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K–Ar ages of plutonic rocks between Hope, British Columbia, and the 49th parallel

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K–Ar ages of plutonic rocks between Hope, British Columbia, and the 49th parallel

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Twenty-two new K–Ar age determinations are reported for the plutonic rocks between Hope, B.C. and the 49th parallel. Ages ranging from 103 m.y. to 16 m.y. suggest an extension in southern British Columbia of Mesozoic plutonism into Late Cretaceous time and three brief and well-defined Tertiary plutonic events.

Introduction

The plutonic rocks lying between Hope, B.C. and the United States border have long been considered a singular batholithic complex of late Tertiary age. As part of the study of these plutonic rocks, 22 new K–Ar ages have been determined. The results reported here in part confirm the presence of upper Tertiary plutonic rocks and modify the concept of a singular batholithic complex.

General Geology

The location and general geology of the area mapped, 100 miles (160 km) east of Vancouver, B.C., are shown in Fig. 1.

Granitic bodies in the central part are bounded on the west by sedimentary rocks of the Chilliwack Group, and on the east by sedimentary and volcanic rocks of the Hozameen Group. The former are considered to be late Paleozoic in age and the latter of either similar or greater age. Both groups are strongly deformed and have undergone greenschist metamorphism.

A migmatite complex which trends northerly and is referred to as the Custer gneiss (or Skagit gneiss south of the 49th parallel) forms much of the eastern contact of the plutonic rocks. This complex may be a high grade metamorphic equivalent of the Hozameen Group rocks (McTaggart and Thompson 1967). Small bodies of hornblende peridotite locally intrude the Custer gneiss.

A conglomerate of Eocene age bisects the map area. South of Hope the conglomerate, forming some of the highest peaks of the area, has been intruded and hornfelsed by the plutonic rocks. North of Hope it is weakly indurated forming low hills within the Fraser River Graben.

Granitic Rocks

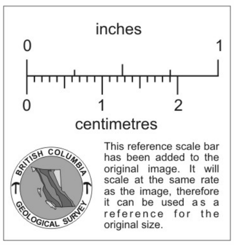
For more than 50 years granitic rocks which straddle the International Boundary south of Hope, B.C., have been considered as part of the Chilliwack batholith, which was assigned a late Tertiary age (Daly 1912; Cairnes 1944). Misch (1966) has shown that the Chilliwack batholith is lithologically composite with ages ranging from Eocene to Miocene. Of these plutonic rocks north of the 49th parallel McTaggart and Thompson suggest ". . . it is quite possible that detailed examination of the main batholithic mass to the west will show it to be a composite mass of successive intrusions" (1967, p. 1220). The present study supports this suggestion. A brief description of the granitic bodies in Fig. 1 is given below. Not all of these plutonic rocks are part of the Chilliwack batholith as originally defined. For convenience of description individual plutonic complexes have been assigned local names by these and previous writers.

Spuzzum Intrusions

The Spuzzum Intrusions, originally named by McTaggart and Thompson (1967) for the partly-sheared, foliated quartz diorites west of Spuzzum, B.C., have been extended southward to include rocks spanning the Fraser River west of Hope, B.C. Here they comprise a zoned domical body with a core of hypersthene–augite diorite and margins of biotite hornblende quartz diorite.

Yale Intrusions

A complex of variably-sheared to gneissic intrusive bodies occur in a belt along the



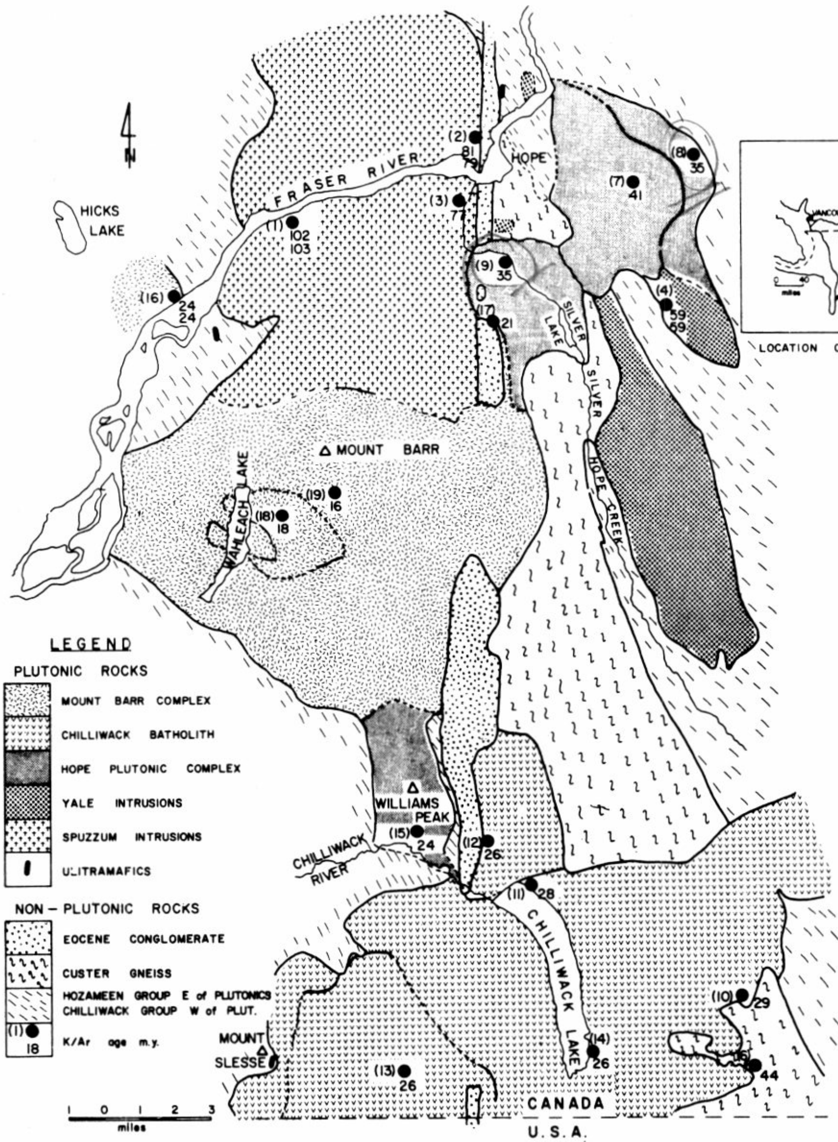


FIG. 1. Location, general geology, and K–Ar ages in the study area.

Fraser River and Silverhope Creek. These bodies, ranging in composition from quartz diorite to quartz monzonite, have been termed the Yale Intrusions by McTaggart and Thompson (1967). Their main identifying characteristic is a ubiquitous cataclastic texture. Their relationship to one another, and to other plutonic bodies is problematic. It is possible that some of the Yale Intrusions are sheared equivalents of Lower Eocene plutonic rocks found along the Fraser River, such as the Hells Gate pluton (McTaggart and Thompson 1967) and older portions of the Hope plutonic complex.

Hope Plutonic Complex

This name applies to three stocks a short distance east and south of Hope, B.C. The largest central body consists of variably-sheared, locally porphyritic, leucocratic quartz monzonite. To the east this body is in sharp contact with a crescent-shaped body of biotite hornblende quartz diorite, characterized by

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large (5 cm), ovoid, composite plagioclase crystals, large rounded books of biotite and by a complete absence of potash feldspar. To the west, near Silver Lake, is the third stock consisting of unsheared, medium-grained biotite hornblende quartz diorite with from 1 to 5% potash feldspar. Contact relations suggest that this body is younger than its larger neighbor.

Another stock, centered on Williams Peak about 17 miles (27 km) southerly from Hope, B.C., although sheared and altered, is nearly identical petrographically to the crescent-shaped body described above. It is, therefore, provisionally considered another member of the Hope plutonic complex.

Chilliwack Batholith

The Chilliwack batholith (Daly 1912) underlies the area on either side of Chilliwack Lake and extends south of the 49th parallel some 20 miles (32 km). Rocks exposed in this complex north of the border, range from hypersthene quartz gabbro to albite granite, with granodiorite greatly predominating. Three main plutons are present. The oldest and most extensive is an irregularly-zoned pluton composed of quartz diorite at the margins, grading inward through granodiorite to a small core of granite. This pluton crops out on either side of Chilliwack Lake. Two younger plutons, one north of Chilliwack Lake, the other 2 miles (3.2 km) east of Mount Slesse, are nearly homogeneous leucocratic biotite quartz monzonites.

