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CRETACEOUS AND PALEOGENE HISTORY OF THE WESTERN CANADIAN CORDILLERA

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ABSTRACT

Cretaceous and Paleogene volcanism in the Canadian Cordillera was distinctly episodic, and had a spatial distribution that varied significantly through time. The following major episodes can be distinguished:

1) Lower Cretaceous and earlier volcanism in the Coast Plutonic Complex that overlies a basement composed of Wrangellia and the Alexander Terrane (Gravina-Nutzotin-Gambier suite)
2) Albian to Cenomanian, mainly terrestrial volcanism in the Cordilleran interior to as far east as Crowsnest Pass in the south and Faro in the Yukon (Spences Bridge-Crowsnest-Mt. Nansen-South Fork suite)
3) Santonian to (earliest) Paleocene volcanism concentrated immediately east of the Coast Plutonic Complex and in a wide belt in the central Yukon (Kingsvale-Kasalka-Brian Boru-Carmacks suite).
4) Eocene volcanism in southern British Columbia, which forms the northeastern end of the Challis-Absaroka volcanic fields (Penticton-Kamloops-Ootsa Lake, Endako suite); to a lesser extent farther north along the eastern margin of the Coast Plutonic Complex (Skukum-Sloko-Nisling Range Suite).

The dominant chemistry of these suites is calc-alkalic, although alkalic and other compositions exist. The Cretaceous and Paleogene extrusive and related intrusive rocks mostly result from arc magmatism, with their timing and distribution related to changing plate convergence vectors through time.

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1.0 INTRODUCTION

This report (a) incorporates the published literature of the last eight years on the Cenozoic volcanic rocks of the Canadian Cordillera to an extant file on that subject (Noel, 1978) and b) expands the file to include all published literature on Cretaceous volcanic rocks in the Canadian Cordillera. The limits of rock units on Figures 1 and 3 are taken from the Tectonic Assemblage Map of the Canadian Cordillera (1978), except where more recent mapping has redefined unit boundaries. The geologic time scale used in this report is the one adopted for the purposes of DNAG (Geological Society of America, 1984) (Appendix A).

2.0 CRETACEOUS

2.1 CRETACEOUS VOLCANIC AND RELATED EVENTS

Figure 1 shows the distribution of Cretaceous rocks in the Cordillera. Only those plutonic rocks whose ages have been satisfactorily established by isotopic methods, or by reasonable extrapolation therefrom (Armstrong pers. comm. 1985), are shown. Figure 2 is a compilation of representative stratigraphic columns, arranged west to east across three transects: southeast Alaska and the Yukon, central B.C. from the Queen Charlotte Islands to the Bowser Basin, and southern B.C. from Vancouver Island to the Tyaughton Basin. The following age and stratigraphic revisions, made since 1976, have aided in constructing our present conception of Cretaceous history:

1) MacIntyre (1976) defined the Upper Cretaceous Kasalka Group near Tahtsa Lake; Woodsworth (1980) showed significant areas of Kasalka Group outcrop in the Whitesail Lake map area where they were previously included in the Eocene Ootsa Lake Group. The Kasalka Group is similar in age, lithology and

stratigraphic position to the Brian Boru Formation in the Hazelton map area (Richards 1980) and the "Tiptop Hill Volcanics" of Church (1972).

2) Palynology from both the Tango Creek and Brothers Peak formations has shown that the Sustut Group is an Albian to Maastrichtian sequence, which is correlative in part with the Skeena Group (P. Read, H. Tipper, pers. comm. 1984). In the Spatsizi and Dease Lake map areas, the tuffs in the Brothers Peak Formation are of Campanian to Maastrichtian age (Read, pers. comm 1984) and thus correlate with the Brian Boru-Kasalka eruptions, rather than with Eocene volcanism as previously thought (Eisbacher, 1974). Extensive zeolitization of the tuffs makes the Eocene age determinations by the K-Ar whole-rock method (Eisbacher, 1974) on them questionable (P. Read, pers. comm. 1984).

3) The Mt. Nansen Group, once considered early Tertiary, has given Albian K-Ar dates (Grond et al., 1984). Lowey (1984) has defined the Indian River Formation as a terrestrial sedimentary sequence of Albian age, correlative with the volcanic Mt. Nansen Group.

4) Basalts of the Carmacks Group, andesites that underlie them, felsic rocks such as the Casino Volcanics, and related intrusions (Grond et al., 1984, Churchill, 1980; Grond, 1980; Godwin 1975, Roots 1982), once mapped as ranging from Cretaceous to Miocene, are now known to give Late Cretaceous to earliest Paleocene K-Ar ages. The Sixtymile Formation in the Yukon (Lowey,1984) was deposited in the same time interval.

5) In the Ashcroft map area, Monger and MacMillan (1984) redefined the Kingsvale Group to include only basalt and pyroclastic rocks, which are radiometrically dated at 85 Ma, and to exclude the underlying sedimentary rocks. Sediments below the basalt lie beneath an unconformity and are part of the volcanic and sedimentary rocks of the Albian to Cenomanian Spences Bridge Group. In the Merritt area, the 112 Ma "Kingsvale" isochron obtained by Preto (1979) is from rocks of the Spences Bridge Group (Monger, pers. comm. 1984).

In general, the increasing but still insufficient volume of radiometric data serves to underline the episodic character of Cretaceous volcanism. At the same time, an increasing amount of stratigraphic detail (Tipper, 1978; Kleinspehn, 1982; Woodsworth, 1980) points to important facies juxtaposition of Albian and older sedimentary and volcanic sequences across the inferred eastern margin of Wrangellia in southern British Columbia.

Coast Plutonic Complex:

A distinctive suite of submarine to subaerial, dominantly andesitic, volcanic rocks and submarine sediments, together termed the Gravina-Nutzotin Belt by Berg et al. (1972), onlaps older rocks of the Alexander Terrane, Wrangellia and the western Yukon-Tanana Terrane generally within or near the Coast Plutonic Complex. It includes the flyschoid Nutzotin Mountains Sequence and the andesitic Chisana Formation in Alaska, the Dezadeash Group and its probable metamorphic equivalent, the Kluane Schist east of the Denali Fault (Eisbacher, 1976), and numerous formations in southeast Alaska for which local names are referenced in Berg et al. (1972). Fossil ages of rocks within the Gravina-Nutzotin belt range from Late Jurassic through Barremian.

