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Society Field Trips in Pacific Northwest Geology

Tectonic Evolution of the Southern Coast Mountains, British Columbia

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Tectonic Evolution of the Southern Coast Mountains, British Columbia

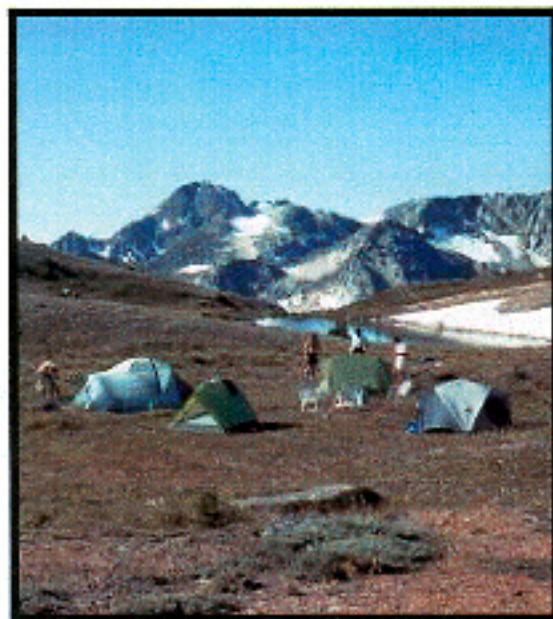
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Introduction

This two-day field trip focuses on plutonic, stratigraphic and structural elements of the southern Coast Mountains that bear on its tectonic evolution. The trip was run initially as part of the Geological Society of America Penrose Conference on the "Tectonic evolution of the Coast Mountains orogen," held from 17-22 May 1992 (reported in GSA Today, October 1992). This guidebook is a revised and updated version of the one used for the conference. It does not claim to give an even-handed overview of all aspects of the geology, but emphasizes structure and tectonics; granitic rocks are not the focus of the guidebook even though they constitute 80% of the Coast Mountains!

The guidebook uses material from earlier mapping and field trips (e.g., Roddick, 1965; Roddick et al., 1977; Woodsworth and Roddick, 1977; Roddick and Woodsworth, 1979; Price et al., 1985; Monger, 1989a; Monger et al., 1990), and unpublished theses from the Universities of British Columbia, Washington and Western Washington. New data and ideas come from recent mapping in the region by the Geological Survey of Canada and British Columbia Geological Survey Branch (e.g., Schiarizza et al., 1990a,b, Journeay et al., 1992; Journeay, 1993; Monger, 1993; Journeay and Mahoney, 1994) and from university research conducted under the



auspices of the Litho-probe southern Canadian Cordillera transect (Friedman and Armstrong, 1990, in press; Coleman and Parrish, 1991; Varsek et al., 1993; Zelt et al., 1993).

The guidebook contains an introduction with summary overviews of the geology and tectonic evolution of the entire Coast Belt and some details of the geology of the southern-Coast Mountains and its relationship with that

of the Cascade Ranges, and field trip logs for Days 1 and 2 with “comments” whose purpose is to enlarge on the regional significance of the geology of that part of the route. The introduction and comments are intended to provide enough background so that the field trip can be taken without a leader. The route of Day 1 follows the Fraser River east from Vancouver to Hope and then north to Lillooet, along the physiographic boundary between Coast and North Cascade mountains. Day 1 emphasizes similarities and differences between the two orogens. The route of Day 2 crosses the entire Coast Mountains, and runs southwest from Lillooet via Pemberton to Whistler and then south through Squamish to Vancouver. During Day 2, emphasis is placed on the stratigraphic, structural and tectonic evo-

lution of the southeastern Coast Mountains and its bearing on interpretations of the tectonic evolution of the geology of the Coast Mountains as a whole.

In the guidebook, the geologic time scale of Harland et al. (1989) is used to relate ages in years, derived from isotopic determinations, to biostratigraphic stages. This aspect is important because of the nature of the geology of the Coast Mountains. In order to understand its tectonic evolution, it is necessary to establish the time and space relationships between the results of deeper lithospheric processes such as metamorphism and plutonism which dominate Coast Mountains geology, and surface processes such as basin sedimentation and volcanic effusion.

General Geology of the Coast Mountains

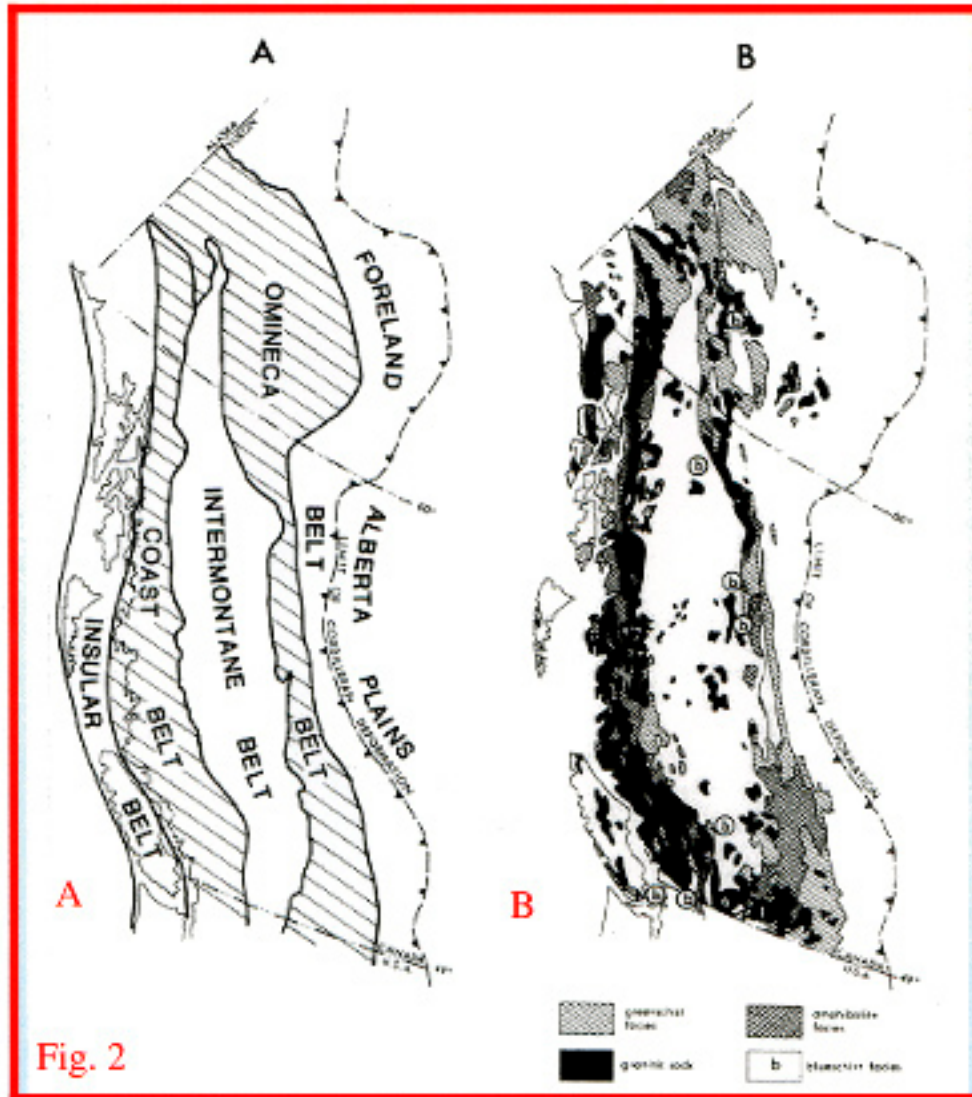
Terminology and General Description

The “Coast Belt” is one of the five morphogeological belts of the Canadian segment of the North American Cordillera, and includes both the physiographic Coast Mountains and Cascade Ranges (Fig. 2A: Wheeler and McFeely, 1991; Mathews, 1986). Because of the need on this field trip to discuss the geology of both Coast and Cascade mountains, generally the term “Coast Mountains” is used herein. Older names such as “Coast Range batholith” (Le Roy, 1908), “Coast Crystalline Belt” (Roddick, 1966; Roddick et al., 1967) and “Coast Plutonic Complex” (Wheeler and Gabrielse, 1972) reflect the predominance of plutonic rocks within the orogen. Note that the meaning of Coast Plutonic Complex, widely used synonymously with the now current term Coast Belt, has changed subtly in the most recent general description of Cordilleran plutonic rocks, and now refers exclusively to plutonic rocks within the Coast Belt (Woodsworth et al., 1991).

