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THE PLUTONIC ROCKS OF VANCOUVER ISLAND

DAVID J.T. CARSON

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THE PLUTONIC ROCKS OF VANCOUVER ISLAND, BRITISH COLUMBIA: THEIR PETROGRAPHY, CHEMISTRY, AGE AND EMPLACEMENT

(Report, 17 figures and 15 plates)

David J. T. Carson

DEPARTMENT OF ENERGY, MINES AND RESOURCES

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ABSTRACT

Most plutons of Vancouver Island were emplaced between mid-Early and mid-Late Jurassic (approximately 150 to 180 million years ago). The majority of these were intruded soon after an Early(?) to Middle Jurassic interval of broad regional folding. The Jurassic plutons are granodiorite and quartz diorite, with minor diorite, gabbro, and quartz monzonite, and rare granite. Most are upper mesozonal and are medium grained with granitic texture, but some epizonal porphyries and catazonal(?) gneisses are also present.

Early to Middle Tertiary epizonal plutons (approximately 35 to 60 million years) are much less abundant than Jurassic plutons. They were emplaced during part of an extended interval of block faulting and are quartz diorite, dacite porphyry, and gabbro, with minor granodiorite and quartz monzonite. Limited evidence suggests that some dioritic gneisses and quartz monzonite on the west coast may have crystallized during the Late Cretaceous.

The plutonic rocks of Vancouver Island may be divided into three northwest-trending zones of differing compositions and textures. Quartz diorites and granodiorites low in K-feldspar predominate in the structurally-elevated axial area. They are flanked along the east and northeast by a zone containing granodioritic plutons, most of which are relatively homogeneous, and along the west and southwest by another zone containing a wider variety of plutonic rocks that range in composition from granite (very minor) to peridotite (rare), but have an average granodioritic composition similar to that of the eastern zone. Plutonic gneisses, and complex plutons with extensive border migmatite zones, are common only in the western belt. This over all northwest-trending textural-compositional zoning is somewhat similar to zoning of the plutonic rocks of the Coast Intrusions of mainland British Columbia.

Jurassic plutons occur throughout Vancouver Island but the known Tertiary plutons are restricted to the western belt and to two zones that cross the northwesterly structural trend of the island.

The chemistry of the plutons of known Jurassic age differs somewhat from that of the Tertiary plutons although there is some overlap and they appear to have been derived from similar parental material. Jurassic differentiation trends show similarities to those of the southern California batholith. The known Jurassic plutons contain more Ca and Fe, and possibly K, and less Na than the Tertiary plutons. These differences may have been the results of greater assimilation of host rocks combined with more advanced stages of differentiation by the deeper-seated Jurassic plutons.

During emplacement, many Jurassic plutons advanced passively upward in competent volcanic rocks but spread laterally and forcibly in less competent sedimentary rocks. The net effects were the strong deformation of host rocks, the accumulation of magma, and the deposition of abundant Cu-Fe skarn deposits (Zeballos Iron, Coast Copper, etc.) at the stratigraphic interval that included the uppermost Karmutsen Formation, the Quatsino limestone and the lower Bonanza Formation. Many of the intrusive bodies, including some of batholithic proportions, assumed roughly horizontal and sheet-like forms. High-level offshoots of these bodies intruded upward into the Bonanza Formation and many reached the surface, supplying volcanic material to the upper Bonanza Formation. Some of these offshoots have associated porphyry copper deposits (Island Copper, etc.).

Most Tertiary stocks and dyke-like bodies were forcibly emplaced in subvolcanic environments. Intrusive and explosive breccias are common. Some of the Tertiary plutons are associated with porphyry copper deposits (Catface, etc.) and copper or gold veins (Mount Washington, Privateer, etc.). The Mount Washington intrusive complex consists of a centrally located quartz diorite stock with a peripheral diatreme and other irregularly shaped explosion breccias, and radiating sills and laccolithic tongues of dacite porphyry intruding gently-dipping Late Cretaceous sediments of the Nanaimo Group that surround the stock. Extensive dacite porphyry laccoliths and sills were emplaced at several other localities by lateral extension of stocks and dykes that penetrated upward into the lower Nanaimo Group. Large sill-like(?) gabbro plutons cut the Eocene Metchosin volcanics in southern Vancouver Island, whereas smaller trondhjemite plutons of the same area are stocks.

RÉSUMÉ

La majeure partie des plutons de l'île Vancouver ont été mis en place entre le milieu du Jurassique inférieur et le milieu du Jurassique supérieur (il y a environ 150 à 180 millions d'années). La plupart de ces plutons ont fait intrusion peu de temps après une période de plissement régional à grande échelle entre le début(?) et le milieu du Jurassique. Ces masses intrusives du Jurassique sont formées de granodiorite et de diorite quartzeuse, d'un peu de diorite, de gabbro et de monzonite quartzeuse, le granite y est rare. La plupart sont mésozonales supérieures, à grain moyen et à texture granitique, mais il se trouve aussi quelques porphyres épizonaux et quelques gneiss catazonaux(?).

Les masses intrusives épizonales datant du début jusqu' au milieu du Tertiaire (il y a environ 35 à 60 millions d'années) sont beaucoup moins abondantes que celles du Jurassique. Elles ont été mises en place pendant une partie d'une longue période de faillage en blocs et sont composées de diorite quartzeuse, de porphyre dacitique et de gabbro, d'un peu de granodiorite et de monzonite quartzeuse. Il existe des indices restreints qui font supposer que des gneiss dioritiques et de la monzonite quartzeuse sur la côte ouest se sont cristallisés pendant le Crétacé supérieur.

On peut diviser les roches plutoniques de l'île Vancouver en trois zones orientées vers le nord-ouest, dont la composition et la texture diffèrent. Des diorites quartzeuses et des granodiorites, dont la teneur en feldspath potassique est faible, prédominent dans la zone axiale structuralement soulevée. A l'est et au nord-est, ces roches sont flanquées d'une zone contenant des masses intrusives granodioritiques, pour la plupart relativement homogènes; à l'ouest et au sud-ouest, elles sont flanquées d'une autre zone contenant une plus grande variété de roches plutoniques dont la composition va du granite (très petite quantité) jusqu' à la péridotite (rare), mais elle est surtout granodioritique comme celle de la zone orientale. Les gneiss plutoniques et les plutons complexes accompagnés de zones de migmatite à large bordure ne se trouvent communément que dans la zone occidentale. Toute cette structure zonée ressemble, par son orientation vers le nord-ouest, sa texture et sa composition, à la structure zonée des roches plutoniques qu'on retrouve dans les intrusions côtières du continent, en Colombie-Britannique.

On trouve des plutons du Jurassique partout dans l'île Vancouver mais les plutons connus du Tertiaire ne se trouvent que dans la zone occidentale et dans deux zones qui recoupent la direction structurale vers le nord-ouest de l'île.

La composition chimique des plutons d'âge jurassique connu diffère quelque peu de celle des plutons du Tertiaire bien qu'il y ait une certaine imbrication et que les plutons semblent provenir d'un même matériau. Les directions différentielles du Jurassique montrent des ressemblances avec celles des batholites de la Californie méridionale. Les plutons connus du Jurassique contiennent plus de Ca et de Fe, probablement plus de K, de moins de Na que les plutons du Tertiaire. Ces différences sont peut-être le résultat d'une plus grande assimilation des roches encaissantes et d'une différenciation plus avancée des plutons du Jurassique plus profondément enracinés.

Pendant la mise en place, plusieurs plutons du Jurassique se sont aisément engagés vers le haut dans des roches volcaniques compétentes alors qu'ils se sont vigoureusement étendus de part et d'autre dans des roches sédimentaires moins compétentes. Il en est résulté une déformation profonde des roches encaissantes, une accumulation de magma, et d'abondants dépots de Cu-Fe en skarn (Zeballos Iron, Coast Copper, etc.) au niveau stratigraphique qui comprend la formation supérieure Karmutsen, le calcaire Quatsino et la formation inférieure de Bonanza. Plusieurs masses intrusives, même parmi celles qui ont la dimension de batholites, ont pris grossièrement une forme horizontale, en couches. Des apophyses élevées de ces masses ont pénétré vers le haut dans la formation de Bonanza et plusieurs ont atteint la surface, enrichissant la formation de Bonanza supérieure en matériau volcanique. Certaines de ces apophyses sont associées à des gisements de porphyre cuprifère (Island Copper, etc.).

La plupart des stocks et des masses en forme de dyke du Tertiaire ont été vigoureusement mis en place dans un environnement subvolcanique. Les brèches intrusives et les brèches de projection sont nombreuses. Des plutons du Tertiaire sont associés à des gisements de porphyre cuprifère (Catface, etc.) et à des filons de cuivre ou d'or (Mont Washington, Privateer, etc.). Le complexe intrusif du mont Washington est constitué d'un stock de diorite quartzeuse au centre entouré d'une diatrème et de brèches de projection de formes irrégulières, de filons-couches rayonnants et des laccolites en forme de langues constitués de porphyre dacitique pénétrant les sédiments à pendage léger du Crétacé supérieur du groupe de Nanaimo qui entoure le stock. Des laccolites et des filons-couches de porphyre dacitique de grande dimension ont été mis en place à plusieurs autres endroits lors de l'extension latérale des stocks et des dykes qui ont pénétré vers le haut dans le groupe de Nanaimo inférieur. De grands plutons de gabbro en forme de filon-couche(?) pénètrent dans les roches volcaniques Metchosin de l'Eocène dans la partie sud de l'île Vancouver, tandis que des plutons plus petits de trondhjemite constituent des stocks dans cette même région.

THE PLUTONIC ROCKS OF VANCOUVER ISLAND, BRITISH COLUMBIA: THEIR PETROGRAPHY, CHEMISTRY, AGE AND EMPLACEMENT

INTRODUCTION

This report is part of the doctoral thesis "Metallogenic Study of Vancouver Island with emphasis on the relationships of mineral deposits to plutonic rocks" submitted by the author to Carleton University, Ottawa in 1968. The illustrations accompanying this paper are reproduced essentially as drafted by the author as is the tabular material included in the pocket.

Chief Scientific Editor
Geological Survey of Canada

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Chemical analyses, potassium argon age determinations, and preparation of samples for microscopic studies were done by the Geological Survey of Canada. R.N. Delabio of the same institution made numerous X-ray identifications for the writer. Many thin sections were made by W. Yzerdraat of Carleton University. H.G. Bassett and E.R. Parker of Shell Canada Limited kindly made available several K-Ar ages done by Shell Development Company.

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Author's address: Noranda Exploration Co. Ltd.,
1700, 44 King St. W., Toronto 105.

METHODS AND CLASSIFICATION USED IN THIS INVESTIGATION

This paper includes most of the data on the plutonic[1] rocks obtained by the writer during a metallogenic study of Vancouver Island (Carson, 1968). Also included are the pertinent data of previous studies, and additional information obtained by the author and others from 1968-1971.

The writer collected more than 1,000 samples from most of the larger plutons and from dykes. The Tertiary plutons of the Mount Washington area were mapped in detail. Limited mapping was done of Jurassic plutons of Adam River and near Nanaimo Lakes (Adam River and Skarn plutons; Fig. 2). Several samples suitable for K-Ar age determinations were collected.

Modal analyses were made of thin sections of 227 representative specimens and these are presented in Table 3 (in pocket). Potassium feldspar was stained in all sections. Most of the rocks are homogeneous, medium grained, and relatively equigranular so that the point-count method proved very useful.

Four-fifths of the modal analyses were made from extra large thin sections in which the area counted was approximately 800 square millimetres. Areas counted on smaller, standard-sized thin sections averaged about 450 square millimetres. The minimum number of points counted per slide was 500 and in most cases the number of points counted totalled either 500 or 800.

Granitic pebbles collected from Aptian conglomerates were sliced and stained for potash feldspar. They were point-counted under a binocular microscope with the aid of 1/10-inch-square grid.

Chemical analyses of 38 selected samples were made in the laboratories of the Geological Survey of Canada. X-ray fluorescence methods were used to determine most major oxides[2] excepting FeO, P_2O_5, CO_2, and H_2O which were determined by chemical methods. The oxide Na_2O was determined by flame photometry. These analyses, and 24 from previous publications that are used in this paper, are presented in Table 5 (in pocket). Norms of all 62 analyses were calculated by computer and are also presented in Table 5.

Proportions of quartz, alkali feldspar, and plagioclase (oligoclase or more calcic plagioclase) in thin sections largely determine the names applied to the rocks in this paper. Some factors used in the classification are:

(1) plagioclase in diorite is $An_{<50}$ and in gabbro is $An_{>50}$

(2) in diorite the ratio of Qz[3]/Qz + Kf[4] + Pc[5] is <.05 whereas in quartz diorite it is >.05

---

[1] The term "plutonic" is used in this paper to denote igneous and/or metasomatic rocks which crystallized below the surface of the earth.

[2] Standard deviations in the range of oxide percentages of the analyzed rocks are as follows:
0.15 Na_2O, 0.23 CaO, 0.10 K_2O, 0.56 MgO, 1.0 SiO_2, 1.0 Al_2O_3, 0.2 FeO, 0.25 Fe_2O_3, 0.07 TiO_2, 0.01 MnO (J.A. Maxwell, pers. comm., 1967).

[3] Qz = quartz

[4] Kf = potassium feldspar

[5] Pc = plagioclase

(3) trondhjemite is oligoclase quartz diorite

(4) in granodiorite the ratio of $Kf/Qz + Kf + Pc$ is $>.05$ whereas in quartz diorite it is $<.05$

(5) quartz monzonite has $Kf > 1/3$ total feldspar; granodiorite has $Kf < 1/3$ total feldspar; in both cases, plagioclase is oligoclase or andesine.

(6) in granite the feldspars are albite and Kf; in albite granite, albite > Kf; in true granite Kf > albite.[1]

---

[1] This differs slightly from the most widely used classification in which granite has $Kf > 2/3$ total feldspar. The low over-all content of Kf in the plutonic rocks of the Coast Intrusions (Roddick, 1965) and Vancouver Island, make the above classification more useful.

GENERAL GEOLOGY OF VANCOUVER ISLAND

The main rock units and deformations of Vancouver Island are shown in Table 1, as well as some of the Cordilleran time-equivalent units and orogenies of White (1959). Distribution of the various rocks units is shown on Figure 1. Plutonic rocks are shown in Figure 2 (pocket).

Sicker Group

The Sicker Group is the oldest rock unit on Vancouver Island. It is of eugeosynclinal origin and is equivalent to part of the Cache Creek Group of mainland British Columbia. Sicker rocks are exposed in northerly- and northwesterly-trending uplifted zones or horsts formed prior to the Late Cretaceous (J.E. Muller, in Muller and Carson, 1969).

The lower and thicker part of the Sicker Group is composed chiefly of greenstones derived from volcanic breccias and tuffs of intermediate composition. These rocks generally occur in gently-plunging north-northwesterly-trending open folds of regional extent, but locally they are isoclinally folded and converted to chloritic and sericitic schists. Hornblende-plagioclase gneisses of the Tofino area are believed by Muller to have been derived largely from the lower Sicker Group. The lower Sicker Group in Buttle Lake area is estimated to be at least 10,000 feet thick (Jeffery, 1965b).

The upper part of the Sicker Group is largely greywacke, argillite, and minor conglomerate overlain by limestone and chert. The limestone near Buttle Lake and Horne Lake reaches 1,000 feet in thickness but in some localities it is missing. It is of Early Permian age (Yole, 1963). Unlike much of the younger Quatsino limestone, it is generally fine to medium grained, being recrystallized to coarse marble and converted to skarn, at very few localities.

Karmutsen Formation

The Karmutsen Formation is the lowest of three formations of the Vancouver Group (Table 1). It is the most widespread rock unit on Vancouver Island, and like the Sicker Group, is of eugeosynclinal origin. It overlies the Sicker Group disconformably and is composed largely of pillowed and porphyritic basalt with interlava pillow breccia (Carlisle, 1963) and tuff, and minor argillite and quartzite. Estimates of thickness vary from 5,000 feet (Gunning, 1931) to a maximum of 25,000 feet (Carlisle, 1971) but it is believed by Sutherland Brown (1966) to have been at least 10,000 feet thick in most localities.

Diabase dykes and sills that are as much as several hundred feet in thickness and intruding the Sicker Group, are believed to be intrusive equivalents of Karmutsen volcanics.

Most of the Karmutsen Formation is only weakly metamorphosed (Carlisle, 1971) and pumpellyite is a common constituent of the amygdules (Jambor, 1960). A narrow zone of plagioclase-hornblende hornfels is common adjacent to plutons. In places, the Karmutsen Formation has been gently folded along north-northwesterly-trending axes but structural adjustment most commonly occurred by large-scale block faulting, and dips are rarely steep.

ERA	PERIOD	AGE	m.y.	ROCK UNITS	DEFORMATIONS (Plutons)	CORDILLERAN TECTONIC UNITS OF WHITE (1959)
CENOZOIC	TERTIARY	PLIOCENE	7			Kamloops
		MIOCENE	26	Sooke Formation	BLOCK FAULTING, UPLIFT & EROSION	PUGET OROGENY
		OLIGOCENE	37-38	Metchosin Formation		White Lake
		EOCENE	53-54	Tertiary Plutons	(Tertiary Plutons)	ROCKY MT. OROGENY
		PALEOCENE	65			
MESOZOIC	CRETACEOUS	LATE		Nanaimo Group		Upper Cretaceous
		MIDDLE				
		EARLY	136	Unnamed Sediments, Quatsino Sound	FAULTING, UPLIFT & EROSION	Nass
	JURASSIC	LATE	162	Unnamed Sediments, West Coast	(Jurassic Plutons)	COAST R. OROGENY (Coast Intrusions)
		MIDDLE	172	Jurassic Plutons (Is. Intrusions)	MAJOR FOLDING	
		EARLY	190-195	Bonanza Fm. (Vancouver Group)	FOLDING, UPLIFT & EROSION	Hazelton
	TRIASSIC	LATE		Quatsino Fm. (Vancouver Group); Karmutsen Fm. (Vancouver Group)		Takla
		MIDDLE				
		EARLY	225			
PALEOZOIC	PERMIAN		280	Sicker Group		CASSIAR OROGENY; Cache Creek
	PENNSYLVANIAN				FOLDING, UPLIFT & EROSION	

Table 1. Formations and deformations of Vancouver Island and Cordilleran tectonic units of White (1959). Absolute age of some important time boundaries shown in age column (Geol. Soc. London, 1964).

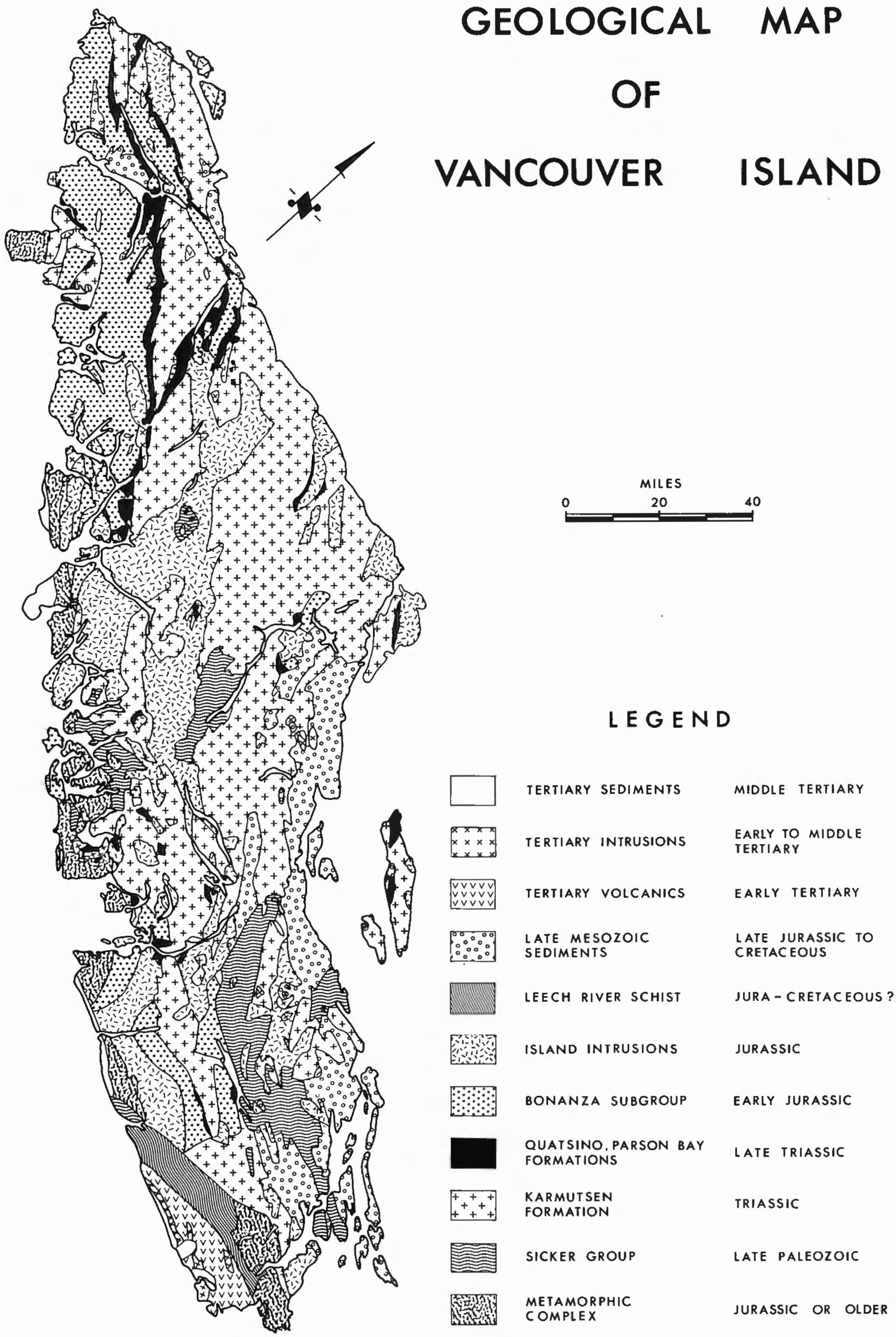

Figure 1. Geology of Vancouver Island (courtesy of J.E. Muller).

The Karmutsen Formation is entirely late Triassic (J.E. Muller, pers. comm., 1972); it is correlative with the Takla and Nicola Groups of mainland British Columbia.

Quatsino Formation

Overlying the Karmutsen Formation, apparently conformably, is the Quatsino limestone. It is up to 3,000 feet thick and is Upper Karnian in age. Granitic plutons are common within and near to it, and near the contacts the limestone has been converted to coarse marble and skarn. In places near some plutons it is dolomitic.

The limestone over large areas is flat lying or gently dipping. Elsewhere, especially near faults and intrusions, it has been greatly deformed and is isoclinally folded.

One or more thin intervolcanic limestone layers, until recently not distinguished from the Quatsino Formation, occur up to several hundred feet lower in the Karmutsen Formation (Carlisle and Susuki, 1965).

Bonanza Formation

The Bonanza Formation, consisting of a lower sedimentary member and an upper volcanic member, conformably overlies the Quatsino Formation. It is in part correlative with the Hazelton Group of mainland British Columbia.

Carbonaceous shale, calcareous shale, and greywacke are the commonest rocks of the lower member, whereas dacitic to andesitic lavas, tuffs and breccias constitute the bulk of the upper member which is lithologically similar to much of the lower Sicker Group.