In the western Canadian Cordillera, the only other Cretaceous marine to subaerial andesitic volcanic rocks and associated marine sedimentary rocks comprise the Hauterivian to Albian Gambier Group, which occurs as roof pendants in the southern Coast Plutonic Complex. Equivalents of the Gambier Group outcrop near Harrison Lake as the Peninsula and Brokenback Hill formations (Lowes, 1972); as volcanic and sedimentary rocks at Doctors Point, from which an Albian ammonite has recently been recovered (H. Tipper, pers. comm. 1984); and Hauterivian volcanic rocks in Whitesail and Taseko Lake map areas (Tipper, 1978; Woodsworth, 1980). The eastern extent of the Gambier Group and its equivalents seems to coincide with the inferred eastern border of Wrangellia (Fig. 1). Rocks of the Gambier Group both overlie (McKillop, 1973) and are intruded by plutons (Heah, 1982), suggesting that they are comagmatic with the Coast Plutonic Complex.

The age of the Gambier Group is very poorly established, coming as it does from scattered fossil localities and a few, probably partly reset radiometric ages. It may even contain Jurassic strata (M. MacColl pers. comm. 1985). It probably embraces several separate volcanic episodes.

Whole-rock geochemical data from the volcanic rocks of the Gravina-Nutzotin Belt are indicative of calc-alkaline (Berg et al., 1972), alkaline and possibly tholeiitic affinities (Ford and Brew, 1977). Heah (1982) identified both calc-alkaline and tholeiitic chemistry in rocks of the Gambier Group in the Sky Pilot area of southwestern British Columbia.

Central British Columbia and Yukon:

All Cretaceous volcanic suites east of the Coast Plutonic Complex, except the trachyte and phonolite of the Albian Crowsnest Formation in the Fernie basin (Price, 1962, 1965), are subaerial. Associated sediments are fluviatile to lacustrine.

Two phases of Cretaceous volcanic activity can be identified. The first is mid-Cretaceous, Albian and locally Cenomanian. The second is Late Cretaceous (Fig. 2). The mid-Cretaceous phase consists of the Spences Bridge Group, the Rocky Ridge Volcanics, the Mt. Nansen Group in the Dawson Range, and the South Fork Volcanics near Faro (Fig. 2). Albian bentonite layers in the Fort St. John Group (Stott, 1982) may have been derived from contemporaneous volcanism to the northwest in the Yukon. The Spences Bridge Group consists of the products from a series of felsic volcanic centres surrounded by sedimentary accumulations (Monger 1985).The Mt. Nansen Group contains intermediate to felsic flows and pyroclastic rocks which are commonly associated with subvolcanic porphyry intrusions, as at Mount Nansen and at the Klazan prospect, both in the Dawson Range, Y.T. The South Fork Volcanics are calc-alkaline andesite, dacite pyroclastic rocks and minor basaltic andesite flows (Wood, 1981). The few whole-rock analyses from the mid-Cretaceous volcanic suites suggest entirely calc-alkaline chemistry (Wood, 1981; Preto, 1979).

The second, Late Cretaceous, phase of volcanic activity in central British Columbia and the Yukon commenced between 85 Ma and 75 Ma, and continued in some areas into the earliest Paleocene. The timing of volcanism seems to vary from place to place. Units included in this episode are, from southeast to northwest, the Kingsvale Group, the Kasalka Group and Tiptop Hill Volcanics, the Brian Boru Formation, the Hutshi Volcanics, the Carmacks Group, and the Donjek Group (Fig. 2). The age of the Kingsvale Group is so far defined by a single 85 Ma K-Ar whole-rock date. In the Ashcroft map area, the group consists of basalt and related pyroclastic rocks that postdate deformation of the Spences Bridge Group of Albian to Cenomanian age (Monger and MacMillan, 1984). The Kasalka Group in the Whitesail map area and the Brian Boru Formation near Hazelton overlie Albian to Cenomanian or? younger sediments of the Skeena Group either unconformably (Richards, 1980) or disconformably (P. van der Heyden, pers. comm. 1984). They are primarily of acid to intermediate composition with subordinate basalt. Both are intruded by coeval and possibly comagmatic plutons and are probably equivalent (MacIntyre, 1976; Richards, 1980). The Tiptop Hill Volcanics (Church, 1972) near Francois Lake also closely resemble volcanic rocks of the Brian Boru and Kasalka in both lithology and K-Ar ages.

Volcanic rocks of the Carmacks Group and its correlatives underlie large areas of the Yukon and northernmost British Columbia, such as the Donjek Group in northwestern Yukon, the Carmacks Group in the Dawson and Miners Ranges and the Hutshi Volcanics near Atlin Lake. Radiometric dates from these rock units range from 75 to 64 Ma. A few small volcanic remnants in the Teslin Trough give approximately 80 Ma dates (Templeman-Kluit, pers. comm. 1984).

The Carmacks Group and its equivalents range from rhyolite such as the Casino Volcanics, through andesite, as exposed at Prospector Mountain, to piles of basalt that in the older literature were correlated with the Miocene-Pliocene flood basalts of southern British Columbia. Radiometric ages of the upper basalt-dominated and lower andesite to rhyolite subdivisions of the Carmacks Group are indistinguishable (Churchill, 1980; Grond, 1980; Godwin, 1975). Subvolcanic porphyry systems occur in "lower" Carmacks volcanic centres, for example the Casino prospect and the 68 Ma syenite of Prospector Mountain. These volcanic-intrusive settings bear a close resemblance to the partly coextensive Mount Nansen Group.

Sparse geochemical data indicate both a calc-alkaline and an alkaline character for rocks of the Carmacks Group (Churchill, 1980; Grond, 1980). The Kasalka Group and associated intrusions are calc-alkaline (MacIntyre, 1976).

