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EOCENE EXTENSIONAL TECTONICS AND GEOCHRONOLOGY OF THE SOUTHERN OMINECA BELT, BRITISH COLUMBIA AND WASHINGTON

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Abstract. Eocene extension contributed significantly to the present crustal architecture of the southern Omineca Belt in British Columbia and Washington. High grade gneiss complexes (Valhalla, Okanagan, Kettle-Grand Forks, Monashee, and Priest River) preserve Cretaceous to Eocene deformation superimposed on older structures and have Eocene biotite and muscovite cooling ages. They are juxtaposed by regionally extensive, low- and moderate-angle, ductile and/or brittle normal faults (Valkyr-Slocan Lake, Okanagan Valley, Kettle River, Granby-Greenwood, Columbia River, Standfast Creek (in part), and Newport and Purcell Trench faults) against metamorphosed rocks with a late Paleozoic to Middle Jurassic compressional tectonic history. Some upper plate rocks are overlain by Middle Eocene strata. Upper plate rocks preserve middle Cretaceous and older mica cooling dates indicating that they were less than 300°C in the Eocene, in contrast to lower plate rocks. The complexes have features in common with metamorphic core complexes of extensional origin elsewhere. U-Pb zircon and monazite dates on mylonitic granitic rocks in the footwalls of the Okanagan and Valkyr-Slocan Lake shear zones prove that a significant part of their ductile fabric is related to displacement on Eocene extensional faults. On the eastern side of the Monashee complex, 55 Ma U-Pb zircon and circa 54 Ma Rb-Sr synkinematic muscovite ages demonstrate that the ductile-brittle Columbia River fault is a predominantly Early Eocene normal fault. Contrary to previous interpretations, the circa 162 Ma Galena Bay stock does not intrude footwall mylonites, and therefore the interpretation that at least some of the mylonites are related to Eocene extension is permissible. The distribution of Eocene cooling ages implies that part of the Standfast Creek fault on the eastern boundary of the Clachnacudainn complex is a ductile (+/-brittle) normal fault. Analogous interpretations are made for the Kettle-Grand Forks and Priest River complexes where similar isotopic cooling age patterns prevail. Normal fault systems which bound the metamorphic complexes are fundamental crustal breaks, with displacements of 10-20 and in some cases 40 km, and probably accommodated about 30% extension across the 300 km width of the southern Omineca Belt. Most of the east dipping fault systems were active mainly between 58 and 52 Ma, in contrast to west dipping systems which are 52 - 45 Ma old, although both systems may have had some younger brittle displacement. Comparison of east-west cross sections with palinspastic restorations implies that the crust was more than 50 km thick prior to extension, that the high grade core complexes were not exposed to erosion prior to the Eocene, and that they were

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tectonically denuded and exhumed on Eocene normal fault systems. This extensional model is consistent with known geology, helps to explain several enigmatic geologic relationships, and has important implications for interpreting the pre-Eocene, compressional deformation in the region.

INTRODUCTION

The Omineca Belt is the eastern metamorphic core zone of the Cordilleran orogen. In southern British Columbia it comprises Early Proterozoic basement gneiss, deformed and metamorphosed stratified rocks of the North American continental margin sequence (including high-grade rocks termed the Shuswap metamorphic complex), allochthonous rocks of Intermontane superterrane, and Paleozoic, Early and Middle Jurassic, Late Cretaceous, and Paleogene granitic rocks (Plate 1). It is characterized by widespread crustal extension which is superimposed on preexisting crustal compression. Metamorphic core complexes in the sense of Coney [1980] characterize much of the region, although core complexes do not encompass all exposures of high-grade metamorphic rocks. These two contrasting tectonic regimes - compression and extension - have produced very complicated geologic relationships. Understanding the style and magnitude of the superimposed extensional deformation is crucial to determining the protracted tectonic history.

A number of studies making reference to generalized models have suggested significant Eocene crustal extension for southern British Columbia and northern Washington [Price, 1979; Price, 1981a; Coney, 1980; Ewing, 1981; Armstrong, 1982; Harms, 1982]. The evidence for extension includes Eocene normal faults which juxtapose Eocene and other strata of low metamorphic grade against various gneisses of the Shuswap metamorphic complex (Plate 1), and the regional occurrence of Eocene K-Ar mica dates which characterize the majority of exposures of high-grade core complexes and imply rapid denudation [Price et al., 1981; Ewing, 1981] (Figure 1). Previous studies, however, have not provided enough structural or geochronological evidence to convince the Cordilleran geologic community of the importance of extension. The main obstacle has been the view that extension features are brittle structures of small displacement, unrelated to any of the ductilely deformed rocks which characterize the Shuswap complex.

Core complexes in the western United States have, by and large, been regarded as originating from crustal extension [Coney, 1980; Crittenden, 1980; Armstrong, 1982], and a number of Canadian studies have concurred with this view [Price, 1979, 1981a; Harms, 1982; Ewing, 1981; Mathews, 1983]. Other studies have invoked an Eocene "thermal event" to explain the patterns of isotopic dates on mica and have attributed ductile deformation in core complexes to older compressional deformation [Ross, 1981; Read and Brown, 1981; Brown and Read, 1983; Brown et al., 1986; Okulitch, 1984; Rhodes and Hyndman, 1984]. Because evidence of Middle Jurassic orogeny is clearcut and undeniable in many parts of the hanging walls of the main normal faults [Wheeler, 1970; Armstrong, 1982; Archibald et al., 1983], many studies have assumed a predominantly Jurassic age for formation of core complexes [Brown and Read, 1983; Okulitch, 1984; Brown et al., 1986]. Coney and Harms [1984], Burchfiel and Royden [1985], and Brown and Journeay [1987] have offered models whereby extension is related spatially, dynamically, or temporally to significant crustal thickening.

In this paper we present data in support of a model [see Price, 1981a; Harms, 1982; Ewing, 1981; Parrish and Carr, 1986] in which Eocene extension is in part ductile, of large magnitude, and the main cause of the present crustal architecture. With this view in mind, the paper offers a comprehensive tectonic reinterpretation and synthesis of southern Omineca Belt.

COMPRESSIONAL TECTONICS OF THE EASTERN CORDILLERA

Before launching into the evidence for extension in the southern Omineca Belt, it is prudent to summarize the main elements of Mesozoic and Paleocene compression and accretion which substantially thickened and shortened the Eastern Cordillera prior to Eocene extension and crustal thinning. In the Early to Middle Jurassic an allochthonous terrane termed the Intermontane superterrane [Price et al., 1985] collided with and accreted to both the pericratonic Kootenay Terrane and the continental margin of the western Canadian craton [Monger et al., 1982; Brown et al., 1986]. This event has been recognized the full length of British Columbia and involved more than 100 km of tectonic overlap of eugeosynclinal and disrupted ophiolitic rocks onto the continental margin. These rocks may represent both distal continental margin rocks and part of a late Paleozoic-early Mesozoic back arc basin [Monger, 1977; Klepacki, 1986]. Further shortening resulted in metamorphism, back-folding, and west-directed thrusting of continental margin rocks over Intermontane superterrane near the west edge of the Omineca

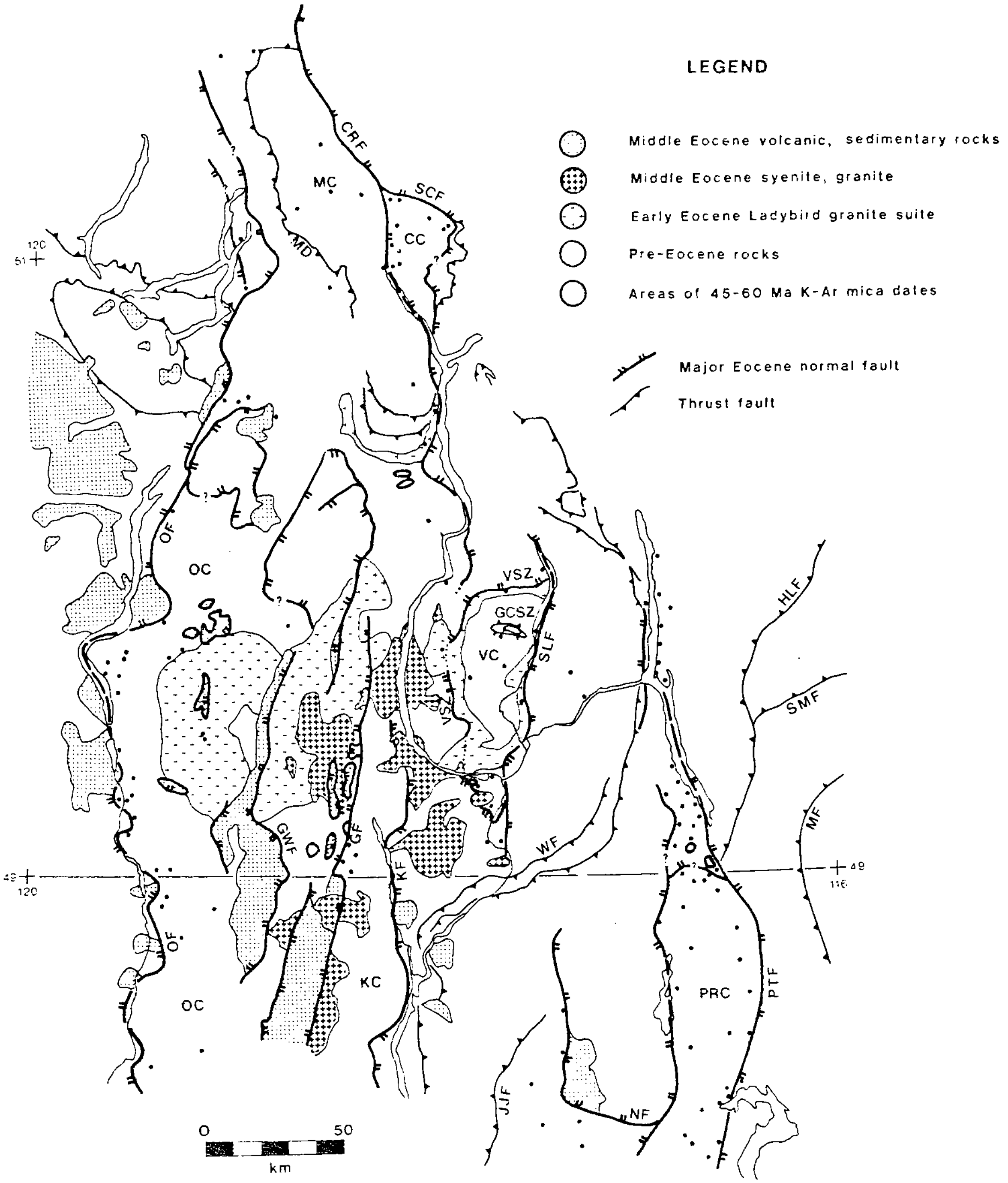


Fig. 1. Tectonic map of southern Omineca Belt, simplified from Plate 1. Features shown with patterns are the Early Eocene Ladybird granite suite, Middle Eocene syenite and granite, Middle Eocene volcanic and sedimentary rocks, and areas of older rocks characterized by K-Ar mica dates of 45-60 Ma, dated localities being shown by dots. In the hanging walls of the major Eocene normal faults, K-Ar dates are generally older than 100 Ma (dated localities are not shown but in general are at least as numerous as in the footwalls). Major thrust faults within Monashee and Valhalla complexes are the Monashee decollement and Gwillim Creek shear zones, respectively. Also shown are major thrust faults (mostly Middle Jurassic to mid-Cretaceous in age) within Kootenay Arc and Shuswap Lake areas, outside of the core complexes. This later belt of arcuate discontinuous structures involves west verging backfolds and thrusts which overrode rocks of Quesnel terrane to the west. See Plate 1 for names of complexes and faults and for geographic features. K-Ar mica and Rb-Sr biotite data are from Wanless et al. [1968, 1978, 1979], Stevens et al. [1982a, b], Archibald et al. [1983, 1984], Medford [1975], Miller and Engels [1975], Birnie [1976], Carr et al. [1987], Geological Survey of Canada (unpublished data, 1982 to 1986) and R. L. Armstrong (unpublished data file, 1984).

Belt in central and northern British Columbia and within the Kootenay Arc of southern British Columbia [Glover, 1978; Archibald et al., 1983; Gabrielse, 1985; Brown et al., 1986; Price, 1986].

Renewed crustal shortening between Late Jurassic and Paleocene time resulted in progressive development of the foreland fold and thrust belt of the Canadian Rocky Mountains. It is characterized by listric foreland stepping thrusts involving miogeoclinal and platformal Paleozoic and Mesozoic rocks and deformation of the Cretaceous to Paleocene foredeep [Price and Mountjoy, 1970]. Farther west in the core zone of the orogen, high grade metamorphism and development of easterly verging structures affected Precambrian crystalline basement and overlying metasedimentary rocks which are presently exposed in the Omineca Belt (for reviews see Brown et al. [1986] and Journeay [1986]). Magmatism was episodic with suites of Early to Middle Jurassic, middle to Late Cretaceous, and Paleocene to Mid-Eocene age with a prominant lull in the Early Cretaceous and severly diminished intensity in latest Cretaceous to Early Paleocene time [Armstrong, in press].

Convergence was also accompanied by Late Cretaceous to Eocene dextral north-south strike slip faulting [Gabrielse, 1985; Price and Carmichael, 1986]. The period of compression and/or transpression apparently ended rather abruptly over a very large region at the close of Paleocene time because Eocene strata in southern British Columbia are associated with extensional deformation that is also linked, further north, to dextral north-south strike-slip faulting [Price, 1979, 1981a; Price and Carmichael, 1986]. Paleocene strata are the youngest rocks involved in the foredeep and fold and thrust belt.

EXTENSIONAL TECTONICS: KEY RECENT WORK

Valhalla Complex

The Valhalla complex [Reesor, 1965; Parrish et al., 1985b; Carr, 1985, 1986; Carr et al., 1987] is an elongate north-trending structural and metamorphic culmination east of Lower Arrow Lake bounded on all sides by outward dipping Eocene faults (Plate 1, Figure 2). The eastern bounding fault is a north trending, east dipping normal fault, the Slocan Lake fault, which juxtaposes the circa 169 Ma Nelson batholith and early Mesozoic eugeosynclinal rocks against the complex. These upper plate rocks preserve mainly Jurassic potassium-argon mineral dates [Nguyen et al., 1968; Archibald et al., 1983; Fyles, 1984; Harrison, 1985; R.L.Armstrong, unpublished data file, 1984] indicating that they were less than about 300°C throughout the Late Cretaceous and Paleogene. The Valhalla complex contains uniformly high grade metamorphic rocks of uncertain age and several middle Cretaceous to Paleogene orthogneiss bodies disposed in arched sheets [Parrish, 1984; Parrish et al., 1985a, b].

Polydeformed sillimanite-orthoclase paragneiss occurs in three sheets (Figures 2 and 3). The lower two paragneiss sheets are exposed in Gwillim Creek as windows at the lowest exposed structural levels. These two sheets are structurally overlain and in sheared contact in the Gwillim Creek shear zones with circa 100 Ma orthogneiss [Parrish et al., 1985b; Carr et al., 1987]. These ductile shear zones are post-80 Ma east directed, high-grade shears of probable thrust type and large displacement [Parrish et al., 1985b, 1987a].