Mount Barr Plutonic Complex

This complex is centered about Wahleach Lake 12 miles (19 km) southwest of Hope. Four plutons are present. The main pluton, comprising 80% of the area, is a concentrically zoned mass ranging in composition from quartz diorite to quartz monzonite. Within the core of this main phase are two younger stocks—an earlier fine-grained biotite hornblende granodiorite and a later leucocratic biotite quartz monzonite. West of Silver Lake, lying between the quartz diorite of the Hope Plutonic complex and the Eocene conglomerates is a granophyric hornblende plagioclase porphyry dike 200 to 300 ft (60 to 90 m) wide, which appears to be an offshoot of the main Mount Barr pluton.

A heterogeneous biotite hornblende quartz diorite pluton underlying the northwest corner of the area, north of the Fraser River near Hicks Lake, is provisionally included in the Mount Barr Complex.

Potassium–Argon Results

Samples taken for K–Ar dating were processed in laboratories of the Department of Geology, University of British Columbia, using procedures and equipment previously described (White *et al.* 1967). Table I gives pertinent analytical data and on Figure 1 sample numbers, locations, and ages are shown.

Interpretation of Potassium–Argon Results

Results indicate that three of the granitic complexes within the area of Fig. 1 reflect fairly closely-defined plutonic events of Tertiary age and one less closely-defined or more protracted event of Late Cretaceous age. These events are listed in chronological order in Table II.

A specimen from near the core of the Spuzzum intrusive complex was dated 103 m.y. —a number that agrees fairly well with others reported from various granitic members of the Coast Crystalline Complex in the Vancouver region (Mathews 1968). On the other hand, three specimens of Spuzzum rock, well separated but all somewhat closer to the Fraser River fault zone, gave ages of 81, 79, and 77 m.y. The first age was based on hornblende, the other two on biotite. These numbers compare closely with a conformable hornblende–biotite age of 76 m.y. reported by McTaggart and Thompson (1967, p. 1212) from Spuzzum tonalite some 12 miles (19 km) north of Hope.

The Spuzzum Intrusions should be considered part of the Coast Crystalline Complex, representing a phase of the wide-spread and protracted Mesozoic plutonism that persisted at least locally into late Late Cretaceous time.

The 'Yale Intrusions' are not included in Table II as being indicative of a separate plutonic event, because the group has not been adequately studied or sampled. The age of 59 m.y. obtained from a single sample of Yale granodiorite, though perhaps not representative of the group, may still have some significance. It is compatible with the conclusion of McTaggart and Thompson that, "The Yale Intrusions

TABLE I

K/Ar samples and analytical results for the plutonic rocks between Hope and the United States border

Spec. No.	Min	Rock	%K	s	Ar^{40*}/Ar^{40tot}	Ar^{40*}:10^{-5} cm^3 (stp)/g	Age (m.y.)
Spuzzum Intrusions							
1 (*a*)	Bio	QD	5.73	±0.07	0.82	2.404	103±5
(*b*)	Bio	QD			0.79	2.392	103±5
2 (*a*)	Bio	QD	6.10	±0.06	0.89	1.930	79±4
(*b*)	Hb	QD	0.540	±0.007	0.65	0.176	81±4
3	Bio	QD	6.02	±0.02	0.73	1.872	77±3
"*Yale Intrusions*"							
4 (*a*)	Bio	Gdior.	6.75	±0.04	0.81	1.598	59±3
(*b*)	Bio	Gdior.			0.53	1.588	59±3
Custer Ridge Mica–Hornblende Peridotite							
6	Hb	Hbite	0.280	±0.005	0.26	0.049	44±3
Hope Plutonic Complex							
7	Bio	QM	5.17	±0.02	0.53	0.851	41±2
8	Bio	QD	7.65	±0.08	0.41	1.054	35±2
9	Hb	QD	0.433	±0.012	0.39	0.06	35±2
Chilliwack Batholith							
10	Bio	Gab.	6.24	±0.06	0.30	0.723	29±1
11	Bio	QD	7.51	±0.05	0.67	0.824	28±1
12	Bio	QM	6.83	±0.07	0.33	0.718	26±1
13	Bio	QM	6.97	±0.04	0.77	0.732	26±1
14	Bio	QM	5.90	±0.06	0.50	0.609	26±1
15	Mafic Conc.	QD	1.109		0.31	0.105	24±1
16 (*a*)	Bio	QD	6.87	±0.05	0.50	0.643	24±1
(*b*)	Bio	QD			0.57	0.647	24±1
17	Bio	Grano-phyre	4.85	±0.03	0.61	0.411	21±1
18	Bio	Gdior.	6.58	±0.06	0.22	0.464	18±1
19	Bio	QM	6.91	±0.03	0.24	0.438	16±1

†Potassium analyses by T. Richards using KY-1 flame photometer. s—standard deviation of quadruplicate analyses.
‡Argon analyses by J. E. Harakal and T. Richards using MS-10 mass spectrometer.
§Constants used in age calculations: $\lambda_e = 0.58 \times 10^{-10} y^{-1}$, $\lambda_\beta = 4.72 \times 10^{-10} y^{-1}$, $K^{40}/K = 1.181 \times 10^{-4}$.

TABLE II

Ages of Plutonic events

Plutonic event	Geological age	K/Ar age range (m.y.)
Spuzzum intrusion	Mid. to Late Cretaceous	103–77
Hope plutonic complex	Upper Eocene–lower Oligocene	41–35
Chilliwack batholith	Upper Oligocene–lower Miocene	29–26
Mt. Barr complex	Middle Miocene	21–16

are younger than Spuzzum tonalite and older than Eocene sedimentary rocks. . ." (1967, p. 1216).

Ages obtained for the three main stocks of the Hope Plutonic Complex, ranging from 41 to 35 m.y., indicate a brief plutonic event in Late Eocene to Early Oligocene times. Similar ages previously reported from an intrusion 25 miles (40 km) north of Hope (Baadsgaard *et al.* 1961) and from a batholith 10 miles (16 km) northeast of Hope (Wanless *et al.* 1966) suggest that the influence of this episode of plutonism may be wide-spread.

Potassium–argon ages of different intrusive phases that comprise the Chilliwack batholith (as defined by Daly) range narrowly from 29 to 26 m.y. Although the method does not discriminate between the absolute ages of relatively younger and older plutons of the complex, the implication is that evolution and emplacement of the complex was accomplished in a brief interval of geologic time. The Williams Peak stock is correlated with the Hope Plutonic Complex on grounds of petrographic similarities. In the specimen analyzed much of the biotite appeared to be of metamorphic origin. Evidently, the radiometric date of 24 m.y. represents a time of contact metamorphism associated with emplacement of the Chilliwack batholith.

The three ages of 21, 18, and 16 m.y. obtained from different plutons of the Mount Barr Complex, together with two 18 m.y. ages reported by Baadsgaard *et al.* (1961), indicate still another younger plutonic event of brief duration. An isolated stock north of the Fraser River near Hicks Lake was provisionally correlated by petrographic similarities with the Mount Barr Complex. Its 24 m.y. age suggests that it might be either an early phase of that complex or an episode of plutonism synchronous with emplacement of the Chilliwack batholith.

The age of 44 m.y. obtained for a sheared mica-hornblende peridotite intrusion in Custer Gneiss east of Chilliwack Lake is an enigma. The body clearly transects the metamorphic foliation of the gneiss. Kulp (1961) reported potassium–argon ages of 43, 44, and 48 m.y. for the Custer Gneiss equivalent in northern Washington, but Peter Misch has suggested[1] that these numbers may represent an older age of metamorphism of the Custer Gneiss that has been partly 'reset' by intrusion of the Chilliwack batholith.

In summary, granitic rocks in the Hope area of southwestern British Columbia provide geologic and radiometric evidence of an extension of Mesozoic plutonism into late Late Cretaceous time, followed after an apparently quiescent interval of some 35 m.y. by three brief and closely-spaced plutonic epochs extending into mid-Miocene time. Granitic rocks even younger than the Mount Barr pluton are known to exist within the Cascades of Washington and Northern Oregon. The 14 m.y. Tatoosh pluton (Fiske *et al.* 1963) and the 12 m.y. Larel Creek stock from Mount Hood (Wise 1969), along with the petrologically similar High Cascade vulcanism suggest a period of igneous activity in the Cascades that began somewhere in the Eocene Epoch and has continued up to the present time.

[1]Peter Misch, personal communication.

