Late Cretaceous to Paleogene cooling adjacent to strike-slip faults in the Bridge River area, southern British Columbia, based on fission-track and ^{40}Ar-^{39}Ar analyses

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Abstract: Zircon fission-track (ZFT) ages and ^{40}Ar-^{39}Ar ages on biotite and hornblende are used to constrain the timing of low-temperature cooling in the Bridge River area of southern British Columbia. Cooling ages at ~78-75 Ma and ~55-52 Ma (ZFT), from the Dickson and Bendor plutons respectively, may be related to either normal cooling of high-level plutons by conduction or to cooling induced by erosional or tectonic denudation, possibly driven by strike-slip faulting. Zircon fission track ages of rocks cut by the Marshall Creek fault, and from rocks in the footwall of the fault system indicate movement must have occurred during the interval ~43 to 39.5 Ma. This episode of movement on the Marshall Creek fault may be kinematically related to dextral strike-slip faulting on the Fraser fault system.

Résumé : La datation du zircon par la méthode des traces de fission (TFZ) et les âges $^{40}Ar/^{39}Ar$ sur biotite et sur hornblende permettent de préciser les limites dans le temps de l'épisode de refroidissement à basse température reconnu dans la région de Bridge River, dans le sud de la Colombie-Britannique. Les âges de refroidissement, évalués à 78-75 Ma et à 55-52 Ma (TFZ), pour les plutons de Dickson et de Bendor respectivement, pourraient être liés soit à un refroidissement normal par conduction de plutons mis en place à faible profondeur, soit à un refroidissement dû à une dénudation érosionnelle ou tectonique, causée peut-être par le jeu de décrochements. Les âges obtenus par la méthode des traces de fission sur zircon des roches traversées par la faille et des roches du mur du système de failles indiquent que le mouvement a dû se produire dans l'intervalle de 43 à 39,5 Ma. Cet épisode de mouvement dans la faille de Marshall Creek pourrait être relié cinématiquement au décrochement dextre s'étant produit dans le système de failles du Fraser.

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INTRODUCTION

The Bridge River area is located on the eastern flank of the Coast Range, about 200 km north of Vancouver, British Columbia, and is located between the Insular terrane to the west and the Intermontane terrane to the east (Fig. 1). The area is underlain by several distinct tectonostratigraphic terranes, which are blanketed by upper Middle Jurassic to upper Cretaceous strata of the Tyaughton basin. The basement terranes and the basin strata are intruded by plutonic rocks which represent the eastern margin of the Coast Plutonic Complex (Roddick and Hutchison, 1973; Woodsworth, 1977; Monger and Journeay, 1992). These igneous rocks are important in that they provide some of the only constraints on the timing of structural development in the area. The Tyaughton basin strata are interpreted to rest unconformably on volcanic and volcanic-rich sedimentary rocks of the Upper Triassic Cadwallader terrane (Schiarizza et al., 1989, 1990 and references therein). Structurally interleaved with the Cadwallader terrane and strata of the Tyaughton basin is the Bridge River Complex, which is composed of highly deformed oceanic rocks that range in age from Mississippian to Middle Jurassic based on radiolarians and conodonts from chert and limestone (Cordey and Schiarizza, 1993). Clastic rocks of the Cayoosh assemblage, which may be Jura-Cretaceous in age, may rest unconformably on rocks of the Bridge River Complex (Fig. 1; Monger and Journeay, 1992).

Cretaceous to Paleogene contraction and strike-slip faulting dominate the regional structural pattern, and considerable controversy surrounds the timing and style of deformation. Mid-Cretaceous orogenesis involved significant northeast-southwest and east-west contraction, but the role of contemporaneous strike-slip faulting is uncertain. Directly to the south of our area, Journeay and Friedman (1993) have documented a distinct period of west-vergent contraction that occurred between ~97 to 91 Ma. In the Bridge River area, mid-Cretaceous contraction was followed by a discrete phase of strike-slip faulting (Schiarizza et al., 1989, 1990; Garver et al., 1989; Garver, 1991). An important and unresolved question, in terms of the regional geology of this area, centres around the timing of initiation, duration, and magnitude of strike-slip faulting. Umhoefer and Schiarizza (1992) have proposed that slip on strike-slip faults stepped from southwest

