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Résumé de l'article

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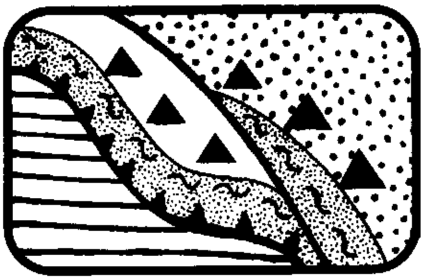

Plate Tectonics and Northern Cordilleran Geology: An Unfinished Revolution

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SUMMARY
The northern Cordillera, located on a continent-ocean interface in existence for 750 million years, is an orogenic collage mostly made up of Paleozoic through early Mesozoic intraoceanic arc and subduction complex terranes accreted to the craton margin, and mid-Mesozoic to Holocene arcs emplaced mainly in and on the accreted terranes. Mountain building results from crustal thickening most likely caused by persistent movement of the North American plate towards, and over, various Pacific oceanic plates since Early Jurassic time. Location of collage components in time and space is needed to show the succession of plate configurations that led to the collage, but current conflict between estimates of amounts of lateral displacements means that pre-Tertiary paleogeographies remain in doubt.

RÉSUMÉ
Située sur une interface continent-océan vieille de 750 millions d'année, la portion septentrionale de la cordillère est un collage principalement constitué de terranes d'arcs intra-océaniques et de complexes de subduction d'âge paléozoïque à mésozoïque inférieur soudés à la marge du craton, et de complexes en arc d'âge mésozoïque moyen à holocène et que l'on retrouve principalement au sein des terranes ou reposant sur ceux-ci. Les montagnes sont le résultat d'un épaississement de la croûte, fort probablement causé par les mouvements persistants de la plaque nord-américaine en collision ou en chevauchement sur les divers plaques l'océan Pacifique qui se sont succédées depuis le début du Jurassique. Il faut connaître la position spatiale et temporelle des divers éléments du collage pour pouvoir déterminer la configuration des plaques dont il est issu. Voilà pourquoi les disparités actuelles des estimations des déplacements latéraux n'ont-elles pu mener à ce jour, qu'à reconstitutions paléogéographiques pré-Tertiaires mal assurées.

INTRODUCTION
The geology of the North American Cordillera has been studied for nearly 150 years, but for much of that interval Cordilleran geology was being explored for the first time, and its contributions to general tectonic concepts such as the origin and evolution of mountain belts were limited in comparison with contributions from European and Appalachian orogens. This changed some 30 years ago with the advent of the plate tectonic theory and its application to Cordilleran geology, when tectonic concepts developed in the Cordillera became widely applied to other orogens. Initially, new ideas came from California, where late Mesozoic magmatic activity, sedimentation, deformation and metamorphism were linked to coeval underthrusting of Pacific Ocean lithosphere beneath western North America (*e.g.*, Hamilton, 1969), and where patterns of dated ocean floor magnetic anomalies were related to on-land Tertiary magmatism and tectonism (Atwater, 1970). Later, stratigraphic analysis of widespread Paleozoic and Mesozoic marine volcanic and sedimentary sequences in the Cordillera of western Canada and Alaska (herein called the northern Cordillera) provided the foundation for the concepts of orogenic collages and suspect terranes (Helwig, 1974; Coney *et al.*, 1980). This paper attempts to show how Canadian and Alaskan geology contributes to our present understanding of the origin and evolution of mountain belts and discusses unresolved, and maybe unresolvable, problems.

TECTONIC ANALYSIS OF OROGENIC BELTS

Early Analyses: Geosynclines and Tectonic Cycles
From the later 1800s through the 1960s, at least in North America, hypotheses on the origin of mountain belts were based on the concepts of geosynclines and tectonic cycles (Dawson, 1901; Kay, 1951; King, 1969). Even though rocks thought to originate in ocean basins and volcanic archipelagos had been recognized within, for example, the Alps and Cordillera (respectively by Argand (1924) and by Crickmay (1931)), such rocks mostly were called geosynclinal deposits. A geosyncline was the initial, pre-orogenic, stage of the deterministic tectonic cycle, and in the Cordillera comprised a western Paleozoic and early Mesozoic eugeosyncline composed of volcanic and sedimentary rocks, and a coeval eastern sedimentary miogeosyncline. It was succeeded in the tectonic cycle by orogenic and post-orogenic stages, each with characteristic associations of rocks and structures; the end product of the cycle was an orogenic belt. Within this concept, paleogeographic mobility was limited essentially to cumulative displacements recorded by folds and faults. Unfortunately, no extant geosynclines were recognized, in violation of the old geological precept that the present is the key to the past!

"Genetic" Tectonic Analysis: Tectonic Assemblages
Advent in the 1960s of the plate tectonics theory caused a revolution in Cordilleran tectonic concepts. It also introduced levels of complexity and uncertainty undreamed of within the context of the deterministic tectonic cycle.

In 1963, Dietz re-interpreted geosynclinal rocks in "actualistic" terms such as collapsed continental slope and rise deposits, within the framework of the nascent plate tectonic theory. In so doing, he catalysed a major change in tectonic terminology. Cordilleran eugeosynclinal rocks became identified as fragments of magmatic island arcs and subduction complexes formed at convergent plate margins, and miogeosynclinal strata were seen as intraplate continental shelf and slope deposits. Middle Jurassic and younger, former syn- and post-orogenic rocks of the western Cordillera formed while the upper plate margin was in compression or transpression and the crust was thickened, as shown by the general change from marine to non-marine deposits. The rocks formed in continental arcs and were accompanied by basins filled with clastic detritus eroded both from the arcs and from the synchronously uplifted mountains (Hamilton, 1969; Burchfiel and Davis, 1972; Monger *et al.*, 1972; Dercourt, 1972).

