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# Fission-track ages of detrital zircons from Cretaceous strata, southern British Columbia: Implications for the Baja BC hypothesis

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**Abstract.** The Methow/Tyaughton basin contains a thick sequence of mid-Cretaceous (Albian-Cenomanian) marine clastic sediments, which have been interpreted as synorogenic fill deposited during collision and accretion of the Insular superterrane at the North American margin. Three distinct, regionally extensive petrofacies have been recognized in this sequence: (1) a west-derived volcanic petrofacies, (2) a cherty petrofacies derived from a local intrabasinal high, and (3) an east-derived arkosic petrofacies. Grain ages for detrital zircon are used here to identify provenance. The fission track (FT) method is used to date seven sandstone samples, with ~45 grains ages per sample. Grain age distributions show marked differences between petrofacies and close similarities within a petrofacies. All petrofacies are dominated by a young population of grain ages (113 to 89 Ma), statistically indistinguishable from the depositional ages of the samples. This population is attributed to contemporaneous volcanism in the source region. The age of older populations varies among the petrofacies, indicating that each petrofacies was derived from different source terrains. Most important, all Arkosic samples have nearly identical grain age distributions, even though they come from widely separated parts of the Methow/Tyaughton basin. This evidence suggests that the Arkosic petrofacies is an overlap sequence that ties together disparate basement terranes, including the Bridge River, Cadwallader, and Methow terranes, by the Albian (~100 Ma). The source of the Arkosic petrofacies provides an important constraint on the mid-Cretaceous location of these outboard terranes. This petrofacies increases in thickness and coarseness to the east, suggesting a source inboard of the Methow/Tyaughton basin. The detrital composition of the sediment indicates that high-grade metamorphic rocks and S-type plutonic rocks were present in the source. Given the rapid onset of arkosic sedimentation in the Albian, we infer that this petrofacies was derived from newly uplifted metamorphic and plutonic rocks. We consider two interpretations for this arkosic source. An in situ interpretation would derive these sediments from metamorphic and plutonic rocks of the Omineca Crystalline belt, which presently lies to the east of the basin. The onset of arkosic sedimentation during the Albian is compatible with evidence from the Alberta foreland basin that indicates Albian uplift and denudation of the Omineca Crystalline belt. However, Nd/Sm data from the Arkosic petrofacies (Barfod and Nelson, 1992) indicate a fairly primitive source, which is not consistent with the presence of Precambrian rocks in the Omineca belt. The second interpretation accounts for paleomagnetic data that indicates the outboard terranes of western British Columbia have been transported 3000 km northward during the latest Cretaceous and early Tertiary. In this case, the arkosic sediments would most likely have been derived from an inboard continental setting near the present-day latitude of central Mexico. A possible source might have been the western half of the Peninsular Ranges batholith, which is characterized by plutonic rocks with relatively primitive isotopic characteristics.



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## Introduction

A basin filled by clastic sediments holds a fragmentary record of the tectonic evolution of the surrounding highlands. A principal objective of provenance analysis is to reassemble that record. Provenance analysis has become increasingly sophisticated over the years (see *Morton et al.* [1991] for a recent overview) and now includes a range of methods: (1) modal measurements of framework grains in sandstones; (2) texture, composition, and isotopic age of individual detrital minerals; and (3) chemical and isotopic composition of bulk samples. In this study we employ a relatively new method, fission track (FT) dating of detrital zircons, to resolve the mid-Cretaceous (Albian-Cenomanian) tectonic evolution of source terrains that bordered the Methow/Tyaughton basin of southern British Columbia and western Washington State (Figure 1).

The external detector method for FT dating is one of the few methods of isotopic dating that routinely provides individual grain ages. *Hurford et al.* [1984] were first to publish a study that specifically used the FT method to date individual detrital grains from unreset sandstones. This application has been further utilized and extended by *Baldwin et al.* [1986]; *Kowallis et al.* [1986]; *Naeser et al.* [1987]; *Cerveny et al.* [1988]; *Naeser et al.* [1989]; *Galbraith and Green* [1991]; Garver [1988b]; *Vance* [1989]; *Brandon* [1992]; *Brandon and Vance* [1992]; *Garver and Brandon* [1992]; and *Garver and Brandon* [1994].

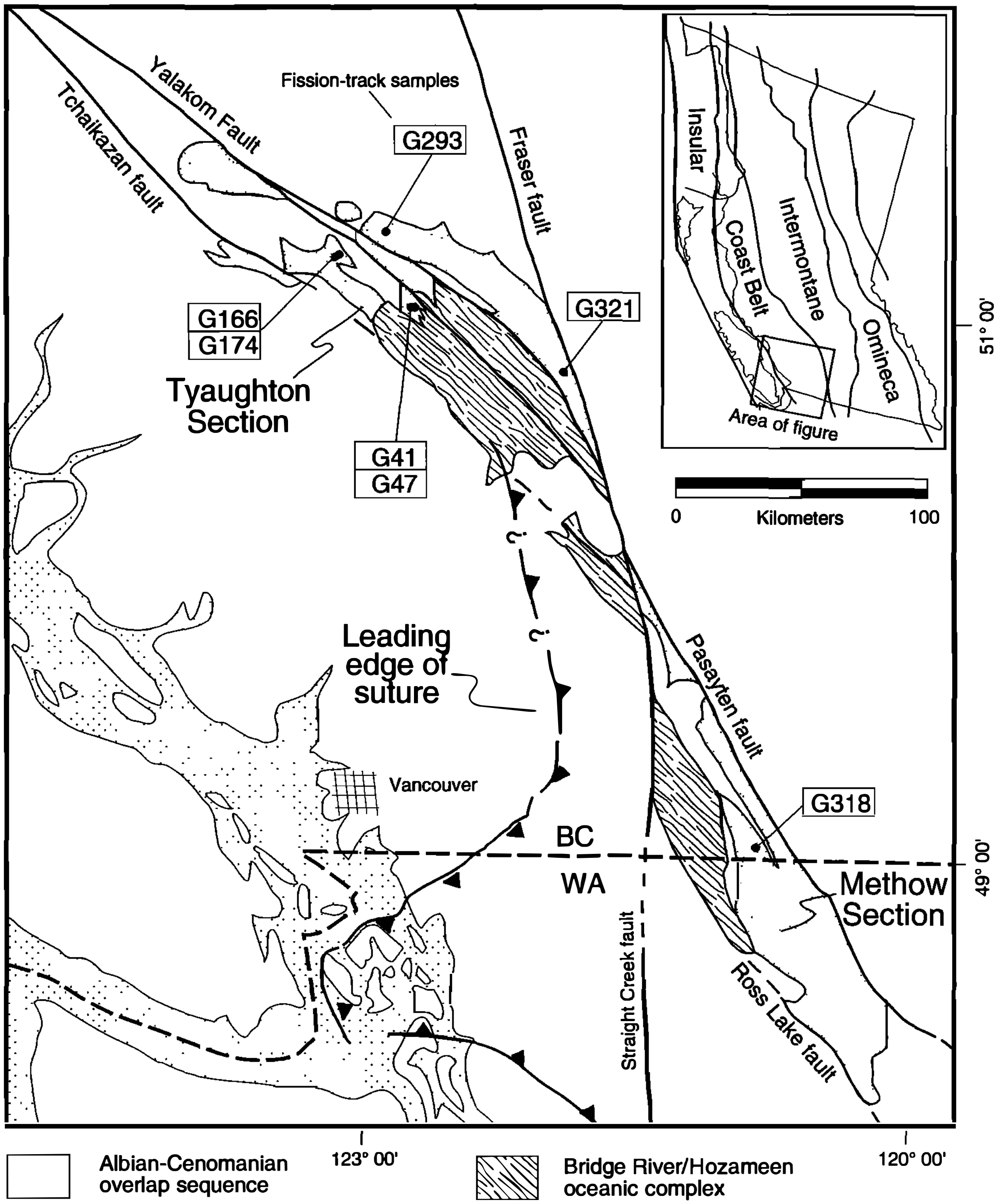


**Figure 1**. Simplified map of the Methow/Tyaughton basin and the Bridge River /Hozameen terrane. The Bridge River/Hozameen represents an upper Paleozoic-lower Mesozoic oceanic terrane (chert, basalt, limestone) that was uplifted and shed chert-lithic detritus into both the Methow and the Tyaughton basins during the mid-Cretaceous. The inset shows the principal tectonic belts of British Columbia. The study area occupies an area in the Canadian Coast Mountains that lies between the Intermontane superterrane to the east and the Insular superterrane to the west (see inset).

These studies have demonstrated that FT dating of unreset detrital grains can be used not only as a method of provenance analysis but also as a means for correlating sedimentary units and for constraining the depositional age of sediments.

We are interested here in using this tool for correlation and provenance analysis. Because the zircon FT system has a relatively low closure temperature (~240° C) [*Brandon and Vance*, 1992], it is most sensitive to tectonic and volcanic events that have affected the upper crust in the source region from which the sediments were derived. By upper crust, we mean the upper 8 km, assuming a normal continental thermal gradient of 30° C/km and an average surface temperature of 10°C. This relatively shallow depth means that the time lag between closure and exposure at the surface is short relative to other isotopic chronometers. Studies have shown that in areas of active tectonism or volcanism, a significant fracion of the zircons can have lag times of less than 3 to 5 m.y. [*Cerveny et al.*, 1988; *Brandon and Vance*, 1992]. In contrast, closure temperatures for the K-Ar, Rb-Sr, and U-Pb isotopic systems are greater than ~350°C for the most commonly utilized detrital phases (e.g., muscovite, hornblende, and zircon; potassium feldspar is a notable exception).

The mid-Cretaceous Methow/Tyaughton basin of western Washington State and British Columbia (Figure 1) is well suited for a provenance study using the FT method. The tectonic and petrologic evolution of the basin has been studied extensively using convention methods of basin analysis and sedimentary petrology [Trettin, 1961; *Jeletzky and Tipper*, 1968; *Cole*, 1973; *Coates*, 1974; *Barksdale*, 1975; *Trexler*, 1984; *Kleinspehn*, 1985; *McGroder*, 1988; *McGroder et al.*, 1990; *Garver*, 1989; 1992]. Even so, regional correlations across the proposed basin remain speculative because it is cut and fragmented by younger strike-slip faults.

Our first objective is to use FT dating to test the interpretation of *Garver* [1989, 1992] that the Methow and Tyaughton sections were part of a single coextensive basin by Albian time. The expectation is that correlative strata in these fragments should show a common provenance, as indicated by their FT grain age distributions. Our second objective is to better resolve the source region that supplied sediment to the Methow/Tyaughton basin during the Albian and Cenomanian. This objective is particularly important in light of controversial paleomagnetic results that indicate that much of western Washington State and British Columbia, including the Methow/Tyaughton basin, may have been located some 3000 km to the south prior to 85 Ma [*Beck et al.*, 1985; *Irving, et al.*, 1985; *Bogue et al.*, 1989; *Ague and Brandon*, 1992]. We are interested in determining if the provenance of the sediment is consistent with the proposed southern site, located adjacent to northwest Mexico.