The Coast Mountains extend for 1700 km (between lats. 49° and 62°N), are between 100-200km wide, and reach elevations of over 4000 m, although most summits are 2000-3000m high. The Coast Mountains are composed mainly (80-85%; Roddick, 1983) of Late Jurassic to early Tertiary granitic rocks and form one of the largest Phanerozoic plutonic complexes in the world. In general, the plutonic rocks become younger from west to east. The Late



Jurassic-Early Cretaceous plutonic rocks that characterize the western part of the Coast Mountains south of Prince Rupert (lat. 54°N) are absent from it north of this, so that the plutons which give integrity to the entire belt are of mid-Cretaceous through early Tertiary ages. Subordinate, variably metamorphosed septa and fault-bound slivers of stratified rocks, and rare stratigraphic caps of volcanic and sedimentary strata are distributed throughout the Coast Mountains (Fig. 2B). and range in protolith age from Proterozoic(?) to Holocene. The Coast Mountains lie mostly within the domain of the accreted terranes (Fig. 3: Table



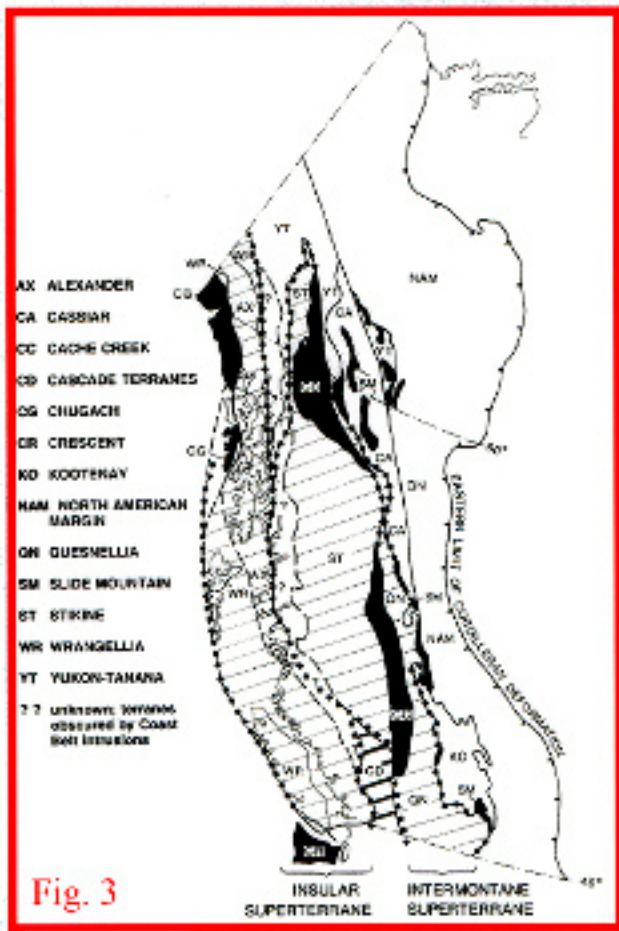
1), which feature juvenile crust with low initial strontium ratios (Armstrong, 1988), and positive ϵNd values (Samson and Patchett, 1991).

Plutonic Rocks

The plutonic rocks of the Coast Mountains are mainly quartz diorite to granodiorite, with an average composition of tholeiitic andesite in the Irvine and Baragar (1971) classification (Roddick, 1983; Armstrong, 1988). The general distribution of ages of granitic rocks in and near the Coast Mountains is shown in Figure 4: it should be recognized that far more isotopic dating is needed even on a reconnaissance level, particularly between latitudes 51°N and 53°N. South of Prince Rupert (lat. 54°N), most granitic rocks are late Middle Jurassic to mid-Cretaceous (ca. 165-91 Ma) in

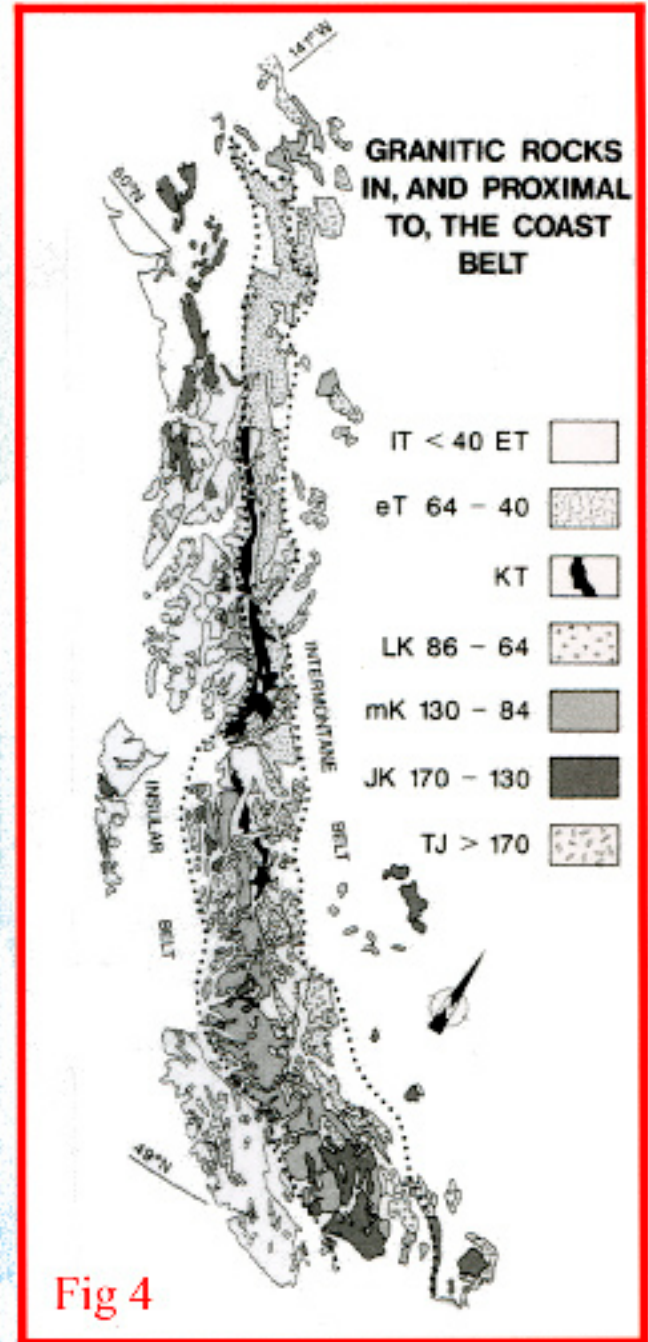
western parts, and mid-Cretaceous to early Tertiary (110-46 Ma) in eastern parts, with plutons ranging in age from about 110-90 Ma common to both parts (Fig. 4; Armstrong, 1988; Friedman and Armstrong, 1990, in press; Wheeler and McFeely, 1991; Monger and McNeill, 1993). North of Prince Rupert, the plutonic rocks of the Coast Mountains are Late Cretaceous and early Tertiary (84-46 Ma; Gehrels et al., 1991); Late Jurassic-Early Cretaceous plutons lie to the west, in the Insular Belt.

A distinctive suite of high-pressure (ca. 8 kb) mid-Cretaceous (ca. 95 Ma) quartz diorite plutons is present just west of the western boundary of the Coast Mountains in southern southeast Alaska, and coeval, high-pressure plutons occur in the southeast-



ern Coast and Cascade mountains, and on the west side of the Idaho Batholith (e.g., Zen, 1985). On the Tectonic Assemblage Map of the Canadian Cordillera, Wheeler and McFeely (1991, and Fig.4) include these high-pressure plutons within a broader suite of mid-Cretaceous igneous rocks (130-87 Ma) that also contains granodioritic plutons emplaced at high crustal levels in the southwestern Coast Mountains.

In places, Paleozoic, Triassic, and Early Jurassic plutons and or-thogneisses are present in the Coast Mountains, but are a minor component of the whole. As these rocks are coeval with plutons that are integral parts of flanking terranes (Fig. 3: mainly Stikinia and Yu-kon-Tanana (or Nisling) north of lat. 52°N, Wrangellia and Alexander terrane south of lat. 54°N), they bear no direct relationship to the Late Cretaceous and younger plu-tonic suites that give integrity to the Coast Belt. Under debate is whether Middle Jurassic to Early Cretaceous plutons and associ-



ated arc-related volcanic and sedimentary strata (Gambier Group; Gravina-Nutzotin strata), em-placed in and overlying Wrangellia, Alexander and Harrison terranes, are specific to these terranes, or are part of a broader "ancestral Coast Belt" (van der Heyden, 1992; Monger et al., 1994).

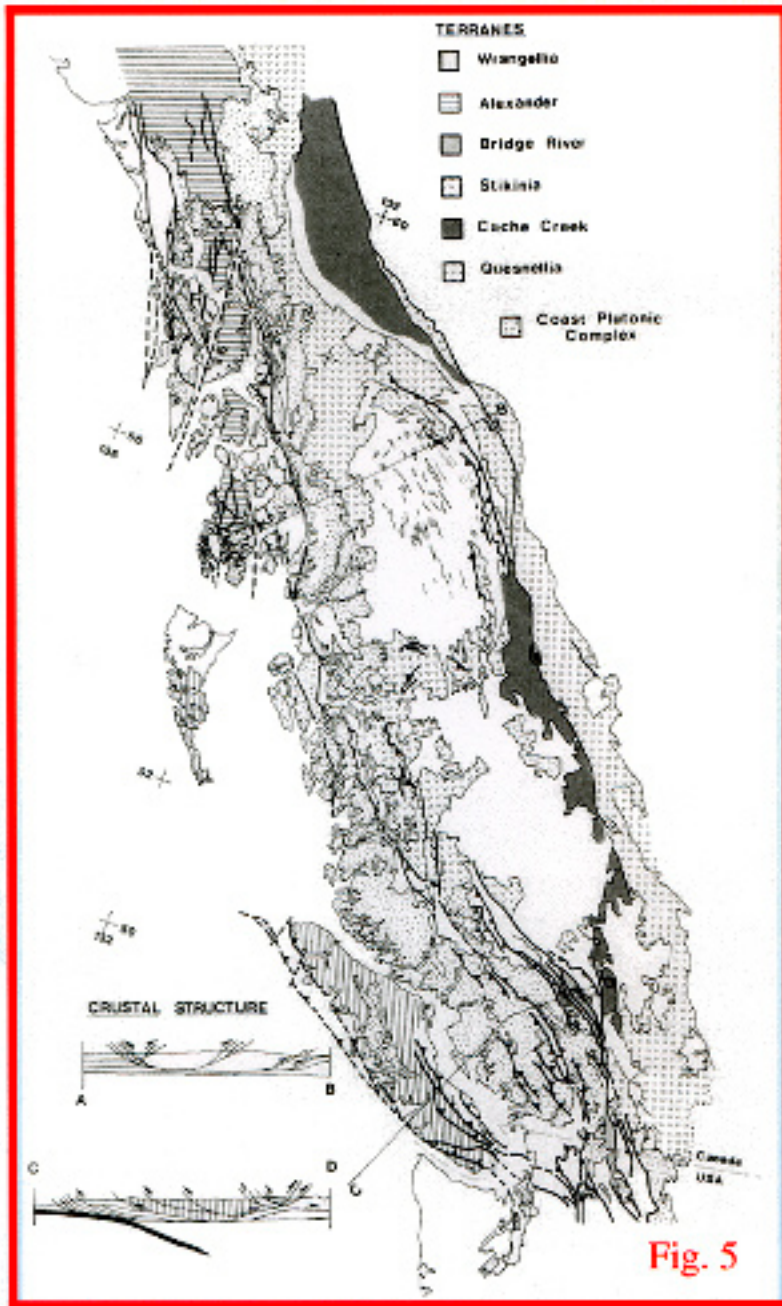


Fig. 5

Structures

Major structures affecting rocks of the entire Coast Mountains are mid-Cretaceous to early Tertiary in age and include systems of both west and east-vergent contractional faults, right-lateral strike-slip faults and Eocene extensional faults (Fig. 5. Woodsworth et al., 1983; Monger, 1986; Crawford et al., 1987; Rubin et al., 1990; Journeay, 1990a,b; Rusmore and Woodsworth, 1991; Coleman and Parrish, 1991; Journeay and Friedman, 1993; Varsek et al., 1993).