2.2 CRETACEOUS SEDIMENTATION AND TECTONICS:

Western edge of the Cordillera:

In southeast Alaska, the Yakutat and Valdez groups make up the Chugach Terrane which is considered to be an analogue of the Franciscan Terrane. The Pacific Rim Complex on Vancouver Island strongly resembles the Chugach Terrane. Ages for each are shown on Figure 2. Rocks of the Chugach Terrane are in part Lower and in part Upper Cretaceous (Campanian to Maastrichtian) while those from the Pacific Rim Complex only range up to Albian (Muller et al., 1974).

The Yakutat and Valdez formations represent the western edge of the Cretaceous North American Plate where it rode over the subducting Farallon Plate (Decker and Plafker, 1983). Brandon (1984) pointed out that the melanges of the Pacific Rim Complex depositionally overlie Triassic arc-related basement. Thus, while they do represent accumulations along a tectonically unstable margin, they are not accretionary wedges.

Cordilleran Interior:

Jurassic to Lower Cretaceous (up to Hauterivian) sedimentary sequences that span the Jurassic-Cretaceous border are found in five areas of the western Cordillera:

1) the Gravina-Nutzotin Belt, including westerly derived flysch in the Dezadeash Group, which Eisbacher (1976) suggested are dextrally offset segments of the same sedimentary package

2) the Nooksack Group and Jurassic to Cretaceous rocks at Harrison Lake, which may be equivalent to (1) and/or (3)

3) the Relay Mountain Group in the Tyaughton-Methow Basin (Coates, 1974; Tipper, 1978)

4) the Tantalus Formation in the Teslin Trough

5) the Bowser Lake Group in the Bowser Basin is a complex deltaic sequence (Richards, 1980). Richards considered the upper, nonmarine part of the Bowser Lake Group to be Lower Cretaceous, while Tipper (pers. comm. 1984) regarded the entire Bowser Lake Group as Jurassic (Tipper and Richards, 1976). The Kootenay macroflora of the upper Bowser Lake is nondiagnostic, and because pollen has not been recovered, the age assignment of these rocks is very tenuous.

The first three sequences are generally deep marine but the Tantalus Formation and upper part of the Bowser Lake Group to the east are nonmarine.

a) Northern Transect:

The westerly derived Nutzotin Mountains Sequence, Dezadeash Group and Kluane Schist may represent a single deep-sea fan accumulation, deepening to the east, that has been dismembered by the Denali Fault (Eisbacher, 1976) (Fig. 1). East of the Kluane Schist, the Tantalus Formation is nonmarine and of probable Late Jurassic to Early Cretaceous age, based on macrofloral assemblages (Bultman, 1979). The Dezadeash and its correlatives on one hand and the Tantalus Formation on the other, are two very different sedimentary facies juxtaposed in mid- to Late Cretaceous time.

b) Central Transect:

Southwestward along this transect, Lower and Upper Cretaceous strata range from the fluviatile sediments of the Sustut Group, through the shallow marine and fluviatile sedimentary and volcanic rocks of the Skeena Group to the volcanic-rich primarily marine strata of the Gambier Group (Fig. 2). In Hauterivian time, sedimentation of the Bowser Lake Group was replaced by new sedimentary patterns shown by the Sustut and Skeena groups. The Sustut Group is contemporareous with the upper part of the Skeena Group. Paleocurrents in the Skeena Group and coeval, lower part of the Sustut Group indicate a southwesterly paleoslope (Tipper and Richards, 1976; Eisbacher, 1974). Abundant muscovite, derived from the Omineca Crystalline Belt, is a characteristic component of the sandstone of the Skeena and Sustut groups.

Farther west in the Coast Plutonic Complex, volcanic and minor sedimentary rocks of Hauterivian(?) age are correlated with the Gambier Group (Woodsworth, 1980). Their volcanic-rich stratigraphy contrasts to the sediment-dominated successions of the adjacent Intermontane Belt. Perhaps some facies telescoping is called for across the faulted eastern margin of the Coast Plutonic Complex (cf. Woodsworth, 1979).

On the Queen Charlotte Islands, the Longarm Formation is coeval with the youngest rocks of the Gravina-Nutzotin Belt, but is essentially nonvolcanic. It is succeeded by the Middle to Upper Cretaceous Queen Charlotte Group.

c) Southern Transect:

The Cretaceous stratigraphy of Vancouver Island is similar to that of the Queen Charlottes (Fig. 2). Both the Longarm Formation and Queen Charlotte Group are present and give comparable ages to those obtained farther north. The Nanaimo Group records a sedimentary basin developed west of the Coast Plutonic Complex in Santonian to Maastrichtian time that has no equivalent in Hecate Depression east of the Queen Charlotte Islands.

The outstanding feature of the southern transect is the widely contrasting facies of Albian and older age that result from juxtaposition by faults on the eastern margin of the Coast Plutonic Complex and the Cascades. This margin corresponds to the suture among Wrangellia, the Bridge River Terrane (Potter, 1983a; 1983b) and Quesnellia. Final telescoping across this boundary, accompanied by dextral transcurrent motion on the Pasayten-Yalakom fault system, occurred in latest Albian through Turonian time (Tennyson and Cole, 1978; Kleinspehn, 1982). The minimum age for this event may be set by an 84 Ma pluton (Coates 1974) that intrudes the Pasayten Fault, and on the east side of the fault system, the relatively undeformed, 85 Ma Kingsvale basalts that unconformably overlie the folded Albian to Cenomanian rocks.

2.3 CRETACEOUS PLUTONISM:

Armstrong (1985) has recently completed a compilation of all radiometric dates for the Canadian Cordillera. He has identified two important Cretaceous maxima in histogram plots, at 110-90 ma and at 80-70 ma. These are based on combined plutonic and volcanic dates. They suggest a close temporal relationship between plutonic and volcanic activity.

Plutonic rocks concentrate in the Coast Plutonic Complex and the Ominecas-western Rocky Mountains, whereas coeval volcanic rocks are most abundant in the Intermontane belt. This difference may be in part erosional and in part due to the different character of the magmatism: the mid-Cretaceous intrusions in the eastern belt are S-type granites, a suite typified by paucity of extrusive equivalents.