## Geologic Overview

For some time now, the informal terms "Methow basin" and "Tyaughton basin" have been used to refer to Middle Jurassic through Upper Cretaceous strata exposed in the Methow region of southwest British Columbia and western Washington State, and the Tyaughton region of the Canadian Coast Mountains in southwest British Columbia (Figures 1-3). Several papers, including *Rusmore et al.* [1988] and *van der Heyden* [1992], have proposed that the Tyaughton and Methow sections were deposited together within a single basin that originated during the late Middle Jurassic (Callovian). However, *Garver* [1989; 1992] has noted significant contrasts in the Jurassic and Lower Cretaceous portions of these sections, including stratigraphy, depositional rates, and provenance. In this view, a single Methow/Tyaughton basin did not come into existence until Albian time. Also relevant are geochemical data for shales [*Garver and Scott*, 1993; *Scott and Garver*, 1993] that indicate that, prior to the Albian, the Tyaughton sequence accumulated in an intraoceanic setting adjacent to an island arc.

Therefore to avoid confusion between observations and interpretation, the terms Tyaughton section and Methow section, refer to actual outcrops, and the term Methow/Tyaughton basin is used to distinguish those strata of the Methow and Tyaughton sections that were deposited in a single coextensive basin. This paper focuses on the Albian and Cenomanian portions of the Methow and Tyaughton sections. Most authors would agree that these strata were deposited in a single basin, but this interpretation is based primarily on lithostratigraphic correlations. Our FT data provide a more rigorous test of these correlations.

The Methow and Tyaughton sections straddle the boundary between two major tectonostratigraphic units of the western Canadian Cordillera, the Intermontane, and Insular superterranes [*Monger et al.*, 1982]. The critical position of these sections is illustrated in Figure 2 which shows an approximate restoration of tectonostratigraphic relationships during the latest Cretaceous. The significance of the Methow and Tyaughton sections is further elucidated by examining them in relation to the regional stratigraphic framework (Figure 3), which we divided into three distinctive elements: basement terranes, clastic linking sequences, and overlap sequences.

Basement terranes are the oldest stratigraphic element. They correspond to upper Paleozoic and lower Mesozoic terranes units that originated as volcanic arcs or ophiolites in the proto-Pacific and were subsequently accreted to North America. The exoticity of these terranes remains in question, but most tectonic syntheses acknowledge that these terranes formed in settings with at least a modest degree of separation from North America. The Methow-Tyaughton area is flanked to the east by the Intermontane superterrane and to the west by the Insular superterrane [*Monger et al.*, 1982]. The Intermontane superterrane includes two volcanic arc terranes (Quesnellia, Stikine) and an oceanic limestone-chert terrane (Cache Creek), which were assembled and also accreted against the western edge of North America sometime prior to the Late Jurassic [*Monger et al.*, 1982]. Accretion is often correlated with the Middle Jurassic Columbian orogeny, an event that is well documented in the eastern Canadian Rockies and the Kootenay arc [e.g., *Brown*, 1982].

The Insular superterrane is dominated by two relatively coherent volcanic arc terranes, Wrangellia and Alexander. The tectonic history of the Insular superterrane remains controversial. Some have argued that the Insular superterrane was emplaced in its present position by Middle Jurassic [*Rusmore et al.*, 1988; *van der Heyden*, 1992; *McClelland et al.*, 1992]. This interpretation, however, is complicated by the fact that the Cascade orogen, a major mid-Cretaceous orogenic zone, separates the Insular superterrane from North America [*Monger et al.*, 1982; *Brandon et al.*, 1988; *Garver*, 1989; *Brandon*, 1989; *Rubin et al.*, 1990; *McGroder*, 1991; *Journeay and Friedman*, 1993; *Cowan and Brandon*, 1994], and that paleomagnetic data indicate substantial coast-parallel transport during the latest Cretaceous and earliest Tertiary [*Beck et al.*, 1985; *Irving et al.*, 1985; *Ague and Brandon*, 1992].

Lying between the Insular and Intermontane superterranes, in the Methow/Tyaughton area, are four additional basement terranes (Figure 3) [*Potter*, 1986; *Rusmore*, 1987; *McGroder*, 1988; *Cordey and Schiarizza*, 1993]: (1) Cadwallader, a lower Mesozoic volcanic arc terrane; (2) Shulaps, a Permian(?)

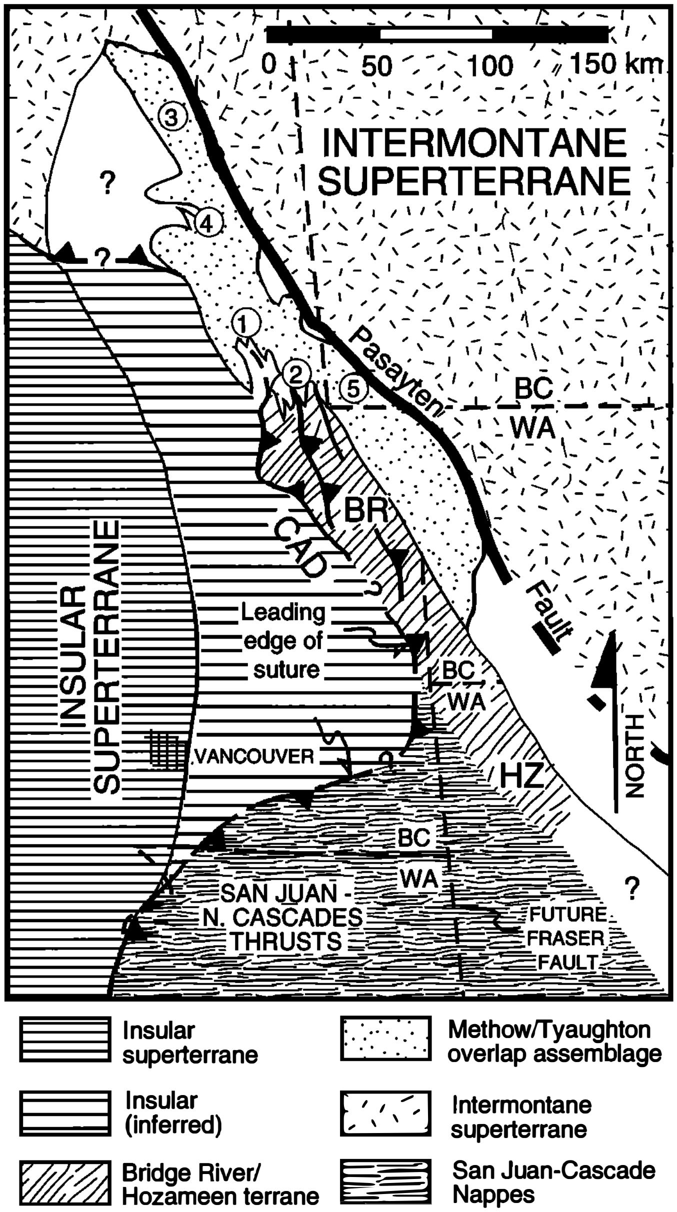


**Figure 2.** A simple reconstruction of the Tyaughton-Methow basin following the restoration of *Garver* [1989]. The Fraser-Straight Creek fault and Yalakom faults have been restored assuming 90 km and 170 km of right-lateral slip, respectively. This restoration requires internal deformation of individual blocks. Note that the Insular superterrane bounds the west side of the basin, and the Bridge River terrane is exposed as a high within the basin. Presumably, much of the western part of the basin has been eroded away. The Intermontane superterrane is shown as lying on the east side of the basin, although paleomagnetic data indicate that rocks to the west of the Paysayten fault, the eastern bounding fault to the Methow basin, may have lain several thousand kilometers to the south prior to 85 Ma. "?" denotes geology obscured by younger rocks.

ophiolite; (3) Bridge River, an upper Paleozoic-lower Mesozoic chert-basalt-limestone terrane; and (4) Methow, an oceanic terrane characterized by Lower Triassic mid-ocean ridge basalts. These terranes are important here because they include the basement on which the Methow and Tyaughton sections were deposited. Correlations have been proposed that would link some of these terranes to the adjacent superterranes, but these relationships have been obscured by younger faulting. In the Tyaughton area in particular, geologic relations have been highly fragmented by strike-slip faults

Overlying the basement terranes is the next stratigraphic element, the clastic linking sequences. This element corresponds to a variety of Upper Jurassic and Lower Cretaceous units which are commonly composed of marine clastic sedimentary rocks. Local examples (Figure 3) are the Relay Mountain Group of the Tyaughton area, and the Buck Mountain and Jackass Mountain groups of the Methow area. Similar Jura-Cretaceous units are present in the San Juan Islands, Harrison Lake area, North Cascade Mountains, and Vancouver Island (Figure 1) (see summary by *Brandon et al.*

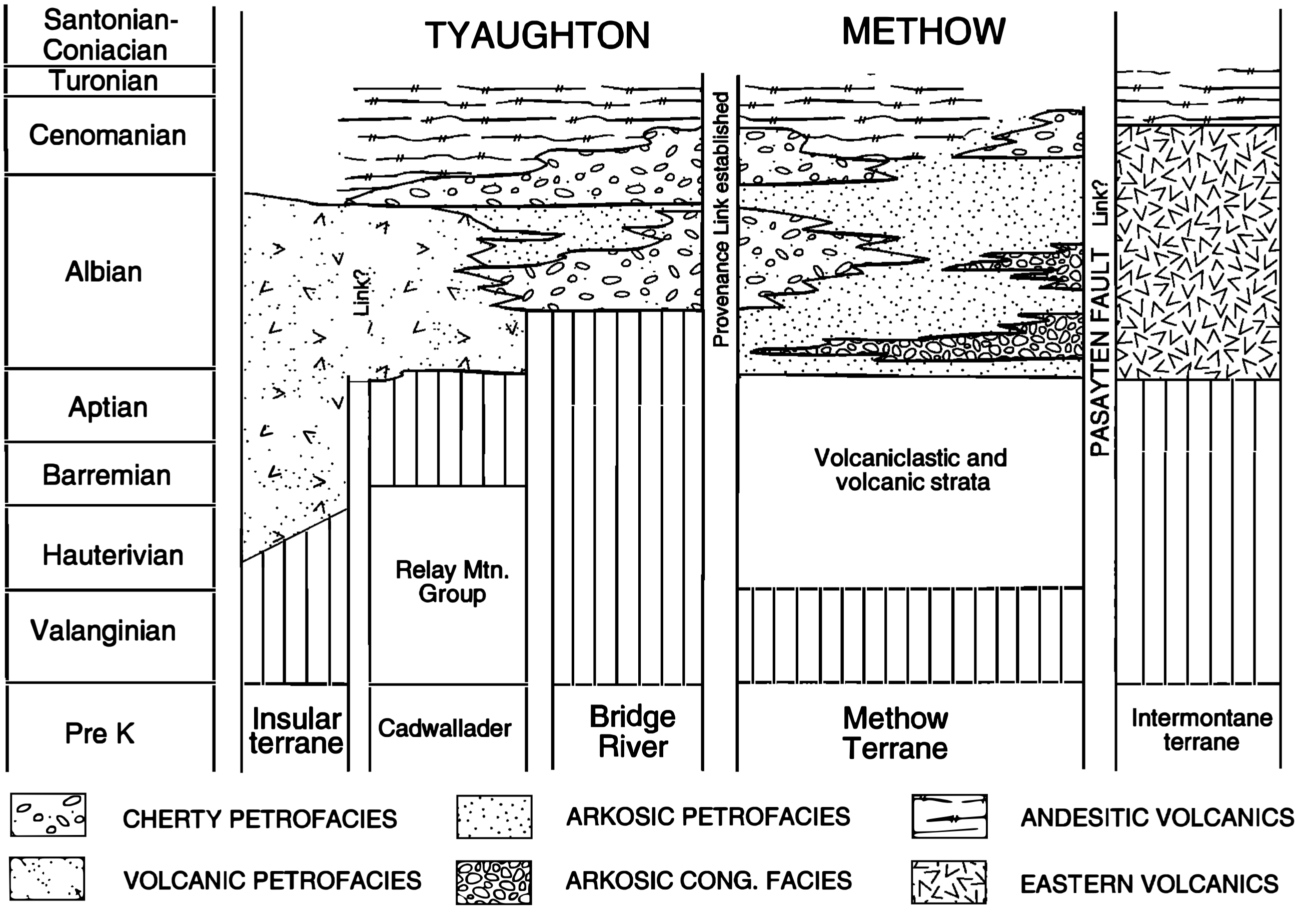


**Figure 3.** Schematic representation of the stratigraphic framework of the Tyaughton/Methow basin; see *Garver* [1992] for details concerning age control, and stratigraphic nomenclature.

