Erosional denudation of the British Columbia Coast Ranges as determined from fission-track ages of detrital zircon from the Tofino basin, Olympic Peninsula, Washington

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ABSTRACT

In this study, we use up-section changes in fission-track (FT) ages of detrital zircons to infer the tectonic evolution of the source region that fed sediments to the Tofino basin, a Tertiary forearc basin in northwestern Washington State and southwestern British Columbia. We have dated 50 grains from each of eight samples from a 6-km-thick section that ranges in age from 40 to 19 Ma. The detrital zircons have not been reset and thus preserve information about the thermal and denudation history of the source region from which the sediments were derived. Each of our eight samples contains a distinct set of grain-age populations or peaks, indicating that the source region contained several FT source terrains. The number of peaks and their lag time (peak age minus depositional age) contain thermochronologic information about these source terrains. In this study, there is little evidence of active volcanism in the source region; thus the FT ages reflect cooling during denudation of the source regions. The oldest sample in our suite, from the upper Eocene Lyre Formation, shows a dominant peak at ca. 40 Ma, coincident with cooling ages of denuded metamorphic rocks of the Leech River Schist on southern Vancouver Island. This interpretation is supported by paleocurrent directions indicating a source in the vicinity of Vancouver Island, the development of a late Eocene unconformity across much of southern Vancouver Island and western Washington, and the predominance of lithic detritus in this part of the section. Samples from strata above the Lyre Formation are feldspathic, and they presumably reflect erosional denudation of a plutonic source terrain. Peaks in samples from the lower part of this feldspathic interval have widely scattered Jurassic to mid-Cretaceous FT ages; young zircons are notably absent. Up-section, peak ages in samples from the upper part of the feldspathic section form a dominant peak that gets progressively younger with time. While the age of the dominant peak becomes younger in younger samples, the lag time for this peak remains constant at ~40 m.y. This peak can be recognized in a compilation of zircon FT ages from modern exposures of the Canadian Coast Mountains. We infer that zircons in our samples were derived from progressive erosional denudation of the Coast Plutonic Complex, which had, based on our results, a constant rate of denudation of ~250 m/m.y. The scatter of ages in the older samples from the feldspathic interval may indicate the unroofing of a high-level sedimentary basin (containing the Cretaceous Nanaimo and Burrard Groups) that used to overlie parts of the Coast Plutonic Complex. Our study, along with others, shows that up-section studies of FT ages of detrital zircons can be effective in resolving the long-term denudation history of continental source regions.

INTRODUCTION

Basin strata record the composition and thermotectonic evolution of adjacent terrains, and in most studies, the provenance of the clastic sedimentary units have been determined through traditional means, mainly point counts of sandstones (for example, Dickinson, 1988). Although this approach has been useful in subdividing broad tectonic provenance, there are many instances where the technique cannot resolve local variations in source regions or provide specific information concerning the thermotectonic evolution of the source region. Recently, isotopic work on detrital minerals has been helpful in discriminating sources and providing information about the age and thermal history of these source terrains. For example, single-grain U/Pb studies of detrital zircon have been helpful in delimiting protolith ages in source areas (for example, Gehrels and others, 1991), but the presence of recycled grains (sedimentary or igneous) can complicate interpretation of these data. Fission-track (FT) ages of detrital zircon record low-temperature thermochronology of a source region, because different rocks of a source are commonly reset to a common age that generally corresponds to the time of denudation, regardless of protolith age. Therefore, FT dating of detrital minerals is one of the few isotopic methods that can be used on single grains to directly relate cooling/denudation in a source to deposition in an adjacent basin. In this study, we are particularly interested in how FT ages of detrital zircon change up-section in a stratigraphic sequence that records the evolution of a source region. We refer to this sort of analysis as *FT stratigraphy*.

Petrographic data for sandstones in the Pacific Northwest indicate that many units are compositionally similar, but recent isotopic dating indicates that these sandstones have distinct source terrains. In the Olympic Mountains of northwestern Washington State, isotopic data from minerals in quartzo-feldspathic sandstones suggest that most of this detritus originated from thermally reset terrains in eastern Washington, Idaho, and

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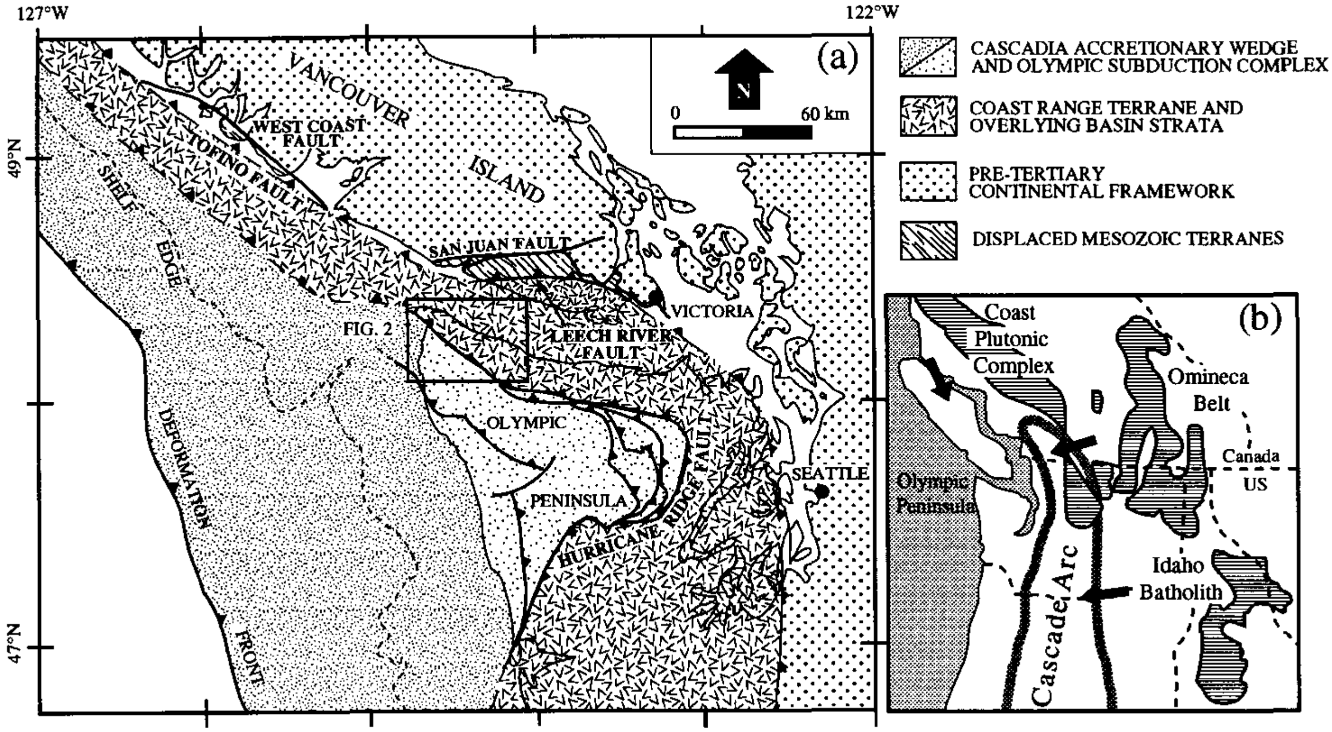


Figure 1. (a) Geologic map of the Pacific Northwest and the tectonic setting of the Olympic Mountains (modified from Clowes and others, 1987) showing the location of the study area (Fig. 2). Structurally above the Olympic Subduction Complex (OSC), which is the accretionary complex, is a sequence of Eocene basalts (Coast Range terrane) with an overlying sequence of Eocene and younger strata of the Tofino basin from the northwestern Olympic Mountains north along the west coast of Vancouver Island. On the northwestern part of the Olympic Peninsula, Eocene to lower Miocene strata of the Tofino basin are exposed in a north-dipping sequence. (b) The inset (modified from Brandon and Vance, 1992) shows the Cascade arc in southern British Columbia, Washington, and Oregon, as well as the distribution of the principal metaplutonic source regions in the Pacific Northwest. These source regions include the rapidly cooled plutonic and metamorphic rocks of the Idaho batholith and the Omineca Belt east of the Cascade arc, and the Coast Plutonic Complex, which is mainly north of the arc. Arrows represent the principal sediment paths for detritus that has accumulated in the area of the Olympic Mountains.

British Columbia as well as the coeval Cascade arc, which was built along the continental margin (Fig. 1; Brandon and Vance, 1992; Heller and others, 1987). In this study, we show how FT ages of detrital zircons from quartzofeldspathic sandstones of the northern Olympic Peninsula (part of the Tofino basin) indicate a different plutonic source terrain, which lay to the north, with a distinct thermal evolution that is very different than the thermal history of terrains that fed coeval sandstones elsewhere on the Olympic Peninsula.

In this paper, we synthesize the stratigraphy, petrology, and provenance of strata of the Tofino basin on the Olympic Peninsula. We then examine the FT stratigraphy by showing how the FT grain ages vary up-section in the stratigraphic sequence and how this variation is related to the provenance and evolution of the source terrain of the sediments. Finally, we hypothesize that the detrital zircon FT ages in the upper part of the Tofino basin have recorded the progressive erosional denudation of the Coast Ranges of western British Columbia.

GEOLOGIC SETTING OF THE OLYMPIC PENINSULA

Regional Setting

The Cenozoic evolution of the Pacific Northwest is dominated by four major tectonic elements (Fig. 1a; see Brandon and Vance, 1992, for details). The pre-Tertiary continental framework includes various Mesozoic and Paleozoic terranes that served as a relatively rigid upper plate to Cenozoic subduction of the Farallon/Juan de Fuca plate. This framework includes the Coast Plutonic Complex of western British Columbia, which is a late Mesozoic to early Cenozoic batholithic complex (Roddick, 1983). Some Mesozoic rocks, displaced from this framework, sit outboard of the continental framework and are bounded by faults of probable Eocene age (that is, "displaced Mesozoic terranes" on Fig. 1a; Fairchild and Cowan, 1982; Rusmore and Cowan, 1985; Brandon, 1989a, 1989b).