Overlying these rocks are two granitic sheets of Paleogene age; the 62+/-1 Ma Airy quartz monzonite and the 58+/-1 Ma Ladybird granite (U-Pb zircon ages, see below). They are variably deformed [Carr et al., 1987], but particularly strongly in the footwall of the Slocan Lake fault zone. Posttectonic Ladybird granite intrusions are also common in the southwest part of Valhalla complex (Figures 2 and 3). The ductile Valkyr shear zone forms the roof of the complex [Carr et al., 1987] and juxtaposes Middle Jurassic Nelson batholith (about 169+/-2 Ma, R. Parrish, unpublished data, 1986) and metasedimentary rocks of the Mount Roberts formation and Nemo Lakes belt [Parrish, 1981] against and over the Ladybird granite (Figures 2 and 3). The amphibolite grade Valkyr shear zone is about 2 km thick, extends around the entire complex, and is east directed (hanging wall to the east sense of shear [Carr, 1986; Carr et al., 1987]). The Valkyr shear zone is in part intruded by late phases of Ladybird granite, but it is deformed by and generally merges with the slightly younger and more brittle Slocan Lake fault which bounds the complex on the east and has late stage greenschist facies mylonite in its immediate footwall.

The Eocene age of displacement on the Valkyr shear zone and the Slocan Lake fault zone is demonstrated by extensive U-Pb and Rb-Sr dating on Eocene granitic rock units involved in and cross-cutting the structure. The geochronological data are presented in detail in Figure 4 and Tables 1 and 2. Lithological descriptions and sample localities are outlined in the appendix. The Ladybird granite, the uppermost unit of the complex, is a 0.5 to 3 km-thick variably foliated sheet of biotite

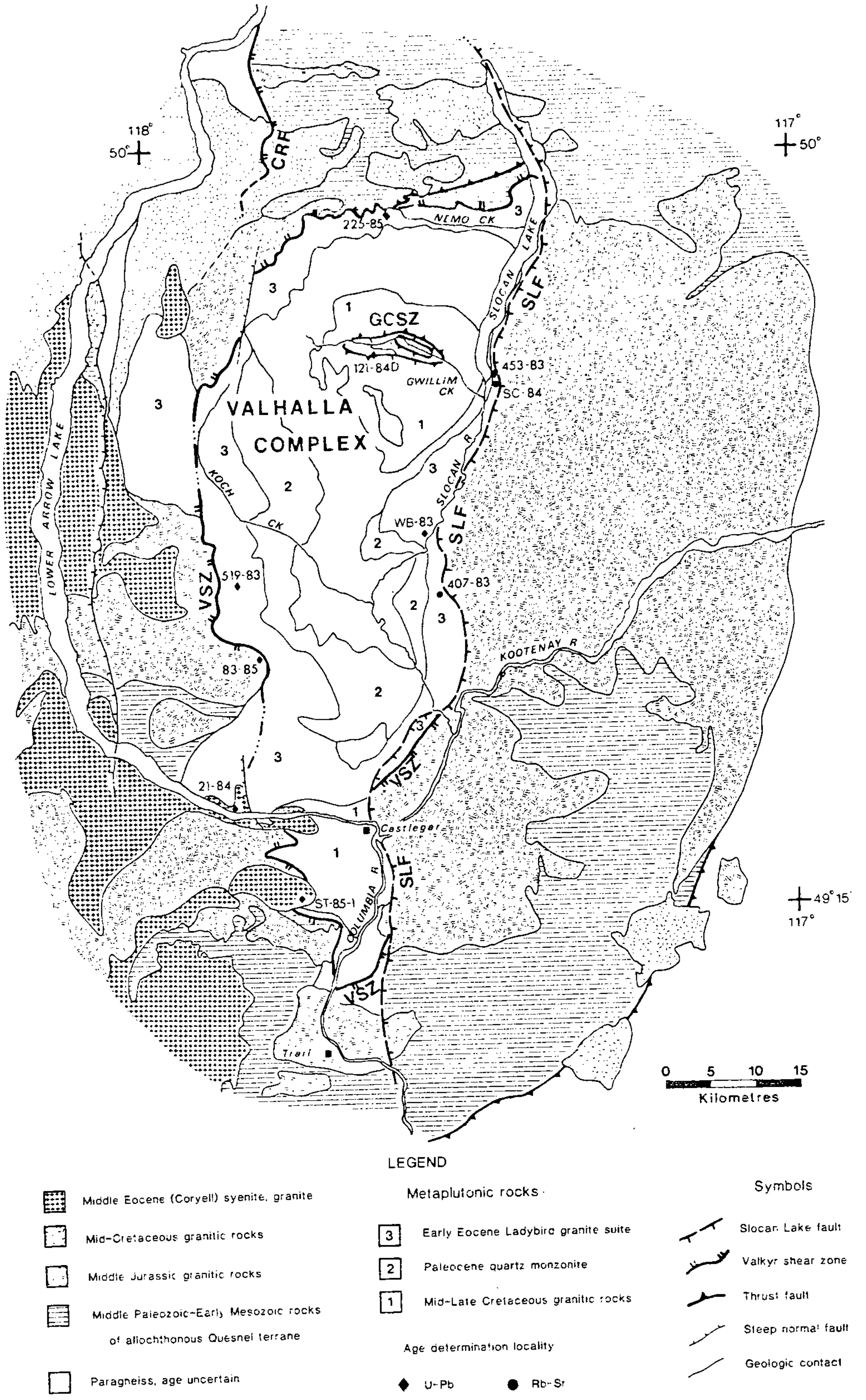


Fig. 2. Geological map of Valhalla complex, modified from Carr et al. [1987] including additional mapping adjacent to Lower Arrow Lake west of Valhalla complex. The location of the Valkyr shear zone south of Castlegar corresponds to a high strain zone of Halwas and Simony [1986]. Localities of U-Pb and Rb-Sr age determinations referred to in the text, in Figure 4, and in Tables 1 and 2 are indicated. SLF, Slocan Lake fault; VSZ, Valkyr shear zone; GCSZ, Gwillim Creek shear zones; CRF, Columbia River fault.

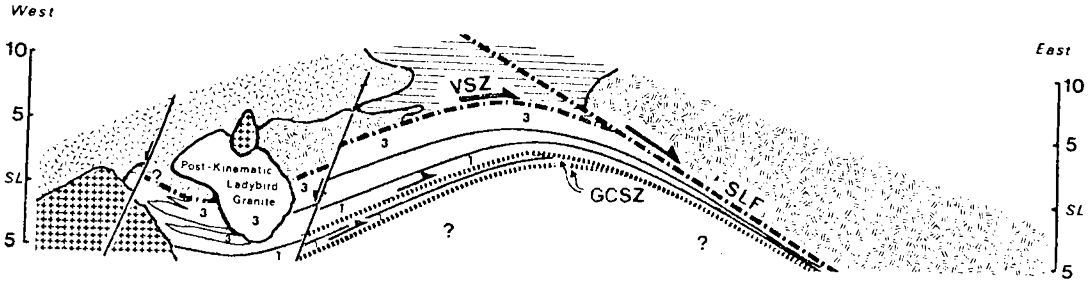


Fig. 3. East-west oriented cross section across Valhalla complex in the vicinity of Gwillim Creek and the south end of Slocan Lake (see Figure 2). Note the truncation of Valkyr shear zone by the slightly younger Slocan Lake fault. Note that both Slocan Lake fault (SLF) and Valkyr shear zone (VSZ) are interpreted as having normal displacement but that the Gwillim Creek shear zones are considered to be somewhat older thrust faults (see text for discussion). SL and numbers on scale bar refer to sea level and kilometers, respectively. No vertical exaggeration.

leucocratic granite. U-Pb dates on zircon and monazite from this unit at four different sites (shown on Figure 2) indicate a range of age from 56.5 to 59 Ma. These ages are deduced from the lower intercepts of arrays of points for each sample on a concordia diagram (Figure 4). Such arrays are the result of analyzing zircons with variable mixtures of older zircon as inherited cores with younger magmatic overgrowths. There is considerable scatter in analyses from this suite of rocks, both on single samples and on the suite as a whole. The field of analyses for Ladybird granite defines a wedge-shaped area beneath concordia which converges on a lower intercept of about 58 +/- 1 Ma. Scatter in the analyses is probably produced by variable ages of cores with variable degrees of Pb loss within the older cores. It is unlikely that Pb loss postdating the Eocene crystallization of the zircons has been significant. The older inherited zircons are of Precambrian age, ranging from perhaps 1000 to 2500 Ma. Monazite ages from 57 to 55 Ma are interpreted to indicate the time of cooling below the monazite closure temperature of approximately 650°-700°C [Parrish and Roddick, 1985; R. Parrish, unpublished data, 1987]. Monazite from sample 519-83 on the western side of the complex is about 51.5 Ma, suggesting a local(?) thermal disturbance possibly related to emplacement of nearby circa 52 Ma Coryell syenitic rocks. Displacement on the Valkyr shear zone closely followed or was synchronous with emplacement of Ladybird granitic rocks. Slightly younger late kinematic to postkinematic granite and pegmatite of the Ladybird intrusive suite intrude deformed rocks of the Valkyr shear zone and have a U-Pb zircon lower intercept age of 56.5 +/- 1.5 Ma (sample 83-85, Figures 2 and 4). Together these data allow a maximum of about 4 Ma for the episode of ductile movement on the Valkyr shear zone.

In the footwall of the east directed Slocan Lake fault, mylonites in the Ladybird granite contain muscovite and minor chlorite indicative of recrystallization in lower greenschist facies. In a number of places these mylonites are characterized by metamorphic muscovite porphyroblasts. The muscovite is not present in the biotite-bearing protolith and is unique to the fault zone. Muscovite occurs as porphyroblasts that grew and were subsequently deformed during mylonitization in subbiotite grade conditions (less than 450°C). These deformed micas have been dated by Rb-Sr methods as 54.5+/-1 Ma (calculated with coexisting K-feldspar, Table 2a, localities shown in Figure 2). Since the closure temperature of Sr diffusion in muscovite is about 500°C [Wagner et al., 1977; Parrish and Roddick, 1985] and because the fault zone muscovite formed at temperatures less than 450°C their Rb-Sr age of 54.5 Ma is the age of late greenschist mylonitization. K-Ar ages on the same muscovite porphyroclasts are 47 to 49 Ma (Table 2a), and these are interpreted as the age of cooling below about 350°C, the closure temperature of Ar in muscovite [Wagner et al., 1977].

Late in the displacement history of the Valkyr shear zone/Slocan Lake fault system, Eocene Coryell syenite and granite of the Sheppard intrusions [Little, 1960, 1982; Halwas and Simony, 1986] intruded the region. Stocks of both of these intrusive suites crosscut the Valkyr shear zone and related fabrics; these two suites of rock have been dated by U-Pb zircon methods as 51.5+/-0.5 Ma and 47.2+/-0.5 Ma, respectively (Figures 2 and 4 and Table 1a). The U-Pb analyses for these two rocks are either concordant (sample 21-84, Coryell syenite) or

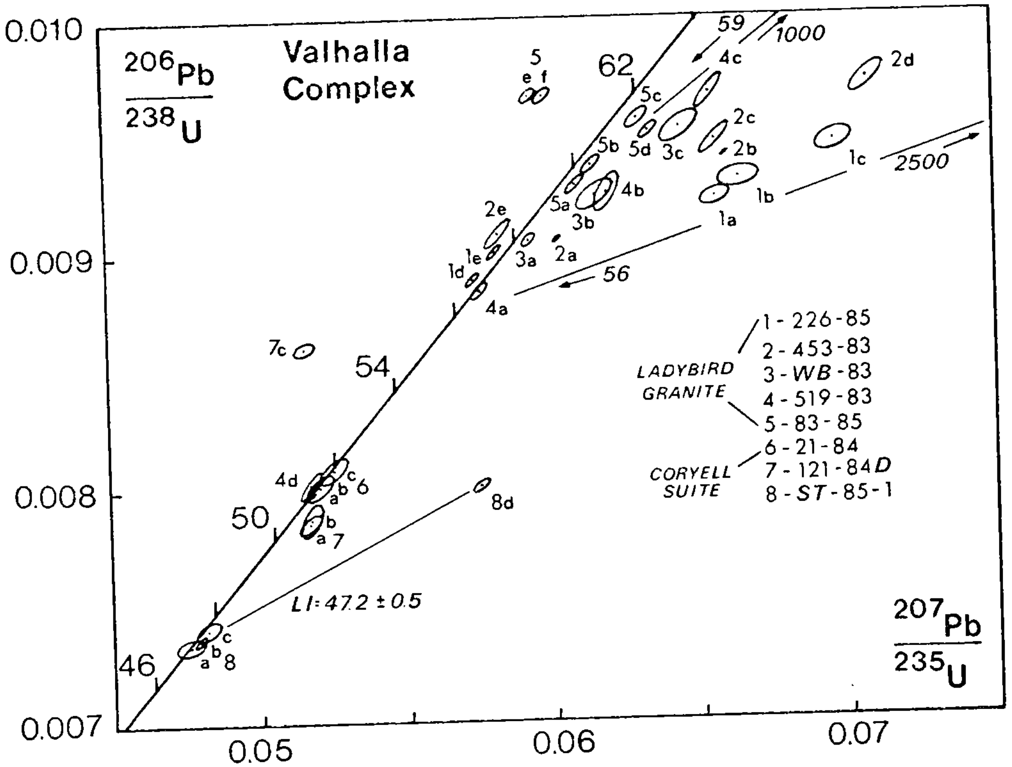


Fig. 4. U-Pb concordia diagram showing zircon and monazite analyses of Eocene granitic and syenitic rocks of Valhalla complex. All monazite analyses plot slightly to moderately above concordia for reasons discussed in the appendix and by Scharer [1984], whereas all zircons fall on or below concordia. The monazite ages accepted as correct are the $^{207}Pb/^{235}U$ ages. Two lines are drawn in the upper part of the figure to the right of concordia; these lines connect 59 and 1000 Ma (upper) and 56 and 2500 Ma (lower), and they bound the spectrum of analyses of Ladybird granite. An age of about 58 +/- 1 Ma can be inferred from this pattern as well as arrays of individual points from individual samples. The scatter is related to variation in age of inheritance and variable lead loss of inherited zircons prior to or during growth of magmatic crystals. No precise age of inheritance can be estimated, although it appears to consist predominantly of inherited crystals 1.5 to 2.5 Ga old. Sample 8 (ST-85-1) has an age of 47.2 +/- 0.5 Ma; Coryell syenite (sample 6, 21-84) is 51.5 +/- 0.5 Ma old; and all monazite $^{207}Pb/^{235}U$ ages are younger than zircon ages from the same sample. Sample localities, sample numbers, and analysis numbers refer to corresponding numbers in Figure 2 and Table 1a. All error ellipses are shown at the 95% confidence level.

disposed on a linear array with a well-defined lower intercept (sample ST-85-1, Sheppard granitic intrusions). In addition, an aplite which crosscuts the upper of the two Gwillim Creek shear zones has slightly discordant zircons and monazite which imply an age of 50-51 Ma (sample 121-84D). These geochronologic data constrain the timing of a rapidly evolving continuum of east directed shearing events on first the Valkyr shear zone and later the Slocan Lake fault, spanning no more than 5-6 Ma [Carr et al., 1987].