Many new Geological Survey of Canada maps (1:250 000 scale) covering much of the Canadian Cordillera fortuitously, but fortunately, became available just before arrival of the plate tectonic theory (see Gunning, 1966). On the maps, unconformity-bound sequences of interfingering volcanic and sedimentary rocks were called "groups", an informal stratigraphic rank which facilitated the later change to actualistic terms. Groups composed of volcanic rocks with a range of compositions and interbedded sedimentary rocks (*e.g.*, Nicola Group of south-central British Columbia) and in many places co-extensive with coeval granitic plutons, were readily interpreted as remains of former magmatic arcs. Groups featuring disrupted pillow basalt, radiolarian chert and other sedimentary rocks, associated alpine-type ultramafics and local blueschist (*e.g.*, Cache Creek Group in the British Columbia interior) were identified as ocean floor remnants in subduction complexes. Thick successions of Cambrian though lower Mesozoic limestone and shale in the easternmost Cordillera were recognized as ancient continental, or craton, margin deposits (Monger *et al.*, 1972).

Tectonic Assemblage Maps

The new data and interpretations led eventually to a new kind of regional geological map whose principal units are associations of rock types grouped in the inferred tectonic settings in which they formed, rather than in the rock stratigraphic divisions of most conventional geological maps. These units are called "tectonic assemblages" (resurrecting the term "assemblage" from papers in Gunning, 1966, for rock packages composed generally of more than one coeval group). They are major divisions of maps of the Canadian Cordillera (scale 1:2M; Tipper *et al.*, 1981; Wheeler and McFeely, 1991) and, called "tectonostratigraphic units," of the conterminous United States (scale 1:2.5M; Burchfiel, 1993).

Continental Growth

The initial assignments of magmatic rocks to actualistic tectonic settings, based on rock types, generally have been confirmed by later geochemical studies in which analyses of old rocks are matched with those of rocks forming today in known tectonic settings (*e.g.*, Mortimer, 1987). In addition, the low initial strontium ratios (Armstrong, 1988) and positive ϵ_{Nd} values (Samson and Patchett, 1991) of most older and many younger arc and subduction complex rocks suggest that they are geochemically "juvenile," that is, they are derived from mantle differentiates with little or no contamination by old continental crust.

This last finding has big implications for continental growth processes. In combination with interpretations of the probable depth distribution of rocks within Cordilleran crust based on deep seismic reflection and refraction profiles (see Cook, 1995), it appears that volumetrically about half of the crust of the southern Canadian Cordillera was originally non-continental, upper crustal material accreted as enormous thrust sheets to the craton margin to form new continental crust. At surface, the continental margin migrated about 600 km oceanward from a position it occupied in early Mesozoic time in the eastern Cordillera (near the southern Rocky Mountain Trench) to its present position near the toe of the continental slope, west of Vancouver Island. The circum-North Pacific region, between the North American and Siberian cratons, appears to be the place on Earth where most new continental crust has formed in the last 200 million years (Nokleberg *et al.*, 1997).

New Isotopic and Biostratigraphic Dates

Changes since the early 1970s in our understanding of Cordilleran tectonic evolution are imposed by new, abundant isotopic and biostratigraphic dates. Since 1970, the number of isotopic dates has increased at least ten-fold. In addition, the new dates have greater precision, and dates based on different isotopic systems have become widely available. The new dates show how former convergent plate margins, delineated by Paleozoic to Holocene magmatic arcs, migrate in time and within present coordinates of latitude and longitude, as well as when formerly deeply buried rocks were cooled by uplift and erosion or tectonic exhumation during mountain building (Armstrong, 1988; Armstrong and Ward, 1993).

Radiolarian and conodont biostratigraphy, rarely used in the western part of the Cordillera before 1970, now date strata of previously unknown age, with one important result that most subduction complexes are known to be much younger than they were originally thought to be. For example, the Bridge River Complex on the east side of the southern Coast Mountains of British Columbia (Fig. 1) was undated until 1971. It had been correlated with the lithologically similar Cache Creek Complex, which in those days was known to contain late Paleozoic fossils. The Bridge River Complex is known now to range in age from Mississippian to at least Late Jurassic (340-155 Ma; Cordey and Schiarizza, 1993). Its composition, mainly radiolarian chert, argillite and pillow basalt, and the great time (≥185 million years) spanned by these rocks, together suggest that the complex is the remains of the floor of a large ocean basin which contained pelagic facies (radiolarian chert) at least as late as Late Jurassic time. Today, remnants of this former ocean basin are located well within the Cordillera, about 300 km from the present margin of the Pacific Ocean, raising the question of how these oceanic rocks came to be there so late in the long history of the Cordillera.

Records of Plate Tectonic Disorder: Orogenic Collages

Location of arc rocks (Stikine, Alexander and Wrangellia terranes of Fig. 1) oceanward of coeval subduction complexes (Cache Creek terrane, Fig. 1) in the northern Cordillera contrasts with the seemingly more orderly geology to the south in the conterminous United States' Cordillera, where subduction complexes lie oceanward of coeval arcs and gradually decrease in minimum age oceanward (*cf.* Monger *et al.*, 1972, their Fig. 7; Burchfiel and Davis, 1972). The scrambled pattern in Canada influenced Helwig (1974) to conclude that plate tectonic processes acting for a long time have enormous capacity to create geological disorder. His statement that "each orogen is a unique time-space collage of mappable elements, all generated, assembled and rearranged by tectonic processes" contrasts with the orderly evolution of mountain belts portrayed by the tectonic cycle and in some early plate tectonic models. The collage concept implies that in order to fully understand the evolution of an orogen, its "mappable elements" must be identified and their positions tracked in time and space; in these aspects it anticipated what became known as the terrane concept.