The second element, the Coast Range terrane, lies outboard of these displaced Mesozoic rocks and is distinguished by a coherent sequence of lower Eocene basalts. This basement unit, which is extensively exposed in the Pacific Northwest, is composed of a 5- to 15-km-thick sequence of basalt and minor interbedded sedimentary rocks known as the Crescent Formation in the Olympic Mountains and the Mechosin Formation on southern Vancouver Island. Well-preserved depositional contacts demonstrate that the Coast Range terrane is the basement to much of the Tofino basin (Shouldice, 1971; Clowes and others, 1987).

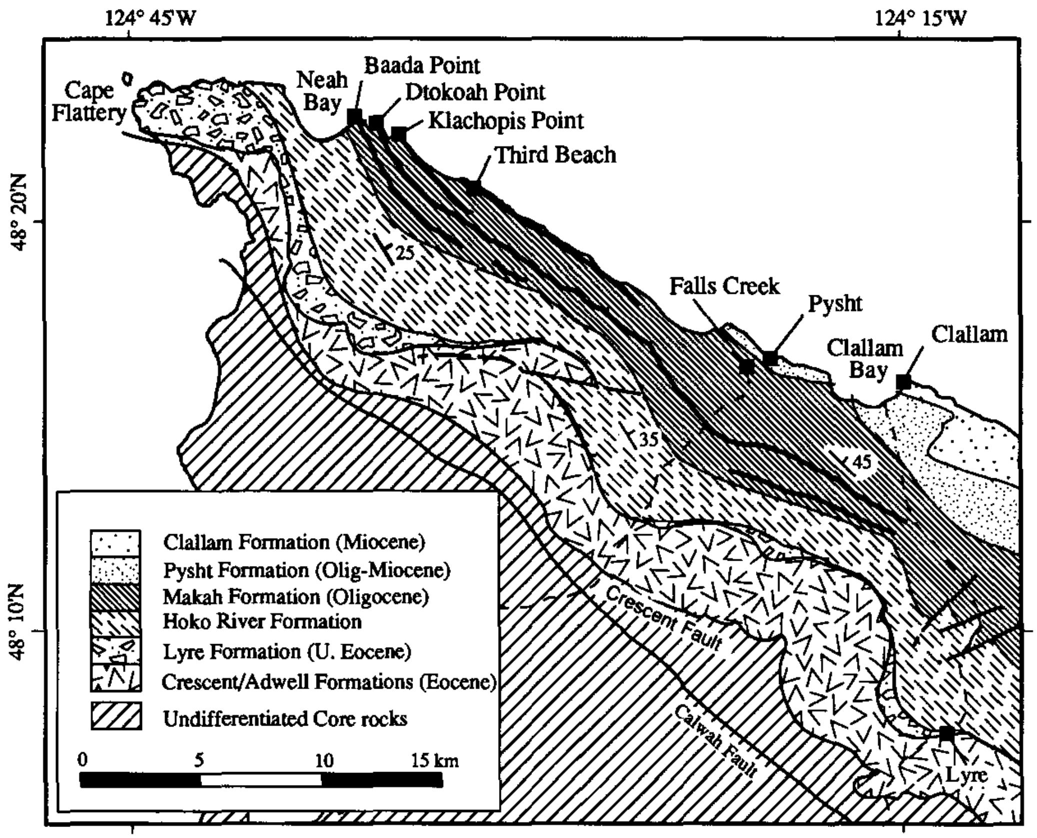


Figure 2. Geologic map (modified from Tabor and Cady, 1978b) of sample localities for the northwestern Olympic Peninsula. See Appendix for map coordinates and outcrop descriptions of each sample.

The third element, the Cascadia accretionary prism, is mostly offshore, with the exception of the Olympic subduction complex (OSC), which is uplifted and exposed in the core of the Olympic Mountains. In the Olympic Mountains, the OSC is composed of an imbricated assemblage of Cenozoic sandstone, mudstone, and minor pillow basalt (Tabor and Cady, 1978a, 1978b; Brandon and Calderwood, 1990; Brandon and Vance, 1992). The fourth element is the modern Cascade volcanic arc, which is a continental arc built on the pre-Tertiary continental framework and formed by subduction of the Juan de Fuca plate (Fig. 1). It has been active since at least 36 Ma (Armstrong and Ward, 1991).

Northern Olympic Peninsula

The northern peripheral sequence of the Olympic Peninsula exposes a north-dipping sequence of the Tofino basin and underlying Crescent Formation (Tabor and Cady, 1978a, 1978b; Snavely and others, 1986). The clastic strata and the basalts are ~9 km thick in the study area and are regionally part of a broad syncline presently occupied by the Strait of Juan de Fuca (MacLeod and others, 1977; Muller and others, 1981; Snavely and others, 1986). The Tofino basin as originally defined by Shouldice (1971) is mostly confined to the shelf of western Vancouver Island and is locally exposed along the west coast of Vancouver Island and on the northern Olympic Peninsula of Washington (Figs. 1, 2, and 3; Shouldice, 1971; Tiffin and others, 1972; Muller, 1977; Snavely and others, 1980; Muller and others, 1983; Clowes and others, 1987). We refer to the sequence of rocks exposed on the northwestern part of the Olympic Peninsula as the *northern peripheral sequence* to distinguish these strata from coeval, yet distinct, strata south of the Olympic Mountains (*southern peripheral sequence*).

The relatively coherent stratigraphic sequence of the northern peripheral sequence is separated from the more outboard OSC by the Hurricane Ridge fault (Tabor and others, 1978a, 1978b; Brandon and Vance, 1992; Fig. 1). The OSC, which underlies most of the Olympic Mountains, is composed of structurally imbricated and deformed Eocene, Oligocene, and Miocene sedimentary rocks and basalts (Tabor and Cady, 1978a, 1978b; Brandon and Calderwood, 1990; Brandon and Vance, 1992). Workers have interpreted the OSC as an uplifted subduction complex formed by frontal accretion and underplating of sediments along the Juan de Fuca subduction zone (Clowes and others, 1987; Brandon and Calderwood, 1990; Brandon and Vance, 1992). The uplift and exhumation of the OSC in the Olympic Mountains occurred in the middle to late Miocene as indicated by clasts in basinal units that flank the uplift (Gower and Pease, 1965; Tabor and Cady, 1978a; Bigelow, 1987; Brandon and Calderwood, 1990) and by

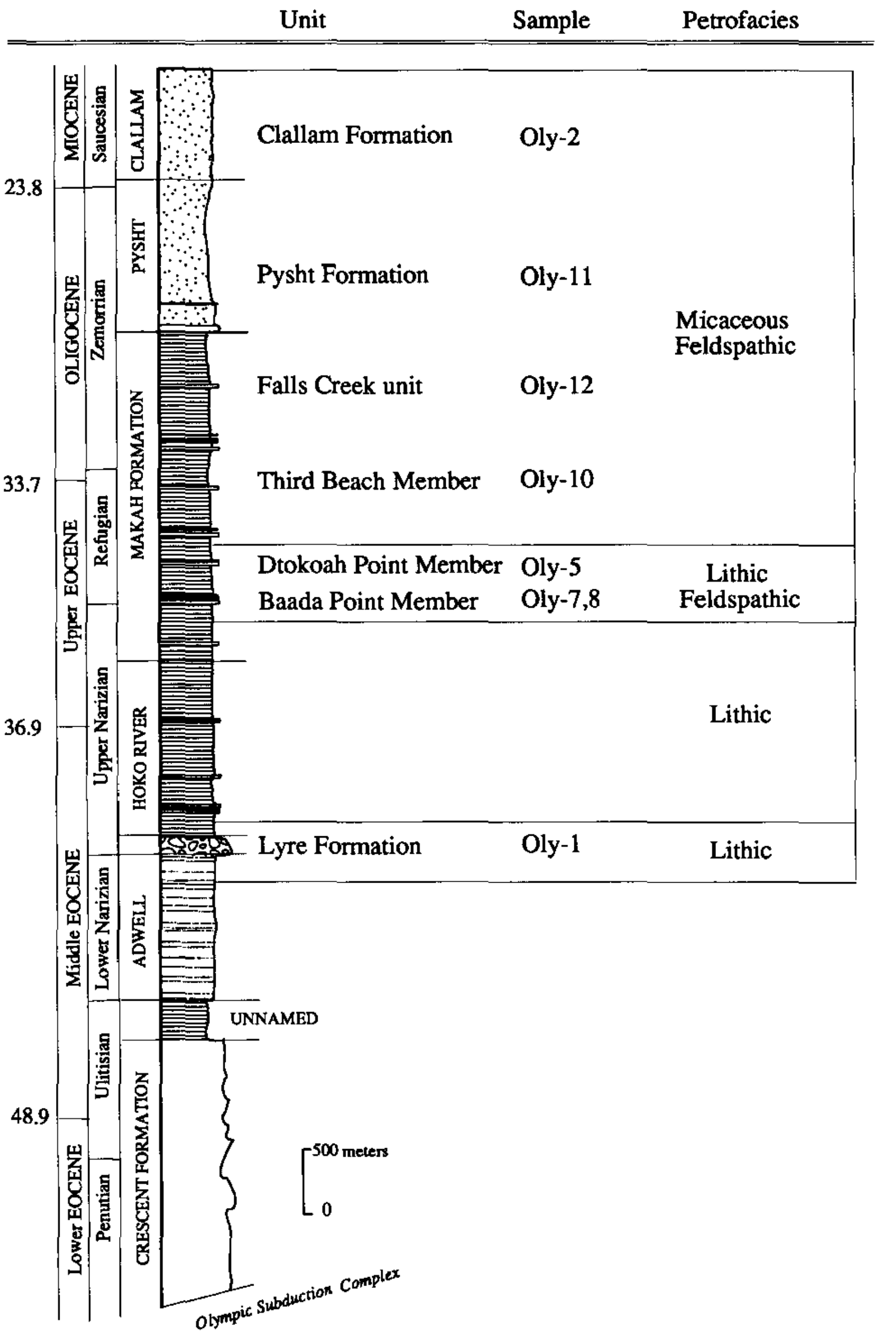


Figure 3. Stratigraphic column of the Tertiary sequence on the northwestern part of the Olympic Peninsula (modified from Muller and others, 1983) showing sample numbers with locations. Informal petrofacies designations, shown to the right, are discussed fully in the text. Strata of the Hoko River, Makah, and Pysht Formations comprise the Twin Rivers Group. Our estimate of the age of individual samples (Table 2) and stratigraphic units is shown to the left (Fig. 4, Table 2).

the FT cooling ages (Brandon and Vance, 1992; Roden and others, 1994).