The Early Eocene Valkyr shear zone and Slocan Lake fault are interpreted as a ductile and ductile-brittle low-angle extensional fault system [Parrish and Carr, 1986; Carr et al., 1987]. The Slocan Lake fault is pinned at both ends and is an eastward rooting normal fault [Parrish et al., 1985a; Corbett and Simony, 1984]. The Valkyr shear zone was inferred to be a related eastward rooting zone of normal displacement by Carr et al. [1987], who also suggested that arching of the Valhalla complex deactivated the western flank of the Valkyr shear zone while still structurally beneath the brittle-ductile transition, whereas movement continued on the east side of the complex on the ductile-brittle Slocan Lake fault. This normal

TABLE 1a. U-Pb Zircon and Monazite Data for Valhalla Complex

Analysis number, size[a]	wt. mg	U, ppm	Pb,[b] ppm	$\frac{^{206}\mathrm{Pb}}{^{204}\mathrm{Pb}}$[c]	$\mathrm{Pb_c}$,[d] pg	^{208}Pb,[b] %	$\frac{^{206}\mathrm{Pb}}{^{238}\mathrm{U}}$+/-1SEM%[e]	$\frac{^{207}\mathrm{Pb}}{^{235}\mathrm{U}}$+/-1SEM%[e]	$\frac{^{207}\mathrm{Pb}}{^{206}\mathrm{Pb}}$+/-1SEM%[e]	$\frac{^{207}\mathrm{Pb}}{^{206}\mathrm{Pb}}$ age, error,[f] Ma
225-85, Ladybird Granite, Upper Nemo Creek; Weakly Foliated, Late Synkinematic to Postkinematic										
1a -74+62	0.339	1374	12.56	499	562	8.7	0.009225 (0.21)	0.06560 (0.38)	0.05157 (0.33)	266.5 (7.5)
1b -62	0.187	1625	14.62	337	559	6.4	0.009308 (0.24)	0.06640 (0.52)	0.05174 (0.49)	273.8 (11.3)
1c -105+74	0.697	1206	11.22	430	1216	7.9	0.009460 (0.26)	0.06962 (0.44)	0.05337 (0.39)	344.7 (8.8)
1d monazite	0.233	6160	201.4	1881	430	75.4	0.008882 (0.17)	0.05732 (0.21)	0.04681 (0.11)	39.4 (2.6)
1e monazite	0.263	4599	178.9	2205	313	79.0	0.008999 (0.18)	0.05807 (0.21)	0.04680 (0.09)	39.0 (2.2)
453-83, Ladybird Granite, 1 km East of South End of Slocan Lake, Strongly Foliated C-S Mylonite										
2a -149+105	0.149	970	8.278	5037	16	4.5	0.009051 (0.08)	0.06021 (0.11)	0.04825 (0.07)	111.6 (1.6)
2b -105+74	0.278	1089	9.731	5263	34	4.9	0.009406 (0.06)	0.06595 (0.10)	0.05085 (0.05)	234.1 (1.1)
2c +149	4.58	786	7.23	3390	604	7.1	0.009470 (0.35)	0.06564 (0.40)	0.05028 (0.15)	207.0 (4.9)
2d -149+105	1.98	897	8.38	1691	615	5.8	0.009723 (0.35)	0.07080 (0.40)	0.05281 (0.15)	320.7 (3.3)
2e monazite	1.644	3715	157.4	1906	1768	80.6	0.009077 (0.35)	0.05823 (0.40)	0.04652 (0.15)	24.8 (3.2)
WB-83, Ladybird Granite, 18 km South of Slocan Lake on Slocan River, Chloritic Mylonite										
3a -74+62	0.175	2291	33.39	2835	81	5.84	0.009049 (0.15)	0.05926 (0.19)	0.04749 (0.15)	74.1 (3.5)
3b -74+62	0.71	1409	12.91	719	781	8.2	0.009239 (0.35)	0.06156 (0.40)	0.04832 (0.15)	115.2 (3.3)
3c -105+74	0.156	929	8.62	745	120	7.4	0.009525 (0.35)	0.06446 (0.40)	0.04908 (0.15)	151.9 (3.1)
519-83, Ladybird Granite, 30 km Northwest of Castlegar, Weakly Foliated										
4a -62	0.202	1228	11.23	1499	93	13.0	0.008836 (0.21)			
4b -74+62	0.359	952	8.994	572	360	11.6	0.009250 (0.35)	0.05757 (0.24)	0.04725 (0.15)	61.8 (3.5)
4c -105+74	1.785	816	8.027	2122	400	11.3	0.009673 (0.35)	0.06196 (0.40)	0.04858 (0.15)	127.8 (3.3)
4d monazite	2.868	1772	138.2	986	2506	90.7	0.008017 (0.35)	0.06547 (0.40)	0.04909 (0.15)	152.2 (3.3)
								0.05174 (0.40)	0.04681 (0.15)	39.5 (3.6)
83-85, Pegmatite of Ladybird Granite Suite, Intrudes Valkyr Shear Zone, 23 km Northwest of Castlegar										
5a -149+105c	0.164	8490	73.10	1464	562	2.9	0.009282 (0.22)	0.06089 (0.26)	0.04758 (0.13)	78.2 (3.0)
5b -74+62c	0.200	8139	71.51	1252	777	4.0	0.009366 (0.21)	0.06144 (0.26)	0.04758 (0.15)	78.3 (3.5)
5c -149+105c	0.249	10338	93.03	975	1618	4.3	0.009563 (0.23)	0.06303 (0.30)	0.04780 (0.20)	89.5 (4.6)
5d -74+62c	0.169	3753	33.47	1236	311	3.9	0.009510 (0.19)	0.06341 (0.24)	0.04836 (0.14)	116.9 (3.2)
5e monazite	0.155	2524	239.0	1137	212	90.8	0.009663 (0.16)	0.05936 (0.23)	0.04455 (0.16)	<0
5f monazite	0.153	3045	290.3	1109	260	90.8	0.009663 (0.17)	0.05983 (0.23)	0.04491 (0.17)	<0
21-84, Coryell Syenite, 15 km West of Castlegar on Lower Arrow Lake										
6a -149+105	0.568	433	3.645	1332	94	14.7	0.007973 (0.08)	0.05172 (0.16)	0.04705 (0.11)	51.6 (2.6)
6b -105+74	2.25	454	3.777	887	556	13.3	0.008007 (0.35)	0.05206 (0.40)	0.04716 (0.15)	57.2 (3.6)
6c +149	3.31	475	4.099	922	830	15.6	0.008079 (0.35)	0.05254 (0.40)	0.04717 (0.15)	57.7 (3.7)
121-84D, Aplite Cross-Cutting Upper Gwillim Creek Shear Zone, 12 km West of Slocan Lake, Gwillim Creek Valley										
7a +105c	0.703	7615	56.1	728	3723	4.0	0.007859 (0.27)	0.05171 (0.37)	0.04778 (0.26)	88.1 (6.2)
7b -74+62c	1.36	7381	54.4	440	10784	3.9	0.007868 (0.35)	0.05177 (0.45)	0.04772 (0.25)	85.5 (5.8)
7c monazite	0.274	1541	137.7	652	361	91.3	0.008597 (0.17)	0.05162 (0.34)	0.04354 (0.30)	<0

ST-85-1, Coryell-Sheppard Intrusions, Hornblende-Biotite Granite 11 km SW of Castlegar, Intrudes Valkyr Shear Zone									
8a +149	0.345	1637	13.96	1134	255	15.0	0.008007 (0.18)	0.05748 (0.24)	0.05207 (0.16)	288.3 (3.5)
8b -62	0.119	2602	20.63	1457	99	16.3	0.007361 (0.17)	0.04739 (0.21)	0.04719 (0.12)	58.7 (2.9)
8c +149a	0.483	2282	17.52	556	954	13.1	0.007405 (0.27)	0.04817 (0.43)	0.04718 (0.35)	58.5 (8.4)
8d +149a	0.346	2257	18.28	431	873	18.3	0.007337 (0.24)	0.04756 (0.50)	0.04701 (0.46)	49.8 (11.6)

See appendix for UTM coordinates of sample locations, and Figure 2 for locations on map.

[a] Numbers (e.g., 10c) refer to Figures 5 and 6; sizes (e.g., +105) refer to aspect of zircons in microns; letters attached to sizes: a, abraded, e, equant, l, long and prismatic, c, cloudy; fractions otherwise unlabelled are generally clear to slightly cloudy crystals which show rare faint evidence of cores.

[b] Radiogenic Pb.

[c] Measured ratio, corrected for spike and fractionation.

[d] Total common Pb in analysis corrected for fractionation and spike.

[e] Corrected for blank Pb and U, common Pb; errors quoted are 1 standard error of the mean in percent.

[f] Corrected for blank and common Pb; errors are 1 standard error of the mean in Ma.

TABLE 1b. U-Pb Zircon and Monazite Data for Okanagan Complex, South of Kelowna

Analysis number, size[a]	wt. mg	U, ppm	Pb,[b] ppm	$\frac{^{206}Pb}{^{204}Pb}$[c]	Pb_c,[d] pg	^{208}Pb,[b] %	$\frac{^{206}Pb}{^{238}U}$+/-1SEM%[e]	$\frac{^{207}Pb}{^{235}U}$+/-1SEM%[e]	$\frac{^{207}Pb}{^{206}Pb}$+/-1SEM%[e]	$\frac{^{207}Pb}{^{206}Pb}$ age, error,[f] Ma
A, Rhomb Porphyry, Anorthoclase-Pyroxene-Hornblende-Biotite Porphyry, Foliated and Metamorphosed, 28 km S of Penticton										
9a +105	1.4	1923	16.1	617	2656	13.0	0.007930 (0.6)	0.05110 (1.8)	0.04675 (0.9)	36.7 (40)
9b -105	1.6	1100	9.5	799	1383	14.6	0.008020 (0.6)	0.05400 (0.7)	0.04888 (0.27)	142.2 (25)
B, 7-84, Foliated and Folded Leucocratic Granitic Sill 27 km South of Penticton, East Shore Vaseaux Lake										
12a +105	0.151	666	5.18	441	129	3.8	0.008309 (0.19)	0.05500 (0.36)	0.04801 (0.33)	99.5 (7.9)
12b -105	0.228	1057	9.567	935	170	5.6	0.009458 (0.17)	0.06485 (0.24)	0.04973 (0.16)	182.5 (3.8)

See appendix for UTM coordinates of sample locations.

[a] Numbers (e.g., 10c) refer to Figures 5 and 6; letters (e.g., A) refer to localities in Plate 1, sizes (i.e. +105) refer to aspect of zircons in microns; letters attached to sizes: a, abraded, e, equant, l, long and prismatic, c, cloudy; fractions otherwise unlabelled are generally clear to slightly cloudy crystals which show rare faint evidence of cores.

[b] Radiogenic Pb.

[c] Measured ratio, corrected for spike and fractionation.

[d] Total common Pb in analysis corrected for fractionation and spike.

[e] Corrected for blank Pb and U, common Pb; errors quoted are 1 standard error of the mean in percent.

[f] Corrected for blank and common Pb; errors are 1 standard error of the mean in Ma.

TABLE 1c. U-Pb Zircon and Monazite Data for Footwall of Columbia River Fault, Southern Monashee Complex

Analysis number, size[a]	wt. mg	U, ppm	Pb,[b] ppm	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$[c]	Pb_C,[d] pg	^{208}Pb,[b] %	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$+/-1SEM%[e]	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$+/-1SEM%[e]	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$+/-1SEM%[e]	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$ age, error,[f] Ma
C, Fosthall Pluton, Muscovite-Bearing Leucocratic Granite Mylonite										
11a +105a,e	0.41	1164	10.2	3837	70	8.5	0.008901 (0.19)	0.05839 (0.21)	0.04758 (0.06)	78.3 (1.5)
11b +105a,l	0.344	1767	15.11	2722	125	7.0	0.008826 (0.17)	0.05836 (0.19)	0.04796 (0.07)	97.2 (1.8)
11c -105a,l	0.443	1560	13.61	1005	399	6.4	0.009058 (0.17)	0.06074 (0.25)	0.04863 (0.19)	130.2 (4.4)
11d -105a,e	0.070	1325	11.74	1435	37	7.4	0.009095 (0.19)	0.06046 (0.25)	0.04822 (0.16)	109.8 (3.8)
D, Sugar Mountain, Leucocratic Muscovite-Biotite Granite, Weakly Foliated to Massive										
10a +177	0.075	1973	15.60	3927	21	2.0	0.008606 (0.07)	0.05616 (0.11)	0.04733 (0.07)	65.6 (1.8)
10b -177+149	0.103	2801	23.20	4361	37	4.0	0.008816 (0.14)	0.05941 (0.17)	0.04887 (0.13)	141.8 (3.1)
10c -149+105	0.033	1872	23.13	2429	17	21.4	0.01063 (0.12)	0.08910 (0.14)	0.06077 (0.09)	631.1 (1.9)
10d monazite	0.298	2284	204.2	2284	408	78.1	0.008744 (0.16)	0.05551 (0.19)	0.04604 (0.08)	<0

See appendix for UTM coordinates of sample locations.

[a] Numbers (e.g., 10c) refer to Figures 5 and 6; letters (e.g., A) refer to localities in Plate 1, sizes (i.e. +105) refer to aspect of zircons in microns; letters attached to sizes: a, abraded, e, equant, l, long and prismatic, c, cloudy; fractions otherwise unlabelled are generally clear to slightly cloudy crystals which show rare faint evidence of cores.

[b] Radiogenic Pb.

[c] Measured ratio, corrected for spike and fractionation.

[d] Total common Pb in analysis corrected for fractionation and spike.

[e] Corrected for blank Pb and U, common Pb; errors quoted are 1 standard error of the mean in percent.

[f] Corrected for blank and common Pb; errors are 1 standard error of the mean in Ma.

TABLE 2a. Rb-Sr and K-Ar Data on Muscovite, Valhalla Complex

Mineral	ppm Rb	ppm Sr	$\frac{^{87}Rb}{^{86}Sr}$	$\frac{^{87}Sr}{^{86}Sr}$, error[a]	Age, error[b] Ma	%K	^{40}Ar,*[c] 10^{-7}cc/gm	%$\frac{^{40}Ar^*}{^{40}Ar_t}$[d]	Age, error,[e] Ma
407-83, Ladybird Granite C-S Mylonite, 27 km NNE of Castlegar									
Muscovite	656.8	23.04	83.22	0.77640 (15)	55.0 +/-0.8	8.79	163.3	33.8	47.2 +/-1.1
Feldspar	244.0	426.0	1.656	0.71268 (5)					
SC-84, Ladybird Granite C-S Mylonite, 1 km East of South End of Slocan Lake									
Muscovite	2195.0	15.67	418.5	1.04038 (10)	55.1 +/-0.6	8.56	164.1	24.2	48.7 +/-1.1
Feldspar	39.28	52.42	2.167	0.71453 (10)					

See appendix for UTM coordinates of sample locations.