[1988], *Brandon* [1989], *Umhoefer* [1989], *Garver* [1988a,b]). Most of these units have been variably disrupted by younger faulting. Even so, there is clear evidence that all of these Jura-Cretaceous units, which are composed almost entirely of terrigenous sediment, were deposited on or adjacent to the older basement terranes. These units have been referred to as clastic-linking sequences [*Brandon et al.*, 1988] because they indicated that the underlying basement terranes were proximal to a large continental mass, presumably the North American continent, by Late Jurassic time. However, these linking relationships do not preclude the possibility of subsequent transport parallel along the continental margin.

The youngest stratigraphic element is the overlap sequence, which refers to a distinctive Albian-Cenomanian sedimentary unit found throughout the Methow/Tyaughton area. Prior to the Albian, sediments in the Tyaughton and Methow sections were derived from separate eastern and western volcanic sources [*Garver*, 1989; 1992]. Beginning in the Early Albian and extending through the Cenomanian, both the Tyaughton and Methow sections show a marked increase in accumulation rates and the development of three petrofacies (Figure 3) [G*arver*, 1989, 1992]. The Volcanic petrofacies is not particularly distinctive because pre-Albian strata are also composed mainly of volcaniclastic sediment. In contrast, the Chert petrofacies and the Arkosic petrofacies signal the initiation of new sediment sources. The Chert petrofacies was derived from, and unconformably overlies, the Bridge River terrane [*Garver*, 1989,1992]. Thrust faulting apparently produced uplifted blocks of the Bridge River terrane, both within the Methow-Tyaughton basin and also along its western flank (Figure 2).

In contrast, the Arkosic petrofacies has no local source. In this case, paleocurrent directions only provide a record of axial transport within the basin, and thus are of little use for resolving the source of the arkosic sediment. The source may have laid to the east of the basin as indicated by an eastward increase in thickness and grain size in strata of this petrofacies [*McGroder*, 1989; *Garver*, 1992]. In this context, it is important to note that the Methow/Tyaughton basin is currently bordered on its east side by the Pasayten and Fraser faults, both of which show evidence of young displacement [e.g., *Hurlow and Nelson*, 1993]. As outlined below, the Baja BC hypothesis would require significant post-Albian strike-slip displacement on these faults. Thus the source of the sediments might not have been the Intermontane superterrene.

The Albian-Cenomanian sequence is referred to as an overlap sequence because it provides a direct link between the various basement terranes in the Methow/Tyaughton area. *Tennyson and Cole* [1978], *Trexler* [1984], and *Trexler and Bourgeois* [1985] have argued that the change in provenance in the Albian was due to the development of a mid-Cretaceous system of strike-slip faults. An alternative interpretation, favored here, is that the Albian event marks the formation of a foredeep along the eastern side of the Cascade orogen [*McGroder*, 1989; *Garver*, 1992]. The main evidence for this interpretation is that increased rates of accumulation and tectonic subsidence in the Methow/Tyaughton basin and the introduction of chert-rich sediment from the Bridge River terrane coincide with the onset of mid-Cretaceous orogenesis in the North Cascades and Coast Mountains of British Columbia.

The Cascade orogeny marks the amalgamation of the Insular superterrane with basement terranes of the Methow and Tyaughton areas, the San Juan Islands, and the North Cascades [*Monger et al.*, 1982; *Brandon et al.*, 1988; *Garver*, 1989; *McGroder*, 1991; *Cowan and Bruhn*, 1992; *Cowan and Brandon*, 1994]. This event is characterized by considerable orogenic shortening, on the order of several hundreds of kilometers and associated high-pressure metamorphism. *Rubin et al.* [1990] argue that the collision zone may be as much as 1300 km long, extending from western Washington to southeast Alaska. We discount the interpretation of *Brown* [1987] that the Cascade orogen resulted from strike-parallel transcurrent shear, with little or no contraction across the belt (see *McGroder* [1990, 1991] and Cowan and Brandon [1994] for details). Faults, synorogenic sediments, and cross-cutting plutons provide clear-cut evidence that amalgamation was complete by 85 Ma.

What remains controversial is the relationship of this Late Cretaceous assemblage to the more inboard Intermontane superterrane. Paleomagnetic data from Late Cretaceous plutons [*Beck et al.*, 1985; *Irving et al.*, 1985; *Ague and Brandon*, 1992] indicate that this outboard assemblage, which *Irving et al.* [1985] called Baja BC, was transported along the margin some 3000 km during the interval 85 to 50 Ma. *Butler et al.* [1989] argued that these results were biased because of unresolved systematic tilts, but *Ague and Brandon* [1992] have directly measured tilt in one of the batholiths, the Mount Stuart, and have shown that correction of the tilt does not significantly reduce the estimated latitudinal offset.

Paleomagnetic data also indicate northward translation of the Intermontane superterrane relative to North America during the Late Cretaceous and early Tertiary, but only about 1000 km [*Marquis and Globerman*, 1988], which is consistent with the total offset estimated for Late Cretaceous-early Tertiary strike-slip faults that lie to the east of the Intermontane superterrane in the vicinity of the Canadian Rockies [*Gabrielse*, 1985]. Thus we conclude that if the Baja BC hypothesis is correct, a major Late Cretaceous-early Tertiary fault with ~2000 km of offset must have bordered the western side of the Intermontane superterrane. Unfortunately, there are many faults located along this contact (see Figure 1; Hozameen, Pasayten, Yalakom, and Fraser-Straight Creek faults), some of which were active as recently as the Eocene. The presence of these younger faults greatly complicate the recognition of the postulated "Baja BC fault."

## Sample Preparation and Dating Methods

The external detector method [*Gleadow*, 1981] was used to date zircons from seven samples, each consisting of 1 to 4 kg of medium to coarse sandstone. Our procedures are similar to those outlined by *Naeser* [1976] and *Gleadow* [1984]. Each sample was crushed, pulverized, sieved, and separated in heavy liquids. Then, 300 to 700 nonmagnetic zircons were picked, mounted on a Teflon disk, polished, and etched in a molten KOH-NaOH eutectic at 225°C for 6 to 10 hours, as necessary to obtain a high-quality etch [*Gleadow*, 1981]. The mounts were covered with a flake of low-U muscovite and irradiated in the University of Washington nuclear reactor. Cadmium ratios, relative to an Au monitor, measured at the irradiation positions in this reactor were ~100, indicating that the neutron fluence was well thermalized [*Wagner and Van den Haute*, 1992]

A standard of known age (Oligocene Fish Canyon Tuff) and glass dosimeters with known uranium concentration (SRM 612) were included in the sample package during irradiation and used in the calculation of a Zeta calibration factor [*Hurford and Green*, 1983]. In this study, a Zeta factor of 316.7 ± 13.4 (±2 standard error) was calculated from five different samples of Fish Canyon zircon irradiated during three different reactor runs between 1986 and 1988 (see Appendix A[1] for sample locations and Appendix B[1] for analytical data). All tracks were counted using the same microscope setup (Zeiss microscope, 1250x magnification using oil). Systematic traverses were made, and all suitable grains were counted. Care was taken to count only properly etched grains, where the section was parallel to the C crystallographic axis and where all tracks were clearly resolved. An effort was made to count grains with both low and high track densities to avoid systematic biases between young and old grains.

## Interpretation of Unreset Grain-Age Distributions

### Thermal Stability of Fission Tracks

The external detector method can be used to determine FT ages for individual detrital zircons. If after deposition, the sediment remains at temperatures below ~175° to 185°C [*Brandon and Vance*, 1992], then the detrital zircons will retain predepositional FT ages which will be related to the thermal history of the source region from which the zircons were derived. The youngest population of grain ages in an unreset sample also provides information about the depositional age of the sample, in that the sediment can be no older than its detrital components.

Zircons will be variably reset if temperatures exceed ~175° to 185°C. If the depositional age of the sample is known, partial resetting can be detected in those cases where a significant fraction of the grains are younger than deposition. On this basis, FT data from two sandstone samples reported by *Garver* [1989] are considered to be partially reset and are excluded in our analysis here. Indirect evidence for partial resetting, such as variations in etch times and changes in the ages of characteristic peaks, may be applicable in regional-scale FT studies (see *Brandon and Vance* [1992]).

Zircon fission tracks will be completely annealed if subjected to temperatures in excess of about 220° to 260°C, given a heating event on the order of 1 to 100 m.y. [*Brandon and*

[1] Appendix A and B are available with entire article on microfiche. Order from the American Geophysical Union, 2000 Florida Avenue, N.W., Washington D.C. 20009. Document T93-004; $2.50. Payment must accompany order.

*Vance*, 1992]. If the zircons have been totally reset after deposition, then the FT ages will record when the sample cooled through the zircon FT closure temperature. For monotonic cooling at rates typical of geologic settings, closure temperatures are estimated to be in the range 210° to 260°C [*Brandon and Vance*, 1992], with higher temperatures corresponding to faster rates of cooling.

### Decomposition of Component Populations

An unreset grain-age distribution can be viewed as a mixture of component populations, with each component derived from a specific FT source terrain [*Brandon*, 1992]. The term FT source terrain refers to a discrete area in the general source region that yields zircons of a characteristic FT age [*Brandon and Vance*, 1992]. (The American spelling for "terrain" is used to avoid confusion with the term "tectonic terrane" and to emphasize that the zircons are derived from surface outcrops and are not necessarily representative of the subsurface geology.) In reality, a given source region is probably capable of delivering a range of FT grain ages, but it is anticipated that a few dominant component populations will account for the bulk of the ages. It is important to note that while zircon is a common mineral in the continental crust, it may be absent in some lithologies that compose a source region. Therefore FT dating as a provenance tool is only capable of determining the cooling and denudation histories of those source terrains that contain a significant amount of datable zircon.

One problem in dating unreset detrital zircons is that the individual grain ages usually have fairly low precision, with an average relative standard error of about 13%. As a result, it is necessary to find related groups of grain ages in order to improve the precision of the age estimates. *Brandon* [1992] introduced two methods for identifying component populations in a mixed population of grain ages. The first decomposition method, the $\chi^2$ age method, isolates the youngest fraction of "plausibly related" grain ages and assigns an age to this fraction, called the $\chi^2$ age. This age estimate is useful in that it provides a maximum limit for the depositional age of the sandstone sample. The second method, the Gaussian peak-fitting method, decomposes the entire grain age distribution into a finite set of component Gaussian distributions, each of which is defined by a unique mean age, a relative standard deviation, and the size of the component distribution relative to the total distribution. Through a series of simulation experiments [*Brandon*, 1992] and a practical application [*Brandon and Vance*, 1992], it has been shown that both of these methods can produce satisfactory results given a sufficient number of grain ages for each peak and adequate separation between adjacent peaks.