Space-time Tectonic Analysis: The Terrane Concept

It had been recognized for a long time that some orogenic belts contain regions whose geological records are very different from those of other parts of the orogen. For example, Argand (1924) suggested that the Alps contain rocks originating in Europe and Africa and an intervening ocean basin, and that central Asia

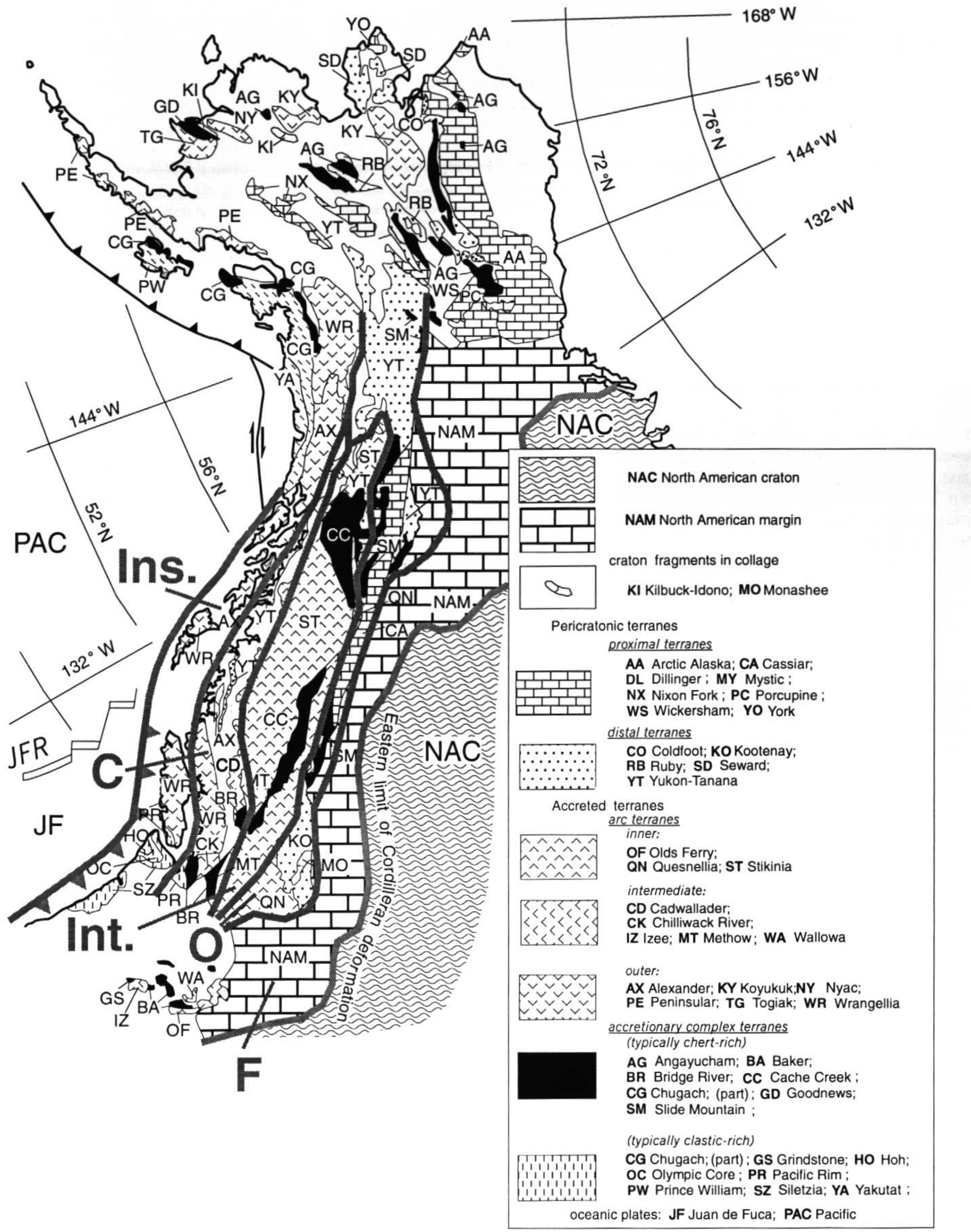

Figure 1 *Terrane map of the northern Cordillera; JFR Juan de Fuca Ridge; unpatterned areas are either ocean floor, or extensive areas of plutonic rock or extensive post-accretionary cover. Heavy lines are boundaries of the five morphogeological belts of the Canadian Cordillera;* ***F****, Foreland Belt;* ***O****, Omineca Belt;* ***Int****, Intermontane Belt;* ***C****, Coast Belt;* ***Ins****, Insular Belt (modified from Monger and Nokleberg, 1996; Gabrielse* et al.*, 1991).*

contains originally dispersed Precambrian massifs brought together during Paleozoic mountain building. In a seminal plate tectonic paper, Wilson (1968, fig. 6) identified "fragments of Asia" within the Cordillera. By the early 1970s, "terrane" was employed in the northern Cordillera to delineate regions with distinct geology. Berg *et al.* (1972), used "Alexander terrane" for a region in southeastern Alaska with distinctive Paleozoic stratigraphy, and Wheeler and Gabrielse (1972) employed "Atlin terrane" for part of northern British Columbia underlain by Cache Creek rocks.

By the late 1970s, the stratigraphy of the western northern Cordillera was becoming relatively well known. In 1977, Jones *et al.* applied the terrane name "Wrangellia" (taken from the Wrangell Mountains of southern Alaska) to rocks in southern Alaska and Queen Charlotte and Vancouver islands with remarkably similar Triassic stratigraphy and a paleomagnetic signature indicating an origin some 3000 km south of their present position with respect to the craton. Also in 1977, Monger distinguished six regions of upper Paleozoic rocks in the western Canadian Cordillera based on differences of stratigraphy, rock associations, major element geochemistry of volcanic rocks, and coeval faunas. Building on these examples, Coney *et al.* (1980) identified, named and summarily described about 200 "suspect terranes" within the Cordillera from northern Alaska to southern Mexico. The terrane concept in its present form was launched, subsequently became used in other orogenic systems (*e.g.*, Williams and Hatcher, 1982), and entered the general geological literature.

Each terrane was distinguished mainly on the basis of stratigraphy, and some terranes carried paleomagnetic and/or paleontological signatures distinct from those of adjoining terranes and from the nearby craton margin. Most terranes were separated from other terranes and/or the craton margin by major faults, or else terrane boundaries were concealed by younger intrusions or cover. The qualifier "suspect" rightly referred to the uncertain location of most terrane homelands.