[a] Error refers to the last digit(s) and is 1 standard error of the mean.

[b] Error is expressed as 2 standard errors of the mean.

[c] Radiogenic ^{40}Ar.

[d] Radiogenic as percentage of total ^{40}Ar.

[e] Error expressed as 2 standard errors of the mean.

TABLE 2b. Rb-Sr and K-Ar Data on Muscovite, Monashee Complex, Footwall of Columbia River Fault

Mineral	ppm Rb	ppm Sr	$\frac{^{87}Rb}{^{86}Sr}$	$\frac{^{87}Sr}{^{86}Sr}$, error[a]	Age, error[b] Ma	%K	^{40}Ar,*[c] 10^{-7}cc/gm	%$\frac{^{40}Ar^*}{^{40}Ar_t}$[d]	Age, error,[e] Ma
Fosthall-1, Ladybird Granite C-S Mylonite, 22.5 km South of Revelstoke									
Muscovite	532.4	19.75	78.52	0.77432 (5)	53.9 +/-0.8	8.65	155.0	26.0	45.5 +/-0.9
Feldspar	456.1	257.9	5.113	0.71811 (5)					
Fosthall-2, Ladybird Granite C-S Mylonite, 22.5 km South of Revelstoke									
Muscovite	565.4	18.99	86.77	0.78305 (5)	56.0 +/-0.9	8.51	157.9	21.0	47.1 +/-1.3
Feldspar	427.3	258.3	4.781	0.71789 (5)					
Pingston Creek, Ladybird Granite (?) C-S Mylonite, Bridge Over Pingston Creek, 20 km South of Revelstoke									
Muscovite	528.6	30.66	50.11	0.75636 (11)	59.7 +/-1.2	8.58	159.3	22.0	47.1 +/-0.9
Feldspar	435.4	232.0	5.435	0.71845 (4)					

See appendix for UTM coordinates of sample locations.

[a] Error refers to the last digit(s) and is 1 standard error of the mean.

[b] Error is expressed as 2 standard errors of the mean.

[c] Radiogenic ^{40}Ar.

[d] Radiogenic as percentage of total ^{40}Ar.

[e] Error expressed as 2 standard errors of the mean.

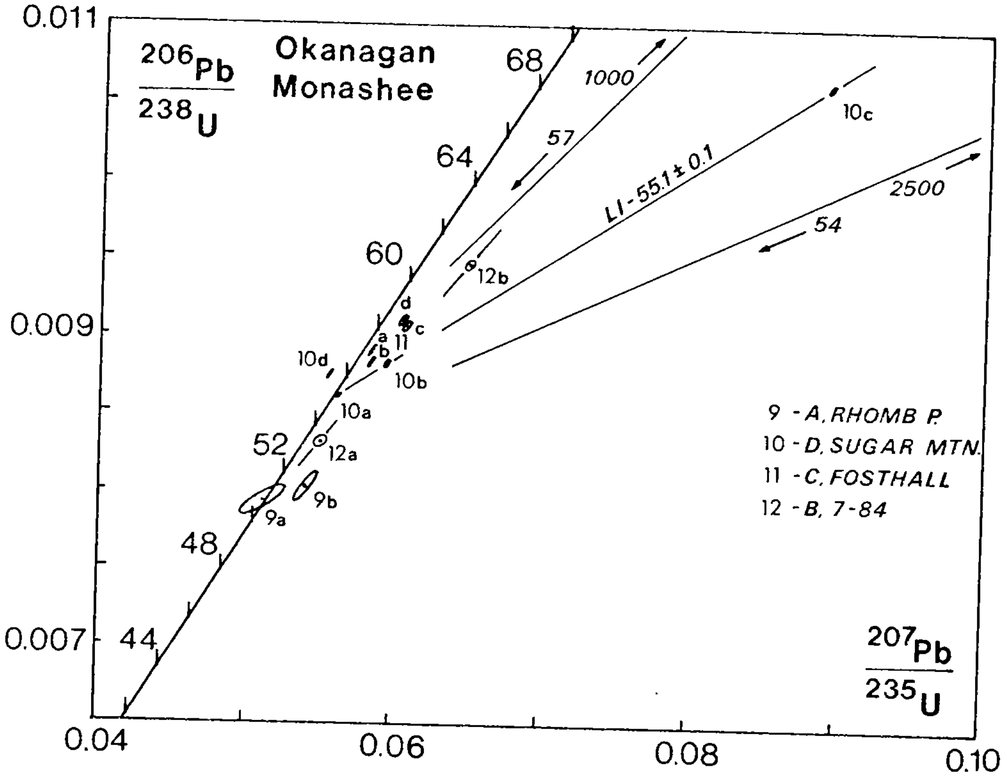


Fig. 5. U-Pb concordia diagram showing zircon and monazite analyses of Eocene igneous rocks from the footwall of Okanagan Valley fault near Oliver and from the footwall of Columbia River fault (Monashee complex area) west of Nakusp. Sample numbers (i.e., FOSTHALL), locality letters (i.e., C), and analysis numbers (i.e., 11a,b...) refer to Table 1 and Plate 1. All of these samples are mylonitic and involved in ductile shearing. The monazite analysis (10d) plots slightly above concordia for reasons discussed in the appendix and by Scharer [1984], whereas all zircons fall on or below concordia. The monazite age accepted as correct is the ^{207}Pb/^{235}U age. Two lines are drawn in the upper part of the figure to the right of concordia; these lines connect 57 and 1000 Ma (upper) and 54 and 2500 Ma (lower), and they bound the spectrum of analyses of Fosthall - Sugar Mountain pluton shown in Plate 1. The Sugar Mountain analyses (10a,b,c) fit on a line and yield a lower intercept age of 55.1 +/- 0.1 Ma, with an upper intercept of about 1900 Ma. The age of the zircons in the deformed rhomb porphyry sill (sample 9, locality A) is inferred to be 51 +/- 1 Ma. Scatter in analyses is due to inheritance, as discussed in the text, and in the caption to Figure 4. Error ellipses are plotted at the 95% confidence level.

fault system clearly penetrated the brittle-ductile transition of the early Eocene crust.

Okanagan Complex and Fault Zone

Recent work in the Okanagan complex has demonstrated the timing and extent of a westerly directed, west dipping ductile-brittle shear zone, termed the Okanagan Valley fault [Parkinson, 1985a, b; Bardoux, 1985; Parrish et al., 1985a; Tempelman-Kluit and Parkinson, 1986]. The Okanagan Valley fault juxtaposes various hanging wall rocks against mylonitized orthogneiss and paragneiss of middle to upper amphibolite grade.

The hanging wall of the Okanagan Valley fault contains rocks of several tectono-stratigraphic assemblages but differs from the higher grade footwall in being almost entirely of greenschist or lower metamorphic grade (exceptions being in the Shuswap Lake area). Eugeosynclinal rocks of late Paleozoic and early Mesozoic age preserve evidence for both penetrative pre-Late Triassic and rather modest Middle Jurassic deformation [Read and Okulitch, 1977; Roddick et al., 1972; Medford, 1975; Parkinson, 1985a; Fox et al., 1977]. These rocks were subsequently overlain in places by Eocene strata [Little, 1961; Church, 1973]; complete sections are characterized by syndepositional normal faulting in their upper parts.

The footwall of the Okanagan Valley fault is composed of deformed Mesozoic granitic rocks and paragneiss of uncertain age. Kinematic indicators in mylonitic rocks within the Okanagan Valley fault zone show a west directed (hanging wall to the west) sense of shear, a pattern observed from Omak Lake in northeast Washington [Goodge and Hansen, 1984] to north of Kelowna [Bardoux, 1985; Parrish et al., 1985a] and Sicamous [Journeay and Brown, 1986]. Parkinson [1985a] and Bardoux [1985] have presented evidence that the fault is predominantly an Eocene structure.

Intrusive rocks in the deformed footwall range in age from Early Jurassic to Middle Eocene [Solberg, 1976; Parkinson, 1985b]. In southern Okanagan Valley these include a mylonitic Late Cretaceous granite gneiss (100 +/- 5 Ma, U-Pb zircon), a synkinematic leucocratic granitic sill, and a metamorphosed and mylonitic Eocene anorthoclase rhomb porphyry dike/sill; near Vernon a folded and gneissic Eocene sill occurs in the footwall of the Okanagan Valley fault [Solberg, 1976]. U-Pb systematics of igneous zircons from the granitic sill and the rhomb porphyry dyke from the southern Okanagan Valley are presented in Table 1b and Figure 5. Analyses for the rhomb porphyry sill are concordant to slightly discordant and indicate an age of 51 +/- 1 Ma; those for the granitic sill are mildly discordant with a lower intercept age of 49.9 +1.6/-2.1 Ma. These rocks are strongly foliated; thus the footwall rocks were ductilely deformed in the Okanagan Valley fault as late as 50 Ma.

Virtually all K-Ar analyses on micas and hornblendes from the footwall adjacent to the Okanagan Valley are late Paleocene (hornblendes) to Eocene (hornblendes and micas) in age (Figure 1) [Medford, 1975; Stevens et al., 1982a, b; Wanless et al., 1978, 1979; R. L. Armstrong, unpublished data file, 1983). Fission track dates are Middle and Late Eocene [Medford, 1975]; together, these data imply that the rocks must have cooled from about 500°C at 52 Ma to about 100°C by about 40-45 Ma [Medford, 1975; Parkinson, 1985a].

A kinematic link between faulting and footwall deformation appears inescapable, pointing to Middle Eocene (younger than 51 Ma) extensional tectonics on this regionally extensive normal fault system.

MONASHEE COMPLEX

Introduction

The Monashee complex (Plate 1) is a structural culmination exposing amphibolite grade Early Proterozoic crystalline rock and a predominantly metasedimentary sequence which unconformably overlies it [Read and Brown, 1981; Brown and Read, 1983]. The roof of the complex is a shear zone termed the Monashee decollement, described in detail by Journeay [1986]. The Monashee decollement (Plate 1) is a major east directed, west rooting ductile thrust fault documented on the west flank of the Frenchman Cap area northwest of Revelstoke [Journeay, 1983, 1986; Scammell, 1986]. Footwall rocks in the shear zone are characterized by structural truncations, reclined and rotated folds, prominent east-directed kinematic indicators, and, in places, inverted isograds. Journeay [1986] has inferred two periods (Middle Jurassic and Cretaceous) of east directed thrusting on the decollement on the west side of the Frenchman Cap area. A possibly correlative zone of imbrication is present on the southwest side of the complex, as described by Duncan [1984].

Inferences that the Monashee decollement occurs on the east flank of the Monashee complex are based mainly upon the presence and correlation of mylonites and a projected truncation of the feature by the younger Columbia River fault about 80 km north of Revelstoke [Brown and Journeay, 1987]. The decollement is difficult to uniquely identify on the east dipping flank because of superposed extensional brittle faulting and probable mylonite development (see below).

Southwest of Revelstoke the boundary and characteristics of the Monashee complex and decollement need clarification because a range of interpretations has appeared in the literature [Read and Brown, 1981; Read, 1979b; Brown and Read, 1983; Lane, 1984; Okulitch, 1984; Journeay and Brown, 1986; Brown et al., 1986; Brown and Journeay, 1987]. In Plate 1 the continuation of the Monashee decollement is suggested to parallel the trace of westernmost exposures of slices of crystalline basement south of the Trans Canada highway toward Thor-Odin nappe [Duncan, 1984; Parrish et al., 1985a; Brown and Journeay, 1987]. It is shown as being discontinuous because of a lack of mapping on the west side of Thor-Odin region. Although not specifically named, this same boundary was originally recognized and mapped as a lithologic boundary by Wheeler [1965], but Read and Brown [1981] chose to diverge from Wheeler's view near the south edge of the Big Bend map-area. They drew it instead southwest toward Sicamous, following faults which now are known to be normal faults [Journeay and Brown, 1986], similar to the Columbia River fault, and to be unrelated to the Monashee decollement.

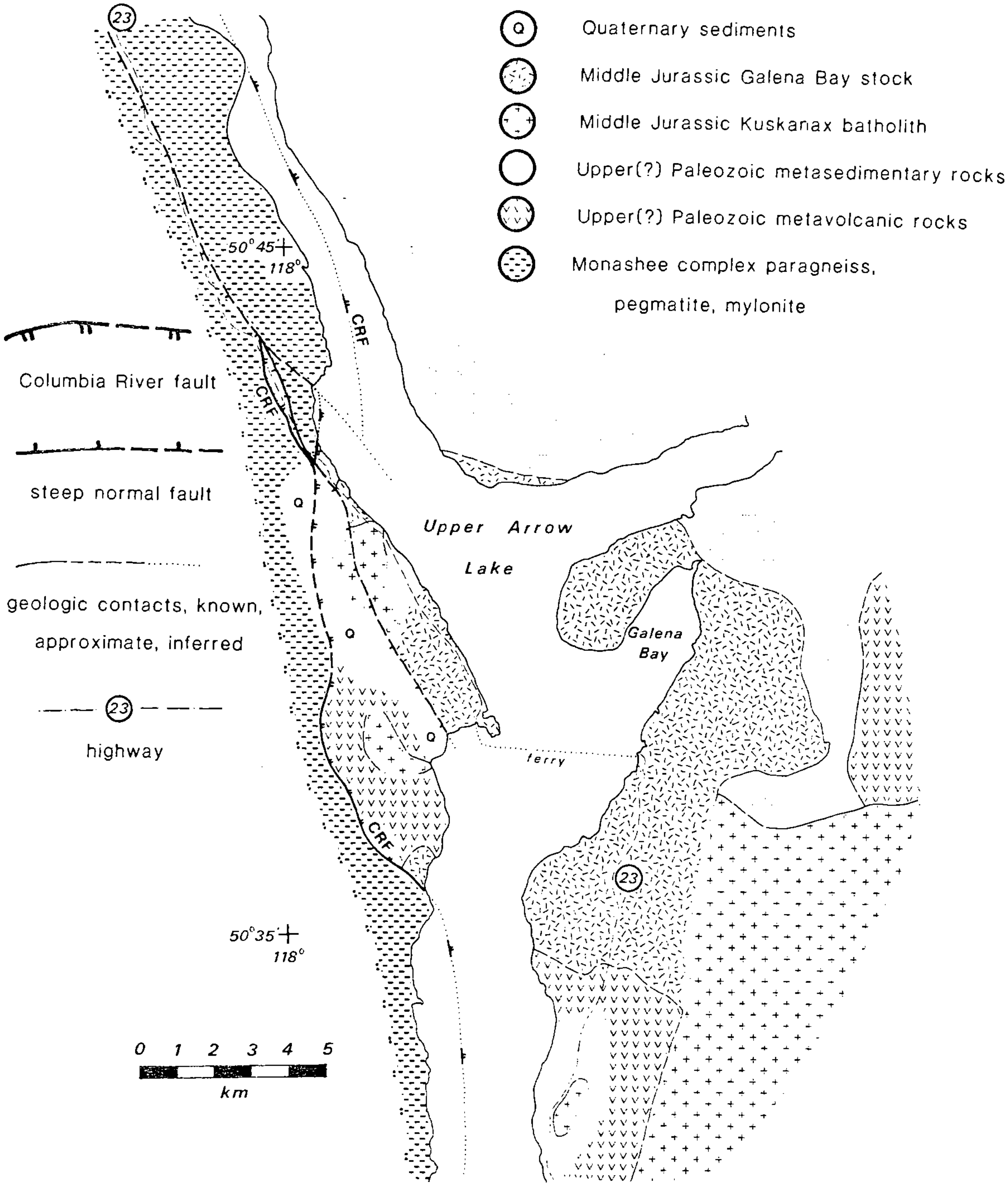


Fig. 6. Geological map of the Galena Bay stock and Columbia River fault, Upper Arrow Lake south of Revelstoke. Generally east dipping strongly foliated and mylonitic high grade paragneiss and pegmatite compose the Monashee complex beneath the east dipping Columbia River fault. It is broken by at least two north trending steep faults which probably dip west. The correlation of the metasedimentary and metavolcanic rocks in the hanging wall is uncertain but may include the Kaslo formation, the McHardy assemblage of the Milford group [Klepacki and Wheeler, 1985], or part of the Lardeau group [Read and Wheeler, 1976].