Stratigraphic Units and Petrofacies of the Northern Olympic Peninsula

The sedimentary sequence that overlies the Coast Range terrane is ~6000 m thick and includes a virtually continuous section of marine clastic strata (Figs. 2 and 3). Numerous studies have investigated the stratigraphy and provenance of this section (Gower, 1960; Ainsfield, 1972; Pisciotto, 1972; Pearl, 1977; Snavely and others, 1980; Marcott, 1984; Melim, 1984; Anderson, 1985; Rauch, 1985; DeChant, 1989; Shilhanek, 1992). From these studies it is clear that the older strata (Eocene) record a relatively local provenance, and the Oligocene to Miocene strata are dominated by arkosic to quartzofeldspathic (*sensu lato*) sandstones that must have been derived from a source region composed primarily of plutonic rocks (Table 1).

To simplify discussion of the different units and their clastic composition, we subdivide the units into three distinct petrofacies: (1) lithic, (2) lithic feldspathic, and (3) micaceous feldspathic. The lithic petrofacies, characteristic of units low in the stratigraphic section, is dominated by basaltic-lithic and phyllitic-lithic detritus. Sediments of the lithic feldspathic petrofacies and the micaceous feldspathic petrofacies are very similar in general appearance but can be distinguished by the increase in abundance of sedimentary lithic fragments and biotite in the latter, and, as we show in this paper, they have distinct FT ages of detrital zircon.

Lithic Petrofacies. This petrofacies is characteristic of sediments in the Adwell, Lyre, and Hoko River Formations (Fig. 3). Clastic sediments in these units are dominated by basaltic and phyllitic detritus, as well as chert, polycrystalline quartz, and volcanic lithic fragments. The basaltic detritus is interpreted to have been derived from the Coast Range terrane and the remaining lithic detritus was derived from pre-Tertiary rocks of southern Vancouver Island, the San Juan Islands, and the displaced Mesozoic rocks (Fig. 1; Ainsfield, 1972; Marcott, 1984; De Chant, 1989).

Lithic Feldspathic Petrofacies. This petrofacies is characterized by abundant quartz and feldspar, with lesser quantities of lithic fragments and other accessory minerals, especially mica. The lower two sandstone members of the Makah Formation (Baada Point and Dtokoah Point) are quartz-

TABLE 1. STRATIGRAPHIC INFORMATION FOR STRATA OF THE STUDY AREA

Unit	Age*	Thickness†	Environment	Depth	Sandstone composition	References§
			Micaceous feldspathic petrofacies			
Clallam Formation	early Miocene	800 m	deltaic	inner neritic	mica quartzofeldspathic	1, 2
Pysht Formation	late Oligocene	1030 m	submarine fan/deltaic	inner neritic	mica quartzofeldspathic	2, 3, 4, 5
Makah Fm. (total)	late Olig.–late Eocene	2800 m	submarine fan	upper neritic–bathyal	mica quartzofeldspathic	2, 3, 5, 6, 7
Falls Creek unit	late Oligocene	(30 m)	submarine fan	upper neritic	mica quartzofeldspathic	2, 5, 7
Third Beach Mbr.	late Eocene	(43 m)	submarine fan	upper neritic	mica quartzofeldspathic	2, 5, 7
			Lithic Feldspathic petrofacies			
Dtokoah Pt. Mbr.	late Eocene	(65 m)	submarine fan	upper neritic	lithic quartzofeldspathic	2, 5, 7
Baada Pt. Mbr.	late Eocene	(120 m)	submarine fan	upper neritic	lithic quartzofeldspathic	2, 5, 7
			Lithic Petrofacies			
Hoko River Fm.	late Eocene	1.6–2.3 km	submarine fan	outer neritic	phyllitic and basaltic lithic	6, 2, 8
Lyre Formation	late Eocene	0–900 m	submarine fan	N.D.#	phyllitic lithic	2, 9, 10, 11
Adwell Formation	late Eocene	900 m	submarine fan	middle-lower bathyal	basaltic lithic	2, 12

*See Table 2 for discussion of age control of individual samples.
†Thickness of individual members of the Makah Formation are shown in parentheses because they are part of the total thickness of the Makah Formation.
§(1) Anderson, 1985; (2) Snavely and others, 1980; (3) Brown and others, 1956; (4) Gower, 1960; (5) Snavely and others, 1978; (6) Muller and others, 1983; (7) Snavely and others, 1986; (8) De Chant, 1986; (9) Shilhanek, 1992; (10) Ainsfield, 1972; (11) Pisciotto, 1972; (12) Marcott, 1984.
#No data.

ofeldspathic but characteristically rich in lithic fragments (lithic feldspathic petrofacies, Fig. 3; Snavely and others, 1980).

Micaceous Feldspathic Petrofacies. The transition from the lithic feldspathic petrofacies to the micaceous feldspathic petrofacies is a change in the relative abundance of lithic and mica grains (Pearl, 1977). The Klachopis Point and Third Beach Members and the Falls Creek unit (all of the Makah Formation), and the overlying Pysht and Clallam Formations are characteristically rich in mica and feldspar (as compared to the stratigraphically lower lithic feldspathic petrofacies) and are classified as micaceous arkose to lithic arkosic sandstones (Fig. 3). Flutes and grooves on the base of sandstone beds of the Makah Formation (containing both feldspathic petrofacies) consistently indicate transport from the northwest along the axis of the basin (Snavely and others, 1980). Sandstones of the Clallam Formation are interpreted to have been derived from andesitic to dacitic volcanic rocks, chert, metamorphic rocks, and quartz monzonitic to granodioritic plutonic rocks (Anderson, 1985). These data suggest that magmatic arc rocks dominated the source region, and the changes in framework grains from the lithic feldspathic petrofacies up-section to the micaceous feldspathic petrofacies suggest unroofing of a source where lithic-rich material was stripped off a plutonic basement.

Contrasts in Coeval Tertiary Strata in the Pacific Northwest

Oligocene to Miocene strata of the northern Olympic Peninsula are similar to coeval strata to the northwest along western Vancouver Island, but are unlike coeval strata to

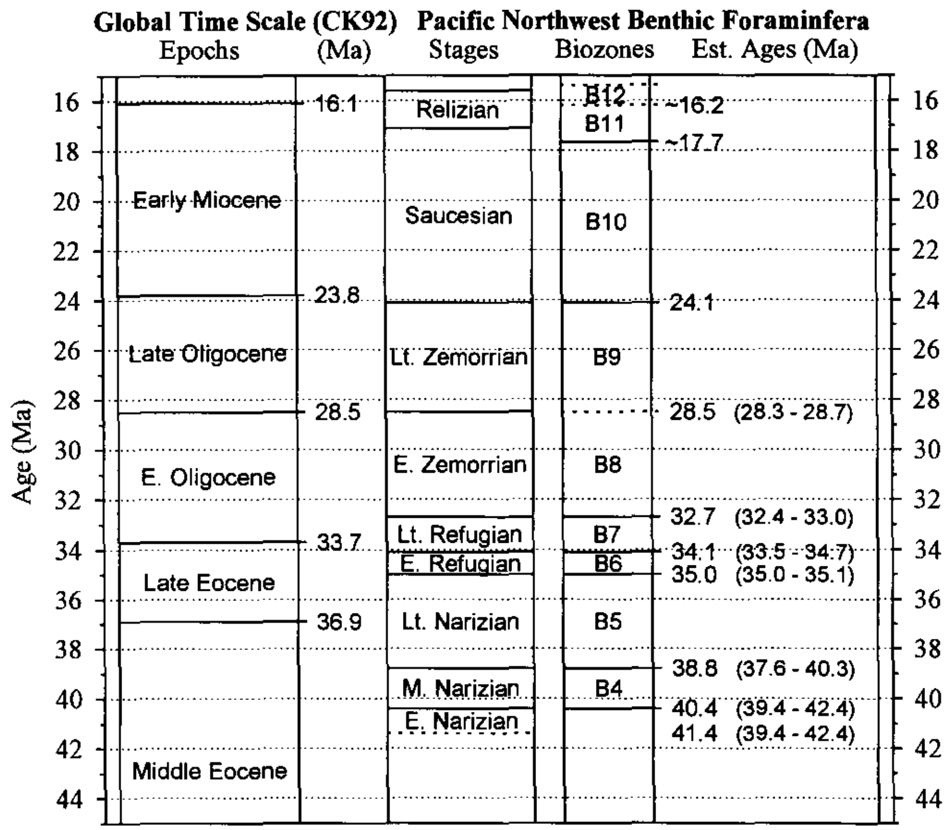


Figure 4. Correlation of the Pacific Northwest benthic foraminifera biozones (Rau, 1981; Armentrout, 1981; Prothero and Armentrout, 1985) to the time scale of Cande and Kent (1992). For this paper, we use the Pacific Northwest stages of Rau (1981; his Fig. 11) as correlated to the global time scale by Armentrout (1981), Armentrout and others (1983), and Prothero and Armentrout (1985). Cande and Kent (1992) is used for global correlation of epochs and magnetic chrons. All isotopic ages are relative to modern constants (see Harland and others, 1990), and all uncertainties are cited at the 95% confidence level (approximately ±2 standard error).