West-vergent thrust faults in southeast Alaska, near Prince Rupert, and in northwestern Washington are interpreted to be segments of a regionally extensive contractional belt that formed in mid- to Late Cretaceous time (Fig. 5: Rubin et al., 1990). In the southern Coast Mountains, the Coast Belt Thrust System (CBTS; Journeay and Friedman, 1993) is part of this contractional belt and is an important structural link between thrust systems of the Cascade Ranges and the northern Coast Mountains. In the CBTS, crosscutting plutonic suites constrain timing of west-vergent thrusting to between 97-91 Ma. The thrust sheets and bounding faults of the CBTS extend south into the North Cascade ranges (Crickmay, 1930; Misch, 1966; Lowes, 1972; Davis et al., 1978; Monger, 1986). Northward, they have been traced within the Coast Mountains to lat. 51°N; west-vergent faults are not well-documented between lats. 51° and 53°N, possibly due to the abundance of post-kinematic Late Cretaceous and Tertiary intrusions in this segment of the Coast Mountains. North of lat. 54°N, thrust faults of the Prince Rupert shear zone carry metasedimentary rocks of the Central Gneiss Complex westward over lower grade rocks of the Alexander terrane and overlapping strata of the Jura-Cretaceous Gravina belt (Crawford et al., 1987). Crosscutting plutonic suites constrain the timing of west-vergent thrusting between 100-84 Ma in the Prince Rupert region (Crawford et al., 1987) and between 95 and 90 Ma for equivalent structures in southern Southeast Alaska (Rubin and Saleeby, 1987; Arth et al., 1988; McClelland et al., 1990). The similarities in geometry, timing and regional tectonic setting support correlation of segments of this west-directed thrust system.

The west-vergent contractional fault system in both northern and southern parts of the Coast Mountains coincides with the in-board, eastern margin of the Insular superterrane (Fig. 3). This consists of Wrangellia, Alexander and Harrison terranes, linked by Middle Jurassic time (ca. 165 Ma), if not before, by the suite

of magmatic and sedimentary rocks (Gravina-Nutzotin-Gambier vol-canic-plutonic-sedimentary belt of Nokleberg et al., in press) in the western part of the southern half of the Coast Mountains and the northern half of the Insular Belt. The margin crosses the axis of the Coast Mountains at an acute angle, from the Harrison Lake-Lillooet River Valley in the southeast to the coastal fiord region on the west side near Prince Rupert and farther north. The west-vergent thrust system is consistent with the hypothesis that shortening was driven by oblique convergence and northeastward under-plating of the Insular superterrane beneath Intermontane superterrane and intervening "Cascade" terranes (Bridge River, Cadwallader and Methow) in early Late Cretaceous time (Davis et al., 1978; Monger, 1986; Crawford et al., 1987; Journeay, 1990a; Rubin et al., 1990; McGroder, 1991).

East-directed thrust faults are recognized in various places along the east side of the Coast and Cascade mountains, and are antithetic to the west-directed structures (Fig. 5: Wheeler and Gabrielse, 1972; Schiarizza et al., 1990b; Rusmore and Woodsworth, 1991; McGroder, 1991; Journeay et al., 1992). Although physical continuity has not been established, they may correlate with the extensive Cretaceous, northeast-directed thrust system in the Bowser Basin of the Intermontane Belt of north-central British Columbia (Fig. 5: Evenchick, 1991). In the eastern Coast Mountains near of lat. 52°N, these structures root westward beneath high-grade meta-morphic rocks, and crosscutting plutons indicate that the faults were active between 86 Ma and 68 Ma (Rusmore and Woodsworth, 1991). In the south, east-directed thrust faults on the east side of the Cascade Ranges root westward beneath the Cascade metamorphic core and appear to have been active between 100-88 Ma (McGroder, 1991).

At the latitude of the field trip, the pattern of west- and east-vergent folds is obscured at the surface by offset of about 130 km on the Eocene dextral strike-slip Fraser-Straight Creek Fault. However, the pattern at depth of seismic reflectors in the Lithoprobe transect, some of which align with thrust faults at surface, suggests that the southeastern Coast Mountains are a two-sided contractional orogen whose crust is composed of a stack of west- and east-vergent rootless tectonic flakes (cross-section on Fig.6). East-directed thrust faults intersect and displace west-directed thrusts at depths of between

9-18 km (3-6 s two-way travel time) below the southeastern Coast Mountains, and apparently root westward into a decollement zone at the base of the crust at about 12 s; (section on Fig. 6: Journeay, in Monger et al., 1990; Varsek et al., 1993). The fabric and scale of the seismic images in the southeastern Coast Mountains generally resemble those across the Alps and Pyrenees respectively reported by Pfiffner et al. (1991) and Blois et al. (1991). Note that the Alps and Pyrenees are considered to be "collisional orogens." The main difference between them and the Coast Mountains is that there is no deep crustal root beneath the southeastern Coast Mountains; the Moho there is relatively flat, and the locus of active subduction is west of Vancouver Island.

Orogen-parallel dextral strike-slip faults of Late Cretaceous and earliest Tertiary age contribute to the general transpressional fabric of the southern Coast Mountains (Monger, 1986; Brown and Talbot, 1989; Schiarizza et al., 1990a,b), but have not been recognized in the northern Coast Mountains. Suggestions for displacements on these structures range from a few hundred kilometres deduced from offsets of sedimentary basins (Kleinspehn, 1985), to displacements relative to the southwestern Intermontane Belt of nearly 2000 km, derived from interpretations of paleomagnetic data from the eastern margin of the Coast Mountains and the Cascade metamorphic core (Ague and Brandon, 1992; Wynne et al., 1993).

Eocene (ca. 47 Ma) extensional structures are recognized in the eastern margin of the southern Coast and Cascade mountains (e.g., Coleman and Parrish, 1991), and in regions just east of the Coast Mountains (Friedman and Armstrong, 1988). Such structures appear to be restricted to the eastern side of the southern Coast Mountains, but are widespread farther east.

A fragmentary record of pre-mid-Cretaceous deformation is recognized at scattered localities within the Coast Mountains and flanking terranes; much has been obliterated by the widespread younger intrusions. There is evidence for Jurassic contraction in southwestern Coast Mountains, along the east side of the central Coast Mountains, and in the flanking southwestern Intermontane Belt rocks (Monger, 1991 a; Greig, 1992; Greig et al., 1992; van der Heyden, 1992). Some rocks of the Bridge River terrane on the east side of the southern Coast Mountains were deformed and metamorphosed in blueschist facies, probably in Triassic time (Archibald et al., 1991; Mon-

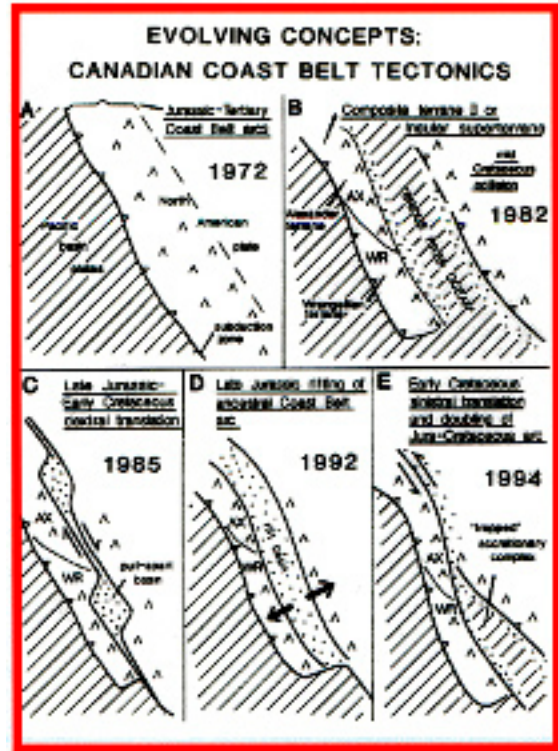
ger, 1991 a). A rare record of probable Jura-Cretaceous extension is preserved in parts of southwestern Coast Mountains, west of the region of intense Late Cretaceous deformation (Monger, 1991 a).

