of subsequent intrusions, but have been active subsequently, especially during Eocene extension. To the west, the Nicola Group is unconformably overlain by arc-derived clastics of the Lower and Middle Jurassic Ashcroft Formation.

The Nicola Group has been interpreted to range in age from Late Carnian to Late Norian on the basis of fossil data collected from limestone units in western, central and eastern portions of the Nicola arc. A general younging of the Nicola Group from west to east is interpreted from the data, whereby rocks underlying the Kamloops region are, in general, Late Norian in age.

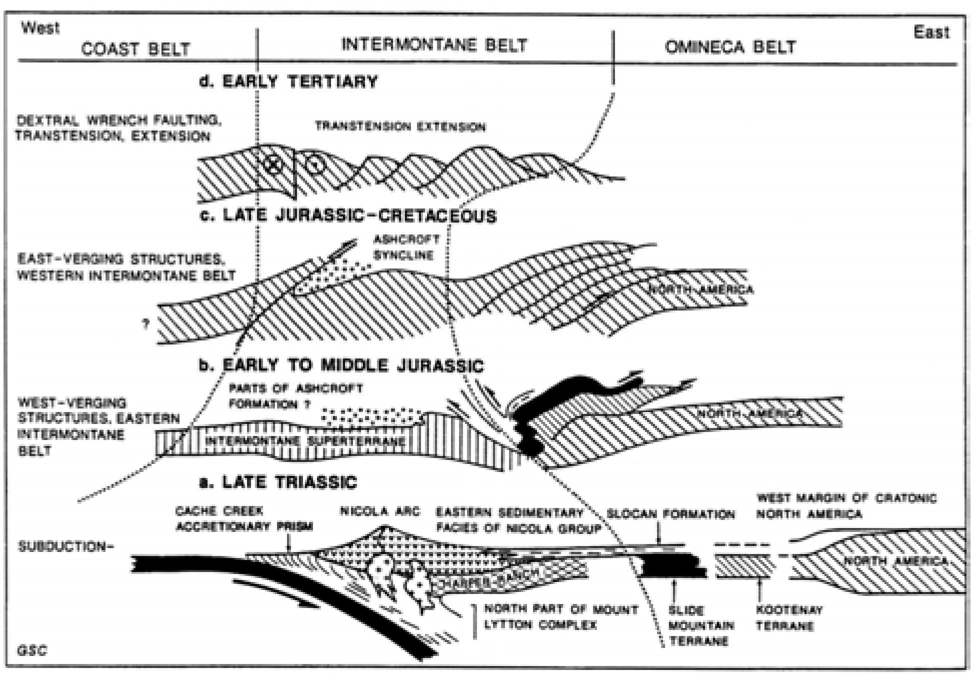


Figure 9.1: Cartoons illustrating the evolution of the Intermontane Belt and its relationship to the Omineca Belt. Possibly the rocks including and west of Slide Mountain terrane were positioned by south to north movements in late Early Jurassic time (~185 Ma) immediately before their accretion to the old continental margin. The west-directed structures at the boundary between Omineca and Intermontane belts are reported by Schiarizza and Preto (1984) and Smith (1979) and may include the Louis Creek-Bolean Creek fault system crossed on Highway 1, and may be congruent with Middle Jurassic west-directed structures in the Selkirk Fan (Fig. 2-14).

Assignment: describe the rock types, and identify any phaneritic minerals. Answer the following:

Main questions: what are these rocks and in what tectonic environment did they originate? Identify and record orientation of layering. What is the origin of the layering evident in these rocks? Would these rocks be suitable for paleomagnetic analysis? Explain.

SAVONA VIEWPOINT – NICOLA VOLCANICS (CENTRAL VOLCANIC BELT)

Alkaline-subalkaline volcanic facies of the Nicola Group in contact with dark carbonaceous, calcareous argillite and siltstone. Sediments exposed here contain the small, warm-water bivalve *Monotis salinaria* of Late Norian (Upper-most Triassic) age. In fault contact with these rocks to the west are volcaniclastics (showing graded bedding and slump features) containing lithic volcanic fragments and euhedral and broken pyroxene crystals.

Assignment: Identify the three main rock types exposed in this outcrop and determine their relationship with respect to one another.. Keep a look-out for fossils of Norian-aged *Monotis salinaria*, of Tethyan affinity. Answer the following:

Main questions: in what environment were these rocks deposited? What is their relationship to the rocks at the previous stop?

MCABEE FOSSIL SITE – KAMLOOPS GROUP

The Kamloops Group is a Tertiary post terrane accretion overlap assemblage within Quesnellia, a member of the Intermontane Belt. The Intermontane Belt is an amalgam of terranes – including the Stikinia, Quesnellia, Slide Mountain and Cache Creek. Flat-lying Tertiary volcanic rocks overlie the terranes and basins, producing the widespread low uniform low relief of the southern half of the belt.

Quesnellia consists of Upper Triassic and Lower Jurassic arc volcanics, volcaniclastics, and contemporaneous intrusive rocks overlain by Jurassic arc-derived clastics. These units form the basement complex for the widespread Tertiary lacustrine and tephra sequences of the Kamloops Group and the younger plateau basalts.

Numerous fault controlled sedimentary basins of Late Cretaceous to Early Tertiary age are found throughout the Intermontane (and Omineca) Belt(s). Of specific interest are the Eocene freshwater lacustrine deposits that crop out primarily in six different areas – Princeton, Quilchena, McAbee, Chu Chua, Horsefly, and Driftwood Creek. The Eocene strata at all these localities are slightly deformed, with local dips of less than 45^{o}. Slumping is apparent at many outcrops and there are small folds in the Horsefly strata. Although the strata from the different basins are approximately contemporaneous, their nomenclature varies greatly.

The McAbee fossils are hosted by Eocene-aged lakebed shales exposed on a steep, south-facing slope north of the Trans-Canada Highway, approximately 11 km east of Cache Creek. The fossil beds consist of 30 metres of siliceous lacustrine shales interbedded with tephra layers within a 550 metre-thick, unnamed formation of the lower to middle Eocene Kamloops Group. The shale is believed to have been deposited as diatomite, which has been diagenetically altered, and accounts for the fine fossil preservation. The shale beds are capped by flow breccia and sit atop an ash-flow tuff. Tephra deposits bracketed by fossiliferous layers yielded K–Ar dates of 49 ± 2 and 52 ± 2 Ma from plagioclase and 51 ± 2 Ma from biotite contained within a bentonitic tuff. These dates generally support the interpretation of a late Early Eocene age.

Some five dozen plant species have been preserved, including more than 40 broadleaf and some 17 conifer species. The delicately preserved leaves of sassafras, katsura and several species of ginkgo have been found, as well as a diversity of insects, fish fossils, and even some feathers. Some of the McAbee fossils are the first occurrence known of extant plant species, providing valuable data for the study of plant evolution and Eocene paleoenvironments. Some two thirds of the fossils are from plant families still extant, but a large number of rarer leaves have yet to be identified. Known and unknown plant species number more than 100, supporting the theory that the Eocene forests of British Columbia were more diverse than modern forests.

Sassafras hesperia and Vitis sp.

Ginkgo adiantoides

Camaecyparis sp

Assignment: construct a stratigraphic section through the sedimentary succession and underlying rocks as you descend the road back to the vans. Propose a depositional setting for sequence that explains the sedimentary succession, the magmatism, structure and alteration. Provide a sketch showing your proposed tectonic model. Answer the following:

Main questions: what is the relationship between the sediments and the over/underlying rocks? In what tectonic setting were all these rocks deposited? What evidence suggests the overlying rocks were hot when they were deposited?

CACHE CREEK – CACHE CREEK (AKA MR. MIKE'S) MÉLANGE

The Pennsylvanian through Middle Jurassic Cache Creek Complex represents the remains of the accretionary complex that likely accompanied the early Mesozoic Nicola and Rossland arcs and therefore represents the western edge North America at that time. The complex includes melange belts, mafic–ultramafic volcanic–plutonic complexes, and large intact stratigraphic sequences (up to 75 km long by 40 km wide and 1 to 2 km thick) that consist mostly of shallow water reefal carbonates characterized by Tethyan fauna, implying an origin within the Tethys, the internal ocean that separated the northern (Laurasia) and southern (Gondwana) portions of Pangea. The carbonates commonly stratigraphically overlie alkalic basalt and likely represent fringing reefs and banks around seamounts originating above a hotspot or mantle plume within an ocean basin setting. The Cache Creek Complex is overthrust by and lies in the forearc region of the Stikinia and Quesnellia arcs (**Figure 9-2**), and is interpreted as the accretionary prism that developed during subduction beneath the arcs.

The eastern belt of the southern part of the complex is characterized by a highly disrupted mélange composed of Middle Pennsylvanian to Permian carbonate blocks (containing conodont and fusulinid fossils), together with ribbon chert, basalt, minor gabbro and ultramafic rock, in an argillite-chert matrix (containing radiolarians and conodonts) of Early Permian to Late Triassic age (**Figure 9-3**). A pervasively faulted and broken road cut exposes the mélange behind what was at one time the local Mr. Mike's restaurant. Ribbon cherts at the southern end of the exposure contain Middle Triassic radiolarians, which appear as ≤1 millimetre, dark dots.

Assignment: examine the dark-coloured, disrupted rocks exposed on the west side of the Bonaparte River. Describe the main rock types, their relationships to one another, and the structures evident in this section. Answer the following:

Main Questions: what is the depositional environment in which these rocks were deposited? What types of structures are developed in these rocks, and where did deformation take place? What is the origin of the somewhat different looking rocks exposed at the north end of the outcrop? Is there a link between the types of rocks, and the types of structures observed here? In what tectonic setting would you expect to find these kinds of rocks? What is the implied origin of the Cache Creek terrane?

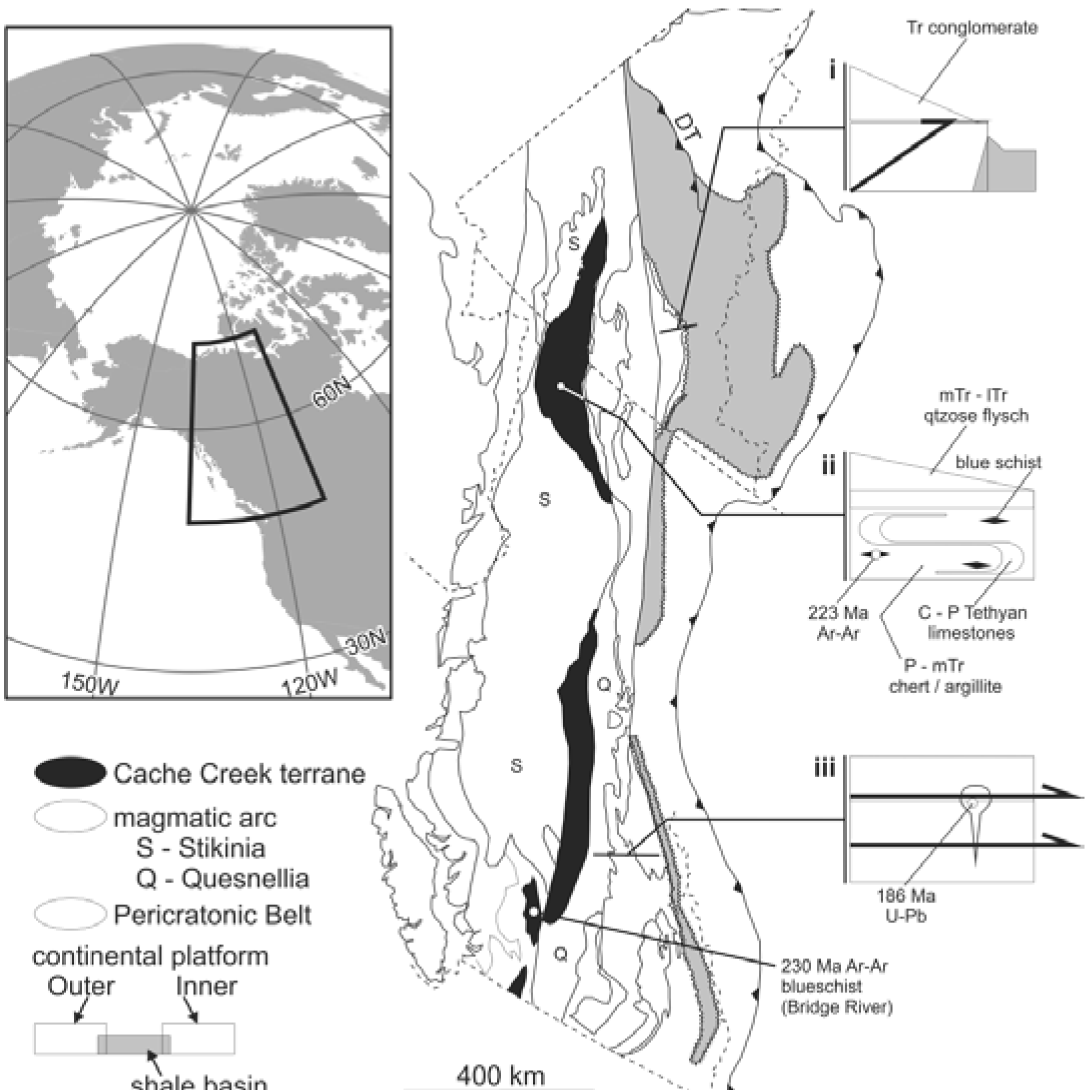


Figure 9-2 – Tectonic map of the Canadian Cordillera. Schematic cross-sections at right show (i) Triassic conglomerate unconformably overlying the thrust that places pericratonic belt crystalline rocks on top of the outboard continental platform; (ii) Middle Triassic and younger arc flysch, interpreted to be derived from Stikinia, unconformably overlying folded and metamorphosed (blueschist facies) Cache Creek strata; and (iii) 186 Ma plutons intruding and stitching together previously imbricated strata of the Quesnellia arc terrane, the pericratonic belt and the outboard continental platform. Cooling ages from Cache Creek and correlative blueschists indicated. DT — Dawson thrust (Johnston & Borel, 2006)

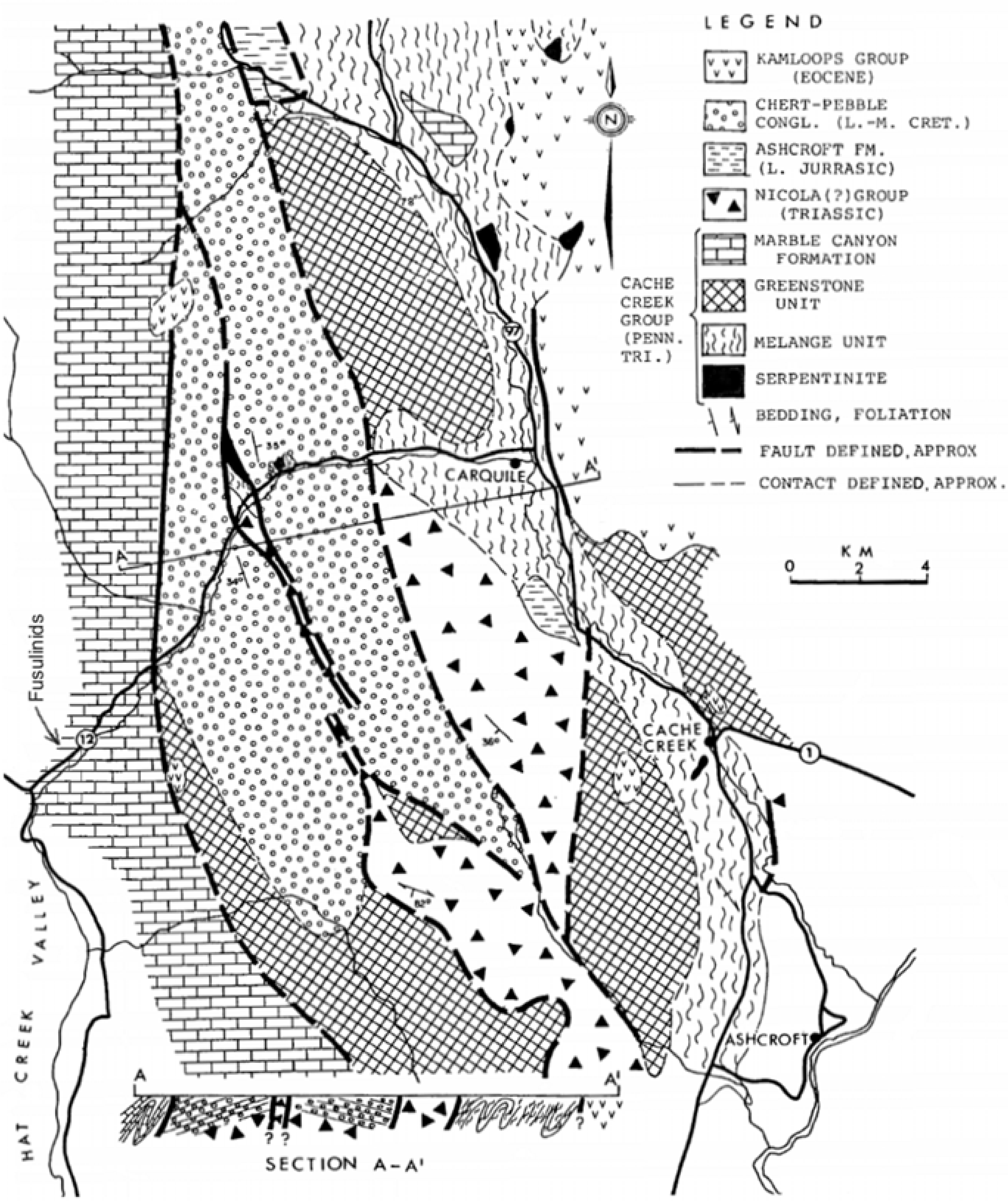


Figure 9-3 – General Geology of the Cache Creek area (after Shannon, 1981)

HAT CREEK TURN-OFF – MARBLE CANYON FORMATION

The central belt of the southern part of the Cache Creek Complex (**Figure 9-3**) comprises massive, shallow water limestone of the Marble Canyon Formation, together with local thin-bedded carbonate, argillite, tuff, minor basalt and chert. The carbonates are characterized by fauna that are exotic with respect to other terranes of the Cordillera and to autochthonous North American strata. The distinct Cache Creek fauna range in age from Upper Carboniferous into the Triassic, and are characterized by the distinct Permian Verbeekinid (*Yabeina*) fusulinids (**Figure 9-5**) that are known elsewhere only from the Tethyan domain of southern Asia. Based on this faunal character, the Marble Canyon Formation is interpreted to have originated within or immediately adjacent to the Tethyan Ocean that separated the southerly Gondwanan and northerly Laurasian portions of the supercontinent Pangea.