The terrane concept met with criticism by some who saw it as a backward step because it said nothing about the plate tectonic settings in which the rocks formed, and by others who felt that identification of numerous terranes within a region of distinctive geology, such as the Franciscan Complex of California, obscures its unifying characteristics, which in the Franciscan example were those of a subduction complex. Most criticisms can be met by using qualifiers, such as "accreted" for terranes composed of juvenile rocks added to the craton margin, "pericratonic" for terranes containing abundant material eroded from a craton but in uncertain paleogeographic relationship to it, or genetic terms such as "arc" or "accretionary or subduction complex" for their predominant tectonic settings during formation (Fig. 1).

The Case for Enormous Lateral Mobility

The western part of the Cordillera contains a cryptic record of potentially enormous lateral displacements across the convergent plate boundaries delineated by magmatic arcs ranging in age from at least Devonian to Holocene (380-0 Ma). Intra-Cordilleran lateral displacements on the scale of hundreds of kilometres long had been recognized from measurements of offset of rock units across faults such as the dextral strike-slip Tintina Fault in Yukon (Roddick, 1967), and cumulatively across thrust faults in the Rocky Mountains (Bally *et al.*, 1966; Price and Mountjoy, 1970). Amounts of displacement across the convergent plate boundary between North American and various Pacific Ocean plates may be at least an order of magnitude larger. Maps of the age of the Pacific Ocean floor show its marked age asymmetry, with active spreading ridges located in the easternmost Pacific (Fig. 2). Oldest rocks of the small Juan de Fuca Plate, presently being subducted beneath Vancouver Island, are only about 6 million years old, whereas south of Japan a large tract of Pacific Ocean floor is older than 145 Ma. When patterns of dated ocean floor magnetic anomalies are combined with hot spot tracks to provide an "absolute" reference frame, it appears that a strip of oceanic lithosphere about 13,000 km long — a length equivalent to one third of the circumference of the Earth — has disappeared beneath western North America since the end of the Jurassic, 145 million years ago (Engebretson *et al.*, 1992).

One hundred and forty-five million years is only one-fifth of the time spanned by Cordilleran evolution, which was initiated in the latest Proterozoic (*ca.* 750 Ma) by rifting and dispersal of parts of the Rodinian supercontinent (*e.g.*, Ross, 1991).

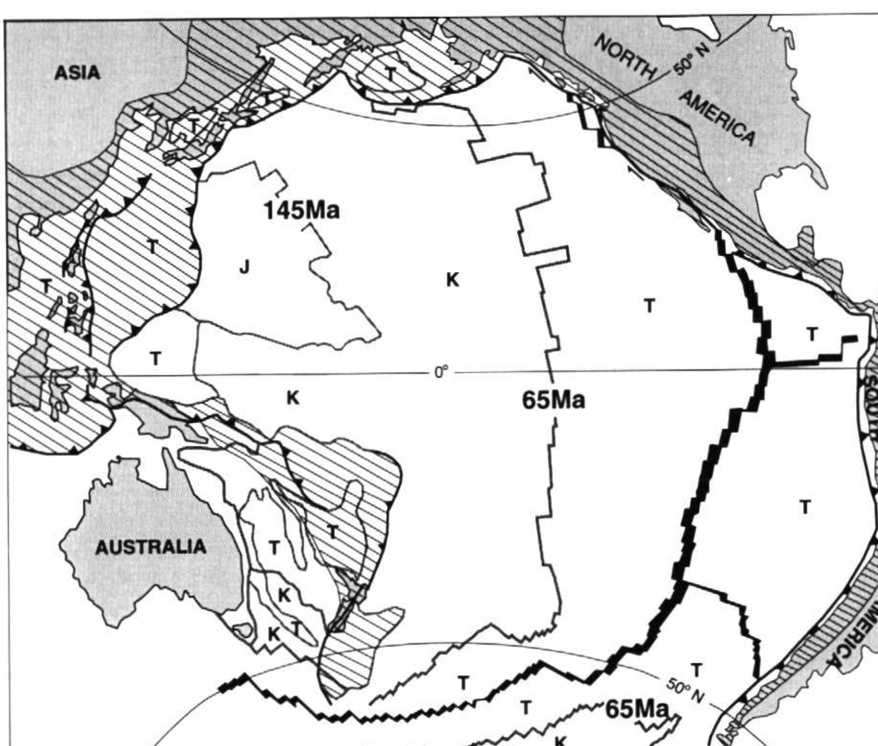

Figure 2 *The Pacific Ocean basin; age of Pacific Ocean crust shown by **J**, Jurassic; **K**, Cretaceous; **T**, Tertiary; **black**, Holocene; **hachured regions**, Mesozoic-Holocene orogenic belts; **barbed lines**, hanging walls of subduction zones (modified from Pacific Ocean map, Commission for the Geological Map of the World, UNESCO, Paris, 1976).*

Plate convergence, as recorded by arc magmatism, is as old as latest Proterozoic (600 Ma) in southeastern Alaska (Gehrels and Saleeby, 1987) (although the rocks there probably reflect convergence along some plate margin other than that of the western North American Plate). Probable arc magmatic rocks of Late Devonian age (*ca.* 370 Ma) occur within craton margin deposits from central California to northern Alaska and so reasonably are regarded as belonging to the North American Plate. Paleozoic through Holocene (340-0 Ma) arcs and less extensive subduction complexes form much of the western Cordillera (Monger and Nokleberg, 1996). The time spanned by these arcs suggests that a region **greater in width** than the present Pacific Ocean may have been consumed by subduction since Proterozoic time. The little that remains at surface of the lithosphere of that vast region resides in the circum-Pacific orogenic belts (Fig. 2).

Estimating Very Large Amounts of Lateral Displacement

Some idea of the amounts of displacement of potentially far-travelled rocks can be obtained by comparing paleontological and paleomagnetic records of Cordilleran rocks with those of rocks of the same age on or marginal to the western North American craton. In 1970, Tozer (p. 635) suggested that Triassic warm-water, low-latitude faunas now in the western Cordillera lived, died and were buried south of coeval cooler-water, higher-latitude faunas in the eastern Cordillera, and later were transported northwards along dextral strike-slip faults such as the Tintina Fault. Monger and Ross (1971) recognized that the oceanic Cache Creek Complex in the central Canadian Cordillera (Cache Creek terrane of Fig. 1) contains Permian fusulinid faunas, which are similar to those in parts of Asia near the present western Pacific and the former Permian Tethys Ocean. The Permian Cache Creek faunas are very different from coeval fusulinid faunas in flanking arc deposits (in Quesnel and Stikine terranes on Fig. 1), which are similar to those of the southwestern United States and parts of the Andes. This faunal and lithological distribution was explained by invoking large amounts of transport of Permian Cache Creek rocks and faunas on moving oceanic plates, and their eventual juxtaposition, during subduction, with arc rocks to the east in Quesnel terrane. Later northward movement on dextral strike-slip faults brought Stikine arc rocks to their present position oceanward of Cache Creek terrane.