In northern Vancouver Island, rocks of the Bonanza Formation have been extensively hydrothermally altered and pyritized in the vicinity of a northwest-trending series of Jurassic plutons (Northcote, 1971; see Fig. 16, this paper).

The upper Bonanza Formation may be as young as Middle Jurassic (Jeletzky, 1954a). In the Quatsino area it is estimated to be 9,000 feet thick (Sutherland Brown, 1966).

Jurassic Plutons ("Island Intrusions")

Plutonic rocks of Vancouver Island are described in detail in the following chapters. Most are Middle to early Late Jurassic batholiths and stocks which vary in composition from gabbro to quartz monzonite, but are mainly granodiorite and quartz diorite. They intrude the Bonanza Formation and all older rocks, and in many localities are unconformably overlain by Late Cretaceous sedimentary rocks of the Nanaimo Group.

Contacts of the Jurassic plutons with the Sicker Group and Bonanza Formation are in places gradational, with gneisses and migmatites common, but contacts with the Karmutsen Formation are generally steep, with a narrow hornfelsic zone in the host rocks. Near Quatsino limestone the plutons are commonly in the form of tongues and irregularly-shaped apophyses, many of which are semiconcordant and up to several miles long.

Muller (Muller and Carson, 1969) has mapped gneisses, diorites, and amphibolites in the Tofino area, which he believes are the products of recrystallization at depth of mainly Sicker Group rocks.

Upper Jurassic and Lower Cretaceous Sediments

Greywacke, conglomerate, and minor argillite occur along the west coast near Tofino. They are tentatively correlated by Muller (Muller and Carson, 1969) with similar rocks of Late Jurassic or Early Cretaceous age near Kyuquot described by Jeletzky (1950). The conglomerates contain granitic pebbles derived from Jurassic plutons. Greywackes near Tofino are intruded by a Tertiary stock.

Clastic sedimentary rocks of Aptian age, including conglomerates with granitic pebbles, occur in the Quatsino Sound area (Jeletzky, 1954b).

Nanaimo Group

Along eastern Vancouver Island, rocks of the Sicker and Vancouver Groups and Jurassic plutons are unconformably overlain by the Nanaimo Group, a thick succession of clastic marine and continental rocks containing several coal seams (Muller and Jeletzky, 1970). This group is of Late Cretaceous age, and attains a thickness estimated to be about 10,000 feet near Nanaimo.

Rocks of the Nanaimo Group are unmetamorphosed except adjacent to a few Tertiary plutons such as the Mount Washington Tertiary stock (Carson, 1960) where sandstones and shales are converted to quartzites and argillites. On the whole, the rocks are little deformed. However, the group has been involved in extensive Tertiary block faulting, and near faults the rocks are sheared and crumpled (Buckham, 1947).

Tertiary Volcanic Rocks

The late Eocene Metchosin Formation of the Sooke-Jordan River area (Clapp and Cooke, 1917) consists largely of submarine sodic basalts. They are equivalent to the Eocene volcanics of the Olympic Peninsula. In places they are albitized, but they are little metamorphosed, except immediately adjacent to Oligocene plutons.

Dacite-tuff and ignimbrite near Kennedy Lake, are believed by Muller (Muller and Carson, 1969) to be early Tertiary in age. Fresh basaltic volcanics capping Twin Peaks west of Port McNeill appear to be late Tertiary or Quaternary (Symons, 1971b).

Tertiary Plutons

Tertiary plutons are fully described in later chapters. They include quartz diorite, granodiorite, and gabbro stocks and dykes in rocks as young as Eocene, and dacite porphyry sills and laccoliths cutting the Nanaimo Group. These are Oligocene-Eocene and many may be of subvolcanic origin.

Tertiary Sediments

The late Oligocene Sooke Formation, mainly sandstone and shale, unconformably overlies Tertiary plutons and volcanics in the Sooke area (Clapp and Cooke, 1917) and similar sedimentary rocks occur at places along the west coast. They are unmetamorphosed, but are cut by major faults.

The Relationship Between Plutonism and Deformation

In most areas of Vancouver Island, such as Cowichan Lake (Fyles, 1955), Sooke-Duncan (Clapp and Cooke, 1917) and Zeballos-Nimpkish (Hoadley, 1953), the most important interval of regional folding is believed to have occurred during Early(?) and Middle Jurassic, after deposition of at least part of the Bonanza Formation and immediately previous to and possibly in part during the emplacement of granitic plutons. The interval including both the folding and intrusion has, in many previous papers, been referred to the "Coast Range Orogeny".

Recent K-Ar ages (see Table 2) indicate that the emplacement of granitic plutons occurred at various times throughout much of the Jurassic, but with a concentration in Middle to middle Late Jurassic. The ages, like the field data, would appear to indicate that most of the plutons are slightly younger than the main episode of regional folding, but the two are not necessarily unrelated. During emplacement, many of the plutons caused intense local deformation of their host rocks (see p.).

Jurassic deformational episodes affecting the Karmutsen and Quatsino Formations at Open Bay on Quadra Island were described by Carlisle and Susuki (1965). The first and most intense episode involved regional folding along north-northwest trends and was succeeded by a subsidiary episode of gentle folding along nearly horizontal east-southeast axes. The first episode appears to have been followed by the emplacement of granitic plutons and was initiated in Early or Middle Jurassic time. A much later (possibly Tertiary) deformation involved local folding about steep axes related to north-northeast-trending fracture zones and shears.

At the Price Zn-Pb-Cu property near Buttle Lake (Carson, 1968), rocks of the Sicker Group exhibit structures of the first and last of the Jurassic deformations of Open Bay described above. In addition, granitic dykes were emplaced in northeast-trending tension fractures formed during the first deformation or at an intermediate time. The only other structures observed are east-west-trending faults that offset all other structures. Therefore, all deformational intervals appear to be Jurassic or younger.

At Cowichan Lake (Fyles, 1955), the main granitic plutons are dyke-like bodies of granodiorite that were emplaced in northwest-trending tensional fractures which crosscut the earlier regional folds. In the Zeballos-Nimpkish area (Hoadley, 1953) deformational structures caused by the forcible emplacement of the major plutons are superimposed on the regional folds.

In those areas where Late Cretaceous or Oligocene-Miocene sedimentary rocks are present, Tertiary deformation is indicated, involving mainly block-faulting along pre-existing breaks (Buckham, 1947; Muller and Carson, 1969). Intrusion of quartz diorite and related porphyry also occurred during at least part of this interval of faulting but no plutons younger than early Oligocene have been found whereas the faulting appears to have continued much longer, possibly until the present.

Two additional "orogenic" episodes have been suggested, neither of which involved granitic plutons. Folding, uplift and erosion apparently occurred in the late Paleozoic (Muller and Carson, 1960) and in latest Triassic time (Jeletzky, 1970). Also, the interval including Late Jurassic and much of the Cretaceous appears to have been an extended time of tectonic activity with only local basins receiving sedimentation (Muller and Carson, 1969).

In summary, on Vancouver Island the relationship between plutonic activity and regional deformation has been fairly clearly defined. Stratigraphic data and potassium-argon ages indicate that most of the granitic plutons were emplaced at two intervals. The first was in middle Early to middle Late Jurassic, immediately after, but possibly also in part during the later stages of the most prominent period of regional folding. The second interval of intrusion was from early to middle Tertiary and coincided in part with an extended time of block-faulting. In many places, very intense but local deformations occurred during forcible emplacement of the Jurassic and Tertiary plutons. Structures thus formed are superimposed on the older regional structures.

SUMMARY OF PREVIOUS WORK ON THE PLUTONIC ROCKS

Plutons ranging in composition from peridotite to granite, but consisting mainly of granodiorite and quartz diorite, occupy approximately one-tenth of the surface area of Vancouver Island (Fig. 2, in pocket). They range in size from dykes less than one foot wide to the composite Bedwell-Ucona batholith which is fifty miles long and five to twelve miles wide. Most of the plutons are elongated in a northwesterly direction roughly parallel to the regional structure.

Before this project, few quantitative data on the plutons were available, and the only Tertiary intrusions known were those of the Sooke area (Clapp and Cooke, 1917), Mount Washington (Carson, 1960) and some dacite porphyry sills cutting the Nanaimo Group. The granitic intrusions were commonly called granodiorites and included in the "Coast Intrusions".

In the Sooke-Victoria-Duncan area, Clapp (1912, 1913, 1914b) and Clapp and Cooke (1917) distinguished three types of batholithic rocks. They were assigned to the Late Jurassic or Early Cretaceous. The oldest unit, called Wark gabbro diorite gneiss, extends northwest from Victoria to Sooke Lake and forms the southern portion of a composite batholith. Wark gneisses are fine to coarse grained, and dark grey to black. They contain calcic oligoclase or andesine or sodic labradorite, amphibole, pyroxene, quartz (up to 15 per cent), biotite, ilmenite, magnetite, and in some cases, minor potash feldspar. The minerals were crushed and altered. In places Wark gneisses grade into amphibolites.

Closely associated with the Wark gneisses are the Colquitz quartz diorite gneisses which have minor aplitic, pegmatitic, and granitic apophyses extending into Wark gneisses. Colquitz gneisses are strongly banded, light to dark grey and medium to coarse grained. They contain plagioclase (An_{30}), quartz, hornblende, biotite and/or muscovite, magnetite, apatite, titanite and, in leucocratic bands, microperthite. They are moderately to strongly altered.

Intruding the Wark and Colquitz gneisses are plutons of granodiorite which contain local quartz diorite and aplitic and pegmatitic varieties. The type pluton is on Saanich Peninsula and this and all similar granodiorite plutons were called Saanich granodiorite by Clapp (1912). This rock is medium grained, light grey to pink and contains plagioclase (An_{10} to An_{45}), quartz, hornblende, biotite, magnetite, pyrite and potash feldspar which is commonly perthitic. Alteration is common and minerals are strained. Basic contact zones, called Beale diorite, or quartz diorite are common, and weak foliation in places parallels contacts or regional structures.

Clapp and Cooke (1917) also described "gabbro-diorite porphyrite" intrusions which cut the Sicker Group: Fyles (1955) mapped similar rocks near Cowichan Lake as diabase related to Karmutsen volcanics, and diabase sills occurring in the Buttle Lake area are believed to have a similar origin (Jeffery and Merrett, 1964).

Bodies of quartz-feldspar porphyry in the Sicker Group were mapped by Clapp and were named the "Tyee porphyrites". They are schistose in places and their intrusive nature is not clear. They have been found only in the Sicker Group and on the basis of field and microscopic inspection the writer believes that they are probably part of that group.

Small stocks or dykes of unaltered gabbro, quartz diorite porphyry, and altered hornblende porphyry also occur in the Victoria-Duncan area.

In the Sooke area Clapp and Cooke (1917) mapped two types of intrusions both of which cut the late Eocene Metchosin volcanic rocks. They named them the Sooke intrusions. The first type consists of stocks of olivine or augite gabbro with minor anorthosite; the stocks are up to 5 miles long by 2 1/2 miles wide. Small bodies of "granite", some of which are border facies of the gabbros, comprise the second type.

The augite gabbro is dark green, and medium to coarse grained with chilled borders. It contains labradorite, augite, magnetite and apatite. Augite is replaced by hornblende. Olivine gabbro contains bytownite, diopsidic augite, olivine, and ilmenite and is equigranular fine to medium grained. Neither type of gabbro is greatly altered.

The Tertiary Sooke "granites" are light grey, fine to medium grained and contain quartz, oligoclase, hornblende, albite, magnetite, titanite, apatite and, in some cases, potash feldspar.

Fyles (1955) described the granodiorite plutons of Cowichan Lake area which are similar to the Saanich granodiorites. In places they are overlain by Late Cretaceous Nanaimo Group rocks. They are steep-walled dyke-like bodies up to 8 1/2 miles long by 1 1/2 miles wide and contain no linear or planar structures. An aplogranitic roof facies occurs in one body. In the eastern part of the area many of the plutons are quartz diorite, as are the borders of many of the granodiorite bodies in the west. Moderate alteration of the rocks is indicated by widespread chloritization of biotite which may also contain lenses of prehnite, and by the replacement of plagioclase by sericite and epidote.

Sargent (1941) described the quartz diorite, granodiorite, and dykes of Bedwell River area, and Stevenson (1945) described quartz diorite, diorite, and feldspar porphyry of the China Creek area.

Gabbro, diorite, granodiorite, and quartz diorite, all members of the Zeballos batholith, were mapped by Stevenson (1950). The quartz diorite is the youngest member and occurs as a body 8 miles long by 2 miles wide. It has a breccia zone 2,000-3,000 feet wide at its northwestern end.

Gunning (1930, 1932a) and Hoadley (1953) have described the Nimpkish area intrusions. They are similar to Saanich granodiorites and are mainly granodiorite and quartz monzonite with lesser amounts of granite and quartz diorite.

The Nootka batholith described by Hoadley (1953) is quartz monzonite or granite of very uniform composition. The nearby Ehatishat batholith, on the other hand, is variable in composition, ranging from granite to gabbro, and has a migmatite zone along its contact.

Jeletzky (1950) described small bodies of granodiorite, aplite, and pegmatite near Kyuquot on the west coast. They intrude the Early and possibly Middle Jurassic Bonanza Formation, and pebbles similar to these granitic rocks are reported by Jeletzky (1954a) to occur in Callovian conglomerates.

The Coast Copper stock is mainly diorite, with gabbro, monzonite and quartz diorite phases, and minor alaskite and granodiorite apophyses (Jeffery, 1961; Sangster, 1969).

A medium-grained fresh hornblende quartz diorite stock with marginal breccias intrudes Karmutsen volcanic rocks and Late Cretaceous sedimentary rocks at Mount Washington (Carson, 1960). Dykes, sills, lacoliths, and irregularly-shaped bodies of quartz diorite porphyry or dacite porphyry have intruded the Late Cretaceous and Karmutsen rocks for several miles to the east and southwest of Mount Washington (Gunning, 1931; Muller and

Carson, 1969; Figs. 2, 7). Dacite porphyries occur in Nanaimo Group sedimentary rocks at Haslam Creek (Clapp, 1913), at China Creek, Englishman River, and Nanaimo Lakes and at Browns River (Muller and Carson, 1969).

Granitic gneisses along the west coast of Vancouver Island are described by Muller (Muller and Carson, 1969). They are similar to the Wark and Colquitz gneisses and are mainly diorite and quartz diorite in composition. Muller considers these to be largely migmatized Sicker rocks.

AGE OF THE PLUTONIC ROCKS

Stratigraphic Data

The granitic plutons of eastern and southeastern Vancouver Island may be divided into two age groups on the basis of stratigraphic data. The first group contains those that are overlain unconformably by the Nanaimo Group and are therefore pre-Late Cretaceous, and the second group consists of those which intrude the Nanaimo Group and are therefore post-Late Cretaceous, or Tertiary (Fig. 2). One pre-Late Cretaceous pluton, the Quinsam granodiorite, intrudes the Early and Middle(?) Jurassic Bonanza Formation.

The youngest rocks cut by granitic intrusions on the west coast of Vancouver Island, near Kyuquot, are those of the Bonanza Formation. Callovian (latest Middle Jurassic) conglomerates reportedly contain granitic pebbles (Jeletzky, 1954a). Pebbles shown to the writer by J.A. Jeletzky are medium-grained, pink, hornblende granodiorite or quartz monzonite and very coarse orthoclase-quartz pegmatite with minor muscovite and amphibole. They are thought to have been derived from the roof facies of plutons which during the Callovian were exposed by erosion (J.A. Jeletzky, pers. comm., 1966). The writer was unable to find granitic pebbles in the conglomerates described by Jeletzky, but has observed granodiorite and quartz diorite pebbles typical of the Jurassic plutonic rocks in conglomerates of probable Late Jurassic or Early Cretaceous age near Tofino.

The Bonanza Formation is also the youngest rock unit cut by the major granitic plutons in northern Vancouver Island (Northcote, 1971). An abundance of granitic pebbles in Aptian conglomerates at Rupert Arm and Coal Harbour (Figs. 10, 16) indicates that granitic intrusions were present there by late Early Cretaceous time.

The above stratigraphic data indicate that a large number of granitic plutons of Vancouver Island are Middle Jurassic.

The upper age limit of the Tertiary (post-Late Cretaceous) plutons of eastern and southeastern Vancouver Island cannot be determined from stratigraphic data. However, the gabbro and granitic plutons of the Sooke-Jordan River area intrude late Eocene volcanic rocks and are overlain nonconformably by late Oligocene sediments. They are, therefore, of Oligocene age.

Potassium-Argon Age Determinations

The Geological Survey of Canada has made K-Ar age determinations on seventeen plutonic rock samples from Vancouver Island (Table 2, Fig. 3). Most of these have been published (Wanless *et al.*, 1965, 1966, 1967, 1968). It is important to note that all the stratigraphically-dated plutons of Vancouver Island that have been analyzed by K-Ar methods have yielded ages that are in good agreement with the stratigraphic data.

As shown in Table 2, and Figure 3, many rocks dated by K-Ar methods yield Early to Late Jurassic ages according to the Geological Society of London time scale[1] (1964). The age of 148 ± 8 m.y. from skarn adjacent to the Zeballos magnetite deposit may give the upper limit of the Jurassic

[1] In this scale the Jurassic extends from 136 to 190-195 million years, and the Middle Jurassic from 162 to 172 million years.

TABLE 2.

Data for K-Ar Age Determinations of Plutonic and Related Rocks of Vancouver Island

NUMBER (Collector)	LOCATION (see Fig. 2)	ROCK	MINERAL DATED	% K	% Ar^{40}	% CHLORITE in concentrate	AGE m.y.
GSC-64-2 (G. E. P. Eastwood)	Brynnor Mine	Grano-diorite	Biotite	6.13	65	30	167±10
GSC-65-14 (D. J. T. Carson)	Nimpkish "batholith"	Grano-diorite	Biotite	5.23	74	30	151±14
GSC-65-15	same as 65-14	"	Horn-blende	0.36	24	0	143±60
GSC-65-17 (J.E. Muller)	Ucona "batholith"	Grano-diorite	Biotite	6.91	79	10	162±9
GSC-65-18 (J.E. Muller)	Ucona "batholith"	Grano-diorite	Biotite	5.83	77	15	166±8
GSC-66-27 (D. J. T. Carson)	Bonanza "batholith"	Grano-diorite	Biotite	6.01	85	20	150±8)151±8
	re-run	"	"	6.01	86	20	152±7
GSC-66-28 (D. J. T. Carson)	Zeballos Iron Deposit	Skarn	Phlogo-pite	5.47	84	35	148±8
GSC-66-33 (J.E. Muller)	Nanaimo Lakes Road	Grano-diorite	Biotite	6.32	92	2	160±8
K-Ar-1652 (D. J. T. Carson)	Empire Development Mine	Skarn	Phlogo-pite	7.29	85	7	181±8)179.5±8
	re-run	"	"	7.29	89	7	178±8
K-Ar-1694 (J.E. Muller)	Nahwitti Lake	Grano-diorite	Horn-blende	0.40	61	0	154±8
GSC-65-11 (D. J. T. Carson)	Catface Peninsula	Quartz Diorite	Biotite	7.35	73	M 5	48±12
GSC-65-12 (D. J. T. Carson)	Central Zeballos Mine	Quartz Diorite	Biotite	4.28	56	2	38±14
GSC-65-13 (D. J. T. Carson)	East of Sunro Mine	Quartz Diorite	Biotite	5.70	25	12	39±10
GSC-66-29 (D. J. T. Carson)	Faith Lake	Quartz Diorite	Biotite	4.73	71	8	39±7
GSC-66-30 (D. J. T. Carson)	Mount Washington	Quartz Diorite	Biotite	7.33	78	1	35±6
GSC-66-31 (J.E. Muller)	Tofino, Stubbs Island	Grano-diorite	Biotite	6.87	71	10	50±5
GSC-66-32 (J.E. Muller)	Paradise Creek, south of Kennedy Lake	Quartz Monzonite	Biotite	7.14	79	2	59±3
K-Ar-1653 (D. J. T. Carson)	Corrigan Creek	Quartz Diorite	Biotite	6.84	55	10	38±2

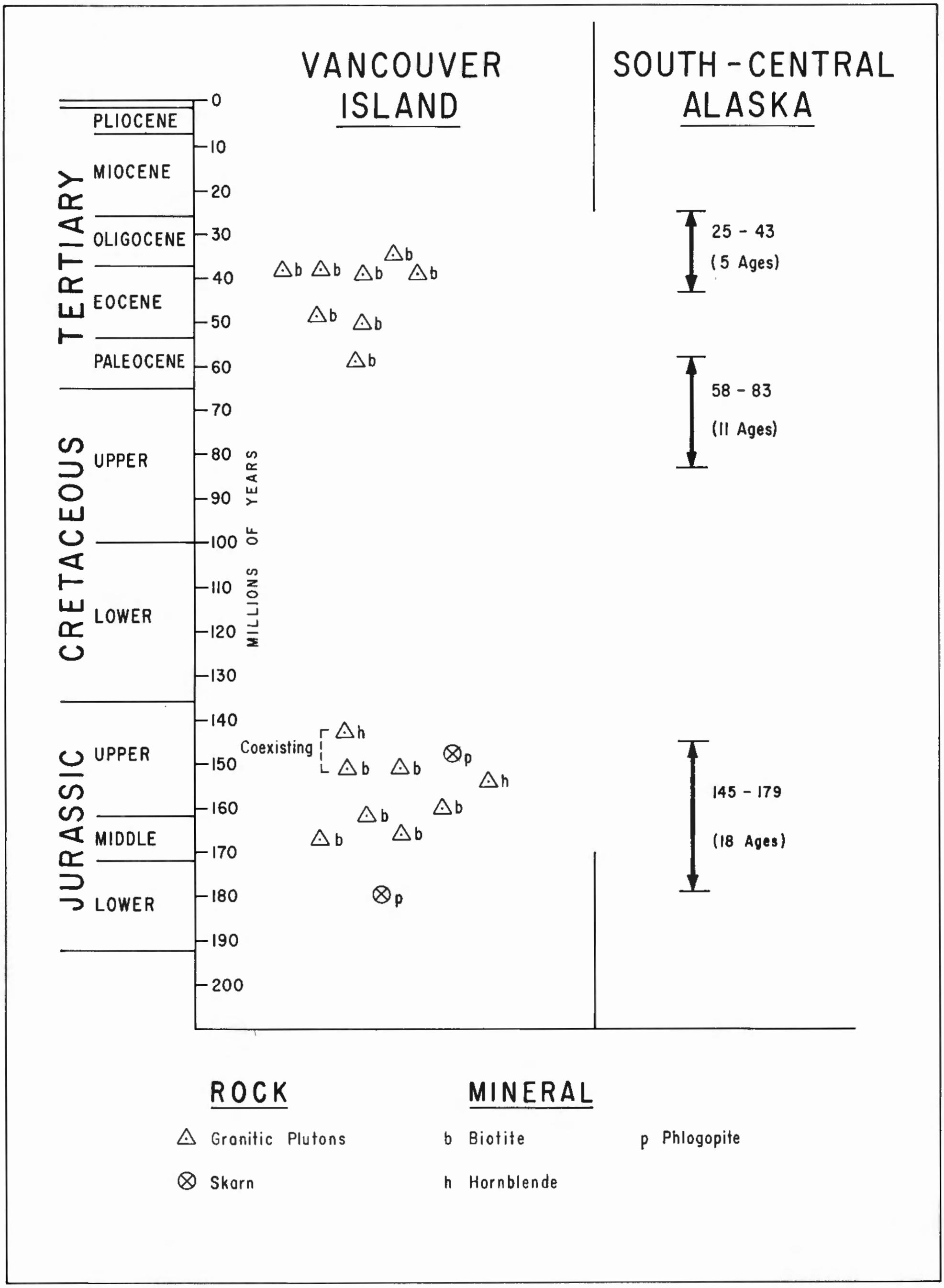

Figure 3. Distribution of available K-Ar ages referred to in this paper (left), and those of south-central Alaska (Reed and Lanphere, 1969).

intrusive activity. The only younger age obtained (143 ± 60 m.y.) is from poikilitic hornblende in a sample for which biotite yielded the age of 151 ± 14 m.y. Feldspar inclusions in the hornblende and the low content of K and ^{40}Ar make the 143 ± 60 m.y. age unreliable as shown by the large error limits. The nearby Bonanza batholith, which Gunning (1932a) considered to be of the same age as the Nimpkish batholith, yields two ages on the same biotite sample of 150 ± 8 m.y. and 152 ± 7 m.y.