TABLE 2. FAUNAL AGES AND ESTIMATED ABSOLUTE AGES OF SAMPLES ANALYZED

Sample	Unit	Age	Pacific NW benthic foram biozones		Est. age and range (Ma)
Oly-2	Clallam Fm.*	early Miocene	lower(?) Saucesian	B10	20.9 (17.7–24.1)
Oly-11	Pysht Formation†	late Oligocene	upper(?) Zemorrian	B9	26.3 (24.1–28.5)
Oly-12	Falls Creek unit§	late Oligocene	lower(?) Zemorrian	B8	30.6 (28.5–32.7)
Oly-10	Third Beach Mbr.#	late Eocene	upper(?) Refugian	B6 or B7	33.4 (32.7–34.1)
Oly-5	Dtokoah Pt. Mbr.#	late Eocene	lower(?) Refugian	B6 or B7	34.6 (34.1–35.0)
Oly-7,8	Baada Pt. Mbr.#	late Eocene	lower(?) Refugian	B6 orB7	34.6 (34.1–35.0)
Oly-1	Lyre Formation**	late Eocene	upper(?) Narizian	B4 orB5	37.7 (35.0–40.4)

*The Clallam Formation contains Saucesian foraminifera (Rau, 1964) with mollusks assigned to the Pillarian stage (Addicott, 1981); we estimate a lower Saucesian age.
†The Pysht Formation contains Zemorrian and lower Saucesian foraminifera (B8, B9, B10; see Rau, 1964, 1981; and Snavely and others, 1986) but mollusks of the Juanian stage of Addicott (1981), which suggests an "upper Zemorrian" age (~upper Zemorrian of Kleinpell; 1938, see Rau (1981).
§The Falls Creek unit of the Makah Formation occurs above the Refugian-Zemorrian boundary, but below the Pysht Formation (Snavely and others, 1980), and we estimate deposition in the lower Zemorrian based on stratigraphic position.
#The Third Beach Member, Dtokoah Point Member, and the Baada Point Member of the Makah Formation all occur within the Refugian; Zemorrian strata occur above and upper Narizian strata directly below this section. We base our estimates on stratigraphic position with the Third Beach Member near the top of known Refugian and the Baada and the Dtokoah near the bottom of the known Refugian (see sections in Snavely and others, 1980).
**The poorly fossiliferous Lyre Formation is bracketed between upper Narizian (B5) rocks of the Hoko River Formation (Rau, 1964, 1981) and middle Narizian strata (B4) of the Adwell Formation below. Although Rau (1993, personal commun.) favors a middle Narizian assignment for the Lyre Formation in this area, our fission-track data support assignment to late Narizian based on our young peak.

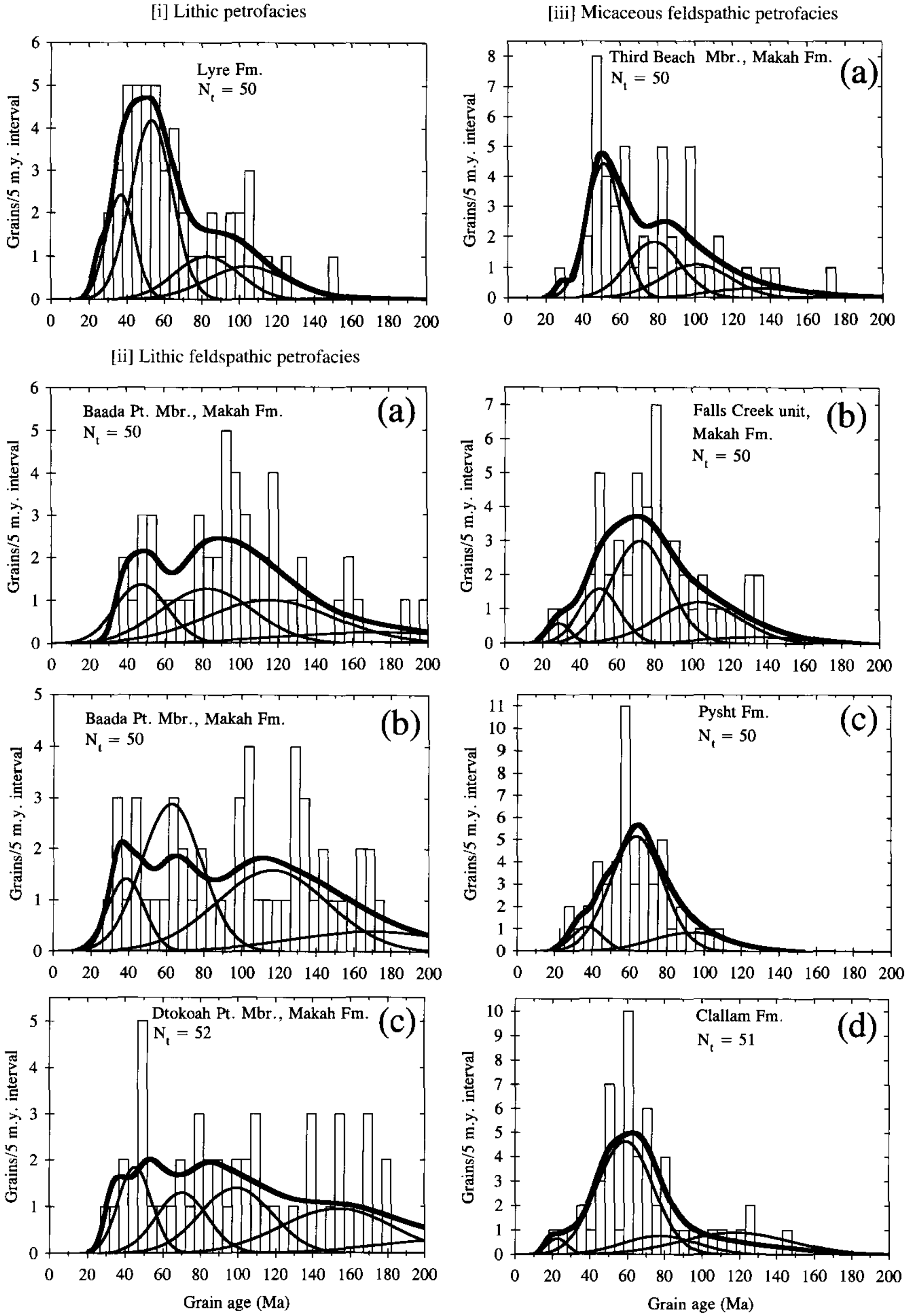
the east and south in Washington. Along the west side of Vancouver Island, coeval strata of the Carmanah Group (Escalante and Hesquiat Formations) are interpreted to be deposited in the proximal part of a submarine fan with paleotransport to the southwest (Cameron, 1979, 1980). These sediments are compositionally similar to those of the northern Olympic Peninsula (Snavely and others, 1980; Muller and others, 1981).

In contrast, coeval strata to the east and south of the Olympics, which have a different source, include compositionally similar quartzofeldspathic rocks. Excluding the rocks of the Tofino basin, rocks that flank the Olympic Mountains are dominated by either volcaniclastic detritus or quartzofeldspathic detritus with an eastern provenance (Snavely, 1987). The volcaniclastic detritus is inferred to have been derived from the contemporaneous Cascade arc, whereas the quartzofeldspathic detritus is inferred to have been derived from extensive reset terrains behind the arc to the east (Fig. 1b). For example, east of the Olympic massif, the Blakeley Formation (Zemorrian) is dominated by volcaniclastic detritus and locally contains meter-scale boulders of volcanic rocks (McLean, 1976). The Blakeley Formation rests above the upper Eocene Puget Group, which contains quartzofeldspathic strata that are inferred to have been deposited in a deltaic complex derived from uplifted metaplutonic rocks east of the Cascade arc (Buckovic, 1979; Brandon and Vance, 1992). Thus by Oligocene time, the

TABLE 3. PEAK SUMMARY OF ZIRCON FISSION-TRACK AGE DATA

Unit (sample)	Age range	Depositional age	Gaussian peak-fit ages				
			P_1	P_2	P_3	P_4	P_5
			(1) Samples without moving peaks (lithic petrofacies)				
(A) Lyre Formation (OLY-1)	25–151 Ma N_t* = 50	35.0–40.4 Ma	36.6 ± 2.9 π_f† = 18.4% W_f§ = 20.7%	53.2 ± 4.2 π_f = 46.2%	82.7 ± 6.8 π_f = 17.2%	103.9 ± 8.3 π_f = 16.6%	163.4 ± 13.2 π_f = 1.4%
			(2) Samples without moving peaks (lithic feldspathic petrofacies)				
(B) Makah Formation Baada Point Member (OLY-7)	36–249 Ma N_t = 50	34.1–35.0 Ma	47.4 ± 4.1 π_f = 19.2% W_f = 19.5%	82.4 ± 7.2 π_f = 31%	115.4 ± 10.1 π_f = 34%	171.6 ± 15.0 π_f = 12.6%	269.7 ± 24.0 π_f = 1.6%
(C) Makah Formation Baada Point Member (OLY-8)	30–228 Ma N_t = 50	34.1–35.0 Ma	38.3 ± 3.4 π_f = 13.8% W_f = 25.5%	62.7 ± 5.5 π_f = 46.2%	116.3 ± 9.5 π_f = 47.0%	169.9 ± 14.0 π_f = 17.2%	N.D.#
(D) Makah Formation Dtokoah Pt. Member (OLY-5)	31–235 Ma N_t = 52	34.1–35.0 Ma	45.3 ± 4.0 π_f = 15.6% W_f = 19.4%	70.2 ± 6.5 π_f = 17%	98.9 ± 8.8 π_f = 25.8%	152.5 ± 13.2 π_f = 27.1%	220.4 ± 19.0 π_f = 12.7%
			(3) Samples with moving peaks (micaceous feldspathic petrofacies)				
(E) Makah Formation Third Beach Member (OLY-10)	29–694 Ma N_t = 50	32.7–34.1 Ma	78.2 ± 6.7 π_f = 26.4% W_f = 18.2%	100.3 ± 9.4 π_f = 20.2%	51.2 ± 4.0 π_f = 41.4%	132.7 ± 12.8 π_f = 8%	181.2 ± 15.9 π_f = 1.6%
(F) Makah Formation Falls Creek Unit (OLY-12)	26–136 Ma N_t = 50	28.5–32.7 Ma	72.1 ± 5.2 π_f = 46.4% W_f = 21.4%	103.4 ± 7.4 π_f = 26.8%	28.7 ± 2.1 π_f = 3.6%	50.5 ± 3.6 π_f = 17.2%	135.4 ± 9.9 π_f = 5.8%
(G) Pysht Formation (OLY-11)	29–110 Ma N_t = 50	24.1–28.5 Ma	63.8 ± 4.6 π_f = 73.6% W_f = 22.3%	92.9 ± 6.8 π_f = 17.6%	37.3 ± 2.8 π_f = 9%	N.D.	N.D.
(H) Clallam Formation (OLY-2)	19–147 Ma N_t = 51	17.7–24.1 Ma	58.9 ± 4.7 π_f = 68.2% W_f = 25.4%	77.3 ± 6.8 π_f = 14.9%	22.5 ± 1.9 π_f = 3.7%	117.8 ± 9.3 π_f = 26.3%	N.D.
			(4) Data from the modern Coast Plutonic Complex (Parrish, 1983)				
(H) Coast Mountains Parrish (1983)	19–100 Ma N_t = 559 (44 fission-track samples)	0.0 Ma	41.2 ± 0.5 π_f = 75.8% W_f = 26.4%	67.0 ± 1.0 π_f = 23.3%	N.D.	N.D.	N.D.