The first paleomagnetic indication of large latitudinal displacements of parts of the western Cordillera came from Beck and Nosun (1971), who suggested that a Cretaceous pluton in the North Cascade ranges of northwest Washington State was transported northward by about 3000 km with respect to the craton. Contemporaneous studies by Symons (1971) and Irving and Yole (1972) on early Mesozoic rocks on Vancouver Island also hinted at large northward displacements.

Potentially, both methods can show amounts of latitudinal displacement with respect to the North American craton, whose western margin was orientated more-or-less north-south in the Mesozoic. However, it may be impossible to measure amounts of displacement across lines of longitude. Attempts to do this quantitatively compare the similarity of western Cordilleran faunas with coeval faunas on the craton margin, and incorporate paleo-oceanic current models. Somewhat equivocal results are obtained, however (Belasky and Runnegar, 1994). The great difference between warm-water Permian fusulinids, conodonts and corals in the Cache Creek Complex, and coeval faunas elsewhere in the Cordillera which are closer to warm-water American cratonal faunas, suggests that the homeland of the Permian Cache Creek faunas was far removed from the Americas, but just how far is not known.

Conflicting Paleontological and Paleomagnetic Interpretations

Initially, paleontological and paleomagnetic studies told similar stories; both suggested large latitudinal displacements northward of parts of the western Cordillera with respect to the craton. Later, the stories diverged, partly because revisions to the North American polar wander path re-located the craton to lower latitudes in Jurassic time (Gordon *et al.*, 1984). The polar wander path revision effectively removes much of the paleomagnetically determined latitudinal difference between lower Mesozoic rocks in parts of the western Cordillera and the craton, if northern paleolatitude options are chosen (Irving and Wynne, 1990). Because of magnetic reversals, extensive paleomagnetic sampling in well-dated rocks is needed to show whether their paleomagnetism was acquired in northern or in southern hemispheres; other lines of reasoning, such as the simplest and shortest movement path, may be used to clarify the ambiguity.

Paleomagnetic results conflict with apparent northward displacements with respect to the craton as deduced from faunal distributions in some of the same Mesozoic rocks. For example, Smith and Tipper (1986) used similarity coefficients to suggest that Lower Jurassic (*ca.* 195 Ma) marine faunas in the western Cordillera were displaced northwards ≥1000 km relative to those near the craton, whereas the re-interpreted paleomagnetic results show very small latitudinal displacements for some of the same rocks which host these faunas. Late Mesozoic (≤85 Ma) paleomagnetic and paleontological results tell the reverse story. For mid- to Upper Cretaceous rocks in different parts of the western Cordillera, paleomagnetic measurements indicate northward displacements ranging from about 1300 km to 4000 km with respect to the craton (Irving *et al.*, 1996), whereas Cretaceous mollusk and radiolarian faunas of the westernmost Cordillera suggest minimal latitudinal displacements (Elder and Saul, 1993; Haggart and Carter, 1994). Rather than latitudinal displacements, tilting and flattening have been invoked to explain the paleomagnetic results, and (conversely) warm or cool oceanic currents to explain the marine faunal distributions. Resolution of this seeming paradox is essential, because advances in understanding of Cordilleran tectonic evolution depend so much on our knowledge of the paleogeographic configurations of its components.

The value of the terrane concept is seen in connection with this controversy. Cowan *et al.*, (1997, figs. 2A,B) show two Late Cretaceous (90 Ma) paleogeographic reconstructions. One, based on geology and paleontology, shows relatively little (<1000 km with respect to the craton) post-mid-Cretaceous latitudinal displacement of terranes in the western Canadian Cordillera. The other, based on paleomagnetism, shows western terranes located about 1500 and about 3500 km to the south. Regardless of their mid-Cretaceous positions, the terranes retain most of their integrity as building blocks of the Cordilleran collage.

Detrital Zircons Provide Additional Paleogeographic Constraints?

Attempts to provide additional paleogeographic constraints compare U-Pb ages of detrital zircons in Cordilleran clastic basins with those of cratonal rocks (Gehrels *et al.*, 1995). Archean zircons dated at about 2.5 Ga in western Cordilleran Cretaceous basins (Mahoney *et al.*, 1997) are more likely to have been derived from the western Canadian Shield than from the 1.0 Ga basement of Mexico. However, the results are equivocal because "piercing point" control of such studies is compromised; cratonally sourced zircon grains probably were recycled several times by unknown transport patterns into western Cordilleran clastic basins.

SYNTHESIS: PLATE RECONSTRUCTIONS AND OROGENESIS

The Challenge

The Cordillera is located on a continent-ocean interface that has existed for about the last 750 million years. During that time, the ancestral Pacific basin was created by latest Proterozoic rifting and separation of a supercontinent, expanded in Paleozoic-early Mesozoic time, and subsequently contracted to its present size. All that remains at Earth's surface of a region which 250 million years ago apparently occupied over half Earth's surface area is preserved now only in the circum-Pacific orogenic belts (Fig. 2). In those orogenic belts older relationships between collage components may be rearranged or destroyed by later tectonic activity. Can we hope to determine the succession of plate tectonic configurations leading to the present Cordillera, or has too much been lost?