In this study we have calculated the $\chi^2$ age and the best fit peaks for each of the FT grain age distributions, using the procedures outlined by *Brandon* [1992]. The results of these calculations are given in Table 1. The estimated $\chi^2$ age is assigned an uncertainty (±2 standard error) and $\pi_f$, which is the percentage of grains in the youngest fraction relative to the total number of grains dated for the sample.

For the peak-fitting method, each peak is assigned an estimated age and uncertainty (±2 standard error); $\pi_f$, the estimated percentage of grain associated with the peak; and W, the width of the peak as measured by its relative standard deviation. The following criteria from *Brandon* [1992] were used to determine the preferred best fit solution for the Gaussian peak-fitting method: (1) W should be approximately equal to 16%, which is the relative standard deviation for a single-age FT grain age distribution (e.g., see Fish Canyon results in Table 1); (2) the sum of the $\pi_f$ values should be close to 100%, indicating that all of the grain ages are represented in the solution; and (3) the solution should be terse in that it should contain only those peaks that significantly reduce the misfit between the observed and calculated distributions.

We used a slightly modified version of *Brandon's* [1992] peak-fitting method, in that a common W value is estimated for all peaks in the distribution, instead of fitting a separate W for each peak, as was done by *Brandon* [1992] and *Brandon and Vance* [1992]. The reason for this change is that, ideally, a peak should correspond to a single-age population of FT grain ages. Because the relative standard deviation, W, of a single-age peak does not change significantly with age, then our expectation is that W should be approximately the same for all peaks. Because fewer parameters are included in the solution, this modification tends to enhance the resolution and stability of the peak-fitting calculation.

### Types of FT Source Terrains

FT source terrains can be divided into three types: (1) a synorogenic source terrain, where the FT age of the source terrain is the result of cooling by erosion and/or extensional faulting of synorogenic topography; (2) a postorogenic source terrain, where the FT age of the source terrain is the result of cooling during postorogenic erosion and/or gravitational collapse of mountainous topography; (3) a volcanic source terrain, where the characteristic FT age is a result of volcanism and near-surface magmatism. A volcanic FT source terrain might include a wide range of rock units, such as volcanic flows and pyroclastic deposits, hypabyssal intrusions and dikes, and thermally reset country rock, all of which would be related by a common FT age corresponding to the time of volcanism. These various types of source terrains can be distinguished but only on the basis of indirect evidence. A general clue is provided by the petrology of the framework grains: metamorphic detritus would imply a synorogenic or postorogenic source terrain, whereas volcanic detritus would imply a volcanic source terrain. The introduction of metamorphic detritus into a basin might reflect the initiation of a synorogenic source terrain, whereas a postorogenic source terrain might be characterized by a decreasing proportion of metamorphic detritus with time.

Another useful diagnostic measure is the *lag time*, defined as the time between the cooling of the FT source terrain, as indicated by the FT age of detrital zircons derived from the terrain, and the time of deposition of the zircons, as indicated by the stratigraphic age of the sandstone that hosts the zircons. A short lag time would be expected for volcanic source terranes, and a variable lag time for orogenic source terrains. Unfortunately, the lag times that characterize these different types of settings are not always easily distinguished. Some tectonically active mountain belts have source terrains with lag times as short as 1 m.y. [e.g., *Cerveny et al.*,1988], and some volcanic terrains may be denuded very slowly, resulting in long lag times, perhaps on the order of tens of m.y.

**Table 1.** Zircon FT Results for Unreset Sandstones from the Methow/Tyaughton Basin

| Sample, Location | Geologic Unit, Depositional Age | Age Range, Number of Grains | Youngest fraction $\chi^2$ Age | Youngest fraction Peak Fit, $P_0$ | Older peaks Peak Fit, $P_1$ | Older peaks Peak Fit, $P_2$ |
|---|---|---|---|---|---|---|
| | | *Volcanic Petrofacies, Tyaughton Basin* | | | | |
| G166 Relay Mountain | Paradise Formation early Albian, possibly as old as Barremian (~132-107 Ma) | 87 - 316 Ma $N_t$ = 43 | 115 ± 7.9 Ma $\pi_f$ = 77% W = 16% | 113 ± 6.5 Ma $\pi_f$ = 60% | 154 ± 9.2 Ma $\pi_f$ = 29% | 275 ± 16 Ma $\pi_f$ = 7% |
| | | *Cherty Petrofacies, Tyaughton Basin* | | | | |
| G41 Taylor Basin | Silverquick Conglomerate middle or late Albian, or possibly Cenomanian (~107-90 Ma) | 73 - 435 Ma $N_t$ = 72 | 94.7 ± 5.9 Ma $\pi_f$ = 94% W = 14% | 89.3 ± 5.1 Ma $\pi_f$ = 52% | 114 ± 6.6 Ma $\pi_f$ = 33% | 168 ± 9.5 Ma $\pi_f$ = 12% |
| | | Arkosic Petrofacies, Tyaughton Basin | | | | |
| G174 Red Mountain, Relay Creek | Lizard Formation middle or late Albian, possibly Cenomanian (~107-90 Ma) | 77 - 242 Ma $N_t$ = 45 | 107 ± 7.4 Ma $\pi_f$ = 84% W = 16% | 97.4 ± 5.5 Ma $\pi_f$ = 57% | 135 ± 7.7 Ma $\pi_f$ = 36% | 235 ± 13.4 Ma $\pi_f$ = 7% |
| G47 Taylor Basin | Lizard Formation middle or late Albian, or possibly Cenomanian (~107-90 Ma) | 67 - 416 Ma $N_t$ = 46 | 95.0 ± 6.9 Ma $\pi_f$ = 61% W = 18% | 91.4 ± 5.1 Ma $\pi_f$ = 44% | 141 ± 7.9 Ma $\pi_f$ = 52% | 208 ± 13.3 Ma $\pi_f$ = 2% |
| | | *Arkosic Petrofacies, Methow Basin* | | | | |
| G293 Lone Cabin Creek | Jackass Mountian Group probably Albian, possibly early Albian (~112-97 Ma) | 72 - 149 Ma $N_t$ = 44 | 102 ± 6.8 Ma $\pi_f$ = 93% W = 14% | 97.0 ± 5.6 Ma $\pi_f$ = 71% | 129 ± 7.5 Ma $\pi_f$ = 28% | - n.d. - |
| G321 Lillooet | Jackass Mountain Group probably Albian, possibly early Albian (~112-97 Ma) | 77 - 147 Ma $N_t$ = 43 | 97.8 ± 6.7 Ma $\pi_f$ = 91% W = 14% | 93.8 ± 5.5 Ma $\pi_f$ = 70% | 126 ± 7.4 Ma $\pi_f$ = 28% | - n.d. - |
| G318 Manning Park | Jackass Mountain Group. Albian, probably early Albian (~112-97 Ma) | 62 - 300 Ma $N_t$ = 43 | 102 ± 6.7 Ma $\pi_f$ = 65% W = 21% | 99.4 ± 5.9 Ma $\pi_f$ = 51% | 140 ± 8.4 Ma $\pi_f$ = 37% | 257 ± 15.2 Ma $\pi_f$ = 11% |
| | | *Reference Sample Containing Unreset Zircons* | | | | |
| | Fish Canyon Tuff (zeta standard, results combine five runs) | 20 - 37 Ma $N_t$ = 59 | 25.7 ± 1.8 Ma $\pi_f$ = 63% W = 16.1% | 28.1 ± 1.6 Ma $\pi_f$ = 97.5% | Mean age = 28.1 ± 1.9 Ma (K-Ar age = 27.9 Ma) | |

$N_t$ is the total number of grains analyzed; $\pi_f$ is the estimated size of a specific peak or fraction relative to the total size of the distribution. All uncertainties are cited at ±2 standard error and include group error. W is the estimated relative standard deviation as a percentage of the peak age; note that a single W is fit for all peaks in a distribution; n.d. means not detected. Not reported are a few small peaks with ages greater than 400 Ma.

Summarized here are some general guidelines for characterizing a source terrain: (1) a volcanic source terrain is probably best indicated when a zircon FT peak has a short lag time (<~ 5 m.y.) and the sandstone contains a significant fraction of primary volcanic detritus; (2) an orogenic source terrain is probably best indicated when a peak makes up a significant proportion of the total grain age distribution ($\pi_f$> ~20%), the lag time for the peak is >5 to 10 m.y., and the sandstone contains a significant fraction of metamorphic detritus; (3) an orogenic source terrain might also be inferred for those peaks where the lag time is short (<10 m.y.), but the sandstone has little or no volcanic detritus; (4) a confident interpretation is probably not possible for those minor peaks ($\pi_f$< ~20%) with relatively long lag times (>10 m.y.); and (5) changes in provenance with stratigraphic level can be used to distinguish between synorogenic and postorogenic source terrains. A synorogenic source terrain might be distinguished by the following changes upsection: the introduction of metamorphic detritus and the simultaneous appearance of a young FT peak, followed by a systematic decrease in the lag time of that peak as the rate of denudation accelerated toward a steady state condition. A postorogenic source terrain might be distinguished by an upsection decrease in metamorphic detritus and an increase in the lag time for the relevant FT peak, reflecting a decreasing rate of denudation as topography becomes more subdued.

### Model Denudation Rates

If a peak can be confidently attributed to an orogenic source terrain, then the FT data can be used to estimate a model denudation rate for the source terrain, defined as the closure depth divided by the lag time. The closure depth is the depth at which the sample passed through the zircon FT closure temperature. To estimate the closure depth, we adopt an assumed continental thermal profile of T(C°) = 10 + 30 * Z(km). A closure temperature is determined using the method outlined in *Brandon and Vance* [1992], which assumes monotonic cooling during closure and accounts for the effect that the rate of cooling has on the closure temperature. In our study the estimated rate of cooling is fairly low (~2° to 6°C/m.y.; discussed below) so that the closure temperature and closure depth are well approximated by the following constant values, ~222°C and ~7.1 km.

We refer to the estimated denudation rate as a model denudation rate in order to emphasize the assumptions involved. The first assumption is that the time needed to transport the eroded zircons from the source terrain to the site of deposition is negligible, which seems reasonable because much of the transport probably occurred in rivers where sediment transport rates are relatively fast. The second assumption is that the model temperature profile is representative of the thermal conditions at the time of closure of the zircon FT system. Given that natural thermal gradients generally fall between 15° to 60°C $km^{-1}$, the assumed temperature profile may introduce errors in our estimate of the model denudation rate by a factor of 1/2 to 2. The third assumption is that the rate of denudation is constant over the interval represented by the lag time. In this regard, the model denudation rate is probably best viewed as an average value. This average can be misleading for a source terrain that is in a state of transition. For instance, at the onset of orogenic deformation, the upper crust must be denuded before the source terrain will deliver zircons that closed during the synorogenic denudation. As a result, the model denudation rates calculated for the first zircons derived from this nascent source terrain will be an average of the very slow rates of denudation that existed prior to orogeny and the accelerating rates associated with the construction of synorogenic topography.