Metamorphism

High-grade regional metamorphism in the Coast Belt is closely associated with the Late Cretaceous and early Tertiary plutons and structures. Where most completely studied (near lats. 54° and 50°N), high pressure/medium temperature (7-8 kb; 600-650°C) regional metamorphism can be directly related to west-directed thrust faults and to the mid-Cretaceous, locally epidote-bearing (=high pressure?) plutons noted above (Zen, 1985). The high-pressure metamorphism is succeeded by lower pressure/high temperature (< 4 kb) metamorphism, again associated with emplacement of Late Cretaceous-early Tertiary plutons (Woodsworth et al., 1983; Crawford et al., 1987; Journeay, 1990a). Widespread greenschist facies metamorphism occurs both with Late Cretaceous-early Tertiary deformation and with earlier episodes of Jurassic deformation and plutonism (van der Heyden, 1992). In the central, southern Coast Mountains, near Harrison Lake, zeolite and lawsonite-albite metamorphism is developed in, respectively, Jurassic and Early Cretaceous strata (Beaty, 1974; Hettinga, 1989). Tri-axial blueschist is present locally in rocks of the Bridge River terrane, in southeastern Coast Belt (Archibald et al., 1991).

Concepts of the Tectonic Evolution of the Coast Mountains

Before the 1960s, Cordilleran tectonics were viewed within the geosynclinal framework. In 1881, Dawson surmised that the Coast Range (sic) had undergone great uplift, metamorphism and “Appalachian-type folding” in addition to introduction of great masses of hornblende granite. From their work in the northern Canadian Cordillera, Gabrielse and Wheeler (1961) similarly recognized the Coast Mountains as the locus of long-lived plutonism, metamorphism and uplift, and interpreted it as the geanticlinal core of their Pacific orogen (Wheeler and Gabrielse, 1972), flanked by divergent thrust systems, with east-vergent thrusts antithetic to the dominant west-vergent thrusts. Thus, from the earliest days of geological mapping, the close association of plutonic rocks, meta-



morphism and structure, were recognized as characteristics of the Coast Mountains.

Following acceptance of the plate tectonic hypothesis, the Coast Plutonic Complex (sic) was identified as a Jurassic to Tertiary magmatic arc formed above an east-dipping subduction zone (Fig. 7A: Monger et al., 1972), a view that persists (Armstrong, 1988; van der Heyden, 1992). Within such a framework, the Late Cretaceous-early Tertiary metamorphism and deformation can be attributed to concentration of strain in the hot, weak, crust of a continental margin arc during strong plate convergence, as in the modern central Andes (Isacks, 1988).

In 1975, Godwin explained the distribution of porphyry copper deposits of the central Coast Mountains (ca. lat. 54°N), and crustal thickening in that region deduced from the high metamorphic grades, as the result of imbrication along two Late Cretaceous-early Tertiary east-dipping subduction zones, one west of the Queen Charlotte Islands and the other along the western margin of the central Coast Mountains.

The distribution of terranes in the Coast Mountains and their time-space relations, and especially the pres-

ence of the oceanic Bridge River terrane (Fig. 6) in the southeastern Coast Mountains (containing then recently identified Permian to Jurassic radiolarians; D.L. Jones, pers. comm. to Monger, 1977), and the Late Cretaceous metamorphism, structures and uplift, led Monger et al. (1982) to view the structure and metamorphism of the entire Coast Mountains as subsequent to mid-Cretaceous accretion of amalgamated Wrangellia and Alexander terranes and overlapping Jura-Cretaceous strata (Composite terrane II or Insular superterrane) to the North American Plate (Fig. 7B). The suture in this model, within the Coast Mountains outlined by the terrane boundaries deduced from scattered variably metamorphosed septa, more-or-less follows the early Late Cretaceous west-directed thrusts of the later named Coast Belt Thrust System (cf. Fig. 3, Fig. 5).

However, north of lat. 54°N, Gehrels and Saleeby (1985) found no evidence for oceanic strata between (mainly) Stikine and Alexander terranes (Fig. 3). Instead, they suggested that Insular Superterrane moved northwards within the western edge of the North American plate in Jura-Cretaceous time (Fig. 7C) and was finally accreted in the Late Cretaceous. In this model, Jura-Cretaceous flysch basins along the western Cordilleran margin from southern Alaska to California, formed as pull-apart basins associated with northward, dextral, translation of the Insular Superterrane, and were collapsed during its final accretion. Plafker (1990) also proposed that the Insular Superterrane was translated northwards from Californian latitudes, but in Late Cretaceous-Paleocene time. He drew on reconstructions of (Kula) plate motions (Engebretson et al., 1985) in which sinistral and orthogonal convergence was succeeded after 85 Ma by dextral plate motions. Although this model agrees with plate reconstructions, and is supported by the structural evidence for Late Cretaceous-early Tertiary dextral transpression in the southern Coast Mountains and by paleo-magnetic data, it does not explain the origin of the Jura-Cretaceous flysch basins.

In 1992, van der Heyden suggested on the basis of isotopic dating in the central segment of the Coast Mountains that the orogen is a long-lived (Middle Jurassic to Tertiary; ca. 165-47 Ma) Andean-style magmatic arc. It was built across Stikine, Wrangellia and Alexander terranes which were accreted in the Middle Jurassic (ca. 170 Ma) along a Cache Creek suture in the Intermontane Belt (Fig. 3). In this model, the Jura-Cretaceous flysch basins formed during intra-arc rifting, and closed in mid-Cretaceous time

(Fig. 7D). This interpretation is based on the presence of Middle and Late Jurassic granites on both sides of the Coast Mountains near lat. 53°N, the absence of any record of oceanic crust within the Coast Mountains north of lat. 51°N, and the general eastward younging of granitic rocks across the Insular and Coast belts.

The models of Gehrels and Saleeby (1985) and van der Heyden (1992) require formation of Jurassic pull-apart and/or rift-related basins within an existing arc. However, in the southeastern Coast Mountains this appears not to be the case. There, Mississippian to Middle and possibly Late Jurassic strata of pelagic facies (radiolarian chert) of the oceanic Bridge River terrane (Cordey and Schiarizza, 1993; F. Cordey, pers. comm., 1994), grade upwards into clastic rocks of the Jura-Cretaceous Cayoosh assemblage (Journey and Northcote, 1992; Mahoney and Journey, 1993). Thus the basin containing the Jura-Cretaceous elastics appears to have been in existence since at least the Mississippian, and is the youngest stage of a long-lived, and therefore probably originally large, ocean basin. The style of structures and older metamorphism suggests that the Bridge River-Cayoosh rocks represent, at least in part, a Mesozoic accretionary complex, analogous to the Chugach terrane in southern Alaska (lat. 60°N), or western Klamath terranes and oldest parts of the Franciscan Complex in California-Oregon (lat. 40°N). To accommodate both the accretionary complex in southeastern Coast Mountains and the intra- or back-arc basin model of Gehrels and Saleeby (1985) and van der Heyden (1992), Monger et al. (1994; Fig. 7E) suggested that Bridge River and Cayoosh rocks were an accretionary complex trapped in Early Cretaceous time (120-100 Ma) east of a fragment of the Jura-Cretaceous North American plate margin arc (carried on Wrangellia and Alexander terranes), which was displaced southward (sinistral) in the Early Cretaceous. Such movement is in accord with local structural evidence for sinistral displacements, with reconstructions of Early Cretaceous relative motions between North American and various Pacific plates (Engebretson et al., 1985; D. Engebretson and K. Kelley, pers. comm., 1993), and permitted by paleomagnetic interpretations (Irving and Wynne, 1990). In Late Cretaceous time, the entire Coast Belt underwent contraction and dextral translation, collapsing the different kinds of basins lying

between Insular Superterrane and North America.

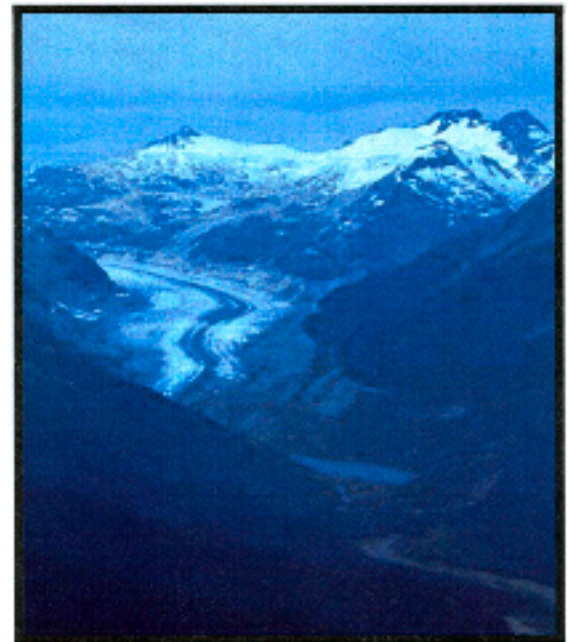
Figure 7, in its variety, illustrates some of the explanations that have been offered to explain the tectonic evolution of the Coast Mountains. The explanations change as we acquire data. More data are needed to satisfactorily resolve the problem, and some fundamental questions require answers. For example, are the Late Cretaceous-early Tertiary plutonic, structural and metamorphic features that give the Coast Mountains integrity due to Andean-style arc collapse during strong plate convergence, or to accretion and underplating of Insular Superterrane, or to both? The available evidence suggests to us that accretion is important. Are the Late Cretaceous-early Tertiary granitic rocks arc-related and formed above a subducting oceanic slab, or

were they generated by anatectic melting of juvenile crust thickened during contraction, or both? Do the Coast Mountains include relics of Jura-Cretaceous arc systems carried by Wrangellia and Alexander terranes, that migrated across an ocean basin, or are they parts of a single North American plate margin arc fragmented and duplicated by transcurrent faulting along the margin of the Pacific Ocean basin and its ancestors? We favour the latter. To resolve these questions requires not only wider knowledge of the composition and ages of the plutonic rocks, the kinematics of their structures, and the plate tectonic framework, but also of the stratigraphy of hosting terranes, and paleogeographies determined from paleomagnetism and paleontology.