The age of 179.5 ± 8 m.y. for skarn related to the Coast Copper Stock is the oldest yet obtained on Vancouver Island. This stock is also the most mafic pluton for which age data are available.

The time range indicated for Tertiary plutons is 59-35 m.y.; middle Paleocene to early Oligocene according to the Geological Society of London time scale.

The quartz diorites, excepting that from Catface Peninsula, give ages from late Eocene to early Oligocene which is the age of the Sooke plutons as determined by both K-Ar methods (39 ± 10 m.y.) and by stratigraphy. As there is an experimental error of ± 14 m.y. for the Catface sample, it is possible that the quartz diorites are all late Eocene or early Oligocene.

The Stubbs Island granodiorite and the Paradise Creek quartz monzonite are early Eocene and middle Paleocene. They have experimental errors of ± 5 m.y. and ± 3 m.y. respectively and could not therefore be of the same intrusive period as the quartz diorites. They may belong to an earlier period of intrusion. However, differentiation trends on the An-Ab-Or diagram (Fig. 13) suggest that all the Tertiary plutons belong to a single magmatic series.

In order to determine the possible significance of Tertiary geological events, Shell Canada Limited made K-Ar age determinations on 31 samples of igneous rocks from Vancouver Island, mostly from along the west coast. Only limited data[1] are available for these ages.

Because the Shell determinations were made primarily to establish the presence of Tertiary events rather than to delimit accurately the various plutonic or metamorphic episodes, most of the 31 ages were whole-rock determinations[2]. Many of the samples were altered. Therefore, only a few general conclusions will be made here regarding their distribution in time. Nine of the 31 samples were from volcanic rocks and andesite and diabase dykes and are not considered here. Of the remaining 22 samples, 19 were from acidic to intermediate granitic plutonic rocks and the remaining three were diorite, amphibolite, and hornblende gabbro. Two major groups were present in the 22 samples; 36-88 m.y. (15 samples), and 132-161 m.y. (5 samples). The only two samples to fall outside these groups were the amphibolite (115 ± 8 m.y.) and the hornblende gabbro (109 ± 8 m.y.). These two samples were from nearby localities. Except for the presence of some late Jurassic-earliest Cretaceous and some Late Cretaceous ages, the two major groups agree with the Geological Survey of Canada determinations (Fig. 3).

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[1] Shell ages were done by Shell Development Company; age data courtesy of H. G. Bassett and E. R. Parker of Shell Canada Limited.

[2] Whole-rock K-Ar age determinations are generally considered to be less accurate than determinations done on minerals that are known to be good argon retainers during post-crystallization events (i.e. - biotite or hornblende).

As noted above, most of the Shell ages were whole-rock determinations and many of the rocks were visibly altered. Thus there is a good possibility that, due to loss of argon, many Shell ages could represent Jurassic plutons that were up-dated by later metamorphism or plutonism. Three mineral concentrates were dated:

granitic intrusion	(biotite)	37 ± 5 m.y.	
granitic intrusion	(orthoclase)	82 ± 5 m.y.	(unreliable)
quartz diorite	(biotite)	161 ± 10 m.y.	

The orthoclase age is at least as unreliable as the whole-rock ages because orthoclase is a poor retainer of argon. The two biotite ages should be more reliable and agree well with the Geological Survey of Canada age determinations shown in Figure 3.

Eight Shell whole-rock ages fall in the 64-88 m.y. range, and the determination on orthoclase is in this range as well. These ages are mostly from gneissic quartz diorites and non-gneissic but relatively salic plutons along western Vancouver Island, which due to moderate to strong alteration, did not yield acceptable biotite concentrates for Geological Survey of Canada age determinations. They are therefore much less reliable than determinations made on biotite or hornblende, but their distinct grouping may indicate a possible Late Cretaceous plutonic or metamorphic event that has not been previously recognized.

As shown on Figure 3, the over-all distribution of K-Ar ages of the plutonic rocks of south-central Alaska (Reed and Lanphere, 1969), is remarkably similar to those of Vancouver Island; two major groups occur in both regions:

	Jurassic	mid-Tertiary–Late Cretaceous
South-central Alaska	145-179 m.y.	25-83 m.y.
Vancouver Island	148-179.5 m.y.	35-59 m.y.

Reliable Late Cretaceous ages have not been obtained from Vancouver Island, but the Shell age determinations described previously indicate the possibility of plutons in the 64-88 m.y. range along the west coast.

Vancouver Island and south-central Alaska have had comparable geological histories, and the plutons of both regions appear to be very similar in composition (mainly granodiorites and quartz diorites). However, the limited data for the Alaskan Tertiary plutons (Reed and Lanphere, 1969) indicate that they may be higher in potassium than those of Vancouver Island.

Paleomagnetic Data

Recent paleomagnetic studies made by Symons (1971a, 1971b) on many of the plutons of Vancouver Island that have been dated by radiometric methods (Table 2), give additional support to the Jurassic and Tertiary K-Ar ages.

Petrographic and Chemical Data

Where the order of emplacement of plutons has been established mafic gneisses are the oldest followed by diorite and then granodiorite.

At Zeballos, Stevenson (1950) established the order of emplacement of granitic rocks to be gabbro and diorite, granodiorite, and quartz diorite from oldest to youngest. The quartz diorite is Tertiary because it yields a K-Ar age of 38 ± 14 m.y. (Wanless et al., 1967). The granodiorite is probably middle Late Jurassic because phlogopite from skarn alongside it is 148 ± 8 m.y. in age (Table 2).

Where gabbro gneisses, diorite gneisses, or quartz diorite gneisses are present they are invariably intruded by granodiorite and are therefore older. This is true in southern Vancouver Island (Clapp and Cooke, 1917) and in several localities along the west coast of the island. Some, if not all of the gneisses are post-Triassic, since in places they appear to have been derived from the Vancouver Group.

Modes plotted on the Qz-Kf-Pc and Qz-Maf[1]-Fp[2] diagrams for 227 samples from plutons of Vancouver Island (Figs. 8, 9) have distributions somewhat similar to those of pebbles of granitic rock from Aptian (late Lower Cretaceous) conglomerates from Holberg Inlet and Rupert Arm (Fig. 10). Two main differences are apparent but may be explained. They are: (a) on the whole the pebbles have higher Kf content. Quartz diorite pebbles are rare, quartz monzonite pebbles are common. At the time of deposition of the conglomerates the plutons were eroded to shallower depths than at present so that many pebbles may have been derived from potassium-rich roof facies. Also, about one-third of the granitic pebbles are similar to the relatively potassium-rich quartz-eye granodiorite porphyry intrusion of the east end of Rupert Arm and may therefore have been derived from it and from other similar high-level plutons cutting the Bonanza Formation of the Cape Scott–Rupert Arm area. (b) there are no (quartz-free) gabbro or diorite pebbles and no gneissic pebbles, probably because such rocks are rare in the vicinity of the conglomerates.

On the basis of chemical and K-Ar age similarities, Northcote and Muller (1971) believe that the Jurassic plutons and the upper volcanic part of the Bonanza Formation are co-magmatic.

The above chemical and petrographic data strongly suggest that all the compositional types of plutons found on Vancouver Island were present in abundance by late Early Cretaceous time, and that all plutons excepting possibly some gneisses are post-Triassic.

Conclusions

The great majority of plutonic rocks of Vancouver Island are undoubtedly late Lower to middle Upper Jurassic. Very subordinate to these, in abundance, are early to middle Tertiary plutons.

Cretaceous plutonic rocks have not been positively identified, but there is some evidence for a Late Cretaceous plutonic and/or metamorphic event along the west coast, as recorded mainly in some gneisses and in some non-gneissic and relatively salic plutons.

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[1] Maf = Mafic minerals (hornblende, pyroxene, biotite, chlorite).

[2] Fp = Kf + Pc.

PETROGRAPHY AND DISTRIBUTION OF JURASSIC AND PROBABLE JURASSIC PLUTONS (ISLAND INTRUSIONS)

Saanich-type Granodiorites of eastern Vancouver Island (eastern zone)

Medium-grained, pale pinkish grey, hypidiomorphic-granular hornblende and/or biotite granodiorite (Pl. 1) is the main rock type in nearly all the large plutons along the eastern and northeastern side of Vancouver Island from the Cape Scott area to Victoria (Figs. 2, 4). In places they contain some quartz monzonite which may be partly coarse grained. Quartz diorite occurs locally, especially near the borders of plutons. Some of the smaller high-level plutons cutting the Bonanza Formation in the Cape Scott–Rupert Arm area are quartz monzonite in composition (Northcote, 1971). The average content of potassium feldspar in 67 samples of the eastern zone is 13.1 per cent. Plutons included in this zone are the Cape Scott–Rupert Arm and Nimpkish–Bonanza plutons, Ucona batholith, Quinsam batholith, Nanaimo River batholith and Saanich granodiorites of the Cowichan Lake and Victoria areas. All of these are known to be pre-Late Cretaceous and most are known to be Middle or early Late Jurassic. They contain no known Tertiary phase.

Foliation is present near the contacts of some plutons. Porphyritic texture is uncommon. It is present at places along the borders of some of the larger plutons, and is dominant only in some small high-level stocks(?) cutting the Bonanza Formation, such as that at the east end of Rupert Arm (Pl. 2) and elsewhere on northern Vancouver Island (Fig. 16). Feldspar phenocrysts are invariably plagioclase.

Nearly all of these rocks are moderately altered (Table 3) by clouding of plagioclase with sericite and kaolin, chloritization of mafic minerals and occurrence of prehnite lenses (Pl. 1) in biotite or in chlorite pseudomorphs of biotite. Biotite is commonly dusty and may be bent or torn. Potash feldspar is commonly perthitic and the albite lamellae appear to decrease in average width with increasing anorthite content of the plagioclase (Table 3). A similar inverse relationship was noted by Roddick (1965) in feldspars of the Coast Range plutons in the Vancouver North and Pitt Lake areas. Plagioclase phenocrysts in the Rupert Arm stock (Pl. 2) owe their red colour to finely disseminated hematite.

Quartz Diorites and Subordinate Granodiorites of the Central Axial Area

Most rocks of the Bedwell batholith and Alberni plutons (Figs. 2, 4) of central Vancouver Island are quartz diorites and granodiorites low in potash feldspar. The average content of potash feldspar in 32 samples is 7.5 per cent. No quartz monzonite or granite has been reported or was observed by the writer in these plutons. Two of the Alberni plutons are overlain by Nanaimo Group sediments and are probably Jurassic.

Bedwell batholith is characterized by conspicuous quartz "eyes" (Pl. 3) which are up to 9 millimetres in diameter but are commonly 4-6 millimetres. They are rare or only weakly developed elsewhere on the island. The border of the batholith near Della Lake is porphyritic and quartz "eyes" (phenocrysts) are abundant.

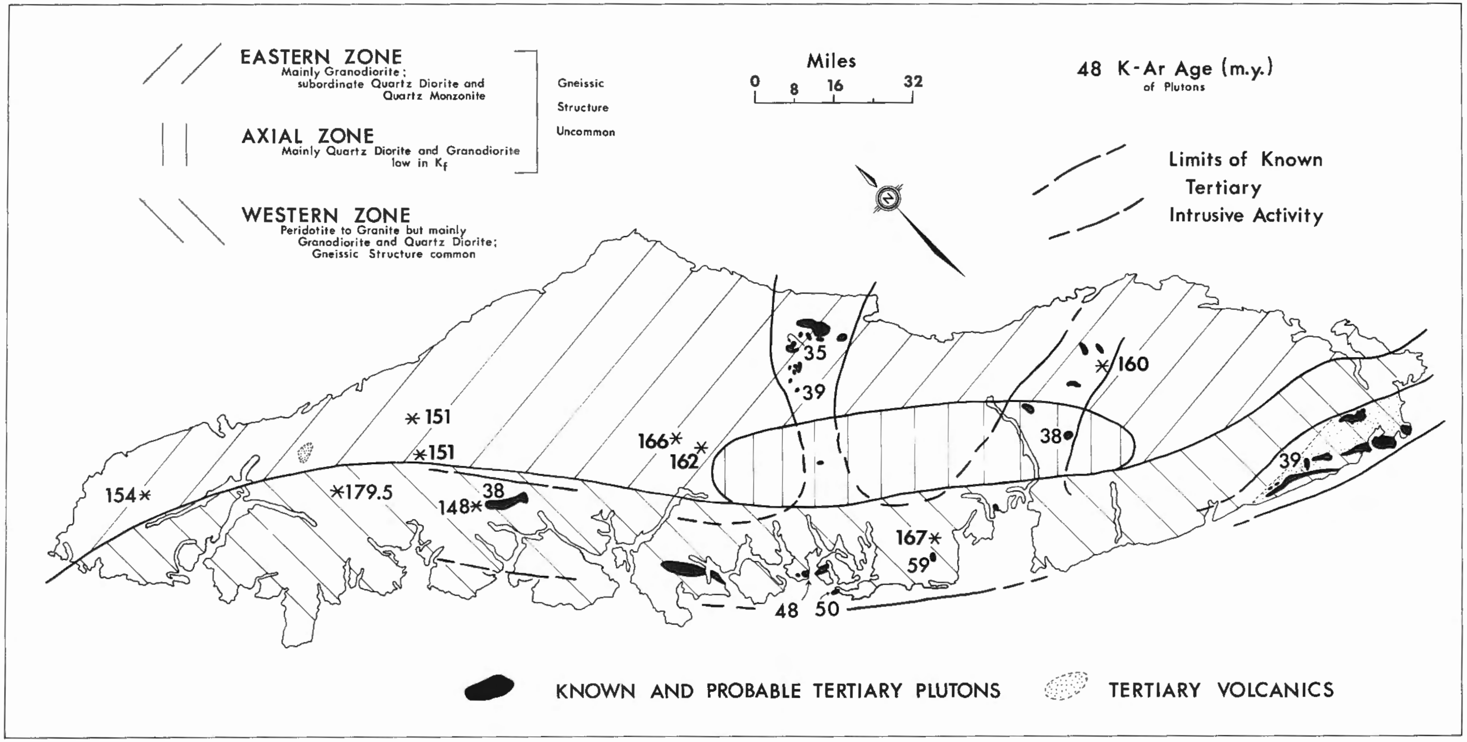

Figure 4. Compositional zoning of the plutonic rocks and zones of known Tertiary intrusive activity.

Most rocks of the Bedwell batholith, including the porphyritic border at Della Lake, are strongly altered. This is revealed by the extremely cloudy nature of plagioclase, which is saussuritized, and by strong chloritization of mafic minerals (Pl. 3). Biotite is dusty and commonly contains prehnite lenses and opaque streaks. Torn and bent biotite and chlorite and fractured quartz indicate that the rocks are somewhat deformed.

Alberni plutons have textures and alterations similar to those of the Saanich granodiorites.

Quartz diorites of probable and known Tertiary age in the central axial area are at Big Interior Mountain and at Corrigan Creek south of Alberni Inlet, respectively.

Wide Variety of Plutonic Rocks in the Western Zone

All the main compositional types of plutonic rocks from peridotite to granite occur associated with one another along the western third of Vancouver Island between Brooks Peninsula and Barkley Sound (Figs. 2, 4). The most common rock type however, is probably granodiorite since the average content of potash feldspar in 67 samples is 12.0 per cent. Many of the plutons are highly variable in composition and a large number are strongly gneissic and/or foliated. Most of the plutons are believed to be Jurassic but the largest and most varied of the known Tertiary intrusions are also found in this area, and it is not possible to estimate the number of plutons of unknown age which may be Tertiary. As already noted there is some evidence for the presence of Late Cretaceous plutons along the western belt. These may include some of the more salic varieties such as the Nootka batholith.

The rocks studied exhibit wide variations in degree of alteration. Most are moderately to strongly altered.

Rocks in the Zeballos-Esperanza Inlet area ranging in composition from gabbro to granite have been described by Hoadley (1953). Modes determined for specimens of these rocks are given in Table 3 (in pocket). A similar wide variety of rocks is present in the Nootka Sound area as is shown by Table 3 and Figure 2. Granite from the Nootka batholith, containing neglibible mafic minerals and with potash feldspar greater than 50 per cent of the total feldspar, is medium grained, fresh, pink hypidiomorphic-granular and contains large twinned perthitic potash feldspar crystals (Pl. 4). These enclose plagioclase crystals with albitized borders.

Gneissic diorites and gneissic quartz diorites of the Sydney Inlet-Ahousat area have highly clouded plagioclase and exhibit extreme development of prehnite lenses in biotite. Quartz may be highly fractured. Gneissic quartz diorites and diorites from Tofino Inlet, Muchalat Arm (Pl. 5) and Nitinat Lake, and the Wark and Colquitz gneisses of the Victoria area are very similar in most respects.

Mesozoic(?) Peridotite - Gabbro

Two bodies of peridotite were observed by the writer and a 75-foot-wide peridotite dyke intrudes the Bedwell batholith near Bedwell River (Sargent, 1941). One of the observed bodies, at Meares Island, is known to contain minor quantities of nickel-bearing sulphide (Muller and Carson, 1969). The other, of unknown size, is exposed near Corrigan Creek.

Medium-grained dark green to black peridotite is exposed for several hundred feet along the southwestern edge of Meares Island near Tofino. At one locality serpentinized peridotite contains masses up to several feet long of pyrrhotite and chalcopyrite with up to 0.7 per cent nickel (J. J. McDougall, pers. comm., 1967).

To the north of the peridotite is coarse-grained gabbro. Both are probably part of the same intrusion. They are within a gneiss complex which is believed by Muller (Muller and Carson, 1969) to have been derived from the Sicker Group. Muller also believes that the peridotite-gabbro intrusion is a sill and is equivalent to the basic sills in the Sicker Group at other localities on Vancouver Island. At several places the peridotite has been intruded by small dykes of grey granodiorite.

Under the microscope the peridotite (no. 85, Table 3) is observed to contain at least 80 per cent of closely-packed pyroxene and olivine crystals up to 4 millimetres long but averaging approximately 2.5 millimetres in length. They are altered to serpentine and chlorophaeite(?) along fractures and cleavages. Pyrrhotite and magnetite occur as interstitial strings and masses, in thin strings along pyroxene cleavages, and as rims on round olivine crystals. The mineral composition of the rock as determined by point counting is given in Table 3. The texture and mineral composition of this rock are typical of a cumulate. The mode of the gabbro exposed north of the peridotite is also given in Table 3 (no. 84).

The peridotite, according to Muller, may be comagmatic with the Karmutsen Formation and therefore of Triassic age. Alternatively, it may be the same age as the peridotite dyke near Bedwell River which is described by Sargent (1941). This dyke intrudes the Bedwell batholith and is probably therefore post Jurassic.

Jurassic (?) and Cretaceous (?) Dykes

A hornblende andesite dyke with small amounts of biotite is the only dyke from Vancouver Island which has been dated by K-Ar methods. It cuts the Brynnor orebody and yields an age of 121 ± 35 m.y. (Wanless et al., 1965). Such hornblende andesite dykes are common near many skarn and vein-type metalliferous deposits.

Relatively salic porphyritic dykes, including plagioclase porphyry, quartz-plagioclase porphyry, and hornblende-plagioclase porphyry, from Coast Copper Mine, Alice Lake Group, Lynx Mine, Price deposit, Buccaneer Mine, and Comego were studied under the microscope. Most are moderately to strongly altered to sericite, kaolin, and chlorite. Many have been described in previous publications. Except for the dyke at Price, which is believed to be related to the Jurassic(?) Bedwell batholith, it was not possible for the writer to deduce much new information on their ages other than that they are unlike any known Tertiary dykes, and are probably therefore, related to Jurassic stocks, batholiths, and (Bonanza) volcanics.

Sutherland Brown (1962) noted the abundance of pre-ore feldspar porphyry dykes near skarn deposits. The writer has noted that at Zn-Pb skarns in particular, pre-ore (?) feldspar porphyry dykes are common.

PETROGRAPHY AND DISTRIBUTION OF TERTIARY AND PROBABLE TERTIARY PLUTONS

Quartz Diorites and Sooke Trondhjemites

Unaltered quartz diorites yielding Tertiary K-Ar ages from Zeballos, Sooke, Catface Peninsula, Faith Lake, and Mount Washington, are very similar in most respects. The Zeballos quartz diorite was fully described by Stevenson (1950) and the quartz diorite stock at Mount Washington by Carson (1960).

Zeballos quartz diorite (no. 54)[1] is typical (Fig. 5). It is light grey, fresh, fine- to medium-grained, hypidiomorphic-granular biotite-hornblende-quartz diorite. It contains 54.8 per cent subhedral plagioclase (An_{18-45}), with intricate oscillatory zoning, 11.0 per cent anhedral biotite pleochroic from dark brown to light yellowish brown, 5.0 per cent subhedral to anhedral amphibole pleochroic from dark green to medium greenish brown, 28.6 per cent anhedral quartz, 0.6 per cent apatite, less than 1 per cent clear green chlorite intergrown with biotite, and less than 1 per cent opaque minerals.

The content of plagioclase in the Tertiary quartz diorites varies from about 50 per cent to 70 per cent. In all cases it is strongly zoned with intricate oscillations (Carson, 1960) and maximum ranges in composition are from approximately An_{15} to An_{65}. Most crystals are almost entirely free from the clouding which is so common in Jurassic plagioclases.

Only minor amounts of biotite are present in the Mount Washington quartz diorite (Pl. 7) but most other Tertiary quartz diorites contain as much as 10 per cent fresh biotite and hornblende. Biotite replacing hornblende at Sooke and Faith Lake is believed to have formed by late magmatic reactions. Clear green chlorite is intergrown with some of the biotite at most localities and is probably also late magmatic.

Quartz may or may not exhibit strain shadows but shows no signs of granulation or recrystallization (Stevenson, 1950, p. 31).

Apatite and magnetite are the common accessory minerals but very small amounts of sphene and epidote may also be present. Potash feldspar is present in small amounts (<5 per cent) in quartz diorites at Catface Peninsula (Pl. 3) and Zeballos, possibly as the result of minor assimilation of host rocks. It is rare in the other quartz diorites. The only potash feldspar observed in numerous samples studied from Mount Washington was in a one-inch-wide aplitic dyke cutting quartz diorite.