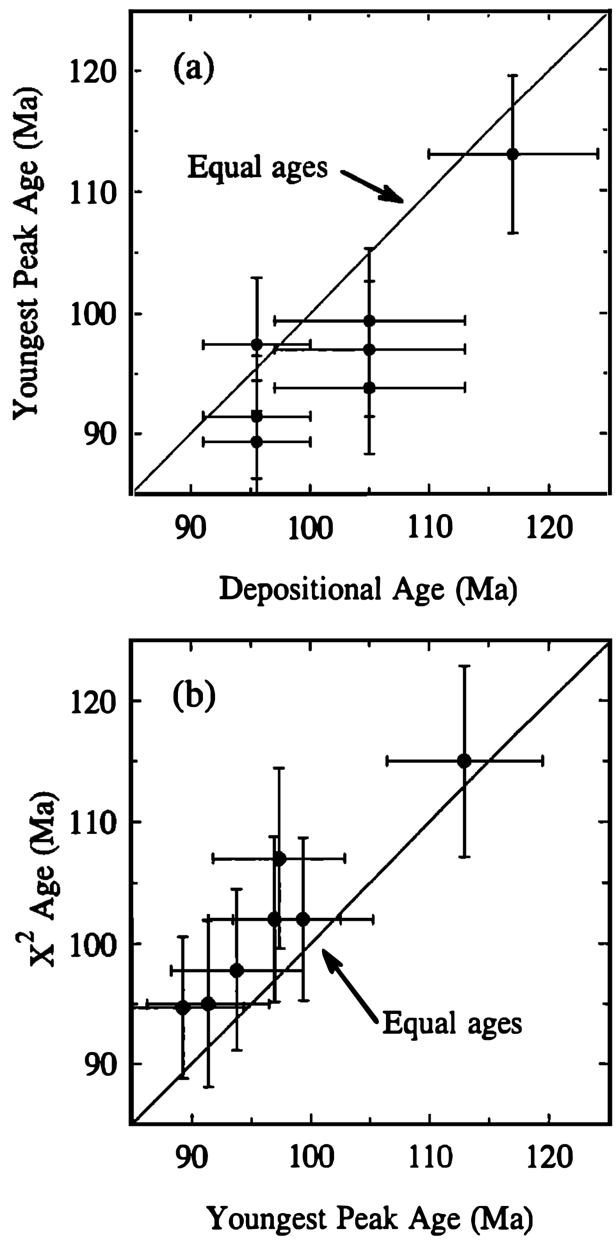


**Figure 4.** Comparison of youngest peak ages with (a) paleontologically determined depositional ages and (b) $\chi^2$ ages. The error bars show the ±2 standard error uncertainty for the estimated ages.

## Results

Of the seven samples dated (Table 1), five are from the Arkosic petrofacies, one is from the Chert petrofacies, and one is from the Volcanic petrofacies. All samples are considered to be unreset because each sample preserves a wide spread of grain ages (spread ranges from 70 to 362 m.y.; Table 1) and because none of the samples have peaks that are significantly younger than the depositional age of the sample (Figure 4a). The fact that the samples are unreset indicates that postdepositional temperatures never exceeded ~175° to 185°C.

The grain age distributions (Figures 5-7) usually have no more than three resolvable peaks in each distribution with peak ages between 89 and 275 Ma (Table 1). Note that we have made no attempt to account for single grains with old grain ages (>400 Ma) which are present in two of the distributions (G41 and G47). The youngest peak is designated as $P_0$, and the two older peaks as $P_1$ and $P_2$. We first focus on how the grain age distributions vary with petrofacies, in order to determine if the distributions provide a useful basis for the correlation between the Methow and Tyaughton sections. Next, we consider the age and provenance of the various FT peaks.

It is important to note that because all samples come from a relatively restricted stratigraphic range, they only provide information about the lithology and cooling history of those

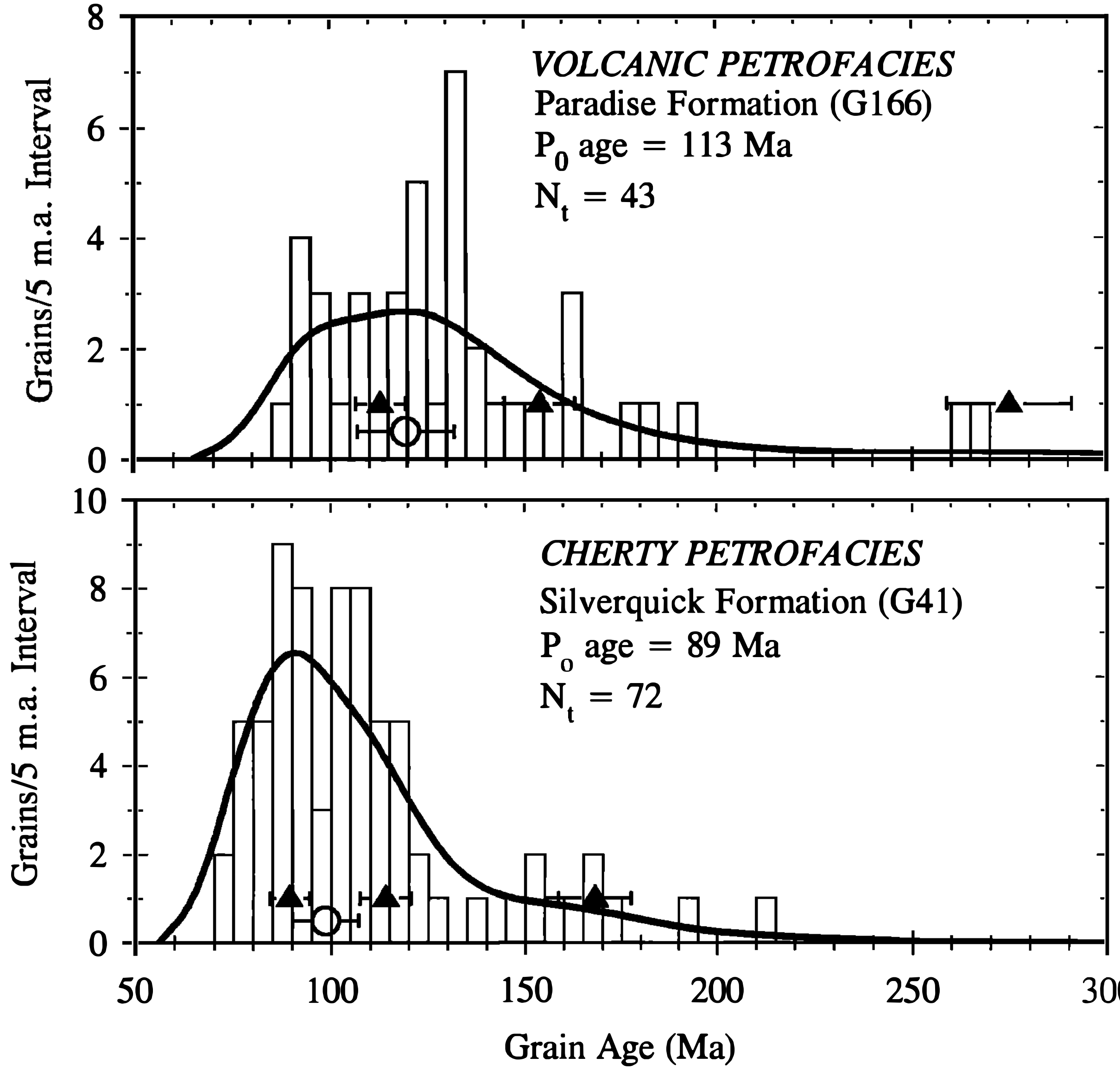


**Figure 5.** Composite probability density plot and grain age histogram for detrital zircons from the volcanic and cherty petrofacies of the Tyaughton basin. Results are summarized in Table 1. The open circle and bar interval show the possible range for the depositional age of each sample as determined from paleontological data. The solid triangles and error bars show the peak ages and ±2 standard error uncertainties as determined by the peak-fitting method. Note that the density plot and the histogram are plotted using the same vertical scale with units of "number of grains per 5 m.y. interval".

rocks of the source region that were exposed at the surface during the Albian and Cenomanian. Our understanding of the long-term evolution of these source regions would require a suite of samples spanning a wider stratigraphic range (see *Brandon and Vance* [1992] and *Garver and Brandon* [1994] for discussion about how peaks evolve with time).

### Comparison of FT Grain Age Distributions

An inspection of the best fit peak ages (Table 1) shows that the FT age distributions (Figures 5-7) correlate closely with petrofacies. This point is highlighted by the synoptic plots shown in Figure 8. These plots are constructed by combining grain ages or best fit peaks from two or more sample and show the probability density for a related group of samples or a selected set of peaks [*Brandon and Vance*, 1992]. Figure 8a shows all grain ages combined, whereas Figures 8b and 8c show those grain ages that define the $P_0$ peaks and the older peaks, respectively.

The synoptic plots can also be decomposed using the peak-fitting method. The resulting best fit peaks (Table 2) provide a useful general description of the dominant peaks that make up a selected group of grain age distributions. We focus attention on the Methow and Tyaughton arkose samples. The plots for these two suites of samples have the same general form but also show some subtle differences (Figures 8a, 8c). The peak-fitting calculation (cf. 3a and 3b in Table 2) indicates that

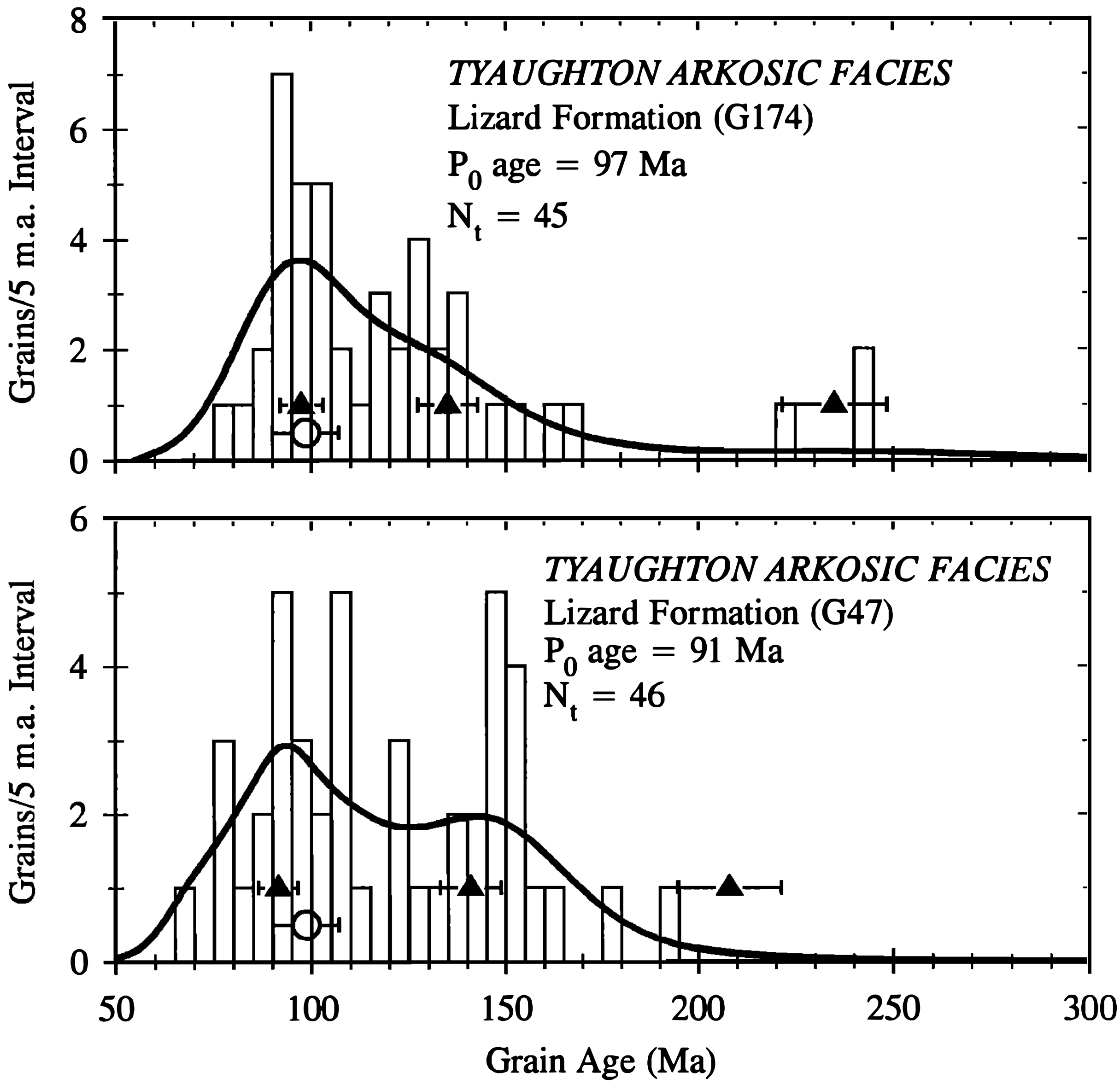


**Figure 6.** Composite probability density plot and grain age histogram for detrital zircons from the arkosic petrofacies of the Tyaughton basin. See Figure 5 for explanation.