Columbia River Fault Zone

The east dipping Columbia River normal fault is a zone of brittle and ductile fault rocks which generally follows the Columbia River on the east flank of the Monashee complex from northeast of Frenchman Cap area to south of Nakusp (Plate 1). Mylonites subjacent to this fault have been interpreted by Read and Brown [1981], Brown and Read [1983], Lane [1984, 1986], Brown et al. [1986] and Brown and Journeay [1987] as part of the compressional (Monashee decollement) evolution of the complex unrelated to normal faulting. In light of new data summarized below, a reinterpretation of its origin as a ductile-brittle normal fault is necessary.

Galena Bay Stock

The Galena Bay stock is a body of two-mica leucocratic quartz monzonite exposed on both shores of Upper Arrow Lake 50 km south of Revelstoke (Plate 1 and Figure 6). Rb-Sr dating of whole rocks and U-Pb zircon and monazite dates indicate that the stock is 161.6 +/- 0.5 Ma old [Parrish and Armstrong, 1987; 157 Ma date cited earlier by Read and Brown, 1981]. Although not without exception [see Price, 1981b; Parrish et al., 1985a], for nearly 10 years it has been generally accepted that this stock intruded the Columbia River fault, Monashee decollement, and high-grade rocks of the Monashee complex [Read and Wheeler, 1976; Read, 1979a; Read and Brown, 1981; Brown et al., 1986; Journeay and Brown, 1986] and this relationship has been used to argue for pre-Middle Jurassic movement on the Monashee decollement and orogenesis within the Monashee complex.

The recent suggestion of Journeay and Brown [1986] and Brown and Journeay [1987] that the Monashee decollement has an important period of Late Cretaceous movement is clearly at variance with the inference that the Galena Bay stock intrudes the complex posttectonically. A recent study (Figure 6) [Parrish and Armstrong, 1987] of the field relationships in the vicinity of the stock on both sides of Upper Arrow Lake shows that the stock intrudes both the Middle Jurassic Kuskanax batholith and deformed and metamorphosed, mainly greenschist-grade actinolite amphibolite and metasedimentary rocks possibly belonging to the middle Paleozoic McHardy assemblage of the Milford Group [Klepacki and Wheeler, 1985]. Together, these metamorphic and intrusive rocks, including the Galena Bay stock, are juxtaposed against high-grade mylonitic gneiss of the Monashee complex footwall across a moderately east dipping brittle fault. At least two steep normal faults cut the Columbia River fault and render the detailed map pattern complicated (Figure 6). The east dipping main fault was originally recognized by Read and Wheeler [1976] but was later disregarded by Read and Brown [1981]. This fault is the Columbia River fault as mapped both to the north and south. There is no evidence, contrary to earlier assertions [Read and Brown, 1981; Brown and Read, 1983; Brown et al., 1986; Brown and Journeay, 1987], that the Galena Bay stock cuts the Monashee decollement, the Columbia River fault, or mylonitic rocks in the footwall of the fault. The Galena Bay stock is confined to the hanging wall of the Columbia River fault, permitting the inference that the fault and its subjacent mylonite are both entirely Eocene in age.

South Fosthall Pluton: Timing Arguments

A lineated and foliated mylonitic biotite and/or muscovite-bearing leucocratic granite, termed the South Fosthall pluton, outcrops at the south end of Thor-Odin nappe and is truncated by the Columbia River fault [Reesor and Moore, 1971; Read and Brown, 1981; Okulitch, 1985]. In the fault zone it is a greenschist facies mylonite with muscovite porphyroclasts and east directed mylonitic fabric identical to the 58+/-1 Ma Ladybird granite in eastern Valhalla complex beneath the Slocan Lake fault. The synkinematic muscovite porphyroclasts have been dated (Rb-Sr) at three different localities within the South Fosthall pluton (Plate 1) and are Early Eocene, ranging from 54 to 60 Ma old (Table 2b). The oldest of these is from a sample of highly sheared and altered mylonitic granite near the mouth of Pingston Creek whose protolith age is uncertain but probably Paleogene. The interpretation of the Rb-Sr dates and their fabric is similar to that of the Ladybird granite and proves an Early Eocene age for a substantial part of the mylonite development at this locality within the Columbia River fault zone.

The South Fosthall pluton, sampled near Vanstone Creek, where it is clearly the predominant lithology mapped by Reesor and Moore [1971], yields a 55 +/- 1.5 Ma zircon lower intercept age from slightly discordant and scattered data (Figure 5 and Table 1c). A second zircon age determination was obtained from a sample of the pluton collected on the western flank of Thor-Odin area near Sugar Lake (Plate 1, Figure 6 and Table 1c). Three zircon analyses from this sample fall on a linear array with a precisely determined lower intercept age of 55.1 +/- 0.1 Ma. The $^{207}Pb/^{235}U$ monazite age for this sample is slightly younger at 54.9 +/- 0.1 Ma. Okulitch [1985] reported a Paleozoic U-Pb zircon age on a sample from near South Fosthall Creek. Our 1986 reexamination of his specific sampling locality strongly suggests that a glacial erratic boulder(?) of hornblende-bearing lineated leucocratic quartz monzonite, quite unlike the local bedrock, was actually sampled and yielded the Paleozoic date. Its source, though probably nearby, is uncertain, and the significance of the Paleozoic age is therefore in doubt.

Because of these Rb-Sr and U-Pb data from the South Fosthall pluton, it seems highly probable that much of the mylonite (particularly that of greenschist facies) subjacent to the Columbia River fault along much of its length is of Early Eocene age and extensional origin. The Ladybird granite suite in this area (Plate 1) appears to be 1-2 Ma younger than in Valhalla complex.

Clachnacudainn Complex and Standfast Creek Fault

Lane [1984, 1986] and Read and Brown [1981] inferred that all deformation related to normal faulting in the Revelstoke area adjacent to the high-grade and enigmatic Clachnacudainn complex [Ross, 1968; Price et al., 1985] was of a brittle nature, postdating mylonite development. In light of the data just presented, it seems unlikely that this is correct. Mineral cooling data (Figure 1) imply that both Monashee and Clachnacudainn complexes were everywhere at similar temperatures in the Eocene. Therefore footwall mylonites should be present in both complexes, and we predict that an Eocene ductile-brittle fault bounds both these complexes on the east.

Northeast of Revelstoke near the Trans Canada highway, the Standfast Creek fault juxtaposes Paleozoic granitic orthogneiss [Okulitch, 1985] in the footwall against much lower grade lower Paleozoic Badshot and Lardeau formations of the hanging wall on a ductile or ductile-brittle shear zone with a very appressed or omitted series of isograds [Price et al., 1985]. South of the Trans Canada highway this fault is intruded by the middle Cretaceous Albert Creek stock [Sears, 1979] (Plate 1) although it apparently branches south of Albert Canyon (R. Price, personal communication, 1987); to avoid a contradiction, we suggest that there may be more than one fault or shear zone and that the boundary between granitic gneiss and Paleozoic rocks is predominantly a ductile normal fault very similar to the Valkyr shear zone, as described by Carr [1986] and Carr et al. [1987]. The compressional segment of the fault has been interpreted both as a west directed thrust [Price et al., 1985] cut by the Albert Peak stock [Sears, 1979] and as an east directed thrust [Read and Brown, 1981; Brown and Read, 1983]. We speculate that the implied Eocene extensional part of the fault diverges from the compressional part of the Standfast Creek fault south of the Trans-Canada highway and continues near the top of the Paleozoic granite gneiss (Plate 1). All other compressional explanations including wedge-type geometry [Price, 1986] or east-directed thrust geometry along this fault [Read and Brown, 1981] are incapable of explaining the sharp thermal and geochronological contrasts present between the Monashee-Clachnacudainn complex and surrounding rocks, unless they include significant superposed Eocene extensional normal faulting. Our inference is that a ductile normal fault is part of a brittle-ductile fault system that was abandoned when displacement shifted westward to the Columbia River valley. This geometry is shown in Plate 1. Our prediction of an extensional fault, however, is clearly testable and implies considerable east directed mylonite in footwall gneiss and increasingly older Mesozoic (greater than 60 Ma) mineral cooling dates upward in the adjacent hanging wall of the fault.

Summary

The Monashee complex is a window of rocks bounded on three sides by thrust fault(s) and along its east side by the Eocene Columbia River fault as shown in Plate 1 [Parrish et al., 1985a; Journeay and Brown, 1986; Brown and Journeay, 1987]. Several dated rocks occurring in the immediate mylonitic footwall of the Columbia River fault prove that it is a ductile-brittle fault of extensional origin and predominantly Early Eocene age. Because direct dating of the Monashee decollement has yet to be undertaken, its absolute age is still uncertain.

Implications

In the absence of contrary data, the Columbia River fault may be interpreted as an Early and Middle (?) Eocene ductile and brittle normal fault of large magnitude with a ductile splay enveloping the Clachnacudainn complex. This episode of faulting is inferred to have tectonically denuded and rapidly cooled the Monashee and Clachnacudainn complexes and accounts for their Eocene K-Ar mica dates (Figure 1).

Thrust faults which generally bound the Monashee complex [Journeay, 1986; Journeay and Brown, 1986; Brown and Journeay, 1987] are apparently arched over the complex with similar geometry to the main structural arch of the complex as defined by overall foliation and lithology [see Brown et al., 1986]. Between the Pinnacles area and the south flank of Thor-Odin (Plate 1), klippen of inferred extensional origin related to Columbia River fault appear similarly arched [see Read and Brown, 1981]. It is therefore likely that much of the north trending structural arch, particularly in southern Monashee complex, is Eocene and related to extension, a view at variance with cross sections of other models for this region [cf. Brown et al., 1986; Monger et al., 1986; Brown and Journeay, 1987], which show most of the arching to be due to older structural events.

Previous models of the evolution of the Monashee complex [Brown et al., 1986; Monger et al., 1986] imply that the present form of the structural arch of the complex is predominantly a result of the formation of a basement duplex during Mesozoic thrusting. This view is implicit in interpretive cross sections attempting to explain the structural evolution of the complex. However, if displacement on the central portion of the Columbia River fault-Standfast Creek fault is significant (30 km or more), then much of the arch and uplift may be Eocene.

OTHER AREAS OF THE SOUTHERN OMINECA BELT

Kettle River Fault

The Kettle River fault was recognized in British Columbia and Washington by Little [1957], Preto [1970], Cheney [1980], and Rhodes and Cheney [1981]. Its trace lies in the Christina Lake-Kettle River valley and separates the high-grade Kettle-Grand Forks complex from much lower grade metamorphic, volcanic, and plutonic rocks to the east (Plate 1 and Figure 1). Rhodes and Cheney [1981] showed that the fault dips east, involves Eocene volcanic rocks, and is in part a brittle extensional fault similar to other core complexes. Hurich et al. [1985] demonstrated by seismic reflection work that subjacent mylonites parallel the fault and continue to considerable crustal depths; in these respects it is very similar to the Valhalla complex and Slocan Lake fault zone.

Even though few published geochronological data are available, particularly for the eastern mylonitic rocks of the Kettle complex, the similarities to the Slocan Lake fault, Columbia River fault, and Valhalla complex are striking and suggest a predominantly extensional origin for both the brittle east dipping fault and the subjacent ductile shear zone. For example, two sheets of orthogneiss in the complex are known to be mid-Cretaceous in age, and all mica ages are less than 60 Ma (R. L. Armstrong, unpublished datafile, 1985). In apparent contrast to the Slocan Lake fault, Middle Eocene Coryell syenite and related volcanic rocks are truncated by the fault, implying that its movement history included Middle Eocene displacement.

On Plate 1 we show the trace of the Kettle River fault somewhat differently from that of Little [1957] and Tipper et al. [1981]. On the east side of Christina Lake near its north end, metaplutonic rocks and subordinate sillimanite-bearing paragneiss are present which more closely resemble those of the Kettle complex than the lower grade rocks which elsewhere constitute the hanging wall of the fault. The trace of the fault in Plate 1 assigns these to the complex, resulting in a salient which, when followed north, curves back to the northwest in a manner similar to the Clachnacudainn complex. The fault appears to have decreasing displacement to the north and apparently is truncated by large plutons of 52 Ma Coryell syenite west of Valhalla complex. Its movement history therefore probably involves both Early and Middle Eocene displacement.

Granby and Greenwood Fault Systems

The Granby fault [Preto, 1970; Little, 1957] is a west dipping brittle normal fault bounding the western margin of the Kettle-Grand Forks complex. It is extensive, perhaps 100 km or more in length, and follows topographic notches and lineaments along the trace shown in Plate 1. The fault drops low-grade eugeosynclinal rocks of the Intermontane superterrane, Jurassic plutons, and Middle Eocene volcanic and sedimentary rocks and syenite down against the gneissic complex. It is younger than circa 52 Ma because it cuts the 52 Ma Coryell syenite (U-Pb zircon age) and the Middle Eocene Marron formation.

Another slightly older and more complicated low- to moderate-angle normal fault system exists in the vicinity of Greenwood, British Columbia, which we term the Greenwood fault system. Faults of this type have been noted by Little [1983], Monger [1968], and J. Fyles (personal communication, 1986) to be low-angle features which involve the Marron and Kettle River formations of Middle Eocene age as well as older rocks. Reconnaissance and detailed work (D. Parkinson and S. D. Carr, manuscript in preparation; J. Fyles, personal communication, 1987) demonstrate that Eocene stratified rocks are juxtaposed on an extensive presently low dipping fault system above subjacent Coryell syenite and other rocks immediately west of the Grand Forks complex at latitude 49°15'N (Plate 1). These are suggested to be extensional klippen which rest on brittle west directed normal faults which root to the west in the vicinity of the upper Kettle Valley west and northwest of Greenwood. West of Greenwood, these faults cut into rocks which lie unconformably beneath Eocene strata [Little, 1983]. Thus the Greenwood fault system is west directed (consistent with tilting of strata [Monger, 1968]), cuts down to the west, and roots as a major west dipping normal fault which is clearly east of the Okanagan Valley fault zone.