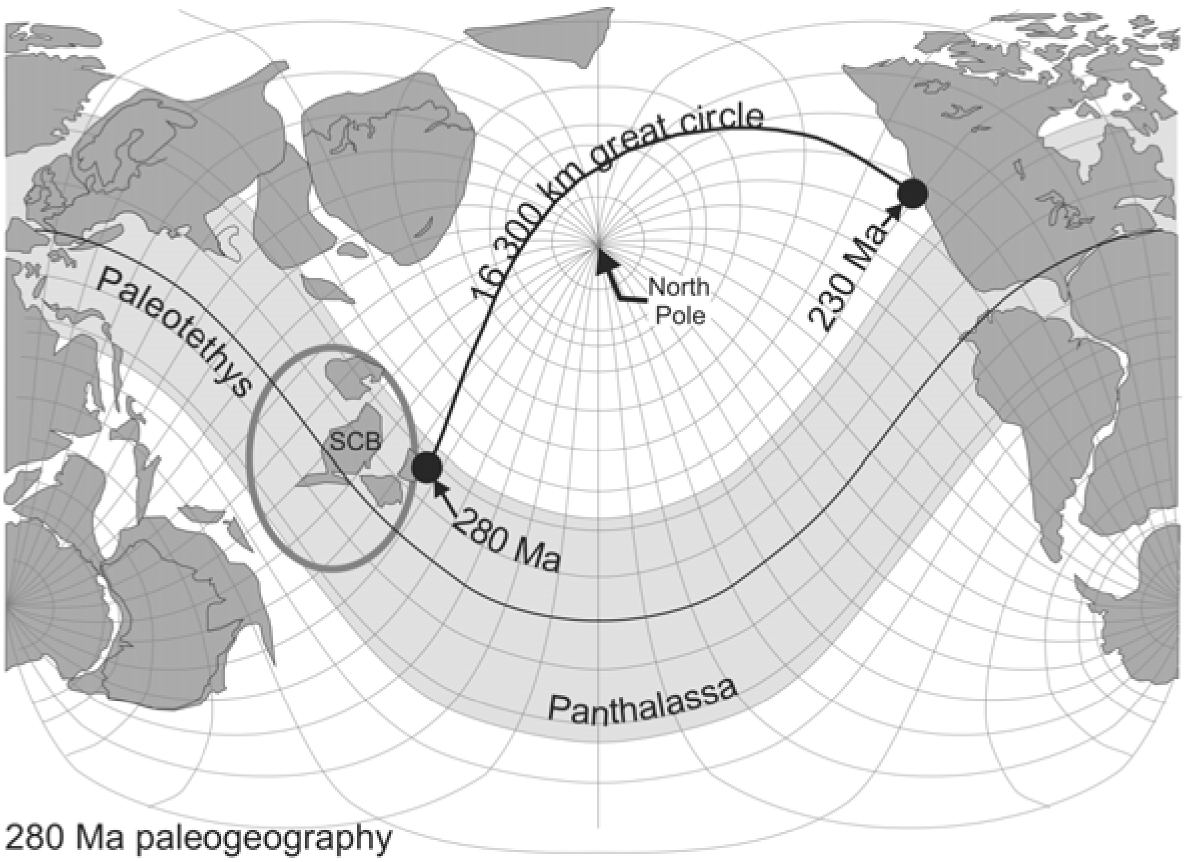


Fig. 9-4 – Early Permian paleogeographic map showing the shortest route between the easternmost Tethyan domain, at left, and the west coast of North America, at right — a 16,300 km long great circle route across Panthalassa. Light grey shading indicates the tropical belt. The grey ellipse encloses the South Chinese blocks (SCB) that lie along and define the eastern limit of the Tethyan domain and indicates the region in which we interpret the Cache Creek seamounts to have originated. The seamounts departed the Tethyan domain in the Permian (280 Ma or later) and accreted to the Stikinia–Quesnellia arc at 230 Ma. This potential translation path requires impossibly high translation rates (>32 cm/year). (Johnston & Borel, 2006)

Assignment: identify and describe the main fossils within this carbonate succession. Answer the following:

Main Questions: what is the significance of the fossils present here? How do these rocks compare with those observed in the town of Cache Creek? What does this say about the nature of the Cache Creek terrane? How do these rocks provide us with a paleogeographic constraint for the Cordillera?

What's a fusulinid?

Fusulinids were small, marine formanifera that inhabited the world's seas between about 315 and 251 million years ago. The earliest fusulinids occur in rocks deposited during the Late Mississippian, and they appear to have become extinct during the mass extinction at the end of the Permian. Their fossils have been found on all continents except Antarctica.

Fusulinids were single-celled organisms, about the size and shape of a grain of wheat, ranging up to 5 centimetres in length. Unlike multi-cellular animals, which accomplish basic life functions (such as locomotion, feeding, digestion, and reproduction) through a wide range of specialized cells, fusulinids had to carry on these same functions within the confines of a single cell. As a result, the cell was highly complex.

In fusulinids, this complexity is evident in the structure of their hard calcium carbonate tests. Internally, the tests, which were secreted by the protoplasm, are divided into a series of chambers. As fusulinids grew, the test coiled around itself, adding chambers along its longitudinal axis. As fusulinids evolved, the internal test walls became increasingly complex, with more ornate subdivisions of their internal chambers.

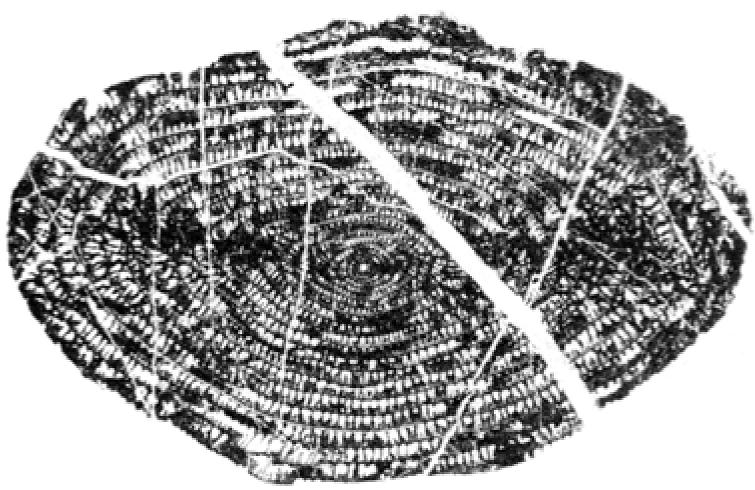
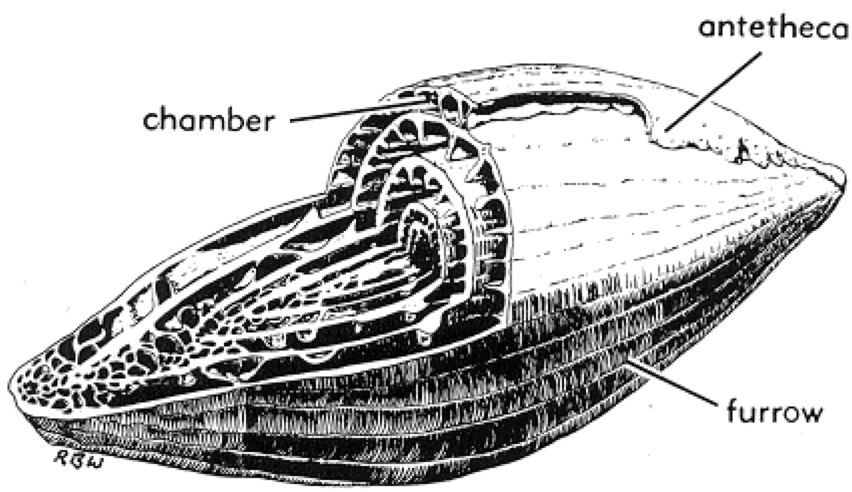


Figure 9-5 – Axial section (x10) showing the internal structure of the verbeekinid fusulinid *Colania columbiana*.



Fusulinids were extremely abundant in tropical and subtropical carbonate environments, and like stalked echinoderms (*e.g.*, crinoids), were major rock-forming fossils. Moreover, they evolved at very rapid rates, having diversified from a single ancestral species in the Early Pennsylvanian to well over 5,000 species by Early Permian time. It is no accident, then, that they serve as index fossils for correlating rocks of this age.

FRASER RIVER VIEWPOINT – FRASER FAULT

The Middle to Late Eocene (47-34 Ma) Fraser Fault (and its southerly extension into Washington State, the Straight Creek Fault) is the only known major high-angle, crustal-penetrating strike-slip fault crossed during our transect. The 500+ kilometre-long fault system separates the western Intermontane belt from the eastern Coast Belt, accommodating 140+ kilometres of dextral offset. Restoration of this amount of offset restores the village of Lillooet to a position near Hope (**Figure 9-6**).

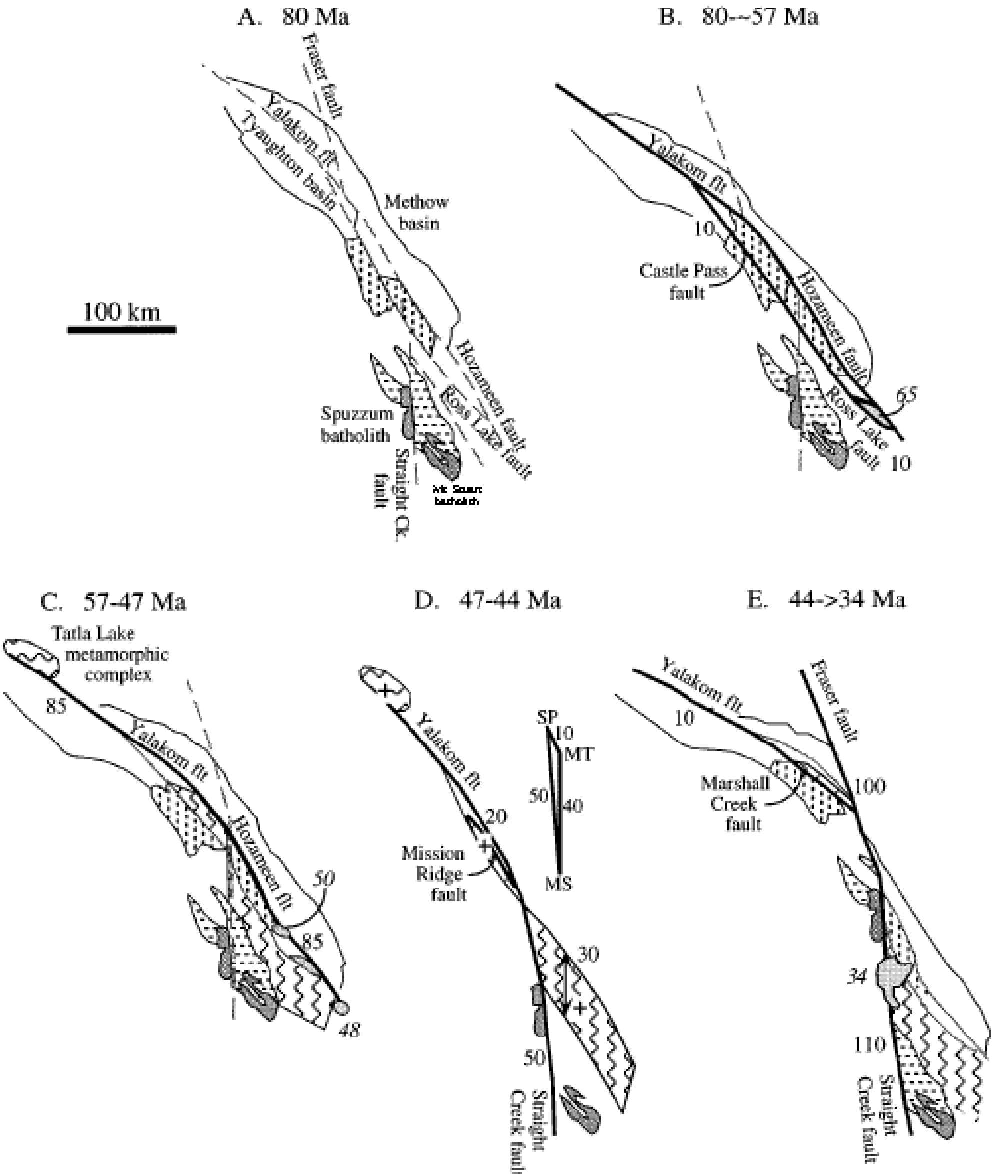


Figure 9-6 – Reconstructions of the dextral strike-slip faults in the southeastern Coast Belt; (A) before all major dextral faulting; (B, C, D, E) near the end of the four main episodes of faulting in the Yalakom fault system. The numbers in the maps are the displacement in kilometers for that fault during the episode shown. Plus symbols indicate regions of significant uplift. In D, the vector diagram units are kilometers, and the three blocks are those containing the Spuzzum batholith (SP), Methow terrane (MT), and Mount Stuart batholith (MS) (Umhoefer & Schiarizza, 1996).

Main Questions: what is the significance of faults for topographic features (*i.e.*, coincidence of gorge with this major strike-slip fault)? Tectonic significance? What drove dextral displacement? Additional evidence for dextral displacement (Spences Bridge Group)?

Day 10 – Coast Belt

Note: we will depart @ 7:30am this morning.

JOFFRE LAKES RECREATION AREA – SPETCH CREEK PLUTON

At 33 kilometres long by up to 16 kilometres wide, the mid-Cretaceous (102 ± 1 Ma) Spetch Creek pluton is one of the oldest of the four plutonic suites in the southeastern Coast Belt. It intrudes Mesozoic sedimentary and volcanic rocks of the Cadwallader and Ladner groups, respectively, and is itself intruded by Cretaceous-aged diorite and quartz diorite (Mount Rohr) plutons in the Joffre Lakes area. It consists of homogeneous, medium (1-5mm) to coarse (>5mm) grained biotite hornblende granodiorite. The Spetch Creek pluton lies in the hanging wall of the east-dipping Central Coast Belt detachment, an early strand of the west-vergent, contractional Coast Belt thrust system (CBTS), and the boundary between the imbricated arc sequences of the Western Coast Belt and the folded island arc and oceanic rocks of the Central Coast Belt. Timing of movement along the CBTS has been constrained to 97-91 Ma through the dating of pre-, syn-, and post-kinematic intrusions along the thrust system.

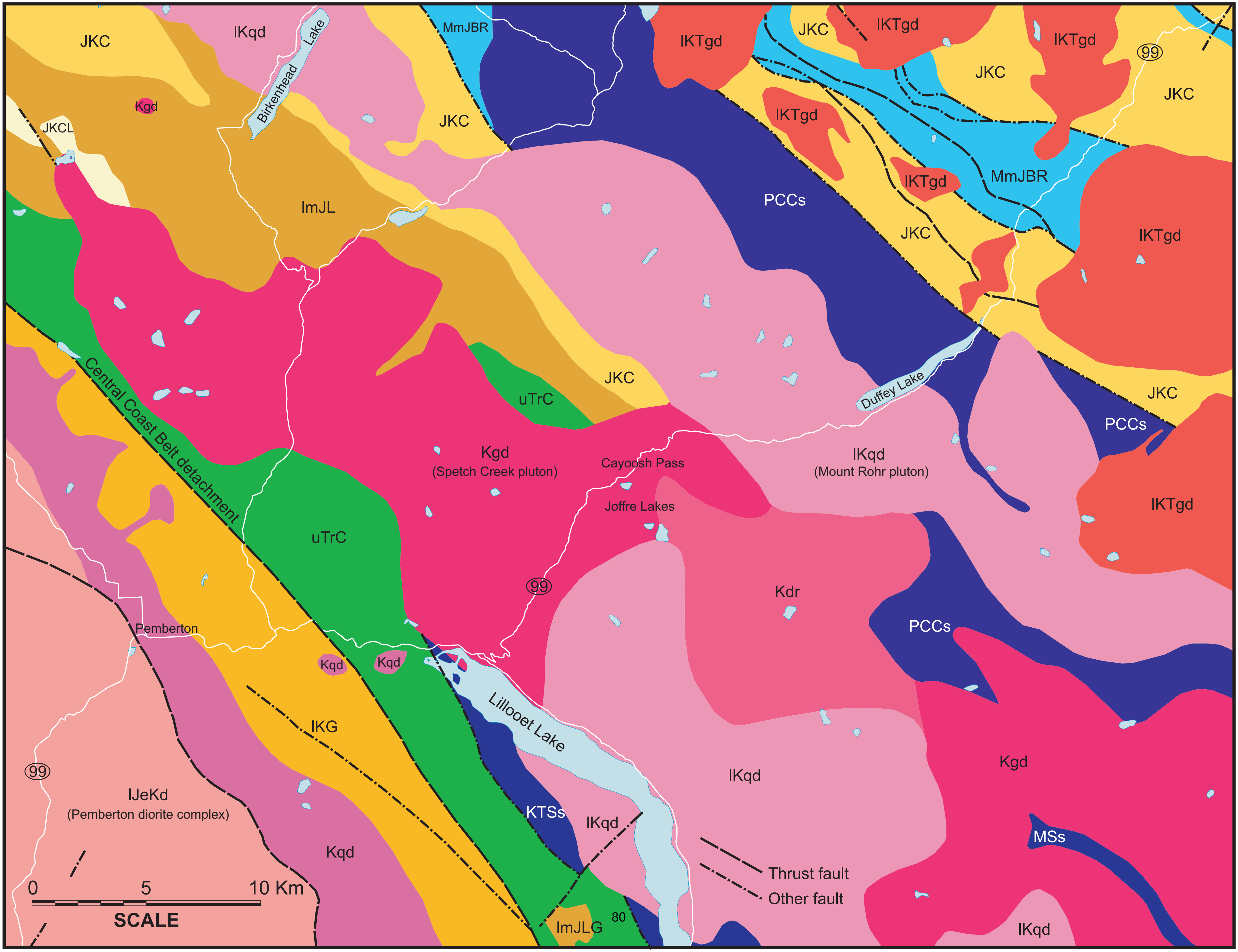
Assignment: identify the main intrusive phases, describe them, and determine the relationship between the phases. Answer the following:

Main Questions: what can you say about the tectonic setting and source rock that gave rise to these rocks? What is the source of the planar fabric evident within some of these rocks? What is pistachio green mineral? What is its origin, and petrological significance? What does it say about vertical motion of the crust?

Magmatic epidote?

