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Cordilleran metamorphic core complexes: An overview

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ABSTRACT

More than 25 distinctive, isolated metamorphic terranes extend in a narrow, sinuous belt from southern Canada into northwestern Mexico along the axis of the North American Cordillera. Appreciation of these terranes has evolved slowly, and more than half of them have been recognized only since 1970. Growing evidence shows that these metamorphic terranes and related features evolved in part during early to middle Tertiary time (55 to 15 m.y. B.P.), that is, after the Laramide orogeny but before basin-range faulting. These terranes have been termed "metamorphic core complexes."

The complexes are characterized by a generally heterogeneous, older metamorphic-plutonic basement terrane overprinted by low-dipping lineated and foliated mylonitic and gneissic fabrics. An unmetamorphosed cover terrane is typically attenuated and sliced by numerous subhorizontal younger-on-older faults. Between the basement and the cover terranes is a zone of "decollement" and/or steep metamorphic gradient with much brecciation and kinematic structural relationships indicative of sliding and detachment. Plutonic rocks as young as early to middle Tertiary age are deformed in the basement terranes of many of the complexes, and some of the deformed cover includes continental sedimentary and volcanic rocks of early to middle Tertiary age.

Some complexes exhibit evidence of prolonged deformation and metamorphism extending back into Mesozoic and even Paleozoic time. All the complexes, however, reveal an early to middle Tertiary deformational and metamorphic overprint that is interpreted to be mainly of extensional origin. The extension coincided with a vast plutonic-volcanic flare-up of magmatic arc affinity mainly during Eocene time in the Pacific Northwest and mainly during late Eocene–Oligocene to middle Miocene time south of the Snake River Plain. The exact tectonic significance of the complexes remains obscure. Their extensional aspect clearly postdates, and seems unrelated to, Cretaceous and early Tertiary Sevier and Laramide compressional tectonics, but predates the more obvious late Tertiary basin-range extension and rifting.

INTRODUCTION

The North American Cordillera has more than 25 distinctive, isolated metamorphic terranes scattered along a narrow, sinuous belt from southern Canada to northwestern Mexico (Fig. 1.). Appreciation of these terranes has come slowly, and more than half of them have been recognized only since 1970. During the past 10 yr, a considerable debate has centered on them, and they have been termed "metamorphic core complexes" (Coney, 1973a, 1976, 1978, 1979; Davis and Coney, 1979; Crittenden and others, 1978).

Orogenic theory long ago acknowledged the importance of regional metamorphism in the evolution of mountain systems. The exact tectonic significance of this metamorphism, however, remained elusive. Largely as a result of ideas of Wegmann (1935) and Haller (1956), the concept of an axial core zone of a mountain system evolved (de Sitter, 1956). This axial zone was visualized as being made up of metamorphic rocks that displayed evidence of extreme ductile flow, gneiss domes (Eskola, 1949), and related plutonic rocks. The zone was termed an "infrastructure" and was seen as distinct from an overlying or flanking, brittle, superficial "suprastructure." The boundary between these two contrasting domains was seen as generally sharp and characterized by steep thermal gradients and structural disharmony. Most of this theory was based on circum–North Atlantic Caledonian and Hercynian examples and the Alpine belt of southern Europe.

Zwart (1969) attempted classification of orogenic metamorphic facies into two basic types. He recognized a Hercynian end-member characterized by granites and by high-temperature and low- to moderate-pressure facies and an Alpine end-member characterized by high-pressure and low-temperature facies. He did not specify any particular tectonic process to explain these types.

A similar distinction was made by Miyashiro (1961, 1973), but was cast in a completely different light. Miyashiro recognized the same two contrasting facies, but he paired them in a single orogen, thus laying a cornerstone of plate-tectonics theory. For him, the high-temperature type was linked directly to processes in magmatic arcs, whereas the high-pressure type was linked to the trench. Both of these contrasting metamorphic facies were interpreted as the result of subduction of oceanic lithosphere along active arc-trench systems in island arcs or along consuming continental margins. Enter plate tectonics and the experience of the Pacific Ocean. Mountain-system evolution suddenly became more comprehensible (Hamilton, 1969; Dewey and Bird, 1970; Coney, 1970), and all moderate- to high-temperature Cordilleran-type metamorphism suddenly appeared to be related to processes associated with magmatic arcs.