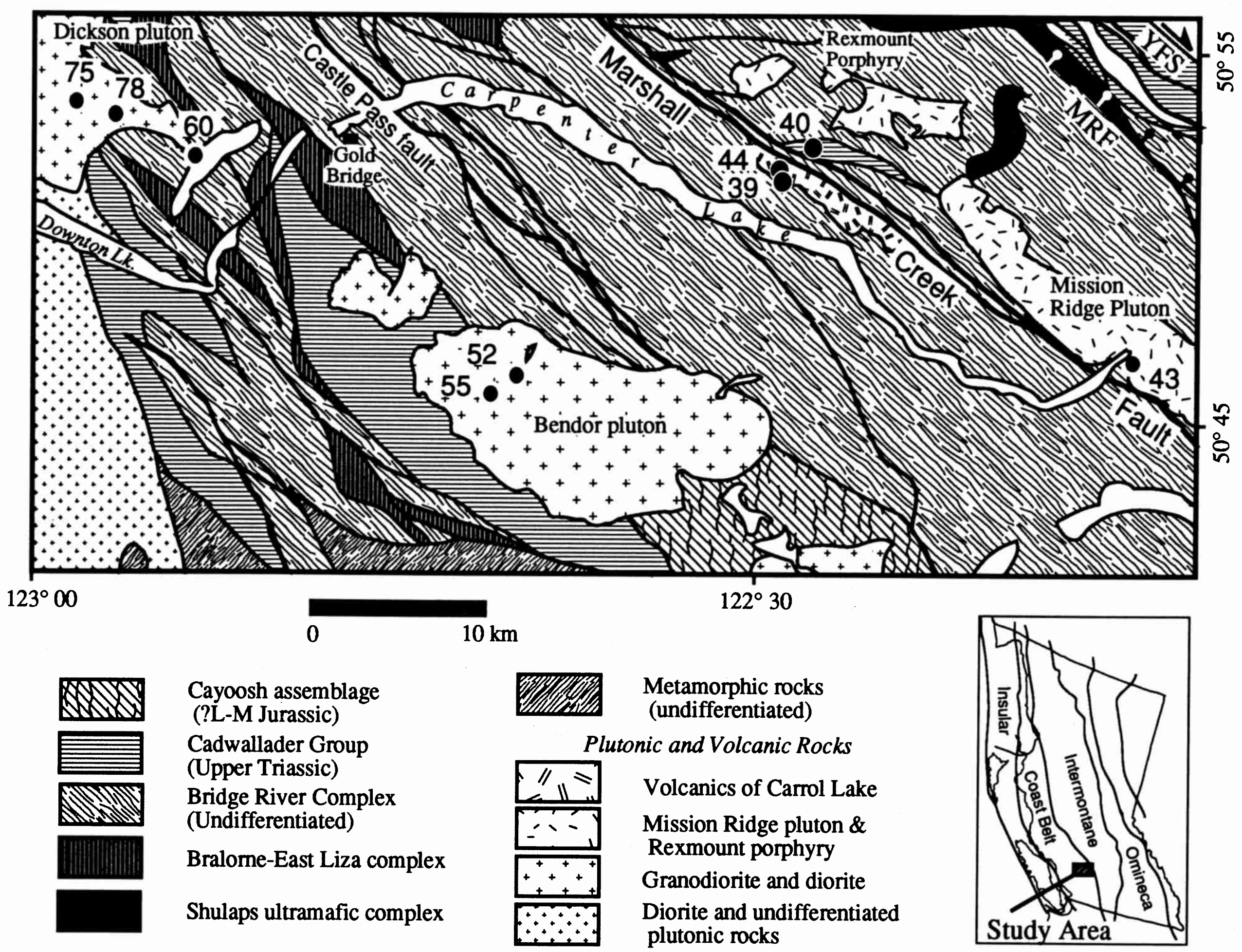

Figure 1. Location and generalized geology of the study area showing zircon fission-track ages. See Table 1 for ages and units; Ar-Ar ages are in Table 2. Figure modified from Monger and Journeay (1992).

to northeast as the system accommodated transfer of movement from the northwest-trending Yalakom fault system to the north-trending Fraser-Straight Creek fault system.