Limitations of "Classical" Plate Tectonics

Plate configurations and motions between western North American and various Pacific oceanic plates, based on global patterns of dated ocean floor magnetic anomalies and hot spots (Engebretson *et al.*, 1985; Engebretson *et al.*, 1992), can be reconstructed with confidence only back through mid-Cretaceous time and agree well with the on-land geology of the Cordillera. The present arc-transform-arc margin of the northern Cordillera has persisted for the last 40 million years (Fig. 3a; Atwater, 1970). In Late Cretaceous-early Tertiary time (85-40 Ma), arc magmatism along the northern Cordilleran margin was far more continuous than later, and combined with northward motions of oceanic Kula and Pacific plates and westward motions of the North American Plate (Engebretson *et al.*, 1985), created "optimum conditions" (Jarrard, 1986) for strike-slip faulting within the arc. The result was an anastomosing network of near orogen-parallel, dextral strike-slip faults (Fig. 3b), which rearranged the northern Cordilleran collage by greater or lesser amounts, depending on whether paleomagnetic or geological–paleontological estimates of amount of displacement are used. In the mid-Cretaceous (105-85 Ma), oceanic plate reconstructions suggest that subduction was orthogonal; within the Cordillera, this interval features voluminous magmatism and widespread contraction (Fig. 3c; Armstrong and Ward, 1993). In Early Cretaceous time (≥105 Ma), oceanic plate reconstructions hint at plate convergence with a southward component, in accord with scattered evidence for sinistral strike-slip displacements within the Cordillera (Fig. 3d; Monger *et al.*, 1994). Extrapolations made from the small area of Jurassic ocean floor in the western Pacific to plate configurations along the North American plate margin are tenuous at best, and pre-Cretaceous relative plate motions are recorded by contractional, transcurrent, and extensional structures of various ages within the Cordillera, but these are mostly of local extent and are compromised by younger overprints.

Attempts to Reconstruct Past Plate Configurations

Past convergent plate margins within the Cordillera are recorded by arc rocks that locally are as old as 600 million years, and by accompanying subduction complexes. Many options are possible when attempting to reconstruct the plate configurations once occupied by components of the Cordilleran collage (see Samson and Patchett, 1991). For example, are the many accreted arc terranes once 1) originally different arcs; 2) parts of one arc system later fragmented and separated or duplicated by transport within the upper plate margin, perhaps during oblique plate convergence (Figs. 3b,d); or 3) coeval arcs along the same plate margin but separated by magmatic gaps, as in today's transform-arc-transform-arc margin (Fig. 3a)? Although so far there are no conclusive answers to these questions for much of Cordilleran history, the rock record seems to favor the second option over the first, **at least for the Mesozoic**; the third may be unanswerable!

Some constraints on possible plate configurations are provided by identifying the facing directions of Cordilleran magmatic arcs, and by establishing their relationship to the craton margin. Facing directions are identified by lateral changes of lithologies and geochemistry within the arc, and by the lateral relationship of the arc to coeval subduction complexes on one side and to back-arc basins on the other. If the arc is separated from the craton by a coeval subduction complex, it faced towards the craton, whereas if arc rocks are emplaced within pericratonic terranes, craton margin deposits, or previously accreted terranes, the arc probably faced away from the craton.

It seems that most mid-Mesozoic (≤160 Ma) and younger northern Cordilleran arcs, with the possible exception of a Jura-Cretaceous arc in west-central Alaska (KY

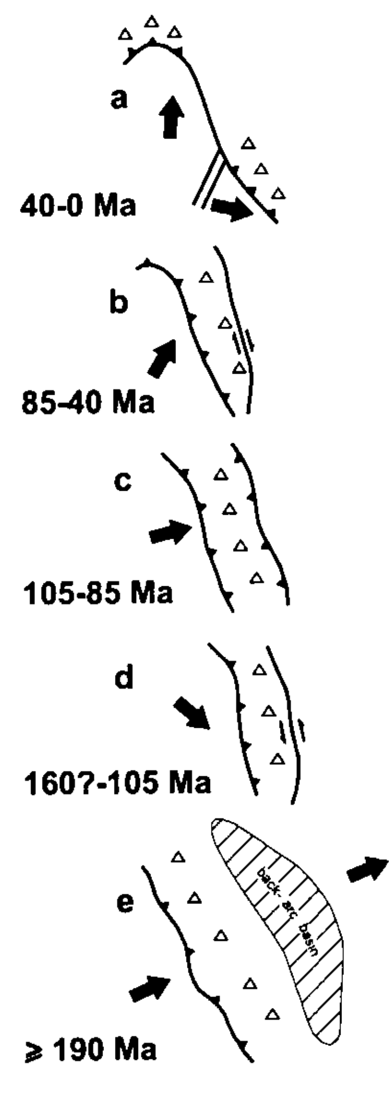

Figure 3 *Variations on a theme of plate convergence; open triangles, magmatic arcs; line with solid barbs, upper plate at convergent boundary; line with open triangles, hanging wall of thrust fault system; heavy black arrows in* ***a, b, c, d****, indicate* ***relative*** *plate motions; in* ***e****,* ***"absolute"*** *plate motions. These variations probably existed within the Canadian Cordillera, at the times indicated.*

of Fig. 1) apparently faced away from the craton and were probably North American plate margin arcs. Oceanic crust of the ancestral Pacific basin was being subducted beneath them, and most were emplaced in previously accreted and pericratonic terranes (Armstrong, 1988; Monger and Nokleberg, 1996). Late Early Cretaceous (*ca.* 110 Ma) sinistral strike-slip faulting may be invoked to account for apparent duplication of Middle Jurassic to mid-Cretaceous arc magmatic rocks and enclosure of Bridge River terrane in southwestern British Columbia (Figs. 1, 4a; Monger *et al.*, 1994).

The earlier record is more complex. In the southern Canadian Cordillera, east of the early Mesozoic Cache Creek subduction complex, early Mesozoic and late Paleozoic arcs in Quesnel terrane faced away from the craton, although separated from it by basins partly floored by Paleozoic oceanic crust (Slide Mountain terrane of Figs. 1, 3e; Mortimer, 1987; Roback *et al.*, 1994). Conversely, in Yukon, late Paleozoic arc rocks are separated from the craton by coeval oceanic and pericratonic rocks containing blueschist and eclogite, which presumably formed in a subduction zone dipping away from the craton (Mortensen, 1992). Such coeval arc polarity differences occur today in the extensional convergent margins of the southwestern Pacific basin. Late Devonian (380 Ma) magmatic rocks found from California to northern Alaska, intrude and interfinger with pericratonic and craton margin strata, were the source of ash deposited locally on the craton margin, and probably represent a North American Plate margin arc (Monger and Nokleberg, 1996).