Geology of the Southern Coast Mountains

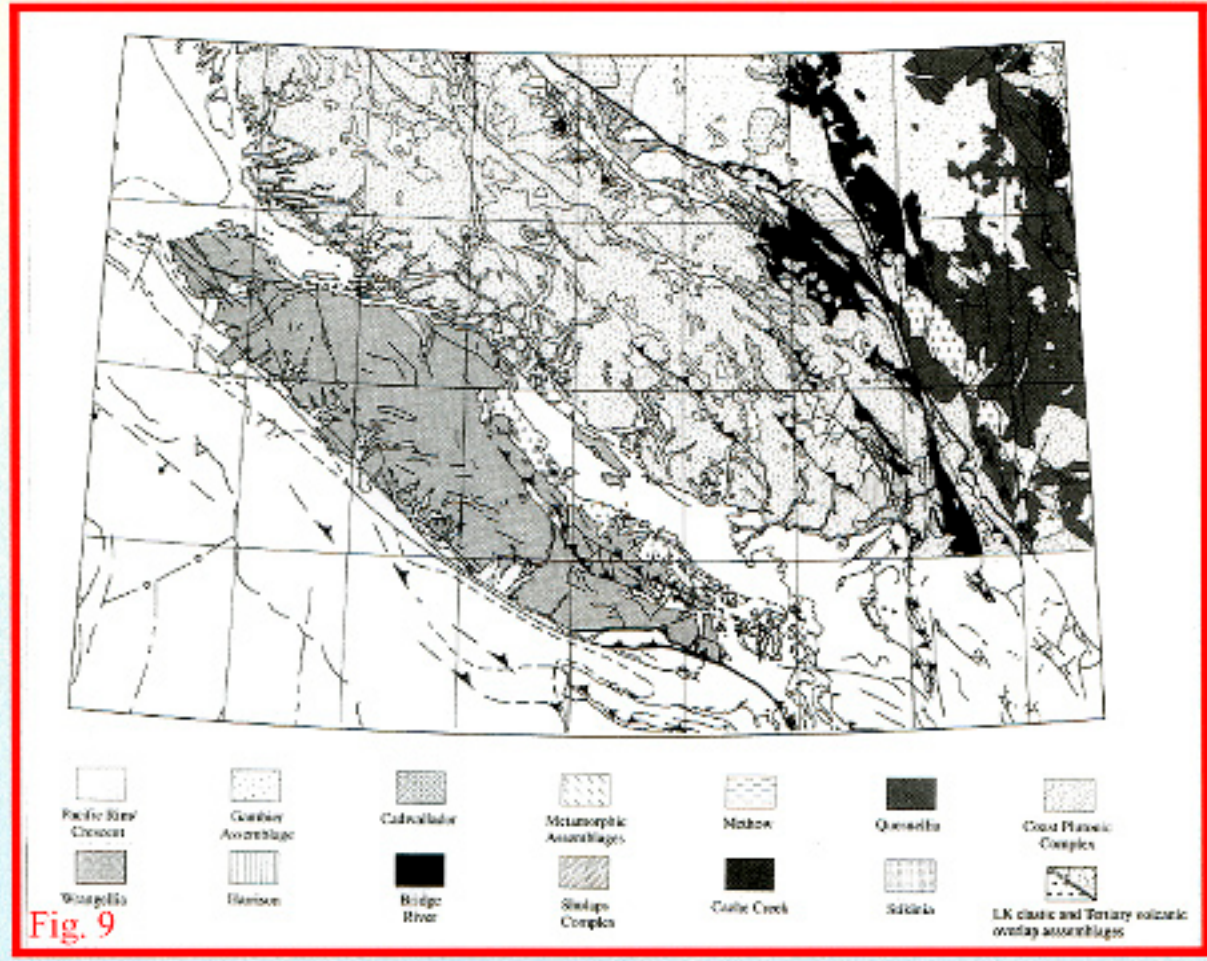
New information on the southern Coast Mountains includes geological map coverage at 1:50 000 to 1:500 000 scales (e.g., Journey, 1990a; Schiarizza et al., 1990a,b; Journey et al., 1992; Monger, 1989a, 1991b, 1993) (Fig. 1). and these mainly at the universities of British Columbia, Western Washington and Washington. In addition to ongoing conodont and radiolarian studies (e.g., Cordey and Schiarizza, 1993), about 50 new U-Pb dates of granitic rocks have been added to the Coast Mountains geological database south of lat. 51 °N, as part of the Lithoprobe supporting geoscience program and on-going GSC mapping (Friedman and Armstrong, 1990, in press; Parrish and Monger, 1992; Journey and Friedman, 1993; Monger and McNicoll, 1993). Integration of Lithoprobe seismic reflection data with structural profiles drawn from geological mapping (Journey in Monger et al., 1990 and Fig. 6: Cook et al., 1992; Varsek et al., 1993) provides a window into the deep crustal structure of the southern Coast Mountains, and the mechanisms of crustal deformation.

That part of the Coast Mountains between lats. 49° and 51 °N is divided into southeastern and southwestern parts based on the distribution of plutonic rocks, terranes and structures (Fig. 1. Fig. 6. Fig. 8: Table 1: Monger and Journey, 1994). The two-fold division of the southern Coast Mountains was first recognized by Crickmay (1930) who saw the southwestern part as a region of plutonic rocks and “Jurasside structures” which were



distinct from the region of “Laramide structures” in the southeastern Coast Mountains and Cascade Range. Misch (1966; his Fig. 7-17), showed a similar division. Mid-Cretaceous (ca. 110-90) plutonic rocks are emplaced in both parts of the southern Coast Mountains, linking them at a time slightly earlier than that at which the earliest structural linkages can be demonstrated.

The southwestern Coast Mountains feature mainly Middle Jurassic to mid-Cretaceous plutons (ca. 165-91 Ma) which intrude su-pracrustal sequences ranging in age from Middle Triassic



to Middle Jurassic of Wrangellia and Harrison Lake terranes, and overlapping Jura-Cretaceous volcanic and sedimentary rocks (Fig. 8, Fig. 9). The western boundary is the western limit of Middle Jurassic intrusions that possibly were localized along pre-and syn-plutonic faults (Nelson, 1979; Monger and McNicoll, 1993). Its eastern boundary is delineated by the high-grade, internal, meta-morphic thrust nappes of the Coast Belt Thrust System (CBTS) that are derived in large part from basinal strata (Bridge River terrane) characteristic of southeastern Coast Mountains (Fig. 1, Fig. 8, Fig. 9; Journeay and Friedman, 1993). Note that rocks (Harrison terrane and Gam-bier Group) characteristic of the eastern part of southwestern Coast Mountains also are internally imbricated along west-directed thrust faults of the external part of the CBTS (Fig. 1, Fig. 9). Below nappes featuring high grade metamorphism to the east. Thus, the southwestern Coast Mountains is a plutonic-dominated crustal block that acted as a foreland buttress during early Late Cretaceous (91-97 Ma) west-directed

thrusting centred in southeastern Coast Mountains, essentially as first recognized by Crickmay (1930).

The southeastern Coast Mountains feature mid-Cretaceous through early Tertiary (103-47 Ma) plutonic rocks, emplaced within (mainly) Bridge River, Cadwallader and Methow terranes (Fig. 1, Fig. 6, Fig. 8; Table 1). This part of the Coast Mountains was the site of the most intense deformation and highest grade metamorphism (Fig. 1, Fig. 3) in Late Cretaceous-early Tertiary time. All three terranes in the southeastern Coast Mountains appear to be founded on oceanic crust (Fig. 6, Fig. 8; Table 1). Of these, the Bridge River terrane consists of lithologies characteristic of oceanic crust, such as pillow basalts associated with radiolarian chert and alpine-type ultra-mafic rocks, whereas the other terranes are predominantly of arc affinity. Bridge River terrane contains fossils in chert facies ranging in age from Mississippian to late Middle Jurassic (350-160 Ma; Cordey and Schiarizza, 1993) and possibly Late Jurassic (Oxford-

ian, 155 Ma; F. Cor-dey, pers. comm., 1994). The long time spanned by this terrane, at least 190 million years, suggests that it represents remnants of a former large ocean basin. In addition, Journeay and Northcote (1992) found that locally chert grades into clastic rocks of the Cayoosh assemblage of Jurassic(?) and Early Cretaceous age. The Bridge River and overlying strata occur both as highly disrupted tectonic melange and relatively coherent units. Rare Triassic blueschist in the Bridge River terrane indicates that part underwent early Mesozoic subduction; other $40\text{Ar}/39\text{Ar}$ data show that the terrane underwent no other thermal perturbation until the Cretaceous (Archibald et al., 1991). Monger (1991 a) argued that the Darrington Phyllite and Shuksan Greenschist of the North Cascades, which contain blueschist yielding Jura-Cretaceous ages (peaking at 140-120 Ma), can be traced northwards into Settler Schist which is correlated with the Cayoosh assemblage. The Bridge River terrane is disposed in thrust slices structurally interleaved with Cadwallader and(?) Methow terranes, variably metamorphosed and intruded by Late Cretaceous and early Tertiary plutons.

On the east, the Coast Mountains are flanked by the southwestern Intermontane Belt, which contains Quesnel, Cache Creek and (north of lat. 52°N) Stikine terranes (Fig. 6. Fig. 8. Fig. 9: Table 1) and plutonic rocks ranging in age from Late Triassic to earliest Tertiary (212-62 Ma). Between lat. 51 - 52°N , Late Cretaceous-early Tertiary plutons characteristic of the Coast Mountains are emplaced in possible Stikine strata (Fig. 3) and in Early Cretaceous strata that may be correlative with the Gambier Group in southwestern Coast Belt.