*N_t is total number of grains analyzed.
†π_f is the proportion of grains that compose the peak.
§W_f is the relative width of the Gaussian peak as a proportion of its age.
#No data.



[i] Lithic petrofacies
Lyre Fm.
N_t = 50
[iii] Micaceous feldspathic petrofacies
Third Beach Mbr., Makah Fm.
N_t = 50
(a)
[ii] Lithic feldspathic petrofacies
Baada Pt. Mbr., Makah Fm.
N_t = 50
(a)
Falls Creek unit,
Makah Fm.
N_t = 50
(b)
Baada Pt. Mbr., Makah Fm.
N_t = 50
(b)
Pysht Fm.
N_t = 50
(c)
Dtokoah Pt. Mbr., Makah Fm.
N_t = 52
(c)
Clallam Fm.
N_t = 51
(d)
Grains/5 m.y. interval
Grain age (Ma)

Figure 5. Histograms with superimposed composite probability density plot and Gaussian distribution of fit peaks for zircon FT data for the various petrofacies. (i) Lithic petrofacies. (ii) Lithic feldspathic petrofacies, which includes samples from the Baada Point and the Dtokoah Point Members of the Makah Formation. Samples are arranged according to stratigraphic order (a, b, c). (iii) Micaceous feldspathic petrofacies, which includes samples from the Third Beach Member and the Falls Creek unit of the Makah Formation, as well as the Pysht and Clallam Formations. Samples are arranged according to stratigraphic order (a, b, c, d).

forearc had three sources: (1) a continental volcanic arc to the east, (2) a dissected metaplutonic source to the east behind the Cascade arc, and (3) a dissected metaplutonic source to the north (Fig. 1b).

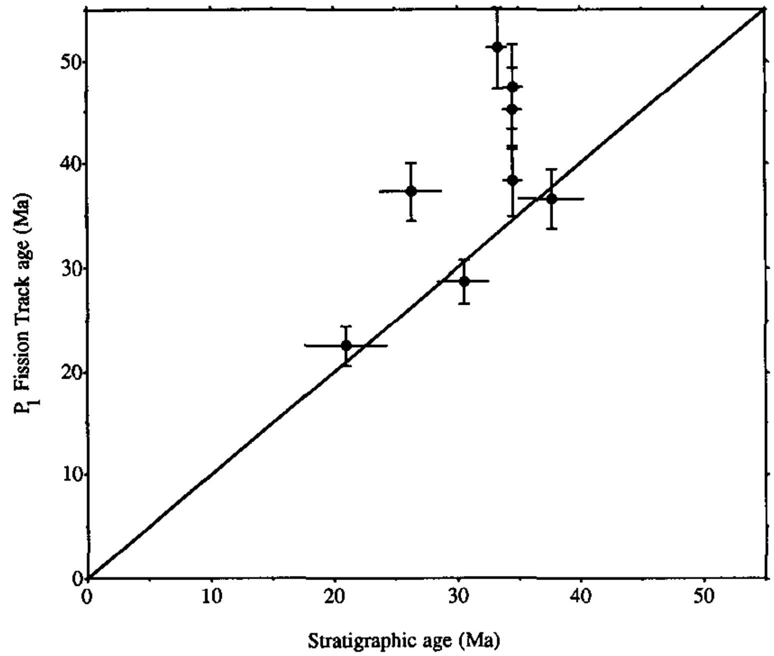


Figure 6. The relationship between the χ^2 age and the P_1 age (both the youngest peaks) against stratigraphic age. Note that unlike other FT studies in the Pacific Northwest, most of these samples appear to lack a peak close to the depositional ages of the unit (diagonal line). The absence of a young peak is probably due to the lack of contemporaneous volcanics in the source region.

SAMPLING AND LABORATORY METHODS

Our procedures for sample preparation and dating are similar to those outlined in Naeser (1976) for the external detector method. The zeta method (Hurford and Green, 1983) was used to provide calibration to an age standard. For each sample, ~4 kg of sandstone was collected from a single bed. Samples were crushed and pulverized, and then mineral separates were made using a Gemini gold table, heavy liquids, and a Franz magnetic separator. The dated zircon fractions were nonmagnetic, with grain sizes between 200 and 80 mesh. These fractions were handpicked, mounted in FEP Teflon, polished, and etched in a KOH:NaOH eutectic at 225 °C for 12–20 hr. For each zircon sample, two different mounts were made, each containing ~750 zircon grains. One mount was given a "long" etch, and the other was given a "short" etch, with etch times differing by ~35% to maximize the total number of countable grains (see Naeser and others, 1987). With low-uranium muscovite flakes affixed to the Teflon, the etched mounts were irradiated at the Oregon State nuclear reactor using a nominal particle fluence of 2×10^{15} neutrons/cm^2. The Cd ratio (relative to an Au monitor) for this reactor is 14, indicating the reactor was well thermalized (see Green and Hurford, 1984). The internal gradient within the irradiated package was estimated by in-

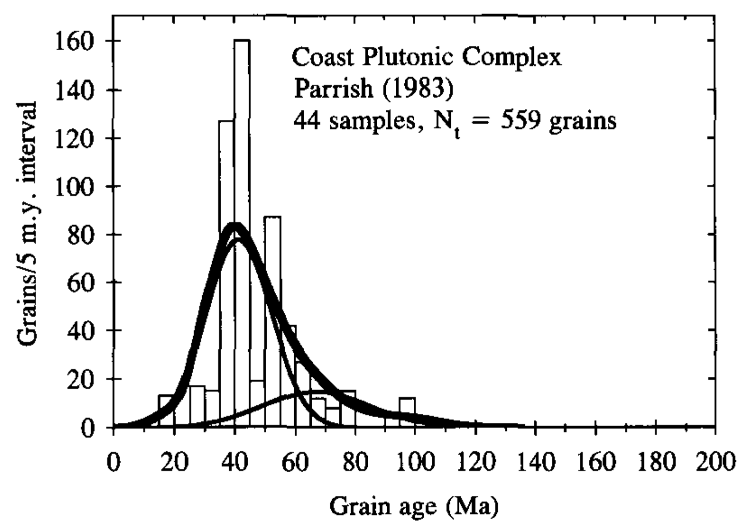


Figure 7. Composite probability-density plot and histogram for zircon FT ages determined by Parrish (1993) for bedrock samples from the Coast Plutonic Complex. This diagram illustrates the expected FT grain-age distribution for zircons derived from present outcrops of the Coast Plutonic Complex. The diagram was constructed by summing Gaussian peaks for all of the samples dated by Parrish (1993). The mean, relative standard deviation, and peak size of each of the component Gaussians was set equal to the FT age, relative standard error, and number of grains determined for each dated sample. Parrish (1983) dated 44 samples and a total of 559 zircons.

terpolating track densities for fluence monitors (CN-5) placed at the top, middle, and bottom of the irradiation tube. Zircon mounts from the Fish Canyon Tuff were included in this and five other irradiations and were used to determine a zeta factor of 323.5 ± 18 (±2 standard error). Fission tracks were counted at 1250× using an oil immersion objective on an Olympus BH-2 microscope.

DATA ANALYSIS

Several studies have used FT dating of detrital minerals to address sediment provenance, stratigraphic correlation, and age control of clastic sediments (Hurford and others, 1984; Baldwin and others, 1986; Kowallis and others, 1986; Cerveny and others, 1988; Brandon and Vance, 1992; Garver and Brandon, 1994). One of the important hurdles in these studies is an accurate and clear portrayal of numerous single grain ages. For this study, we report the FT ages of ~50 detrital zircons from eight unreset samples, representing a total of ~400 grain ages. Dating a number of zircon crystals produces a grain-age distribution that we portray graphically using both histograms and composite probability density plots (Hurford and others, 1984; Brandon, 1992). The density plots are represented by a continuous probability function that is determined using individual grain ages and their estimated analytical error. The density plot can be decomposed into one or more component populations, which are inferred to represent the cooling ages of specific FT source terrains. The identification of these component populations is relatively straightforward if the FT ages of the source terrains are widely separated, but in practice, there is commonly some overlap, so a statistical approach must be used to decompose the distribution. In this paper, we use the χ^2 age and the Gaussian peak-fit method (see Brandon, 1992).

The χ^2 test of Galbraith (1981) was adopted by Brandon (1992) to isolate the youngest fraction of plausibly related grain ages. Grains are first sorted into a list of increasing grain ages. By moving down the list and including sequentially older grains, one can calculate the sum age defined as the pooled age for current fraction of young grain ages, and an associated probability. Following Brandon (1992), we define the χ^2 age as the pooled age of the largest population of young grain ages that still retains a $P(\chi^2) > 1\%$.