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TECTONIC HISTORY OF THE NORTHERN CASCADE MOUNTAINS

by

K. C. McTaggart

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TECTONIC HISTORY OF THE NORTHERN CASCADE MOUNTAINS

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ABSTRACT

The Northern Cascade Mountains and the southern part of the Coast Crystalline Belt offer two views, at different levels, of the same orogen. The Northern Cascade Region, composed mainly of folded and faulted sedimentary, volcanic and metamorphic rocks, displays the upper levels of the orogen, only slightly eroded. The main features here are westerly and easterly spreading thrusts that root near a central crystalline and metamorphic axial zone. The Coast Crystalline Belt, to the northwest, made up largely of granitic plutons with numerous roof pendants, reveals the deeper levels of the tectonic belt. The overlying thrust plates have been stripped off and only the steep root zones of the thrusts and the central crystalline axis can be followed northwest into the plutonic zones. Structures, in general, strike northwest. Anomalous northeast-striking recumbent folds in the boundary region between the Northern Cascade Mountains and the Coast Crystalline Belt were probably produced by late orogenic gravity controlled sliding activated by the rising plutonic complex to the northwest.

The history of the belt includes formation of a pre-Devonian Basement Complex, development of a eugeosyncline that lasted from Devonian to late Mesozoic times, development of an axial zone of gneisses, a tectonic climax in mid-Cretaceous time, with thrusting to east and west, folding and widespread emplacement of granitic plutons, and, finally, uplift of the northwest part of the belt (Coast Crystalline Belt) in early Tertiary. Overlapping these events are the emplacement of granitic plutons in the general region from earliest Jurassic to Miocene, and intermittent activity along the Fraser River fault zone from late Mesozoic (?) through early Tertiary time.

INTRODUCTION

The Cascade Mountains extend from northern California into southern British Columbia, terminating in the north at Lytton (Figure 12-1) and on the west at Fraser River (Holland, 1964). West of Hope, however, geological structures clearly cross the Fraser River, and as Crickmay (1930, p. 486) pointed out, that river forms a physiographic rather than a geological boundary.

In this paper, the author, although dealing mainly with the Cascade Mountains north of Latitude 49° N., will occasionally consider adjacent areas. The Cascade region of northern Washington State has recently been described in a comprehensive account by Misch (1966) and frequent reference will be made to his work. Campbell (1966) has outlined the tectonic history of the northern part of the Cascade Mountains.

ROCK UNITS OF THE NORTHERN CASCADE MOUNTAINS

Basement Complex

The oldest rocks of the northern Cascade Mountains (Table I and Figure 12-2a) belong to the "Crystalline Basement" (Misch, 1966) that consists of metamorphosed igneous rocks, mainly quartz diorite, and also gabbro, trondhjemite, and others. These occur as autochthonous bodies underlying scores of square miles in northern Washington State, mainly southeast of Marblemount on the Skagit River (Figure 12-1), and as allochthonous slices that have been tectonically emplaced along faults. Vedder Mountain, at the International Boundary, is possibly in part an upfaulted block of basement; Lowes (1968) suggests that tectonic slices of basement occur east of Harrison Lake. All of the basement rocks have been subjected to regional metmorphism and, in many places, to strong cataclastic metamorphism. The age of the basement rocks is considered to be pre-Devonian (Misch, 1966, p. 106). This age is based on the presence on Orcas Island, of the San Juan Islands, of Devonian conglomerate containing boulders of amphibolite and diorite that resemble basement rocks which nearby lie unconformably beneath Devonian beds (Danner, 1966, pp. 62-63). Basement rocks are known only northeast of a northwest-trending line extending from the Strait of Juan de Fuca into Washington State. Geophysical evidence (*in,* Hamilton and Myers, 1966, p. 537) suggests that southwest of this line, basement is missing and the crust under western Washington, including the Olympic Peninsula, and northwestern Oregon is composed mostly of Cenozoic volcanic rocks with some older sedimentary material.

Paleozoic Rocks (Figure 12-2a)

The *Chilliwack Group* (Danner, 1966) of northern Washington State and southwestern British Columbia includes Devonian, Pennsylvanian, and Permian strata. A large part of the Chilliwack Group is correlative with the Cache Creek Group (Danner, 1968).

Devonian rocks occur at several localities in Washington State near Vedder Mountain and also in the San Juan Islands. None is known in the adjacent parts of British Columbia. They consist of clastic sedimentary rocks, limestone, and volcanic rocks. Pennsylvanian strata are widespread and include limestone, clastics, volcanics, and, in a few places, plant-bearing beds.

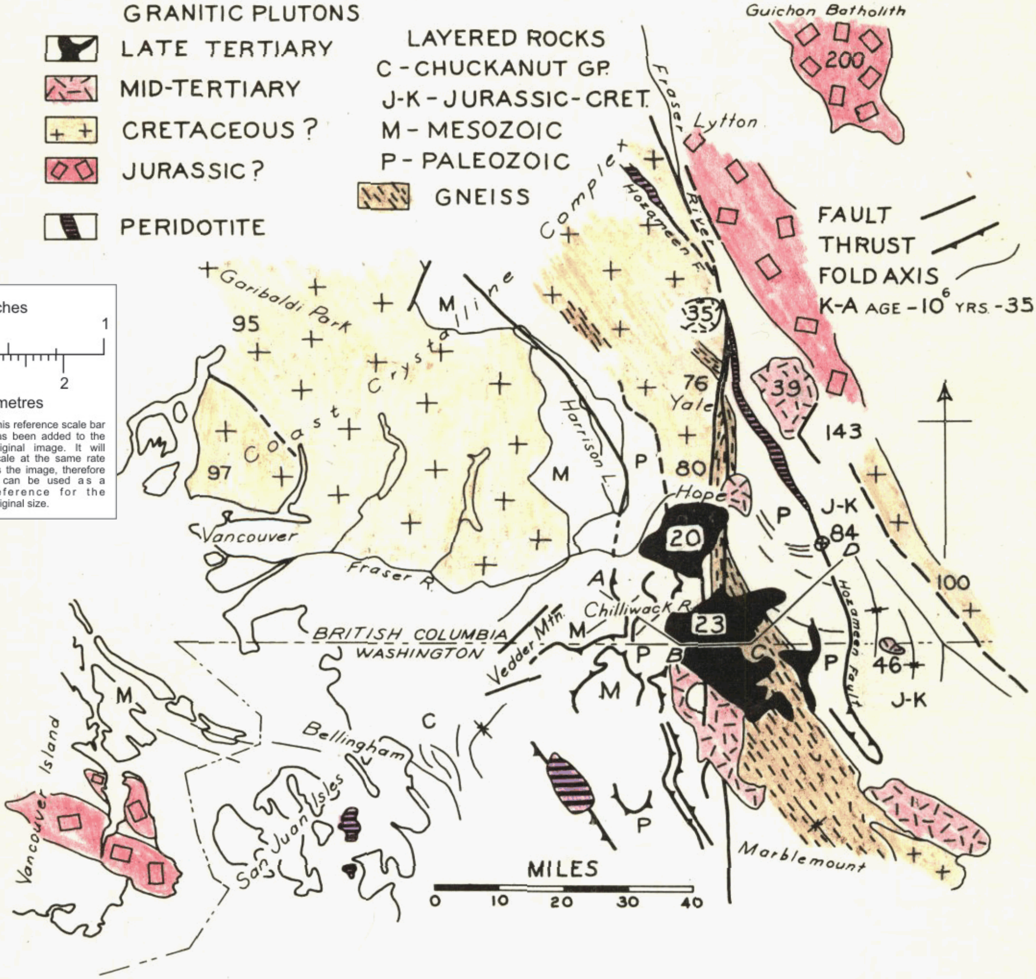
Table I: Summary of the geological history of the Northern Cascades.