2.4 DISCUSSION

The Cretaceous volcanic history of the Canadian Cordillera can be viewed as three distinct episodes, separated from each other by time and/or space. They are as follows:

1) Hauterivian and older volcanism throughout the length of the Coast Plutonic Complex (Gambier-Gravina-Nutzotin rocks) which either merged into or was succeeded by Albian volcanism in the southern Coast Plutonic Complex.
2) Albian to Cenomanian volcanism east of the Coast Plutonic Complex, extending on to the North American Plate near Faro and at Crowsnest Pass. It is mainly calc-alkaline except for the alkaline Crowsnest Formation.
3) Santonian to Maastrichtian and possibly Paleocene volcanism which is probably calc-alkalic, but is also alkaline east of the Coast Plutonic Complex.

The first episode is confined to Wrangellia and the Alexander Terrane. It predates their final amalgamation with the remainder of the Canadian Cordillera, which affected the southeastern border of Wrangellia in the mid-Cretaceous and which is reflected in the tectonic contact between the Gravina-Nutzotin rocks and the Taku Terrane in southeastern Alaska (Berg et al., 1977). The second and third volcanic episodes are partly coextensive. In southern British Columbia, they are separated in time by a mid-Cretaceous deformation, while in the central Yukon no significant deformation occurred between them.

According to Livaccari and Engebretson (1983), the relative motion of the Farallon and North American plates changed from straight-on, east-directed slow subduction to more rapid, northeast-directed dextral oblique subduction at about 100 Ma. This major transition in relative plate motions in the Albian closely coincides with the sudden strong eastward incursion of volcanism into the Cordilleran interior and with the dextral oblique closing of the Methow-Tyaughton basin.

3.0 PALEOGENE

This section of the report is a partial update of Open File 659 compiled by Noel (1978). Although it emphasizes information that has appeared in the literature since 1976, older sources have been consulted for stratigraphic information. Figure 3 shows the distribution of Paleogene rocks in the Cordillera. As in Figure 1, the only intrusive rocks shown are those which geochronometry has firmly established to be of Paleogene age. Figure 4 is a compilation of stratigraphic columns for the Paleogene. Significant age revisions published between 1976 and 1984 or in preparation are the following:

1) reassignment of the Chuckanut Formation to Eocene age (Johnson, 1982, 1984)
2) restriction of the Kamloops and Penticton groups to Eocene age (Ewing, 1981b; Church et al., 1983). Sparse radiometric data suggest that the Ootsa Lake and Endako Groups are also wholly Eocene (see Fig. 4)
3) restriction of the Sustut Group in the Dease Lake and Spatsizi map areas to an Albian to Maastrichtian age range based on palynological data (Read, Tipper, pers. comm. 1984)
4) removal of Mt. Nansen Group from the Cenozoic; reassignment of Carmacks, Casino and Hutshi groups to Late Cretaceous and possibly Paleocene (Grond et al. 1984, Grond 1980; Churchill, 1980; Godwin, 1975)

In addition, new palynological, microfaunal and radiometric data have helped to more closely constrain the ages of major rock units, notably the Hesquiat, Escalante and Sooke Bay (formally Sooke) formations (Cameron, 1979, 1980), the Crescent/Metchosin formations and their correlatives (Fiebelkorn et al., 1983), and the sedimentary formations of the Washington Cascades (Frizzell, 1979; Gresens et al., 1981). Based on detailed stratigraphic studies supported by foraminiferal ages, the Twin River Group of the northern Olympic Peninsula has been divided into three formations (Muller et al., 1983).

3.1 THE CRETACEOUS-PALEOCENE BORDER:

Only a few Cretaceous stratified units span the Mesozoic-Cenozoic border. These include the Kitsilano and Burrard formations in the lower Fraser Valley, and possibly the Nanaimo Group in the Georgia Depression. However, the highest part of the Nanaimo Group may be Eocene rather than Paleocene (Johnson, 1984). In addition, the Carmacks, Donjek, and Hutshi volcanic formations in the Yukon and northernmost British Columbia have yielded age dates ranging from 75 (Late Cretaceous) to 64 Ma (earliest Paleocene). Aside from these minor exceptions, patterns of Cretaceous volcanism and sedimentation in the western Cordillera did not persist into the Cenozoic.

3.2 PALEOCENE:

The Paleocene epoch is poorly represented in the stratigraphic record for western British Columbia and the Yukon. The tholeiites that form the basement of the Olympic Terrane, the Metchosin, Crescent, Siletz River and Roseberg basalts, are Late Paleocene to Early Eocene (Muller et al., 1983). The Olympic Terrane probably did not occupy its present position with respect to the Canadian Cordillera until Late Eocene time (Muller et al., 1983; Magill and Cox, 1981).

In northern British Columbia and the Yukon, the Nisling Range alaskite suite, its associated volcanic rocks and the Skukum Group in the Bennett Lake caldera give earliest Eocene and possibly Paleocene radiometric ages (Lambert, 1974; Templeman-Kluit and Wanless, 1975; Pride, 1985). In the Atlin area, the two 56 Ma plutons, K-Ar dated by Bultman (1979), may be part of this suite. His A-8-1-5 quartz monzonite shows a 10 Ma discordance between hornblende and biotite, which may indicate considerable thermal resetting. The Skukum-Nisling Range episode seems to be separated from the partly coextensive Hutshi episode by a 7 to 10 Ma interval (Figs. 2 and 4). Further isotopic work is needed to establish the validity of this nonmagmatic interval.

Studies from the Prince Rupert area and from northern Washington suggest that rapid uplift of the Central Gneiss Complex and the Okanagan core complexes had commenced by Late Paleocene time (Hollister, 1982; Johnson, 1984).

3.4 EOCENE:

The Eocene epoch represents one of the busiest and most enigmatic phases of northern Cordilleran history. The rapid sequence of events within it strains the precision of present dating techniques. This is an epoch for which the loose age assignations extracted from macroflora are of no use. The entire magmatic flareup in southern British Columbia may have spanned about the uncertainty range of K-Ar dates (Armstrong 1985). Minor discrepancies between foraminiferal zones, palynological age assignments and absolute ages will adjust or even reverse the order of events presently dated by different techniques.