West of the Cache Creek subduction complex, facing directions of Paleozoic and early Mesozoic arcs in Stikine and Wrangellia terranes (Fig. 1) are uncertain, but it is possible that Mesozoic arc terranes in the northern Cordilleran collage belonged to a North American plate margin arc that diverged from the roughly north-south oriented craton margin. Lithological, faunal and paleomagnetic similarities between Quesnel and Stikine terranes and just possibly, the Jurassic arc part of Wrangellia, hint that the western terranes may have been co-latitudinal extensions of the early Mesozoic Quesnel arc, although faunas place the arcs at lower latitudes than the paleomagnetic results (Fig. 4b; Mihalynuk *et al.*, 1994; Monger and Nokleberg, 1996). In addition, Mihalynuk *et al.* (1994) suggested that in Early and Middle Jurassic time, the Stikinian part of the arc was rotated anticlockwise, in accord with paleomagnetic declinations, to enclose Cache Creek terrane at about the same time as the amalgamating terranes (QN, CC, ST of Fig. 1) were accreted to the craton margin.

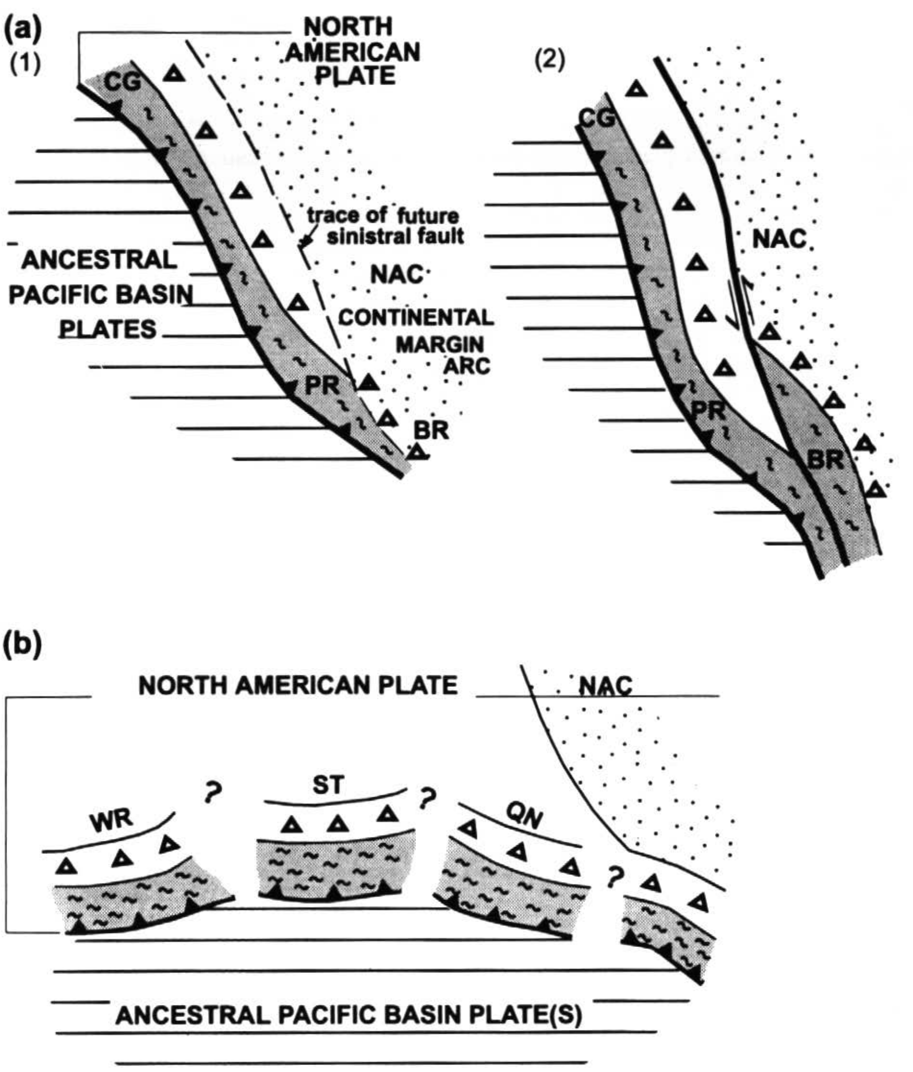

Figure 4 *Possible pre-accretion configurations of arc and subduction complex terranes at the North American plate boundary.* (**a**)*Jurassic-Cretaceous arc/plate margin; heavy line with barbs, subduction complex with barbs on upper plate; possible duplication of arc (triangles) and subduction complex (shaded, with squiggles) in late Early Cretaceous time encloses Bridge River (**BR**) terrane; **CG**, Chugach terrane, **PR**, Pacific Rim terrane; stippled pattern labelled **NAC**, North American continental; (modified from Monger* et al., *1994).* (**b**) *early Mesozoic; **QN**, **ST**, **WR**, Quesnel, Stikine, Wrangellia terranes; (shaded, with squiggles, in part, Cache Creek terrane); patterns as for 4(a) (modified from Mihalynuk* et al., *1994; Monger and Nokleberg, 1996).*

The Cause of Cordilleran Orogenesis?

Orogenic belts form at convergent (or recently convergent) plate margins where the upper plate margin is in compression (or transpression). The stratigraphic record in the Canadian Cordillera shows that early Mesozoic magmatic arc rocks on the North American plate margin were separated from the craton margin by marine basins of unknown width. Starting in the Jurassic (*ca.* 185 Ma) the basins behind the magmatic arcs closed, the Omineca Belt (Fig. 1) formed by crustal thickening on the site of the former basins, and was uplifted and eroded to become the source of clastics to flanking Intermontane and Foreland belts. Marine basins, which separated Middle Jurassic–Early Cretaceous arc rocks (*ca.* 170-100 Ma) of the southwestern Coast Belt and Insular Belt from rocks to the east, were closed in early Late Cretaceous time (95 Ma), and the Late Cretaceous-early Tertiary Coast Belt was uplifted mainly on the site of the former basins. By Late Cretaceous time (95 Ma), the presence of non-marine strata in all except marginal parts of the Cordillera unequivocally attest to high-standing Cordilleran crust. How did this transformation take place?