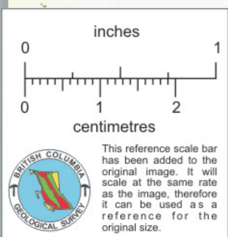
Time (MYBP)	Period or Epoch	Unit deposited or emplaced	Tectonic activity
	Pleist. & Recent	Volcanic Rocks	Volcanoes of the Cascades and Coast Mountains
30-20	Miocene (Late Tertiary)	Youngest phases of Chilliwack Batholith	Intrusions and volcanism extending northward from Washington and Oregon states.
40-35	Oligocene (Mid-Tertiary)	Granitic intrusions	Mild deformation (?)
			Folding and crushing along Fraser River fault zone
	Eocene	Clastic rocks along Fraser River fault zone; Huntingdon Fm.	Uplift and graben filling along Fraser River fault zone
	Paleocene	Chuckanut Formation	Uplift and gravity sliding in Chilliwack Valley region; northeast-trending faults and folds
	Late Cretaceous	Nanaimo Group	Marine basin on west; non-marine basin in central parts
80-76		Spuzzum tonalite, west of Fraser River, north of Hope	Intrusion, metamorphism, and folding
	Mid-Cretaceous	Main part of Coast Crystalline Complex north and east of Vancouver	"Mid-Cretaceous Orogeny"; Shuksan thrust on west; Hozameen-Ross Lake fault on east.
135	Lower Cretaceous	Pasayten Gp. Jackass Mtn. Gp. (Cultus Fm. / Nooksack Gp.)	
	Upper Jurassic Lower Jurassic	Dewdney Ck. Gp. Ladner Group	
	Cretaceous (?!) Pre-Jurassic (?) Late Paleozoic (?) Early Pal. (?!)	Custer-Skagit Gneiss (Cascade Metamorphic Suite)	Regional metamorphism and migmatitization; folding on northwest axis
	Permian	Hozameen Group (?)	
	Devonian	Chillwack Group	Eugeosyncline developing
	Pre-Devonian	Basement Complex	Widespread intrusions, many of them quartz diorite

Permian strata of the northern Cascade Mountains are of limestone, chert, clastics, and volcanics.

The *Hozameen Group* (McTaggart and Thompson, 1967) lies along the eastern side of the core of the Cascade region and underlies large areas southeast of Hope. It consists of more than 20,000 feet of ribbon chert, volcanic greenstone, limestone and argillite. Its age is unknown but is generally considered to be late Paleozoic.

The *Cascade Metamorphic Suite* (Misch. 1966) includes two main groups of metamorphic rocks: Shuksan and Skagit. The first consists of sedimentary and volcanic rocks metamorphosed mainly to phyllites and greenschists but partly to "blue-schists". These rocks, known only in Washington State but possibly extending into the Chilliwack Valley, are succeeded on the east, across a fault, by the Skagit metamorphic belt (Misch, 1968). This belt extends into British Columbia (Figures 12-1 and 12-2b) as the Custer Gneiss (McTaggart and Thompson, 1967) and consists mainly of migmatitic gneiss with small areas of schist. Similar gneisses found at intervals to the northwest within the Coast Crystalline Belt (Crickmay, 1930; Roddick, *et al.*, 1966; Roddick and Hutchison, 1969; Wheeler, personal communication) are perhaps part of the same belt. The question of the age of the metamorphism of the Cascade Metamorphic Suite is not settled and is considered below.





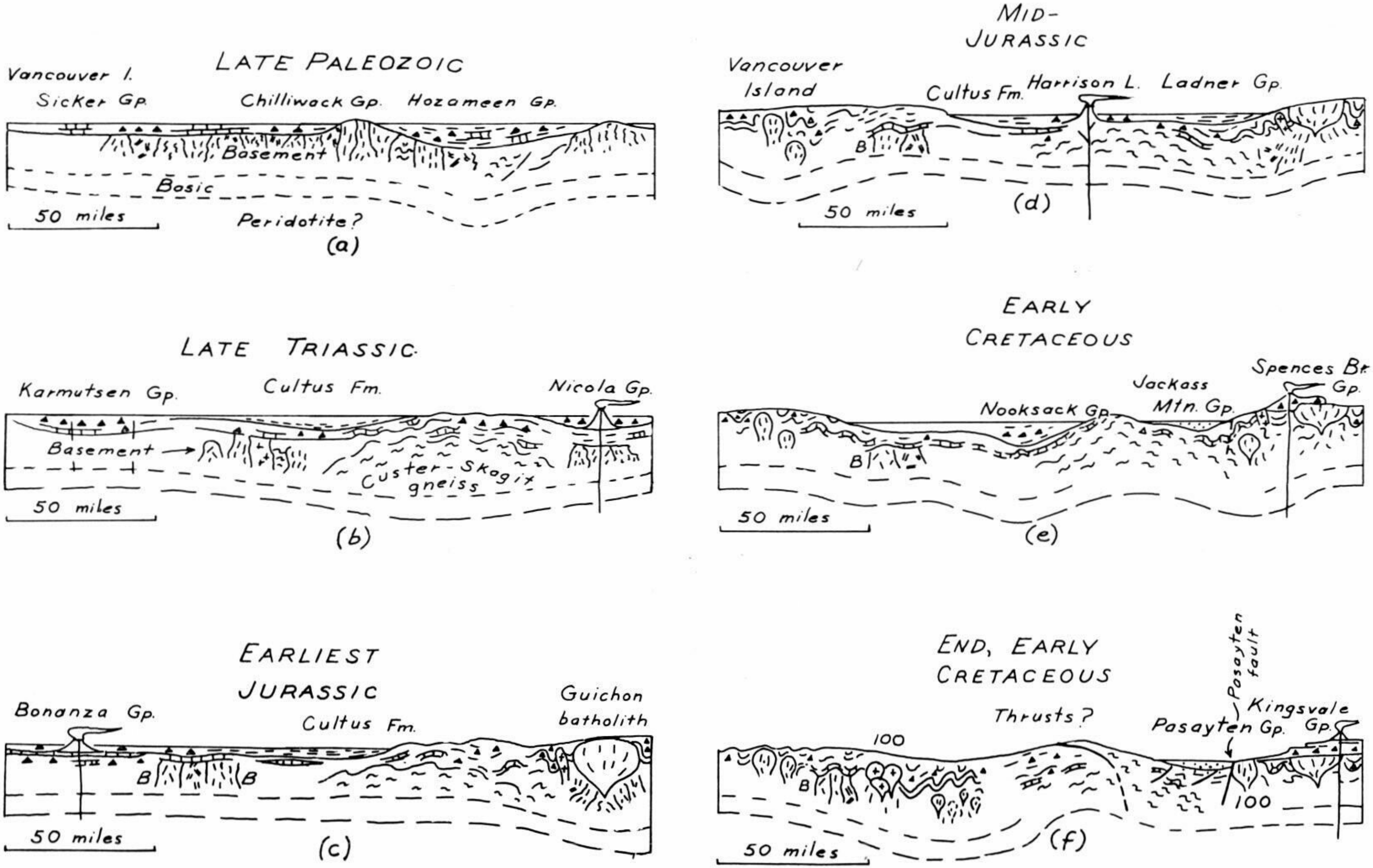
Figue 12-1: Generalized geology of the Northern Cascades Region.

Mesozoic Rocks

Upper Triassic (Figure 12-2b) andesite basalts and sedimentary rocks of the Nicola Group (Schau, this volume) lie along and near the northeast side of the Cascade Mountains. These are intruded by various batholiths: in the north, the Guichon batholith (latest Triassic), and to the south, in succession, the Mount Lytton batholith (Jurassic?) and the Eagle granodiorite composite (?) body (Jurassic and Cretaceous). On the west, slate and volcanic greywacke of the Cultus Formation of Late Triassic and Jurassic age (Monger, 1966; Danner, 1966) occur in the Chilliwack Valley. A short distance south (Misch, 1966), the Wells Creek Volcanics (Jurassic?) are overlain by the Upper Jurassic and Lower Cretaceous Nooksack Group mostly of volcanic greywacke. Cultus and Nooksack correlatives are found at Harrison Lake (Crickmay, 1930). Along the eastern flank of the northern Cascade Mountains (Figures 12-2d, e) the Jurassic to Lower Cretaceous clastics, volcanic clastics, and minor volcanics of the Ladner, Dewdney Creek, Jackass Mountain, and Pasayten Groups (Coates, this volume) record a complex history.

Apparently no sedimentary rocks were deposited in the interval between the Albian Stage of the late Early Cretaceous and the late Late Cretaceous. This period was one of erosion, folding, thrust faulting, and intrusion when many of the plutons of the Coast Crystalline Belt and northern Cascade region were emplaced (Figure 12-1).

In late Cretaceous time marine strata and associated coal measures, both of the Nanaimo Group, accumulated in a trough west of the Cascade region. This deposition overlapped in time with that of the non-marine clastics of the Upper Cretaceous and Paleocene Chuckanut Formation (Figure 12-2h).