The Middle Eocene saw a tremendous proliferation of volcanism in British Columbia south of the Bowser Basin, and the simultaneous deposition of terrestrial sediments in graben and deltaic settings in northern Washington east of Puget Sound (Fig. 4). The youngest radiometric ages in the Nisling Range and Skukum Group in the Yukon and northernmost British Columbia are also Middle Eocene. The northern Olympic Terrane during this time received only fine grained, distal, submarine sediments such as the Aldwell Formation (Fig. 4).

South-central British Columbia:

The Eocene volcanic episode in south-central British Columbia is remarkable for its wide distribution (Fig. 3) and short duration (Fig. 4). K-Ar age dates range from 56 to 38 Ma, with most in the 53 to 42 Ma range. In many areas, the chronological sequence of radiometric ages either partly agrees with or contradicts the stratigraphic sequence (Fig. 4). This disagreement suggests that the duration of the volcanic episode is of the same order as the imprecision in the K-Ar dates.

The Eocene volcanic fields fall into two divisions; the Okanagan-Quesnel area east of the Fraser River Fault System, and central British Columbia west of the Fraser River Fault System. East of the Fraser River Fault System, the Eocene rocks have been studied intensively (Church, 1973, 1977, 1979, 1980b, 1981, 1982a, 1982b; Church and Johnson, 1978; Church and Brasnett, 1983; Church and Evans, 1983; Church et al., 1983; Ewing, 1981a; Mathews, 1981; Mepham, 1977; McMechan, 1983; Pearson and Obradovich, 1977) and detailed stratigraphy is available from most areas. Typically Eocene volcanic strata and accompanying sediments occur within north-northeasterly trending grabens such as the Republic Graben, the White Lake Basin, the Princeton Basin, and others. Major units are the Kamloops, Penticton and Princeton groups. Because local names abound, see Figure 4 and the above references for formations and members within these groups. In general, Ewing (1981b) pointed out that each Tertiary outlier consists of a lower, dominantly sedimentary and tuffaceous division, such as the Tranquille beds near Kamloops, the Kettle River and Springbrook formations near Penticton, the O'Brien Creek Formation in the Republic Graben, and an upper, dominantly volcanic division. Peatfield (1978) further subdivided the volcanic division into a lower eruptive phase, Sanpoil Volcanics in Republic Graben, and an upper, explosive-eruptive phase accompanied by stronger faulting and fanglomerates like the Klondike Mountain Formation in the Republic Graben and the Skaha Formation in the Penticton outlier. However, this division does not clearly apply to outliers farther north (Fig. 4).

West of the Fraser River Fault System, the Eocene volcanic rocks have been studied mainly in the course of regional mapping, except for the Buck Creek area near Francois Lake (Church, 1972). There, as over large areas (Tipper, pers. comm. 1984), they consist of a lower felsic unit, such as the Ootsa Lake Group, and an upper, basalt-andesite pile, such as the Endako Group. Sediments are rare, and the lowermost sedimentary division, that is prominent in the Okanagan, is absent in the north. Rocks of the Ootsa Lake and Endako groups appear on many older maps as ranging from Paleocene to Miocene age. Radiometric age data, albeit limited, restrict their age to Eocene. The span of ages is wider than that in the Okanagan, but this may be due to analytical error on a small suite of samples. It is probable that the volcanic rocks of the Endako and Ootsa Lake groups are contemporaneous with the volcanic rocks east of the Fraser River Fault System, and that they represent a single episode of volcanism. Mathews and Rouse (1985) report a set of K-Ar dates from Eocene rocks in the Gang Ranch-Big Bar area along the Fraser River Fault System (see Figure 4 for summary). They consider the volcanic interval there to be of about 2 ma duration around the 49.9 ma mean of the age determinations.

Stratigraphic correlations should be attempted across the Fraser River Fault System. Remapping west of the Fraser River Fault System will alter the boundaries of the Eocene volcanic rocks, because in the past the Endako basalts have been confused in places with the Chilcotin Group, and in other places the volcanic rocks of the Cretaceous Kasalka Group have been included in the Ootsa Lake Group.

Price (1979) and Ewing (1981a) inferred major ductile extension of the zone between the Fraser River and Tintina fault systems. One surficial manifestation of the ductile extension may be the formation of numerous grabens within a network of faults between the two systems (Ewing 1981a). The apparent absence of sediment-filled grabens northwest of the Fraser River Fault is in accord with the transition across the fault from ductile on the east to brittle on the west.

Chemistry: A complete spectrum from basalt to rhyolite exists in the Eocene volcanic rocks of southern and central British Columbia. Alkaline varieties exist in the Marron Formation (Church, 1973), the Coryell intrusions, and in the Goosly Lake Volcanics, which form part of the Ootsa Lake Group at Buck Creek (Church, 1972).

In the Okanagan, Ewing (1981d) interpreted the Eocene volcanic rocks of the Kamloops Group as belonging to a high-alkali calc-alkaline suite with some crustal contamination as shown by Sr^{87}/Sr^{86} isotopes[1]. The basalts on Ewing's diagrams appear to form a continuous, comagmatic series with the more felsic rocks, and the continuity indicates that they represent a single, differentiated suite; not a bimodal one. The isotopic data indicate that the felsic rocks were not derived from a separate source from the basalts, such as the crust for one and the mantle for the other. The origin of the alkaline rocks is unclear.

Correlation: In age, lithology, chemistry and tectonic setting, the Eocene volcanic rocks of southern and central British Columbia correlate with the widespread Challis-Absaroka volcanic suite of Idaho, Wyoming and Montana. Armstrong (1978) summarized age data from this episode, which spans the period 55 to 36 Ma with most dates in the 54 to 45 Ma range. The chemistry of these rocks is calc-alkalic with a very minor alkalic component.

Taken as a whole, the Challis volcanic belt extends 1500 km in a northwesterly (320°) direction from Yellowstone Park to the southern border of the Bowser Basin. Ewing (1981d) considered the British Columbia segment to be part of a volcanic arc on the basis of its calc-alkaline chemistry and systematic minor element variations perpendicular to the inferred arc axis.