The Gaussian peak-fit method directly decomposes the grain-age spectrum into a series of component Gaussian populations or peaks. Each peak is defined by the mean age of the Gaussian, the width of the Gaussian relative to its mean age (W_f, equivalent to standard deviation divided by the mean), and the size of the Gaussian relative to the total size of the grain age distribution (π_f, Table 3). Our application of the method follows Brandon (1992), except we use a single parameter to represent W_f for all peaks (see Garver and Brandon, 1994, for details). We mainly use the peak-fit results in our analysis here, but the χ^2 age provides a useful com-

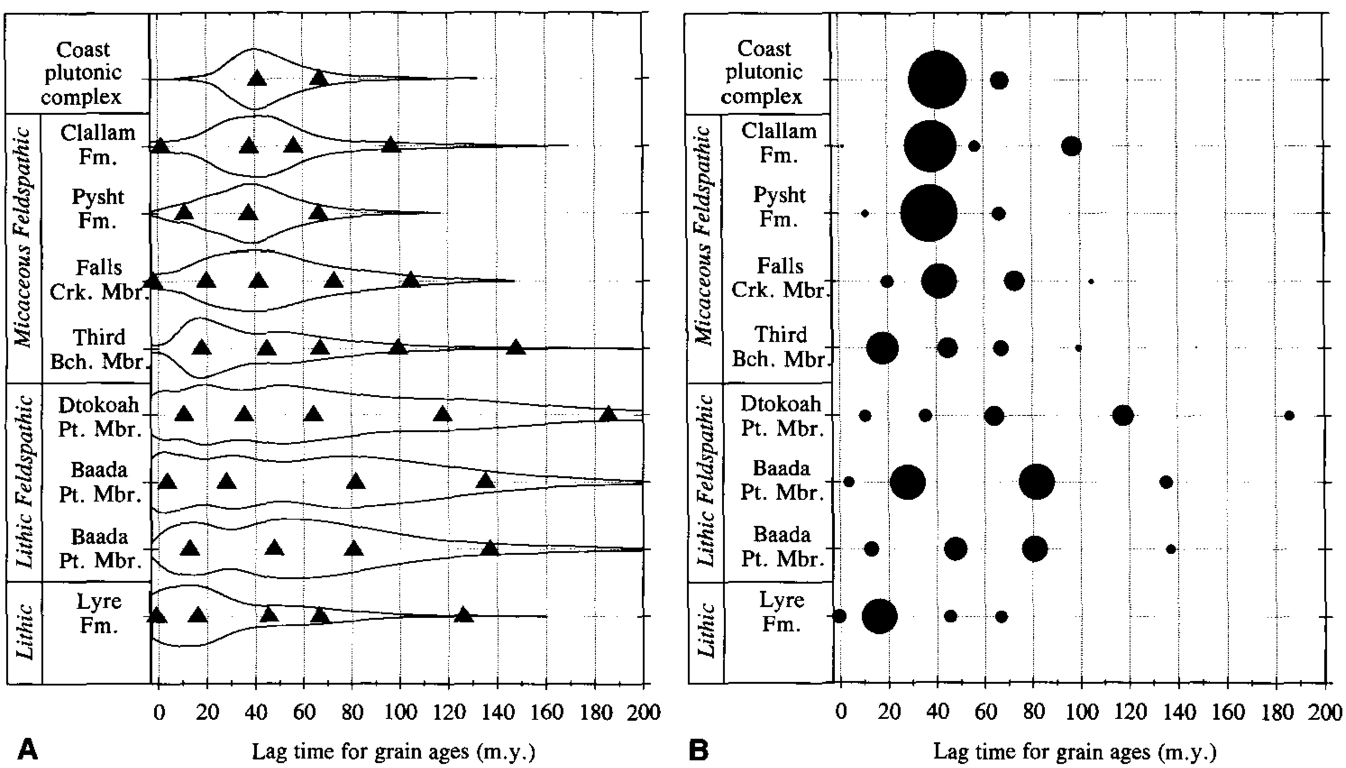


Figure 8. Summary of zircon FT data from all units studied and the zircon FT data from the Coast Plutonic Complex (Parrish, 1983; see Fig. 5) showing (A) lag time for individual peaks as well as the density plot, and (B) lag time for individual peaks and the proportion of grains in each peak. We interpret the progressive reduction in age of the peaks in the micaceous feldspathic petrofacies (from the Third Beach Member of the Makah Formation to the Clallam Formation) to represent the erosional unroofing and progressive cooling of a single plutonic source terrain.

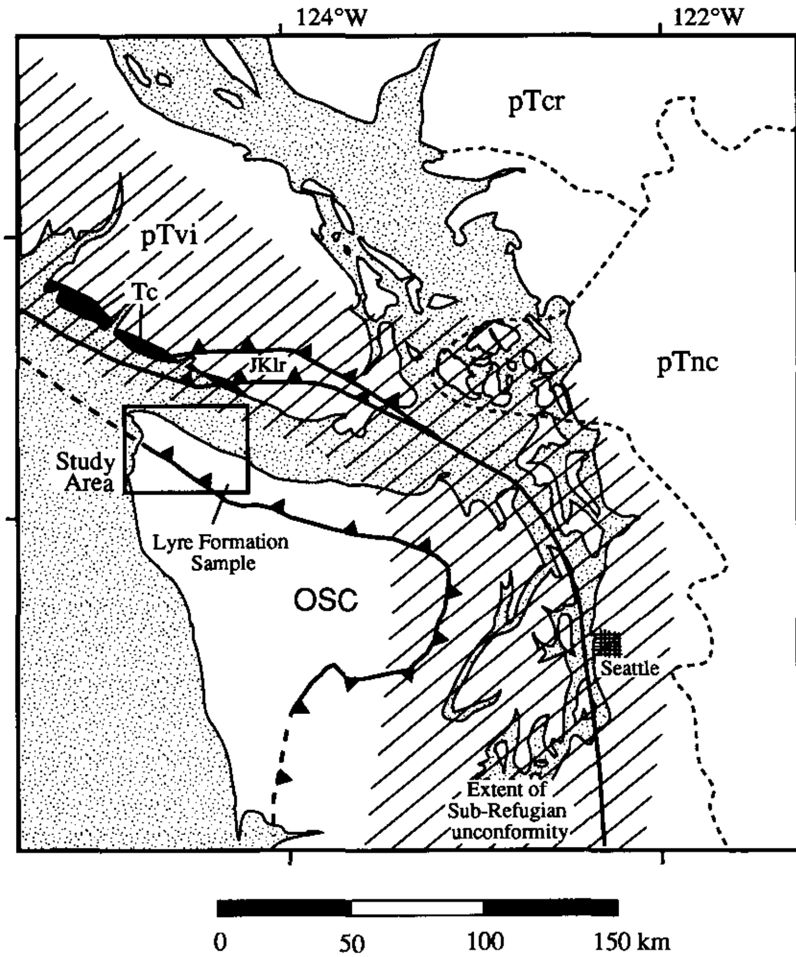


Figure 9. Generalized map of the Pacific Northwest showing our estimate of the limit of the sub-Refugian unconformity (diagonal ruled area) in this area. Stratigraphic sections in this diagonally ruled area have a prominent unconformity where Refugian and younger strata rest on either the Coast Range terrane or pre-Tertiary rocks (pTvi = pre-Tertiary rocks of Vancouver Island; pTnc = pre-Tertiary rocks of the North Cascades and the San Juan Islands; pTcr = pre-Tertiary rocks of the Coast Plutonic Complex; JKlr = Leech River Complex). Tc is the Carmanah Formation, which rests unconformably above the pre-Tertiary rocks of Vancouver Island, but also blankets the San Juan fault. The limits of the sub-Refugian unconformity is bounded by those areas where sub-Refugian Eocene sediments are preserved, indicating little or no erosion at the level of the unconformity.

parison for the youngest peak age. We focus primarily on the dominant peaks ($\pi_f > 20\%$, see discussion on detection limits in Brandon, 1992).

In FT stratigraphy, where a series of stratigraphically related age distributions are evaluated, two types of peaks can be identified: *moving peaks*, defined by a peak age that gets progressively younger or older up-section, and *static peaks*, where the peak age remains relatively constant up-section. A useful measure of the movement of peaks is the *lag time*, defined as the peak age minus the depositional age. The lag time represents the age of the peak at the time of deposition, and it represents the total time required to bring rocks to the surface from the zircon annealing zone. Lag time, therefore, can be related to the denudation rate in a source region. Forward-moving peaks, which get progressively younger up-section, can be produced by a source terrain characterized by either constant volcanic activity or the steady denudation of a source terrain. FT stratigraphy characterized by forward-moving peaks generally represents first-cycle detritus. Backward-moving peaks, which get progressively older up-section, are probably less common. However, erosion of a basin containing first-cycle detritus could produce FT stratigraphy with backward-moving peaks, which would be indicative of recycled sediment.

Following Brandon and Vance (1992) and Garver and Brandon (1994), we recognize three general types of FT source terrains: (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 post-orogenic 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; and (3) a volcanic source terrain, where the characteristic FT age is a result of volcanism and near-surface magmatism.

Several studies have used FT dating to study the provenance of detrital zircon of sandstones in the Pacific Northwest (Brandon and Vance, 1992; Kelly, 1992; Maranville, 1993; Vance and Brandon, 1993; Garver and Brandon, 1994). These studies have shown that sandstone from a specific area typically will have a distinct and reproducible grain-age distribution. In our study, the dominance of moving peaks is a distinct feature of the strata in the northern Olympic Peninsula; elsewhere in the Pacific Northwest, coeval strata have prominent static peaks. For example, sandstones in the core of the Olympic Mountains and in nearby Tertiary strata are characterized by two old static peaks in which the peak ages remain the same, regardless of the depositional age of the sample. Brandon and Vance (1992) attributed the static peaks to Eocene reset terrains (Armstrong and Ward, 1991), which are common east of the Cascade arc (Fig. 1b). There is also a significant young moving peak that apparently represents a component of detritus from the Cascade arc (Brandon and Vance, 1992). Interestingly, FT peak ages of zircon from modern sediment of the major rivers (Fraser, Skagit, and Columbia) that drain the region behind the Cascade arc are similar to those reported for the OSC, a finding that reinforces the interpretation of Brandon and Vance (1992) concerning the source terrains for these sediments (Maranville, 1993).