LATE PALEOZOIC
Vancouver I.
Sicker Gp.
Chilliwack Gp.
Hozameen Gp.
Basement
Basic
Peridotite?
50 miles
(a)
MID-JURASSIC
Vancouver Island
Cultus Fm.
Harrison L.
Ladner Gp.
B
50 miles
(d)
LATE TRIASSIC
Karmutsen Gp.
Cultus Fm.
Nicola Gp.
Basement
Custer-Skagit gneiss
50 miles
(b)
EARLY CRETACEOUS
Spences Br. Gp.
Jackass Mtn. Gp.
Nooksack Gp.
B
50 miles
(e)
EARLIEST JURASSIC
Bonanza Gp.
Cultus Fm.
Guichon batholith
B
B
50 miles
(c)
END, EARLY CRETACEOUS
Pasayten fault
Thrusts?
Kingsvale Gp.
Pasayten Gp.
100
B
100
50 miles
(f)

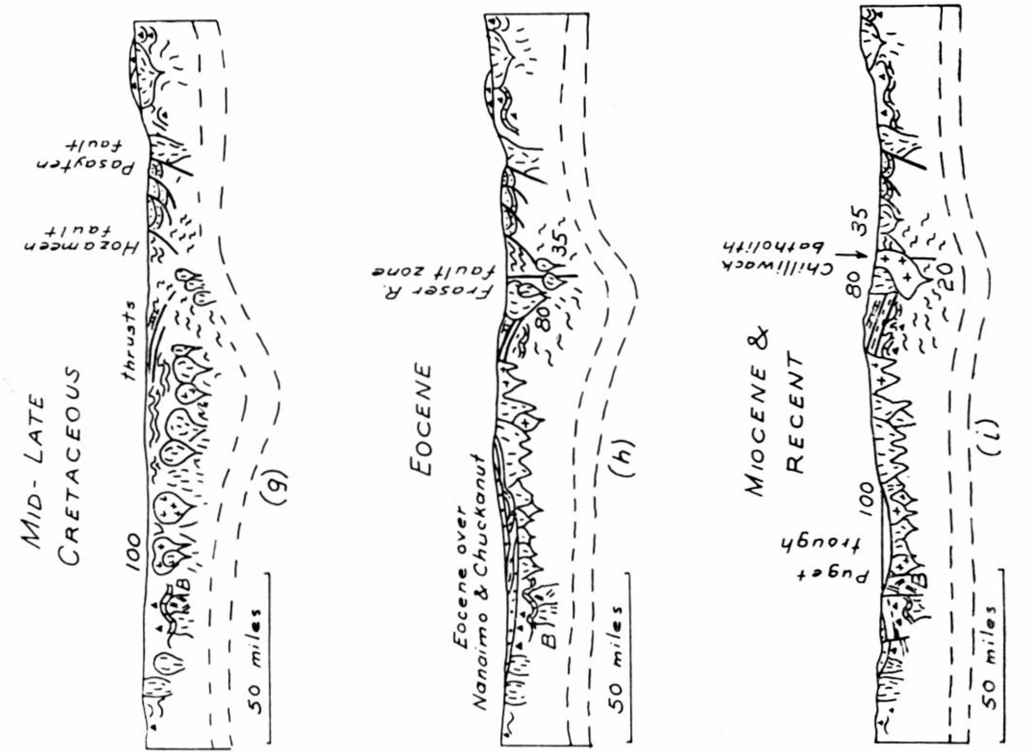


Figure 12-2a to 2i: Diagrammatic restored cross-sections — Strait of Juan de Fuca to Okanagan Valley. B is Basement Complex; triangles denote volcanic rocks; numbers refer to K-Ar ages of plutons.

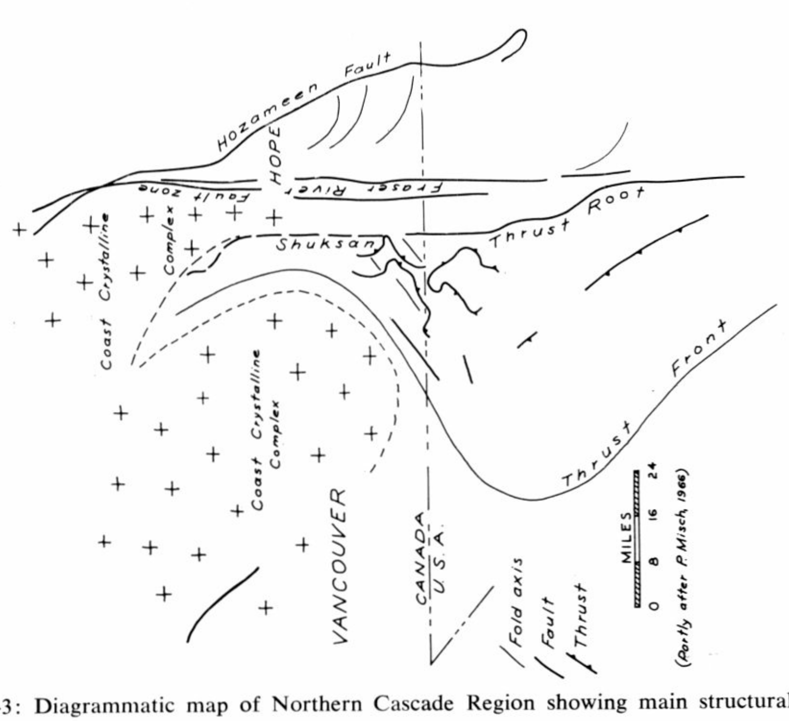


Figure 12-3: Diagrammatic map of Northern Cascade Region showing main structural features.

Cenozoic Rocks

Uncomformably above the Chuckanut Formation lies the Eocene Huntingdon Formation (Miller and Misch, 1963). Other non-marine beds are preserved in small fault blocks along the Fraser River fault zone. Basalts of the Eocene, Princeton and Kamloops Groups border the Cascade Mountains on the northeast and the Eocene Metchosin lavas occur to the west of southern Vancouver Island and the Olympic Peninsula.

In Oligocene and Miocene time, intrusion of granitic bodies, including the bulk of the Chilliwack (T. A. Richards) and Snoqualmie batholiths of the Cascade Mountains was followed closely by great out-pourings of Plateau basalt north of the Cascade region in the Interior Plateau and in central Washington State.

Pleistocene and Recent volcanoes are aligned along a north-trending belt along the Cascade crest in Oregon and southern Washington but are less regularly distributed in northern Washington and British Columbia.

STRUCTURAL RELATIONS OF NORTHERN CASCADE MOUNTAINS TO COAST CRYSTALLINE BELT

Before attempting to sketch the history of the structural development of the northern Cascade Mountains, it is necessary to consider the relationship of this tract to the southern part of the Coast Crystalline Belt. Although the northern Cascade Mountains have been considered to be orogenically separate and distinct from the Coast Crystalline Belt (Crickmay, 1930; Misch, 1966, p. 130, also Fig. 7-17) the present author believes that there are good reasons for treating them as parts of the same orogenic belt. Geologists have considered them to be distinct mountain belts for two reasons. Firstly, the Coast Crystalline Belt is underlain predominantly by "granitic" batholiths with minor, more or less metamorphosed sedimentary and volcanic "roof pendants", whereas the Cascade area is predominantly of supracrustal sedimentary and volcanic rocks cut here and there by plutons. Secondly, a northeast structural trend along the northern part of the western Cascade Segment, discussed at length in a later section, crosses the general trend of the Coast Crystalline Belt and, considered by itself, at first suggests that the two units are structurally distinct.

The first difference is easily explained as due to uplift and deep erosion in the north, with stripping of the stratified cover and exposure of of abundant plutons. The second feature, the northeast trend, is different not only from that of the main trend of the Coast Crystalline Complex but also from that of the main part of the northern Cascade Segment and therefore is not a criterion for distinguishing one from the other. Furthermore, it will be argued below that this incongruous trend is probably a secondary one, superimposed on an original northwest trend.

The writer believes that the southern Coast Crystalline Belt and the northern Cascade region form a single belt. The area north of Vancouver has been relatively uplifted and deep erosion has exposed the Coast Crystalline Complex. Near Vancouver, it plunges beneath its cover of supracrustal folded beds and thrust sheets which are the dominant geological features of the northern Cascade Mountains of southwestern British Columbia and northern Washington State. The central axis of crystalline gneisses and migmatites of the southern Cascade region (Custer-Skagit gneiss) strikes into and is cut by the batholithic rocks near Fraser River, but reappears to the northwest in the heart of the Coast Crystalline Belt. Similarly, the major, Shuksan thrust fault on the west and the Hozameen fault on the east strike northwestward deep into the Coast Crystalline Belt (Figure 12-3). The nature and extent of the Coast Crystalline Complex under its cover is unknown but the author suggests that batholiths become less numerous to the southeast.