Based on experimental and empirical evidence, magmatic epidote is believed to be indicative of high pressure crystallization. Zen and Hammarstrom (1984) concluded that the presence of magmatic epidote in plutons of intermediate composition implies a minimum crystallization pressure of 6 kbar. Their conclusions are in agreement with the experimental data of Naney (1983), who demonstrated that epidote is stable in a granodioritic melt at a pressure of 8 kbar. Experimental and empirical evidence shows that in plutonic rocks, magmatic epidote normally crystallizes at temperatures just above the solidus, and that it is likely formed from the reaction of hornblende and melt. However, the occurrence of epidote phenocrysts in rapidly quenched liquids suggests that the presence of amphibole may not be necessary for the formation of magmatic epidote, and that epidote may exist early in the crystallization history. Most recently, it has been argued that epidote dissolution rates can be used to place constraints on rates of pluton ascent (Brandon et al. 1996).

Figure 9-7 (next page) – Geology of the Southeastern Coast Belt. Legend - Kgd-Cretaceous granodiorite (including Spetch Creek Pluton), lKqd-Late Cretaceous quartz diorite (including Mount Rohr pluton), lJeKd-Late Jurassic-Early Cretaceous diorite (Pemberton complex), Kdr-Cretaceous diorite, Kdr-Cretaceous diorite, Kqd-Cretaceous quartz diorite, lKTgd-Late Cretaceous to Paleogene granodiorite, lKG-Lower Cretaceous Gambier Group, uTrC-Upper Triassic Cadwallader Group, KTSs-Cretaceous to Tertiary Slollicum schist, lmJL-Lower to Middle Jurassic Ladner Group, JKC-Jurassic to Cretaceous Cayoosh assemblage, PCCs-Permian Chism Creek schist, MmJBR-Mississippian to Middle Jurassic Bridge River Complex. (after GeoFile 2005-1)


JKC
IKqd
Birkenhead Lake
MmJBR
IKTgd
99
Kgd
JKCL
ImJL
PCCs
uTrC
Central Coast Belt detachment
Kgd
(Spetch Creek pluton)
Cayoosh Pass
Joffre Lakes
IKqd
(Mount Rohr pluton)
Duffey Lake
Kdr
Pemberton
Kqd
IKG
Lillooet Lake
KTSs
MSs
IJeKd
(Pemberton diorite complex)
ImJLG
80
Thrust fault
Other fault
0
5
10 Km
SCALE

WHISTLER MOUNTAIN – GAMBIER GROUP

The Gambier Group is a post terrane accretion overlap assemblage that developed on the eastern edge of Wrangellia in Early Cretaceous time. It consists of thick sequences of marine to nonmarine clastic and calc-alkaline volcanic rocks that are part of an extensive Cretaceous volcanic-arc system that spans the length of the Coast Belt. Correlations to the Gambier Group include rocks of the Gravina-Nutzotin belt of southeast Alaska, the Monarch Group of western-central British Columbia, as well as the Nooksack Group to the south in Washington State.

In the southwestern Coast Belt, the Gambier Group outcrops, discontinuously, around Howe Sound (where it hosts the Britannia VHMS deposit) and Jervis inlet, on the west side of Harrison Lake/Lillooet River and in the Whistler area (**Figure 10-1**). In the Howe sound area, the group is informally divided into a lower volcanic complex, a middle sedimentary interval, and an upper volcanic complex (**Figure 10-2**). It has been affected principally by greenschist and prehnite-pumpellyite metamorphism.

The lower volcanic complex is typified by a basal sequence of clastic rocks and mafic volcanic flows overlain by an extensive pyroclastic complex dominated by poorly sorted heterolithic volcanic breccia. The middle sedimentary interval is well bedded, consisting mainly of shale, pyritic shale, siltstone, and wacke. The upper volcanic complex overlaps with and overlies the middle sedimentary interval and passes upwards from predominantly subaqueously deposited mafic and intermediate flows to felsic domes and pyroclastic centres.

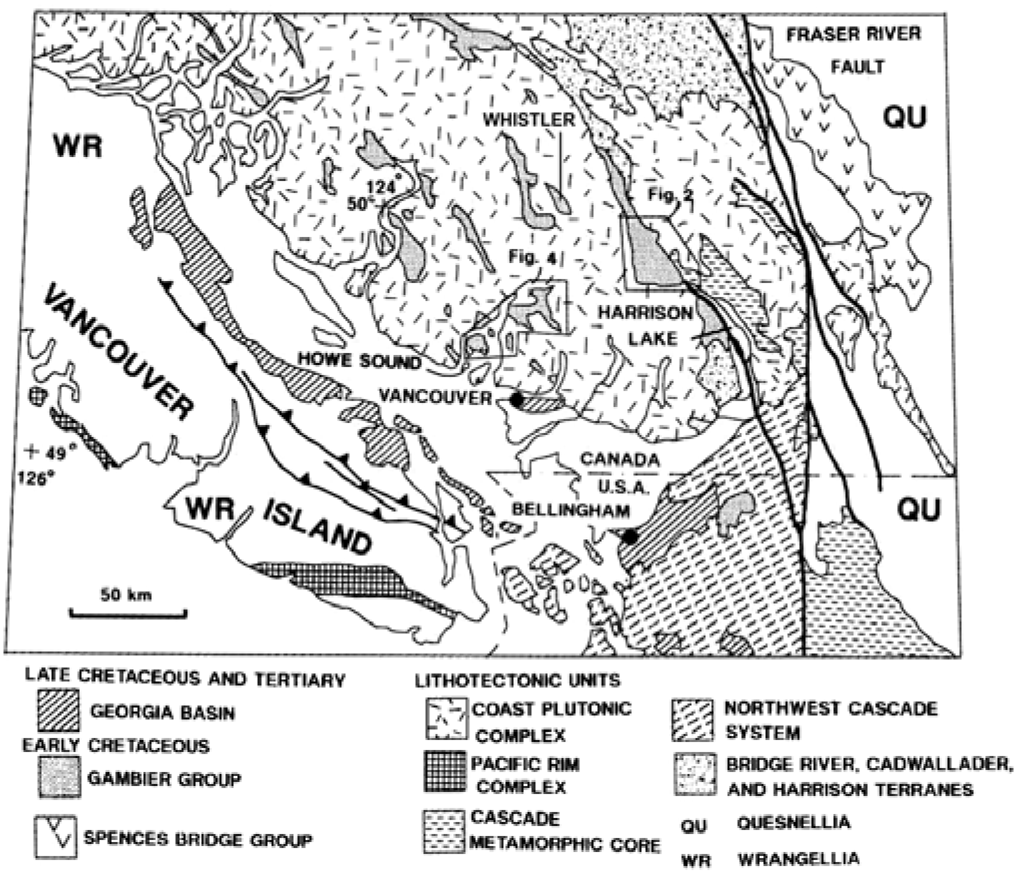


Figure 10-1 – Location map and distribution of Cretaceous volcanic assemblages in southwestern British Columbia. Tertiary fault systems in the eastern portion of the map area are shown as heavy lines and include the Fraser River Fault. Modified from Brown (1987), Wheeler and McFeely (1987), England (1989), Journeay (1990a), and Lynch (1992).

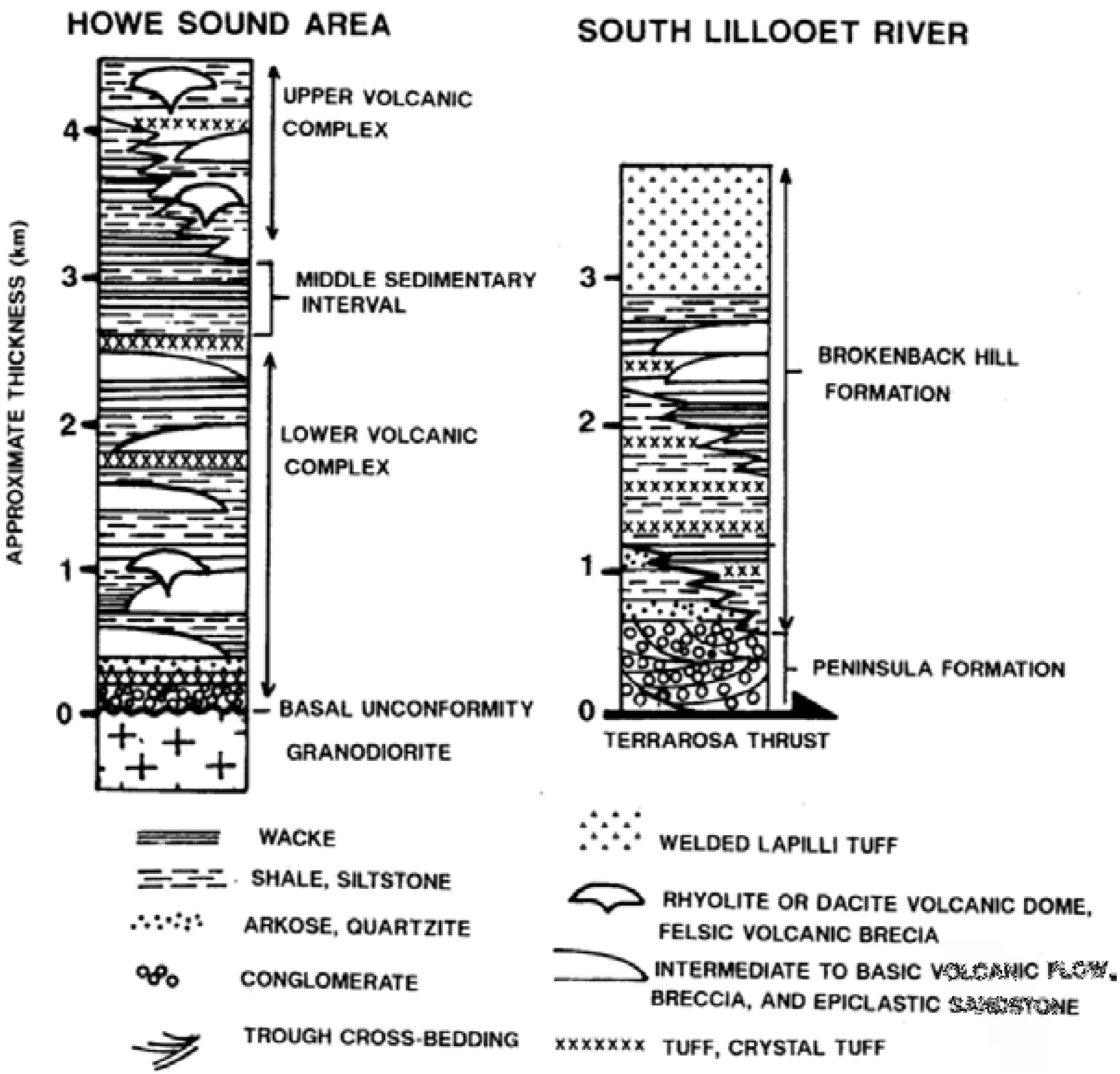
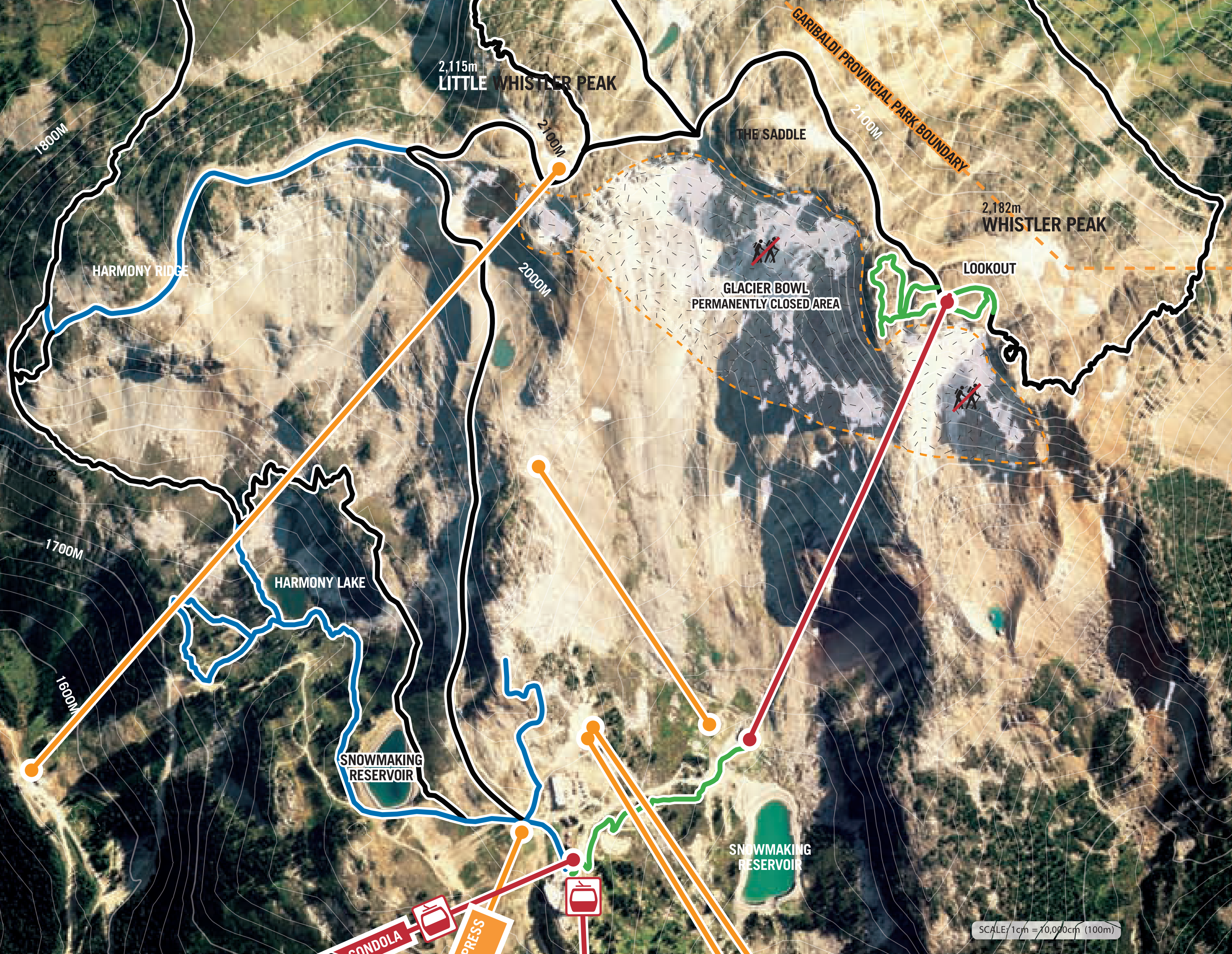


Figure 10-2 – Stratigraphy of the Gambier Group. South Lillooet River section. (Lynch, 1992).

Assignment: Using the Whistler Mountain air photo (next page) as a base map, produce a geological map showing the distribution of units and any structural features. Your map should include a legend describing all the main map units, and should include a cross-section showing the relationships between the units. Describe the relationship between Gambier Group strata and the adjacent plutonic rocks. Quantitatively describe the main structure feature observed (include a stereonet). Answer the following:

Main Questions: what is the relationship between the map pattern and the main structure? Where portion of the Gambier Group stratigraphy is exposed here (consult the field guide)? What is the tectonic significance of these mid-Cretaceous volcanics and related plutons? Where else have we seen mid-Cretaceous magmatism? Provide a tectonic model explaining all mid-Cretaceous magmatism?

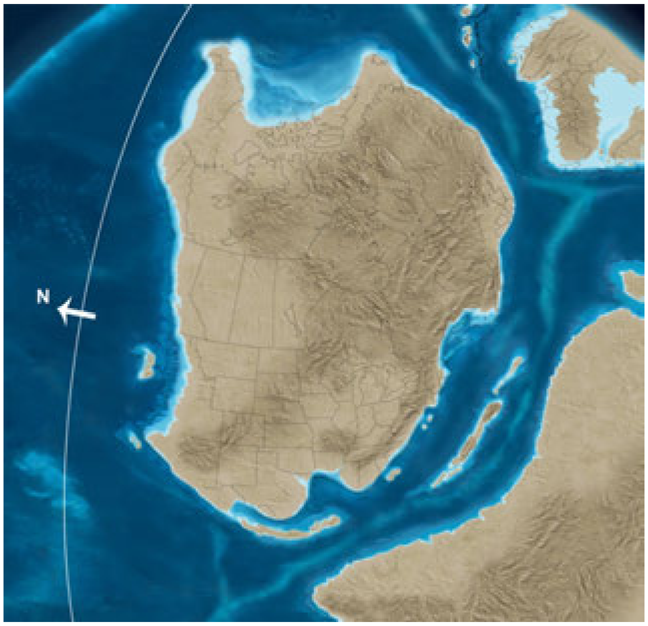
Please hand in <u>all</u> the equipment you were originally issued <u>before</u> boarding the ferry.