Zircon fission track (ZFT) age determination allows us to estimate the time at which rocks have cooled below about 240 ± 40°C (Brandon and Vance, 1992), and the Ar-Ar total fusion dates reported here correspond to cooling below about 280 ± 40°C for biotite and about 500 ± 50°C for hornblende, although the closure in both systems is dependent on the rate of cooling. Previous work indicates that the low-temperature cooling of the Coast Plutonic Complex (CPC) occurred at relatively slow rates in the early Tertiary, but cooling adjacent to the strike-slip faults in the Bridge River area occurred much more rapidly (Parrish, 1983). The location of our study area allows us to examine the cooling from the eastern flank of the Coast Plutonic Complex into and across this strike-slip fault system.

SAMPLING AND LABORATORY METHODS

Fission-track dating

For zircon fission-track analysis, our procedures for sample preparation and dating are similar to those outlined in Naeser (1976) for the external detector method. The Zeta method was used to provide calibration to an age standard and glass dosimeters were used in all irradiation packages (Wagner and van den Haute, 1992). The dated zircon fractions, which were non-magnetic with grain sizes between +200 and -60 mesh, were mounted in FEP Teflon, polished, and etched at 225°C for 12 to 20 hours. Low-uranium muscovite flakes were affixed to the Teflon mounts and the mounts were irradiated at the Oregon State nuclear reactor using a nominal fluence of 2 x 10^{15} neutrons/cm^2. The CN-5 glass standard, which was placed at the top, middle, and bottom of the irradiation tube, was used to monitor the fluence. Zircon mounts of the Fish Canyon Tuff were also irradiated and were used to determine a Zeta factor for JIG and WFV (see Table 1). Fission tracks were counted at 1250X using an oil immersion objective on an Olympus BH-2 petrographic microscope. The ages, Zeta factors, glass dosimeter densities were calculated using the computer programs of Brandon and Vance (1992).

Ar-Ar analysis

Unknowns and flux monitors (standards) were irradiated with fast neutrons at the McMaster nuclear reactor for 29 hours. Although monitors were spaced throughout the irradiation container, J-values for the samples were determined by comparison to values from a well-characterized sample (TL88-17); calibration to the flux monitors may change these ages slightly and as a result the Ar-Ar total fusion ages in this report should be considered preliminary. The ultra-high vacuum, stainless steel argon extraction system is operated online to a substantially modified A.E.I. MS-10 mass-spectrometer run in the static mode. Measured mass-spectrometric ratios were extrapolated to zero time, corrected to a $^{40}Ar/^{39}Ar$ atmospheric ratio of 295.5 and corrected for neutron induced ^{40}Ar from potassium and ^{39}Ar and ^{36}Ar from calcium. Dates and errors are calculated according to the methods of Dalrymple et al. (1981) and the constants used are those recommended by Steiger and Jäger (1977). The errors shown in Table 2 represent the analytical precision at 2% assuming a J-value error of zero.

RESULTS

Our fission track data and Ar-Ar data are from three principal regions in the Bridge River area: the Dickson peak area in the western part of the area, the Eldorado pluton and the Bendor

Table 1. Summary of zircon fission track (ZFT) data.