Most of the small granitic plutons of the Sooke area (Fig. 6) are trondhjemite (Pl. 14). They are more highly altered than other Tertiary plutons and coarse epidote is especially abundant. Gradational contacts with their host rocks are common. The interiors of two of the larger plutons are quartz diorite which is petrographically very similar to those elsewhere on Vancouver Island. Gradations between Sooke trondhjemite and typical Tertiary quartz diorite or dacite porphyry have been observed in the large pluton west of Sunro mine, and the pluton six miles north of Sooke (Fig. 6); "granitic" zones in Sooke gabbro at Merryth copper deposit are quartz diorite or trondhjemite.

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[1] Number refers to the number of the specimen in Figure 2 and Table 3.

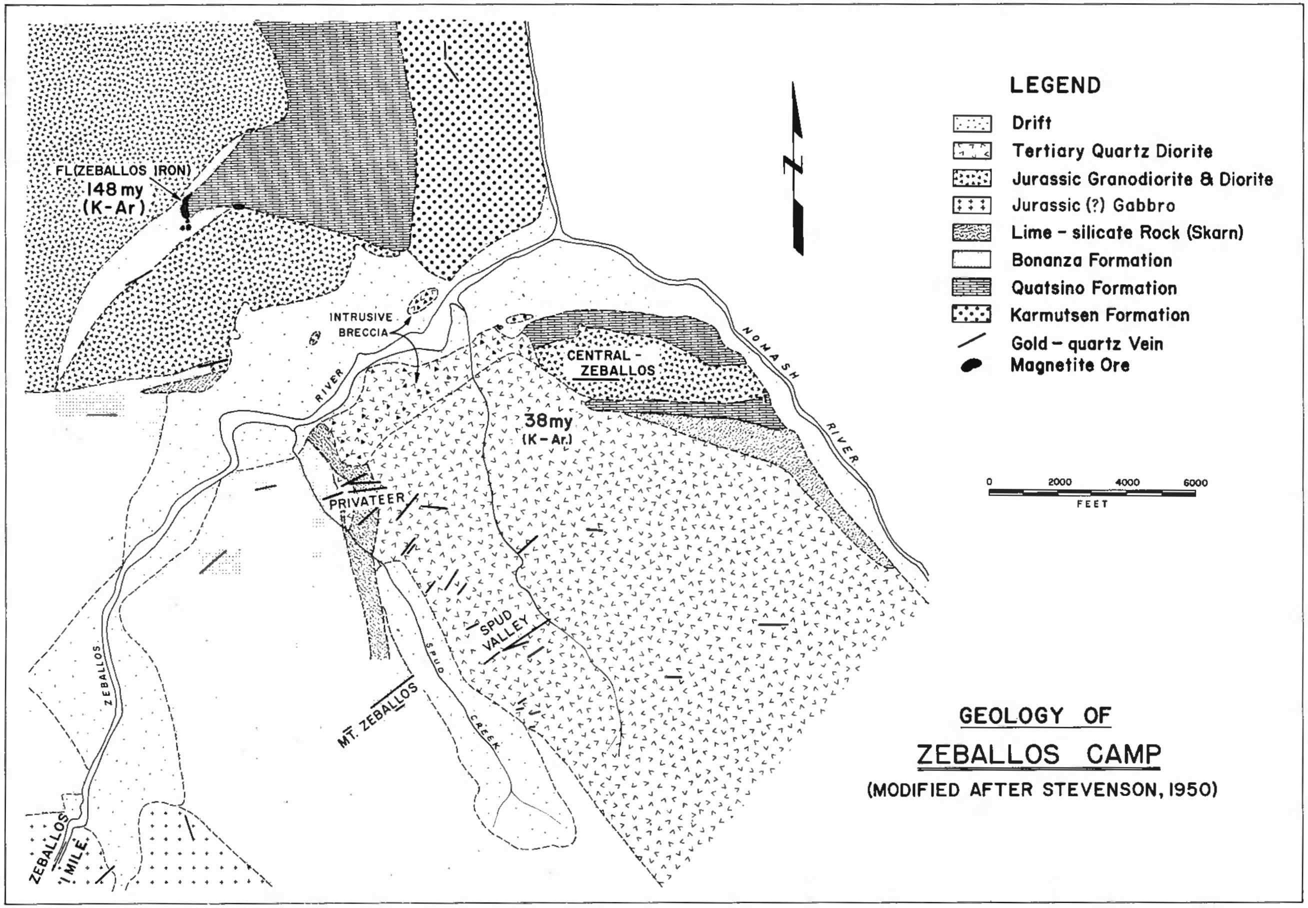

Figure 5. Geology of the Zeballos gold-mining area (modified after Stevenson, 1950). Note the contact breccia at the north end of the Tertiary quartz diorite pluton.

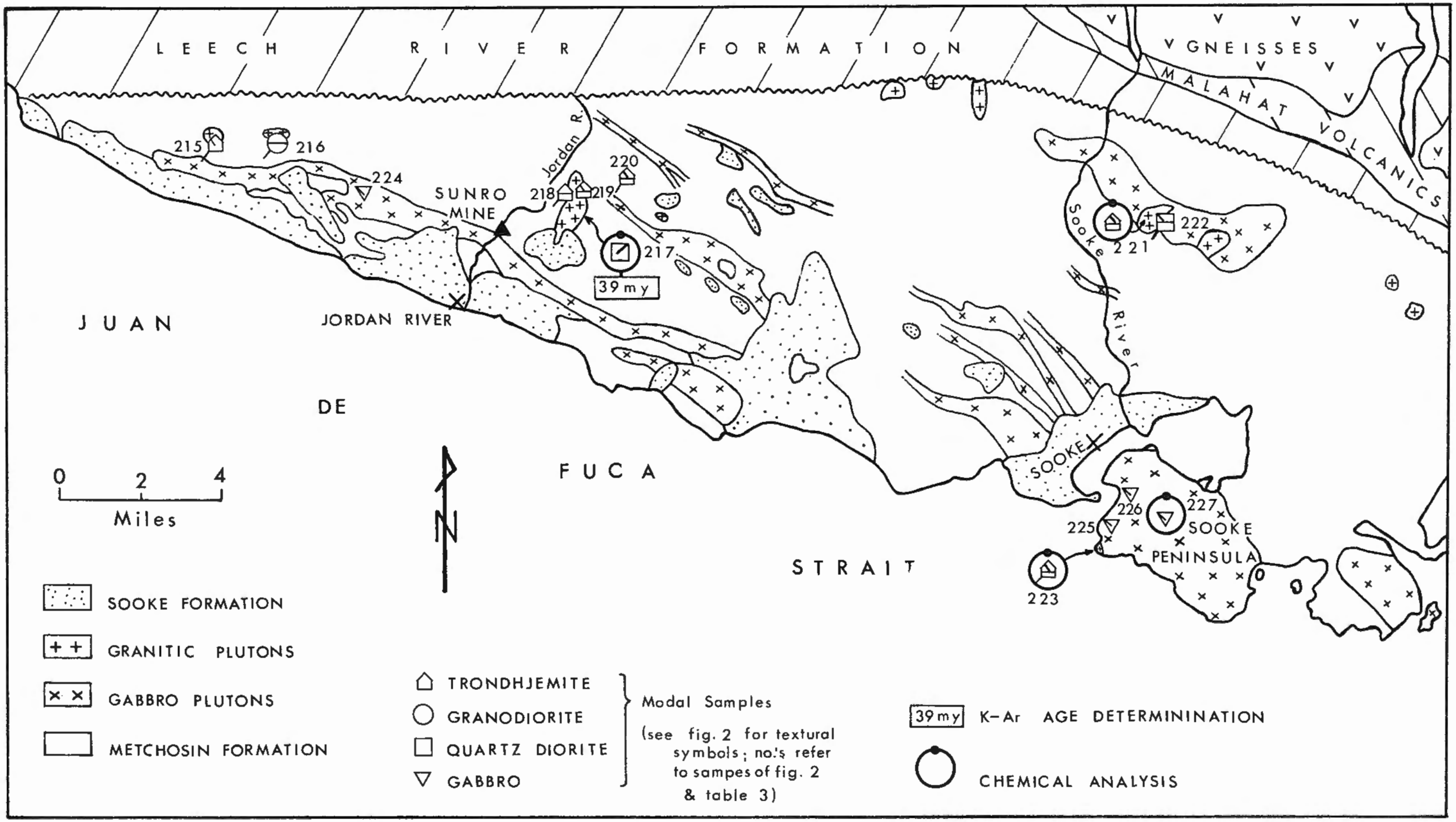

Figure 6. Geology of the Sooke-Jordan River area (after Clapp and Cooke, 1917, and unpublished map of Macsan Expl. Co. Ltd., with modifications and additions by the present writer).

Relatively unaltered, seriate, hornblende-biotite quartz diorite occurs in two small patches in the cirque of Big Interior Mountain; it is probably Tertiary. These patches are cut by quartz diorite porphyry dykes which are also probably Tertiary (next section). Largely unaltered quartz diorite which is also Tertiary occurs at Corrigan Creek south of Alberni Inlet (Fig. 2).

The quartz diorites at Catface Peninsula, Big Interior Mountain, Faith Lake, Gem Lake, and Mount Washington are alike. They occur in a northeast-trending zone which contains many gold-quartz veins and porphyry copper deposits that are believed to be Tertiary in age (Carson, 1969).

Dacite Porphyries

Hornblende dacite porphyry dykes, sills, laccoliths, and irregularly-shaped bodies of the Mount Washington–Constitution Hill area (Fig. 7) have been described in detail by Carson (1960). Texturally they grade into fine- to medium-grained quartz diorites. Concordant sill-like bodies of hornblende dacite porphyry occur in the Nanaimo Group at several other localities (Fig. 2). Dykes and irregular bodies of known Tertiary age occur at Zeballos, Catface, Sooke and Faith Lake.

Typical dacite porphyry (Pls. 8, 9) is a light grey porphyritic or seriate rock with abundant hornblende and plagioclase phenocrysts which range in size up to 9 millimetres, but average 1-2 millimetres in length. Some porphyries at Mount Washington contain broken phenocrysts. The fine-grained matrix consists of quartz, plagioclase and hornblende. Quartz phenocrysts are present in some porphyries. Plagioclase may range from oligoclase to labradorite and generally exhibits strong oscillatory zoning. Some crystals are composite; some are highly saussuritized. Biotite and potash feldspar are not common.

Unaltered dacite porphyry dykes believed by the writer to be of Tertiary age have been observed at Big Interior Mountain and Warn Bay. Seriate or porphyritic quartz diorite forms portions of the small plugs at Faith Lake and Gem Lake (Fig. 2).

Granodiorite and Quartz Monzonite

Small granodiorite and quartz monzonite plutons occur at Tofino and Paradise Creek near Kennedy Lake, respectively. They yield Tertiary K-Ar ages of 50 ± 5 m.y. and 59 ± 3 m.y., respectively. Another small plug of unknown composition occurs at Barkley Sound and has been mapped as Tertiary by Muller (Muller and Carson, 1969). Many other small granodiorite porphyry plutons of unknown age will probably be found to be Tertiary by future investigators.

The Tofino pluton has a medium-grained equigranular core, but along its eastern edge it is porphyritic with a very fine grained matrix. Both varieties (nos. 86, 87) are greyish pink. They contain more than 25 per cent quartz, approximately 40 per cent plagioclase which is more calcic in the porphyritic variety, 18 per cent potassic feldspar, several per cent biotite, and approximately 1 per cent accessory minerals.

Most plagioclase crystals are unaltered but a few are highly clouded. They occur as zoned phenocrysts up to 5 millimetres long in the porphyritic rock but are only moderately zoned in the equigranular phase. Very fine grains of potash feldspar are interstitial in the porphyry, but are up to 2.5 millimetres long in the equigranular rock where they are finely to coarsely perthitic.

The presence of haloes up to 0.04 millimetre in diameter around minute decomposed zircon(?) crystals enclosed in biotite in the equigranular granodiorite from Tofino is unusual for the granitic rocks of Vancouver Island. The haloes resulted from the decomposition of radioactive elements in the zircon(?). Some biotite crystals contain chlorite streaks and prehnite lenses. Small amounts of pyroxene (cores in amphibole crystals) and rutile(?) are also present in the rock.

The Paradise Creek quartz monzonite porphyry is fresh pink, fine to medium grained, and inequigranular. It is the only rock of Vancouver Island seen by the writer which contains phenocrysts or porphyroblasts of potash feldspar (Pl. 10). These crystals are up to 5 millimetres in diameter, and larger than any of the phenocrysts of quartz, biotite, or plagioclase. They are commonly twinned (Carlsbad).

Moderately zoned oligoclase, and biotite and quartz crystals reach maximum lengths of approximately 3 millimetres. Biotite is deep brown to pale yellow. The occurrence of zoned poikilitic tourmaline crystals (Pl. 10) which are pleochroic from light brown to very deep green is unusual. This mineral was noted in only one other rock studied, a diorite from Sharp Point (no. 73).

Gabbro

The elongate gabbro plutons at Sooke have been fully described by Clapp and Cooke (1917), Cooke (1919), and Stevenson (1951). Modes of four specimens are given in Table 2 and their localities are shown in Figures 2 and 4.

These Tertiary gabbros are in most localities relatively unaltered except for amphibole replacing pyroxene and some saussuritization of plagioclase. Similar, relatively unaltered gabbro plutons of possible Tertiary age occur in the Cowichan Lake area (Fyles, 1955), and at Rock Bay, Tahsis, and Zeballos (nos. 115, 59, and 58, respectively).

Breccias Related to Tertiary Plutons

Breccias of various types are known to occur near the Tertiary quartz diorite plutons. Two types occurring near the forcibly intruded Mount Washington stock (Fig. 7) are closely akin to explosive diatreme, and to collapse breccias. Breccia believed to be a result of forcible intrusion occurs at the north end of the Zeballos quartz diorite pluton (Stevenson, 1950). It is several thousand feet long and consists of angular fragments of volcanic rock enclosed in a quartz diorite matrix. Similar breccia occurs at the edges of the Sooke plutons (Pl. 13).

The Murray breccia of Mount Washington (Fig. 7) is an oval, pipe-shaped diatreme about 2,500 feet by 800 feet in surface dimensions, which has been shown by diamond drilling to extend downward at least 700 feet (deVoogd, 1964). A similar type of breccia occurs at Murex Creek. It is exposed over a length of more than 3,000 feet and appears to have the form of a gently-dipping

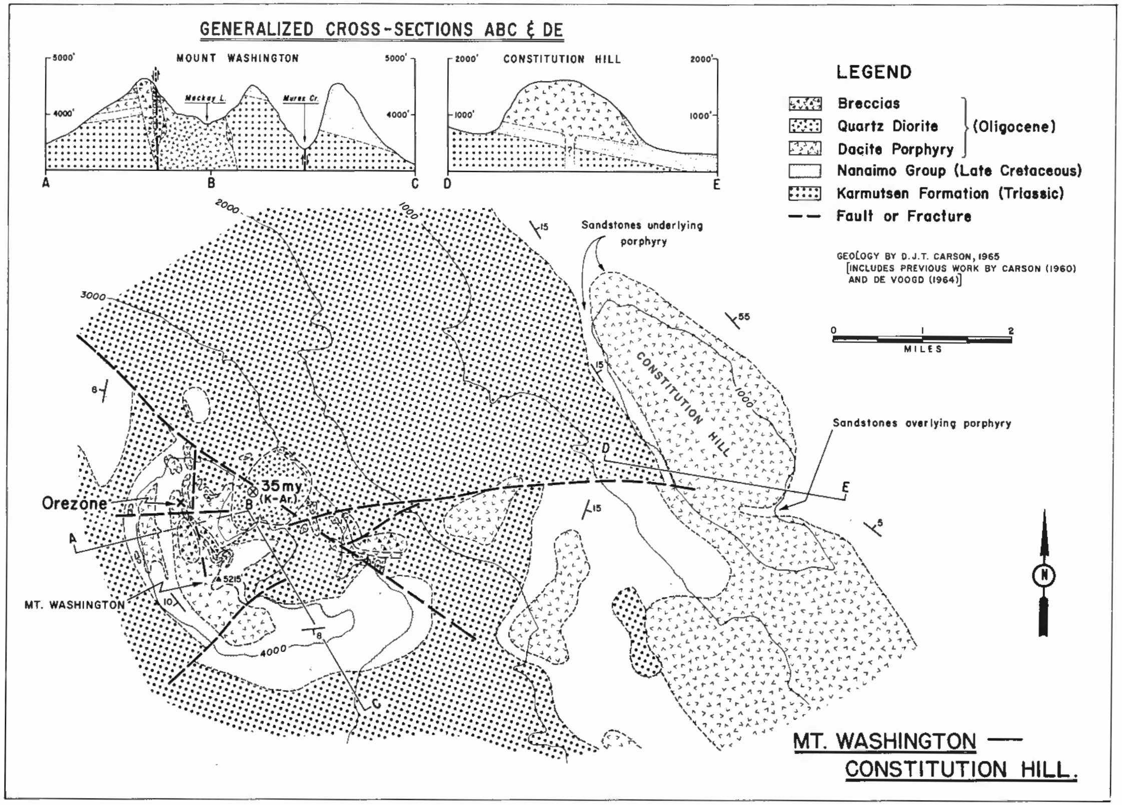

Figure 7. Geology of the Mount Washington-Constitution Hill area. At Mount Washington, note the centrally located quartz diorite stock (35 ± 6 m.y.) and marginal breccias, and the largely concordant sills or laccoliths which intrude gently-dipping Upper Cretaceous sediments underlying the semicircular ridge south and west of the stock. At Constitution Hill, Upper Cretaceous sediments underlie the porphyry laccolith along its western and eastern sides, but at one locality, remnants of the former Upper Cretaceous roof overlie the eastern edge of the porphyry, as shown in cross-section D-E.

lens. The Murray and Murex breccias consist of angular and rounded fragments of dacite porphyry, Nanaimo Group sedimentary rocks, Karmutsen Formation volcanic rocks, and broken and unbroken crystals of plagioclase, quartz and hornblende in a comminuted matrix of similar but much finer material (Pl. 11). The matrix and finer sedimentary rock fragments and cores of some plagioclase phenocrysts in the Murray breccias are commonly biotitized. However, most plagioclase, and quartz, hornblende and dacite porphyry fragments are unaltered. In many places the breccia exhibits crude layering and resembles conglomerate.

The Washington collapse(?) breccia at Mount Washington occurs in narrow, steeply dipping zones at the fringes of the stock (Fig. 7). It differs from Murray and Murex breccias in possessing abundant angular fragments, few rounded fragments, and a magnetite-rich matrix. Identical breccia containing magnetite and minor ilmenite in its matrix occurs at Gem Lake (Pl. 12).

A breccia of unknown extent is associated with Tertiary(?) quartz diorite at the north face of the cirque at Big Interior Mountain. It may be a diatreme or it may be of the same intrusive type as that outcropping at Zeballos. It contains fragments of fine- to medium-grained quartz diorite, dacite porphyry, plagioclase, quartz and radiating amphibole, in a matrix of finer similar material plus calcite and chlorite.

MODAL COMPOSITION OF THE PLUTONIC ROCKS AND COMPARISON WITH COAST INTRUSIONS AND SOUTHERN CALIFORNIA BATHOLITH

Modes of 227 samples are given in Table 3 (in pocket), and their locations are shown in Figure 2 (in pocket). Omitting numbers 123, 127, 130 and all Sooke granitic samples excepting 217 and 223 in order not to give undue weighting to small Tertiary quartz diorite and trondhjemite plutons, the percentage of rock types present according to the classification used is as follows:

Peridotite	0.5	Granodiorite	42.5
Gabbro	7.4	Quartz Monzonite	9.8
Diorite	5.1	Albite-Potash Feldspar Granite	2.2
Quartz Diorite	27.8	True Granite (K_f > albite)	1.4
Trondhjemite	3.2		

On the Qz-Kf-Pc diagram (Fig. 8) most of the granitic rocks of Vancouver Island are in three areas. The first area contains granodiorites with between twenty-five and forty per cent quartz, most of which are of Jurassic or unknown age. A large number of Tertiary quartz diorites with twenty to thirty-five per cent quartz are present in the second area, and the third area contains both Jurassic and Tertiary diorites and gabbros at the Pc apex. There are a relatively small number of Jurassic and unknown quartz monzonites but only three true granites, one of which is known to be Jurassic.

The Qz-Maf-Fp diagram (Fig. 9) indicates that as the quartz content of the rocks increases, the mafic minerals decrease and feldspars remain approximately constant. There is a preferred composition of about 30 per cent quartz, 60 per cent feldspars and 10 per cent mafics. There is no obvious separation of Jurassic and Tertiary plutons on this diagram.

Modes of granitic pebbles from Aptian conglomerates (Fig. 10), from Rupert Arm on northern Vancouver Island, are similar to those of the Jurassic intrusions of all of Vancouver Island (Figs. 8, 9). Certain differences have been discussed previously.

If adjustments are made so that the classification used for Vancouver Island plutonic rocks corresponds with that of Roddick (1965) an over all comparison can be made between the granitic rocks of Vancouver Island and those of the Coast Range near Vancouver. Table 4 lists the relative percentages of various granitic rock types for the Vancouver North and the Pitt Lake areas (Roddick, 1965), the Southern California batholith (Larsen, 1948), and Vancouver Island. Because Roddick, Larsen, and the present writer used different methods for arriving at the relative abundances, the percentage figures can only be considered roughly equivalent. However, a few general comparisons are warranted.

The relative abundances of Vancouver Island and Vancouver North plutonic rocks appear to be somewhat similar. The Vancouver Island rocks may be slightly richer in potassium feldspar as they consist of 11 per cent more granodiorite, quartz monzonite and granite. However, only three of the 227 samples collected on Vancouver Island are true granites as defined in this report (Kf > 1/2 total Fp). Two of these are from the most salic pluton on the island, the Nootka batholith (Fig. 2; Table 3), whereas the other is from a very local salic roof facies in a granodiorite pluton at Cowichan Lake

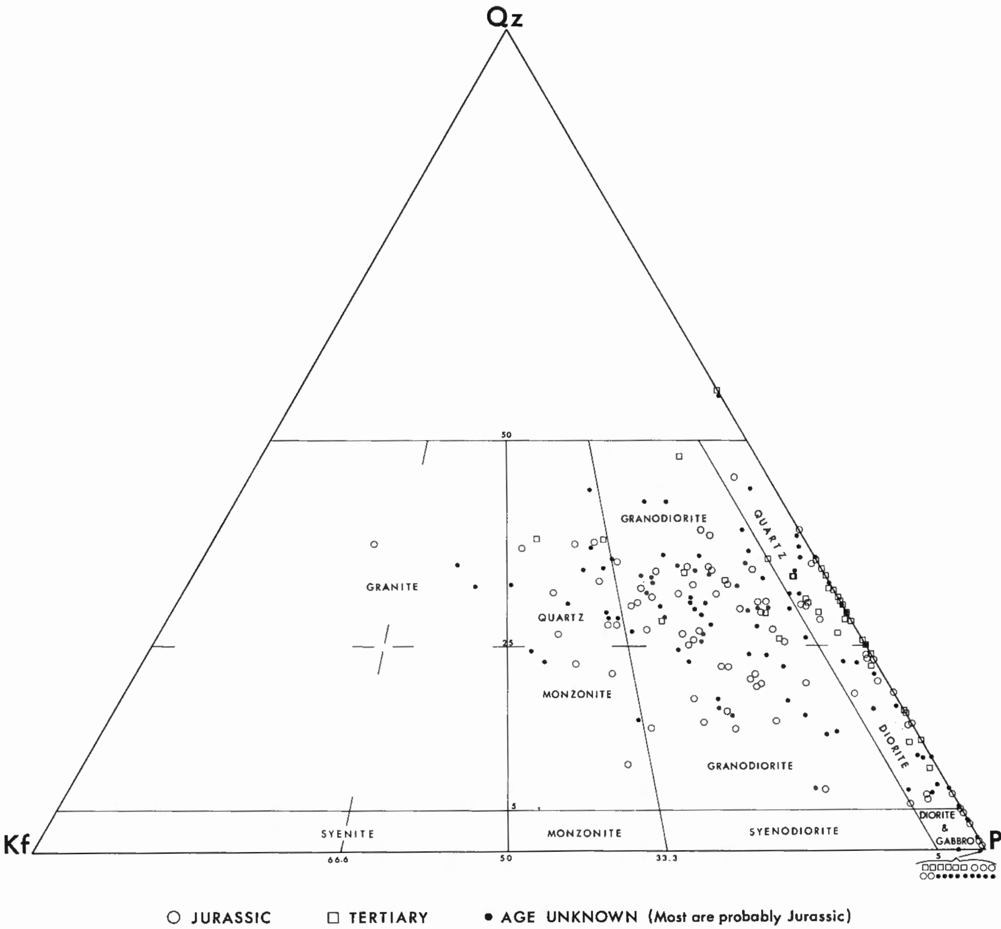

Figure 8. Qz-Pc-Kf modal diagram for plutonic rocks of Vancouver Island.