METAMORPHISM IN THE NORTH AMERICAN CORDILLERA

Of particular interest to the concerns of this volume were developments in the 1960s which focused attention on a belt of metamorphic rocks directly west of the east-verging foreland fold and thrust belt of the North American Cordillera. Recognition of these metamorphic rocks produced various genetic interpretations that attempted to link the metamorphic core zone with the fold and thrust belt in models reminiscent of Caledonian and Alpine orogens. The earliest and most noteworthy were the ideas of Misch (1960), Armstrong and Hansen (1966), and Price and Mountjoy (1970). Out of these studies rose a consensus that the metamorphic core zone was a deep-seated infrastructural culmination, or hinterland, which evolved contemporaneously with and just west of the superficial thin-skinned fold and thrust belt.

To Misch (1960), the most important element of the eastern Nevada structural province, or hinterland, was a regional structural discontinuity, termed a "decollement." This discontinuity separated Precambrian basement and metamorphosed upper Precambrian–lower Paleozoic sedimentary rocks from an overlying unmetamorphosed allochthon. The type area for this regional decollement was the Snake Range of east-central Nevada. Misch reasoned that the decollement and the associated shearing and metamorphism along it were produced during the "mid-Mesozoic orogeny." He thought that the discontinuity was formed as cratonic basement moved westward into deep-seated thrust roots, peeling and shearing off the Phanerozoic cover as it moved. The implication was that the decollement was structurally continuous with pre-Laramide low-angle break-out thrust faults to the east in central Utah, along and west of the Wasatch line.

Working in the same region, Armstrong (1968b) and Armstrong and Hansen (1966) emphasized remobilization of basement rocks and metamorphism of the lowest part of the Phanerozoic cover during the mid-Mesozoic orogeny. In an analogy to Caledonian systems, they termed the remobilized core zone an infrastructure. In contrast to Misch, they emphasized mobility *below* the decollement (or abschrung zone) and contrasted this domain of recumbent folds and planar fabrics to a less-deformed, brittle suprastructure above.