2,115m
LITTLE WHISTLER PEAK
GARIBALDI PROVINCIAL PARK BOUNDARY
THE SADDLE
2100M
2100M
2,182m
WHISTLER PEAK
LOOKOUT
HARMONY RIDGE
2000M
GLACIER BOWL
PERMANENTLY CLOSED AREA
1800M
1700M
1600M
HARMONY LAKE
SNOWMAKING RESERVOIR
SNOWMAKING RESERVOIR
GONDOLA
PRESS
SCALE: 1cm = 10,000cm (100m)

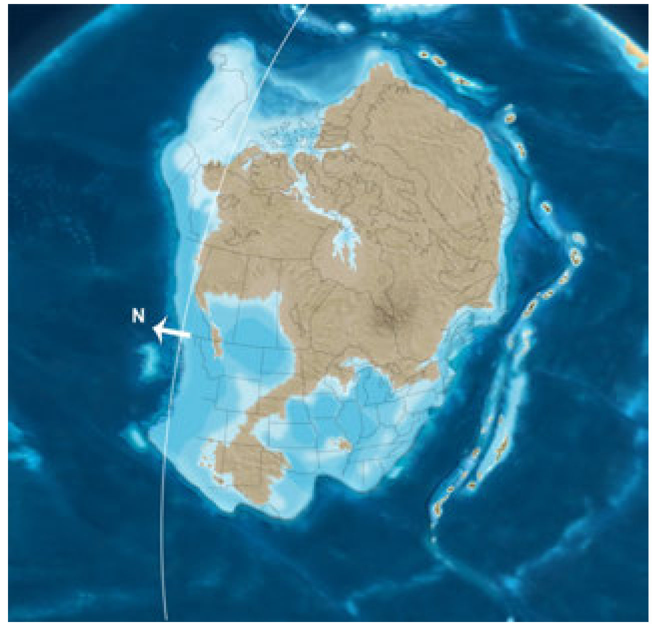
APPENDIX A – North American Paleogeography

The images presented on the following pages show the paleogeography of North America over the last 550 million years of geologic history. The maps were prepared with the core of North America (Laurentia) fixed. All other tectonic elements are shown moving against or splitting away from Laurentia, thus showing clearly accretionary and rifting events in North America's geologic history. The views were prepared by wrapping a rectangular outline map on a sphere and viewing the globe rotated to 35° N and 100° W. Various stratigraphic, tectonic, and sedimentologic data were added to the map. Topography was derived from digital elevation maps of modern Earth from the USGS, NOAA, and other sources. Colors were adjusted to portray climate and vegetation for the given time and location. A key to the various depictions appears below:

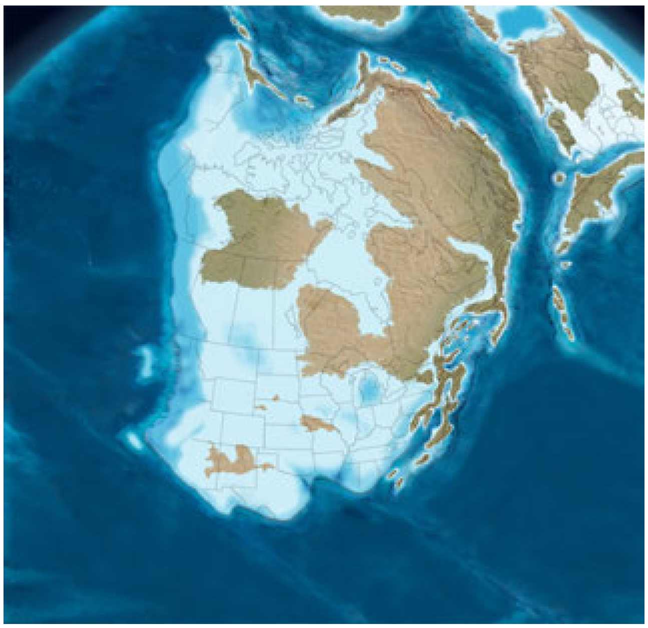
Key



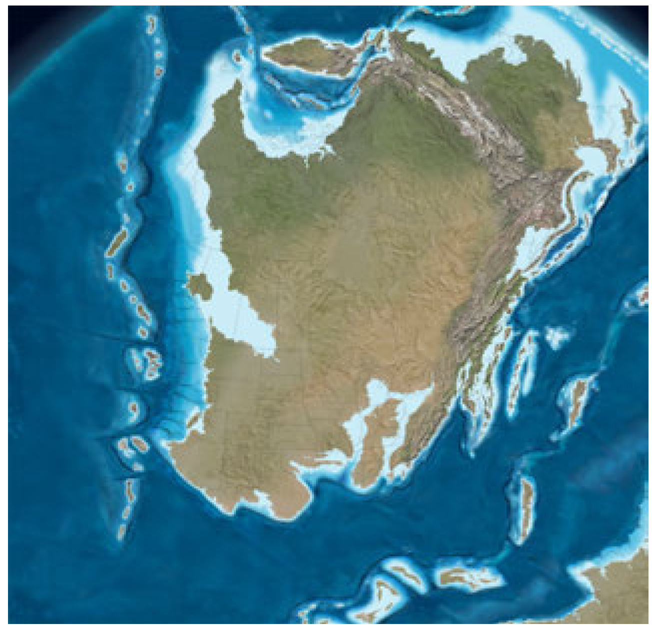
Late Precambrian (550 Ma)



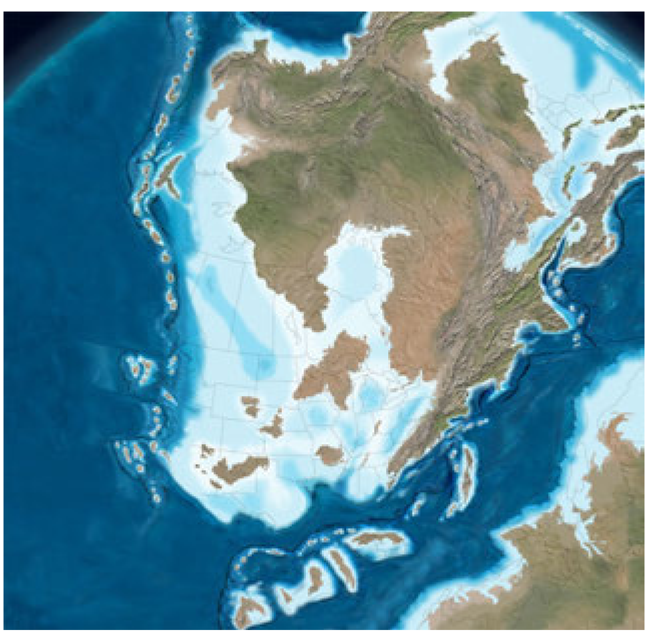
Late Cambrian (500 Ma)



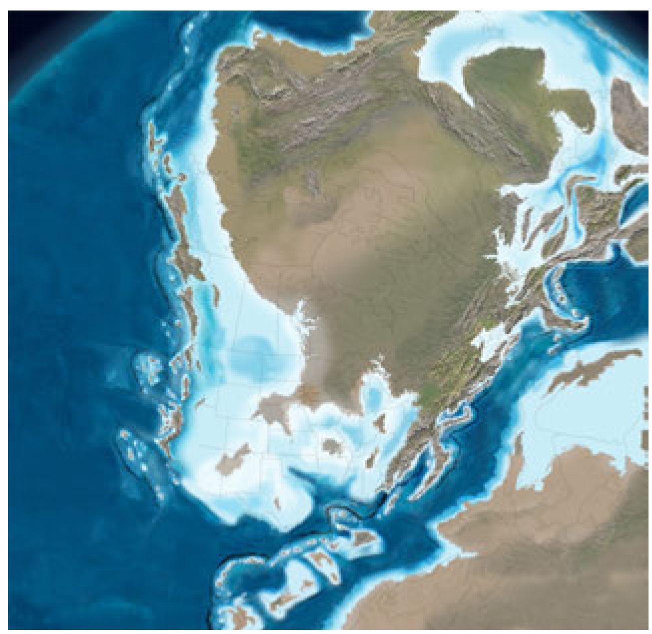
Late Ordovician (450 Ma)



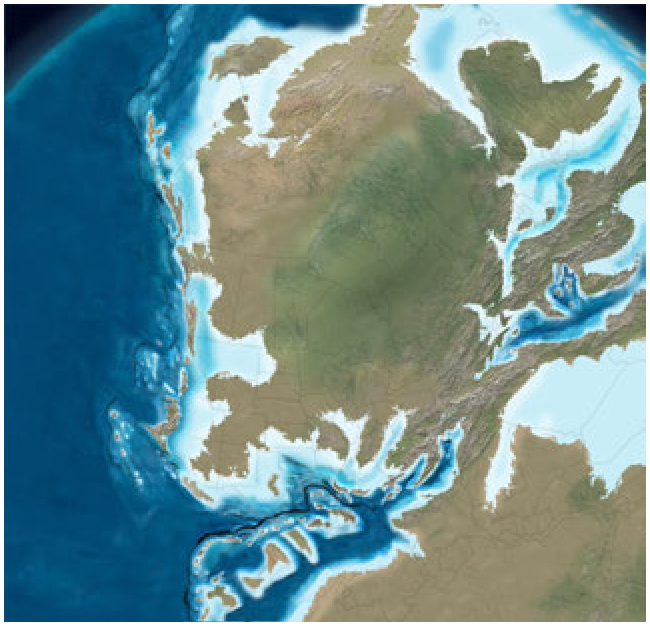
Early Devonian (400 Ma)

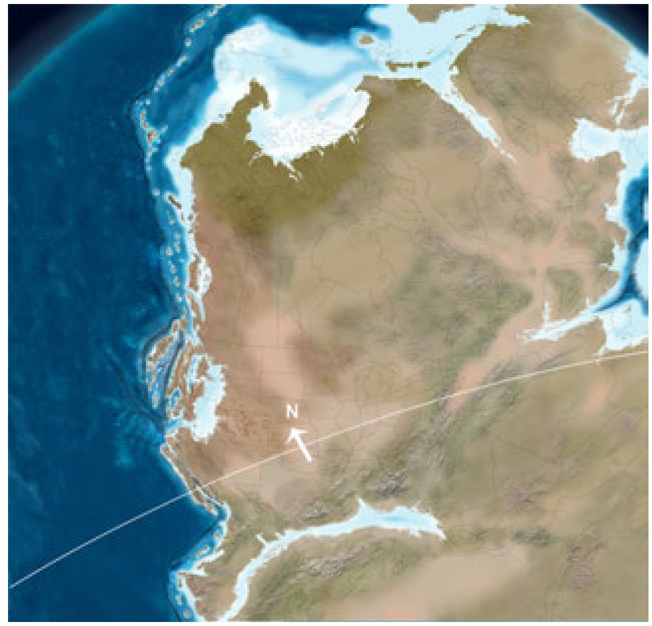


Devono-Mississippian (360 Ma)

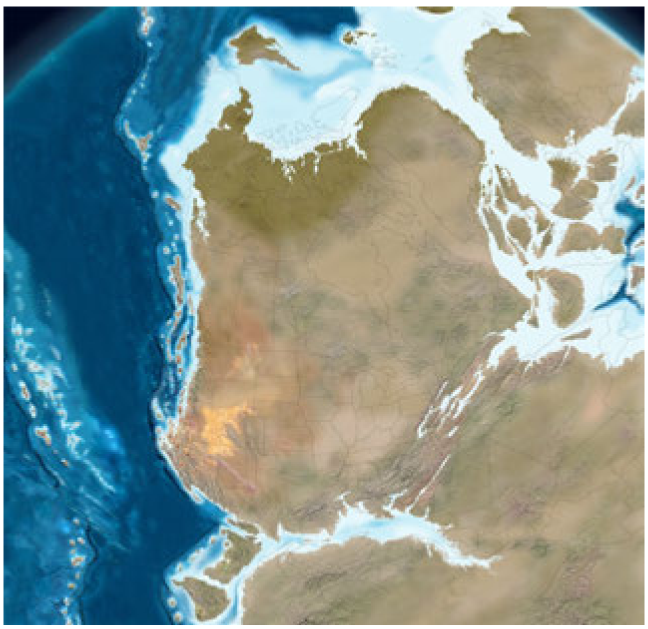


Early Mississippian (345 Ma)


Late Pennsylvanian (300 Ma)



Early Triassic (245 Ma)


Early Jurassic (195 Ma)


Late Jurassic (150 Ma)


Middle Cretaceous (100 Ma)


Late Cretaceous (85 Ma)

Cretaceous-Tertiary (65 Ma)

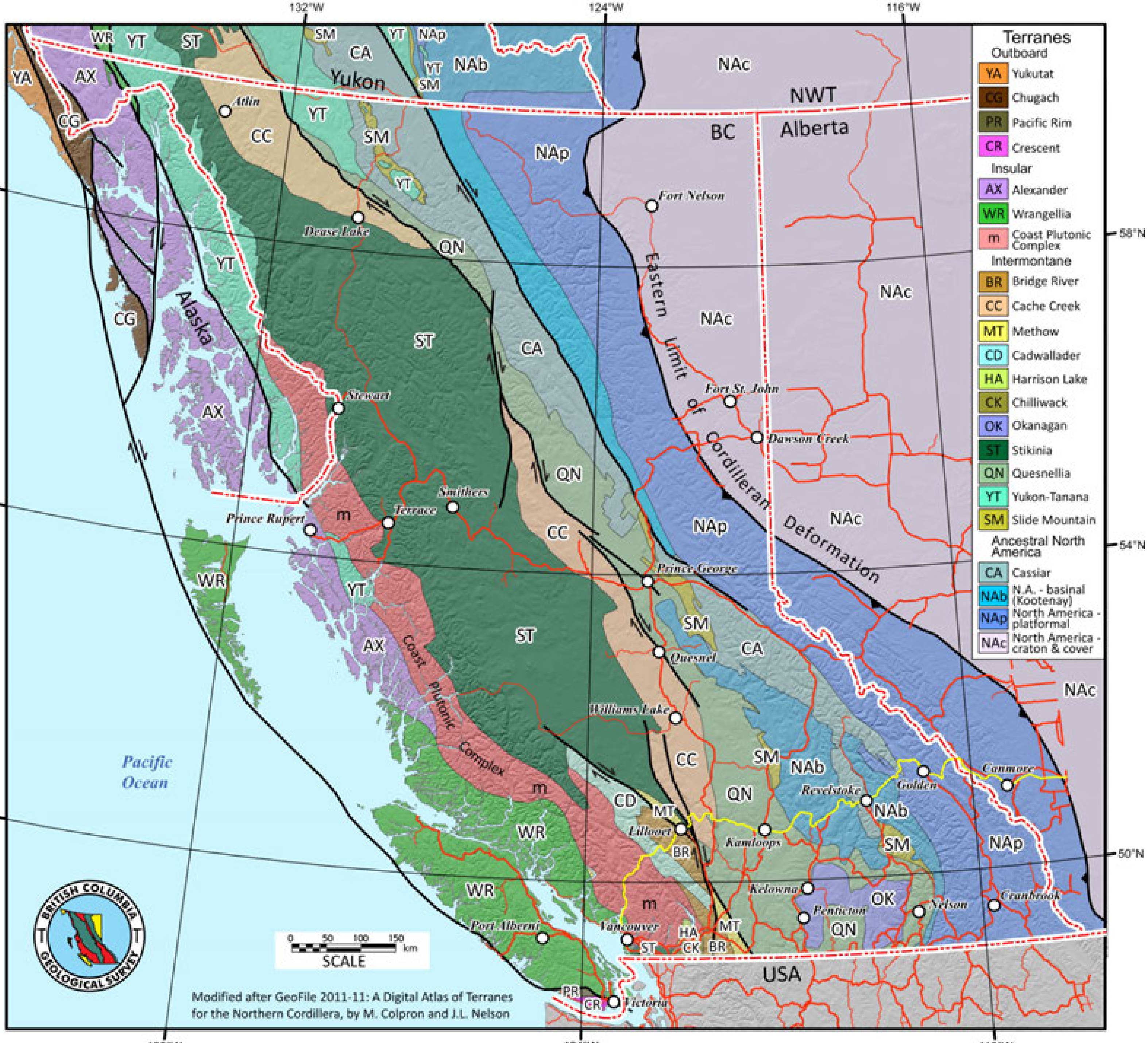
Eocene (50 Ma)

Oligocene (25 Ma)

Pleistocene (0.126 Ma)

Blakey, Ron, 2005: Paleogeography and Geologic History of North America, 550-0.126 Ma

APPENDIX B – Terranes of the Northern Cordillera



Modified after GeoFile 2011-11: A Digital Atlas of Terranes for the Northern Cordillera, by M. Colpron and J.L. Nelson

Terranes of southern British Columbia

BR ***Bridge River terrane.*** An accretionary complex of Carboniferous through Middle Jurassic age sandwiched between Wrangellia and the Cretaceous continental margin of North America.

CA ***Cassiar terrane***. Paleozoic continental platformal and basinal strata considered as a parautochthonous or displaced portion of the ancient North American margin.

CC ***Cache Creek terrane.*** An accretionary complex that accompanied the Quesnel and Stikine terranes and contains Carboniferous to Early Jurassic ocean basin rocks; fossils in Permian limestone similar to fossils in rocks of the same age in eastern and central Asia.

CR ***Crescent terrane***. A Paleocene to Early Eocene oceanic assemblage of basalt flows, breccia, tuff and volcanic sandstones cut by gabbroic intrusions; emplaced beneath the Pacific Rim terrane along the Leech River fault approximately 42 Ma.

CD ***Cadwallader terrane.*** Upper Triassic island arc clastics and volcanics (regarded in part by some workers as Stikinia) overlain by Jurassic arc clastics and volcanics, and Jura-Cretaceous easterly derived continental margin clastic wedge of shale and siltstone in Tyaughton Trough.

CK ***Chilliwack terrane.*** Devonian to Permian island arc; fossils in Permian limestone similar to those in the Quesnel and Stikine terranes, and to fossils in the southwestern United States.

HA ***Harrison (Lake) terrane.*** Jurassic island arc volcanics and clastics. Carbonate clasts in Toarcian conglomerate contain Permian fossils similar to those in the Chilliwack Terrane.

MT ***Methow terrane.*** Ocean basin rocks of Permian age overlain by Early Jurassic through Early Cretaceous mainly sedimentary rocks, mostly eroded from volcanic arcs.

OK ***Okanagan terrane***. Mafic volcanic rocks, chert, argillite and minor ultramafic rocks, which are thought to have been deposited in, or near, an ocean basin and appear to have been emplaced by Late Devonian time.

PR ***Pacific Rim terrane.*** Continental slope (mélange) sediments; accreted to Wrangellia along the Westcoast and San Juan-Survey Mountain fault systems approximately 55 Ma.

QN ***Quesnel terrane (Quesnellia).*** Devonian to Permian island arc rocks overlain and intruded by early Mesozoic island arc rocks; welded to North America about 185 to 170 million years ago.

SM ***Slide Mountain terrane.*** Late Paleozoic to Triassic rocks that originated in a back-arc ocean basin to the east of the Quesnel terrane. Includes the Fennel formation.

ST ***Stikine terrane (Stikinia).*** Devonian to Permian arc volcanics and platform carbonates form the basement to Stikinia. They are overlain by Triassic and Lower Jurassic arc volcanics, volcaniclastics, and arc-derived clastics, which are intruded by comagmatic plutonic rocks.

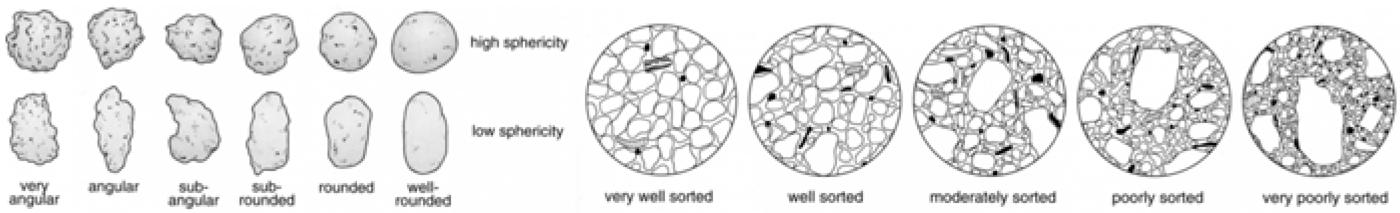
WR ***Wrangell terrane (Wrangellia).*** Devonian to Middle Jurassic island arc with conspicuous Mid-to Late Triassic basalt; welded to North America in Cretaceous time.