(Fyles, 1955). Only this latter sample qualifies as a true granite by the most common definition (Kf/Pc > 2/1). In this connection it is worth noting here that potash feldspar in most rocks of Vancouver Island is interstitial whereas plagioclase commonly forms larger crystals. Only one porphyritic intrusion containing potash feldspar phenocrysts has been found. It is Tertiary tourmaline-bearing granodiorite at Paradise Creek near Kennedy Lake.

As is apparent from the previous section, the central axial area of Vancouver Island (Fig. 4) contains mainly quartz diorite, with lesser granodiorite low in potash feldspar, and no granite. To the northeast of the axial area, the most dominant rock type is relatively homogeneous granodiorite, whereas to the southwest the rocks show wider variations in composition and texture. Most of the complex plutons containing more than one type of granitic rock, the only known ultrabasics, and all the strongly gneissic plutons, occur to the southwest of the axis. Somewhat similar northwest-trending compositional-textural zoning, but on a much larger scale, is exhibited by the Coast Intrusions of mainland British Columbia (Roddick, 1965, 1970).

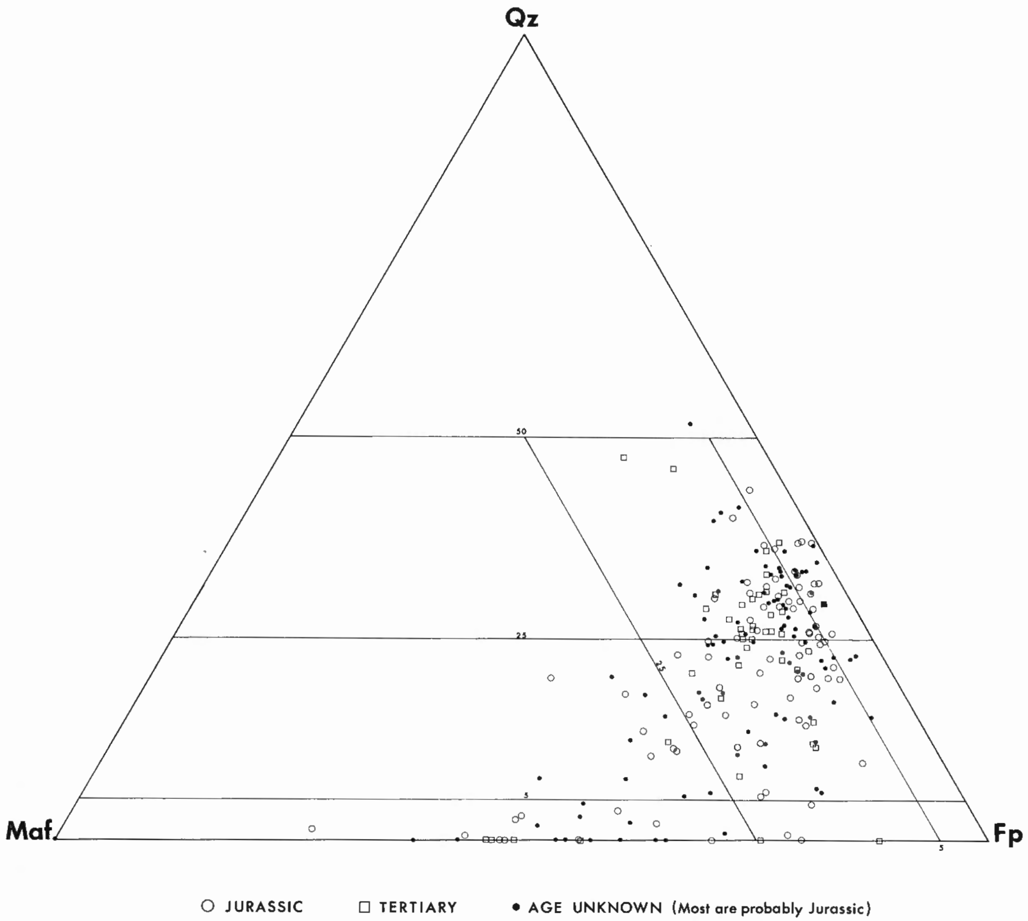

Figure 9. Qz-Maf-Fp modal diagram for plutonic rocks of Vancouver Island.

The granitic plutons of Vancouver Island are to the west of the main Coast Intrusions ("Coast Range batholith"). Vancouver North map-area (Roddick, 1965) includes the western edge of the main Coast Intrusions. Both areas contain higher proportions of granodiorite, quartz monzonite and granite and smaller percentages of quartz diorite, gabbro, and diorite than the Pitt Lake area (Roddick, 1965) which is along the axis of the Coast Intrusions. There is, therefore, a moderate rise in the content of potash feldspar in granitic rocks to the west of the axis of the southern Coast Intrusions, and this rise includes Vancouver Island. It is, however, much less pronounced than the increase in potash feldspar to the east of the Coast Intrusions, east of the northerly projection of the "quartz diorite boundary line" of Moore (1959).

In the southern Coast Intrusions and on Vancouver Island, the axial areas contain larger quantities of quartz diorite than the flanking areas which are richer in potassium feldspar. The axial area of Vancouver Island is shown on Figure 4. The rocks of both axial areas are structurally elevated and deeply eroded. As a result, deeper portions of the plutons are at the present surface, and as noted, these deeper portions are low in potash feldspar.

In the northern Coast Intrusions in the Douglas Channel–Hecate Strait area, Roddick (1970) has attributed a northwest-trending compositional zoning, with more basic plutons in the west, to a change from shield to oceanic crust along the western flanks. The smaller scale but somewhat similar compositional zoning on Vancouver Island is not as satisfactorily explained by this hypothesis although it too could be caused by differences in the subsurface crustal rocks of the three compositional zones. An alternate explanation, favoured by the writer, is that the axial area of Vancouver Island is similar to the eastern area but more deeply eroded, thereby exposing the deeper and less potassic "root" portions of plutons, whereas in the west the major fault systems (Sutherland Brown, 1966) may have been the control. The faults extend to deep levels, thereby allowing for intrusion of basic magma. Sutherland Brown (1966) has suggested that the faults may also have been conduits for heat and fluids with the resulting formation of gneisses.

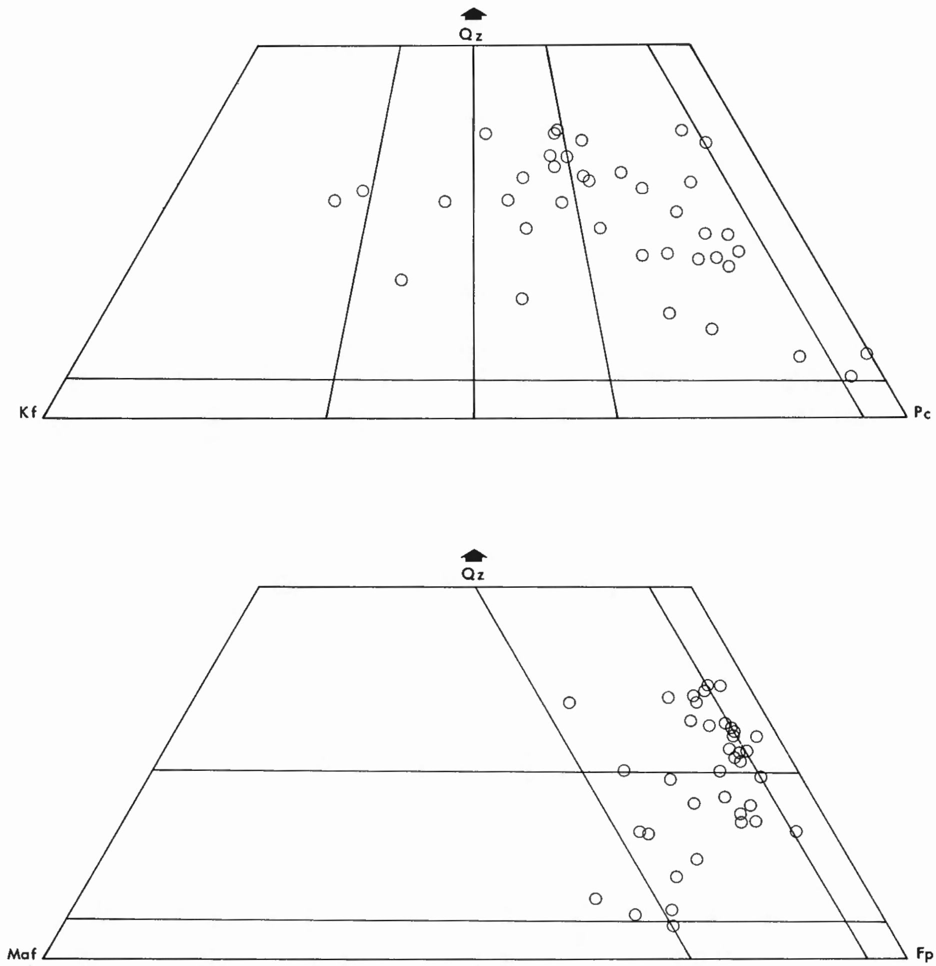

Figure 10. Modes of granitic pebbles from Aptian conglomerates of Rupert Arm and Coal Harbour (see Fig. 2 for sample localities).

TABLE 4

Relative abundances of plutonic rock types of Vancouver Island, Vancouver North, Pitt Lake, and the Southern California batholith (numbers are percentages). The classification used by the writer has been adjusted to allow comparison.

	Vancouver Island (this project)	Vancouver North (Roddick, 1965)	Pitt Lake (Roddick, 1965)	Southern California batholith (Larsen, 1948)
Gabbro, Diorite, Migmatite, Peridotite (very minor, Vancouver Island)	19.0	19.7	27.0	7
Quartz Diorite, Trondhjemite	41.1	51.4	58.4	63
Granodiorite, Quartz Monzonite	38.5	26.5	14.2	28
Granite	1.4	2.4	0.4	2

Although Tertiary plutons are much less abundant and were emplaced about 120 million years later than the Jurassic plutons, available data suggest that they too reflect this compositional zoning by area, with the widest variety of plutons in the west (Fig. 4). Thus the only known Tertiary quartz monzonite (at Paradise Creek south of Kennedy Lake), granodiorite (at Stubbs Island near Tofino), the Sooke gabbros, and the Zeballos and Catface quartz diorites occur in the west whereas the only Tertiary plutons that have been found elsewhere are quartz diorite and dacite porphyry.

Vancouver Island is much farther west of the "quartz diorite line" of Moore (1959) than is the Southern California batholith. The Vancouver Island plutons would therefore be expected to be lower in K-feldspar. However, from Table 4, the reverse would appear to be true. The larger proportion of quartz diorite and smaller proportion of granodiorite plus quartz monzonite as reported by Larsen for the Southern California batholith may possibly be partly explained by different methods of calculating the proportions. For example, whereas the writer considers individual samples, Larsen considered map-units. Portions of Larsen's tonalite plutons are granodiorite. A probable additional factor could have been that due to their different physical forms (large composite batholith versus numerous separate and smaller plutons), they had slightly different crystallization histories, thereby affecting the distribution of potassium in the various mineral phases (K-feldspar, biotite, plagioclase). This is supported by the close correspondence of their K variation curves (Fig. 11), which suggests that despite their apparent differences in K-feldspar content, the two rock series probably have similar amounts of potassium.

CHEMICAL AND NORMATIVE COMPOSITIONS OF THE PLUTONIC ROCKS

General Statement

Chemical compositions of 62 granitic rock samples from Vancouver Island are listed in Table 5 (in pocket) which also lists the corresponding norms. Many of the analyzed samples are from known Jurassic and Tertiary plutons but the number of samples from each type is not indicative of its relative abundance. In Figures 11 to 14, the different ages of intrusion are distinguished from one another by the use of different symbols.

Variation Diagrams

Variation diagrams of the types proposed by Nockolds and Allen (1953) and which are believed to illustrate trends of differentiation, are given in Figures 11 and 12. Relatively uniform trends are indicated for all elements plotted.

A separation of known Jurassic and known Tertiary[1] plutons is suggested on the Na, K, Fe, and Ca diagrams. It is absent on the Mg, Al, and Si diagrams. The fact that the curves either lie close together and parallel, or else overlap, probably indicates that the Jurassic and Tertiary plutons have somewhat similar origins.

Most known Jurassic plutons have a higher content of Ca and Fe than do known Tertiary plutons of the corresponding stage of differentiation. Higher Ca and Fe may be caused by contamination (see next section) of the Jurassic plutons by their host rocks, which were largely basic volcanics and limestone of the Vancouver Group and rocks of the Sicker Group. Tertiary plutons are smaller and may have been less able to incorporate large quantities of their host rocks.

The K content of known Jurassic plutons is generally higher and the Na content lower than that of known Tertiary plutons, and a greater number of the Jurassic plutons are more highly differentiated. The differences in K and Na may be reflections of slight differences in the parental rocks. The Jurassic plutons are larger and crystallized at greater depths (see p. 48). This probably enabled them to reach more advanced stages of differentiation over a longer period of cooling.

Chemical similarities between plutons of Vancouver Island, particularly the Jurassic plutons, and those of the batholith of southern California (Larsen, 1948) are suggested by the close correspondence of variation curves. As already mentioned, it is interesting to note that although the plutons of Vancouver Island are much farther to the west of the "quartz diorite line" of Moore (1959) than is the batholith of southern California, the variation diagrams (Figs. 11, 12) suggest that the over all contents of K and Si in the plutonic rocks of the two areas are similar.

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[1] It should be noted that the two most potassic Tertiary members which plot near the end of the series yield the oldest K-Ar dates. This is not considered to nullify the validity of the diagram since it is believed that separate chambers of magma undergoing differentiation may have been present in various places and at various times during the early Tertiary.

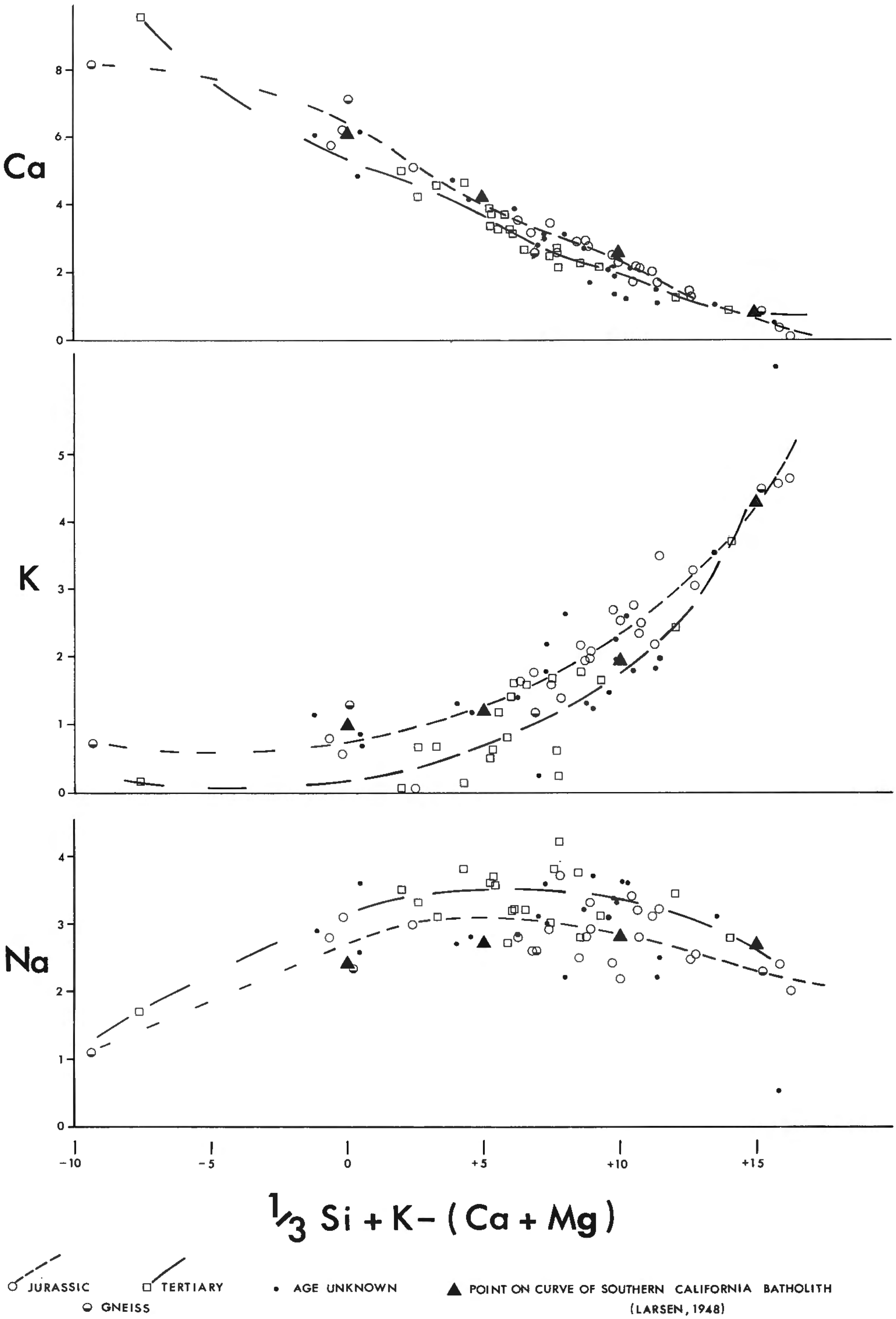


Figure 11. Na-Ca-K variation diagrams for plutonic rocks of Vancouver Island.

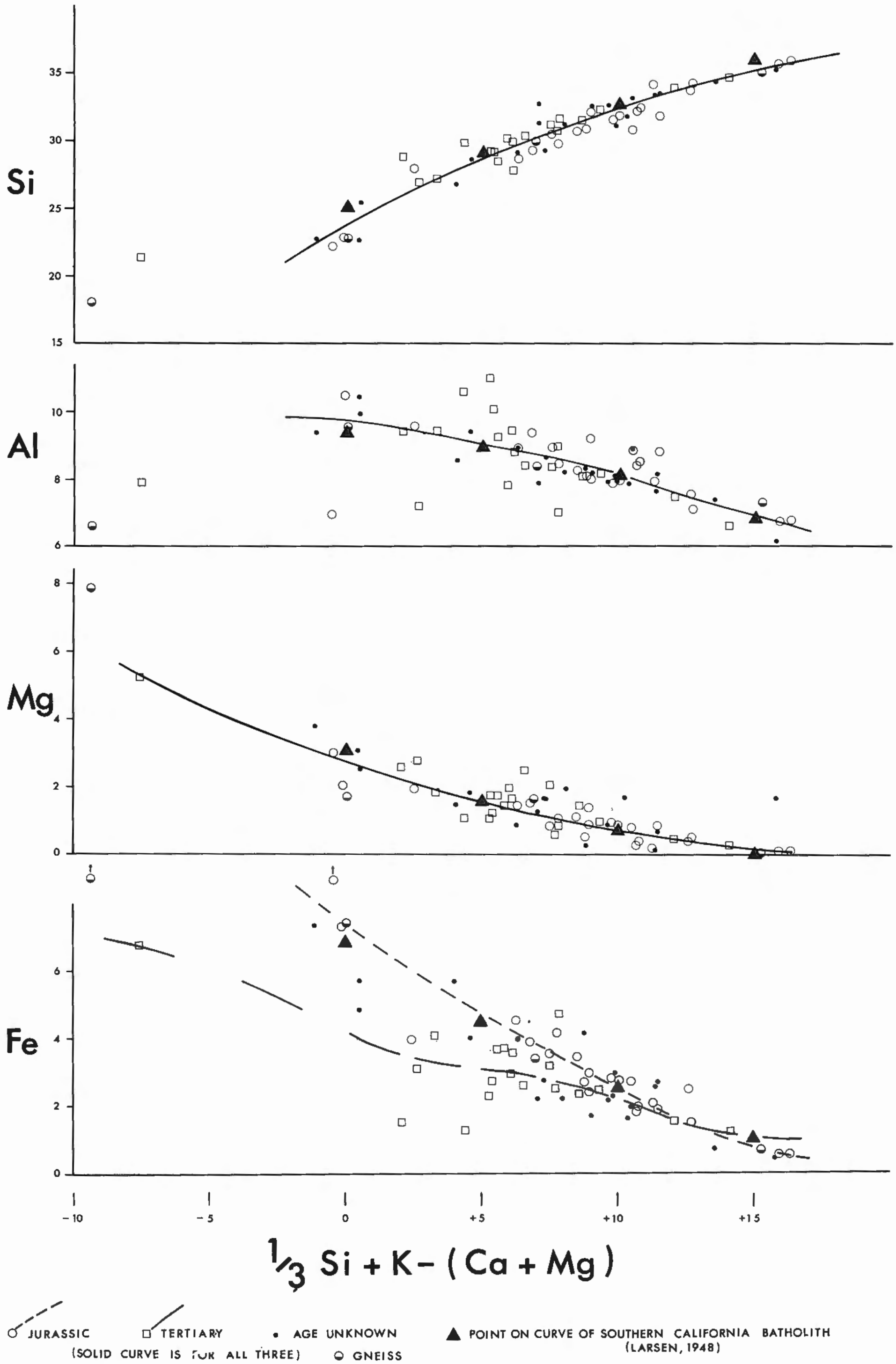
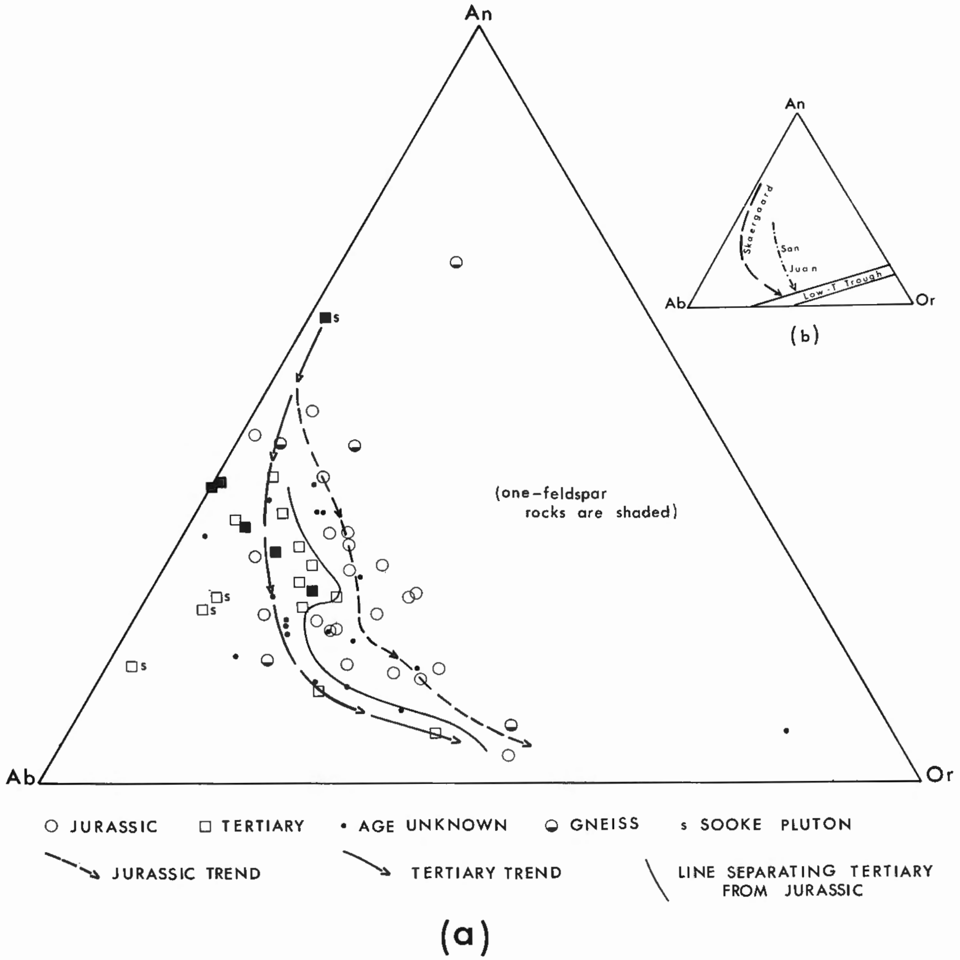


Figure 12. Fe, Mg, Si, Al variation diagrams for plutonic rocks of Vancouver Island.