The along-strike extension of the Coast Mountains to the south across Fraser River is the Cascade Range. This comprises a core of Late Cretaceous-early Tertiary plutons and high-grade metamorphic rocks, equivalent to rocks in southeastern Coast Mountains, but offset dextrally by ca. 130 km on the early Tertiary Fraser-Straight Creek Fault (Fig.1). The core is flanked by little metamorphosed strata; on the east are Methow and Bridge River terranes, and on the west rocks of Bridge River (?), Chilliwack and Harrison terranes. Not recognized in the Cascades are Wrangellian strata (Dickinson, 1976; Davis et al., 1978), and the voluminous Middle Jurassic to Early Cretaceous plutonic rocks so abundant in the southwestern Coast Mountains.

Coast Belt Thrust System

The Coast Belt Thrust System (CBTS) is a major west-vergent contractional belt that formed along the inboard margin of the Insular sub-terrene in Late Cretaceous time (Fig. 1. Fig. 5. Fig. 6. and Fig.9: Journeay and Friedman, 1993). The foreland of this contractional belt comprises rocks of southwestern Coast Mountains and Wrangellia, which are deformed by a system of east-dipping frontal thrusts that imbricate Jurassic and Lower Cretaceous (mainly) arc sequences and related plutons of the southwestern Coast Mountains. Local post- or syn-Albian folds and thrusts that predate the dominant east-dipping structures have southeast-directed vergence (Lynch, 1992).

The dominant faults root eastward into an imbricate zone of folded thrusts and out-of-sequence reverse faults across which the metamorphic gradient is structurally inverted. To the east and structurally above the imbricate zone is a folded stack of thrust sheets mainly comprising metamorphosed island arc and oceanic rocks (mainly Cadwallader and Bridge River terranes). These rocks represent the exhumed crustal root of the CBTS. Metamorphosed volcanic and volcanoclastic rocks that occur in westernmost, structurally lowest, thrust sheets of the imbricate zone yield U-Pb zircon dates which support their correlation with foreland/ lower plate Jurassic and Early Cretaceous arc sequences of southwestern Coast Mountains.

In the southeastern Coast Mountains, southwest-directed structures are cut by northeast-directed thrust faults and by sinistral and dextral transcurrent faults of Late Cretaceous and early Tertiary age (Schiarizza et al., 1990b; Journeay et al., 1992; Parrish and Monger, 1992). These structures are in turn truncated by the dextral transcurrent Fraser Fault and offset about 130-140 km to the north from equivalent structures in the Cascade metamorphic core (Fig. 9).

In the southwestern Coast Mountains the effects of Late Cretaceous contraction are far less, and typically manifested by discrete shear zones spaced up to 10 km apart, that are steeply dipping and mainly southwest, locally northeast, vergent (Fig. 1: Monger, 1991b, 1993; Lynch, 1992). Some major early Late Cretaceous plutons were emplaced during the period of

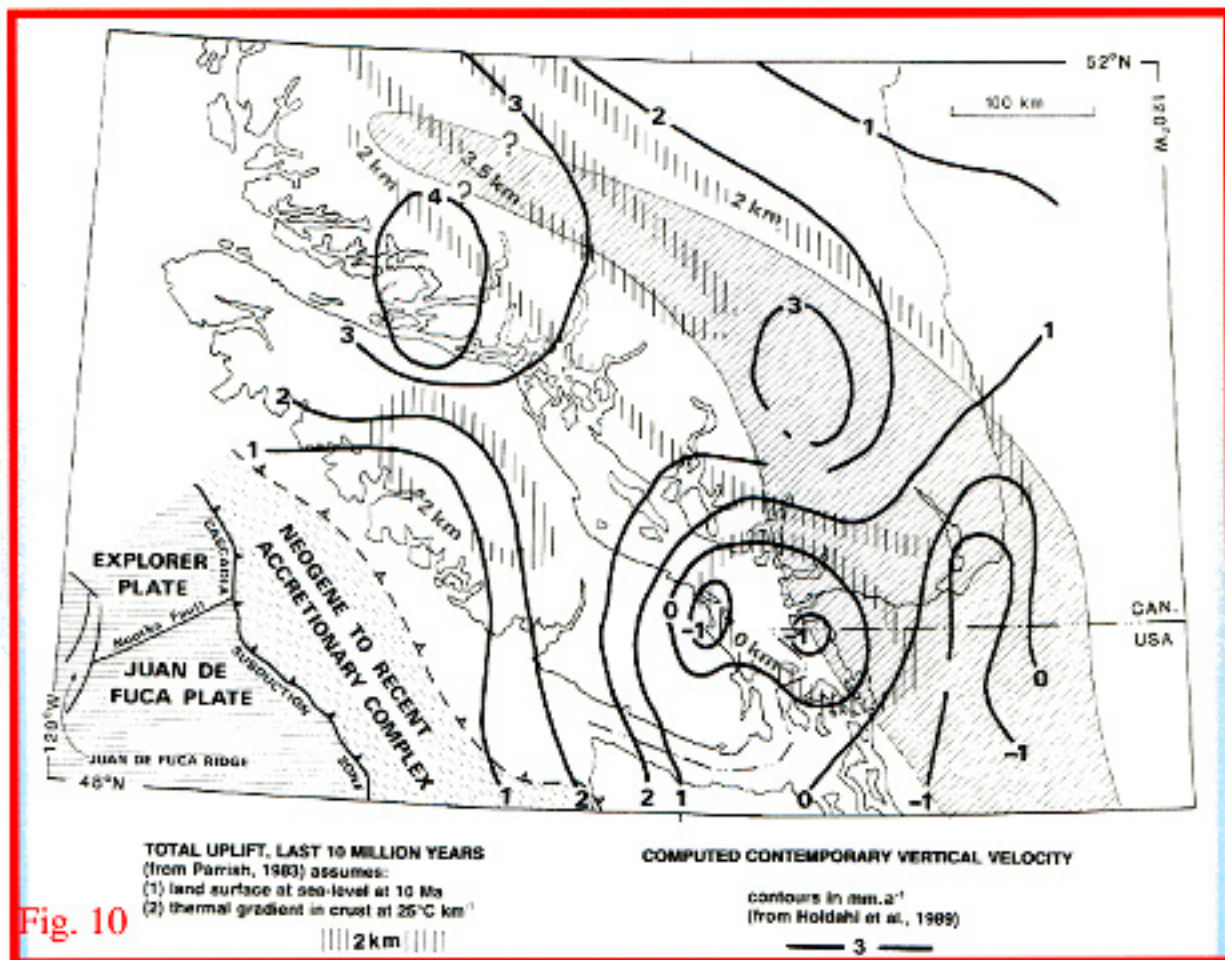
Coast Belt Thrust System contraction (Monger and McNicoll, 1993) and one (ca. 91 Ma), at least, postdates it. In rocks between the shear zones, sparse records of Jurassic contraction (between 185-155 Ma) and Jura-Cretaceous extension are preserved (Monger, 1991b,c).

Metamorphism

The metamorphic grade varies considerably across the southern Coast Mountains. In the southwestern part, metamorphism in septa is mostly of greenschist facies, with higher metamorphic grades locally present at the contacts with large plutons. The grade locally drops to zeolite facies in Jurassic rocks just west of Harrison Lake (Beaty, 1974), and is of lawsonite-albite facies in Early Cretaceous rocks along west and east shores of Harrison Lake, and in thrust sheets in the lowest part of the Coast Belt Thrust System (CBTS; M.T. Brandon, pers. comm., 1986; Hettinga, 1989). Within 20 km to the east, across the imbricate zone of the CBTS, the grade rises to sil-

limanite-kyanite facies (Lowes, 1972; Pi-gage, 1976; Monger, 1986; Hettinga, 1989; Journeay, 1990a). A synthesis of available data from this area suggests that peak metamorphic conditions associated with 91-97 Ma thrust faulting are 7.0-9.6 kb and 600-750°C. The conditions dropped to 3.7-6.1 kb and 575-690°C by 84 Ma (Journeay, 1990a). Note that the metamorphic grade of the southeastern Coast Mountains decreases along strike towards the northwest, so that where traversed on Day 2, the southeastern Coast Mountains are entirely greenschist or lower grade.

In the easternmost Coast Mountains, metamorphic grade generally decreases from greenschist to prehnite-pumpellyite facies to the northeast. Crosscutting relationships with dated plutonic rocks indicate that metamorphism in this part of the eastern Coast Mountains is Late Cretaceous and early Tertiary. Near Lillooet, high greenschist grade rocks are exposed in slivers bounded by outward-dipping Middle Eocene normal



faults (Coleman and Parrish, 1991). An older metamorphic history is present locally. $^{40}\text{Ar}/^{39}\text{Ar}$ dating in adjacent parts of the eastern Coast Mountains reveals local Late Triassic (221 Ma) blueschist metamorphism in rocks of the Bridge River terrane, followed by Early or mid-Cretaceous (ca. 130 Ma or 110-95 Ma) regional and/or contact metamorphism (Archibald et al., 1991).

The Foreland Basin of the Coast Mountains

Clastic foreland basin deposits of the southern Coast Belt are represented by Late Cretaceous (Turonian to Maestrichtian; ca. 90-65 Ma) "molassic" marine and nonmarine clastic rocks of the Nanaimo Group (Fig. 1). which lap up on to the southwestern Coast Mountains, and are best-exposed on Vancouver Island and the Gulf Islands, where they overlie Wrangellia (Fig. 1: Mustard, 1991, 1994; Mustard and Rouse, 1991, 1992). The oldest Nanaimo deposits (early Turonian, ca. 90 Ma, Haggart, 1992) are slightly younger (ca. 2 Ma) than the 91-97 Ma thrust faults of the CBTS (Journey and Friedman, 1993). The Nanaimo Group is involved in Eocene, thick-skinned southwest-directed thrust faulting (England and Galon, 1991), and appears to be an erosional remnant preserved in the late Tertiary(?) - Holocene Georgia Depression, centred along Georgia Strait between Vancouver Island and the mainland. England and Galon (1991) regard Nanaimo Group deposition as occurring in a forearc basin that lies oceanward of the coeval plutonism in southeastern Coast Mountains. Our view, which coincides with that of Brandon et al. (1988) for the northwest Cascades Ranges, is that the Nanaimo Group was deposited in a foreland basin built on the Wrangellian-southwestern Coast Mountains basement, and that clastic sedimentation resulted from tectonic uplift and erosion associated with the Coast Belt Thrust System, rather than erosion from a volcanic edifice built by extrusion. Separation of the Nanaimo foreland basin from the complementary thrust system is at least in part due to uplift of several kilometres and erosion of the southwestern Coast Mountains in late Tertiary to Recent time (Fig. 10; Parrish, 1983; Holdahl et al., 1989; Monger, 1991b; Monger and Journey, 1994).