Before the FT data can be analyzed for provenance, the potential for thermal resetting after deposition needs to be evaluated. The maximum depth of burial in the Tofino basin was no more than 6 km (Roden and others, 1994). The modern and paleogeothermal gradient for the northern Olympic Peninsula is ~20 °C/km (Brandon and Vance, 1992; Roden and others, 1994). Us-

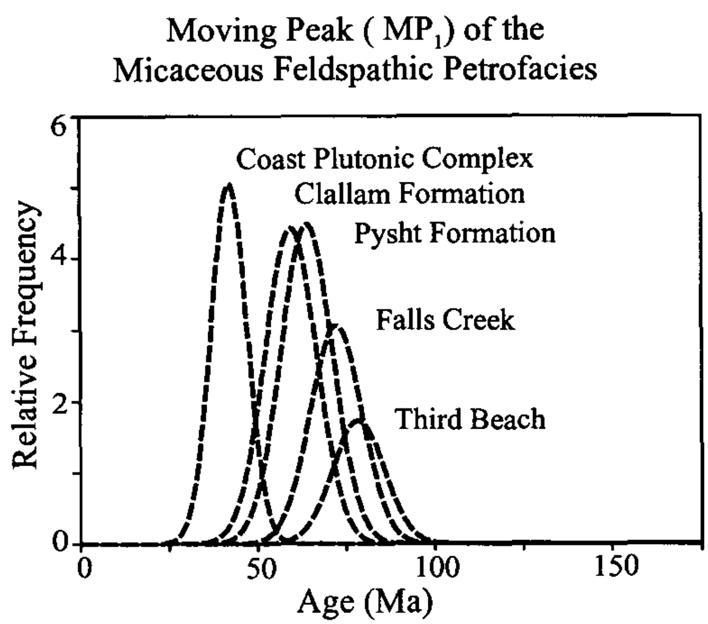


Figure 10. Plot of the age progression of the principal moving peaks in the micaceous feldspathic petrofacies and the presumed correlative peak in the modern Coast Ranges of British Columbia. Individual peaks are shown by their Gaussian distribution, and the height of the Gaussian is proportional to the percentage of zircon in each population.

ing surface temperatures of 8 °C/km, maximum temperatures for the deepest samples were probably no more than 170 °C, well within the limits for thermal stability of zircon fission tracks (Brandon and Vance, 1992).

DATA

The FT results for our eight samples and a summary of FT ages from the Coast Range of British Columbia (Parrish, 1983) are reported in Table 3 and are displayed graphically in Figures 5, 6, 7, and 8 (also see Appendix for locations and data). The majority of the data are shown in Figure 5, where the grain-age distributions for each sample of the three petrofacies are shown in histogram form as well as a composite probability density plot. Also plotted on these diagrams (Fig. 5) are the component populations, or peaks, which are shown as individual Gaussians under the composite probability density plot. For each sample, the youngest fraction of zircon is older than or equal to the depositional age of the sample (Fig. 6). Figure 8 illustrates up-section changes in the age distributions, with the FT results in order of decreasing age, oldest at the bottom, youngest at the top. In Figure 8A, the grain age distributions are represented by density plots and by mean peak ages as determined by the Gaussian peak-fit method. In Figure 8B, the same results are plotted with respect to lag time, but on this plot the relative proportion of grains are represented by larger (more grains) and smaller (few grains) dots. The main feature of the FT age distributions, moving up-section from the lithic feldspathic petrofacies to the micaceous feldspathic petrofacies, is the development of a young forward-moving peak that ultimately dominates the entire grain-age distribution (Figs. 5 and 8).

Lithic Petrofacies

A distinctive feature of the FT grain-age distribution of this one sample is that the youngest peak (P_1) is statistically indistinguishable from the depositional age of the sample (Fig. 5; ca. 40 Ma). None of the other samples show this feature. The lag time between the depositional age of the sample and the youngest peak age must be <4 m.y., but is probably near 0 m.y. (Table 3). This short lag time suggests very rapid cooling (~60–240 °C/km) in the source terrain at ca. 40 Ma. The majority of the grains in this sample fall into a single peak age (P_2) of ca. 53 Ma (Table 3).

Lithic Feldspathic Petrofacies

The lithic feldspathic petrofacies generally lacks young zircons (that is, those close to the depositional age) and is characterized by a range of grain ages, Jurassic through Cenozoic, and many small peaks defined by only a few grains (Fig. 5). Two samples of the Baada Point Member were counted to determine the variability of grain ages in a single unit; both samples have a wide range of grain ages and several common peak ages (Table 3).

Micaceous Feldspathic Petrofacies

The micaceous feldspathic petrofacies also lacks a significant percentage of young zircons but is characterized by well-defined peaks that include a greater percentage of grains up-section (Figs. 5 and 8). A distinguishing aspect of the micaceous feldspathic petrofacies is that it appears to have well-defined forward-moving peaks with a nearly constant lag time. These features are in notable contrast to the results of Brandon and Vance (1992), Maranville (1993), and Vance and Brandon (1993), in which static peaks were identified.

INTERPRETATION OF FT STRATIGRAPHY

An important conclusion from our study is that the source region of the strata on the northern Olympic Peninsula was entirely different from those regions that fed coeval forearc and trench basins to the east and

TABLE 4. MOVING PEAK AGES AND CALCULATED LAG TIMES

Unit	Age (Ma)	MP_1	MP_1 lag	MP_2	MP_2 lag	MP_3	MP_3 lag
Coast Range	0.0	41.2 ± 0.5	41.2	67.0 ± 1.0	67.0	N.D.*	N.D.
Clallam Formation	20.9	58.9 ± 4.7	38.0	77.3 ± 6.8	56.4	22.5 ± 1.9	1.6
Pysht Formation	26.3	63.8 ± 4.6	37.5	92.9 ± 6.8	66.6	37.3 ± 2.8	11.0
Falls Creek Member	30.6	72.1 ± 5.2	41.5	103.4 ± 7.4	72.8	50.5 ± 3.6	19.9
Third Beach Member	33.4	78.2 ± 6.5	41.5	100.3 ± 9.4	66.9	N.D.	N.D.
		Mean	40.6	Mean	65.9		

*No data.

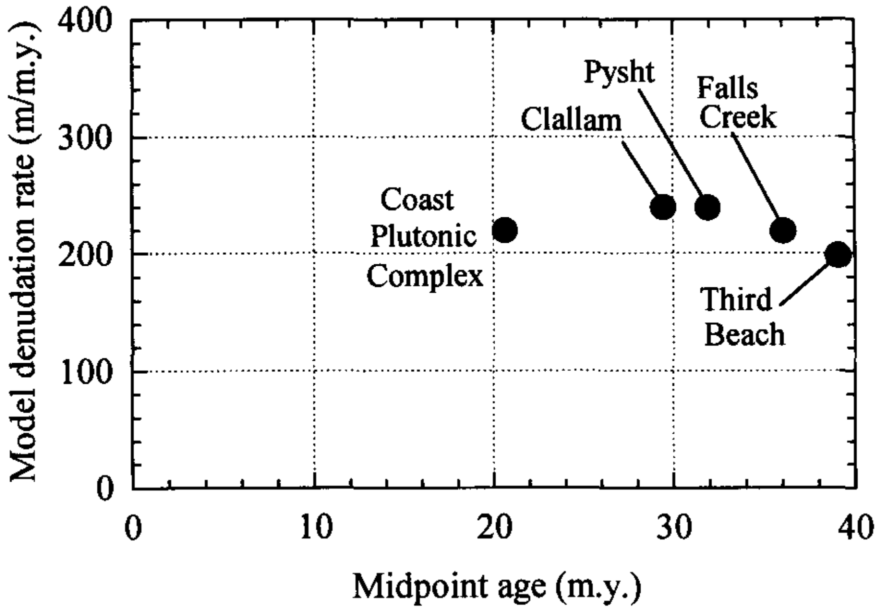


Figure 11. Model denudation rate through time as calculated for the principal peaks seen in the Clallam and Pysht Formations and the inferred correlative peaks in the Falls Creek unit and the Third Beach Member of the Makah Formation. Age plotted is the midpoint between the depositional age and the peak age (Brandon and Vance, 1993; see text for discussion and assumptions).

south. The lithic petrofacies was derived from the general area of Vancouver Island, and the regional extent of the sub-Refugian unconformity (Fig. 9) indicates that a variety of different units may have contributed to the youngest peak in the Lyre Formation. We suggest that the lithic feldspathic and micaceous feldspathic petrofacies record the progressive denudation of the Coast Plutonic Complex (CPC) through the Tertiary. To approximate the FT grain-age distribution of sediment that would be shed off the CPC today, we constructed a density plot and histogram for zircon FT ages determined by Parrish (1983) for samples from the CPC (Fig. 7). The plot was made by summing Gaussian peaks for all of the zircon FT samples of Parrish (1993); this data set includes 44 samples and a total of 559 zircons. It is important to note that most of the older ages that define the minor peak are from the southern part of the CPC (50–52°N).

Lithic Petrofacies

The Lyre Formation is dominated by coarse-grained lithic detritus that includes pebble- to cobble-sized clasts or argillite, quartzite, chert, altered volcanics, granite, and gneiss (Brown and others, 1956; Ainsfield, 1972; Snavely and others, 1986; Shilhanek, 1992). These rock types, combined with sedimentological observations, indicate that the Lyre Formation is a locally derived unit that undoubtedly represents sedimentary detritus from the Leech River Schist, Pacific Rim Complex, and the Mechosin volcanics, which are presently exposed on southern Vancouver Island (Shilhanek, 1992). K/Ar dates for metamorphic biotite from the Leech River Schist, on Vancouver Island, indicate cooling at ca. 40 Ma (Wanless and others, 1978; Fairchild and Cowan, 1982). We would expect similar FT ages for zircons, given a similar closure temperature and the rapidity of cooling (Fairchild and Cowan, 1982). Movement on the Leech River fault occurred at the same time as deposition of the Lyre Formation, and movement must have occurred during a relatively short interval of time, because the fault is blanketed by Refugian sediments of the Carmanah Group (Fairchild and Cowan, 1982; Cameron, 1972, 1973).