Uplift of core complexes: A number of Precambrian to Mesozoic gneissic terranes, such as the Central Gneiss Complex in the Skeena region, the Shuswap Complex, the Wolverine Complex, and the Central Nicola Complex, show anomalous Eocene K-Ar ages. Mathews (1981) and Hollister (1982) have drawn convincing cases for high uplift rates, in the range of 5 km/12 Ma to 20 km/10 Ma, during the Eocene for these core complexes, and similar inferences have been made for gneiss complexes

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1 Additional whole-rock analytical data, not available to Ewing (1981d), is in Church and Brasnett (1983), Church and Evans (1983), Church (1982a), Church (1984a), and McMechan (1983).

in the United States north of 42° (Armstrong, 1978). Harms (1982) documented the close relationship between uplift, listric normal faulting, Eocene resetting of K-Ar systems, sedimentation and Challis volcanism for the Priest River Complex in Idaho-Washington. In part, the rapid setting of isotopic systems can be accounted for by tectonic denudation (Mathews, 1981; Harms, 1982; Templeman-Kluit, pers. comm. 1984). However, erosion was also important in exposing the core complexes. Eocene terrestrial sediments in northern Washington contain a record of this process.

The sedimentary basins of northern Washington:

Eocene terrestrial rocks in northern Washington, the Chuckanut, Swauk, and Chumstick formations, and the Puget Group, are composed of deltaic sediments, with abundant arkose. Johnson (1984) found model fission track ages for zircons in the Chuckanut Formation to be 55 to 59 Ma, comparable to the reset ages in the gneiss complexes.The trace mineral suite in the Puget Group includes mica, zircon, apatite, garnet, tourmaline, kyanite, staurolite and andalusite (Bukovic, 1979), which indicates a high grade metamorphic provenance. Paleocurrents in the Puget Group and Chumstick Formation are from the east and northeast respectively (Bukovic, 1979, Buza, 1979); those in the Chuckanut Formation are from the east and north (Johnson, 1984).

Clearly the uplifted and uplifting gneiss complexes were a major, maybe the major contributor to these fluviatile accumulations. Johnson (1984) reported a total thickness exceeding 6000 meters for the Chuckanut Formation, and the Puget Group is at least 2700 m thick (Bukovic, 1979). Thus at least a part of the eroded volume of the cover of the metamorphic core complexes of southern British Columbia could be accounted for in the Eocene sedimentary basins of northern Washington.

The Olympic Terrane:

A complete record of the Middle to Late Eocene history of the northern Olympic Terrane exists along the northern edge of the Olympic Peninsula. The Early Eocene

Crescent tholeiites are overlain by an unnamed siltstone and then by the early Narizian (early Middle Eocene) Aldwell Formation. The Aldwell Formation contains abundant basaltic debris and is dominated by siltstone. Although coeval with, and presently west of the Eocene deltas of northern Washington, the Aldwell Formation does not "fit", in terms of provenance and lithology, the model of a prodelta or submarine fan facies distal to the deltas (Johnson 1984). A post-early Middle Eocene tectonic telescoping of facies is therefore necessary.

The Late Eocene Lyre Formation contains conglomerate with argillite, quartzite, chert, metavolcanic, granite, gneiss and basalt clasts derived presumably from Wrangellia to the north (Muller et al., 1983). A similar source is inferred for the overlying latest Eocene to Early Miocene Makah, Hoko River and Pysht formations. Because of uplift and erosion in Middle Eocene to Late Oligocene, none of these sedimentary formations is preserved on the Metchosin basalt of southern Vancouver Island.

Northeastern British Columbia and Northeastern Yukon:

Eocene volcanism was volumetrically insignificant in this area. The ages of the Sifton Formation and of the sedimentary rocks preserved along the Tintina Fault are not precisely known. Macrofloral and microfloral ages range from Late Cretaceous to Eocene, with the most reliable determinations in the Eocene. The age data are as follows:

Sifton Formation: macrofloral age Paleocene, poorly preserved microflora indicate Late Cretaceous to Tertiary, but probably Tertiary in age; cut by 47 and 38 Ma lamprophyre dykes (Eisbacher, 1974). Adjacent exposures of metamorphic rocks give ages reset to Eocene and provide the maximum possible age for the Sifton Formation.

Watson Lake: preliminary palynological determinations of Late Paleocene to Late Eocene (Hopkins, in Hughes and Long, 1980).

Ross River: Paleocene macroflora and Early to Middle Eocene microflora (Hopkins, in Hughes and Long, 1980).

Dawson: probable Late Eocene (Hopkins, in Hughes and Long, 1980).

The Coast Plutonic Complex:

The eastern side of the Coast Plutonic Complex seems to have had a vigorous Eocene intrusive history, but because K-Ar dates vary in their reliability as indicators of the age of emplacement, most radiometrically dated plutons are not shown in Figure 3. The volcanism at Mt. Skukum (Pride 1985), in the Nisling Range, the Bennett Lake caldera and the Sloko Group can be regarded as extrusive equivalents of the Eocene activity of the Coast Plutonic Complex.

Tectonics:

The two major right-lateral fault systems that penetrate into the interior of the Cordillera, the Tintina and the Fraser River faults, show approximately 400 to 450 km and approximately 70 to 110 km (Monger 1985) of Late Cretaceous to early Tertiary movement respectively. Ewing (1981a) assumed that this movement occurred substantially in the Eocene, but Vance and Miller (1981) and Hughes and Long (1980) favoured an earlier timing. Monger (1985) favors major Eocene movement on the Fraser River Fault system, as a pluton with 47 Ma zircons is involved in sympathetic thrusting in the Coast Mountains southwest of Lillooet, and the Hungry Valley Fault in the Taseko Lake map-area, also a sympathetic thrust, brings Cretaceous over Eocene rocks. The 32 Ma and younger Chilliwack Batholith intrudes and postdates all right-lateral motion on the Fraser River Fault System.