Terrane Linkages in the Southern Coast Mountains and Adjacent Areas

Terranes that were associated with one another prior to mid-Cretaceous (110 Ma) plutonism and Late Cretaceous (97 Ma) contraction and transpression fall into the following groups

(Fig. 6. Fig. 8. Fig. 11: Ta-blflL).

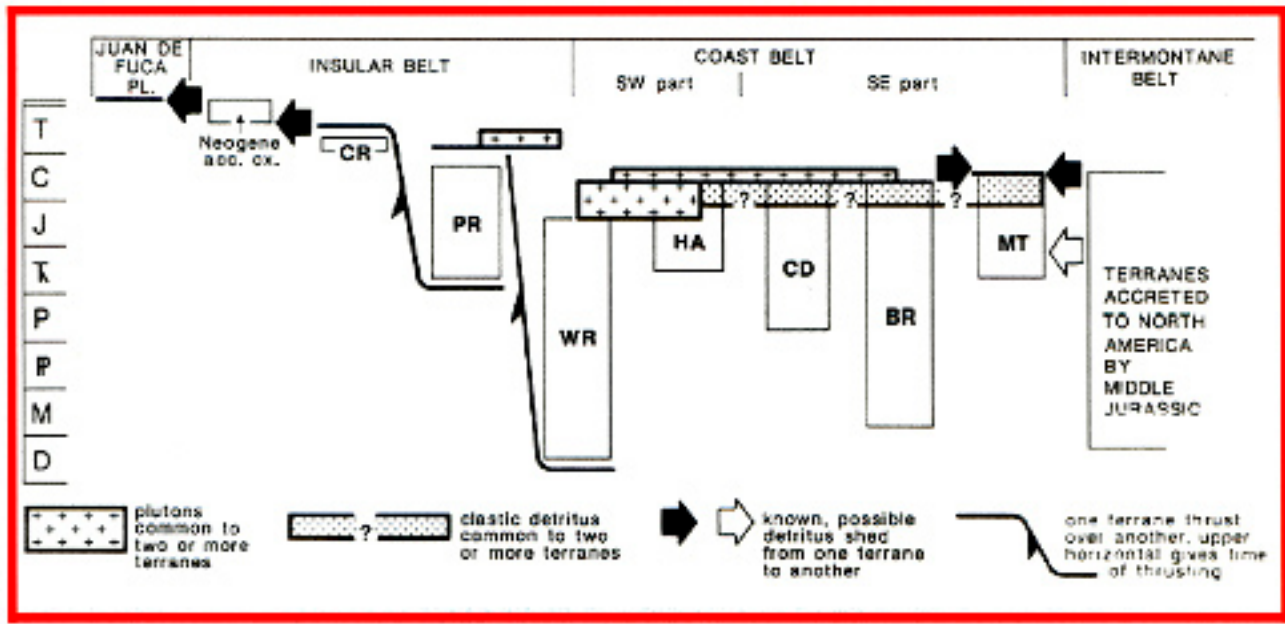
Southwestern Coast Mountains and Insular Belt:

Wrangellia is linked to Harrison terrane by Middle and Late Jurassic (165-147 Ma) plutonic rocks, which intrude Wrangellia on the west and extend more-or-less continuously across southwestern Coast Mountains to intrude Harrison Lake terrane west of southern Harrison Lake, and by widespread Early Cretaceous (Berri-Asian to Albian; ca. 140-100 Ma) calcalkaline volcanic and sedimentary rocks of the Gambier Group (Fig. 6: Friedman et al., 1990; Friedman and Armstrong, 1990, in press; Monger, 1991 b). Wrangellian Triassic(?) and Early Jurassic strata in septa of southwestern Coast Mountains extend at least as far east as southern Howe Sound and middle Jervis Inlet, to within about 70 km of Harrison strata west of Harrison Lake (Friedman et al., 1990; Monger, 1993). Jurassic strata of the two terranes are separated by Cretaceous intrusions and Cretaceous strata along Howe Sound, and by Jurassic-Cretaceous intrusions east of it.

Southeastern Coast Mountains:

Bridge River, Cadwallader and Methow terranes are founded on oceanic crust of, respectively, pre- or syn-Mississippian, Permian and Triassic ages (Fig. 6. Fig. 8. Fig. 11). On a non-palinspastic map these appear to underlie a trough that existed until the latest Early Cretaceous, between the southwestern Coast Mountains-Wrangellian block to the west, and the Intermontane Belt to the east (Fig. 12).

Until the Late Jurassic, the histories of these three terranes apparently differed. Bridge River terrane features abundant Upper Triassic to Middle and possibly Late Jurassic (Oxfordian; ca. 156 Ma) radiolarian chert, Cadwallader terrane contains Upper Triassic arc and Lower Jurassic clastic sedimentary facies, and Methow terrane contains a Jurassic clastic succession including Middle Jurassic arc volcanics (Fig. 6. Fig. 8). There is general agreement that Bridge River, Cadwallader and Methow terranes were linked by the mid-Cretaceous (ca. 100-110 Ma) as Albian chert-rich elastics derived from the Bridge River terrane occur in the uppermost parts

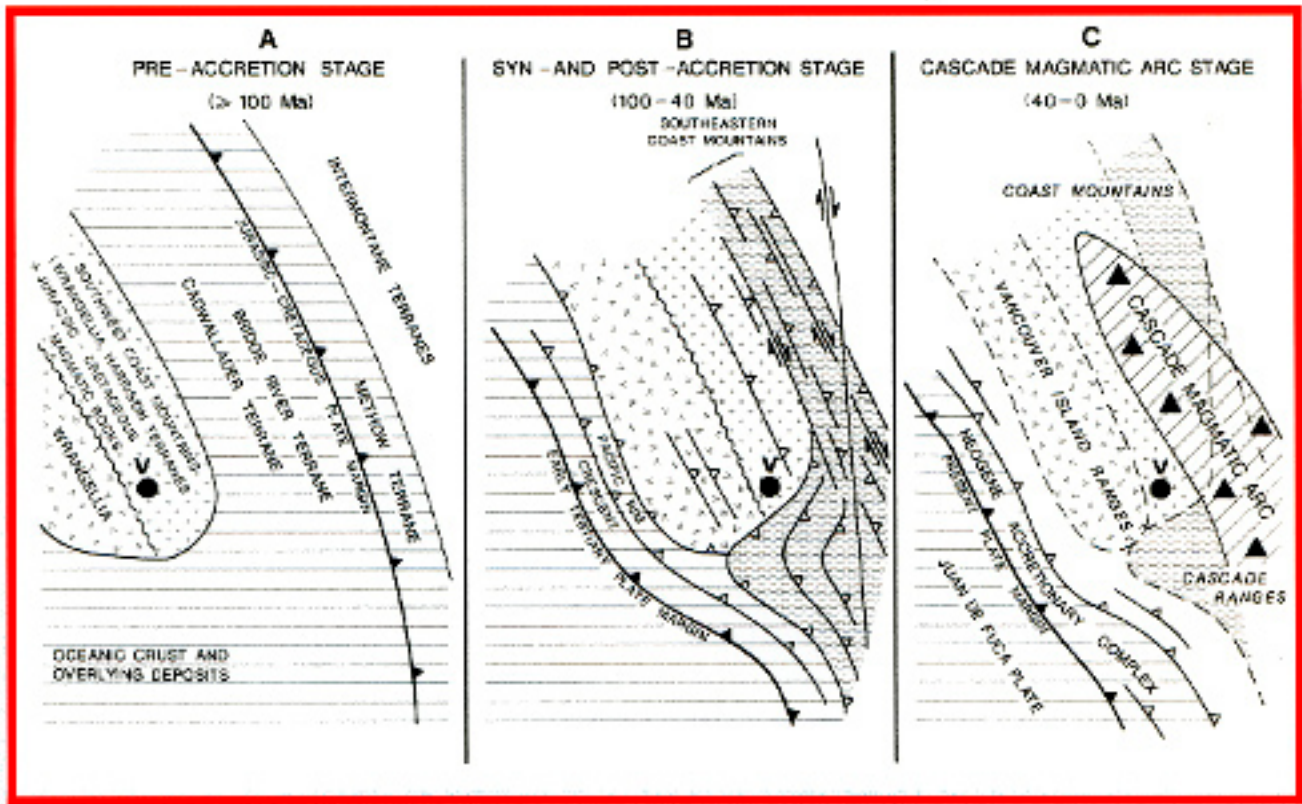


of Cadwallader and Methow terranes (Taylor Creek and Virginian Ridge Formations, Garver, 1992). Prior to this time, linkages between the three terranes are tenuous, but possible, and Late Jurassic clastic basinal strata may overlap all three terranes (Fig. 11: Journeay and Mahoney, 1994).