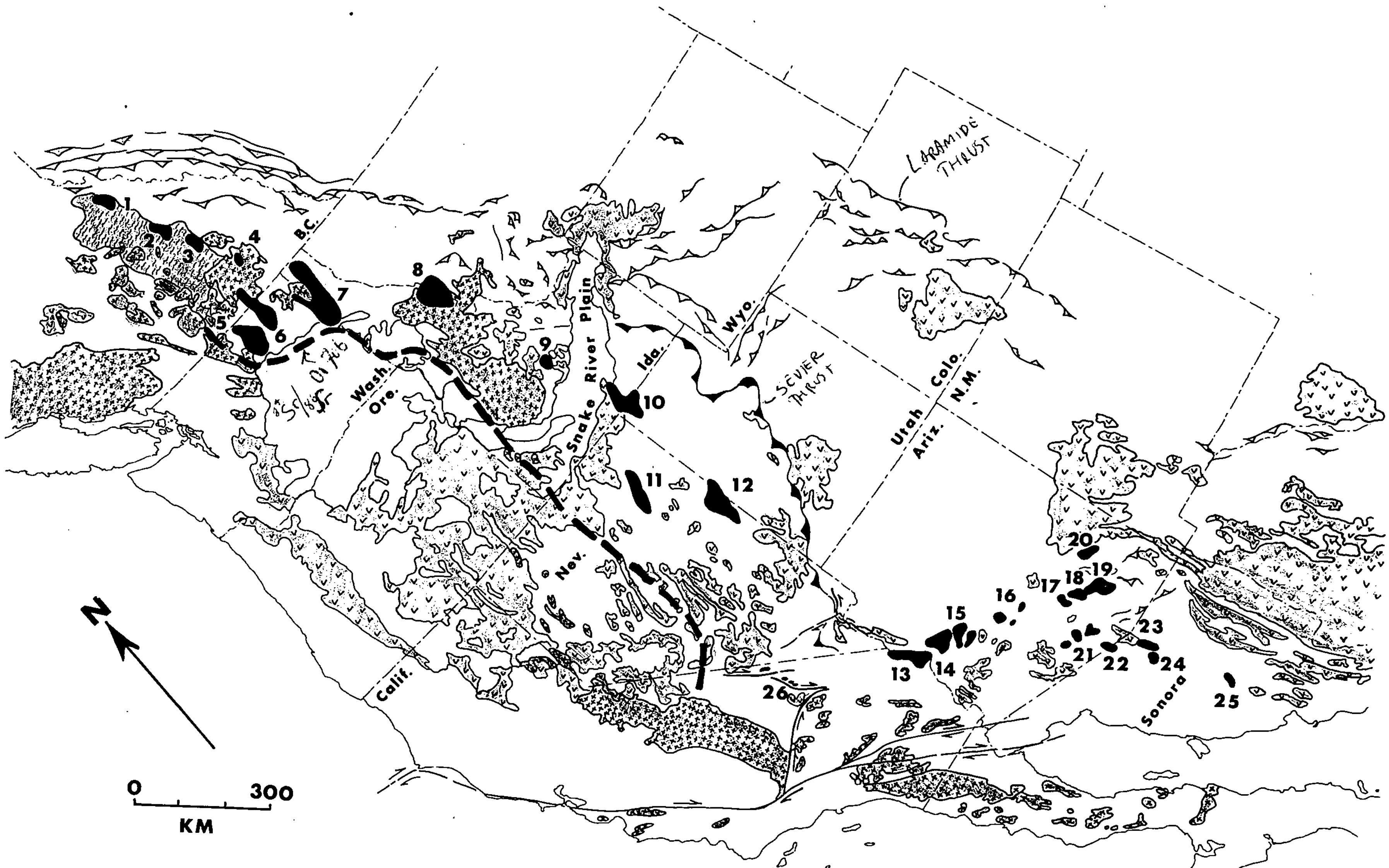
They did not make any specific genetic link between the infrastructure-suprastructure tectonics of the hinterland and the fold and thrust belt to the east.

The Price and Mountjoy (1970) model for the tectonic evolution of the eastern Cordillera of southern Canada was one of the best-formulated and persuasive tectonic syntheses in the history of Cordilleran geologic thought. They proposed that a hot mobile infrastructure rose buoyantly in the Shuswap axial metamorphic core zone, gravitationally spread eastward, and propelled the Rocky Mountain foreland fold and thrust belt to the east. The deformation was seen as continuously evolving upward and eastward from Late Jurassic to early Tertiary time. Price and Mountjoy did not hesitate to directly link the evolving infrastructure with the foreland folding and thrust faulting to the east in a single grand genetic model.

The low-angle thrust faults along the Wasatch line in central and southern Utah are "older-on-younger" faults (Misch, 1960; Armstrong, 1968a) typical of foreland thrust belts the world over (Coney, 1973b). In the hinterland to the west, however, above the metamorphic rocks, low-angle faults are "younger-on-older" (Armstrong, 1972). Nothing quite like these widespread younger-on-older faults has been emphasized in the Canadian Rocky Mountains. In spite of this, the Price and Mountjoy model had great influence on workers in the western United States. As a result, subsequent syntheses attempted to apply modifications of the Canadian example to the battleground of eastern Nevada and western Utah (Roberts and Crittenden, 1973; Hose and Danes, 1973). Hose and Danes, for example, interpreted the decollement and younger-on-older faults in cover rocks as the result of extensional gravity-driven movement of the cover off an uplifted hinterland in eastern Nevada (see Fig. 3B). This cover terrane slid eastward to become the superficially telescoped older-on-younger thrust faults of central Utah.