An important basinwide unconformity exists below these strata where Refugian (late Eocene, ca. 35 Ma; Fig. 4) and younger strata rest on both the Coast Range terrane and the pre-Tertiary continental framework. Our estimate of the extent of the sub-Refugian unconformity (Fig. 9) mirrors the pre-Tertiary continental framework and the outboard Coast Range terrane and is probably a result of uplift of the upper plate during underthrusting of the Coast Range terrane. It is likely that underthrusting and emplacement of the Leech River Schist is marked not only by the uplift and development of the unconformity but also by deposition of coarse clastic detritus. This event corresponds to the establishment of the modern Cascade convergent margin at ca. 36 Ma (Brandon and Vance, 1992), and the FT ages of detrital zircon attest to the very rapid denudation along this part of the continental margin.

Lithic Feldspathic Petrofacies

The wide scatter in grain ages in this petrofacies can be ascribed to a heterogeneous source region with many different thermal histories. The changes in framework constituents recorded in the Makah Formation suggest unroofing of a single source where lithic-rich material was stripped off a plutonic basement. The Upper Cretaceous Nanaimo Group represents a thick sequence of first-cycle sediment that is geographically adjacent to (or blankets) rocks of Vancouver Island, the San Juan Islands, the Coast Plutonic Complex, and the North Cascades. It is likely that sediment of the Nanaimo basin was cannibalized and redeposited in the Tofino basin if paleocurrents and the inferred sediment paths are correct (Anderson, 1985; Snavely and others, 1980). Although subtle, this recycling of sediment is important because strata of the Nanaimo basin are quartz- and feldspar-rich, with a significant fraction of zircon (Pacht, 1984). We speculate that the older peaks of the Baada Point Member (ca. 116 and 170 Ma) and older peaks of the stratigraphically higher Dtokoah Point Member (ca. 152 and 220 Ma; see Fig. 5) are backward-moving peaks that have resulted from the progressive removal and unroofing of strata from the Nanaimo basin.

Micaceous Feldspathic Petrofacies

Samples from this petrofacies display well-defined forward-moving peaks that may be explained by the progressive denudation of a plutonic source terrain (Figs. 5 and 8). Our data suggest that the principal forward-moving peak (Fig. 10) has a remarkably constant peak lag time (Fig. 8), and that this principal peak is defined by a greater and greater proportion of grains upsection (Figs. 8 and 10). Estimating the lag time for the prominent peak in the Falls Creek unit, Pysht Formation, Clallam For-

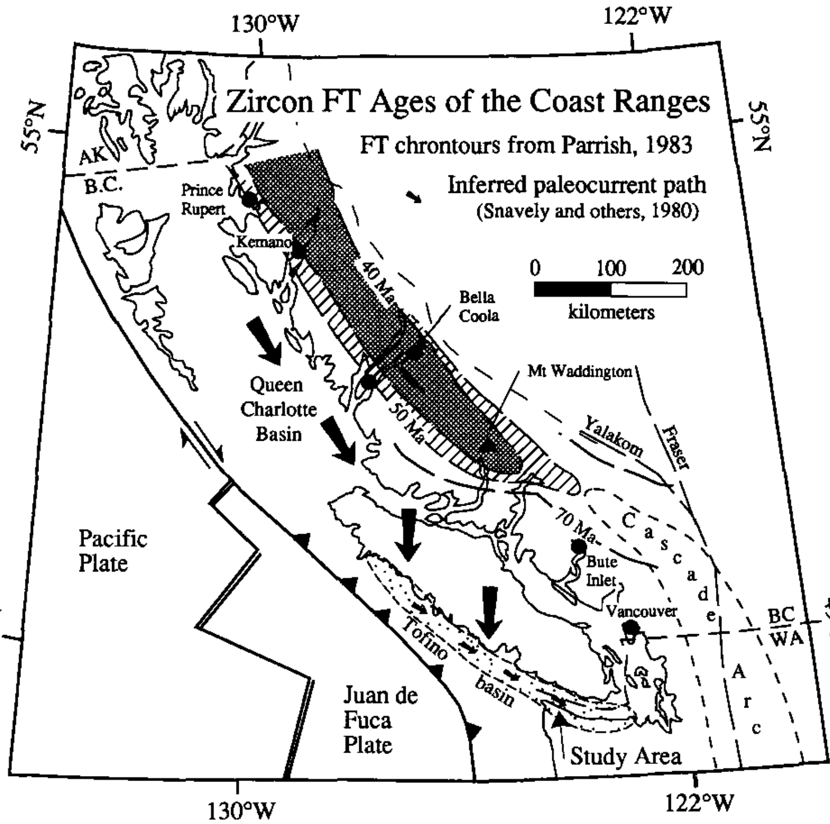


Figure 12. Zircon fission-track ages and plate tectonic setting of the Coast Plutonic Complex (CPC; modified from Parrish, 1983) and sediment transport direction in the upper Eocene to Oligocene strata of the Tofino basin (modified from Snavely and others, 1980). Parrish calculates that the main axis of the Coast Plutonic Complex experienced a maximum of ~5–9 km of total denudation since 40 Ma, although part of this denudation (~2.0–3.5 km) has occurred since the late Miocene. The heavy solid arrows represent the probable path of sediment that fed the Tofino basin.

mation, the presumed correlative peak in the Third Beach Member, and likewise the zircon FT data from the modern CPC (Figs. 8 and 10), we calculate that the lag time remains nearly constant at 40 m.y. from ca. 35 Ma to the present (Table 4). Likewise, a minor secondary peak has a constant lag of ~65 m.y. from ca. 35 Ma to the present (Table 4).

To estimate denudation rates through time, we have used the relationship between peak age and the age of the strata (Tables 2 and 4; Fig. 4). Two reasons suggest that these estimated denudation rates reflect mechanical erosion and not tectonic denudation of the source terrane. First, in the Pacific Northwest, tectonic denudation, due to extensional faulting, is typically short-lived and results in source terrains with static peaks. Second, sediment in the Tofino basin is clearly a product of erosion. The FT peak ages associated with this source approximate the time of cooling of the rocks as they passed through the isotherm for zircon. To calculate a model denudation rate, we assume a closure temperature of zircon (240 °C), a generic paleogeothermal gradient (25 °C/km), and a surface temperature of 10 °C (Garver and Brandon, 1994). Our calculations suggest paleoerosion rates for the principal moving peak were nearly constant at a modest rate of ~225 m/m.y. (Fig. 11).

DISCUSSION

At this point it is useful to compare denudation rates of the Coast Plutonic Complex and adjacent rocks (here collectively referred to as the CPC) to the denudation rates implied from the sediments, as discussed above. FT data from rocks in southwestern British Columbia indicate that the CPC experienced significant cooling throughout the Tertiary (Fig. 12; Parrish, 1983) whereas, aside from local uplifts, none of the adjacent terrains have experienced such significant uplift/cooling during the Oligocene-Miocene (Johnson and others, 1986; Armstrong, 1988; Brandon and Vance, 1992). Therefore, the CPC was very likely a significant source terrain throughout the Tertiary. Parrish (1983) estimated that some 5–10 km of rock was removed during the last 40 Ma from the central part of the modern CPC.

The CPC extends for nearly 1500 km from southern British Columbia to Alaska and is dominated by Jurassic to Tertiary quartz diorites to granodiorites (Roddick, 1983). The modern axis of the topography of the Coast Mountains (British Columbia) closely parallels the plutonic rocks. Significant uplift of the CPC, particularly pronounced in the north-central section, is known to have occurred after intense Paleocene-Eocene plutonic and orogenic activity (Parrish, 1983). Rapid cooling and decompression of the central and northern Coast Range infrastructure occurred at ca. 55 Ma (Cook and Crawford, in press), with estimated denudation rates of ~2000 m/m.y. (Hollister, 1982). If our hypothesis is correct, strata of the Tofino basin record the relatively slow denudation of the CPC infrastructure after this rapid cooling event.

Following rapid postorogenic cooling, the northern CPC (52–55°N) experienced greater and more rapid denudation compared to areas of the southern CPC (50–52°N; Parrish, 1983). The axial region of the northern part of the CPC (52–55°N) saw apparent denudation rates between 100 and 200 m/m.y. during the interval from 25 to 15 Ma (Parrish, 1983). In contrast, the southern CPC (50–52°N) had very low apparent denudation rates (~100 m/m.y.) and active volcanism associated with the Cascade volcanic arc (Fig. 1). Parrish estimated that the area north of Bella Coola (Fig. 12) had apparent denudation rates of ~250–300 m/m.y. at 45–35 Ma (around Kemano) and ~400 m/m.y. at 40–30 Ma in an area near Bella Coola (North Kings Island). Although his FT data suggest that the late Miocene to Recent denudation has been greater in the area south of Bella Coola (50–52°N), apparent denudation rates through the Cenozoic have been <100 m/m.y. for the interval 30–10 Ma. Our FT data, which indicate constant erosion at a rate of ~250 m/m.y. (Fig. 11), together with the paleocurrents (Snavely and others, 1980), and sandstone composition (Pearl, 1977; Snavely and others, 1980; Anderson, 1985), suggest that a likely source for the sediment that composes the Oligocene-Miocene part of the Tofino basin was the northern part of the CPC (Fig. 12).

CONCLUDING REMARKS

If the northern Coast Ranges were the source for the sediments of the Tofino basin, then the sediments must have been transported significant distances along and parallel to the continental margin prior to deposition. Our postulated source terrain requires ~1000 km of coast-parallel transport to the final site of deposition.

The identification of a northern source terrain for strata of Tofino basin exposed in the Olympic Mountains is quite different from the eastern source terrains identified for the Olympic subduction complex (Brandon and Vance, 1992), which are interpreted to lie in southeastern British Columbia, eastern Washington, Idaho, and Oregon. The feldspathic sediments of the northern Olympic Peninsula show no evidence of a significant contemporaneous volcanic component. The absence of young volcanic zircon indicates the source lay to the north of the Pacific/Farallon/North America triple junction (Engebretson and others, 1985). At present, this triple junction lies just north of Vancouver Island, and the northern end of the Cascade arc is at about the same latitude. If our interpretation is correct, then the triple junction has remained roughly at its present position for ~35 m.y. The area north of the triple junction remained amagmatic during that time, which suggests that the plate boundary was a transcurrent fault, much like the modern Queen Charlotte–Fairweather fault system.

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APPENDIX: SAMPLE LOCATIONS AND FISSION-TRACK DATA[1]

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