The linkages between these terranes and flanking regions are also tenuous. The presence of radiolarian chert as young as Middle and(?) Late Jurassic (ca. 160- (?)156 Ma) in the Bridge River terrane suggests that pelagic conditions persisted until the later Jurassic, and that the arc to the west, represented by Middle Jurassic (167 Ma) and younger plutons, was either not present at this latitude or else was separated by a wide basin. To the west, it has long been recognized that some clastic rocks in the late Callovian to Hauterivian (160-135 Ma) Relay Mountain Group, which may lie on Cadwallader terrane, have a southwestern provenance; these have been linked to uplift in the southwestern Coast Mountains (Jeletzky and Tipper, 1968). Tuff beds within the Relay Mountain Group may record Gambier Group volcanism (P. Schiarizza, pers. comm., 1990). To the east, late Early Cretaceous clastic rocks of Methow terrane long have been considered as having been derived from the uplifted western margin of Quesnel terrane and/or forearc deposits of the continental Spences Bridge Group, which is founded on Quesnel and Cache

Creek terranes (e.g., Coates, 1970; Tennyson and Cole, 1978; Kleinspehn, 1985; Thorkelson and Smith, 1989). However, recent interpretations of paleomagnetic data (Wynne et al., 1993) from rocks that appear to be correlative with those in uppermost Methow terrane, and comparisons with paleomagnetic data from Spences Bridge volcanics, cast doubt upon these linkages, and suggest Quesnel and Methow terranes were separated in the early Late Cretaceous by ca. 1800 km (see discussion by Cowan, 1994).

The complex structure of the southern Coast Mountains, including the "tectonic flaking" recorded by surface structures and interpreted from seismic reflection data (Fig. 6). makes it difficult to restore these terranes to their relative pre-mid-Cretaceous paleogeographies. Based on paleocurrent data from chert-rich elastics derived from the Bridge River, Garver (1992) inferred that the probable order from west to east in mid-Cretaceous (Albian to Cenomanian) time was Cadwallader, Bridge River and Methow terranes (as in Fig. 8. Fig. 12). McGroder (1991) suggested a minimum of 500 km of shortening across the Cascade orogen along strike to the south. In addition, as noted above, displacement on dextral, orogen-parallel faults (e.g., Brown and Talbot, 1989) may be considerable; estimates range from a few hundred kilometres based on geology (e.g., Kleinspehn, 1985) to nearly 2000 km based on paleo-magnetic inter-



Intermontane Belt:

The Inter-montane Belt comprises Quesnel, Cache Creek, and (farther north) Stikine terranes (Fig. 3. Fig. 6. Fig. 8. Fig. 9. Table 1). It is separated from Methow terrane by the Cretaceous Pasayten Fault and the Tertiary Fraser Fault. On the field trip, we visit only the westernmost part of Quesnel terrane at one stop. Quesnel terrane is characterized by a west-facing, Late Triassic-Early Jurassic arc (Nicola-Rossland volcanics; Mortimer, 1987), built upon older oceanic and arc rocks (Fig. 8; Monger, 1989a). The arc is unconformably overlain by non-volcanic clastic rocks of the Lower to Middle Jurassic (late Pliensbachian to earliest Callovian; ca. 190-160 Ma) Ashcroft Formation. The early Mesozoic Quesnellian arc probably formed on the western edge of the North American plate, but was not em-placed on pericratonic and continental margin rocks to the east until late Early Jurassic time (ca. 185 Ma). Cache Creek terrane, east of the Fraser River in southern British Columbia, comprises Middle Pennsylvanian to Early Jurassic chert, pelite and volcaniclastic rocks, melange with blocks of chert, gabbro, ultramafics and limestone, and a large body of Late Permian to Late Triassic limestone. (Cordey et al.,

1987; Monger, 1989a; Beyers and Orchard, 1991). Its lithologies, structural character and position relative to the early Mesozoic Quesnel arc, suggest that the Cache Creek represents the accretionary complex complementary to the Quesnellian arc.

In southern British Columbia, the Cache Creek terrane was thrust eastwards over Quesnellia and the Ashcroft Formation in Jurassic time (Travers, 1978). Quesnel and Cache Creek terranes are overlapped by mid-Cretaceous (ca. 105 Ma) continental volcanics of the Spences Bridge Group.

Early workers used both Coast and Cascade ranges as interchangeable names, and both are included within the Coast Belt (see Dawson, 1881; Daly, 1912; Gabrielse et al., 1991). The Cascade orogen is subdivided into three distinct tectonic domains, each of which contains some rocks correlative with those in the Coast Mountains (Fig. 1. Fig. 6; Misch, 1966; Tabor et al., 1989). (1) An eastern tract of low-grade metamorphic rocks intruded by scattered Late Cretaceous and early Tertiary granitic rocks is the southeastern extension (across the Fraser-Straight Creek Fault) of Bridge

River and Methow terranes. (2) The Cascade core features abundant Late Cretaceous and early Tertiary plutons and high-grade metamorphic rocks. Some of which (Napeequa and Chiwaukum schists) resemble high-grade metamorphic rocks (Cogburn Group, Settler Schist) in the southeasternmost Coast Belt (Evans and Berti, 1986; Tabor et al., 1987; Monger, 1991 a), that are derived from Bridge River and Cayoosh rocks. (3) A western tract, called the Northwest Cascades System (Misch, 1966; Brown, 1987), consists of mainly subgreenschist strata belonging to one of four thrust fault-bound terranes (Monger, 1991 a). The terranes from base to top, are: (a) Harrison terrane (Wells Creek volcanics; Nooksack Group); (b) Chilliwack terrane; (c) Elbow Lake Formation (= Bridge River terrane?) and (d) Easton terrane (comprising Shuksan Greenschist and Darrington Phyllite = ? Cayoosh assemblage). The small exposure of rocks correlated with Harrison terrane in the Mount Baker structural window, and possibly the Chilliwack terrane, are the sole representatives of rocks in southwestern Coast Mountains recognized in the Cascades.

The physiographic boundary between the Coast Mountains and the Cascade Ranges is the Fraser River, which follows the north-trending early Tertiary (47-35 Ma) Fraser-Straight Creek Fault north of Hope, and Neogene (24-14 Ma?) northeast-trending faults southwest of Hope (Fig. 1; Monger, 1989a). These faults are superimposed on the fundamental Late Cretaceous-earliest Tertiary structural elements common to the Coast Mountains and North Cascades. The northwestern Cascade and Cascade core structures are congruent with the contractional faults of the Coast Belt Thrust System (Journeay and Friedman, 1993). However, in the Cascades, because the high-grade metamorphic rocks in the core are separated from the low-grade rocks to the west by the Fraser-Straight Creek Fault, historically the two have been treated separately. Restoration of dextral movement on the Fraser-Straight Creek Fault aligns rocks in the southeastern Coast Mountains with those in the Cascade metamorphic core (e.g., Evans and Berti, 1986). Note that different workers in the Cascades emphasize either thrust faulting or strike-slip faulting in interpretations of Cascades structure (cf. Brandon et al. (1988) and McGroder (1991)); with Brown (1987) and Brown and Talbot (1989). Both structural modes are present there, as they are in the southeastern Coast Mountains.

The major differences between the geology of the Coast and Cascade mountains include: (1) absence of Wrangellia in the Cascade orogen; (2) near absence of the Jura-Cretaceous plutonic rocks common in southwestern Coast Mountains in the Cascades; and (3) presence of a Cretaceous-Tertiary "Western Melange Belt" in the western foothills of the Cascades (Frizzell et al., 1987; Tabor et al., 1989). The latter lithologically and structurally resembles the Leech River Schist and Pacific Rim Complex exposed along the southern and western coast of Vancouver Island, which is thrust beneath Wrangellia (Fig. 6. Yorath et al., 1985; Wheeler and McFeely, 1991). This relationship suggests that the Wrangellian-southwestern Coast Mountains block (= ? Insular Superterrane) can be considered as an enormous tectonic flake, mostly not present south of lat. 49°N, incorporated in a long-lived accretionary complex (Fig. 7B. Fig. ZE).

Crystal Evolution of the Southern Coast Mountain Region

In summary, we consider the crust of the southern Coast Mountains to have evolved through three stages (Fig. 12)

(1) *Pre-accretion stage (100 Ma):*

Before the mid-Cretaceous, the North American plate margin probably lay within the southeastern Coast Mountains and Cascade Ranges, which are located on the site of a long-lived accretionary and forearc complex represented by Bridge River and Methow terranes. The paleogeographic relationship between Insular Superterrane (Wrangellia and rocks of southwestern Coast Mountains) and the Early Cretaceous plate margin is uncertain, and only shown schematically on Figure 12A.

(2) *Syn- and post-accretion stage (ca. 100-40 Ma):*

This is the major crust building stage, and appears to have been initiated by mid-Cretaceous (ca. 100 Ma) accretion of Insular Superterrane to the Cretaceous North American plate margin. Following accretion, the margin stepped westwards to a position near the west coast of Vancouver Island. Intense Late Cretaceous-early Tertiary (96-47 Ma) intra-plate contraction and dextral transpression, accompanied by metamorphism

and granitic intrusion, were focused along the former plate boundary in southeastern Coast Mountains and Cascade Ranges (Fig. 12B). There, the crust was thickened to >30 km, so that the region of the former accretion-ary and forearc complex in southeastern Coast Mountains was inverted and became the major source of detritus for the Late Cretaceous foreland basin to the west.

(3) *Cascade magmatic arc stage (40-0 Ma):*

The tectonics of the region today, and probably of the last 40 million years, bear no direct relationship to those which formed most of the crust of the Coast Mountains, although they are dominated by plate convergence. Sub-duction of the oceanic Juan de Fuca Plate beneath the North American Plate was accompanied by generation of the Cascade Magmatic Arc, which extends from southwestern British Columbia to northern California (Fig. 12C). The physiography mainly formed in Neo-gene to Quaternary time (10 Ma), with uplift of the Coast Mountains and(?) western Vancouver Island, and subsidence of the intervening area, which today is covered by the water of Georgia Strait (Fig. 10).