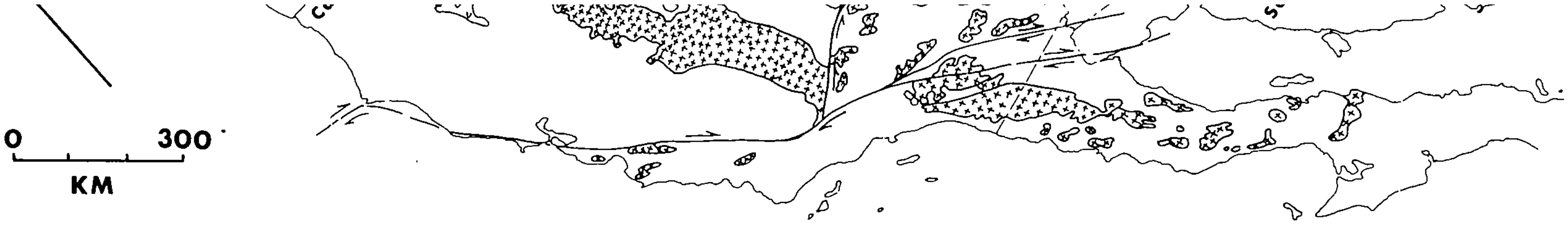
The preceding account sets the stage for developments that were to cast considerable confusion over the simplicity and beauty of the early models. What followed, mostly after 1970, is one of the most fascinating debates in Cordilleran tectonic history.

The debate was predicted. Early workers noted certain data and relationships that were either troublesome or inconsistent with existing models. Damon (Damon and others, 1963; Mauger and others, 1968) found very young (middle-Tertiary) K-Ar "cooling ages" from metamorphic rocks in southern Arizona. Armstrong and Hansen (1966) found similarly young (Tertiary) ages from metamorphic rocks in Nevada. Misch (1960) was aware of Tertiary gravitational gliding and superficial brecciation in the Snake Range of eastern Nevada, and Drewes (1964) discussed multiple thrusting and gravity faulting extending into Tertiary time in the Schell Creek Range of eastern Nevada. Moores and others (1968) recognized Tertiary deformation and metamorphism in the White Pine–Grant Range of eastern Nevada. For many workers, most of these inconsistencies seem to have been explained as the result of a minor Tertiary overprint of a basically Mesozoic tectonic regime of metamorphism and



EXPLANATION

Metamorphic Core Complex



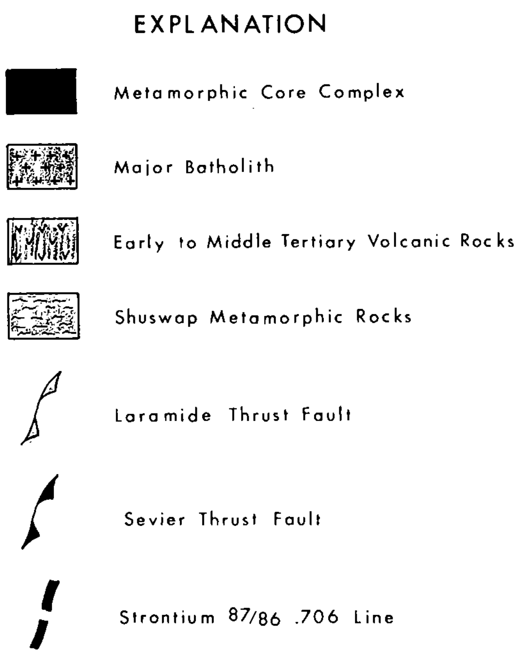


Figure 1 (facing page and explanation, above). Distribution and general regional tectonic setting of Cordilleran metamorphic core complexes, numbered as follows: 1, Frenchman's Cap; 2, Thor-Odin; 3, Pinnacles; 4, Valhalla; 5, Okanogan; 6, Kettle; 7, Selkirk; 8, Bitterroot (Idaho batholith); 9, Pioneer; 10, Albion–Raft River–Grouse Creek; 11, Ruby; 12, Snake Range; 13, Whipple; 14, Harcuvar; 15, Harquahalla; 16, South Mountains-White Tank; 17, Picacho; 18, Tortolita; 19, Catalina-Rincon; 20, Santa Teresa–Pinaleno; 21, Comobabi-Coyote; 22, Pozo Verde; 23, Magdalena; 24, Madera; 25, Mazatan; 26, Death Valley turtlebacks.