Further work needs to be done to determine whether the major movement of the Tintina Fault was Cretaceous, Eocene, or both. This is particularily urgent because many new models of Eocene tectonics involve a transfer of motion via ductile deformation between the two major fault systems (cf. Price, 1979; Ewing, 1981a; Harms, 1982; Monger, 1985).

Discussion and Modelling:

In the western Canadian Cordillera and the northwestern United States, the Eocene involved the following events:

1) Episodic plutonism and volcanism along the eastern side of the Coast Plutonic Complex, with the Nisling Range event succeeding Carmacks magmatism after a quiescent period of perhaps 7 to 10 Ma.

2) A calc-alkaline volcanic event in southern and central British Columbia and the northwestern United States, the 53 to 42 Ma Challis episode, which represents a brief but vigorous, 320°-trending magmatic arc.

3) Unprecedented rates of uplift of metamorphic core complexes, tectonic denudation and rapid erosion, and initiation of rapid deltaic sedimentation in northern Washington.

4) Possibly the inception of rapid right-lateral transcurrent motion throughout the Canadian Cordillera. It is important to note that no major right-lateral transcurrent faults have been mapped, except in the continental borderland, south of 48° north latitude. The penetration of right-lateral faults deep into the North American Plate seems to be an unique feature of the Canadian and Alaskan Cordillera.

5) A complicated succession of events in the Columbia Embayment: (a) Early Eocene oceanic crust of the Olympic Terrane (Crescent-Metchosin-Siletz River-Roseberg) attached to the Klamath Mountains in Middle Eocene time (Baldwin and Perttu, 1980); (b) 46° clockwise rotation of the southern Olympic Terrane during the middle Eocene (Magill and Cox, 1981) and/or individual block rotations within the terrane of up to 69° associated with right-lateral faulting (Wells, 1982). (c) a subduction zone either landward (Magill et al., 1981) or seaward (Hammond, 1979) of the Olympic Terrane that generated the Challis magmatic arc; (d) rapid plate reorganisation in the Late Eocene that caused the

demise of the Challis arc and also of thermal-plutonic activity in the Coast Plutonic Complex; (e) overthrust emplacement (Church, 1984b) of Olympic Terrane against southern Wrangellia (43 to 38 Ma); and (f) establishment of a plate geometry much like the one that has persisted over the last 40 Ma, with subduction generating the Cascade arc and plate margin right lateral motion north of southern Vancouver Island.

The Eocene, with its brief and turbulent magmatic and tectonic history, represents a period of extreme plate tectonic instability at the transition between the Mesozoic and the late Cenozoic, relatively stable configurations. The focus of this instability seems to have been in southern British Columbia and the northwestern United States: the Challis arc, the southerly limit of major right-lateral strike slip faulting that propogated deep into the North American Plate, and the newly accreting Olympic Terrane. These events coincide with increased rates of subduction of the Farallon Plate in Eocene time. Livaccari and Engebretson (1983) inferred rapid (13 cm/year) east-northeasterly to northeasterly directed subduction in the period 72 to 56 Ma and very rapid (15 cm/year) north-northeasterly to northeasterly dextral oblique, flat plate subduction of the Farallon plate between 56 and 43 Ma. The increasing rate of relative movement, particularly the northerly lateral component, and flattening of the Benioff zone would lead to increased coupling between the Farallon and North American plates during the Eocene, which may explain the onset of vigorous dextral movement within the continent. The increase in absolute convergence rate may have generated the Challis magmatism. With the demise of the Pacific-Farallon ridge at about 40 Ma, this geometry was replaced by the one we see today.

A major unresolved problem with this or any Eocene model is the relationship among tectonics in the North American Plate in southern British Columbia, northern Washington, and in the Olympic Terrane.

3.5 OLIGOCENE:

The Oligocene history of the Canadian Cordillera is largely unknown. In the extreme south, the Chilliwack batholith and the Barlow Pass Group represent the northern limit of the Cascade arc, which transgressed farther north into British Columbia in the Neogene. The Tkope River Batholith in the St. Elias Range is Oligocene (Jacobsen, 1979).

Volcanic suites in the interior of British Columbia cluster strongly in either the Eocene or the Miocene. At present there are only five Oligocene dates from such rocks in the Canadian Geochron File at the University of British Columbia (Armstrong pers. comm. 1985). They are all from basalts: two near Cheslatta Falls (93F), one from The Dome (93B), one from the "Brigade Lake Volcanics" in the Ashcroft area (92I), and a 24-ma date from Black Dome (92O)(Mathews and Rouse,1984). Rocks assigned to the "Upper Endako Group" near Bulkley Lake interfinger with Lower Miocene sediments (H. Tipper pers. comm. 1985 and see Figure 4). These basalts may be Oligocene; however no radiometric age data exist to substantiate this assertion.

The Masset Formation on the Queen Charlotte Islands and the Kootznahoo Formation on Kupreanof and neighboring islands (Buddington and Chapin, 1929; Muffler, 1967), all contain basic to acidic rocks, which may or may not range in age from Eocene to Miocene. Young (1981) presented K-Ar dates from the Masset Formation ranging from 45 to 11 Ma. Plants from the Kootznahoo Formation range from Eocene to Early Miocene (Muffler 1967). Both of these time constraints need further refinement. A further suggested line of study is to compare the chemistry of Masset and Kootznahoo volcanic rocks to aid in determining whether the two suites are similar, or represent two distinct volcanic regimes.

Oligocene terrestrial sedimentation is represented by the Amphitheatre Formation preserved along the Denali Fault System (Eisbacher and Hopkins, 1977), the Kishenehn Formation in the Flathead Valley Graben, formed by listric normal faulting localized by the earlier Lewis thrust (McMechan, 1981; McMechan and Price, 1980), the Wenatchee Formation in the Chiwaukum Graben, and by the Australian Creek Formation along the Fraser River near Quesnel (Rouse and Mathews, 1979).

In the northern part of the Olympic Terrane, the Makah and Pysht formations a represent continuation of Late Eocene marine, proximal sedimentation. The Late Eocene to Oligocene Carmanah Group onlapped along the western edge of Vancouver Island. Its upper part, the Sooke Bay Formation, lies unconformably on the basement of the Olympic Terrane along the southern margin of Vancouver Island.