(a) Plutonic rocks of Vancouver Island.
(b) Differentiation trends after Kleeman (1965).

Figure 13. An-Ab-Or diagram.

Ternary Normative Diagrams

The separation of Na, K, and Ca on variation diagrams (previous section) for known Jurassic and known Tertiary plutons is much clearer on the normative An-Ab-Or diagram (Fig. 13a).

Tertiary plutons plot principally near the An-Ab or Ab-Or joins whereas Jurassic plutons plot closer to the centre of the diagram. The areas occupied by Tertiary and Jurassic plutons correspond roughly to the one-feldspar field and the two-feldspar field of the system respectively. This is in accord with their mineralogy. None of the known Jurassic rocks in Figure 13a contains only one feldspar. On the other hand, several Tertiary plutons contain only plagioclase feldspar, yet possess considerable normative orthoclase, much of which is probably in solid solution in plagioclase. Stevenson (1950, p. 43) believed that plagioclase in the Zeballos quartz diorite must contain considerable potassium. This pronounced solid solution is indicative of crystallization at high temperatures and/or low water vapour pressures.

Jurassic and Tertiary differentiation trends appear to begin at approximately the same position on the diagram, indicating that the rocks probably were derived from somewhat similar basic parental material.

Kleeman (1965) discussed the An-Ab-Or system and its bearing on the origin of granites. For most rock series differentiation proceeds from near the An-Ab join towards the low temperature trough near the Ab-Or join (Fig. 13b). Kleeman believed that the trend for the San Juan Province differs from that of the Skaergaard (Fig. 13b), because large volumes of salic host rocks were incorporated in the former during emplacement, causing contamination and modifying the differentiation trend. There is a similarity between the differentiation trends of the uncontaminated Skaergaard and the Tertiary Vancouver Island plutons, and between those of the San Juan Province and Jurassic plutons. This suggests that contamination by host rocks may have been important during emplacement of the Jurassic plutons but that the Tertiary plutons are mainly uncontaminated differentiates. Support for these conclusions may be provided by the following:

(1) Sangster (1969) and Eastwood (1965) believed that the iron of the contact metasomatic magnetite deposits, most of which are related to Jurassic plutons (Carson et al., 1971) was derived from Karmutsen volcanic rocks due to incorporation of the volcanics by magmas. The relatively high calcium and iron contents of Jurassic plutons has been discussed and may be a result of this contamination.

(2) Many Jurassic plutons possess basic border zones and gradational contacts with their host rocks indicating the possibility of contamination. The contacts of Tertiary plutons, other than some of the Sooke trondhjemites, [1] are generally sharp.

(3) Gold-quartz veins and Tertiary plutons are spatially and probably genetically related (Carson, 1969). Despite widely varying host rocks, the gold-quartz veins of all areas of Vancouver Island have very similar sulphide mineralogy. Their composition has been little influenced by their host rocks and this probably holds true for the associated Tertiary plutons.

If contamination did modify the Jurassic trend, salic material (which melts at relatively low temperatures) may have been derived by partial assimilation, especially of Sicker and older rocks. The residual, more basic material, may be represented by gneisses such as those along the west coast, the Wark gabbro-diorites and the Colquitz quartz diorites (Muller and Carson, 1969).

Distribution of known and probable Tertiary plutons and known Jurassic plutons on the Qz-Ab-Or diagram is shown in Figure 14. Many Jurassic plutons and the potassium feldspar-rich Tertiary pluton at Paradise Creek (Fig. 2) are relatively near to the minima for water vapour pressures of 1,000-2,000 bars (Tuttle and Bowen, 1958). Most other Tertiary plutons

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[1] Three Sooke plutons plot towards Ab and to the left of the Tertiary trend in Figure 13a. The Sooke plutons occur in a special environment, being associated with Eocene spilites. Their high sodium content may reflect this association.

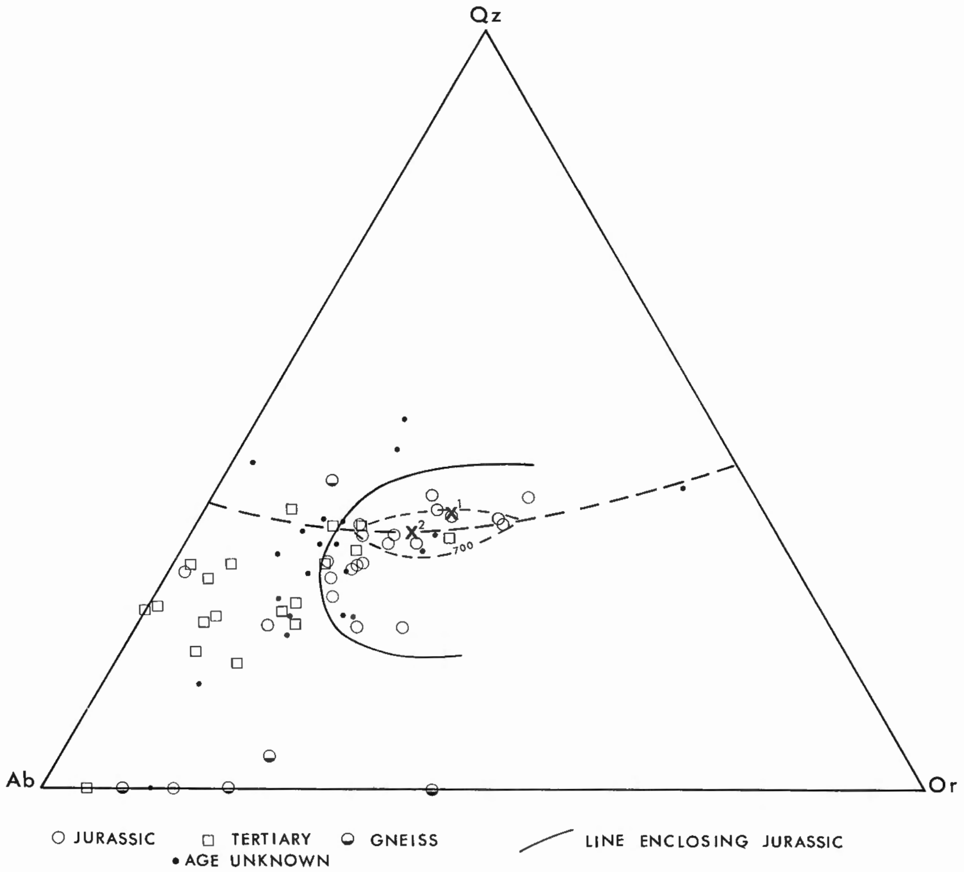

Figure 14. Qz-Ab-Or diagram for plutonic rocks of Vancouver Island. Included are the minimum (X^2), and the quartz-feldspar boundary curve and 700°C isotherm (broken lines) for a water vapour pressure of 2,000 bars, and also the minimum for 1,000 bars (X^1). Data after Tuttle and Bowen (1958).

are near the Qz-Ab join. Many plutons of unknown age occur in both the Tertiary and Jurassic areas, indicating that there may be more overlap of the two ages of plutons than is readily apparent from the diagram.

The above facts support the conclusions that more Jurassic plutons completed crystallization at lower temperatures than did Tertiary plutons, and that they are at a more advanced stage of differentiation and/or have assimilated more salic material.

PHYSICAL FORMS OF THE PLUTONS

Jurassic Gneisses

Wark, Colquitz, and similar granitic gneisses (Clapp and Cooke, 1917; Muller and Carson, 1969) may grade into their host rock and in many places their contacts with older rocks are concordant. These rocks are believed by Sutherland Brown (1966) to be syntectonic. They have many of the characteristics of plutons of the catazone (Buddington, 1959). These include prominent gneissosity and extensive border migmatite zones which are especially common in the Tofino–Hesquiat area, where the rocks are commonly of the amphibolite facies of regional metamorphism (Muller and Carson, 1969).

Non-Gneissic Jurassic Plutons

Included in this grouping are all plutons in which strong foliation or gneissosity are not dominant features.

Saanich-type granodiorite plutons of the Cowichan Lake area (Fyles, 1955) are post-tectonic, northwest-trending dyke-like bodies with steeply-dipping contacts. They intrude the Sicker Group and the Karmutsen Formation.

The physical form of the Nimpkish batholith at Kinman copper property has been studied by Gunning (1932a). The main body of the batholith is elongated in a northwesterly direction and is believed to have steeply-dipping contacts. However, at the Kinman property where the batholith intrudes Quatsino limestone, there are numerous concordant and/or discordant tongues, some of which dip at very low angles.

Most of the granitic plutons in the Zeballos–Nimpkish area (Hoadley, 1953) have been emplaced in the Quatsino and Bonanza Formations. They are northwest-trending bodies reaching batholithic proportions and some, such as the Bonanza batholith, appear to be generally concordant.

Sangster (1969) studied many plutons associated with the contact metasomatic magnetite deposits and concluded that they are transitional between epizonal and mesozonal types. His work was restricted to those parts of the plutons in close proximity to the Quatsino limestone. It is apparent from his work that at this stratigraphic horizon the plutons have varied forms. In places they underlie deposits in a concordant or discordant manner; elsewhere they occur as concordant or discordant tongues.

In the middle Adam River area (Fig. 15) a granodiorite intrusion seems to have the form of a sill. Its lower contact follows the upper surface of the Quatsino limestone for at least seven miles.

A recent map by Northcote (1971) shows that in northern Vancouver Island, granitic stocks occur in a northwest-trending series which follows the regional trend of the upper part of the Karmutsen Formation, the Quatsino Formation, and the sedimentary and lower pyroclastic part of the Bonanza Formation. A generalized version of Northcote's map is given in Figure 16.

From the foregoing it is apparent that in general the over all contacts of the non-gneissic plutons are steep, except in the vicinity of incompetent sedimentary rocks, especially limestone, where many intrusions are gently-dipping and semiconcordant. Some of these semiconcordant plutons are of batholithic proportions. A great majority of them occur in the

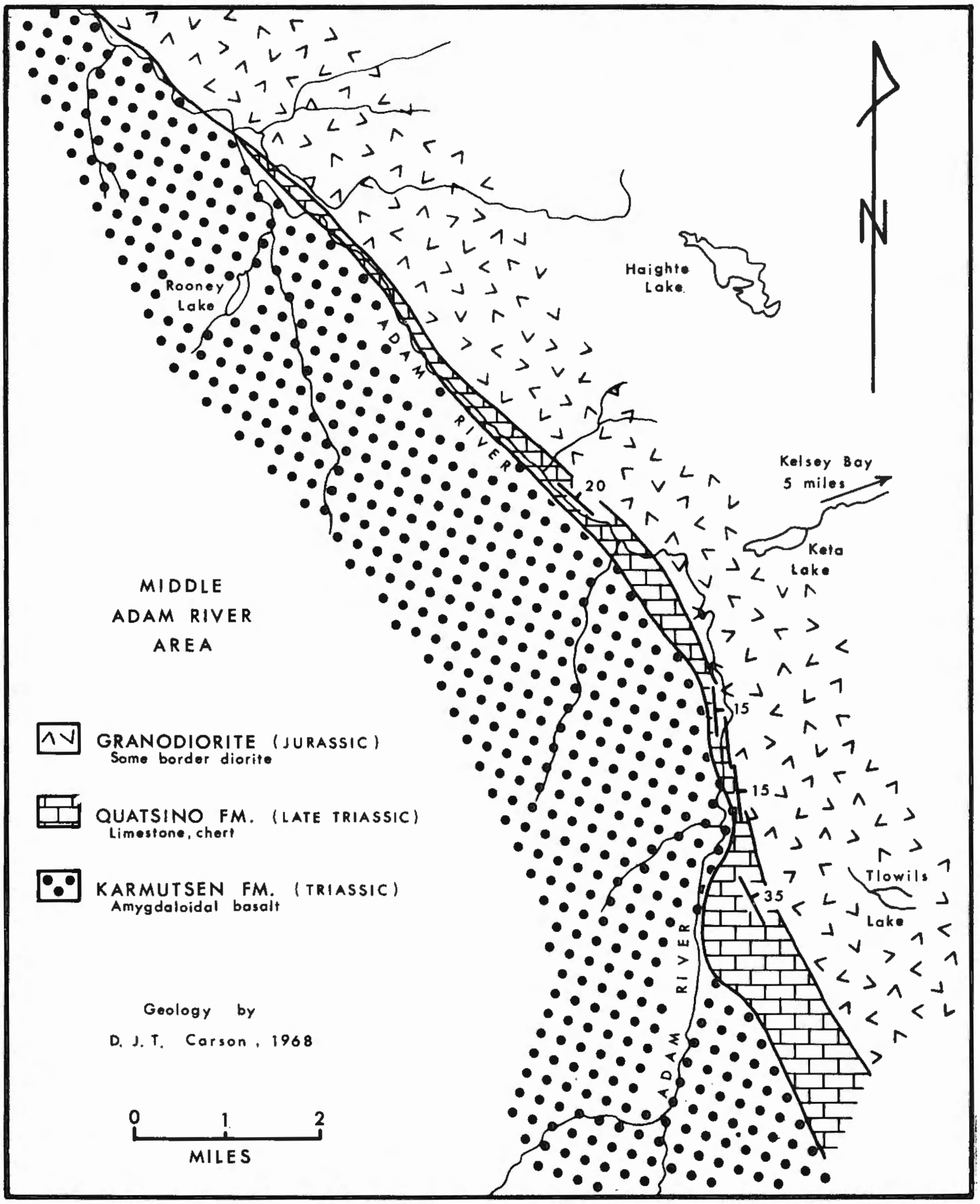

Figure 15. Geology of the middle Adam River area. Note the gently-dipping conformable contact between the Quatsino limestone and the overlying granodiorite. The granodiorite appears to occupy a regional synclinal structure, only the western half of which is shown here, because the Quatsino limestone and Karmutsen Formation reappear along the eastern side of the granodiorite, about 3 miles east of the Adam River.

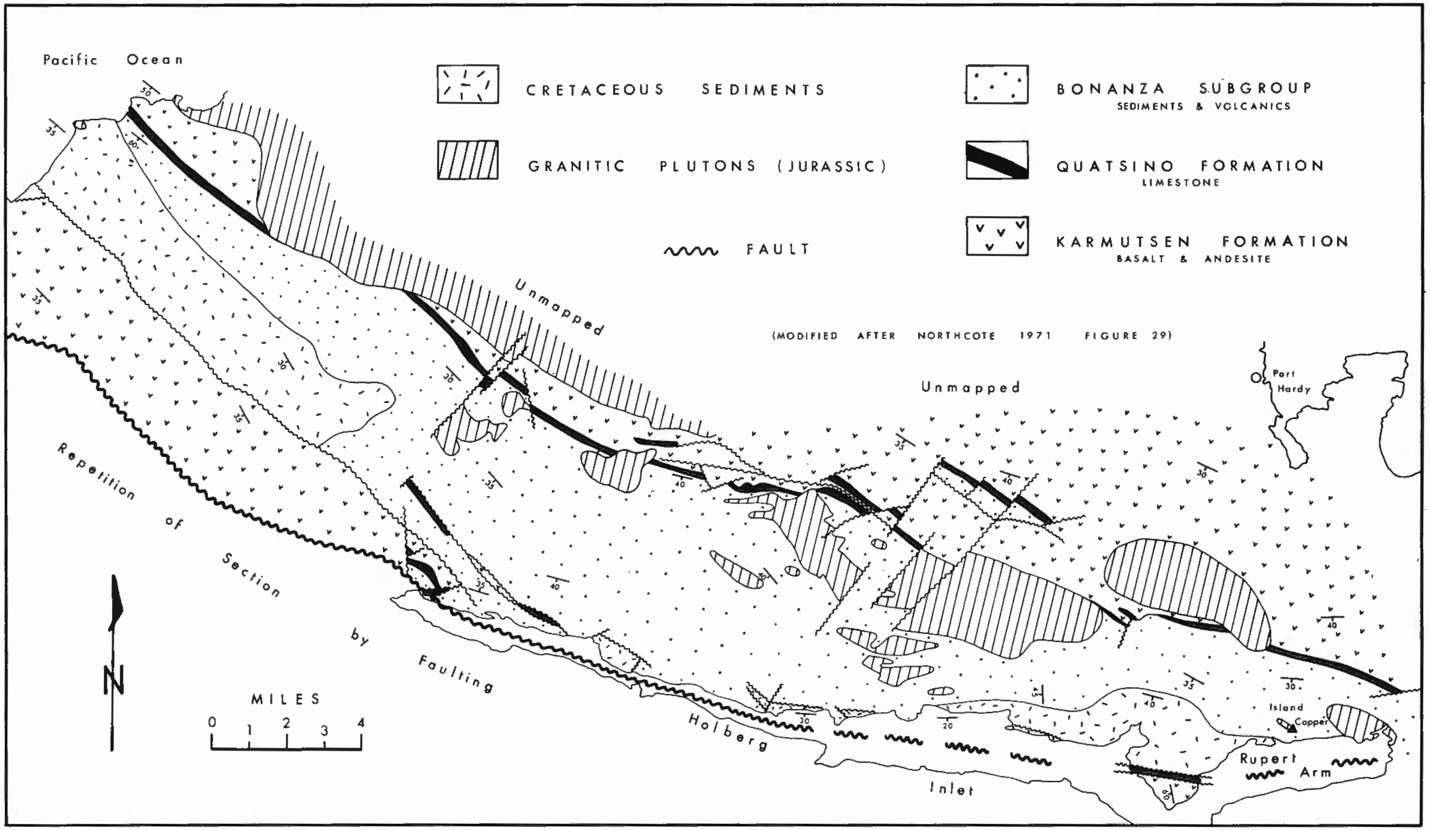

Figure 16. Geology of northern Vancouver Island (modified after Northcote, 1971). Note the spatial relationship between the Quatsino limestone and the granitic plutons.

stratigraphic interval which includes the uppermost Karmutsen Formation, the Quatsino limestone, and the lower part of the Bonanza Formation.

Most of the plutons of Vancouver Island are in many places bounded by steeply-dipping faults. These formed after the emplacement of the plutons and are due to late Mesozoic and Tertiary faulting. Such fault contacts are well displayed in the Bedwell quartz diorite batholith and other plutons of the Alberni area (Muller and Carson, 1969) and the Rupert Inlet–Cape Scott area (Northcote, 1971).

Tertiary Plutons

Tertiary plutons are epizonal and post-tectonic.

The Tertiary quartz diorite stock and dacite porphyry dykes, sills, laccoliths, and irregularly-shaped bodies of the Mount Washington–Constitution Hill area have been described by Carson (1960). More detailed mapping carried out in the course of this project is presented in Figure 7, which includes generalized cross-sections of Mount Washington and of Constitution Hill.

Drilling results of Mount Washington reported by deVoogd (1964) show that the northwest contact of the Mount Washington stock is steeply-dipping but the southwest contact may have more gentle dips. Dacite porphyry bodies intruding the Nanaimo Group sedimentary rocks surrounding the stock are essentially concordant. They occur at several horizons and are from a few feet to several hundred feet thick. The main "sill" which extends south from the ore zone past the summit of Mount Washington, and the tongue-shaped projection of the stock which is exposed in cross-section one quarter of a mile west of the ore zone (Fig. 7), are very similar to laccolithic tongues in the Henry Mountains (Gilbert, 1877) and La Sal Mountains (Hunt, 1958) of Utah.

The dacite porphyry body at Constitution Hill is underlain by nearly horizontal sediments but appears to have domed the sandstones overlying it (Fig. 7, cross-section D-E). It is a bulbous laccolith and may have formed due to a build-up of magma moving eastward from the Mount Washington stock, or may have been intruded along a dyke-like feeder underlying Constitution Hill. Sill-like bodies occur in the Nanaimo Group between Mount Washington and Constitution Hill and to the west of Mount Washington.

Dacite porphyries in the Nanaimo and Alberni areas occur as generally concordant sill-like bodies in the Nanaimo Group sedimentary rocks.

The small pluton at Faith Lake (McDougall, 1963) is approximately 1,500 feet long in an east-west direction and a few hundred feet wide. It occurs in a valley, possibly along a major east-west fault and may widen at depth. Karmutsen Formation host rocks of the valley walls surrounding and above it are highly fractured, metamorphosed to hornfels, and pyritized. They contain numerous dacite porphyry dykes and quartz veins. Many of the dykes and quartz veins are nearly horizontal, are up to several feet in width, and occur between Karmutsen flows.

The small dacite porphyry pluton at Gem Lake (McDougall, 1961) has steeply-dipping contacts. A vertical breccia zone similar to the Washington breccia of Mount Washington occurs alongside it.