these differences are associated with the relative sizes of the $P_0$ and $P_1$ peaks and the estimated ages of the $P_2$ peaks. We think that these differences are not significant to the problem of correlation of the Arkosic petrofacies. For instance, variations in the relative size of the peaks are easily attributed to natural variations in the relative amounts of zircon derived from each source terrain. As for the variation in age among the $P_2$ peaks, we note that these peaks are defined by relatively small populations of grain ages (3a and 3b in Table 2 have only ~4 grain ages each associated with $P_2$). Our estimates of uncertainty are undoubtedly too small in this case because we have not accounted for the downward bias in variance caused by small sample size.

It is our opinion that for purposes of correlation, the estimated ages of the dominant peaks represent the most diagnostic feature of the grain age distribution. A dominant peak is defined as a peak that contains at least 10 grain ages. For a sample with $N_t$ = 50 grains, a dominant peak should have $\pi_f$ >20%. For the Methow and Tyaughton arkose samples we consider the close similarity in the ages of the $P_0$ and $P_1$ peaks as strong evidence that these sediments were derived from the same source area.

## Age and Provenance of the Youngest Peaks

We treat the youngest peaks separately because they are useful, not only as an indicator of provenance, but also as a constraint on the depositional ages of the samples. In all cases, the $P_0$ peaks are well defined and easily separated from their respective distributions (Table 1). The $\chi^2$ age method and the peak-fitting method give nearly identical results (Figure 4b), except for a slight old-side bias in the $\chi^2$ ages, which is typical for this method [*Brandon*, 1992]. To avoid this bias, our

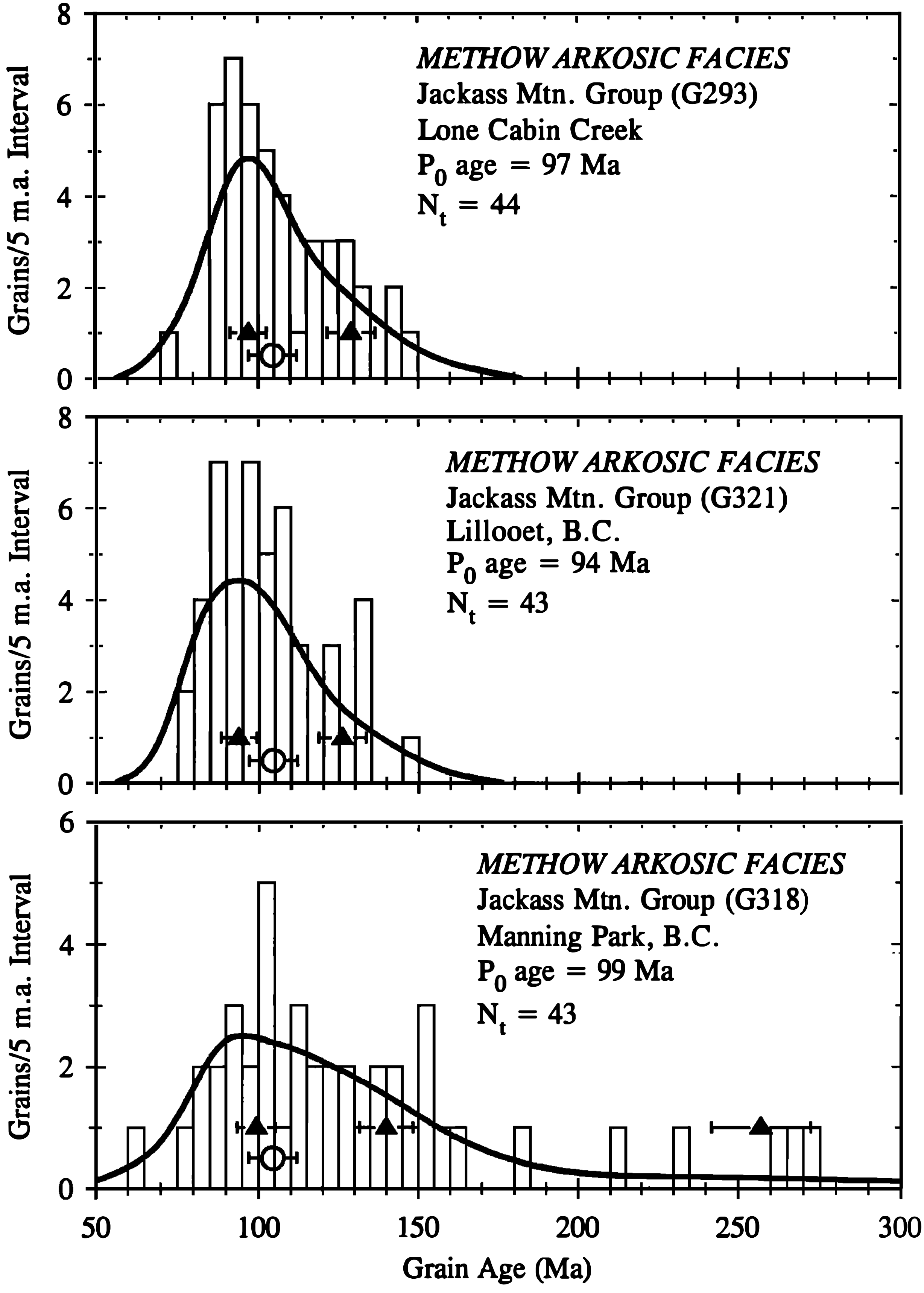


**Figure 7.** Composite probability density plot and grain age histogram for detrital zircons from the arkosic petrofacies of the Methow basin. See Figure 5 for explanation.

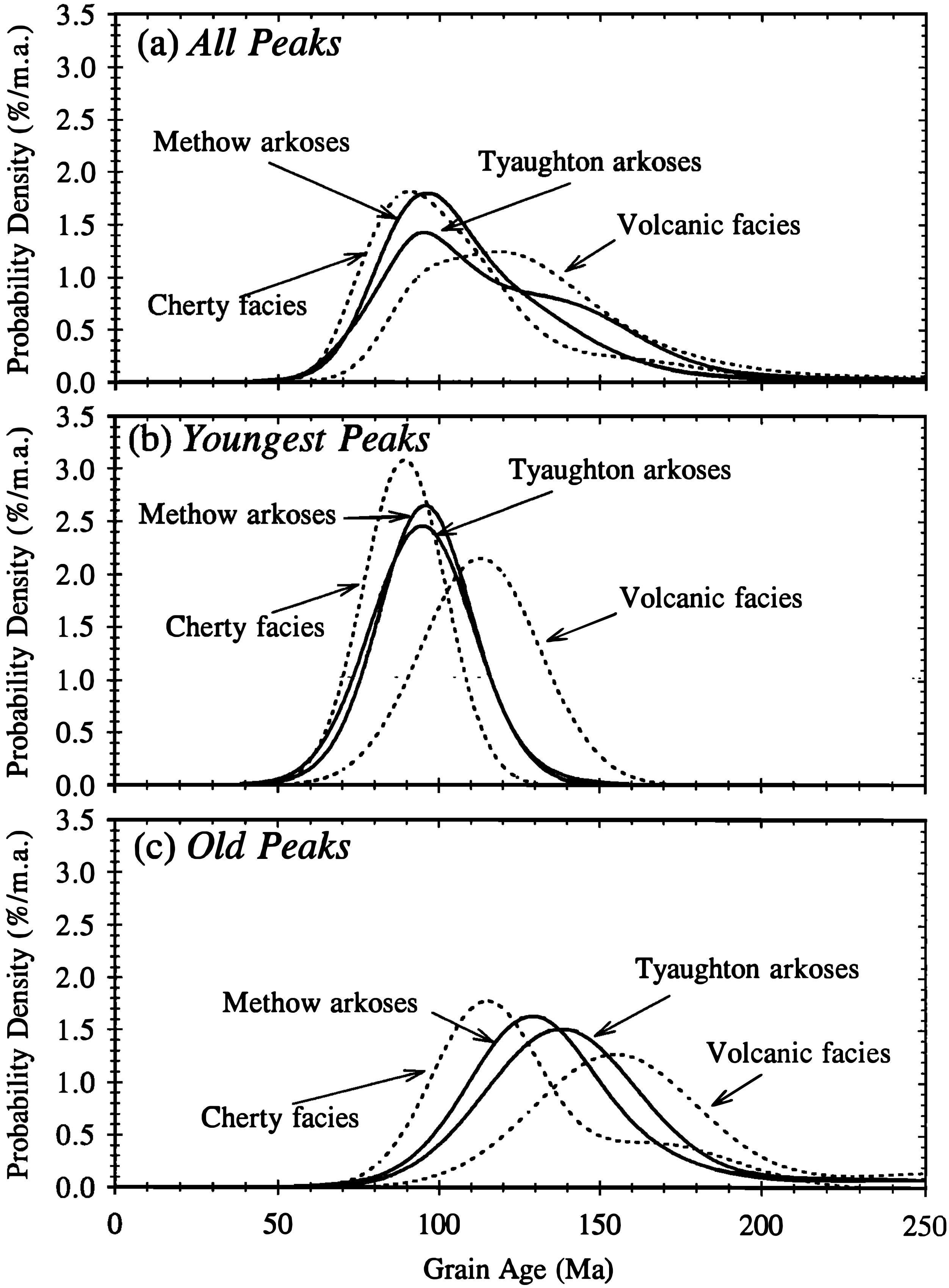


**Figure 8.** Synoptic plots of probability density as a function of petrofacies: (a) all grain ages combined; (b) only those grain ages associated with $P_0$ peaks; and (c) only those grain ages associated with the older peaks. Note the close correspondence between the Tyaughton and Methow arkoses, and the contrast that these distributions have with the volcanic and cherty petrofacies. These plots were decomposed using the peak-fitting method in order to determine average ages for the $P_0$, $P_1$, and $P_2$ peaks (Table 2).