In summary, the Oligocene period in the Canadian Cordillera was magmatically quiescent. Part of the Masset and Kootznahoo formations, a few basalts in the interior of British Columbia, the Tkope River Batholith; and the Chilliwack Batholith and the Barlow Pass Group, which represent the northernmost end of the Oligocene Cascade volcanic arc, are the volumetrically minor exceptions. The Oligocene represents a break of some 20 Ma (Late Eocene to early Middle Miocene) between the end of the Challis episode and the beginning of eruption of the Chilcotin plateau basalts.

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APPENDIX A:

GEOLOGIC TIME SCALE

DECADE OF NORTH AMERICAN GEOLOGY

1983 GEOLOGIC TIME SCALE

DNAG

GEOLOGICAL SOCIETY OF AMERICA

CENOZOIC

PERIOD		EPOCH		AGE	PICKS (Ma)
QUATERNARY		HOLOCENE			0.01
QUATERNARY		PLEISTOCENE		CALABRIAN	1.6
TERTIARY	NEOGENE	PLIOCENE	L	PIACENZIAN	3.4
		PLIOCENE	E	ZANCLEAN	5.3
		MIOCENE	L	MESSINIAN	6.5
		MIOCENE	L	TORTONIAN	11.2
		MIOCENE	M	SERRAVALLIAN	15.1
		MIOCENE	M	LANGHIAN	16.6
		MIOCENE	E	BURDIGALIAN	21.8
		MIOCENE	E	AQUITANIAN	23.7
	PALEOGENE	OLIGOCENE	L	CHATTIAN	30.0
		OLIGOCENE	E	RUPELIAN	36.6
		EOCENE	L	PRIABONIAN	40.0
		EOCENE	M	BARTONIAN	43.6
		EOCENE	M	LUTETIAN	52.0
		EOCENE	E	YPRESIAN	57.8
		PALEOCENE	L	SELANDIAN – THANETIAN	60.6
		PALEOCENE	L	SELANDIAN – UNNAMED	63.6
		PALEOCENE	E	DANIAN	66.4

MESOZOIC

PERIOD	EPOCH	AGE	PICKS (Ma)	UNCERT (m.y.)
CRETACEOUS			66.4	
	LATE	MAASTRICHTIAN	74.5	4
	LATE	CAMPANIAN	84.0	4.5
	LATE	SANTONIAN	87.5	
	LATE	CONIACIAN	88.5	2.5
	LATE	TURONIAN	91	
	LATE	CENOMANIAN	97.5	2.5
	EARLY	ALBIAN	113	4
	EARLY	APTIAN	119	8
	EARLY (NEOCOMIAN)	BARREMIAN	124	8
	EARLY (NEOCOMIAN)	HAUTERIVIAN	131	8
	EARLY (NEOCOMIAN)	VALANGINIAN	138	5
	EARLY (NEOCOMIAN)	BERRIASIAN	144	5
JURASSIC	LATE	TITHONIAN	152	12
	LATE	KIMMERIDGIAN	156	6
	LATE	OXFORDIAN	163	15
	MIDDLE	CALLOVIAN	169	15
	MIDDLE	BATHONIAN	176	34
	MIDDLE	BAJOCIAN	183	34
	MIDDLE	AALENIAN	187	34
	EARLY	TOARCIAN	193	28
	EARLY	PLIENSBACHIAN	198	32
	EARLY	SINEMURIAN	204	18
	EARLY	HETTANGIAN	208	18
TRIASSIC	LATE	NORIAN	225	8
	LATE	CARNIAN	230	22
	MIDDLE	LADINIAN	235	10
	MIDDLE	ANISIAN	240	22
	EARLY	SCYTHIAN	245	20

RAPID POLARITY CHANGES

PALEOZOIC

PERIOD		EPOCH	AGE	PICKS (Ma)	UNCERT (m.y.)
PERMIAN				245	20
		LATE	TATARIAN		
		LATE	KAZANIAN	253	20
		LATE	UFIMIAN		
		LATE	KUNGURIAN	258	24
		EARLY	ARTINSKIAN	263	22
		EARLY	SAKMARIAN	268	12
		EARLY	ASSELIAN	286	12
CARBONIFEROUS	PENNSYLVANIAN	LATE	GZELIAN (S.)		
		LATE	KASIMOVIAN (S.)	296	10
		LATE	MOSCOVIAN (W.)		
		LATE	BASHKIRIAN (W.)	315	20
			(N.)	320	
	MISSISSIPPIAN	EARLY	SERPUKHOVIAN (N.)	333	22
		EARLY	VISEAN	352	8
		EARLY	TOURNAISIAN	360	10
DEVONIAN		LATE	FAMENNIAN	367	12
		LATE	FRASNIAN	374	18
		MIDDLE	GIVETIAN	380	18
		MIDDLE	EIFELIAN	387	28
		EARLY	EMSIAN	394	22
		EARLY	SIEGENIAN	401	18
		EARLY	GEDINNIAN	408	12
SILURIAN		LATE	PRIDOLIAN	414	12
		LATE	LUDLOVIAN	421	12
		EARLY	WENLOCKIAN	428	8
		EARLY	LLANDOVERIAN	438	12
ORDOVICIAN		LATE	ASHGILLIAN	448	12
		LATE	CARADOCIAN	458	16
		MIDDLE	LLANDEILAN	468	16
		MIDDLE	LLANVIRNIAN	478	16
		EARLY	ARENIGIAN	488	20
		EARLY	TREMADOCIAN	505	32
CAMBRIAN		LATE	TREMPEALEAUAN FRANCONIAN DRESBACHIAN	523	36
		MIDDLE		540	28
		EARLY		570	

PRECAMBRIAN

EON	ERA	BDY. AGES (Ma)
		570
PROTEROZOIC	LATE	900
PROTEROZOIC	MIDDLE	1600
PROTEROZOIC	EARLY	2500
ARCHEAN	LATE	3000
ARCHEAN	MIDDLE	3400
ARCHEAN	EARLY	3800?