Although the relationship between mountain building and plate convergence seems to be clear in orogens involving continent-continent collision, it may be obscure in subduction-related orogens. Possible causes, such as increased rates of plate convergence, strong coupling between upper and lower plates of the convergent margin, or decreasing ages of subducting ocean crust (Cross and Pilger, 1982; Jarrard, 1986) may be impossible to recognize in the rock record. However, a relationship between Cordilleran orogenesis and North Atlantic opening, long suspected by proponents of continental drift (*e.g.,* Daly, 1926), was shown to be reasonable within the plate tectonic framework by Coney (1972), who correlated events in the trailing, mid-Atlantic margin of the North American Plate with those in its leading, Cordilleran margin. This correlation is supported by a general explanation of the different types of convergent plate margin, based on motions of converging plates relative to the deep mantle (Hyndman, 1972; Uyeda and Kanamori, 1979; Jarrard, 1986). In places where the upper plate moves **away** from the subduction zone, extensional deformation takes place over a broad region, elevation of the upper plate margin is small, and back-arc basins form, as in the western Pacific (Figs. 2; 3e). Where the upper plate moves **toward** the subduction zone, contraction within weak arc lithosphere causes crustal thickening and formation of a high, Andean-type orogen, as along the eastern Pacific margin (Fig. 2). An **identifiable** cause of Cordilleran mountain-building is the probable persistent motion of the North American Plate towards and over various Pacific Ocean plates (Engebretson *et al.*, 1985), which seems to have been initiated when the North Atlantic basin opened widely in the Jurassic.

Terrane Accretions and Morphogeological Belts

Although subduction accompanied by upper plate arc magmatism is prominent in northern Cordilleran evolution, its mid-Mesozoic to early Tertiary structural, metamorphic and sedimentological records seem to be closer in detail to those of orogens involving continent-continent collision, such as the Himalayas and Alps. In the Canadian Cordillera, the Omineca and Coast morphogeological belts of the Canadian Cordillera (Fig. 1; Gabrielse *et al.*, 1991), are two tracts where formerly deeply buried (10-30 km) rocks are exposed at surface, and result from localized crustal thickening by contraction, and subsequent differential uplift and erosion. In style and scale, crustal (but not mantle) structures of Omineca and Coast belts are generally comparable to those of the Alps (*cf.* Cook, 1995; Pfiffner *et al.*, 1991). The Foreland, Intermontane and Insular belts, whose rocks are little metamorphosed and which flank and separate Omineca and Coast belts, acted as forelands at various times to the contractional deformation centred in Omineca and Coast Belts, and received clastic detritus eroded from them.

An explanation for the two belts of crustal thickening within a primarily subduction-related orogen seems to lie in the space-time distribution of the accreted terranes (Monger *et al.*, 1982). The Omineca Belt is the region in which, between Middle Jurassic and early Tertiary time (185-60 Ma), arc and subduction complex terranes mainly in the Intermontane Belt (CC, QN, SM, ST of Fig. 1) were juxtaposed on thrust faults and tectonically interleaved with rocks of the pericratonic terranes and the craton margin. This process led to crustal thickening and metamorphism, and was accompanied by emplacement of plutons that, with decreasing age, became increasingly contaminated with old crustal material (Ghosh, 1995). Similarly, the Coast Belt is the region in which, between mid-Cretaceous and early Tertiary time (95-50 Ma), arc terranes now located mainly in the Insular Belt (AX, WR of Fig. 1) were juxtaposed and tectonically interleaved with earlier accreted Intermontane terranes.

Although the architecture of the northern Cordillera can be explained by incremental, two-stage accretion of terranes to the craton margin in the Jurassic and Cretaceous, it seems that the arc facing directions at the time they accreted were **away** from the craton, suggesting that the arcs belonged to the North American plate margin when they accreted to the craton. It is possible that duplication of coeval arcs was caused by slivering of the same arc during oblique subduction and, in one case, suggested by Mihalynuk *et al.*, (1994), by oroclinal rotation. Surface structures and deep seismic reflection profiles (Cook, 1995) suggest that most terranes are enormous thrust sheets of mainly upper crustal rocks; terrane lower crust and mantle lithosphere fragments apparently were detached and returned to the mantle during subduction. The accreted terranes seemingly acted as large asperities within the hot, weak upper plate margin. Their boundaries initiated and localized contractional deformation without markedly interrupting the process of subduction.

CONCLUSIONS

Application of the plate tectonic theory to Cordilleran geology shows a level of complexity in its evolution undreamed of thirty years ago. The theory highlights the enormous potential for disorder in a region that contains a continent-ocean boundary in existence for 750 million years, and a record of plate convergence in the form of arc magmatism extending back in time for at least 380 million years. We are forced to recognize that much of the record of events responsible for that complexity is lost. Assignment of assemblages of different rock types to tectonic settings extant during their formation is made with some confidence, and shows how the western margin of the craton has been built oceanwards by accretion of the former interoceanic arcs and accretionary complexes whose fragmented remains form most terranes of the Cordilleran orogenic collage. Ideally, to understand the former plate-tectonic configurations which created the Cordilleran collage, we need to know where each component of the collage was located in time and in paleogeographic space relative to the North American craton. The time requirement is well served by isotopic and paleontological dating. The spatial aspect is problematical; paleolatitudes can be measured but probably not paleolongitudes. In addition, as terranes interacted with one another along the North American craton margin in post-Early Jurassic time, it should be possible from the geological record within the Cordillera to locate collage components with respect to the craton margin. The current disparity between geological-paleontological and paleomagnetic estimates of amounts of latitudinal displacement with respect to the craton makes even this impossible for times as late as Late Cretaceous. The revolution remains unfinished!

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