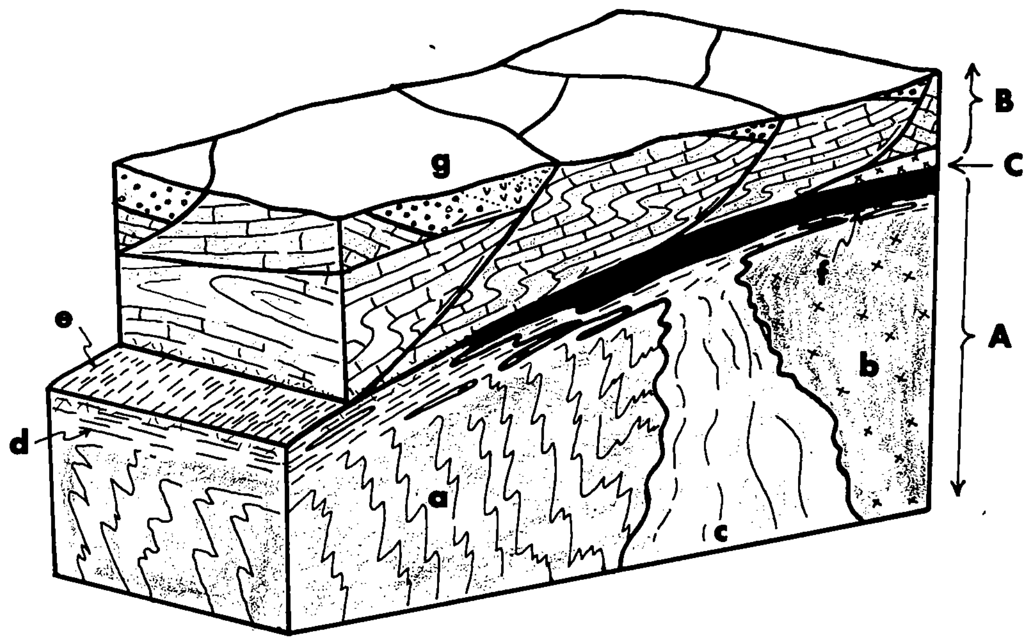


Figure 2. Schematic structural block diagram of typical domains of Cordilleran metamorphic core complexes; A, basement terrane; B, cover terrane; C, decollement zone; a, older metasedimentary rocks; b, older pluton; c, younger pluton (earlty to middle Tertiary); d, mylonitic foliation; e, mylonitic lineation; f, marble tectonite (black); g, lower to middle Tertiary sedimentary and volcanic rocks.

low-angle thrusting. In some cases, the local importance of the Tertiary modifications was adequately emphasized, but the regional significance was not appreciated by others.

The first clear statement that initiated turn-around of this consensus was made by Armstrong (1972). He proposed that widespread "denudational" low-angle faulting in middle Tertiary time was a possible explanation for the "regional decollement" of the eastern Nevada hinterland. Using geochronology and field relations, he reinterpreted existing published geologic mapping and structure sections. His results suggested that at least in part, the extensional younger-on-older faults, which cut well-dated middle Tertiary volcanic rocks as well as associated sedimentary rocks and flatten at depth to merge with the decollement plane, were as young as the Tertiary volcanic rocks they cut. The implication was clear. The decollement surface was, in part at least, of middle Tertiary age and possibly had only little or nothing to do with Sevier (Mesozoic) thrusting to the east. The work of Lee and others (1970) was very significant in regard to this problem. They showed that K-Ar ages from a well-dated Jurassic pluton below the decollement in the southern Snake Range were progressively reset to younger ages as one approached the decollement. The ages decreased to about 18 m.y. at the discontinuity. Lee and others (1970) concluded that the most recent movement on the surface was that young, and Armstrong (1972) entirely agreed with them.

Working independently, Coney (1974) in the Snake Range of eastern Nevada and Davis (1973, 1975) in the Catalina-Rincon Mountains of Arizona both advocated middle Tertiary low-angle gravity sliding of unmetamorphosed cover rocks off metamorphic basement on a decollement surface. At about the same time, I heard (M. D. Crittenden, Jr., 1972, oral commun.) that Todd (in Compton and others, 1977), working in the Raft River–Grouse Creek area, had found that allochthonous sheets of Paleozoic cover rocks had moved off a metamorphic basement onto middle to upper Tertiary sedimentary rocks. Finally, Compton and others (1977) found evidence that the younger metamorphic fabric characteristic of the Albion–Raft River–Grouse Creek metamorphic complex was imprinted on a middle Tertiary pluton.