The quartz diorite pluton at Catface (McDougall, 1962) is approximately one mile in diameter but probably underlies a much greater area as only the top appears to be exposed. Dacite porphyry occurs as steeply-dipping dykes and irregularly-shaped bodies up to several hundred feet in length cutting Tertiary(?) quartz monzonite at the centre of Catface Peninsula.

Zeballos quartz diorite (Fig. 5) forms a northwest-trending pluton approximately eight miles long by two miles wide. Its southwestern contact probably dips steeply to the southwest whereas moderate dips of approximately 60 degrees to the northeast are indicated for the northeastern contact. The northern contact is marked by a zone of intrusive breccia 2,000 feet to 3,000 feet wide and is believed by Stevenson (1950) to dip gently to the southeast.

The forms of the probable Tertiary quartz diorite intrusions at Big Interior Mountain and Corrigan Creek, and of the small granodiorite and quartz monzonite plutons at Tofino and Kennedy Lake are little known. However, they are probably stocks.

The small Sooke quartz diorite and trondhjemite plutons were believed by Clapp and Cooke (1917) to be roof facies and apophyses of steeply-dipping gabbro stocks. More recent work by Stevenson (1951), mapping by Macsan Exploration Co. Ltd. (Fig. 6), and observations made by the writer suggest that the gabbros are in part sill-like, and the quartz diorite and trondhjemite appear to be discordant plugs and stocks.

MODE OF EMPLACEMENT OF THE PLUTONS

Jurassic Gneisses

Strongly gneissic rocks along the west and southwest of Vancouver Island are believed by Muller (Muller and Carson, 1969) to be granitized rocks of the Sicker Group, and to a lesser extent, of the Karmutsen Formation. According to Muller, the gneisses were crystallized in situ at depth. In the few localities where crosscutting relationships have been observed, they may have attained sufficient mobility to begin to move upward and intrude the overlying rocks. By this hypothesis, sufficient depth of burial would require that the granitized rocks be derived largely from the Sicker Group or older units.

Sutherland Brown (1966) has suggested that the abundance of major faults along the west coast of Vancouver Island may have enabled heat and fluids to form extensive gneisses. If true, even the relatively high level rocks of the Bonanza Formation may have been granitized.

Some upward motion of the gneisses has probably occurred due to fault movements in the Jurassic and at later times.

Non-Gneissic Jurassic Plutons

Muller (Muller and Carson, 1969) considered that the relatively homogeneous and non-gneissic plutons of Vancouver Island (Island Intrusions) represent the mobilized portions of granitized rock that, unlike the gneisses, became detached and intruded upward to higher levels.

Fyles (1955) cited several factors including the occurrence of rotated inclusions and variations in composition unrelated to the composition of host rocks, probably caused by differentiation, in support of the conclusion that the Cowichan Lake granodiorite plutons had an intrusive magmatic origin. There are no marginal breccia zones and the host rocks, which are mainly volcanic rocks of the Sicker Group and Karmutsen Formation, are only slightly disturbed. Fyles believed that the plutons were intruded in a passive manner along northwesterly-trending tension fractures.

The Skarn pluton (Fig. 2) is similar in both composition and texture to those at nearby Cowichan Lake. There are no marginal breccia zones. Isolated screens of chert are little disturbed but the Sicker limestone may have been disrupted. The pluton was probably emplaced in a manner somewhat similar to plutons in the Cowichan Lake area with one main difference caused by a difference in host rocks. In the bedded Sicker Group rocks, especially the limestone, the Skarn pluton formed relatively small, generally concordant apophyses.

Gunning (1932a) discussed the mechanics of intrusion of the Nimpkish batholith. It is composed mainly of granodiorite similar to the Saanich types at Cowichan Lake. It is also elongated in a northwesterly direction. He (op.cit., p. 303) proposed the following mode of emplacement:

> "The magma ... arose along a northwesterly-trending line of weakness. It ascended through the competent Karmutsen volcanics in rather restricted form but under great pressure. Except in so far as stoping was operative at this stage, the magma found

> great difficulty in enlarging its chamber. But when the intrusion has pierced through the volcanics it encountered the less competent limestone and argillites which yield more readily to compressive forces than the underlying volcanics. Once in the limestone the magma was able to enlarge its chamber by lateral extension. It overrode the underlying volcanics, pushing back the limestone into a series of more or less tightly compressed folds ...".

Jeffery (1961) observed that the Coast Copper stock caused local folding and bending of its host rocks. Sangster (1969) noted an increase in the degree of deformation of host rocks as the plutons related to several of the iron skarn deposits were approached. He attributed this deformation to forceful intrusion.

In his report on the Zeballos-Nimpkish area, Hoadley (1953, p. 38-39) stated:

> "The rocks of the Vancouver group are folded into broad, regional anticlinoria and synclinoria that strike northwesterly...
>
> In the vicinity of major batholithic intrusive bodies, regional structures have been largely obliterated or masked by secondary structures imposed during intrusion. Where the intrusions have invaded volcanic rocks, general upwarping and relatively mild folding are observed, and some of the smaller roof pendants have, apparently, been tilted en masse from their original position. However, where the intrusive bodies have invaded the Quatsino limestone or the sedimentary part of the Bonanza Group, the degree of secondary folding is much more pronounced. The rocks are intricately folded and overturned, and, in places recumbent folds are common."

At middle Adam River (Fig. 15) the granodiorite pluton overlies the Quatsino limestone for at least seven miles. It must have forced its way laterally like a sill along the Quatsino-Bonanza contact. The northwest-trending series of plutons in northern Vancouver Island (Fig. 16) also appears to have resulted from an accumulation of magma at or near the level of Quatsino limestone.

Throughout Vancouver Island, there is a profusion of intrusive tongues and apophyses in and near Quatsino limestone but not in Sicker limestone[1]. The controlling factors may have been lithostatic pressure and rock competency. In Middle to early Late Jurassic the Quatsino Formation was approximately 10,000 feet[2] closer to the earth's surface than the Sicker limestone. Lithostatic pressure at the former was, therefore, lower, enabling ascending intrusions to spread laterally in the plastic limestone, once they had breached the top of the Karmutsen volcanics. Thus the ascent of many intrusions was halted and accumulations of magma occurred near the Quatsino Formation. Direct results of this were the deformation of rocks at this level, and the widespread recrystallization to marble and abundance of skarn deposits in the Quatsino limestone. This mode of emplacement is depicted in Figure 17a.

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[1] The abundance of granitic plutons cutting the Quatsino Formation and their scarcity in the Sicker limestone was first noted by Mathews and McCammon (1957).

[2] Approximate average thickness of Karmutsen Formation which occurs between the two limestone horizons (Sutherland Brown, 1966).

In Figure 17a - (3) the line a-a' represents the erosional surface in the vicinity of typical skarn deposits in or near Quatsino limestone. High-level offshoots of deeper masses of magma are shown intruding the Bonanza Formation. They represent small porphyritic plutons such as that at Rupert Arm which is associated with the Island Copper porphyry copper deposit (see Fig. 16). Many small plutons cutting the Bonanza Formation may similarly be offshoots of larger masses of magma that accumulated near the upper Karmutsen and Quatsino Formations. As suggested by Northcote and Muller (1971), some offshoots that reached the surface were probably feeders for volcanics of the upper Bonanza Formation. Line b-b' represents a deeper erosional surface in relatively barren plutons such as the Bedwell "batholith" and the steeply-dipping dyke-like intrusions of the Cowichan Lake area.

From Figure 17a and from the facts noted above, it is evident that the over all contacts of the Jurassic granodioritic plutons are generally steeply-dipping in those rocks occurring below the Quatsino Formation (i.e. - in the Karmutsen Formation and Sicker Group) but may be concordant, semiconcordant or discordant in the Quatsino and the rocks overlying it (Bonanza Formation). It is also evident that due to magma accumulation, a large percentage of the plutons occur near the Quatsino Formation and that many of the larger "batholiths" may be nearly horizontal sheet-like masses of limited thickness. These over all conclusions are in agreement with the findings of Hamilton and Myers (1967) who studied granite batholiths in the United States and concluded (op. cit., p. C1): "batholiths generally are thin, having spread out laterally at shallow depth". Hamilton and Myers believe that these thin batholiths were feeders for overlying volcanics.

In Figure 17a the pluton is shown to extend as a dyke-like body at depth in the Sicker rocks. It is also probable that many plutons were completely detached from their source, rising as "bubbles" of magma to the Quatsino Formation, and do not therefore, possess deeply-extending roots. This alternative is also depicted in Figure 17a.

Feldspar porphyry dykes exhibiting greatly varying degrees of alteration are abundant near Jurassic plutons. Many were probably emplaced at the peripheries of rising plutons during their ascent and during and in the late stages of their consolidation. Most dykes emplaced above the pluton would be metamorphosed and possibly mineralized by the pluton as it advanced upward, whereas the later dykes would be less affected.

Eastwood (1965) deduced that the time interval which included both the crystallization of each pluton, and the deposition of related Cu-Fe skarn deposits, was probably less than two million years.

Tertiary Plutons

Tertiary plutons occur along the west coast of Vancouver Island and in two subsidiary zones that cross the island (Fig. 4). Because they seem restricted to the western area, which is known to contain major faults, and to the two subsidiary zones which are roughly linear, their emplacement may have been controlled by major faults although, there is no conclusive evidence to support this. In all cases where the plutons have been studied in detail, they are found to contain porphyritic phases and breccias, and are thought to have been forcibly intruded.

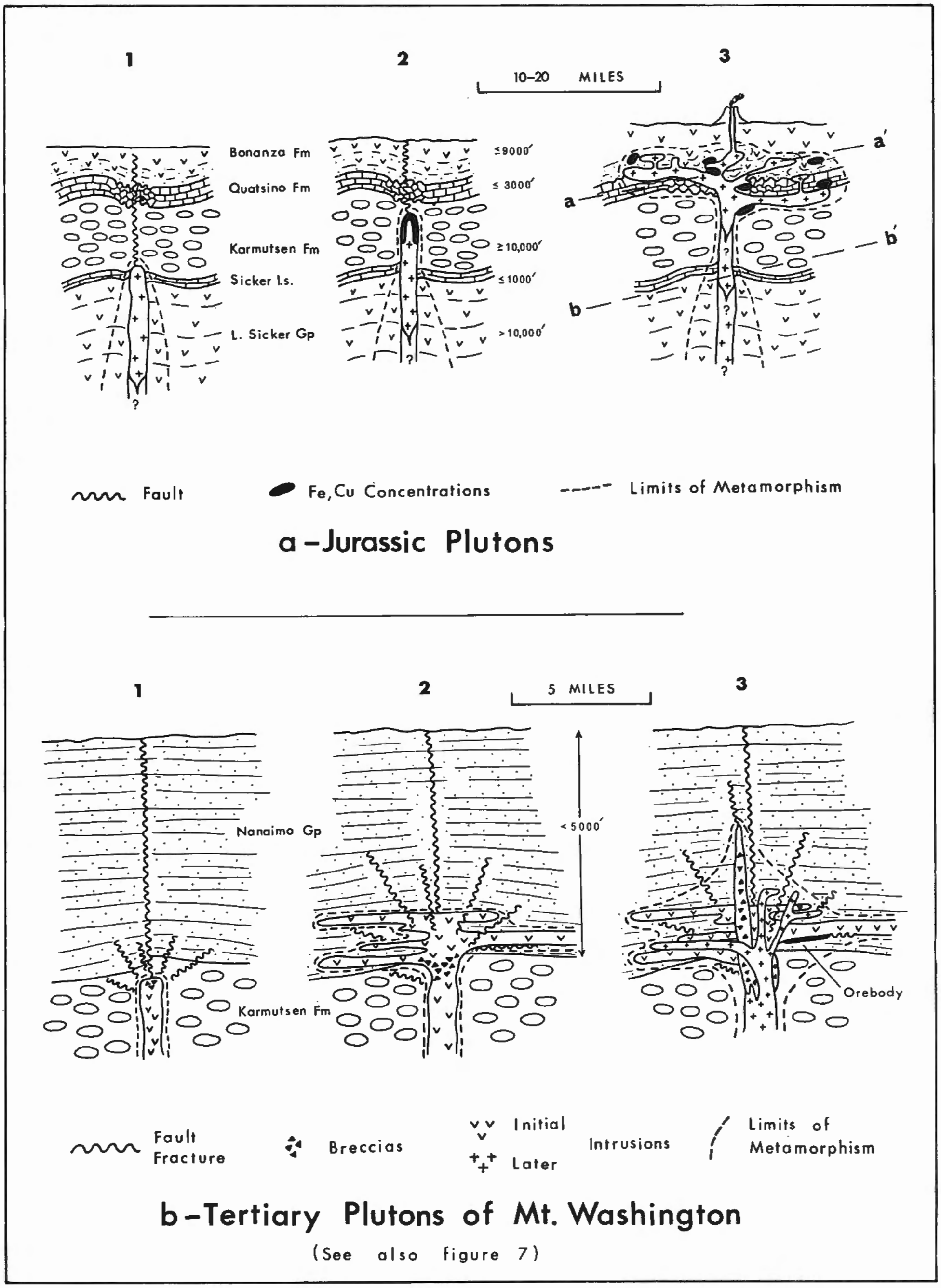

Figure 17. Mode of emplacement (a) of many Jurassic plutons, and (b) of the Tertiary plutons of the Mount Washington area (diagrammatic: approximate horizontal scales are indicated).

The methods of emplacement of the quartz diorite stock, dacite porphyry sills and laccoliths, and the Washington and Murray breccias of the Mount Washington–Constitution Hill area (Figs. 7, 17) are fully described by Carson (1960).

The Mount Washington stock and dacite porphyry bodies appear to have been forcibly intruded in a manner similar to that proposed by Gunning for the Nimpkish batholith. Dacite porphyry magma arose in constricted form at the present site of the stock until it had broken through the top of the Karmutsen volcanic rocks. It then spread laterally in the Nanaimo sedimentary rocks to form dykes, sills, and tongue-shaped laccoliths, including possibly the porphyry laccolith at Constitution Hill. The configuration of the unconformity between the Karmutsen Formation and the Nanaimo Group at Mount Washington (Fig. 7, cross-section ABC), and the presence of a radial fracture pattern, indicate that the host rocks above the stock were domed. Several pulses of intrusion occurred because the main porphyry sills at Mount Washington are cut by similar but fresher porphyries. Also, the porphyries and the Nanaimo and Karmutsen host rocks are metamorphosed to hornfels in the vicinity of the stock, which probably remained active for some time after the initial intrusion of porphyry. The stock yields the youngest K-Ar age yet obtained from Vancouver Island (35 ± 6 m.y.). Origin of the breccias, which formed after the intrusion of much porphyry, possibly by explosions and gas-streaming caused by a build-up of gaseous pressure from the still-active stock, has also been discussed by Carson (1960).

Extreme fracturing of the rocks of Faith Lake may have been caused by forcible intrusion of the quartz diorite pluton. The occurrence of thick, nearly horizontal quartz veins and dacite porphyry sills between Karmutsen flows in the valley walls above the pluton suggests that tension fractures were formed along S-planes by subsidence on the release of magmatic pressure. The possibility remains, however, that the extreme fracturing is a side effect of fault movements.

Extensive dacite porphyry sills occurring in the lower Nanaimo Group in the Nanaimo and Alberni areas and throughout Forbidden Plateau represent lateral extensions of feeders which may have been small stocks or dykes.

Volcanic rocks and limestone occur around the fringes of Catface Peninsula whereas quartz diorite, quartz monzonite, and dacite porphyry form much of the core. It has been suggested by McDougall (1962) that during a prolonged period of intrusive activity, the rocks of the peninsula were domed.

Concerning the emplacement of the Zeballos quartz diorite pluton, Stevenson (1950, p. 33) stated:

> "The numerous quartz diorite dykes and the sharply fragmented contact breccias that characterize the contact zones of the quartz diorite intrusive, as compared with an almost total absence of these features associated with the hornblende diorite and granodiorite bodies, suggest that the quartz diorite intrusive was emplaced more forcibly and with less passive replacement of the wallrocks than the hornblende diorite and granodiorite."

Depth of Emplacement

On the basis of their epizonal and mesozonal characteristics, and on depth estimates for these types of plutons given by Buddington (1959), Sangster (1969) estimated that the depth of intrusion of the Jurassic plutons related to magnetite deposits was 4.5 miles. However, the stratigraphic evidence suggests that somewhat less than 4.5 miles of rock overlay the Quatsino Formation, which is the site of the deposits, in the Middle to early Late Jurassic. The thickest Bonanza section on Vancouver Island occurs in the Quatsino-Suquash area where it is estimated to average about 9,000 feet (Sutherland Brown, 1966). This may be a reasonable estimate of the depth of intrusion of many of the Jurassic plutons since many appear to have halted their ascent at or near the Quatsino Formation (Fig. 17).

Carson (1960) has shown that when the Mount Washington Tertiary intrusions were emplaced, the sedimentary cover was much less than 10,000 feet. A closer estimate of the depth of intrusion may be obtained by considering estimates made by Gilbert (1877) and by Hunt (1958) for the relatively constant depth to which the numerous diorite porphyry stocks of the Henry and La Sal Mountains of Utah rose before spreading laterally to form laccoliths. Host rocks for the stocks are Cretaceous and Tertiary shales and sandstones that are physically similar to those of the Nanaimo Group. Hunt's estimate of the depth of lateral extension of the stocks is 5,000 feet. It is based on stratigraphic data. Gilbert arrived at a slightly higher figure mathematically.

The Mount Washington stock rose through the massive and competent Karmutsen volcanics, broke through their surface and immediately spread laterally in the Nanaimo sediments. If the comparison between the Henry and La Sal Mountains and Mount Washington is valid, this lateral movement probably occurred at depths of less than 5,000 feet. Had it been more than 5,000 feet, the stock would have continued upward in the Nanaimo sediments.

From the foregoing, it is apparent that both Jurassic and Tertiary plutons commonly spread laterally once they had breached the top of the Karmutsen Formation.

TABLE 6

Main Characteristics of Jurassic and Tertiary Plutons of Vancouver Island.

AGE	MODAL CLASSIFICATION	MAIN PHYSICAL FORMS	DEPTH AND CLASSIFICATION (Buddington, 1959)	DEPTH AND MODE OF EMPLACEMENT	MAIN CHEMICAL DIFFERENCES	COMMON TEXTURES	ALTERATION
Late-Early to Mid-Late Jurassic	Gabbro to granite but mainly granodiorite and quartz diorite.	Stocks, batholiths, dykes; laccolithic and sill-like forms up to several miles in length.	Mesozonal-epizonal, mesozonal and mesozonal-catazonal.	Mostly 9,000 feet and greater, forcible to passive.	Higher Ca, Fe, and possibly K, than Tertiary plutons of same modal type.	Medium grained, equigranular; porphyritic textures not common; gneissic structure common in western areas. Plagioclase weakly to moderately zoned.	Moderate to strong alteration; chloritization of mafics, clouding of plagioclase; biotite and chlorite dusty; prehnite lenses in biotite.
Mid-Paleocene to Early Oligocene	Mainly gabbro, quartz diorite, and dacite porphyry; subordinate granodiorite and quartz monzonite.	Stocks, sills, dykes, laccoliths.	Epizonal	<5,000 feet; forcible breccias common.	Possibly higher Na than Jurassic plutons of same modal type.	Quartz diorites fine to medium grained; seriate and porphyritic textures common. Gabbros medium to coarse. No gneisses. Plagioclase strongly oscillatory-zoned.	Negligible to moderate alteration; plagioclase mainly clear; chlorite clear; prehnite lenses in biotite rare.

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PLATES 1-15

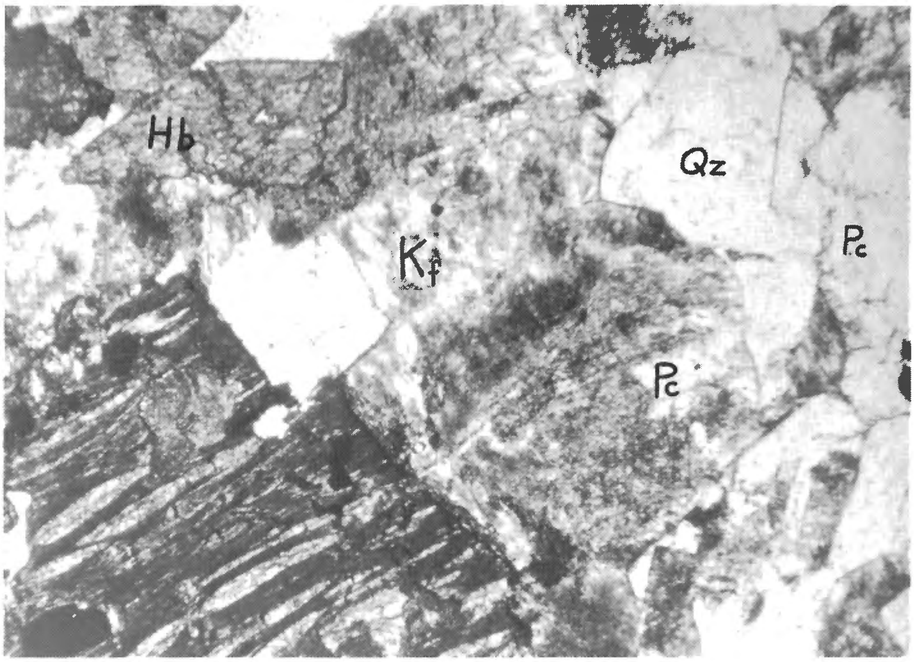

Plate 1. Photomicrograph of Jurassic Saanich-type granodiorite from Skarn pluton. Plagioclase (Pc), perthitic potash feldspar (Kf), hornblende (Hb) and biotite with prehnite lenses (lower left). Plane light. Spec. no. 178, Table 3; fig. 2. Field length 3.0 millimetres. GSC photo 200387-C.

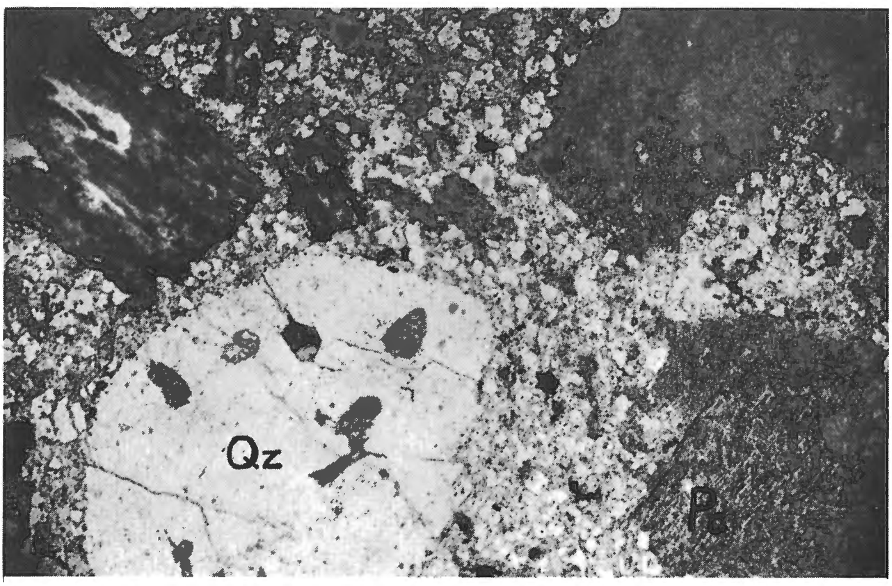

Plate 2. Photomicrograph of Jurassic quartz eye granodiorite porphyry from the Rupert Arm stock. Phenocrysts of quartz (lower left), chloritized biotite (upper left) and clouded plagioclase (right) in matrix of the same minerals plus abundant K-feldspar. Plane light. Field length 3.5 millimetres. GSC photo 200387-X.