**Table 2.** Best-fit Peaks for Synoptic Composite Probability Density Plots

| Sample Group | Best Fit Peaks $P_0$ | $P_1$ | $P_2$ |
|---|---|---|---|
| 1) Volcanic Petrofacies<br>one sample, $N_t$ = 43 grains | 113 ± 6.5 Ma<br>$\pi_f$ = 60%<br>W = 16% | 154 ± 9.2 Ma<br>$\pi_f$ = 29% | 275 ± 16 Ma<br>$\pi_f$ = 7% |
| 2) Cherty Petrofacies<br>one samples, $N_t$ = 72 grains | 89.3 ± 5.1 Ma<br>$\pi_f$ = 52%<br>W = 14% | 114 ± 6.6 Ma<br>$\pi_f$ = 33% | 168 ± 9.5 Ma<br>$\pi_f$ = 12% |
| 3) Arkosic Petrofacies<br>Tyaughton and Methow<br>five samples, $N_t$ = 221 grains | 96.6 ± 5.5 Ma<br>$\pi_f$ = 62%<br>W = 17% | 137 ± 7.9 Ma<br>$\pi_f$ = 33% | 241 ± 14 Ma<br>$\pi_f$ = 4% |
| 3a) Tyaughton Arkoses Only<br>two samples, $N_t$ = 91 grains | 94.9 ± 5.3 Ma<br>$\pi_f$ = 51%<br>W = 17% | 139 ± 7.8 Ma<br>$\pi_f$ = 44% | 230 ± 13 Ma<br>$\pi_f$ = 4% |
| 3b) Methow Arkoses Only<br>three samples, $N_t$ = 130 grains | 96.2 ± 5.6 Ma<br>$\pi_f$ = 66%<br>W = 16% | 132 ± 7.6 Ma<br>$\pi_f$ = 29% | 208 ± 12 Ma<br>$\pi_f$ = 3% |

$N_t$ is the total number of grains analyzed; $\pi_f$ is the estimated size of a specific peak or fraction relative to the total size of the distribution. All uncertainties are cited at ±2 standard error and include group error. W is the estimated relative standard deviation as a percentage of the peak age; note that a single W is fit for all peaks in a distribution.

interpretations are based on the ages determined by the peak-fitting method, but this decision has no significant affect on our conclusions.

The $P_0$ peak makes up from 44 to 70% of the zircons dated from each sample (Figure 6). For each sample, the age of the $P_0$ peak is indistinguishable from the paleontologically determined depositional age (Figure 4a). The lag time for the $P_0$ peak can be no greater than the difference between the FT age of the $P_0$ peak and the minimum depositional age permitted by the paleontological data (Table 1). On the basis of this calculation, the lag times for the $P_0$ peaks are < 7.4 to 0.8 m.y., which represents a relatively short period of time when compared with the uncertainties associated with the peak age (~ ±5.5 m.y.) and the paleontologically determined age (~ ±5 m.y.).

We attribute the $P_0$ zircons to one or more zircon-bearing volcanic source terrains. This conclusion is consistent with the relatively short lag times for this peak and the observation that the framework grains in all three petrofacies contain a significant percentage (> 30%) of intermediate and felsic volcanic detritus [*Garver*, 1989; 1992]. Local volcanic/plutonic suites are known east of the Methow area [*Thorkelson and Smith*, 1989; *Greig*, 1992; *Greig et al.*, 1992; *Hurlow and Nelson*, 1993] and west of the Tyaughton area [Jeletzky and Tipper, 1968; *McLaren*, 1990; *Garver*, 1989]. Some magmatic activity might have occurred within the Methow/Tyaughton basin, as evidenced by mid-Cretaceous dikes of intermediate composition in the Bridge River complex [*Archibald et al.*, 1990, 1991]. It is important to note that magmatism was not unique to this part of the Cordillera during the mid-Cretaceous. Regional compilations show widespread igneous activity along the entire length of the Cordillera at this time [*Armstrong*, 1988; *Cowan and Bruhn*, 1992].

The $P_0$ peak ages can be used to refine our estimate of depositional age. Those depositional ages reported in Table 1 are based solely on the age range permitted by the paleontological data, as correlated to the timescale of *Harland et al.* [1990]. We propose that the depositional age of a sample should be no older than the age of the $P_0$ peak plus 2 standard error. Using this constraint, we revise the estimates of depositional ages as: middle Aptian-early Albian for the Paradise Formation (volcanic petrofacies; G166: 120 to 107 Ma), Cenomanian for the Silverquick conglomerate (cherty petrofacies; G41: 94 to 90 Ma ), late Albian-early Cenomanian for the Lizard Formation (Tyaughton arkosic petrofacies; G174: 103 to 90 Ma; G47: 96 to 90 Ma), and late Albian for parts of the Jackass Mountain Group (Methow arkosic petrofacies; G293: 104 to 97 Ma; G321: 99 to 97 Ma; G318: 105 to 97 Ma).

## Age and Provenance of the Older Peaks

The older peaks in our samples provide additional information about the provenance of each petrofacies. Sandstone petrography indicates that the volcanic petrofacies is composed almost entirely of volcaniclastic sediment [*Garver*, 1992]. On the basis of this observation, we infer that most, if not all, of the zircon FT grain ages are related to volcanic source terrains. The $P_2$ peak is relatively small (~7%) and perhaps insignificant. However, the $P_1$ peak (~154 Ma) is significant; it makes up ~29% of the total distribution (~14 grain ages). It is about 40 m.y. older than the depositional age of the sample. We infer that the $P_1$ peak was derived from an older volcanic source terrain. Consistent paleocurrent directions suggest that sediments of the volcanic petrofacies were transported from the west [*Garver*, 1989]. The west side of the basin is flanked by nonmarine volcanics (Taylor Creek volcanics of *McLaren* [1990]) and a belt of Upper Jurassic (163-147 Ma) plutonic rocks [*Monger*, 1993], both of which might mark the location of the volcanic source terrain from which the $P_1$ zircons were derived. The wall rocks for this plutonic belt include the Wrangellia terrane of Vancouver Island. If the $P_1$ zircons could be confidently tied to this source terrain, then this connection would indicate that the Insular superterrane was adjacent to the Methow/Tyaughton basin by middle to late Albian time when strata of the Paradise Formation were first interbedded with the Arkosic petrofacies [*Garver*, 1992].

The older peaks for the Cherty petrofacies are difficult to interpret because the bulk of the sediment is composed largely of zircon-poor lithologies, mainly chert. Paleocurrent directions are variable, consistent with the interpretation that this petrofacies was derived from local sources within the Methow/Tyaughton basin [*Garver*, 1989]. On the basis of stratigraphic relations and sedimentary petrography, possible candidates for zircons in the $P_1$ and $P_2$ peaks include the Cadwallader terrane, older strata of the Tyaughton section, and sandstones in the Bridge River complex.

The Arkosic petrofacies is distinguished by a significant proportion of plutonic and metamorphic detritus [*Garver*, 1992]. A medium to high grade of metamorphism is inferred based on the presence of detrital kyanite, garnet, biotite, and muscovite, and diagnostic metamorphic textures in detrital quartz [*Garver*, 1989]. Compositional data for detrital garnets from the Tyaughton arkosic samples (G174 and G47) are summarized in Figure 9. Most garnets have almandine/pyrope and spessertine compositions, indicative of amphibolite-facies metapelite and garnet-bearing S-type granites. A minor fraction have a grossular composition, suggesting derivation from metamorphosed limestones.

The two Tyaughton samples suggest some additional features of the arkosic source. Sample G174 is rich in plutonic detritus, mainly quartz, feldspar, and biotite, but contains only minor metamorphic detritus. In contrast, sample G47 contains a much greater amount of both metamorphic and plutonic detritus. The important observation is that this increase in the modal abundance of metamorphic and plutonic detritus is marked by an increase in the relative size of the $P_1$ peak, from $\pi_f$ = 36% in sample G174 to $\pi_f$ = 52% in sample G47. From this we infer that the metamorphic detritus in the arkosic petrofacies is related to the source terrain for the $P_1$ peak. Because sample G174 contains relatively little metamorphic detritus and yet it still has a significant, albeit smaller, $P_1$ peak, it seems likely that the source terrain for the $P_1$ peak included both plutonic and metamorphic rocks.

To summarize, we prefer a relatively simple interpretation for the Arkosic petrofacies. The zircons that make up the $P_0$ peak were derived from an active volcanic source terrain, and those that make up the $P_1$ peak are derived from a heterogeneous metamorphic/plutonic source terrain. We suggest that the $P_1$ source was a synorogenic terrain as indicated by the abundance of metamorphic and plutonic detritus and by the abrupt introduction of the Arkosic petrofacies in the Albian (Figure 3). The $P_2$ peak is too small to interpret with confidence.

Table 3 summarizes lag times and model denudation rates for the $P_1$ peaks of the Arkosic petrofacies. The denudation rates range from about 150 to 220 m/m.y., which is a relatively modest rate for an active orogenic setting. Because our samples come from the lowest part of the Arkosic petrofacies, it is likely that the $P_1$ zircons were derived from units that were already near the earth's surface and above the zircon FT closure depth. In this case, the age of the $P_1$ peak (137 Ma) would predate orogenesis, and the model denudation rate would be an average of the slow rate of denudation prior to orogenesis and the

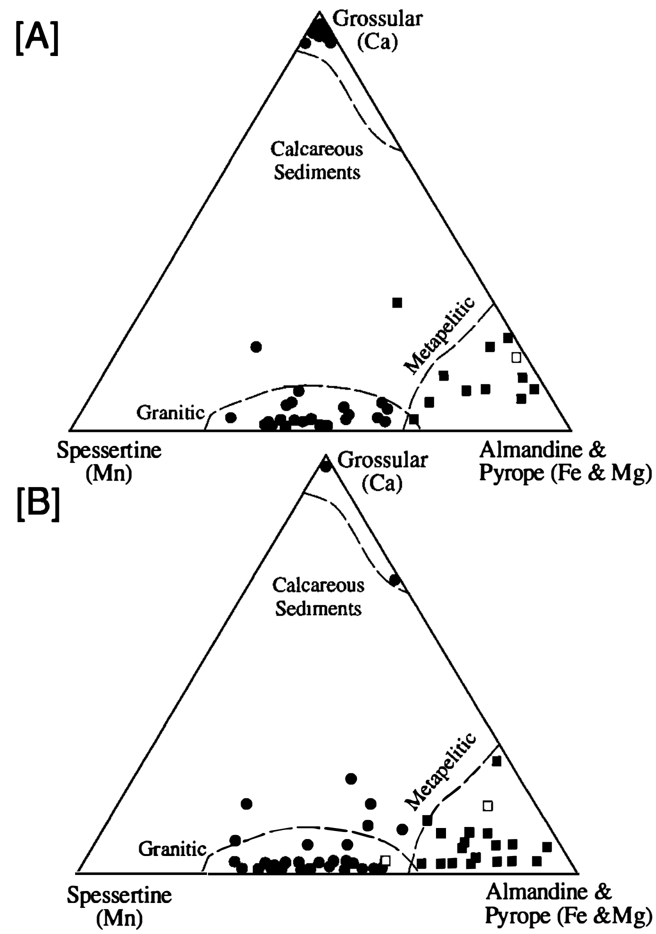


**Figure 9.** Composition of detrital garnets from the Tyaughton arkosic samples [from *Garver*, 1989]. Sample are from: (a) plutonic-rich arkose (G174), and (b) metamorphic and plutonic-rich arkose (G47). Analyses are from a micoprobe using energy-dispersive spectrometry. Open squares have a pyrope component >10%. End members were calculated according to the garnet formula $X_3Y_2Z_3O_{12}$ (see *Garver* [1989] for procedures and data). All samples were point-counted using a EDS on a JOEL electron microprobe.