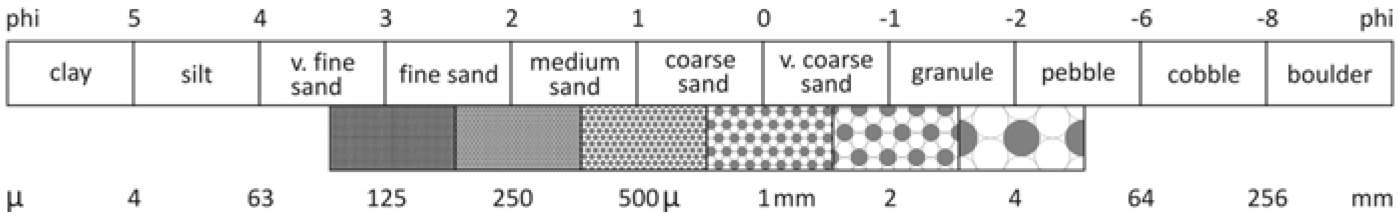
Autochthonous Rocks:

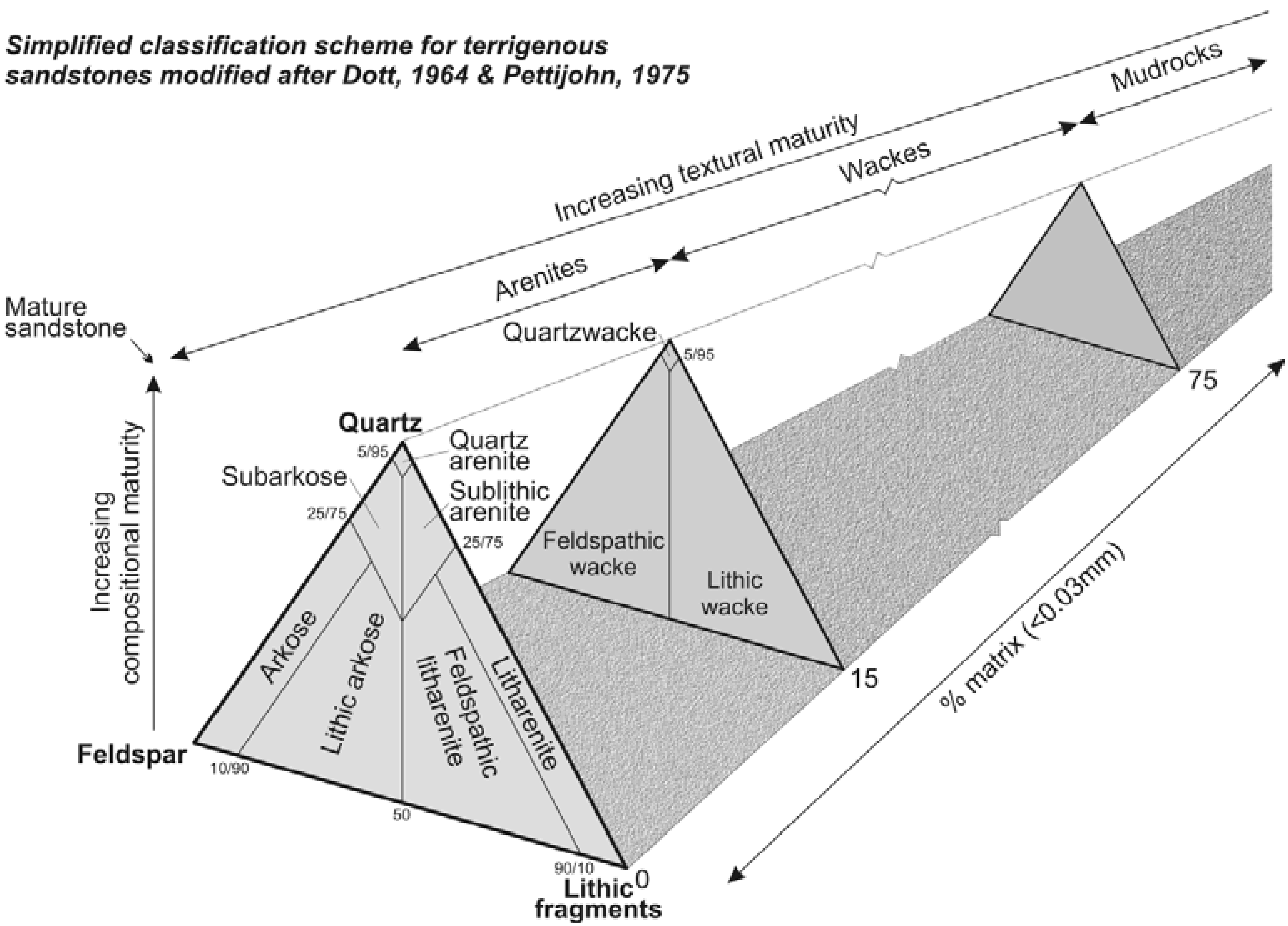
NAp ***North America – platformal.*** Middle Proterozoic to Carboniferous passive and off-shelf continental margin sediments, Devonian to Carboniferous clastic wedges, Pennsylvanian to Jurassic passive continental margin prism, and Permian clastics.

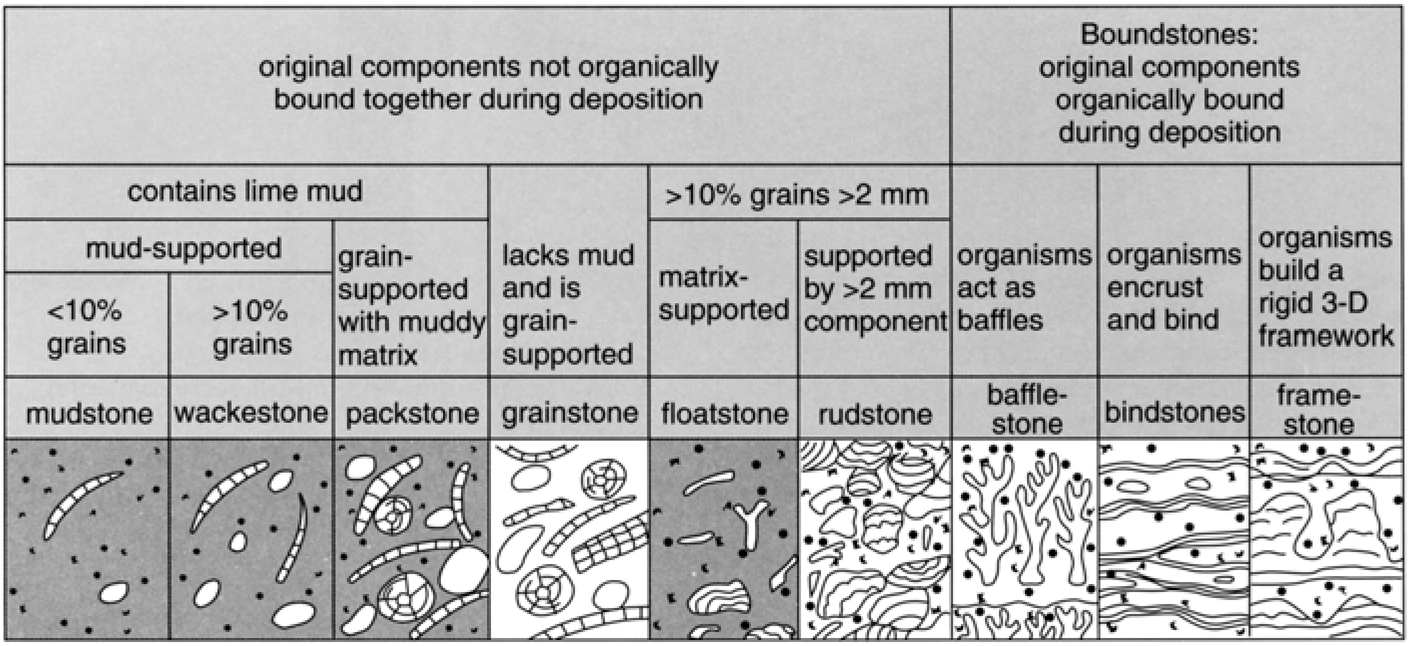
NAb ***North America – basinal.*** Lower Paleozoic pericratonic rocks depositionally linked to and conformable with underlying rocks that form part of the North American Cordilleran miogeocline. Also known as the ***Kootenay terrane***.

APPENDIX C – Classification Schemes

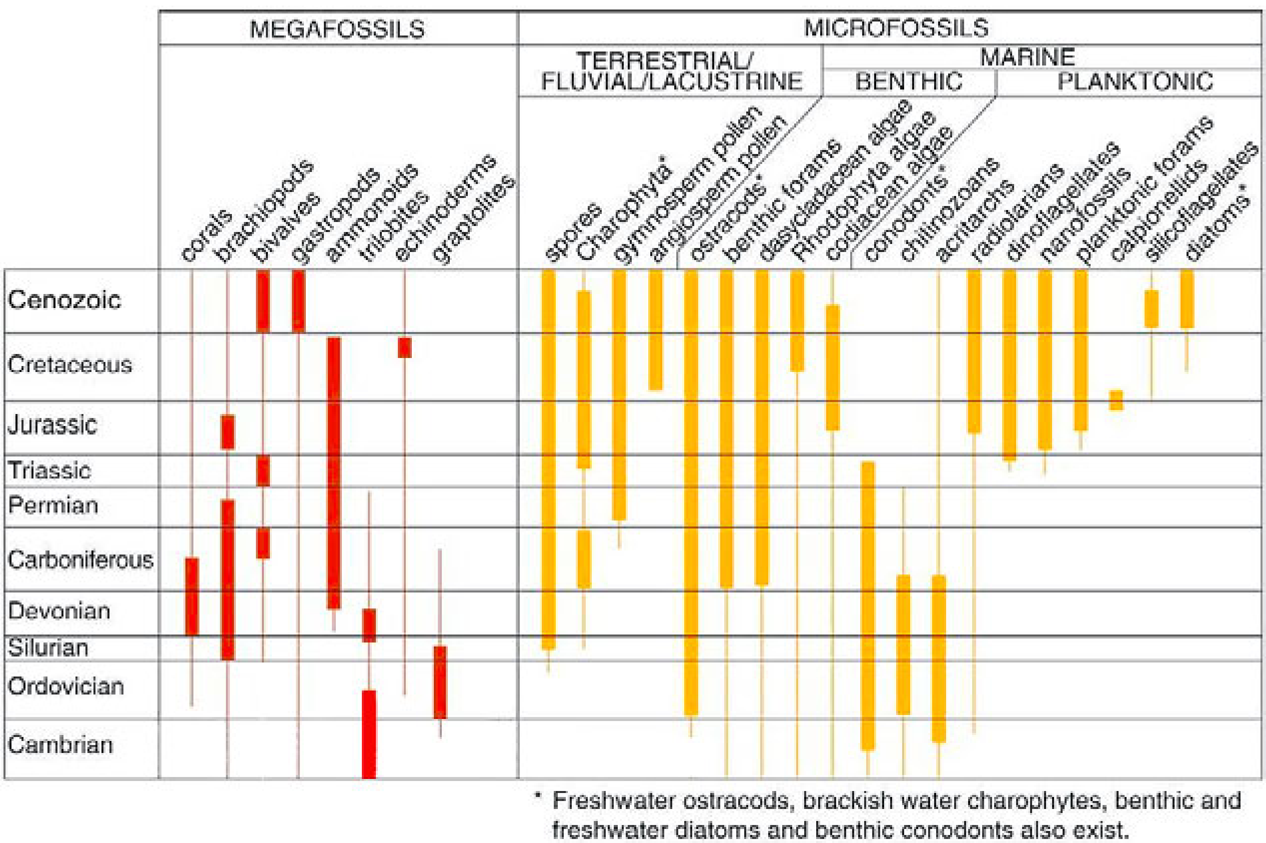




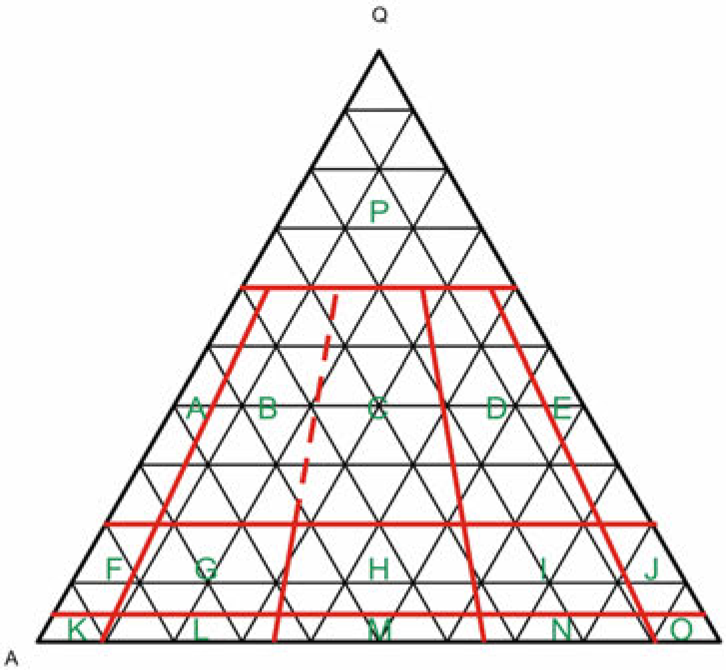




Modification of Dunham's limestone classification (after Embry & Klovan, 1972)

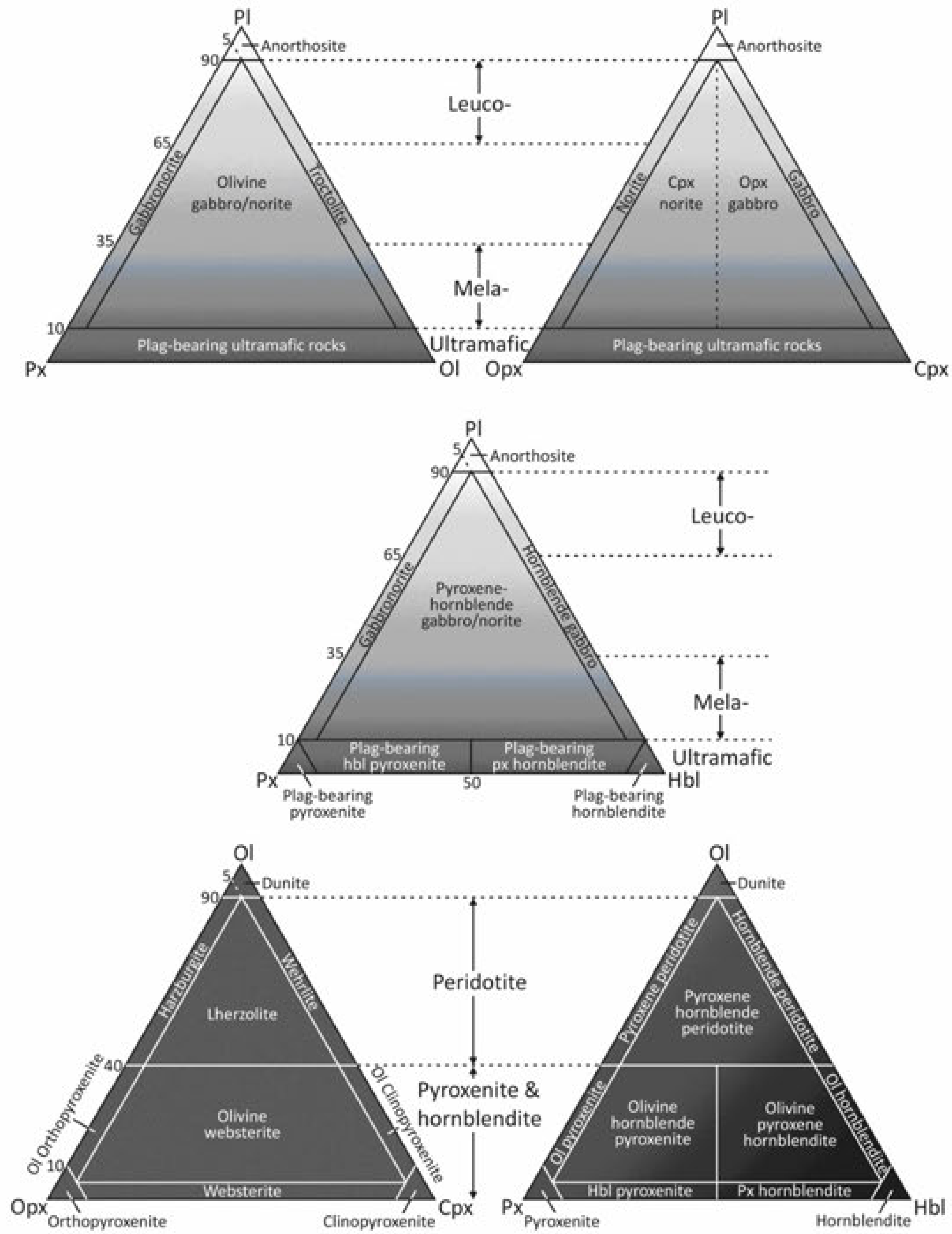


Biostratigraphically important organisms. Thick part of the line indicates interval of greatest diversity. (after Nichols, 1999 and Emery & Myers, 1996)