All of this work implied that significant thermal disturbance, metamorphism, and deformation in the hinterland extended into middle Tertiary time. This is much younger than, and well clear of, the proven age of foreland thrusting to the east. This time sequence raised the disturbing prospect that we were dealing with a very young, special, and enigmatic tectonic response of obscure significance.

CHARACTERISTICS

The metamorphic complexes discussed in this symposium volume occur in a discontinuous belt extending from southern Canada south through the Cordillera into Sonora, Mexico (Fig. 1). In general, these complexes are characterized by distinctly similar rock types, structures, and fabric. These similarities are among the most remarkable aspects of the complexes and are noticed by anyone with more than a casual acquaintance with more than one of them. The striking similarities among the complexes form the thread that binds the issue before us.

Two distinct domains characterize the complexes (Fig. 2). These are a metamorphic-plutonic basement terrane and an overlying or adjacent unmetamorphosed cover. Separating the two is a sharp discontinuity, or zone, marking rapid or abrupt change in rock types and structure. Rarely do the rock types and structural fabric that are characteristic of either the basement or cover cross the discontinuity into the other domain.

The gross aspect of the complexes is domal or anticlinal, usually with an asymmetry such that one flank is slightly steeper than the other. The complexes usually form the highest mountains in their respective regions and may be recognized from afar by their distinctive low domal profile on the horizon.

Metamorphic-Plutonic Basement Terrane

The metamorphic basement is characterized by a low-dipping foliation whose attitude usually conforms to the overall domal or archlike shape of the complex. This foliation imparts a distinct gneissic aspect to the rock. Within the foliation plane is an inevitable mineral lineation. The bearing of the lineation (but not necessarily the plunge) is often remarkably constant within a given complex and sometimes in adjacent complexes as well. In more than 15 complexes located across a distance of 400 km in southern Arizona and Sonora, for example, the lineation bears about N60°E (Davis, this volume). To the north, the lineation is more variable, but generally trends either due west or northwest (Coney, 1974; Misch, 1960). In some cases, the lineation lies close to the axes of the domes or arches, but in other cases, it cuts across this trend. The dip of foliation on flanks of the domes rarely exceeds 20° to 30°. Both the foliation and lineation are usually described as "cataclastic," but do involve recrystallization, particularly in quartz, as well as cataclasis (Todd, this volume). The rocks are best described as mylonitic gneiss. Strain is extreme; the elongated minerals and stretched pebbles in conglomerate can attain axial ratios of 8:2:1 (Coney, 1974; Compton, this volume; Compton and others, 1977; Davis, this volume). The overall strain picture is one of maximum shortening and flattening perpendicular to the subhorizontal foliation plane and maximum extension parallel to the lineation (Compton, this volume). The direction of maximum elongation is frequently described as subparallel to recumbent, flattened, and attenuated minor fold axes. Davis has found small late-stage normal faults whose strike is perpendicular to the lineation (Davis and others, 1975; Davis, 1975, 1977, and this volume). These faults seem to be the result of progression from ductile behavior to brittle failure. On the fault surfaces are slickensides whose bearing is subparallel to the lineation.

In some complexes where erosion has cut deeply into the uplifts, the foliated and lineated fabric diminishes into either an earlier, usually steeper metamorphic fabric or a more homogeneous plutonic fabric (Coney, 1974; Todd, this volume; Reynolds and Rehrig, this volume). The deeper, earlier metamorphic fabrics are often quite complex and record polyphase deformation and complex history (Reesor, 1970; Hyndman, 1968; Miller, this volume). The distinctive mylonitic foliation and lineation are therefore superimposed on the earlier fabrics.