	Number	Unit/Area	Elev.	Ns	Ni	ρd x 10^5 cm^{-2}	N	χ^2%	U (ppm)	Pooled age	Mean Age
1	WV-08	Unk. ss; Carrol Lk.	4020'	1464	1468	2.289	10	29.7	229	39.1 ± 5.1	39.8 ± 5.6
2	WV-07	Rhy vx; Carrol Lk.	5120'	1068	965	2.296	9	80.4	369	43.5 ± 6.1	43.5 ± 5.4
3	WV-06	Hurley Cg. clast	7120'	366	366	2.307	6	85.8	159	39.5 ± 7.5	39.3 ± 5.9
4	JG - 01	Bendor; tarn	6300'	925	789	2.777	7	8.2	242	52.0 ± 6.4	52.1 ± 8.2
5	JG - 02	Bendor; ridge crest	8150'	947	775	2.791	9	51.9	199	54.5 ± 6.7	55.1 ± 6.2
6	JG - 03	Mission Rdg. Plut.	2000'	883	926	2.806	7	2.9	356	42.8 ± 5.1	42.9 ± 7.4
7	JG - 04	Dickson; Slim Ck.	4490'	861	416	2.749	7	11.1	206	90.7 ± 13.2	94.3 ± 19.4
8	JG - 05	Dickson; Roxy Ck.	5940'	937	627	3.271	7	42.2	220	78.0 ± 9.8	80.6 ± 11.0
9	JG - 06	Dickson Pk.	7560'	1133	761	3.140	10	95.3	224	74.6 ± 8.8	75.4 ± 8.8
10	JG - 08	Dickson; Gun Lk.	2820'	894	794	3.324	7	32.1	401	59.8 ± 7.3	61.0 ± 7.8

Notes: ZFT ages calculated using the Zeta method of calibration (see text). Counting parameters as follows: 1) Van Order (WV samples) Zeta = 346.26 ± 15.36 (± 1 se); 2) Garver (JG) Zeta = 320.97 ± 7.79 (± 1 se). Ns = number of spontaneous tracks; Ni = number of induced tracks. ρd = density of tracks on the glass dosimeter extrapolated to the position of the sample. χ^2 % is the probability (%) that grain ages are representative of a single population; the $\chi2$ test is failed when the probability falls below 5%. The pooled age (age calculated from the total Ns/Ni) is preferred when the sample passes the $\chi2$ test, and the mean age (mean of individual grain ages) is used when the sample fails $\chi2$. For both the Mean age and the Pooled age, the error shown is the 95% confidence interval.

Table 2. Summary Ar-Ar total fusion data.

Number	Unit/Area	Mineral	Grain size	Mass	$^{40}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	Vol $^{39}Ar^1$	%^{40}Ar rad	Age (± 2σ)
JG - 01	Bendor; tarn	biotite	40/60	45	5.670	0.0018	0.017	17.268	91.79	64.36 ± 0.34
JG - 02	Bendor;ridge crest	biotite	60/80	74	6.288	0.0062	7.816	2.118	71.10	62.86 ± 1.79
JG - 02	" "	hnb	+40	59	5.527	0.0012	0.039	20.110	93.60	63.99 ± 0.28
JG - 04	Dickson; Slim Ck.	biotite	+40	56	7.782	0.0011	0.016	21.662	95.75	91.35 ± 0.21

Note: Dates are calculated relative to a previous age determination on TL87-17 (biotite). For these data 47 mg of a 40/60 mesh split of TL88-17 gave an age of 67.06 ($^{40}Ar/^{39}Ar$ = 5.927; $^{36}Ar/^{39}Ar$ = 0.0017; Vol ^{39}Ar = 17.286; %^{40}Ar rad = 91.50). J values used for all samples are 7.0150e3. (1) Vol ^{39}Ar is in units of E-08 cm^3.

Range in the south-central part of the study area, and rocks along the Marshall Creek fault northeast of Carpenter Lake (Fig. 1).

Dickson pluton

The Dickson pluton is composed of granodiorite to diorite. Two samples from high elevations yield zircon fission track ages within error of one another: one from the southern flank of Dickson Peak (7560′), gave an age of 74.6 ± 8.8 Ma, and a second sample from the upper reaches of Roxy Creek (5940′) gave an age of 78.0 ± 9.8 Ma (Table 1). A sample from a small arm of the pluton at a low elevation (2820′) (Woodsworth, 1977), has a zircon fission track age of 59.8 ± 7.3 Ma (Table 1). An Ar-Ar total fusion age of 91.35 ± 0.21 Ma on biotite and a zircon fission track age of 90.7 ± 13.2 Ma were obtained from a sample collected at the edge of the pluton along Slim Creek (just off the northwest corner of Fig. 1; 4490′; Tables 1, 2).