We interpret the Okanagan Valley, Greenwood, and Granby faults as related Middle Eocene (post-52 Ma) normal fault systems which together have accommodated a large amount of west-directed displacement. The age of these west directed faults is younger than most displacement on east directed faults. The Columbia River, Valkyr, and Slocan Lake fault systems are intruded by the 52 Ma Coryell syenite near Lower Arrow Lake, whereas both circa 52 Ma rhomb porphyry sill and Coryell syenites are extensively involved in younger faults farther west.

Priest River (Selkirk Crest) Complex

The Newport fault [Miller, 1974a, b, c, d] is a low-angle spoon-shaped normal fault in northeast Washington [Price, 1979, 1981a, b; Harms, 1982]. Hanging wall strata, comprising Eocene sedimentary rocks and Precambrian Belt series, generally dip to the west, outlining an internally asymmetrical hanging wall. K-Ar biotite dates in the Priest River complex are also asymmetrical in that they young to the east, being less than 45 Ma on its eastern side [Miller and Engels, 1975] (Plate 1 and Figure 1). Bounding the Priest River Complex on the east is the Purcell Trench fault, an east dipping normal fault bounding the core complex [Rehrig and Reynolds, 1981].

In a view modified from Price [1979] and Harms [1982], we suggest that the Purcell Trench fault is the root zone of the Newport fault. This implies that the north trending eastern segment of the Newport Fault is a west dipping normal fault superimposed on a relatively flat Newport structure, dropping the east side of the Newport fault down and in part forming the rollover anticline in its hanging wall [Harms, 1982; Miller, 1974a, b, c, d]. In this interpretation, the trace of the fault is drawn along a north-south trend from south of the town of Newport to north of the international border joining with the Blazed Creek fault [Glover, 1978; Archibald et al., 1983] as shown in Plate 1. This west dipping younger fault isolated segments of the hanging wall of the original Purcell Trench fault, forming the Newport "spoon-shaped" block. We predict that a ductile or ductile-brittle segment of the original fault analogous to the Valkyr shear zone may be found near the international border southwest of Creston, British Columbia. A possible trace of this shear zone is shown on Plate 1. Arching later in the displacement history of the Purcell Trench fault is suggested to have caused abandonment of this segment and the initiation of a north trending normal fault which we propose exists in southern Kootenay Lake (Plate 1).

This interpretation of Eocene faulting is consistent with the fact that young (less than 60 Ma) K-Ar biotite dates are found between Kootenay Lake (the Purcell Trench fault) and the east side of the Blazed Creek fault which has Jurassic granitic rocks and older K-Ar dates in its hanging wall 25 km west of Creston [Archibald et al., 1983, 1984] (Figure 1). This proposal can be tested by mineral dating and field work along the proposed shear zone looking for indications of Eocene deformation.

This interpretation also implies that some and possibly a considerable amount of the consistently east directed fabric of the Priest River complex documented by Rhodes and Hyndman [1984] could be extensional in origin and Eocene in age. U-Pb dating in the metamorphic complex could be used to test this suggestion. Significant normal displacement on the Purcell Trench fault has tectonically exhumed a large terrane of metamorphic rocks which in part formed at a relatively deep level of the crust. Late Cretaceous to Paleocene compressional shear zone(s) analogous to the Gwillim Creek shear zones of the Valhalla complex should be present at or near the surface. Only careful structural work in conjunction with accurate geochronological studies and seismic reflection data will shed light on these complex tectonic relationships.

Okanagan Complex East of Vernon

The structure of the region east of Vernon is both complicated and poorly understood. Lithology includes high-grade paragneiss and orthogneiss, greenschist-grade metasedimentary and metavolcanic rocks similar to those southwest of Shuswap Lake, granitic rocks of uncertain age, fossiliferous upper Paleozoic to Triassic rocks of chlorite or lower grade, and Eocene strata. The area is in part an Eocene structural depression which preserves Eocene strata in the midst of older rocks, but it is also the locus of intersection of (1) the northwest trending belt of mostly greenschist grade deformed rocks which extends from near

Shuswap Lake to Nakusp and (2) the superimposed NNE trending Eocene anticlinal arch immediately east of and parallel to the Okanagan Valley fault (Plate 1). Relationships in this complex region include the through going Okanagan Valley fault which juxtaposes Eocene strata against gneiss [Jones, 1959], Eocene strata resting unconformably upon lower grade rocks with older K-Ar dates [Mathews, 1981], lower grade metamorphic rocks faulted against gneiss [Jones, 1959; Mathews, 1981], normal faults with steep and gentle (?) dips, and Eocene strata interpreted to unconformably overlie gneiss [Mathews, 1981]. The interpretation shown in Plate 1 is tentative but tries to accommodate most of these data. It is suggested that several generations of normal faults are superimposed, some being low-angle detachment faults of westerly and possibly easterly displacement sense, while others appear steeper. Eruption of volcanic rocks between episodes of faulting (perhaps 43-48 Ma [Mathews, 1981]) may explain why some Eocene strata are faulted while other outliers apparently are not.

Northern Monashee Mountains and Beyond

The Eagle River fault is interpreted [Journeay and Brown, 1986] as the northern continuation of the Okanagan Valley fault north of Sicamous (Plate 1). It coincides in part with a fault recognized by Jones [1959], Okulitch [1979], and Read and Brown [1981]. This feature was thought to be a thrust by Read and Brown [1981] which they believed to be part of the Monashee decollement. Though K-Ar data are sparse, extensive areas in the northern Monashee Mountains have young K-Ar mica dates indicative of Eocene uplift and cooling (Figure 1). It is suggested that the northern continuation of the Okanagan Valley fault, or a splay of it, tracks northeast of Shuswap Lake toward the North Thompson River and joins a known fault in the North Thompson Valley on the west side of the Malton gneiss [Campbell, 1968]. This fault probably terminates while approaching the Rocky Mountain Trench near Valemount (D. C. Murphy, unpublished data, 1986). Throughout its trace, as shown on Plate 1, this fault system is inferred to be west dipping and of normal sense.

Occurrences of Eocene core complexes farther northwest into central British Columbia are mostly restricted to smaller areas such as bodies of gneiss with Eocene K-Ar dates northeast of Prince George [Wanless et al., 1972], part of the Wolverine Complex [Armstrong, 1949; Parrish, 1979], perhaps part of the Sifton and Cormier Ranges adjacent to the Northern Rocky Mountain Trench [Wanless et al., 1979; Evenchick et al., 1984], and the Horseranch Range [Gabrielse, 1963, 1985]. These complexes and their probable extensional origin may be related to tectonically exhumed and denuded exposures of pull-apart basins bounded by dextral transcurrent faults in the vicinity of the Northern Rocky Mountain Trench and its various splays [Gabrielse, 1985; Struik, 1985].

GEOLOGICAL SUMMARY-SOUTHERN OMINECA BELT

Following Price [1979, 1981a, b, 1985], Ewing [1981], Armstrong [1982], Price et al. [1985], and Parrish and Carr [1986], we interpret the geology of the southern Omineca Belt as consisting of two types of tectonic elements: (1) upper Proterozoic to Jurassic rocks of variable but predominantly low to moderate metamorphic grade with a clear late Paleozoic to Middle Jurassic tectonic history, overlain in part by Eocene strata, and juxtaposed on major normal faults against and above (2) generally much higher grade middle crustal rocks with a strong Cretaceous and early Tertiary overprint preserved. These faults are fundamental crustal breaks of regional extent which juxtapose rocks with very different Eocene thermal characteristics; some are well in excess of 100 km in length and have displacements varying from perhaps 10-20 km (Greenwood fault, Granby fault?) to probably over 30 km (Columbia River fault, Valkyr shear zone-Slocan Lake fault, Okanagan Valley, Kettle River, and Purcell Trench faults). Calculations of displacement which assume 30° dips, temperature contrasts between footwall and hanging wall of 150° to 400°C [Carr et al., 1987], and relatively normal thermal gradients require movement of this order of magnitude. There are no structural data in any of the complexes (such as hanging wall-footwall cutoffs) which contradict these estimates.

Because there is no evidence that the recognized normal faults flatten or become markedly listric into the ductile-brittle transition region of the crust and because some are known to have penetrated well into the region of ductile strain, we have chosen to draw them as crust-penetrating shears in a manner proposed by Wernicke [1981, 1984] and Harms [1982]. This approach admittedly facilitates the construction of balanced cross sections and their restored counterparts, but it is supported by seismic reflection data across the Columbia River fault [Cook, 1986], Kettle River fault [Hurich et al., 1985], and Slocan Lake fault [Cook et al., 1987; Price et al., 1986]. In particular, the data across the Slocan Lake fault strongly suggest that the fault can be followed from its surface trace to middle and most probably lower crustal depths without marked flattening.

CRUSTAL CROSS SECTION AT 49°20'N

Self-consistent, quasi-balanced, present and restored cross sections (Plate 2) have been drawn along the line of section shown in Plate 1. The amount of extension appears to decrease northward in concert with the narrowing of the zone bounded by major normal faults (Plate 1 and Figure 1). The sections were constructed from the geological and geochronological database in addition to permissible inferences of the deep structure of normal faults [Cook et al., 1987]. Crustal thickness constraints are from Monger and Price [1979] and are consistent with those estimates obtained by Potter et al. [1986] for northern Washington.

The salient features, from east to west, are summarized as follows:

1. The structure of the thrust and fold belt east of Kootenay Lake is modified from Price [1981b] and is confirmed in general by the seismic data of Cook et al. [1987]. The Purcell Anticlinorium has travelled eastward with respect to underlying passive crystalline basement whose upper surface dips gently to the west toward the hinterland [Price et al., 1986].
2. Crystalline basement, though not seen at the surface along this line of section, is considered an extension of the Canadian Shield, and we infer that it is present at least as far west as the Okanagan Valley, though considerably thinned and perhaps of transitional character. The geochronological data from Precambrian crystalline rocks of the Monashee complex are consistent with this hypothesis; these rocks can be temporally correlated with Early Proterozoic (1.9-2.1 Ga) crystalline rocks in the southwest trending Thelon-Taltson zone of the northwest Canadian Shield and adjacent Phanerozoic cover [Parrish, in press; van Breemen et al., 1987; Hoffman, 1987].
3. The crustal thickness change between the Purcell Trench and Rocky Mountain Trench is interpreted as being due to Late Proterozoic thinning (rift-related [Price, 1981b]) with superposed Eocene extension.
4. In the Kootenay Arc an important zone of mid- to late(?)-Mesozoic west directed thrusts (back-thrusts) placed miogeoclinal rocks westwards over allochthonous rocks of the eastern Intermontane superterrane. This allochthonous terrane originally overrode these same rocks in a collision somewhat earlier in Middle Jurassic time [Klepacki, 1983, 1986; Klepacki and Wheeler, 1985]. The structure of the zone has been interpreted as an east directed tectonic wedge [Price, 1986].
5. The Valkyr shear zone-Slocan Lake extensional fault system in the Valhalla complex deforms all preexisting compressional features including the basal decollement of Late Cretaceous to Paleocene age which accommodated eastward displacement of the Rocky Mountain thrust belt to the east. Gwillim Creek shear zones (Figure 3) may be this type of feature and are exposed at the surface because of Eocene tectonic denudation [Parrish et al., 1987a].
6. The circa 52 Ma Coryell syenite is diagrammatically shown to truncate both the Valkyr shear zone and northern Kettle River fault, relationships which are known to exist on the ground [Carr et al., 1987].
7. The Monashee and Kettle-Grand Forks complexes have been exhumed from considerable depths by extensional tectonic denudation on temporally distinct outward dipping normal fault systems on their east and west flanks. The structural arch of both the Monashee complex [Read and Brown, 1981] and of the Kettle complex in Washington [Cheney, 1980] are north and south of the line of section and are not illustrated as distinct features on Plate 2. Considerable structural differences probably exist along strike of these complexes, and it is unwise to project structures for large distances.
8. Timing considerations require that the near-surface continuations of the Valkyr shear zone and Kettle River fault were truncated by the Granby and Greenwood fault systems and were displaced westward.
9. The Middle Eocene White Lake basin [Church, 1973] is broken by the Okanagan Valley fault south of Penticton. The eastern counterparts of what may have been the same Eocene basin are preserved near and west of Greenwood. We suggest that the dissection of this single or composite basin was accomplished on multiple extension faults rather than on a single fault, as suggested by Tempelman-Kluit and Parkinson [1986], although we agree with their inference of large-magnitude extension, our estimate being 80 km of cumulative displacement.