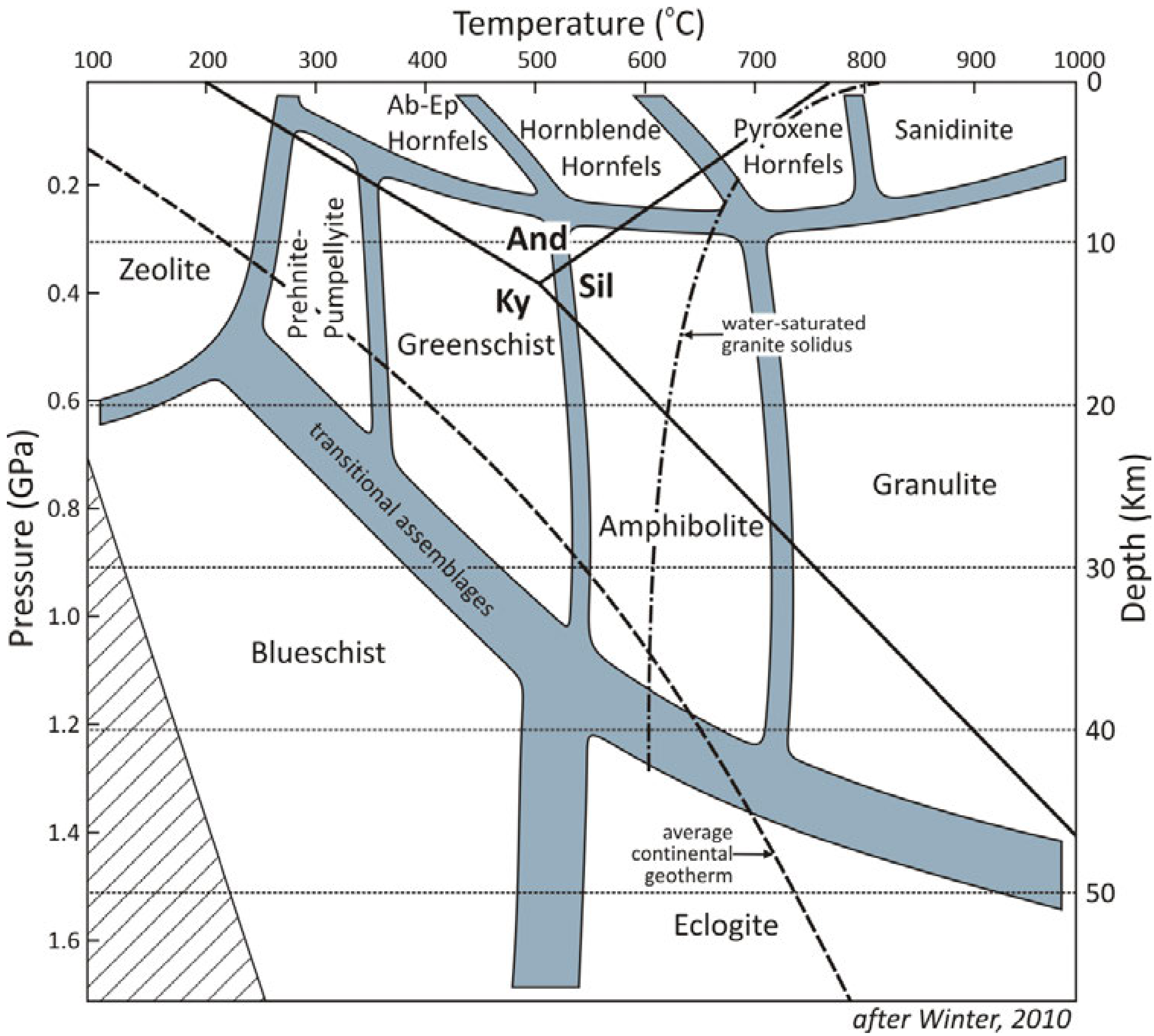


	Plutonic		Volcanic
A	Alkali feldspar granite		Alkali feldspar rhyolite
B	Syeno-	Granite	Rhyolite
C	Monzo-		Rhyodacite
D	Granodiorite		Dacite
E	Tonalite		Quartz andesite
F	Quartz alkali feldspar granite		Quartz alkali feldspar trachyte
G	Quartz syenite		Quartz trachyte
H	Quartz monzonite		Quartz latite
I	Quartz monzodiorite[1]		Quartz latite andesite
	Quartz monzogabbro[2]		
J	Quartz diorite[1,4]		Andesite
	Quartz gabbro[2,4]		
	Quartz anothosite[3]		
K	Alkali feldspar syenite		Alkali feldspar trachyte
L	Syenite		Trachyte
M	Monzonite		Latite
N	Monzodiorite[1]		Latite basalt
	Monzogabbro[2]		
O	Diorite[1,4]		Basalt
	Gabbro[2,4]		
	Anorthosite[3]		
P	Quartz-rich granite		Quartzolite
[1] plagioclase: An_{0-50} hornblende chief mafic	[2] plagioclase: An_{50-100} pyroxene chief mafic		[3] mafics <10% / [4] mafics >10%

IUGS classification of plutonic & volcanic rocks (w/ <90% mafics).



IUGS classification of gabbroic and ultramafic rocks.
Shading indicates the appoximate colour index of the rocks.



Temperature-Pressure Diagram showing metamorphic facies boundaries

Metamorphic Facies Table

	Pelite	Calcareous	Mafic	Ultramafic
Zeolite	illite/phengite + chlorite +quartz	calcite and/ or dolomite	Ca-zeolite + chlorite + albite + quartz	lizardite/ chrysotile + brucite + magnetite
+/-	kaolinite, paragonite	quartz	prehnite, analcime, pumpellyite	chlorite, carbonate
Prehnite-pumpellyite	phengite + chlorite + quartz	calcite and/ or dolomite	prehnite + pumpellyite + chlorite + albite + quartz	lizardite/ chrysotile + brucite + magnetite
+/-	pyrophyllite, paragonite, K-feldspar, stilpnomelane, lawsonite	quartz	actinolite, stilp- nomelane, lawsonite	antigorite, chlorite, carbonate, talc, diopside
Greenschist	muscovite + chlorite + quartz	calcite and/ or dolomite	chlorite + epidote + albite	antigorite + diopside + magnetite
+/-	biotite, K-feldspar, chloritoid, para- gonite, albite, Mn-rich garnet	quartz, talc, actinolite	actinolite, biotite	chlorite, brucite, olivine, talc, carbonate
Amphibolite	muscovite + biotite + quartz	calcite and/ or dolomite	plagioclase + hornblende	olivine + tremolite
+/-	garnet, staurolite, kyanite, sillimanite, andalusite, cor- dierite, chlorite, plagioclase, K-feldspar	quartz, tremolite, diopside, forsterite, phlogopite, epidote, grossular, scapolite, vesuvianite	epidote, garnet, orthoamphi- bole, cumming- tonite	antigorite, talc, antho- phylite, cum- mingtonite, enstatite
Granulite	K-feldspar + plagioclase + sillimanite + quartz	calcite and/ or dolomite	orthopyrox- ene + plagio- clase	olivine + diopside + enstatite
+/-	biotite, garnet, kyanite, cordierite, orthopyr oxene, spinel, corundum, sappharine	diopside, forsterite, wollastonite, scapolite, spinel monticellite, periclase, grossular	clinopy- roxene, hornblende, garnet	spinel, plagioclase
Blueschist	phengite + chlorite + quartz	calcite and/ or dolomite	glaucophane/ crossite + lawsonite/ epidote	antigorite + olivine + magnetite
+/-	albite, jadeite, lawsonite, garnet, chloritoid, paragonite	quartz, aragonite, phengite	pumpellyite, chlorite, garnet, albite, aragonite, phengite, paragonite, chloritoid	chlorite, brucite, talc, diopside
Eclogite	phengite + gar- net +quartz	calcite and/ or dolomite	omphacite + garnet + rutile	olivine

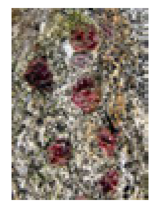
(from The Geoscience Handbook, AGI Data Sheets, 2006)

APPENDIX D – Metamorphic Indicator Minerals

Almandine (Garnet)

- **Color** is typically red to brown, occasionally with a tinge of purple and sometimes a deep enough red to appear black.
- **Luster** is vitreous.
- **Transparency** crystals are transparent to translucent.
- **Crystal System** is isometric; 4/m bar 3 2/m
- **Crystal Habits** include the typical 12-sided rhombic dodecahedron. Also seen is the 24-sided trapezohedron. Massive occurrences are also common.
- **Cleavage** is absent.
- **Fracture** is conchoidal.
- **Hardness** is 6.5 - 7.5.
- **Specific Gravity** is approximately 4.3 (above average for non-metallic minerals).
- **Streak** is white.
- **Associated Minerals** are micas, staurolite, quartz and feldspars.
- **Best Field Indicators** are crystal habit, color, density and hardness.



Andalusite

- **Color** is white, red, brown, orange and green.
- **Luster** is vitreous.
- **Transparency** crystals are transparent to translucent.
- **Crystal System** is orthorhombic; 2/m2/m2/m.
- **Crystal Habits** include prismatic crystals with a square cross section terminated by a pinacoid. also massive and granular.
- **Cleavage** is good in two directions.
- **Fracture** is splintery to subconchoidal.
- **Hardness** is 7.5.
- **Specific Gravity** is approximately 3.15+
- **Streak** is white.
- **Associated Minerals** are cordierite, biotite, feldspars, quartz, kyanite and sillimanite.
- **Other Characteristics:** dark inclusions produce cruciform shapes in the variety chiastolite.
- **Best Field Indicators** are crystal habit, color, inclusions (if present) and hardness.




Chlorite

- **Color** is usually green but can also be white, yellow, red, lavender and black.
- **Luster** is vitreous, dull or pearly.
- **Transparency:** crystals are translucent transparent.
- **Crystal System** is monoclinic; 2/m.
- **Crystal Habits:** rarely in large individual barrel or tabular crystals with an hexagonal outline. Usually found as alteration products of iron-magnesium minerals and as inclusions in other minerals. Aggregates can be scaly, compact, platy and as crusts.
- **Cleavage** is perfect in one direction, basal; not seen in massive specimens.
- **Fracture** is lamellar.
- **Hardness** is 2 – 3.
- **Specific Gravity** is variable from 2.6 - 3.4.
- **Streak** is pale green to gray or brown.
- **Other Characteristics**: cleavage flakes are flexible but not elastic.
- **Associated Minerals** include garnets, biotite, quartz, magnetite, talc, serpentine, danburite, topaz and calcite, among many others.
- **Best Field Indicators** are color, cleavage, mineral associations and crystal habits.




Kyanite

- **Color** is blue usually but also can be white, gray or green. Color is often not consistent throughout the crystal and can be blotchy or in streaks.
- **Luster** is vitreous to almost pearly.
- **Transparency** crystals are transparent to translucent.
- **Crystal System** is triclinic; bar 1.
- **Crystal Habits** include flat, pinacoid dominated, prismatic crystals often embedded in metamorphic rocks and quartz veins.
- **Cleavage** is good in one direction parallel to the flat pinacoid face.
- **Fracture** is splintery.
- **Hardness** is approximately 4.5 when scratched parallel to the long axis of the crystal and approximately 6.5 when scratched perpendicular to or across the long axis.
- **Specific Gravity** is approximately 3.58+.
- **Streak** is white.
- **Associated Minerals** are biotite, staurolite, garnets, quartz, andalusite and sillimanite.
- **Other Characteristics:** Sometimes intergrown with **staurolite**.
- **Best Field Indicators** are crystal habit, color, luster and unusual hardness.



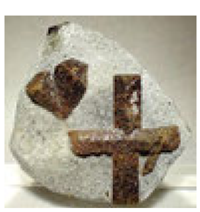

Sillimanite

- **Color** is white, brown and green.
- **Luster** is silky when fibrous or vitreous otherwise.
- **Transparency** crystals are transparent to translucent.
- **Crystal System** is orthorhombic; 2/m2/m2/m.
- **Crystal Habits** include rare prismatic crystals but mostly fibrous masses.
- **Cleavage** is good in one direction lengthwise.
- **Fracture** is splintery.
- **Hardness** is 7.5 in large crystals but more fibrous forms are softer.
- **Specific Gravity** is approximately 3.2+.
- **Streak** is white.
- **Associated Minerals** are garnets, biotite, feldspars, quartz, kyanite and andalusite.
- **Other Characteristics:** fibers are brittle, distinguishing them from asbestos minerals. Fibrous form (left, below) known as **fibrolite**.
- **Best Field Indicators** are crystal habit, color, brittleness and hardness if not fibrous.

Staurolite

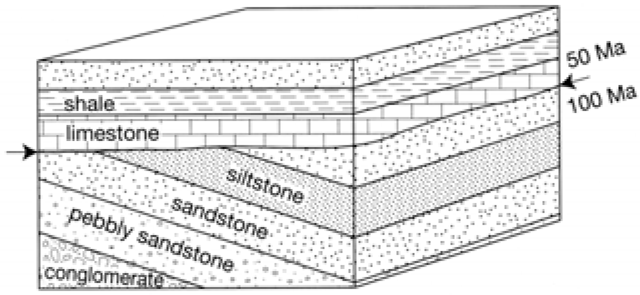
- **Color** is reddish-brown, brown, and black.
- **Luster** is vitreous to resinous to dull.
- **Transparency** crystals are translucent to opaque.
- **Crystal System** monoclinic; 2/m.
- **Crystal Habits**: the typical crystal are prismatic or tabular. Some crystals can have a psuedo-hexagonal cross-section but most are flattened into a more diamond shaped cross-section with two of the four points truncated. Twinning is seen in about 35% of the specimens encountered in nature. Twins are cross (+) or x-shaped and can be both at the same time. Crystals sometimes grown onto kyanite crystals.
- **Cleavage** poor, in one direction.
- **Fracture** is uneven to conchoidal.
- **Hardness** is 7-7.5.
- **Specific Gravity** is 3.7-3.8.
- **Streak** is white.
- **Associated Minerals** include almandine, micas, kyanite and other metamorphic minerals.
- **Best Field Indicators** are color, associations, twinning and crystal habit.

APPENDIX E – Unconformities

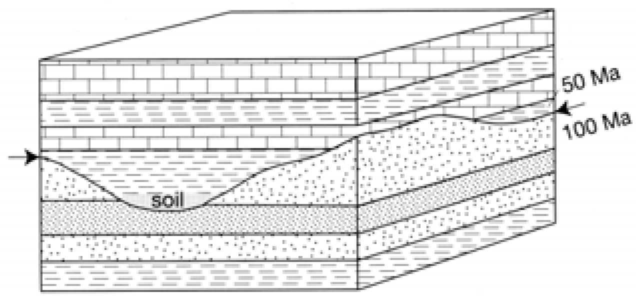
An unconformity is a structure that is not directly related to tectonic deformation. It is usually caused by cessation of sedimentation for a considerable time period in geological history. Sedimentary beds deposited during a cycle of sedimentation are said to be conformable to each other, as they lie as parallel layers one above the other. When a sedimentation cycle is complete, there may be a period of no sedimentation over the already laid formation. If the cessation period is long enough, the earlier beds may undergo deformation which may lead to tilting, folding and/or faulting of the beds. Erosion may also take place during this phase, if the beds are exposed to weathering processes. When the next cycle of sedimentation begins, the initial surface of deposition will be an eroded surface. This second phase leads to deposition of another set of conformable beds which make up a formation. The two formations are said to be separated by an unconformity. There are four generally recognized types:

The most common and distinct type of unconformity is an angular unconformity. In this type, the older beds are tilted and truncated at the surface of unconformity. The younger beds lie at an angle to the older beds.



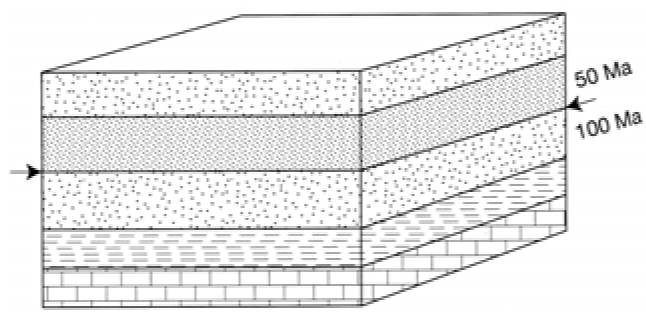
A. Angular Unconformity

A disconformity is similar to paraconformity, with the exception that the unconformity in this case is directly recognizable as a surface resulting from erosion of underlying beds. The rocks above and below a disconformity are parallel in this case too.



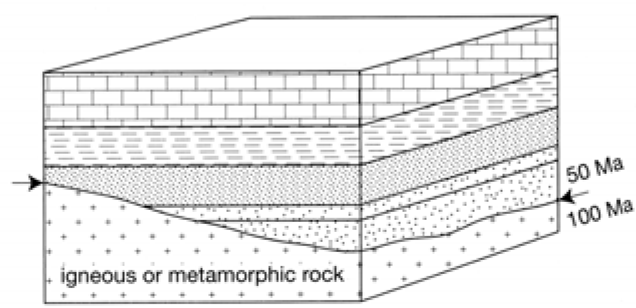
B. Disconformity

When an unconformity is simply due to non-deposition, it is termed as a paraconformity. Beds above and below the paraconformity are parallel and the unconformity is identified by some evidence such as lack of certain diagnostic zone fossils in some horizon.



C. Paraconformity

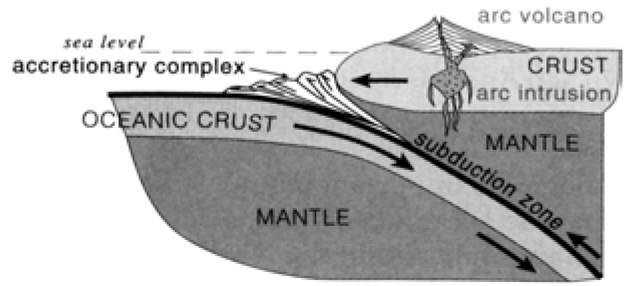
A non-conformity separates igneous or metamorphic rocks from overlying sedimentary or volcanic rocks which are nearly horizontal.



D. Nonconformity

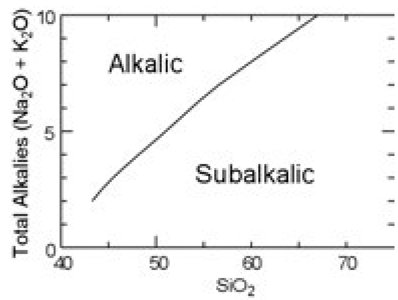
APPENDIX F – Glossary

Accretionary wedge (**complex**) **–** a body of deformed sediments, wedge-shaped in two dimensions or prism-shaped in three dimensions, that has been scraped off the surface of the oceanic lithosphere as it subducts beneath a continent. The sediments are added to the continental edge.



Agglomerate – a coarse accumulation of volcanic ***tephra*** (volcanic breccia) typically found near volcanic vents and within volcanic conduits, where they may be associated with pyroclastic or intrusive volcanic breccias.

Alkalic – said of igneous rocks that contain more sodium and potassium than is required to form feldspar with the available silica. Cf: ***subalkalic***.

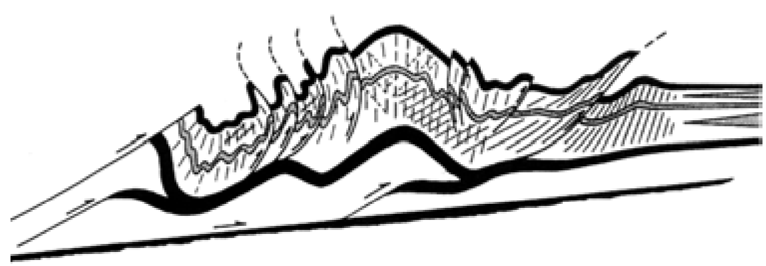


Allochthonous – said of rocks, deposits, *etc.* found in a place other than where they or their constituents were formed. Ant: ***autochthonous***.

Anatexis – the melting of pre-existing rock.

Ankaramite – a mafic olivine basalt primarily composed of pyroxene with smaller amounts of olivine and plagioclase and accessory biotite, apatite, and opaque oxides.

Anticlinorium – a composite anticlinal structure of regional extent composed of lesser folds. Cf: ***synclinorium***.



Antithetic fault – a minor normal fault that is oriented opposite to the major fault to which it is associated.