Eldorado pluton

The main intrusion of the Eldorado pluton is a biotite-hornblende granodiorite but smaller related stocks and a wide alteration zone are present in this area (Garver et al., 1989). A sample from the centre of the pluton gives a ^{40}Ar-^{39}Ar plateau age on biotite of 67.05 ± 0.88 Ma (D.A. Archibald, unpub. data). The excellent plateau age, and the presence of zircon, apatite, biotite, and amphibole, make this sample a possible candidate for an age standard.

Bendor pluton

One of several granodioritic plutons in the Bendor Range, the Bendor pluton is a biotite-hornblende granodiorite that is the largest in the suite of Bendor intrusions (Roddick and Hutchison, 1973). Our zircon fission track data from different elevations indicate cooling below the zircon closure temperature at about 55-52 Ma (Table 1). We obtained a younger age (52.0 ± 6.4 Ma) from a low elevation sample (~6300′) and a slightly older age (54.5 ± 6.7 Ma) from a sample taken from a nearby ridge crest (~8150′). Three Ar-Ar total fusion ages are from these same two samples (Table 2); both samples yield biotite ages within error of each other with an average age of ~63.5 Ma, and a hornblende age of ~64 Ma (Table 2).

Mission Ridge pluton and adjacent rocks

We sampled rocks on both sides of the northwest-trending Marshall Creek fault (MCF) to better constrain the timing of movement (Van Order, 1993). On the southwest side of the fault, in the Carrol Lake area, a zircon fission track age of ~39 Ma was obtained from detrital zircon from the lithic arkosic sandstones that are interbedded with and underlie rhyolitic and dacitic pyroclastic rocks (unit 12 of Roddick and Hutchison, 1973). Because these sandstones contain a significant percentage of felsic volcanic fragments, we suggest that this age represents a maximum age of deposition. In this same stratigraphic section, a zircon fission track age of 43.5 Ma was obtained from the overlying volcanics. As an age of this stratigraphic section, we favour the age of the volcanics (~43.5 Ma) over the age obtained from the detrital zircon because of problems associated with variable etch properties of detrital fission track samples. On the northeast side of the fault, we have obtained a zircon fission track age of 39.5 ± 7.5 Ma from a granitic clast in metamorphosed conglomerates of the Upper Triassic Hurley Formation (Schiarizza et al., 1990). Zircons from the Mission Ridge pluton, at the Terzaghi Dam, yield a mean zircon fission track age of 42.9 ± 7.4 Ma.

DISCUSSION OF AGE DATA

Dickson pluton

The Dickson pluton, at the western edge of the study area and at the eastern edge of the Coast Plutonic Complex, has a U-Pb age of 92.4 ± 0.3 Ma (Parrish, 1991). The Ar-Ar total fusion age of ~91 Ma on biotite and a zircon fission track age of 90.7 ± 13.2 Ma are close to the crystallization age of the pluton. These ages indicate rapid cooling, presumably at the border of the pluton, at a relatively high level (<~9 km - the approximate closure depth of fission-tracks in zircon). Zircon fission track ages in the centre of the pluton and from low elevations (JG-5, 6, 8) indicate cooling below the zircon closure temperature at about 78 to 60 Ma. Farther to the northwest, Archibald et al. (1989) reported an Ar-Ar total fusion ages of 82 Ma (hornblende) and 71.8 Ma (biotite) from what has been mapped as the same plutonic body. An Ar-Ar total fusion age of 78 Ma (sericite) was obtained from the alteration zone around the pluton. The Dickson pluton is presently poorly mapped, and it is not clear if the plutonic body as mapped is composite or if younger plutons are present.