Potassium-argon ages from the Coast Crystalline Belt (Roddick, 1966) show a range very much like the range described for the northern Cascade region (Figure 12-1)—mid-Cretaceous ages are common and early Cenozoic ages are not rare. Late Cenozoic plutons (like those of the Chilliwack Batholithic Complex) are not known in the southern part of the Coast Crystalline Belt. These belong to a well-defined north-trending belt of intrusions and related volcanic rocks lying along the Cascades of Oregon and central Washington (Waters, 1955, p. 713).

The Coast Crystalline Belt and the northern Cascade Mountains of the region shown in Figure 12-1 are coaxial and contemporaneous. What of the transition zone betwen these two segments? Many roof pendants within the Coast Crystalline Complex at its southern margin and also many of the strata flanking the Complex strike nearly east. Faults and folds near Vedder Mountain, affecting rocks as young as Paleocene, strike northeasterly. These and other features, transverse to northwest trends, apparently mark the axis of relative uplift to the northwest, perhaps as the result of isostatic uplift of the predominantly "granitic" terrane. The possibility that northeast-trending recumbent folds (Figures 12-3, 12-5) are due to back-sliding off a rising Coast Crystalline Complex will be explored later in this paper.

The evidence suggests that the northern Cascade region and the Coast Crystalline Belt offer two views, at different levels, of the same orogen —the Coast-Northern Cascades orogen. To separate the two tracts is to obscure the orogenic history of the western Cordillera.

STRUCTURAL DEVELOPMENT OF THE NORTHERN CASCADES
(Table I; Figures 12a-i)

Basement Complex

Rocks of the Basement Complex are apparently entirely of igneous origin. Original structural trends have been obliterated by later tectonism and little can be said of this pre-Devonian intrusive episode except that it was widespread and probably represented a notable orogeny.

Western Cordilleran Eugeosyncline

In mid-Paleozoic time a eugeosyncline (Danner, 1968) was established along the present site of the western Cordillera (Figure 12-2a). Its floor was, locally at least, composed of plutonic rocks of the Basement Complex. It persisted through Devonian into Mesozoic times. In the latest Triassic (Figure 12-2b), non-volcanic clastic sedimentation was flanked by volcanic belts in the Insular Trough (Karmutsen Group) and the Nechako Trough (Nicola Group). In the Jurassic (Figure 12-2c, d), mainly clastic sedimentation was interrupted by local emergence and by local volcanism. In the Early Cretaceous (Figure 12-2e) clastic sedimentation was perhaps in two troughs, east and west. Detritus was being supplied from early phases of the Coast Crystalline Belt (north of the section), and from intrusions and metamorphics of the Eagle Granodiorite Complex to the east. In mid-Cretaceous time (Figures 12-2f, g) this pile of Mesozoic rocks, with its underlying Paleozoic strata and metamorphics, participated in a mid-Cretaceous orogeny involving great overthusting both to west and east and also emplacement of the main part of the Coast Crystalline Belt. Complicating this already involved history is an orogeny of uncertain age, during which there was widespread regional metamorphism with the development of the Cascade metamorphic suite.

Cascade Metamorphic Suite (Cascade Metamorphism)

The rocks of the Cascade metamorphic suite are represented in southwestern British Columbia by the Custer Gneiss which forms the crystalline core of the northern Cascade region. In northern Washington State, the correlative Skagit gneiss is succeeded to the west by the Shuksan metamorphics. Metamorphic gneisses extend northwest into the Coast Crystalline Belt though in many places they have been obliterated by younger intrusions. Uncertainty regarding the age of this belt of metamorphics constitutes a serious weakness in this account of the geological history of the Cascade region.

The age of the metamorphism is said by Misch (1966, p. 103, 113) to be "pre-Jurassic and probably pre-Mesozoic" and possibly latest Permian. Near Hope, the Custer Gneiss has been formed from late Paleozoic (?) Hozameen beds and is overlain unconformably by Eocene conglomerate. Although Monger (1966) finds on the west side of the Custer Gneiss belt evidence of widespread erosion between Early Permian and Late Triassic time, he finds no angular discordance marking a strong orogeny during this interval or, indeed, within the whole sequence from Pennsylvanian to Upper Jurassic. It is conceivable, however, that the effects of an orogeny could have diminished rapidly with distance from the axis of metamorphism and produced negligible structural and metamorphic effects in rocks a few miles away. It is also possible that the metamorphism is pre-Pennsylvanian and corresponds to the mid-Paleozoic orogeny mentioned by Wheeler (1966, p. 34). In Figure 12-2b the Custer-Skagit gneiss is shown to be in existence in Late Triassic time.

Gneisses of the Cascade metamorphic suite seem to form one of the main tectonic units common to and connecting the northern Cascades and the Coast Crystalline Belt. If it turns out that the metamorphism is, in fact, Paleozoic in age, the time interval for the development of the Coast-Northern Cascade orogen could well be a few hundreds of millions of years. Such a long time span is quite in harmony with the long lives of other orogens (Sutton, 1965).

Could the Custer-Skagit migmatites of the Cascade Metamorphic Suite be Early to mid-Cretaceous in age and be closely related to the mid-Cretaceous orogeny discussed below? The writer has seen no fragments of Custer Gneiss in the Jurassic and Cretaceous strata to the east described by Coates (this volume). In an earlier paper (McTaggart and Thompson, 1967, p. 1214) it was argued that gneisses in the Fraser River canyon north of Yale, which seem to be related to Upper Cretaceous Spuzzum tonalite, were distinct from the Custer Gneiss. This view was held mainly because of the supposed pre-Jurassic age of the Custer Gneiss. The possibility exists that the Custer migmatitic gneiss is not much older than the Spuzzum tonalite and other plutonic rocks of the Coast Crystalline Belt which comprise a metamorphic-plutonic axial belt contemporaneous with the main (mid-Cretaceous) orogeny.

These migmatitic gneisses and schists resemble closely the rocks of the Shuswap Terrane of the Okanagan Valley and it is possible that the two terranes are correlative. White (1966, Fig. 10-1) shows a connection between the metamorphic rocks in the Cascade region and those in the Shuswap terrane by way of Lake Chelan in northern Washington State.

Structures associated with the Cascade metamorphism trend northwest (Misch, 1966, p. 144; McTaggart and Thompson, 1967, p. 1207). Folds overturned to the northeast and to the southwest are reported. The original folds of the terrane have been deformed, tightened, and obliterated by later tectonism. Gneisses have been especially heavily crushed and broken between and along the faults of the Fraser River fault zone. The contact zone between the gneisses and the Paleozoic rocks, from which they were made, was a zone of structural adjustment—the locus for faults, shear zones and late plutons.

Mid-Cretaceous Orogeny

The main structural features of the Coast-Northern Cascades orogen (with the possible exception of the axial zone of the Custer-Skagit gneiss) were developed during a mid-Cretaceous orogeny (Misch, 1966) when regional thrusting and widspread emplacement of granitic plutons brought to a close the long eugeosynclinal history of this western belt.

The mid-Cretaceous orogeny was featured by thrusting to the west and east from a central zone. The westerly directed thrust sheets were displaced considerable distances along the nearly horizontal soles and were associated with recumbent folds, whereas the easterly directed thrusts are steep and are involved with open folds.

The age of the westward thrusting lies between that of the Nooksack Group (early Early Cretaceous) and that of the Chuckanut Group (late Late Cretaceous and Paleocene). The first forms the floor of certain of the thrust sheets and the second is not involved in and is younger than the westward thrusting (Figure 12-4). On the east, the Hozameen fault and its related thrusts are probably early Late Cretaceous in age because latest Lower Cretaceous beds are folded and the Hozameen fault zone is partly, at least, older than 84 ± 6 million years (late Late Cretaceous), the age of a pluton emplaced in the fault zone (Coates, this volume).