Aulacogen – a radially oriented tectonic trough on a craton, bound by convergent normal faults. Cf: ***graben***

Autochthonous – said of rocks, deposits, *etc.* found where they and their constituents were formed. Ant: ***allochthonous***.

Automorphic (also **idiomorphic**) **–** said of the holocrystalline texture of an igneous rock; characterized by crystals completely bound by their own rational facies (*i.e.*, euhedral). Cf: ***hypidiomorphic***.

Back-arc basin – A basin that develops behind a chain of subduction-related volcanic islands, or island arc, in an ocean basin and is located on the opposite side of the arc from the subducting ocean plate.

Bentonite – a plastic, light-coloured clay composed essentially of montmorillonite, formed by chemical alteration of volcanic ash.

Calc-alkalic – said of igneous rocks in which the weight percentage of silica is between 56 and 61 when the weight percentage of CaO and of K_2O+Na_2O are equal. More generally, igneous rocks containing plagioclase feldspar.

Carbonatite – a carbonate rock of apparent magmatic origin generally associated with ***kimberlites*** and ***alkalic*** rocks. Variously explained as derived from magmatic melt, solid flow, hydrothermal solution and gaseous transfer. May be calcitic or dolomitic.

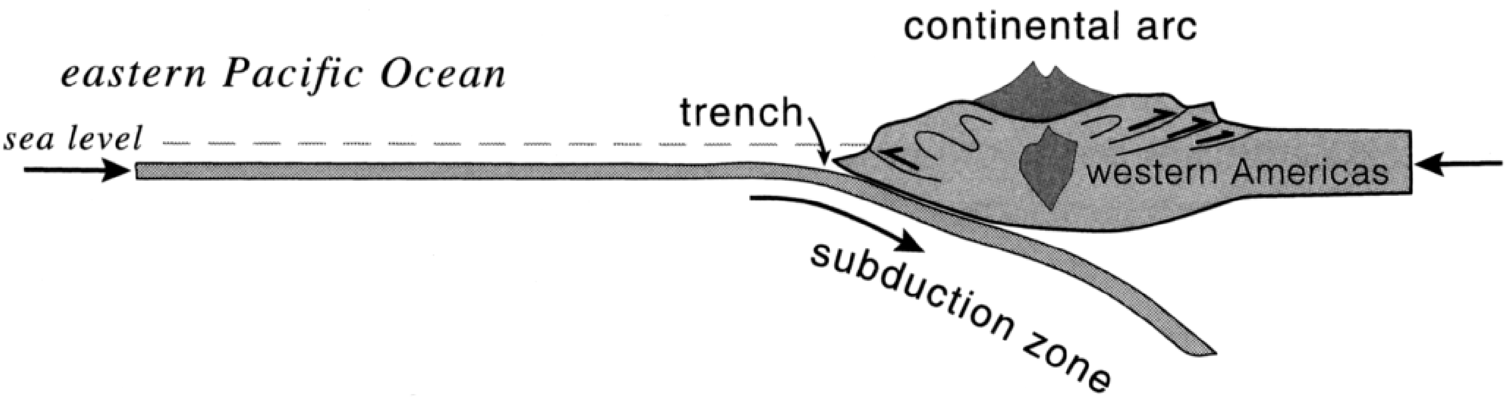
Cataclasis – the process of fracturing and breaking apart of rock particles and crystal components, together with the rotation and mechanical mixing of particles. The product may be incoherent clastic materials, breccia or gouge, or form cohesive rocks: ***cataclasites***

Cataclasite – a metamorphic rock produced by ***cataclasis*** (*i.e.*, a tectonic breccia).

Coeval – of or belonging to the same age or generation.

Collophane – any of the massive, cryptocrystalline, carbonate-bearing varieties of apatite which commonly occurs in phosphatic sediments.

Continental arc – A subduction–related chain of volcanoes formed on a continental margin.



Craton – a stable part of the earth's crust or lithosphere that has not been deformed significantly for many millions, even hundreds of millions of years. Its use is restricted to continents.

Crenulation – small-scale folding that is superimposed on large-scale folding. Crenulations may occur along cleavage planes of a deformed rock. **Crenulation cleavag**e is a planar fabric or foliation in a rock resulting from polyphase deformation (e.g., small scale folding of a pre-existing tectonic fabric).

Culmination – the highest point of a structural feature (*e.g.*, a dome or anticline). Syn: apex.

Cyclothem – a series of beds deposited during a sedimentary cycle of the type that prevailed during the Pennsylvanian Period. Non-marine sediments, commonly including coal, comprise the lower half, while marine sediments typify the upper half. Most cycles are incomplete.

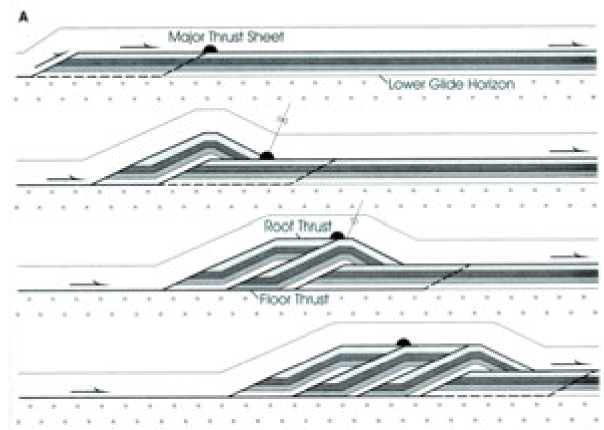
Décollement – detachment structure of strata owing to deformation, resulting in independent styles of deformation in the rocks above and below. Associated with folding and overthrusting.

Diatexite – a type of migmatite where the neosome (or portion of the migmatite newly formed by partial melting) dominates and melt was pervasively distributed throughout.

Diachronous – said of a rock unit that is of varying age in different areas, as occurs when a marine sediment laid down by an advancing sea is noticeably younger in the direction of advancement.

Dysaerobic – applied to a depositional environment with 0.1–1.0 ml of dissolved oxygen per litre of water.

Duplex – a tilted, imbricate set of ***horses***, each of which is separated by a tilted imbricate set of thrust faults.



Ediacaran fauna – an assemblage of distinctive soft-bodied, marine sea-pen or jellyfish-like fossils of latest Neoproterozoic age – between the first recorded occurrences of multi-cellular animals and the so-called 'Cambrian Explosion'. Initially found in the Ediacara Hills of Australia.

Epeiric (also **epicontinental**) **sea –** a sea, either on the continental shelf or in its interior.

Eugeocline – a ***geosyncline*** in which volcanism is associated with clastic sedimentation. Cf: ***miogeosyncline***.

Eustasy – the global change in sea level.

Facies – the aspect, appearance and characteristics of a rock unit, usually reflecting the conditions under which it originated.

Failed rift – extensional basins where continental rifting began, but then failed to continue to the point of break-up. Typically the transition from rifting to spreading develops at a triple junction where three converging rifts meet over a hotspot. Two of these evolve to the point of seafloor spreading, while the third ultimately fails, becoming an ***aulacogen***.

Fiamme – fragments of hot, relatively low viscosity, high porosity volcanic glass which have erupted from a volcano. These fragments accumulate on the ground and flatten via compaction from subsequent deposits of hot volcanic ash layers. Fiamme are associated with pyroclastic flow deposits. The lithified product is a welded tuff. The name fiamme comes from the Italian word for 'flame'.

Flocculation – the process by which many minute suspended particles are held together in clot-like masses or loosely aggregated into small lumps or granules.

Flooding surface – a surface separating younger from older strata, across which there is evidence of an abrupt increase in water depth. The surface may also display evidence of minor submarine erosion. It forms in response to an increase in water depth and typically bounds ***parasequences***.

Flysch – a marine sedimentary facies characterized by a thick sequence of thinly-bedded, poorly fossiliferous, graded **marls** and sandy to calcareous shales and muds rhythmically interbedded with coarser sandstones, conglomerates and greywackes. Cf: ***molasse***.

Forearc basins – sea floor depressions located between subduction zones and their associated volcanic arc.

Foreland – a stable area marginal to a mountain belt toward which rocks were thrust-faulted and folded.

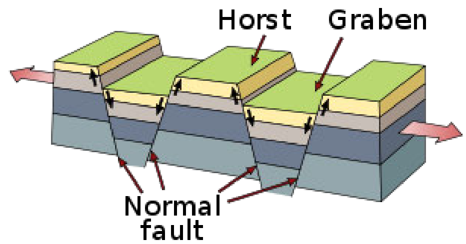
Foreland fold and thrust belt – an ***accretionary wedge*** consisting of ***supracrustal*** rocks that have been scraped off the under-riding North American plate and accreted to the over-riding orogenic collage comprising accreted oceanic ***terranes*** and detached ***pericratonic*** and ***miogeoclinal supracrustal*** rocks. The belt is dominated by southwest-dipping, concave-upward thrust faults that flatten at depth and merge along a regional ***décollement***, close to the underlying Paleoproterozoic basement.

Fusulinid – Any single-celled foraminifer belonging to the suborder Fusulinina, family Fusulinidae, characterized by a multi-chambered calcareous test, commonly resembling the shape of a grain of wheat. Common from Pennsylvanian through Permian time.

Geopetal – pertaining to any rock feature that indicates the relation of top to bottom at the time of formation of the rock (*e.g.*, cross-bedding).

Geosyncline – a large, trough- or basin-like down warping of the earth's crust, in which a thick succession of sedimentary ± volcanic rocks have accumulated. Cf: ***miogeosyncline***.

Graben – an elongate, depressed crustal unit or block bound by normal faults. Cf: ***horst***.



Grand cycle – a distinctive cyclic style of large-scale sedimentation that involves alternations of abrupt-based, recessive lower siliciclastic units and resistant, upper carbonate units. The term grand cycle was proposed by Aitken (1966) for Cambrian strata of the southern Canadian Rocky Mountains where they were interpreted to represent a continental passive margin succession that records a cycle of sea-level rise and fall.

Granulite – silicate rocks, of varied composition, that have experienced granulite-facies metamorphism. Granulites rarely include micas (and thus lack a well-developed schistosity) because of the intense dehydration that occurs at such extreme P-T conditions.

Greywacke – informal name applied to texturally-immature, matrix-rich sandstones comprising poorly-sorted, angular grains of quartz, feldspar, and lithic fragments. Typically a dark grey-green colour (hence the name), greywackes are interpreted as having originated in environments where erosion, transportation, and deposition happened so quickly that minerals and rock fragments do not have sufficient time to break down.

Hogback – any sharp-crested ridge with steep slopes of nearly equal inclination.

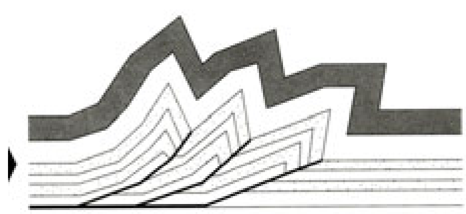
Horse – a displaced rock mass that has been caught between the walls of a fault. Also describes a mass of barren country rock occurring within a vein.

Horst – an elongate, uplifted crustal unit or block bound by normal faults. Cf: ***graben***.

Hypidiomorphic (also **subautomorphic**) **–** said of the texture of igneous or metamorphic rocks characterized by crystals only partly bound by their own rational faces (*i.e.*, subhedral).
Cf: ***automorphic***.

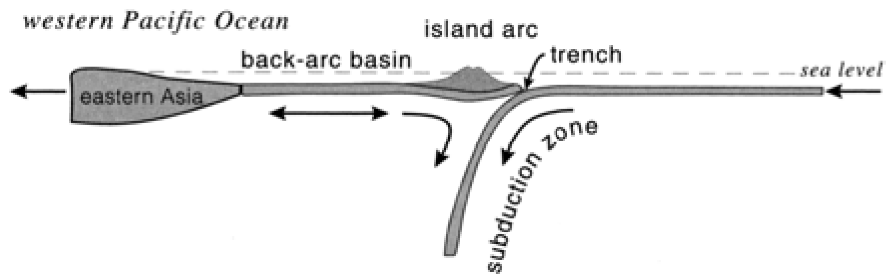
Ignimbrite – rock formed through the widespread deposition and consolidation of ash flows and nuées ardente. The term includes both non-welded (but recrystallized) ash and ***welded tuffs***.

Imbricated fan – marked by a sole thrust, downward into which a swarm of curved triangular thrust slices converge.



(Clay) Ironstone – a hard, sedimentary rock composed of clay (up to 30%), and iron carbonate (siderite) occurring as nodules/concretions or irregular thin beds and usually associated with carbonaceous strata.

Island arc – A chain of volcanic islands within an ocean basin that is arcuate in nature, forms above a subduction zone, and is separate from the closest continent by a ***back-arc basin***.



Isograd – a boundary separating ***metamorphic zones***, marked by the first appearance of the associated index mineral. A line in the field of constant metamorphic grade.

I-type granitoid – derived by partial melting of a mafic mantle-derived igneous source rock – most likely sub-crustal underplate. Contain accessory titanite but little or no muscovite. Cf: ***S-type granitoid***.

Lag –the coarse material left behind on top of a flooding surface after currents have winnowed or washed away the finer material.

Lamprophyre – a group of mafic dike rocks containing phenocrysts, usually of biotite and hornblende, often also of olivine and augite, but not of feldspar. Associated with ***carbonatites***.

Laramide orogeny – a time of deformation, whose several phases extended from the Late Cretaceous through until the end of the Paleocene.

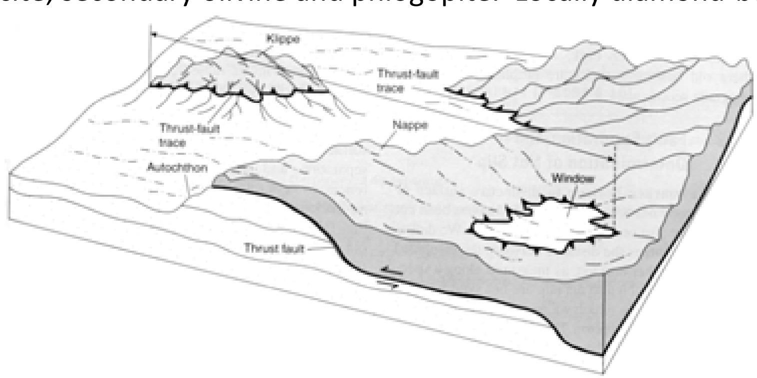
Leucocratic – light-coloured. Applied to igneous rocks containing <30% mafic minerals. Cf: ***melanocratic***.

Leucosome – light-coloured, granitic fraction of a partially melted rock (see ***migmatite***). Cf: ***melanosome***.

Listric fault – curved normal faults in which the fault surface is concave upwards (*i.e.*, its dip decreases with depth).

Kimberlite – an ***alkalic*** peridotite containing abundant phenocrysts of olivine (–>serpentine) and phlogopite in a fine-grained groundmass of calcite, secondary olivine and phlogopite. Locally diamond-bearing.

Klippe – an isolated mass of rock that is an erosional remnant or outlier of a ***nappe***.



Kootenay arc – a north-south trending belt of complexly deformed sedimentary, volcanic and metamorphic rocks extending from northeast Washington State some 400 km to near Revelstoke. The Arc rocks occur as a broadly conformable, thick succession of sediments and volcanics ranging in age from Cambrian in the east to Late Mesozoic in the west. The rocks of the Kootenay Arc have a complex structural history involving at least three phases of folding, complex faulting and major regional thrust fault dislocations.

Mantle plume – An upwelling of hot material from the deep mantle that is generally columnar in form and thought to have a mushroom-shaped head. Its surface manifestation may be called a hot spot.

Marl – a soft carbonate rock composed of a mixture of fine-grained calcite and clay. Syn: argillaceous limestone.

Mélange – a totally disordered body of rock that includes fragments and blocks of all sizes, both exotic and native, embedded in a fragmented and generally sheared matrix. It may be an ***olistostrome*** of sedimentary origin, or a tectonic mélange.

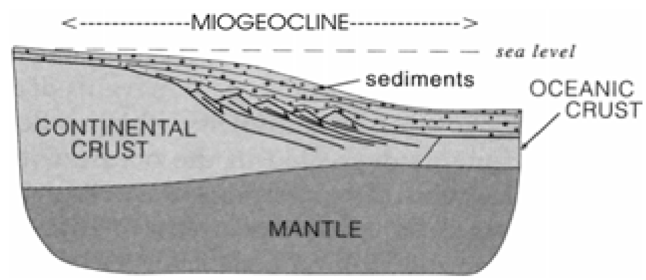
Melanocratic – dark-coloured. Applied to igneous rocks containing >60% mafic minerals. Cf: ***leucocratic***.
Melanosome – dark-coloured, refractory residue resulting from the partial melting of a rock.

Metamorphic zones – a sequence of zones, in metamorphosed pelitic rocks, defined by the first appearance of the associated index mineral and representative of the specific P-T conditions under which the rocks formed. Separated by ***isograds***.

Migmatite (also **diatexite**) **–** literally: 'mixed rock'. A composite silicate rock, pervasively heterogeneous on a meso-megascopic scale formed at the threshold between high-grade metamorphic recrystallization, and complete igneous melting. Typically consists of darker (melanosome - exhibiting features of metamorphic rocks) and lighter (leucosome - looking more plutonic) parts.

Milankovitch cycles – long period fluctuations in the amount of solar radiation reaching the earth due to changes in the direction of the its axis of rotation (precession), the angle between its axis and plane of orbit (obliquity) and orbital eccentricities.

Miogeocline – in reference to the Cordillera, the gently-sloping surface (cratonic platform) upon which Paleozoic and early Mesozoic shallow-marine sediments accumulated to form a tapering apron of strata. More generally, a ***geosyncline*** in which volcanism is not associated with sedimentation. Cf: ***eugeocline***.



MOHO (**Mohorovičić Discontinuity**) **–** the boundary surface that separates the earth's crust from the subjacent mantle.

Molasse – a partly marine, partly continental sedimentary facies consisting of a thick sequence of soft ungraded fossiliferous conglomerates, sandstones, shales and marls characterized by primary sedimentary structures ± coal & carbonate deposits. More clastic and less rhythmic than ***flysch*** facies.

Montmorillonite – a clay mineral of the smectite group. It is the main constituent of the volcanic ash weathering product, ***bentonite***.

Mylonite – a fault rock which is cohesive and characterized by a well-developed schistosity resulting from tectonic reduction of grain size, and commonly containing rounded ***porphyroblasts*** and lithic fragments of similar composition to the minerals in the matrix.

Nappe – a sheet-like, allochthonous rock unit that has moved along a predominantly horizontal surface as a result of thrust faulting, recumbent folding or gravity sliding. See ***klippe***.