Bendor and Eldorado plutons

Friedman and Armstrong (in press) reported a discordant U-Pb crystallization age of 64 +11/-2 Ma for the Bendor pluton; the fractions cluster below concordia and the age is difficult to interpret. The actual crystallization age may be similar to the age of the Eldorado pluton (~67 Ma). Our Ar-Ar total fusion ages of ~63.5 (biotite) and ~64 Ma (hornblende) indicate very rapid cooling during this time, suggesting crystallization and cooling at shallow levels. A K-Ar age of ~59.5 Ma (biotite - Wanless et al., 1978) from the centre of the pluton is slightly younger than our Ar-Ar total fusion age on biotite. Both zircon fission track samples, taken from different elevations, give ages that are within analytical error.

Mission Ridge pluton and adjacent rocks

The Mission Ridge pluton, which intrudes metamorphic rocks of the Bridge River Complex ("Bridge River schist"), lies in the footwall to the low-angle Mission Ridge fault and the high-angle Marshall Creek fault. The map relations, kinematics, and timing constraints of these faults have been recently studied by Coleman and Parrish (1991) and Schiarizza et al. (1990). The Mission Ridge fault separates high-level, low-grade rocks of the Bridge River Complex (and overlying sedimentary rocks) in the hanging wall, from the Bridge River schists and intrusives in the footwall; the footwall was exhumed during movement on both faults (Coleman and Parrish, 1991). The Marshall Creek fault cuts the Mission Ridge pluton which has a U-Pb date of 47.4 ± 0.3 Ma (Coleman and Parrish, 1991). An ^{40}Ar-^{39}Ar age of 46.4 Ma on biotite from a high elevation (~8600′) biotite reaction zone, in a footwall position at the southern edge of the Shulaps ultramafic complex (Archibald et al., 1991), indicates cooling that was perhaps related to tectonic denudation caused by movement on the MRF (Coleman and Parrish, 1991). The Marshall Creek fault juxtaposes low-grade rocks of the Bridge River Complex and unconformably overlying Tertiary(?) volcanics and sedimentary rocks on the southwest against Bridge River schists and metamorphosed rocks of the Cadwallader Group on the northeast (Schiarizza et al., 1990). In the Carrol Lake area, the Marshall Creek fault cuts Tertiary volcanic and underlying sedimentary rocks, which rest unconformably on the underlying Bridge River Complex.

Our zircon fission track ages indicate that faulting must have, in part, postdated the deposition of the volcanic and sedimentary rocks at 43.5 Ma. Likewise, the zircon fission track ages of 39.5 Ma and 42.9 Ma on the granite clast and the Mission Ridge pluton respectively, indicate cooling of the footwall rocks at this time. Together, these data indicate movement of and cooling along the Marshall Creek fault between ~43.5 Ma and 39.5 to 43 Ma; this timing constraint is one of our most significant findings. To bring rocks on the northeast side of the fault towards the surface, dip-slip movement was likely, but the amount of strike-slip movement is uncertain.

DISCUSSION

Our cooling ages young from southwest to northeast across the study area. Our interpretation of all these data, however, is complicated by the fact that our cooling ages are from plutonic rocks that also young from southwest to northeast. For this reason, we are in the difficult position of determining whether these ages reflect either post-intrusion thermal decay or denudation of overlying rocks and subsequent downward movement of low-temperature isotherms.

In the case of the Bendor and Dickson plutons, the zircon fission track ages could represent: 1) post-intrusion cooling by conduction at high levels in the crust (above the closure temperature of zircon); or 2) cooling induced by either erosional or tectonic denudation. We cannot rule out either option 1 or 2 above, but our ongoing studies using fission track and Ar-Ar dating of other mineral phases may shed additional light on this problem. However, the presence of a vertical thermal gradient, as suggested by younger ages at lower elevations in the Dickson and Bendor plutons, suggests cooling proceeded downward when zircon passed through its closure temperature. This pattern of cooling suggests, but is not diagnostic of, cooling by either erosional or tectonic denudation.