The great thrust faults of the western Cascade region were first mapped by Crickmay (1930) and later greatly extended and clarified by Misch (1966) and in the Chilliwack valley, by Monger (1966). The main thrust (Figures 12-1, 12-3), along which the Shuksan metamorphics are carried westward across Paleozoic and Mesozoic rocks, shows a displacement of up to 30 miles (Misch, 1966, p. 122). Tectonic lenses of peridotite and basement are found in many places along the thrust. The Church Mountain

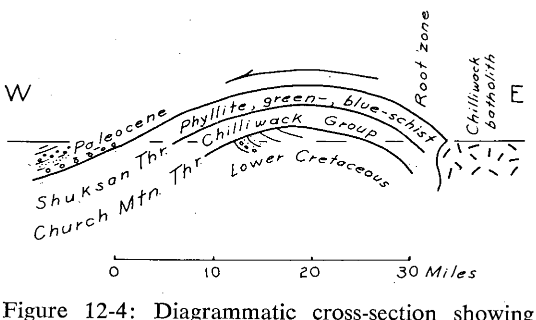


Figure 12-4: Diagrammatic cross-section showing thrusts in Northern Washington.

thrust plate, itself overlain by the Shuksan thrust sheet (Figure 12-4), contains rocks of the Chilliwack Group and Mesozoic formations thrust over beds of the Nooksack Group. Monger's detailed work in Chilliwack Valley (Figure 12-1; Figure 12-5, section A-B) shows that Pennsylvanian to mid-Mesozoic rocks are involved in thrusts and recumbent folds that trend northeast.

A quite different interpretation of the thrusting is offered by Hamilton and Myers (1966, p. 515). They suggest, on the basis of similarities of blueschist metamorphism between the Shuksan Belt and the Franciscan Formation of California, that the Shuksan metamorphic suite represents offshore sediments deposited on the ocean floor, over which units from the east, the continental side, have been thrust. By this interpretation, the western Shuksan rocks are autochthonous rather than allochthonous.

On the eastern flank of the Cascade Mountains, the Ross Lake fault zone, the southern extension of the Hozameen fault (**Figures 12-1,** 12-3), appears to be an easterly directed thrust along which Hozameen strata are thrust over Lower Cretaceous beds. To the north, the Hozameen fault seems to be nearly vertical. East of this fault, west-dipping thrusts cut Jurassic and Cretaceous beds (Coates, this volume).

Problem of the convex thrust front

Misch (1966, figure 7-17) suggests that the movement on the Shuksan and Church Mountain thrusts was westward in the latitude of Bellingham, southwestward, southeast of Bellingham and, northwestward, north of the International Boundary. Thus the thrust fault is strongly convex towards the west (Figure 12-3). Lowes (1968) suggests that the Shuksan thrust root zone extends northward in a northerly direction and, after being interrupted by various younger granitic plutons, gradually swings northwestward east of Harrison Lake.

The strongly westward-convex thrust front (Figure 12-3) is a puzzling feature. At, and north of the International Boundary, northeasterly trending recumbent folds associated with thrust faults strike at right angles to the northwesterly trending folds in the Hozameen Group a few miles to the east. Northward from near the Boundary the fold trends gradually swing from northeasterly through northerly to northwesterly thus describing an arc some 50 miles long (Crickmay, 1930, p. 488). This arc, which is the northern half of the westward convex thrust front, is delineated by a combination of fold axes (Crickmay refers to "trends of structures"), by the traces of thrust faults, and by the strikes of the formations. The arc, in a general way, parallels the bulge of the batholiths of the Coast Crystalline Belt lying west of Harrison Lake and north of Fraser River. It is hard to believe that the arc and the bulge of the batholiths are not related even though parts of the arc are as

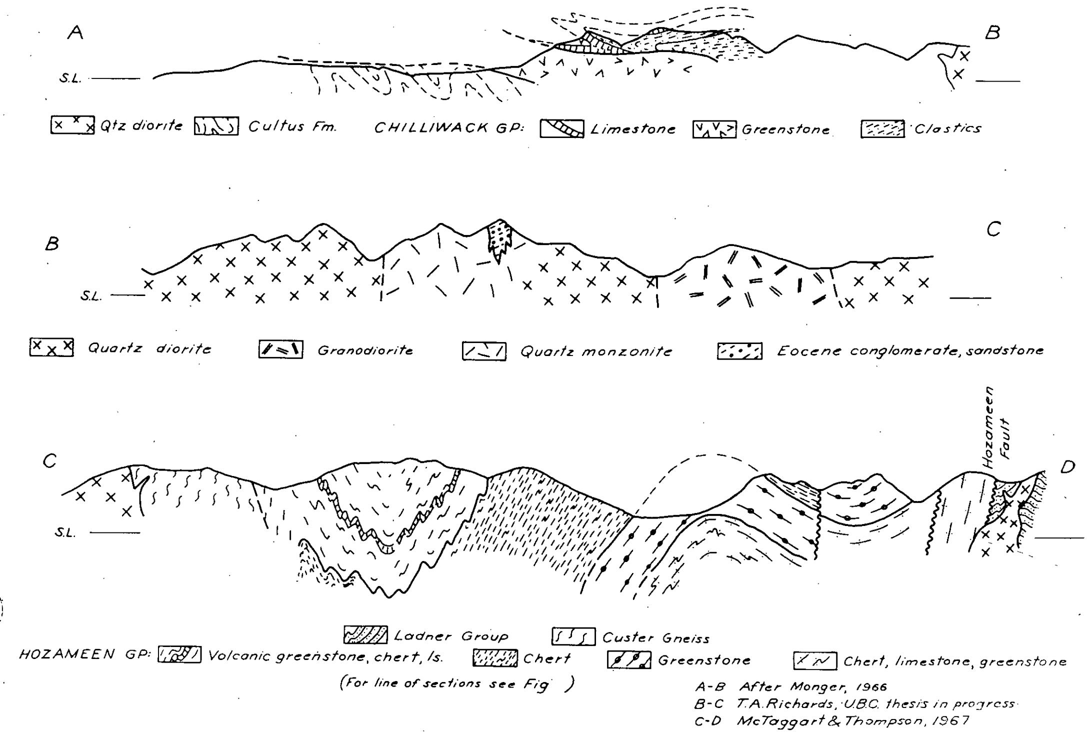


Figure 12-5: Cross-sections in the Northern Cascade Mountains. For lines of sections see Figure 12-1.

much as 15 miles from the exposed batholithic margin. The arc shows a striking resemblance to the Kootenay Arc. In the paragraphs that follow, the writer examines several hypotheses for the origin of the arc.

Misch (1966), p. 128) assumes that the direction of thrusting was normal to the axes of the recumbent folds, and suggests that the thrust front was curved as the thrusting developed, the central part advancing farther than the northern and southern parts. That northeasterly trending fold axes extend almost up to the projected line of the Shuksan root zone in Chilliwack Valley seems to the writer to be incompatible with thrusting on a curved front. It seems unlikely that the thrust would emerge from the root zone and immediately travel diagonally to it at an angle of about 45 degrees. The writer prefers the hypothesis that the northeasterly folds are younger than the thrusting.

An obvious suggestion is that the arc was formed as the batholithic complex pushed back its walls during emplacement but parts of the arc lie 10 to 15 miles from it, and it is not easy to imagine magmatic pushing at such a distance. Signs of distension around the plutonic margins (Roddick, 1965, maps 1151A, 1152A, 1153A) are not obvious.

Crickmay (1930, p. 486) considered that the thrust belt had been folded against the rigid mass of batholithic rocks at and south of Harrison Lake, thus producing the arc in question. His hypothesis is supported by recent studies. At the east side of the Fraser River fault zone (Figure 12-3), southeast of Hope, and also at its continuation in northern Washington State, rocks of the Cascade Metamorphic Suite change in strike abruptly from northwest to north. Fold axes in the Hozameen Group swing from westerly to northwesterly trends as the fault zone is approached. The Coquihalla Serpentine Belt, lying along Hozameen fault, shows similar deflection. These deflections are compatible with the idea of a wedge, in plan, moving northward, west of the Fraser River fault zone. During such movement, earlier structures, including the thrust sheets along the western side of the wedge, would become realigned and conform to the outline of the rigid batholithic mass to the west. Difficulties are seen in the lack of clear signs of drag along the east side of the wedge, at the Fraser River fault zone, and the great distance of parts of the arc from the batholithic buttress.