RESTORED CROSS SECTIONS

The crustal cross section has been restored in three steps, with a fixed reference or "pin" near the Rocky Mountain Trench at the east end of the sections. The first restoration involves removing the Middle Eocene normal

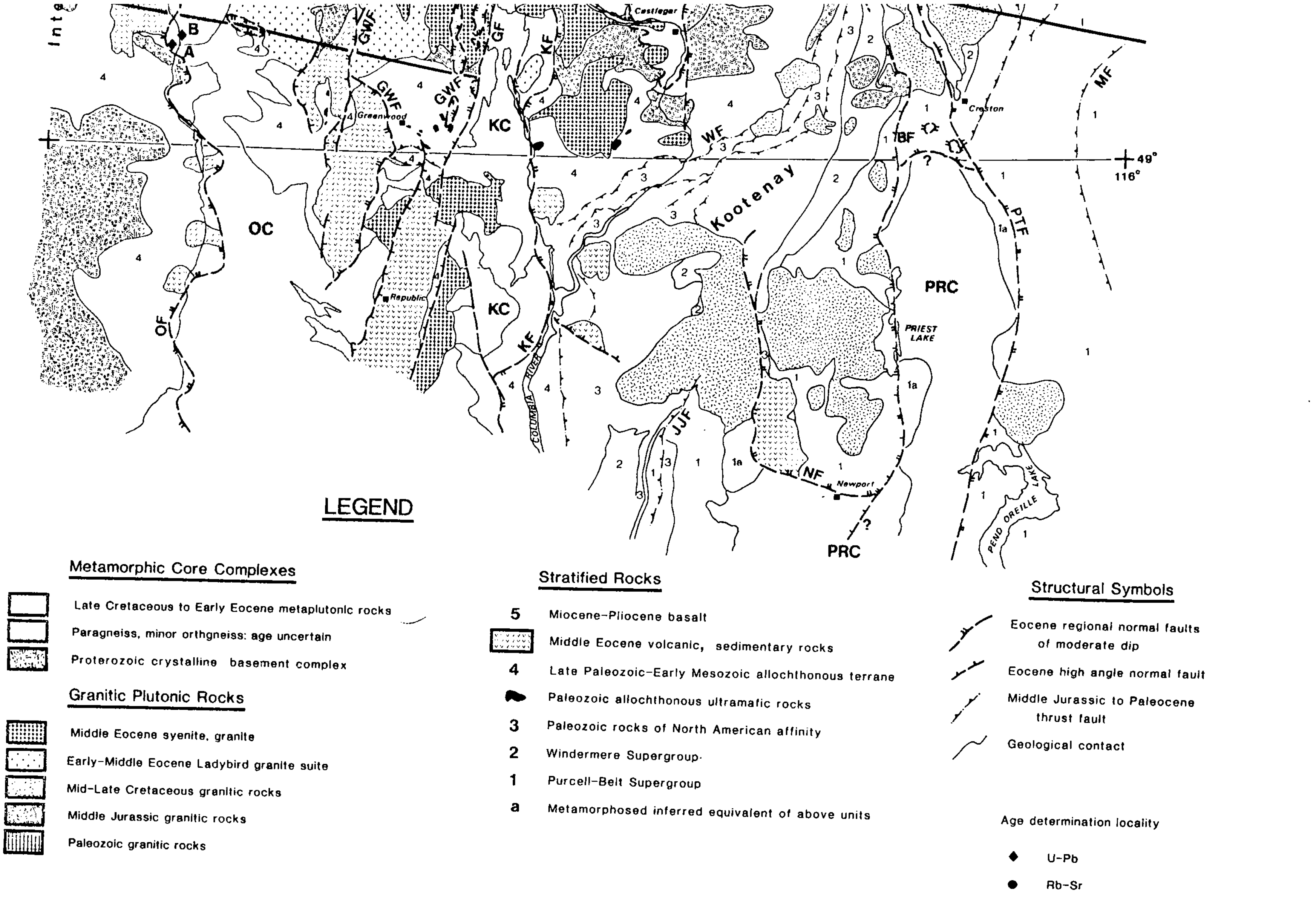
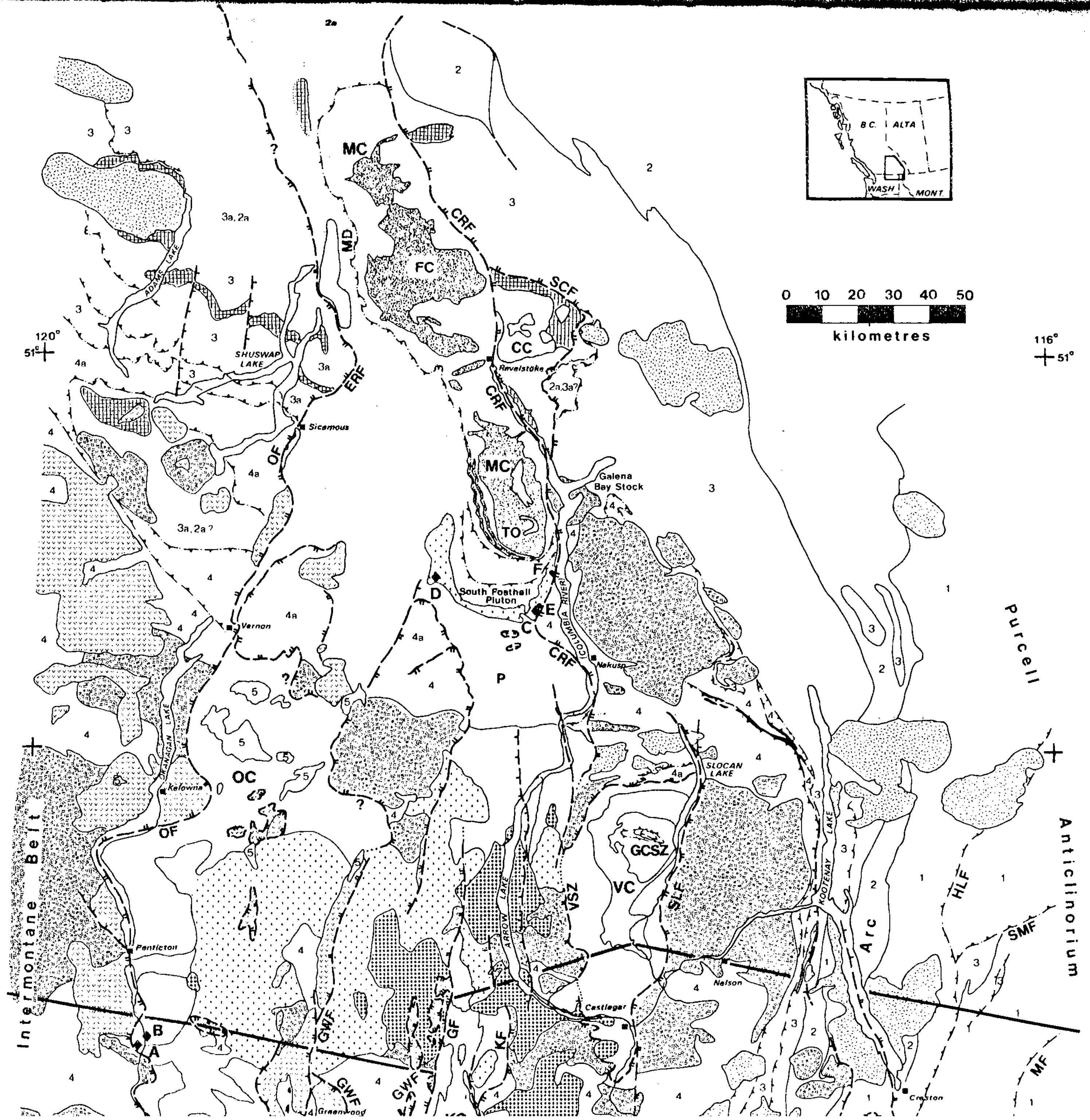


Plate 1. Tectonic map of southern British Columbia and northern Washington, Idaho, and Montana, as modified from Parrish et al. [1985a], Parrish and Carr [1986] and Carr et al. [1987]. Cross sections shown in Plate 2 are drawn along the line of section shown. Sources of data for this compilation are listed in the above publications with additional information from Campbell [1964], Simony [1979], Schiarizza [1986], Schiarizza and Preto [1984], Journeay and Brown [1986], Halwas and Simony [1986], and Armstrong et al. [in press]. Metamorphic complexes and faults are designated as follows: BF, Blazed Creek fault; CC, Clachnacudainn complex; CRF, Columbia River fault; ERF, Eagle River fault; FC, Frenchman Cap area; GCSZ, Gwillim Creek shear zones; GF, Granby fault; GWF, Greenwood fault system (see below); HLF, Hall Lake fault; JJF, Jumpoff Joe fault; KC, Kettle-Grand Forks complex; KF, Kettle River fault; MC, Monashee complex; MD, Monashee decollement; MF, Moyie fault; NF, Newport fault; OC, Okanagan complex; OF, Okanagan Valley fault; P, Pinnacles complex; PRC, Priest River complex; PTF, Purcell Trench fault; SCF, Standfast Creek fault; SLF, Slocan Lake fault; SMF, St. Mary fault; TO, Thor Odin area; VC, Valhalla complex; VSZ, Valkyr shear zone; WF, Waneta fault. GWF (Greenwood fault system) is a composite system of west dipping normal faults including Deadwood Ridge, parts of Greyhound and Windfall Creek, and McCarren Creek faults of Little [1983] with offset measured in kilometers. For the sake of clarity, a fault trace, termed GWF, is shown which predominantly bounds the Eocene strata on the east. Age determination localities are shown with symbols and identified with letters (see Tables 1 and 2, appendix, and Figure 5).


B.C.
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Purcell
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Galena Bay Stock
South Foothill Pluton
P
OC
VC
GCSZ
VSZ
SLF
GWF
GF
KF
HLF
SMF
MF
A
B
C
D
E
F
Revelstoke
Sicamous
Vernon
Kelowna
Penticton
Nakusp
Nelson
Castlegar
Creston
Greenwood
ADAMS LAKE
SHUSWAP LAKE
OKANAGAN LAKE
COLUMBIA RIVER
ARROW LAKE
SLOCAN LAKE
KOOTENAY LAKE
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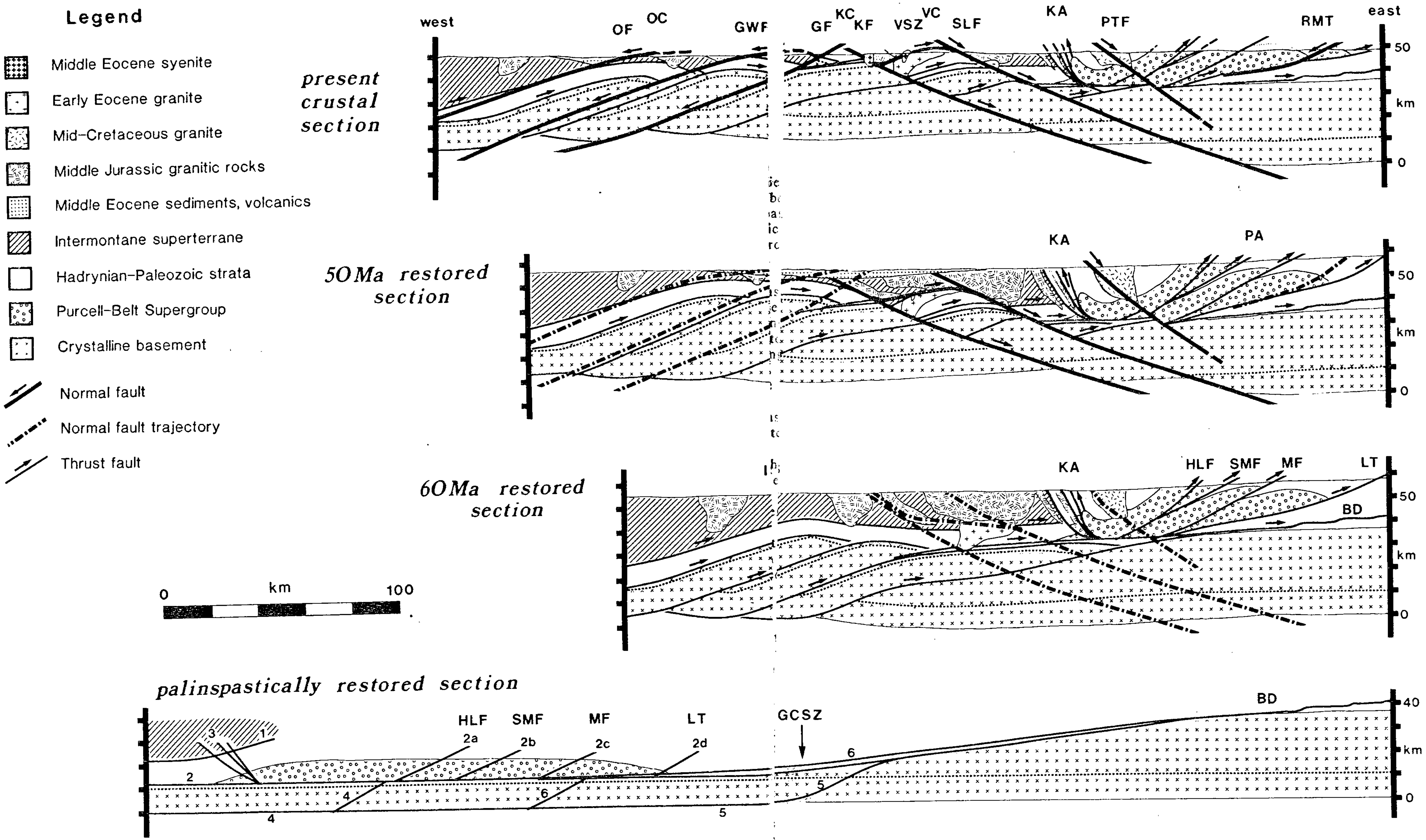

Plate 2. Present and restored crustal cross sections drawn without exaggeration along lines shown in Plate 1. These sections are modified only slightly from those of Parrish and Carr [1986]. Large bodies of granitic rock are omitted to illustrate the interpretation of the structure as presented in this paper. Hadrynian and Paleozoic rocks of North American affinity are shown without shading. Top, present crustal structure; the crustal architecture consists of predominantly Early Eocene east dipping major normal faults (KF, VSZ-SLF, PTF) which are in part truncated by Middle Eocene west dipping normal faults (OF, GWF, GF). High grade metamorphic core complexes are exposed at the surface because of extensional faulting; the age of metamorphic rocks within the Okanagan, Kettle, and Valhalla complexes, and elsewhere at depth is inferred and uncertain. Second from top, cross section restored to about 50 Ma; the Early Eocene normal faults are shown as heavy solid lines, and the trajectories of the "future" west dipping Middle Eocene faults are dashed; Middle Eocene strata are interpreted to have been depos ted in a basinal area near the breakaway zone(s) of the Kettle and Sloca Lake faults above thinned crust. Third from top, cross section resto ed to about 60 Ma, prior to any extensional faulting and crustal thin ng; crustal thickness is in excess of 50 km, no prominent culm ations of basement rock are shown, and no metamorphic comp xes were exposed to erosion. Early Eocene fault trajectories are show as heavy dashed lines. Bottom, section palinspastically restored prior o shortening. Solid lines show the approximate locations of future thrus faults, with numbers corresponding to a proposed order of sequ tial development. Letters used are the same as listed in Plate 1 with he addition of IS, Intermontane superterrane; KA, Kootenay Arc; PA, ırcell Anticlinorium; RMT, Rocky Mountain Trench; LT, Lewis thrus , and BD, basal decollement.

displacement to yield the geometry at about 50 Ma (Plate 2, second from top), the second, by removing all Early Eocene extensional faulting to yield the crustal geometry at the close of the compressional period, about 60 Ma (Plate 2, third from top), and finally by palinspastically restoring some of the continental margin rocks (Purcell supergroup) to their position prior to late Mesozoic-Paleocene thrusting (Plate 2, bottom).

Restoration of displacement on the Kettle, Slocan, Valkyr, and Purcell Trench faults yields a crustal geometry which existed at the close of the compressional period, as depicted in Plate 2. The pre-extended crust was much thicker than today, perhaps 60 km. The Valhalla and Grand Forks-Kettle complexes restore to nearly adjacent positions in the middle crust and are very near a zone of compressional thrusting presumed to be above crystalline basement. The basement is likely to have experienced significant duplication, and we have incorporated this by duplex geometry with reactivated roof thrusts. The geometry of the Monashee complex has been interpreted by Brown et al. [1986] and Monger et al. [1986] as a Mesozoic culmination, whereas we would suggest that the presently exposed Monashee culmination may be a result of arching and denudation on Eocene extensional faults with less structural relief at the close of Paleocene time. The middle to lower crustal duplex or duplication geometry can be drawn any number of different ways as long as foreland thrusting is balanced in the hinterland.