The protoliths of the metamorphic basement varied both in rock type and age. This is a point that cannot be overemphasized. In most cases, a single complex had several protoliths. In one complex or another, the protoliths include proven *older* Precambrian metasedimentary basement (Reynolds and Rehrig, this volume), *older* Precambrian plutons that intrude the metasedimentary rocks (Banks, this volume; Compton and others, 1977; Shakel and others, 1977), upper Precambrian sedimentary rocks, Paleozoic sedimentary rocks (Misch, 1960; Howard, 1971; Thorman, 1970), probable Mesozoic sedimentary rocks (Rehrig and Reynolds, this volume; Hyndman, 1968), Laramide Upper Cretaceous–lower Tertiary plutonic rocks (Anderson and others, this volume), and even lower to middle Tertiary plutonic rocks (Reynolds and Rehrig, this volume). All of the above protoliths have the distinctive late mylonitic foliation and lineation superimposed on them in one complex or another.

As one approaches the discontinuity separating the basement and cover terranes, all of the basement fabrics (including the late mylonitic fabric) are demonstrably brecciated. They are truncated at the discontinuity by a still later deformation apparently related to movement along the discontinuity (Coney, 1974). This latest deformation usually places unmetamorphosed cover rocks in direct contact with brecciated and locally truncated and disturbed basement rocks. Regionally, however, the discontinuity, or decollement, is subparallel or exactly parallel to the underlying mylonitic and gneissic fabric.

Granitic plutons are extremely common in the basement terrane. Of special interest are some described as the garnet-bearing two-mica type (Chappell and White, 1976; Best and others, 1974). Besides the plutons, pegmatitic and migmatitic rocks are common, as are other late-stage differentiates and leucocratic phases. These smaller bodies generally form sheetlike or lensoid masses and fine stringers that are subparallel to the foliation, but can also cross it. Some have the mylonitic fabric superimposed on them; others do not. At deeper levels, the larger plutons are commonly homogeneous, but as the decollement is approached, they progressively acquire the characteristic foliation and lineation. The pegmatitic and migmatitic bodies generally do not cross the decollement and are commonly terminated abruptly at it. In a few cases for which documentation is still emerging, even the largest plutons are apparently sill-like masses emplaced at or just below, and subparallel to, the decollement surface (Banks, this volume).

Metamorphic grade in the basement terrane is quite variable. In many complexes, the older and deeper metamorphic grade was quite high, and kyanite, sillimanite, and andulusite are not uncommon (Reesor, 1970; Armstrong, 1968b; Compton and others, 1977). The younger mylonitic fabric formed at more moderate conditions.

Unmetamorphosed Cover Terrane

The overlying cover terrane consists of unmetamorphosed rocks separated from the metamorphic-plutonic core by the decollement or by a zone of very steep metamorphic gradient. In many cases, little of the cover terrane remains because of erosion. Commonly, the only remnants are isolated "klippen," as they are usually termed, scattered around the margins of the complex.

Like the basement terrane, the types and ages of cover rocks are highly variable. In one complex or another, the cover rocks consist of slivers of original Precambrian basement (Davis, this volume; Drewes, 1977), upper Precambrian sedimentary rocks, Paleozoic sedimentary rocks (Coney, 1974; Compton and others, 1977; Thorman, 1970), probable Mesozoic sedimentary rocks (Rehrig and Reynolds, this volume), and Tertiary volcanic and sedimentary rocks (Davis and others, 1977 and this volume). All the cover rocks—including, it must be emphasized, lower to middle Tertiary volcanic and associated Tertiary sedimentary rocks (Davis and others, 1977 and this volume)—can be demonstrated to have moved along the decollement relative to the basement terrane.

Where sufficient cover terrane is preserved to make observations, structures within it are very complex. Workers are usually impressed by many low-angle, younger-on-older bedding-plane faults and by many extensional listric normal faults (Coney, 1974; Hose and Danes, 1973). The entire cover terrane can take on the character of a megabreccia. Faulting rarely penetrates into the basement terrane below the basal decollement. In other words, the decollement marks a discontinuity of extreme ductility contrast—brittle above, ductile below.