The Castle Pass fault, which is interpreted to be a strike-slip fault, is intruded by the 67 Ma Eldorado pluton, which is just north of the limit of our study area in Figure 1 (Garver et al., 1989; Schiarizza et al., 1989; Garver, 1991), but cuts rocks as young as 94 Ma (Silverquick conglomerate - see Garver and Brandon, in press). Strike-slip faulting, therefore, affected the rocks in the western part of the map area sometime between 94-67 Ma. Two of the four zircon fission track ages from the Dickson pluton (78-75 Ma) fall within this permissable age range of strike-slip faulting. Amphibole from a hornblende porphyry dyke near the Yalakom fault system, gives an age of ~76 Ma ($^{40}Ar/^{39}Ar$; Archibald et al., 1990). Likewise, low-temperature cooling ages near the Dickson pluton in the Warner Pass area (Archibald et al., 1989) give ages between 78 and 72 Ma. Therefore, the zircon fission track and Ar-Ar data suggest a period of cooling and dyke emplacement during the interval between ~78-72 Ma. These cooling ages could be linked to either the initiation of dextral transpression, and cooling that may have been driven by uplift and denudation, or post-orogenic uplift and denudation following the regionally significant mid-Cretaceous contractional episode, or both. The oldest zircon fission track age (~91 Ma) is from rocks at the edge of the pluton and presumably represents rapid cooling at the edge of the pluton, or possibly cooling of a separate unrecognized plutonic body. The youngest zircon fission track age (~60 Ma) is from a very low elevation and therefore may have been deeper than the other samples during cooling; this young age may be related to a separate cooling event that is preserved in the Bendor Range (see below).

Umhoefer and Schiarizza (1992) argued that the Late Cretaceous to early Tertiary strike-slip faults in the Bridge River area evolved as a transfer zone between movement on the northwest-trending Yalakom fault system and related faults in Washington state. They suggested that the region experienced a change from transpression to transtension at about 58 Ma, coincident with a change to rapid and oblique convergence of the Kula plate and the North American plate; they note, for example, that northwest along the Yalakom fault system, ~58 Ma cooling and extension occurred in the Tatla Lake metamorphic complex (Friedman and Armstrong, 1988). It is possible that both the K-Ar age of ~59.5 Ma and the zircon fission track ages of ~55-52 Ma from the Bendor Range, and the zircon fission track ages of ~60 Ma from the Dickson pluton record cooling associated with uplift and erosion that may have been controlled by vertical movements of crustal blocks separated by dextral strike-slip faults.

From data collected in the Bridge River Canyon area, Coleman and Parrish (1991) suggest that about 100 km of dextral movement on the Fraser fault (nearby to the east) occurred after 46.5 Ma, but before intrusion of a 34 Ma phase of the Chilliwack batholith (see Tepper, 1991). Umhoefer and Schiarizza (1992) postulated that at ~47 Ma, the Straight Creek fault in Washington state, was the active southern continuation of the Yalakom fault system. As faulting progressed, ~110 km of dextral offset on the Straight Creek fault was transferred to ~20 km on the Marshall Creek fault-Yalakom fault system and ~90 km on the Fraser fault. Our data from rocks along the Marshall Creek fault and below the Mission Ridge fault indicate that rapid cooling occurred between 43 and 39 Ma. We suggest, as have others, that the latest movement on the Marshall Creek was kinematically linked to movement on the Fraser fault to the east (Coleman and Parrish, 1991; Umhoefer and Schiarizza, 1992), and that our low-temperature cooling ages from rocks adjacent to the Marshall Creek fault date an episode of dip-slip movement (northeast side up) driven by dextral slip on the Fraser fault. Therefore, our data suggest that an episode of movement on the Marshall Creek fault, and probably the Fraser fault, occurred between 43.5-39 Ma. Our ongoing studies using fission-track dating of apatite and ^{40}Ar-^{39}Ar analyses of biotite and K-spar will allow us to better resolve the spatial and temporal aspects of low-temperature cooling in this area.

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