Plate 2 depicts our interpretation of Cordilleran structural geometry before the widespread disruption of the extensive Middle Eocene volcanic and sedimentary basin(s) on mostly west dipping normal faults. Some modest tilting of footwall blocks has been allowed to effect a sensible restoration as indicated by reversals in dip of normal faults. The upper plate of the Valkyr shear zone is presumed to be tilted, deformed, and extended over a wider area than originally present. The subsurface location of normal faults is shown to be both coincident and divergent from older thrust boundaries. This indicates our opinion that such normal faults need not necessarily follow preexisting anisotropies or old faults. In any case, the details of subsurface structure below 5 km are speculative. Implicit in this restoration is that the formation of the large Middle Eocene volcanic-sedimentary basin was spatially related to both the subjacent Coryell syenitic rocks of the same age and the "depression" created by the breakaway zone and crustal thinning related to slightly older east dipping faults (Kettle River fault, Valkyr shear zone, Slocan Lake fault).

IMPLICATIONS OF RESTORED CROSS-SECTIONS

These cross sections have important implications for the tectonic history of the southern Omineca Belt.

1. All major exposures of Eocene stratified rock west of the Grand Forks complex can be interpreted as being part of a single large basin (Plate 2, second from top). The stratigraphic correlation between several of these exposures [see Church, 1973, 1982] supports this interpretation.

2. The derivation of sediments in this basin may have been mostly from the west because during deposition the crust may have remained thicker and therefore at a higher elevation to its west because of Early Eocene normal faulting to the east. Generally there was little or no sedimentary contribution from metamorphic complexes, which were still deeply buried.

3. Except for a metamorphic belt of Jurassic-Cretaceous age along the Kootenay Arc (Plate 1) that is generally characterized by westerly verging structures, all presently exposed high-grade metamorphic complexes were at middle (10-20 km) crustal levels at the close of the compressional phase (Paleocene time) and were not exposed to erosion.

4. The Mesozoic metamorphic belt along the Kootenay Arc [Archibald et al., 1983], which formed during terrane accretion, was uplifted by backthrusting as the amalgamated Intermontane superterrane and its Paleozoic-Proterozoic substrate of North American affinity were thrust beneath it from the west, perhaps during continuing eastward transport toward the foreland (Plate 2, third from top). This tectonic style is present along the once continuous western edge of the Omineca Belt [Wheeler and Gabrielse, 1972; Price, 1986], including the northern Kootenay Arc [Klepacki, 1986], Shuswap Lake area [Schiarizza and Preto, 1984], the Cariboo Mountains [Ross et al., 1985; Brown et al., 1986; Murphy, 1987], and farther north in northern British Columbia [Gabrielse, 1985].

5. The Mesozoic west verging structural and metamorphic culmination in the central Kootenay Arc can be correlated by structural style, timing, and lithology with the Shuswap Lake - Adams Plateau region (Plate 1) [Schiarizza and Preto, 1984; Preto and Schiarizza, 1985]. This once continuous belt has been dissected by both east and west directed Eocene normal faults.

6. Culminations of compressional origin may have been formed by basement duplexing [Brown et al., 1986; Monger et al., 1986], but the compressional structural relief was much less

than at present (Plate 2), need not have coincided spatially with present culminations, and may not have been exposed to erosion until the Eocene [Price, 1981a; Ewing, 1981]. Most of the arching in these complexes is a result of extension. Price [1985] has also argued this because the trends of extensional and compressional structures from 49°N to 51°N are generally different.

7. The Gwillim Creek shear zones, exposed at the deepest levels of Valhalla complex, are interpreted as deep seated middle crustal compressional thrust faults, which were active at depths of 15 to 20 km in latest Cretaceous to Paleocene time (Plate 2). Present depth to the sole fault above passive(?) basement beneath the Purcell Anticlinorium has been suggested to be about 15 km [Price, 1981b], a value consistent with recent seismic reflection data of Cook et al. [1987] and Price et al. [1986]. The Gwillim Creek shear zones may form the very prominent seismic reflector in southern Valhalla complex [Cook et al., 1987]. Prior to extension these fault(s) restore to a location in the crust at which major east directed compressional shear zones were active (Plate 2). We feel this adds plausibility to our magnitude of extension estimates and although the reasoning is somewhat circular, it is entirely consistent. If true, the age of the Gwillim Creek shear zones should include important Late Cretaceous to Paleocene(?) movement, concurrent with the east directed displacement in the Rocky Mountain foreland. The geochronology of the zone is consistent with this [Carr et al., 1987; Parrish et al., 1987; R. R. Parrish, unpublished data, 1986], although the minimum age constraints are not yet precise. The deep-seated shear zones are exposed today not because of a compressional culmination but rather as a result of large-magnitude extensional faulting and tectonic denudation.

8. The distance between Purcell Trench (southern Kootenay Lake) and the hanging wall rocks west of Okanagan valley has been increased by 80%, and the overall extension across the Omineca Belt relative to a pin at the Lewis thrust is about 30%, the difference in length of present and 60 Ma restored sections of Plate 2. This extension was accomplished on four or five major faults over a maximum of 15 Ma. Such rates of extension are comparable to most estimates in the Basin and Range province of the western United States [Sonder et al., 1987].

DISCUSSION

It has taken some time for widespread extensional deformation to be recognized in the southern Omineca Belt. In contrast to Basin and Range examples [see Crittenden et al., 1980], Eocene strain is difficult to document, largely because Eocene stratified rocks and brittle structures are less common. These circumstances served to prolong both resistance to the views advocating ductile extension [Price, 1979, 1981a, 1985; Ewing, 1981] and adherence to opposing views that extensive faults with metamorphic omission were Mesozoic thrusts and that metamorphic complexes were affected by an Eocene thermal or reheating event [Ross, 1981; Read and Brown, 1981; Brown and Read, 1983; Okulitch, 1984].

It is probable that an increasing amount of evidence will surface in the high grade terranes for Late Cretaceous to Paleocene compressional, metamorphic, and intrusive events. Some will have been overprinted by extensional structures. The explanation envisioned for the quite different environments and history of deformation and metamorphism of the two domains of the southern Omineca Belt, namely, the hanging walls which were at low temperatures and metamorphic grades in the Eocene and the much warmer high-grade footwalls, is that they originated and evolved in different levels of the crust which did not always experience the same tectonic events and certainly did not have the same rheology. Only late in the extensional episode were they juxtaposed.

Concerning the cause of extension, there are probably two important considerations: (1) a favorable preexisting thermal and rheological regime in the crust and (2) an externally induced tectonic cause such as that recently outlined in the model of Sonder et al. [1987]. At the end of the Paleocene the crust is considered to have been thick (about 60 km), warm, and therefore weak, with a temperature at the base of the crust probably exceeding 700°C, as implied by the abundance of midcrustal granitic rocks of Paleocene and Eocene age. Any area underlain by thickened, isostatically compensated crust exerts a gravitationally induced compressive stress on surrounding regions of lower elevations [Artyushkov, 1973]. In fact, it has been argued that the strength of continental lithosphere in compression is directly reflected by the elevations attained by high plateaus [Molnar and Tapponnier, 1978; Dalmayrac and Molnar, 1981]. Thus areas of significantly thickened crust are inherently unstable; a reduction of supporting compressive stress in adjacent regions should result in extensional collapse. This view is qualitatively supported by the model of Armstrong [1982] and Coney and Harms [1984] for Cordilleran core complexes.

Price [1979], Price et al. [1985] and Price and Carmichael [1986] have suggested that extension was due to transformation of strike-slip displacement from the Tintina-Northern Rocky Mountain Trench fault zone to the en echelon Fraser River-Straight Creek fault zone when the later came into existence in Eocene time. The northward tapering of the extended terrane into a narrow zone north of 54°N bounded by dextral transcurrent faults adds plausibility to this model. The beginning of extension is roughly coincident with changes in plate motion in the northeast Pacific, as outlined by Engebretson et al. [1985]. Such changes may have significantly reduced the overall horizontal compressive stress exerted in this region. The end of extension coincides in time with both the major bend in the Hawaiian-Emperor seamount chain (about 42 Ma) and the conclusion of displacement on the Fraser River-Straight Creek strike-slip fault zone (pre-35 Ma [Price and Carmichael, 1986]). These externally induced boundary conditions may have been the main causes for the extensional tectonic failure within the southern Omineca Belt.

We concur with the model of Sonder et al. [1987] that both a thick, weakened crust and an external tectonic cause collaborated to produce extensional collapse; if crustal thickening alone were sufficient to induce crustal scale extensional failure [Brown and Journeay, 1987], then it should have occurred earlier and perhaps at a number of different times instead of being restricted in time to the Eocene. In addition, the voluminous early Eocene (circa 57 Ma) magmatism of southern British Columbia significantly contributed to providing or maintaining a thermally weakened rheological state of the crust.

Although this paper is primarily about extension, we stress the very complex history of the Omineca Belt. A careful examination and synthesis of all tectonic aspects, but particularly the extensional ones, are required if a comprehensive and reasonably accurate model of the older compressional and accretionary history is to be constructed.

APPENDIX 1. U-Pb, Rb-Sr, AND K-Ar ANALYTICAL PROCEDURES AND SAMPLE LOCALITIES

Minerals were separated from 5 to 30 kg specimens by standard crushing, grinding, Wilfley table, heavy liquid, and magnetic techniques. Zircons and monazites were selected for analysis by handpicking in alcohol. Analyses labeled "a" in Table 1 were abraded in air using the method of Krogh [1982]. Mineral separates for Rb-Sr and K-Ar dating were given an ultrasonic leaching step in 2N HNO_3 for 20 min followed by rinsing in high-purity H_2O. Zircons and monazites were leached 30 min in warm 3N HNO_3 prior to dissolution. Analytical errors for analyses in tables refer to one standard error of the mean, whereas errors in ages of samples are quoted as two standard errors of the mean. Error ellipses in Figures 4 and 5 are plotted as two standard errors of the mean. Decay constants used are from Steiger and Jager [1977].

U-Pb methods. Zircons and monazites were spiked with either a mixed ^{233}U-^{235}U-^{208}Pb (prior to July 1985) or a mixed U-^{205}Pb (after July 1985) tracer prior to dissolution. Lead 205 tracers used were from Krogh and Davis [1975] and more recently from Parrish and Krogh [1987]. Zircon dissolution and zircon and monazite chemistry follow methods modified from Krogh [1973], in part utilizing Teflon vessels described by Parrish [1987]. Monazites were dissolved in 12N HCl at 150°C, whereas dissolution conditions for zircons were 48% HF at 230°-240°C for 30-60 hours. Procedural blanks varied from about 200 pg (1983) to 10 pg (1987) Pb and 1-50 pg U. Isotopic compositions of Pb and U were measured on a MAT 261 multicollector mass spectrometer, as described by Roddick et al. [1987]. Corrections for common Pb use the model of Stacey and Kramers [1975], assuming a common Pb age equal to the interpreted age of the sample. Pb/U errors have been estimated for pre-1986 analyses from reproducibility of standards and sample aliquots and after early 1986 by direct propagation of errors [Roddick, 1987]. Where used, concordia intercepts have been estimated by a modified York [1969] regression, as described by Parrish et al. [1987b]. U-Pb monazite ages used are the $^{207}Pb/^{235}U$ ages because of the problem of excess ^{206}Pb from ^{230}Th decay in Th-rich minerals as described by Scharer [1984]. Where concordant analyses (error ellipses substantially overlapping the concordia curve) are present, the mean of and overlap with concordia are the accepted age and error, respectively.

Rb-Sr and K-Ar methods. Rb-Sr methods utilize a mixed ^{85}Rb-^{84}Sr tracer and standard HF dissolution and HCl chemistry. Isotopic composition measurements also utilize a MAT 261 machine. Errors in $^{87}Rb/^{86}Sr$ are estimated at +/-1% for two standard errors of the mean. Two-point errors are calculated by considering the extremes of the errors for muscovite and feldspar pairs. K and Ar concentrations were determined by standard atomic absorption techniques and isotope dilution mass spectrometry utilizing an ^{38}Ar spike.

Sample descriptions and localities. Lithologies and UTM coordinates of samples for U-Pb and Rb-Sr dating are as follows:

225-85, weakly foliated leucocratic biotite granite, 2301 m elevation, 200 m southeast of mouth of "south Nemo" lake, upper Nemo Creek, UTM 11u, 4555E-55319N;
453-83, strongly foliated S-C mylonitic leucocratic biotite granite, 640 m elevation 1 km east of Slocan village on highway roadcut, UTM 11u, 4670E-55126N;
WB-83, strongly foliated and altered leucocratic granitic mylonite, roadcut on west side Slocan River at Winlaw bridge, UTM 11u, 4591E-54959N;
519-83, massive to weakly foliated leucocratic biotite granite, upper Russell Creek, elevation 1356 m, UTM 11u, 4392E-54930N;
407-83, muscovite bearing altered leucocratic granitic S-C mylonite, elevation 1463 m on Pedro Creek logging road, UTM 11u, 4605E-54898N;
SC-84, muscovite bearing altered leucocratic granitic S-C mylonite, elevation 732 m, Springer Creek logging road 2 km east-southeast of Slocan village, UTM 11u, 4676E-55122N;
83-85, unfoliated cross-cutting leucocratic pegmatite, elevation 2256 m on ridge crest west of upper Norns Creek, 6.5 km north of Ladybird Mountain, UTM 11u, 4413E-54812N;
21-84, massive hornblende-biotite-pyroxene syenite with local shears, point of land at shore of Lower Arrow Lake on highway 1 km west of mouth of Allandale Creek, UTM 11u, 4376E-54658N;
121-84D, mafic-free cross-cutting aplite intruding upper Gwillim Creek shear zone, elevation 2256 m, 1.5 km northwest of Gladsheim Peak, UTM 11u, 4536E-55154N;
ST-85-1, massive hornblende-biotite granite/quartz monzonite, elevation 1920 m on ridge between Blueberry and China creeks, UTM 11u, 4447E-54561N;
FOSTHALL-1 and FOSTHALL-2, muscovite bearing altered leucocratic granitic S-C mylonite of south Fosthall pluton, 1 km southeast of confluence of Fosthall and Vanstone Creeks, west side of Upper Arrow Lake, UTM 11u, 4288E-55834N, locality E of Plate 1;
PINGSTON CREEK, muscovite bearing altered leucocratic granitic S-C mylonite of south Fosthall pluton (?), north side of bridge across Pingston Creek canyon 1 km west of Upper Arrow Lake, UTM 11u, 4311E-55877N, locality F of Plate 1;
SUGAR MTN, massive muscovite-biotite leucocratic granite, elevation 1006 m on road to Sugar Mountain about 2.5 km southwest of Sugar Mountain, UTM 11u, 3977E-55871N, locality D of Plate 1;
7-84, folded synkinematic sill of foliated leucocratic biotite granite/quartz monzonite, east shore Vaseaux Lake on highway road cut 1.3 km south of Provincial Park, UTM 11u, 3166E-54624N, locality B of Plate 1;
RHOMB PORPHYRY, foliated and mylonitic anorthoclase-pyroxene-hornblende-biotite-garnet porphyritic sill, north side of Covert farm, 1.5 km west of McIntyre Bluff north of Oliver, UTM 11u, 3143E-54584N, locality A of Plate 1.

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