The hypothesis preferred by the writer is that mid-Cretaceous thrust faulting was followed in early Cenozoic time by strong uplift in the region north of Fraser River underlain by batholithic rock. It is suggested that with strong differential uplift, partly accommodated by late Paleocene faulting along northeast trends, the previously formed thrust sheets slid to the southeast off the rising batholithic areas northwest of Fraser River, producing the extremely complex northeasterly trending folds of the Chilliwack

Valley. Paleocene beds of arkose (Chuckanut Formation) were folded partly along northeasterly axes and serpentinized ultramafics and lenses of basement material were reactivated and emplaced along northeasterly trending faults. On the eastern side of the uplifted area, adjustment was made partly along the Shuksan fault zone and partly along the Fraser River fault zone where Eocene beds are strongly deformed. The objection that the thrusts themselves seem not to be strongly folded is not considered to be a serious one. Back-sliding would be expected to occur on the already existing planar thrust surfaces, strata piling up in complex folds above the soles.

It is tentatively concluded that the northeast-trending folds are secondary and that they were probably formed by gravity sliding in early Cenozoic time as the area north and west of Fraser River was elevated.

GRANITIC PLUTONS

The emplacement of the granitic plutons of the Cascade Mountains and adjacent area (Figures 12-1, 12-2b-i) spans an interval of at least 180 million years and involves at least four or five major episodes of batholithic emplacement.

Among the oldest intrusions in areas adjacent to the Cascade region are the Guichon batholith (Figure 12-1) of latest Triassic or earliest Jurassic age (Duffell and McTaggart, 1952; White, *et al.,* 1967), the Jurassic (?) Mount Lytton batholith (Duffell and McTaggart, 1952), and its southern extension, dated as 143 m.y. (Late Jurassic (?) Findlay, 1963). On the west coast of Vancouver Island, a belt of syntectonic intrusions has yielded several dates of about 165 m.y. (Middle Jurassic (?)), (Sutherland-Brown, 1966; Muller, *in* Wanless, *et al.,* 1967).

The batholithic complex between Vancouver and Harrison Lake has been dated only on the west. There, several dates, averaging about 95 m.y. (end of the Early Cretaceous) have been determined north of Vancouver (Baadsgaard, *et al.,* 1961; Mathews, 1968). A single K/Ar determination may indicate the existence of older phases north of this belt and younger phases are undoubtedly present also (Mathews, 1968; Roddick, 1965, p. 178). The plutonic rocks immediately west of Harrison Lake are, in part at least, younger than early Lower Cretaceous beds that themselves contain granitic detritus (Roddick, 1965, pp. 41-42). The Spuzzum Tonalite lying west of Fraser River from Hope to Spuzzum in the Fraser canyon has recently been dated (McTaggart and Thompson, 1967; T. A. Richards) as about 80 m.y. (mid-Late Cretaceous (?)). Emplacement of tonalite was accompanied by regional metamorphism and folding along northwest axes near Spuzzum. There, a northwesterly trending pendant (?), consisting of sillimanite gneiss and other high grade metamorphics, occurs near large tracts of staurolite and kyanite schist (Read, 1960). To summarize, granitic plutons between Vancouver and Hope (Figure 12-1), forming the southern part of the Coast Crystalline Belt, appear to be mainly of mid- or Late Cretaceous age and thus seem to represent an axial plutonic zone of the mid-Cretaceous orogen (already described) exposed by deep erosion.

Relatively smaller granitic plutons of mid-Tertiary age are scattered from north of Yale, in Fraser Canyon, southwards and southeastwards into northern Washington State (Figure 12-1). Radiometric age determinations (Baadsgaard, *et al.,* 1961; Misch, 1966; Wanless, *et al.,* 1967; T. A. Richards) show these to be late Eocene or early Oligocene. These may be considered as post-tectonic high-level plutons with respect to the mid-Cretaceous orogeny or are perhaps related to the Miocene intrusions next to be mentioned.

The youngest intrusions, ranging from gabbro to granite, forming a large part of the Chilliwack batholithic complex, are Miocene in age. These belong to a well-defined north-trending belt of intrusions with related volcanic rocks lying along the Cascade Mountains of Oregon and central Washington (Waters, 1955). They represent elements of the north-trending Cenozoic Cascade Mountains overprinted on the northwest-trending structures of the older Coast-Northern Cascades belt.

POST-MID-CRETACEOUS LAYERED ROCKS

In latest Cretaceous time, restricted sedimentary basins accepted the clastics of the Nanaimo Group. This basin complex, with an extension into the Garibaldi region (Mathews, 1958) was partly contemporaneous with the non-marine flood-plain accumulation of late Late Cretaceous and Paleocene Chuckanut beds. These were strongly folded and faulted, along diverse directions, including northeasterly lines, before Eocene beds were deposited on them (Miller and Misch, 1963).

The youngest rocks of the area are Pleistocene and Recent volcanics. Volcanoes are aligned along a northerly trend from California through Oregon to Washington (Waters, 1955). South of the International Boundary the alignment becomes indistinct whereas north of it the volcanoes, are offset westward to a different line extending northwards from Garibaldi Park (Holland, 1964, Fig. 1).

FRASER RIVER FAULT ZONE

The Fraser River fault zone (Duffell and McTaggart, 1952; Read, 1960; McTaggart and Thompson, 1967) has been traced from the International Boundary northwards to the vicinity of Big Bar (Trettin, 1961), a distance of about 150 miles. The zone, over much of its length, is made up of two main sub-parallel faults joined by many cross-faults and by branches extending from the northwest, as, for example, just north of Lillooet. For long stretches, this pair of border faults seems to form a graben, with prisms of Cretaceous or Eocene rocks preserved along it. In other places, each of the two principal faults appears to show dip-slip movement with rocks down-faulted on the east side. In many places, serpentized peridiotite has been emplaced along the faults. The Straight Creek fault (Misch, 1966), extending 80 miles into northern Washington State, is probably the continuation of the easterly fault of the Fraser River fault zone.

Movement on the zone may have started in the Mesozoic. Right-lateral movement is suggested by deflections (drag?) in structures along the eastern side of the zone but such movement did not persist after the emplacement of the Spuzzum tonalite plutons (mid-Late Cretaceous) in the Fraser Canyon. Eocene conglomerate accumulated in fault troughs at Hope and also north of Lytton. Post-Eocene deformation, perhaps related to renewed movement at the fault zone, is shown by vertical dips of the Eocene beds. There seems to have been little or post-Miocene movement on the zone south of Hope, where Miocene plutons intrude the zone but are not faulted (T. A. Richards).

The Fraser River fault zone is part of the Coast-Northern Cascade orogen but also seems to have affinities with the north-trending Cascade belt of Oregon and Washington. In the north the Fraser River fault zone curves very gradually along the east side of the Coast Crystalline Complex. It is considered a zone along which, in Late Cretaceous and early Cenozoic time, structural adjustment has been made between massive plutons to the west and a belt consisting of bedded and volcanic rocks and relatively small plutons to the east. The zone which was apparently active intermittently for 50 million years, reaches deep into the crust and quite possibly ultramafic masses along it have been tectonically derived from the mantle. To the south, the Miocene Chilliwack plutons seem to lie astride the zone, and it is tempting to speculate that other young Cenozoic plutons like the Snoqualmie batholith and young volcanoes of the Cascade Mountains are in some way related to this north-trending fault zone.

SUMMARY

The Northern Cascade region and the southern part of the Coast Crystalline Belt offer two views, at different levels, of the same orogen. The Northern Cascade region, composed mainly of folded and faulted sedimentary, volcanic, and metamorphic rocks, display the upper levels of the orogen, only slightly eroded. The main features here are westerly and easterly spreading thrusts that root near a central crystalline and metamorphic axial zone. The Coast Crystalline Belt, to the northwest, made up largely of granitic plutons with numerous roof pendants, reveals the deeper levels of the tectonic belt. The overlying thrust plates have been stripped off and only the steep root zones of the thrusts and the central crystalline axis can be followed northwest into the plutonic zones. Structures, in general, strike northwest. Anomalous northeast-striking recumbent folds in the International Boundary region between the northern Cascade region and the Coast Crystalline Belt were probably produced by late orogenic gravity controlled sliding activited by the rising complex to the northwest.

The history of the belt includes: formation of a pre-Devonian Basement Complex, development of a eugeosyncline that lasted from Devonian to late Mesozoic times, generation of an axial zone of gneisses, a tectonic climax in mid-Cretaceous time, with thrusting to east and west, folding and widespread emplacement of granitic plutons, and, finally, uplift of the northwest part of the belt (Coast Crystalline Belt) in early Tertiary, with consequent gravity sliding to the southeast forming northeast folds. Overlapping these events are the emplacement of granitic plutons in the general region from earliest Jurassic to Miocene, and intermittent activity along the Fraser River fault zone from late Mesozoic (?) through early Tertiary time.

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