**Table 3.** Model Denudation Rates for the $P_1$ Peak of the Arkosic Petrofacies

| Sample | Mid-Point Age, Age range | Lag Time | Model Denudation Rate (m/m.y.) | Model Cooling Rate (°C/m.y.) |
|---|---|---|---|---|
| Arkosic Petrofacies, Tyaughton Section | | | | |
| G174 | 116 Ma (97 to 135 Ma) | 38 m.y. | 189 ± 47 | 5.6 |
| G47 | 116 Ma (91 to 141 Ma) | 50 m.y. | 143 ± 27 | 4.2 |
| Arkosic Petrofacies, Methow Section | | | | |
| G293 | 113 Ma (97 to 129 Ma) | 32 m.y. | 222 ± 65 | 6.6 |
| G321 | 110 Ma (94 to 126 Ma) | 32 m.y. | 220 ± 63 | 6.6 |
| G318 | 120 Ma (99 to 140 Ma) | 41 m.y. | 175 ± 44 | 5.2 |

Calculated assuming a thermal gradient of 30° C/km; a surface temperature of 10° C; a closure temperature of 222°C, and a closure depth of 7.1 km. The cited uncertainty for the model denudation rate is ±2 standard error and includes only those uncertainties for the estimate of the lag time.

accelerating rate of denudation during orogenesis. If orogenesis and denudation continued for some time, then we would expect that present-day outcrops of rocks affected by this orogenic event would show cooling ages that are Albian or younger.

Thus we conclude that the synorogenic source terrain was affected by at least two events. The first, which is recorded by the 137 Ma age of the $P_1$ peak, involved an earliest Cretaceous cooling event, related to either post orogenic denudation or cooling after plutonism. The second event, which was iniated during the Albian (113-97 Ma), was marked by uplift, erosion, and deposition of the arkosic sediments in the Methow/Tyaughton basin.

## Discussion and Concluding Remarks

From our analysis, it is clear that the Arkosic petrofacies represents an important overlap sequence that links basement terranes and clastic-linking sequences to one another and to a continental source to east. What remains an intriguing problem is the identity of the source of the Arkosic petrofacies, especially in light of paleomagnetic evidence and some palinspastic restorations that suggest large coast-parallel transport after the mid-Cretaceous (see *Oldow et al.* [1989], and *Cowan and Bruhn* [1992] for reviews). Provenance analysis for the Arkosic petrofacies indicates that by Albian time, the Methow/Tyaughton basin was fed by sediment derived from a metaplutonic complex located to the east of the basin, which we infer to be a synorogenic source terrain. If our interpretation is correct, then our search for this source terrain should focus on metaplutonic complexes that were uplifted, denuded, and cooled during and after the Albian.

A recent Sm/Nd isotopic study by *Barfod and Nelson* [1992] provides another useful clue as to the source of the Arkosic petrofacies. They found that these sediments have relatively high $\varepsilon_{Nd}$ values at the time of deposition ($\varepsilon_{Nd}$ = +2.8 to +3.9), which indicates a source area dominated by relatively primitive rocks, such as ophiolitic rocks or Phanerzoic arc volcanic rocks. We would expect negative $\varepsilon_{Nd}$ values if the source area contained a significant fraction of Precambrian continental crust, or plutons or sediments derived from or contaminated by Precambrian continental crust. The signature of the evolved crust, however, could be masked if most of the sediment is derived from primitive rocks. The present-day extent of Precambrian basement beneath the North America Cordillera is shown in Figure 10.

The paleomagnetic evidence, which seems to indicate young, large-scale transport of Baja BC after the Albian, has forced us to search broadly, from southwest Canada to central Mexico, for the arkosic source terrain. In our discussion here, we start our search in southwest Canada and then move southward.

Two possible sources lay adjacent to the present-day location of the Methow/Tyaughton basin. Immediately to the east are plutonic rocks of the Okanogan Range, which were mainly emplaced during the Early Cretaceous [*Thorkelson and Smith*, 1989; *Greig*, 1992; *Greig et al.*, 1992; *Hurlow and Nelson*, 1993]. Recent isotopic dating indicates that some older plutons with Late Jurassic igneous ages did not cool until the mid-Cretaceous, which might indicate uplift and denudation at that time [*Greig et al.*, 1992; *Greig*, 1992]. The Okanogan Range batholith lies outboard of the "Sr 706" line (initial $^{87}Sr/^{86}Sr$ = 0.706) [*Armstrong et al.*, 1977; *Armstrong*, 1988], so that sediment from this source would probably have an isotopic composition compatible with the $\varepsilon_{Nd}$ data of *Barfod and Nelson* [1992]. *Garver* [1989] has considered this possible source terrain and dismissed it because the aerial extent of the Okonogan Range batholith is too small to account for the volume of arkosic sediment in the Methow/Tyaughton basin and because coarse conglomeratic facies, which one would expect from such a nearby source, are rare.

Another nearby source terrain is the Omineca crystalline belt of southeast British Colimbia, eastern Washington, and Idaho. Albian uplift and denudation of the Omineca belt is recorded in the Alberta foreland basin, which shows an increase in sedimentation rate and the introduction of sediment composed of volcanic/plutonic detritus with subordinate metamorphic detritus [*Mellon*, 1967]. The Middle to Late Jurassic marked another period of intense metamorphic/plutonic activity and associated sedimentation; the intervening time, during the Early Creatceous, was characterized by relative tectonic quiescence and low rates of magmatism [*Eisbacher et al.*, 1974; *Archibald et al.*, 1983; *Armstrong*, 1988]. The Omineca lies inboard of the Sr 706 line and is underlain by crust and sediments of Precambrian age, which indicates that sediments from this area should be isotopically

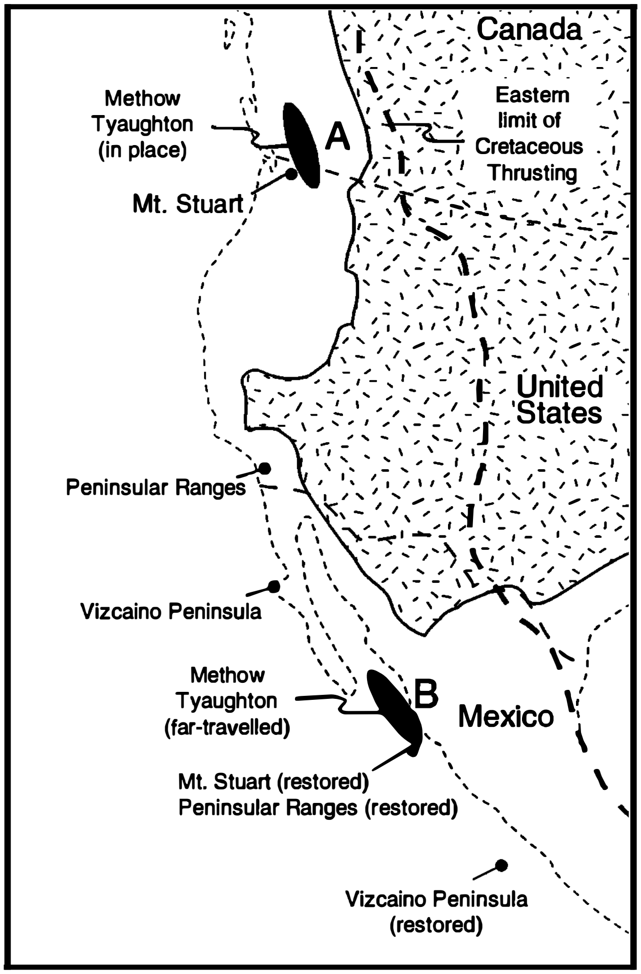


**Figure 10.** Assessment of potential sources for the Methow-Tyaughton Arkosic petrofacies (modified from *Umhoefer* [1987]; and *Coney et al.* [1980]). We can exclude areas where Precambrian rocks or granites that intruded Precambrian basement were being eroded, or where sediments were being accumulated during the mid-Cretaceous. Rice pattern represents known limit of cratonal North America. Based on paleomagnetic data for the Upper Cretaceous Mount Stuart (MS - present location) batholith [*Ague and Brandon*, 1992 and references therein], the Methow/Tyaughton basin is predicted to have formed off of central Mexico. Potential sources at this latitude include granitic rocks that were intruded outboard of the Sr line and which could have delivered sediment with relatively high $\varepsilon_{Nd}$ values. The present and restored position of the Vizcaino Peninsula, Baja California is shown for reference. Note that if this option is correct, the Cretaceous deposits and volcano-plutonic rocks of Baja California would represent the inboard source and/or the southern continuation of the Methow-Tyaughton basin.

evolved with relatively low $\varepsilon_{Nd}$. Thus sediment derived from this area would be inconsistent with the $\varepsilon_{Nd}$ data of *Barfod and Nelson* [1992].

Moving southward along the western edge of North America, the next significant exposure of pre-Tertiary rocks starts in southern Oregon and extends the length of California. During the Cretaceous, this area was the site of a west-facing convergent margin, as represented by the Sierra/Klamath magmatic arc, the Great Valley forearc basin, and the Franciscan subduction complex [*Cowan and Bruhn*, 1992]. This triad of arc, forearc, and subduction complex has remained relatively intact and does not appear to have moved substantially with respect to North America. We discount this area as a source for the Arkosic petrofacies because it seems unlike that Baja BC would have been derived from a site outboard of an active convergent margin. Furthermore, Albian strata of the Great Valley basin are dominated by volcanic lithic detritus. Arkosoic sediments do not appear in any significant abundance until the Late Cretaceous [*Ingersoll*, 1983].

Farther south are the displaced terranes of southern California and Mexico, many of which have igneous and stratigraphic histories that are broadly compatible with our inferences about the arkosic source terrain. For instance, mid-Cretaceous magmatism is recorded in the Salinia, Peninsular Ranges, and Alistos terranes of southern California and Baja California, and the Geurrao terrane of western Mexico [*Campa and Coney*, 1982; *Centeno-Garcia et al.*, 1993]. Isotopic and paleomagnetic data indicate that these terranes formed as an Early Cretaceous magamatic arc that was built on juvenile crustal adjacent to the central Mexican margin [*Campa and Coney*, 1983; *Ague and Brandon*, 1992; *Centeno-Garcia et al.*, 1993]. We examine the Peninsular Ranges terrane more closely because it represents a good example of a possible source terrain in this area.

The western half of the Peninsular Range batholith was intruded between 120-105 Ma outboard of the Sr 706 line [see *Cowan and Bruhn*, 1992]. This part of the batholith is unconformably overlain by Upper Cretaceous strata, which suggests that the batholith was uplifted and exposed during the mid-Cretaceous. All of these features are compatible with what we know about the Arkosic source terrain. Furthermore, paleomagnetic data indicate that during the mid-Cretaceous, the Peninsular Ranges batholith and Baja BC, which includes the Methow/Tyaughton basin, were both located at the latitude of central Mexico (location B in Figure 10).

An important challange for the Baja BC hypothesis is whether or not we can locate in the southern Cordillera the eroded source terrain and remnants of a proximal depositional system from which the arkosic sediments of the Methow/Tyaughton basin were derived. In this regard, a useful investigation would be a comparison of mid-Cretaceous strata of arkosic composition in central Mexico, such as the Valle Formation [e.g., *Hickey*, 1984], with the Arkosic petrofacies of the Methow/Tyaughton basin.

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