Olistostrome (also **olistolith**) **–** a sedimentary deposit consisting of a chaotic mass of intimately mixed heterogeneous materials that accumulate as a semi-fluid body by submarine gravity sliding or slumping of unconsolidated sediments.

Ooid – <2 millimetre, concentrically laminated, spheroidal coated grains (usually composed of calcium carbonate) formed by accretion as wave action or tidal currents sweep grain nuclei back and forth. An oolite is an aggregation of ooids.

Oncoid – 2-10 centimetre, irregularly laminated, spheroidal coated grains formed about a detrital nucleus by accretion of carbonate particles about successive, layered masses of gelatinous sheaths of cyanobacteria. An oncolite is an aggregation of oncoids – essentially a sub-spheroidal stromatolite.

Orthogneiss – a gneiss derived from igneous rocks. Cf: ***paragneiss***

Overlap assemblage – A general term referring to the extension of marine or terrestrial strata beyond underlying rocks whose edges are thereby concealed or overlapped, and to the unconformity that commonly accompanies such a relation.

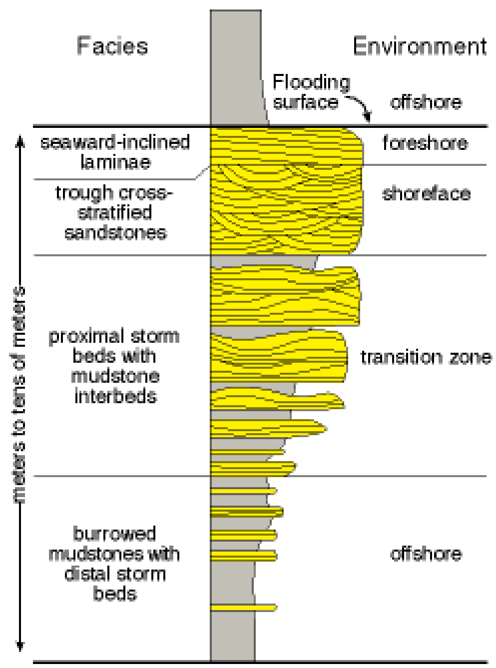
Pangæa (or **Pangea) –** (Greek for 'all lands') the Paleozoic/Mesozoic ***supercontinent*** created when fragments of ***Pannotia*** re-assembled around 300 Ma. The vast ocean that surrounded Pangaea was known as Panthalassa. Pangaea subsequently broke into two parts, Gondwana to the south and Laurasia to the north, approximately 180 Ma.

Pannotia – the Late Neoproterozoic ***supercontinent*** residing in the southern hemisphere that evolved from fragments of ***Rodinia*** around 600 Ma. Sometimes loosely referred to as the 'Vendian supercontinent', Pannotia underwent rifting into four continents: Laurentia, Baltica, Siberia and Gondwana around 540 Ma.

Paragneiss – a gneiss derived from sedimentary rocks. Cf: ***orthogneiss***

Paralic – by the sea, but nonmarine (*e.g.*, lagoonal or littoral). Especially said of intertongued marine and continental deposits laid down on the landward side of a coastline.

Parasequence – a relatively conformable succession of genetically related beds or bedsets bounded by marine flooding surfaces and their correlative surfaces.



Parautochthonous – said of a rock unit that is intermediate in tectonic character between ***autochthonous*** and ***allochthonous***.

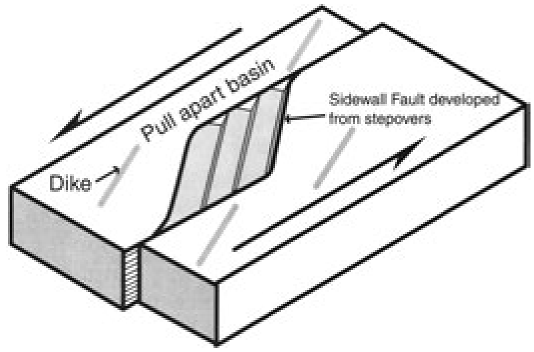
Pelite – a fine-grained aluminous rock formed by the sedimentary deposition of clay and silt. Syn: mudrock.

Peperite – a sedimentary rock formed when hot magma interacts with unconsolidated water-saturated sediment. Typically, the igneous fragments are glassy and show chilled-margins to the sedimentary matrix, distinguishing them from clasts with a sedimentary origin.

Pericratonic – literally: 'around' or 'near' the edge of a ***craton***.

Porphyroblast (also **metacryst**) **–** a large crystal developed in a metamorphic rock by recrystallization.

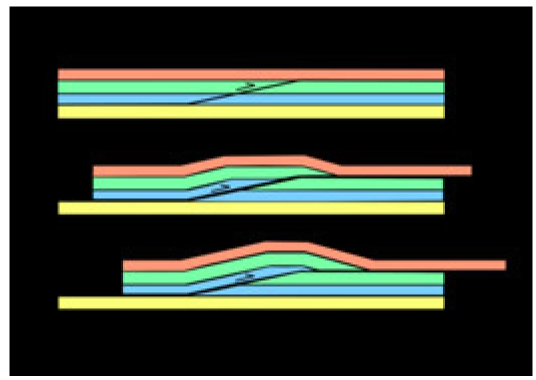
Pull-apart basin – a type of structural basin which develops between two offset segments or at a flexure in a strike-slip or transform fault (*e.g.*, the Dead and the Salton seas)



Pyroclastic – pertaining to fragmental (clastic) rock material formed by a volcanic explosion or ejection from a volcanic vent. More generally termed ***volcaniclastic***.

Pyroclastic flow – a fast-moving (up to 700 km./hr.) gravity current comprising superheated gas and ***tephra*** formed as the result of the collapse of a volcano's eruption column. A nuée ardente ('glowing cloud') is a type of pyroclastic flow.

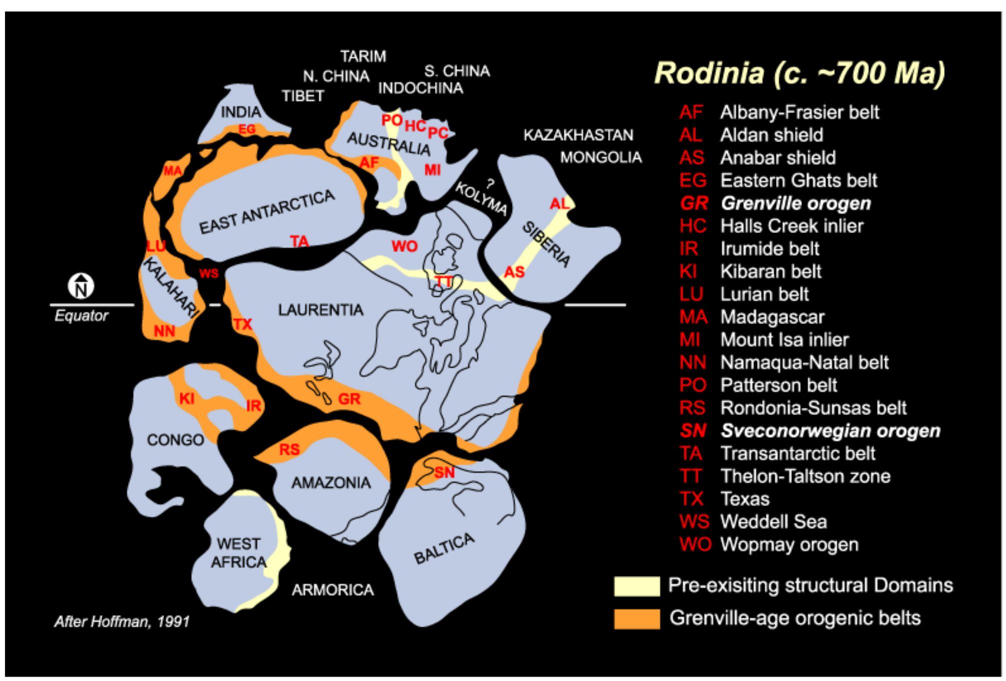
Ramp – the part of a thrust where the fault cuts obliquely across competent beds. The steepened segment of a thrust fault. The near-horizontal segments that typically follow incompetent bedding are known as 'flats'.



Restite – the residual material, comprising predominantly mafic minerals, left at the site of melting during the in place production of granite through intense metamorphism. An important constituent in fractional crystallisation and igneous differentiation processes.

Rift – a valley or trough bounded by normal faults that forms when lithosphere is pulled apart.

Rodinia – the oldest-known ***supercontinent***, which both assembled and broke apart in the Proterozoic. Rodinia is thought to have formed more than a billion years ago and to have embodied most or all of Earth's existing continental crust. It is thought to have broken up into up to eight continents around 750 Ma, which themselves briefly re-assembled into another ***supercontinent*** called ***Pannotia*** during the latest Neoproterozoic.



Sabkha – a supratidal salt flat forming along arid coastlines. Characterized by evaporite deposits.

Salient – literally projecting upwards or protruding. Specifically, a landform that extends outward from its surroundings.

Second sillimanite isograd – a sub-division of the sillimanite ***metamorphic zone***, defining high-temperature metamorphism, above which the index mineral can't coexist with quartz *and* muscovite and the growth of new sillimanite occurs through the reaction:

Muscovite + Quartz (+ Albite) → Sillimanite+ K-feldspar + H_2O

Sequence boundary – A surface that separates older sequences from younger ones, usually the product of a fall in sea level. Commonly an unconformity (indicating subaerial exposure), but in limited cases a correlative conformable surface.

Shoshonite – a basaltic rock, properly a potassic trachyandesite, composed of olivine, augite and plagioclase phenocrysts in a groundmass with calcic plagioclase and sanidine and some dark-coloured volcanic glass.

Stock – a usually discordant, igneous intrusion less than 100 km^2 in surface exposure. A small batholith.
S-type granitoid – produced by partial melting of already peraluminous sedimentary source rocks imprinted by weathering at the earth's surface. Contain andalusite, muscovite and garnet. Cf: ***I-type granitoid***.

Subalkalic – said of igneous rocks that contain no alkali minerals other than feldspars. Cf: ***alkalic***.

Supercontinent – An amalgamation of continents. Formed three times in earth's history: approximately 1 billion years ago (***Rodinia***), ~600 million years ago (***Pannotia***) and 300 million years ago (***Pangaea)***

Supracrustal – literally: 'on top of the crust'.

Suture – a boundary line or line of contact.

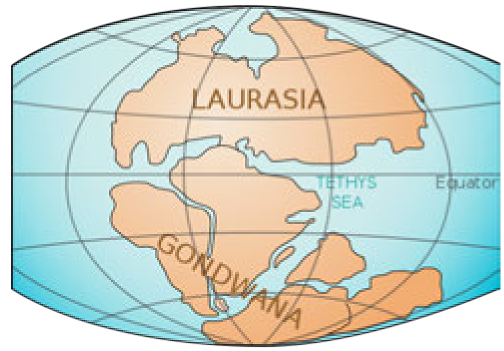
Swelling clays – layer aluminum phyllosilicates belonging to the Smectite group, including beidellite, saponite, nontronite and montmorillonite, that have very high cation exchange capacities and exhibit a common characteristic of hydrational swelling when exposed to water.

Synclinorium – a composite synclinal structure of regional extent with its strata further folded into anticlines and synclines. Cf: ***anticlinorium***.

Terrane – an area possessing unique tectonic assemblages (lithostratigraphic units representing a specific depositional or volcanic setting responding to a tectonic event), which differs from adjacent terranes and is bounded by faults. The term does not have any genetic significance, nor does it imply an origin far removed from adjacent terranes or its present position relative to the craton. Terranes are only defined by their internal assemblage composition. An 'accreted terrane' refers to a terrane that has become attached to a continental margin in the later stage of its tectonic history. Several terranes can become amalgamated by overlap assemblages or 'stitched together' by intrusions and form 'superterranes' before final accretion to a continent. 'Subterranes' are divisions of terranes in which a certain affinity exists, but not necessarily a stratigraphic continuity. '***Pericratonic terranes***' are situated between accreted terranes and ancestral continental margin. They may have stratigraphic affinities to the continental margin or represent metamorphosed sediments that were deposited at or near the continent.

Tephra – a collective term for all volcanic ejecta, including ash, lapilli, blocks and bombs.

Tethys – the sea that lay between Laurasia and Gondwana, the two supercontinents formed by the first split of the larger supercontinent ***Pangaea***. The Tethys Sea can be regarded as the predecessor of today's smaller Mediterranean.



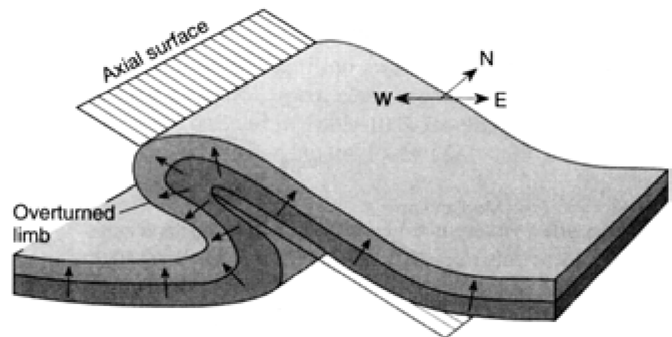
TRIASSIC
200 million years ago

Thermochemical sulphate reduction – the reaction of sulphate minerals (primarily anhydrite) and hydrocarbons (beginning at temperatures of 120-140^{o}C) to form hydrogen sulphide and calcium carbonate ($CH_4 + CaSO_4 \rightarrow CaCO_3 + H_2S + H_2O$).

Tempestite – a shallow-water deposit associated with storms.

Tsunamite (also **tsunamiite**) **–** deposits associated with tsunamis.

Vergence – literally: 'facing'. In asymmetric or overturned folds, the direction that the shorter, more steeply dipping limb of the fold faces. In faults, the direction of tectonic transport (the direction the hanging wall moved).



West verging overturned fold

Volcaniclastic – pertaining to a sedimentary rock comprising volcanic clasts without regard to origin. The term includes but is not limited to pyroclastic rocks (*e.g.*, ***ignimbrite***)

Welded tuff – a glass-rich pyroclastic rock that has been indurated through the welding of glass shards under the combined action of retained heat, the weight of overlying deposits and hot gases. A type of ***ignimbrite***.

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Geologic Time Scale

☠ Mass extinctions

Age	Period	mya	Geologic Events in British Columbia
CENOZOIC	Holocene Epoch		Juan de Fuca Plate continues to subduct under the West Coast.
	Pleistocene Epoch Quaternary	0.01	Last ice age ends about 12,000 years ago. Recently active volcanoes in southwestern BC, such as Mount Garibaldi, belong to the Cascade magmatic arc.
	Pliocene Epoch	2.6	First of several ice ages begins about 2.5 mya. Latest uplift of the Coast Belt begins about 10 mya.
	Miocene Epoch	5.33	Plateau basalt flows across the Intermontane Belt about 10 mya. Cascade magmatic arc starts about 35 mya.
	Oligocene Epoch	23.0	Fraser fault is active 45 to 35 mya.
	Tertiary Eocene Epoch	33.9	Metchosin basalt of Eocene age is accreted to the western margin of Wrangellia (Vancouver Island) between 55 and 40 mya. Beginning 55 mya, the region undergoes stretching; magmatic activity and normal and strike-slip faulting are widespread; much of the Cordillera moves northward for several hundred kilometres along strike-slip faults. Sediment eroded from uplifted Foreland and Coast Belts is deposited, respectively, eastward across the plains and westward into the Insular Belt and Pacific Ocean.
	Paleocene Epoch	55.8	
MESOZOIC	Cretaceous	65.5	Rocks of the Foreland Belt are thrust eastwards onto the North American continent. The Pacific Rim complex is accreted to the western edge of Wrangellia (Vancouver Island) between 86 and 65 mya. Sediments eroded from the rising Coast Mountains accumulate in the Georgia Depression between 90 and 65 mya, forming the Nanaimo group. Wrangellia, carrying a middle Jurassic to early Cretaceous island arc, collides with the continental margin 95 mya, generating the first uplift of the Coast Belt 95 to 85 mya. Granites of the continental arc that forms much of the Coast Belt intrude between 95 and 45 mya. Continental arc forms 105 mya in the Intermontane Belt, extruding the Spences Bridge volcanics. Uplift and erosion of the Omineca Belt and parts of the Intermontane Belt result in deposition of sandstone, shale, and conglomerate to the east (some preserved in the Fernie basin) and west.
	Jurassic	145	Arc forms on eastern Wrangellia 170 to 110 mya. Cordilleran mountain building begins 180 mya as the continent collides with the first of several island arcs; folding, thrust faulting, and metamorphism in the Omineca Belt is associated with accretion of an island arc (Quesnel terrane), the intervening ocean basin (Slide Mountain terrane), and the arc's accretionary complex (Cache Creek terrane).

Geologic Events in British Columbia	mya	Period	Age
About 170 mya the Atlantic Ocean begins to open on the eastern side of the North American Plate. As the supercontinent Pangea breaks up, starting about 200 mya, the new North American Plate advances toward the trench on its western side.		Jurassic	MESOZOIC
The Bonanza island arc begins to form on Wrangellia in latest Triassic time. The Quesnel island arc continues to form offshore of Pangea, separated from the supercontinent by a deepwater basin.	200	Triassic	
The Quesnel island arc begins to form, possibly because the Laurentian continent retreated from the subduction zone on its western margin as Pangea was assembled beginning 300 mya.	251	Permian	PALEOZOIC
	299	Carboniferous	
Devonian granites in the Omineca Belt are the roots of a continental margin arc that formed between 390 and 360 mya, indicating a change from a passive continental margin to a converging margin with a subduction zone.	359	Devonian	
During early Paleozoic time, limestone, mud, and some sandstone are deposited on the Laurentian continental shelf, now in the Foreland Belt; mud, sand, minor limestone, and some basalt are deposited further out to sea on the continental slope, now in the Omineca Belt.	416	Silurian	
	444	Ordovician	
	488	Cambrian	
About 550 mya, deposition of marine sediment begins on the margin of the Laurentian continent, the predecessor of North America, as seawater fills the rift. Sand, shale, and local conglomerate and basalt of the Windermere supergroup accumulate in the continental rift basin between 750 and 570 mya. About 750 mya, the supercontinent Rodinia begins to slowly rift. The Rodinia supercontinent is assembled about 1,000 mya. Between 1.5 and 1.4 billion years ago, the sand, mud, and some basalt of the Belt-Purcell supergroup accumulate in an enormous basin within a continent. Two-billion-year-old rocks in the Monashee Mountains of the Omineca Belt may be the westernmost exposure of rocks from the Canadian Shield.	542	Proterozoic Eon	PRECAMBRIAN
The Canadian Shield, the bedrock nucleus of the North American continent, forms mostly between 3 and 2 billion years ago.	2500	Archean Eon	