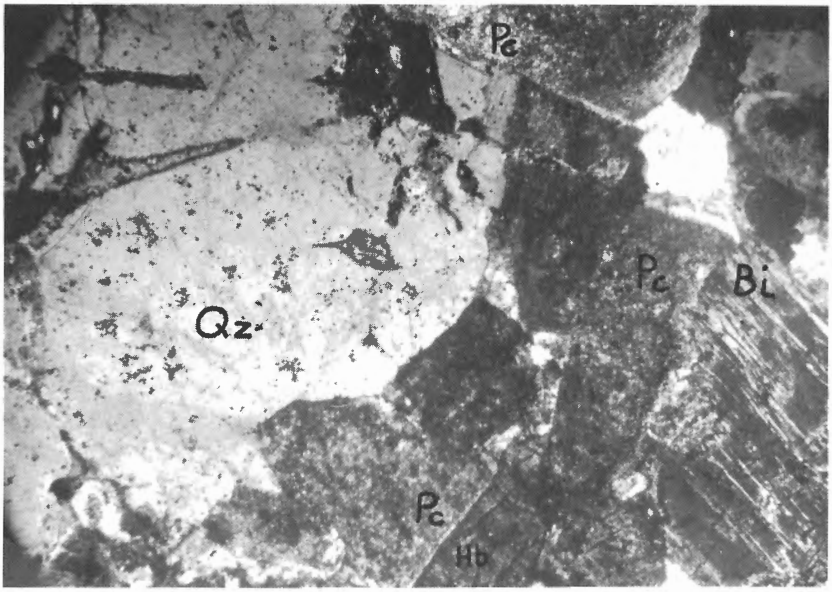

Plate 3. Photomicrograph of Jurassic (?) quartz eye granodiorite from Bedwell batholith. Quartz eye (left), chloritized biotite (Bi), clouded plagioclase (Pc), hornblende (lower centre). Plane light. Spec. no. 146, Table 3. Field length 3.5 millimetres. GSC photo 200387.

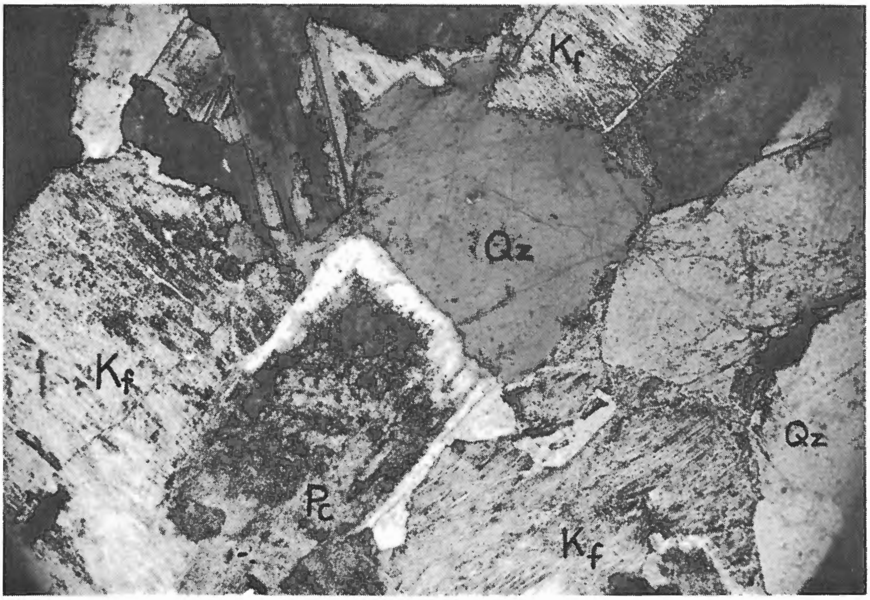

Plate 4. Photomicrograph of Jurassic or Cretaceous granite from the Nootka batholith. Perthitic K-feldspar, plagioclase, quartz. Crossed nicols. Spec. no. 47, Table 3; Fig. 2. Field length 3.5 millimetres. GSC photo 200386-Q.

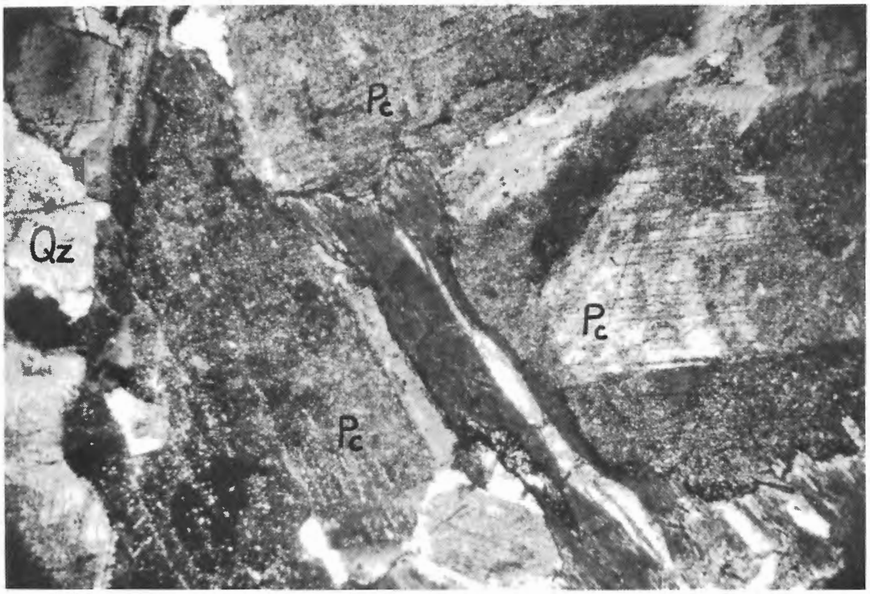

Plate 5. Photomicrograph of Jurassic quartz diorite gneiss from Muchalat Arm. Plagioclase, quartz, and biotite with prehnite lenses. Crossed nicols. Spec. no. 61, Table 3; Fig. 2. Field length 3.5 millimetres. GSC photo 200386-P.

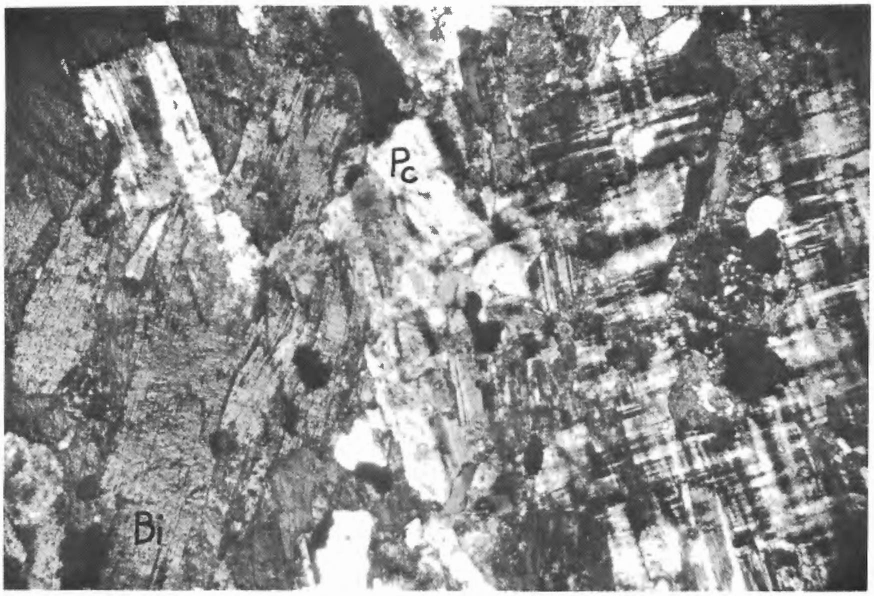

Plate 6. Photomicrograph of Jurassic granodiorite gneiss from Ladysmith containing microcline (very rare on Vancouver Island) (right), biotite, and plagioclase. Crossed nicols. Spec. no. 182, Table 3; Fig. 2. Field length 3.5 millimetres. GSC photo 200386-R.

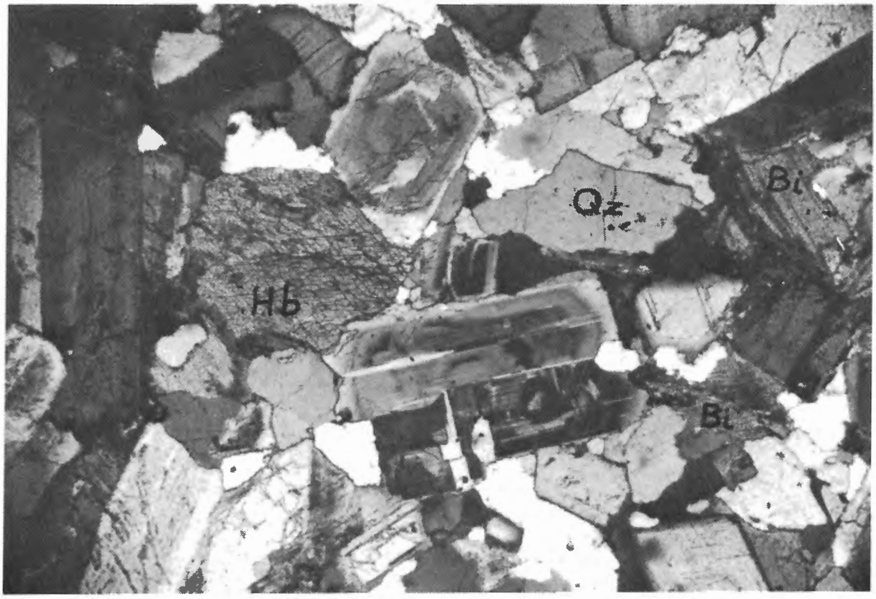

Plate 7. Photomicrograph of typical Tertiary quartz diorite from Mount Washington. Oscillatory-zoned plagioclase, quartz, biotite (Bi) and hornblende (left centre). Crossed nicols. Spec. no. 124, Table 3; Fig. 2. Field length 3.5 millimetres. GSC photo 200387-Z.

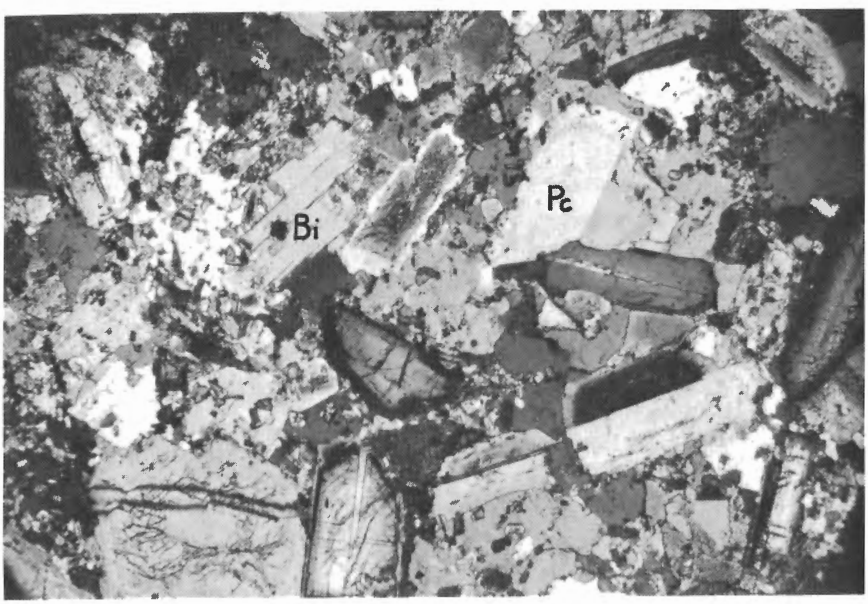

Plate 8. Photomicrograph of Tertiary seriate quartz diorite porphyry from Catface Peninsula. Crossed nicols. Spec. no. 82, Table 3; Fig. 2. Field length 3.5 millimetres. GSC photo 200386-S.

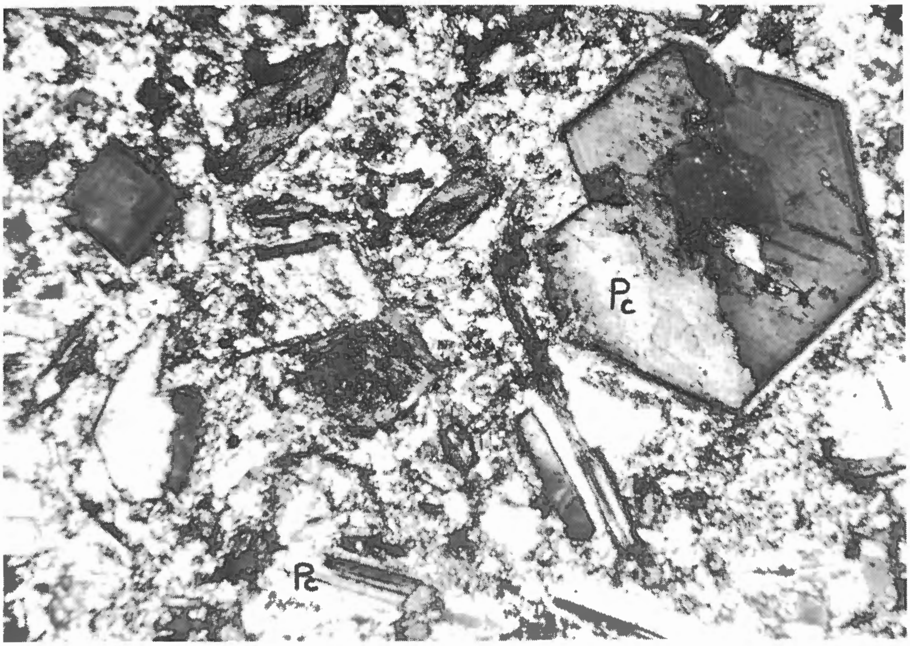

Plate 9. Photomicrograph of dacite porphyry dyke from Spud Valley Mine near Zeballos. Hornblende (upper left), plagioclase, minor biotite, quartz. Crossed nicols. Spec. no. 56, Table 3; Fig. 2. Field length 2.5 millimetres. GSC photo 200387-L.

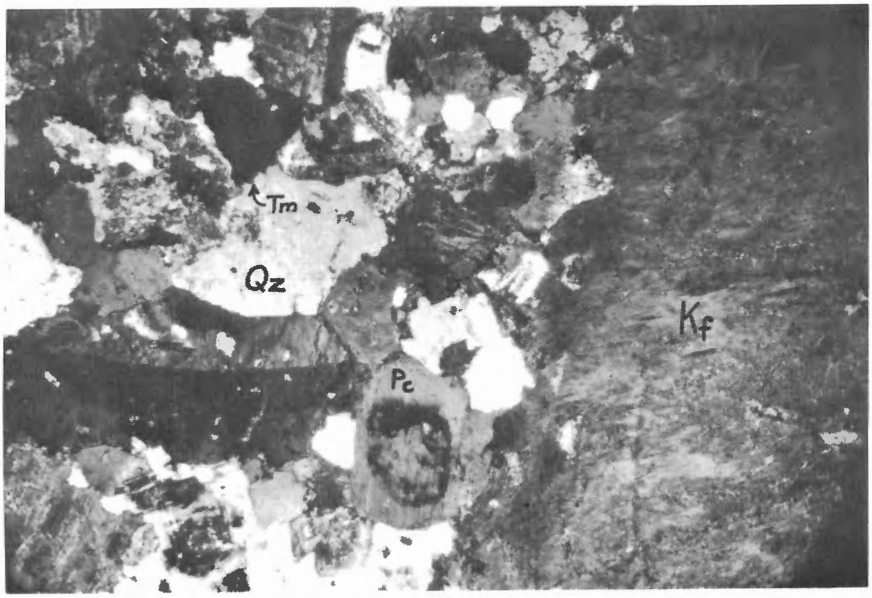

Plate 10. Photomicrograph of tourmaline-bearing Tertiary quartz monzonite porphyry from Paradise Creek. Potash feldspar phenocryst (right) and rounded triangular tourmaline crystal with apatite inclusions (upper left). Crossed nicols. Spec. no. 105, Table 3; Fig. 2. Field length 3.5 millimetres. GSC photo 200386-T.

Plate 11. Murray diatreme breccia of Mount Washington. Note rounded and angular fragments of dacite porphyry and dark rimmed sedimentary rock. GSC photo 200386-U.

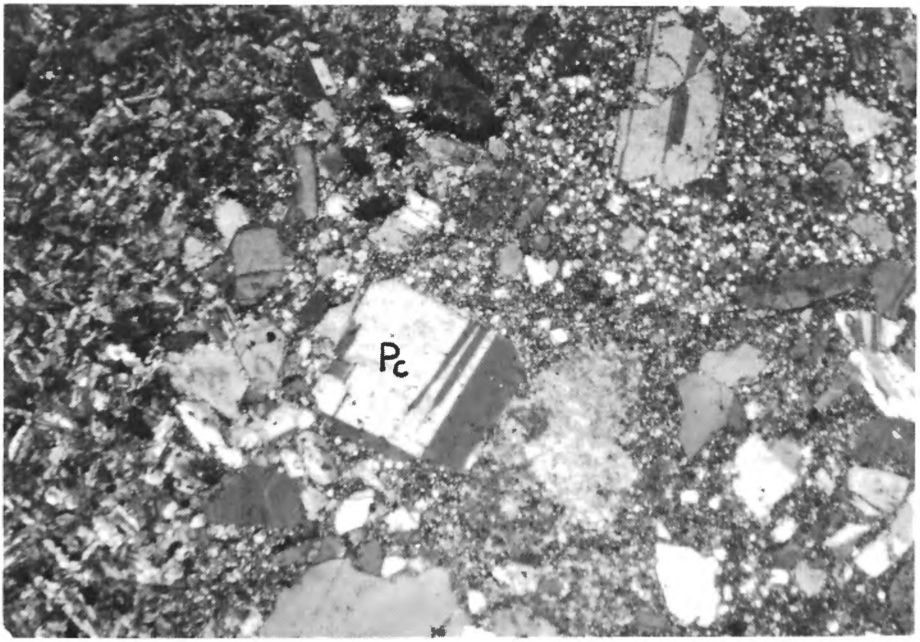

Plate 12A. Photomicrograph of Tertiary Washington-type breccia from the Gem Lake breccia pipe. Fragments of plagioclase, quartz, hornblende, dacite porphyry (upper right) and volcanic rock (lower to upper left) in magnetite-rich matrix of comminuted rock. Crossed nicols. Field length 3.0 millimetres. GSC photo 200387-H.

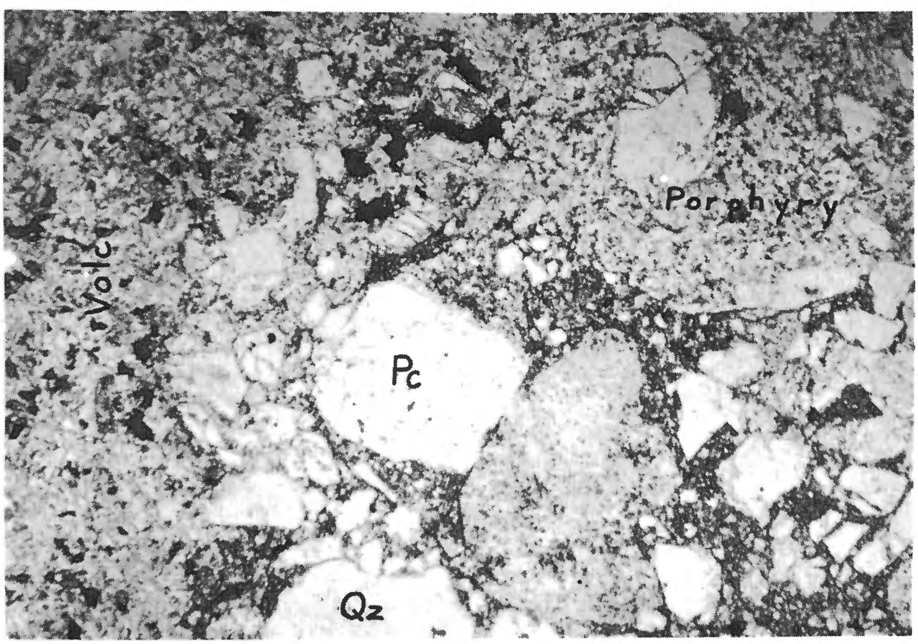

Plate 12B. Same as Plate 12A but taken with plane light. GSC photo 200387-F.

Plate 13. Intrusive breccia at a Sooke Oligocene granitic pluton. Abundant angular gabbro fragments and basalt fragments (lower right) in matrix of medium-grained trondhjemite. GSC photo 200386-V

Plate 14. Photomicrograph of Oligocene granitic rock from Sooke Peninsula. Zoned plagioclase, quartz, pyroxene, amphibole, and opaques are present. Spec. no. 223, Table 3; Figs. 2, 6. Field length 2.5 millimetres. GSC photo 200387-O.

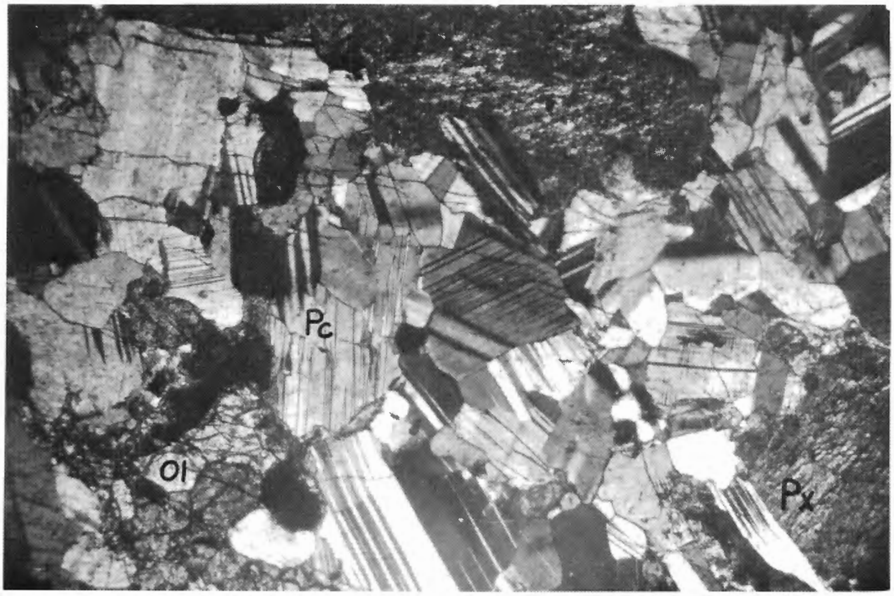

Plate 15. Photomicrograph of Oligocene olivine gabbro from Sooke Peninsula. Olivine (lower left), pyroxene (lower right, upper centre) and plagioclase. Crossed nicols. Spec. no. 227, Table 3; Figs. 2, 6. Field length 3.5 millimetres. GSC photo 200387-Y.