In some areas, detailed analysis of cover rocks reveals structures varying from minor folds to slickensides on faults, or on the decollement surface itself; such structures can be interpreted as reflecting movement of cover rocks down present dips of the decollement surface into adjacent basins (Coney, 1974; Davis, 1975). The movement directions inferred are in some cases at a high angle to the bearing of lineation in the underlying basement, whereas in other cases they are subparallel. Also, the earlier fabrics in the basement, including the mylonitic foliation and lineation, are redeformed (generally brittlely) into geometries consistent with the movement picture derived from the cover (Coney, 1974). This late movement seems to have been associated locally with intense brecciation in both cover rocks and in basement terrane just below the decollement. Water was abundant, from the evidence of clastic dikes and chloritic and hematitic fillings in the pervasive fractures.

The amount of extension in the cover terrane is typically dramatic. In several complexes, attenuation of the original stratigraphic sequence is extreme (Compton and others, 1977; Todd, this volume; Davis, 1975), and lithologic units once very high in the original cover sequence have been brought down into contact with the decollement surface. In some cases, the stratigraphic separation is greater than 2 km. It is not uncommon to find Tertiary rocks, the youngest of the original cover, brought down into tectonic contact with the basement terrane.

In many of the complexes, part of the cover sequence is an early to middle Tertiary continent sequence (usually red beds) composed of conglomerate, fanglomerate, sandstone, and siltstone, wit some lake beds and evaporites (Pashley, 1966). These sedimentary rocks commonly are associate regionally with (usually overlain by) well-dated lower to middle Tertiary volcanic rocks (Armstrong 1972) and are usually tilted to high angles. It is not insignificant that the direction of strike of thes tilted sedimentary and associated volcanic sequences is perpendicular to the bearing of lineation in th basement terrace of the complexes over wide areas in Arizona. These relationships between th continental rocks and the complexes suggest a genetic link.

The sedimentary section is usually very thick, as much as several kilometres. In those few cases where investigations have been made (Pashley, 1966), current indicators and pebble counts suggest that the fluvial systems did not drain from the core complexes, but may have actually flowed toward them. Only in upper levels of the deposits do streams appear to have drained off the complexes, and it is only in these youngest horizons that clasts of foliated and lineated basement rocks occur (see also Todd, this volume).

The Decollement

The decollement or dislocation surface is the most distinctive aspect of the core complexes thus far recognized (Misch, 1960; Coney, 1974; Whitebread, 1968; Nelson, 1966, 1969; Davis and others, this volume; Miller, 1972). Although variations exist, the general characteristics of the decollement are so remarkably similar from one complex to another that the feature is instantly recognized.

In some complexes, particularly in central Nevada and Arizona, the decollement characteristically occurs either close to the Precambrian-Phanerozoic unconformity or in horizons directly above thick upper Precambrian–lower Paleozoic quartzite-siltstone sequences. Carbonates below the decollement are usually metamorphosed, attenuated, and intensely deformed into a marble tectonite rarely thicker than several tens of metres (Misch, 1960; Nelson, 1966; Coney, 1974; Whitebread, 1968). Davis (this volume) has referred to this tectonite band as a metamorphic carapace. Unmetamorphosed Paleozoic carbonates above the decollement can directly overlie their metamorphosed equivalents below the decollement. Where the basement is composed of plutonic rocks, the decollement usually lies directly above them, and the plutons never cross the decollement. A remarkable example in the southern Snake Range of Nevada (Whitebread, 1968, 1969; Lee and others, 1970) has a Jurassic pluton as basement. This pluton is overlain along a clearly tectonic low-dipping planar surface by as much as 30 m of marble tectonite. The decollement lies above the marble and is overlain by unmetamorphosed Cambrian limestone. Here, K-Ar ages on the Jurassic pluton decrease to 18 m.y. approaching the decollement (Lee and others, 1970; Armstrong, 1972; Coney, 1974).

The decollement surface typically is extremely sharp and very visible in topography. It is often highly polished and has slickensides; rock directly below can have the aspect of a fused paste or a breccia of welded small clasts.

Rocks near the decollement, both above and below, are usually brecciated and show extensive alteration (Reynolds and Rehrig, this volume). Retrograde chlorite is very common in brecciated basement rocks, and development of a distinctive hematitic red-stained fracture filling between fragments is ubiquitous. These breccias have the appearance of "exploded rocks." Even in thin section, so-called mylonitic zones are clearly without planar fabric, but rather show an exploded microbreccia aspect.

The decollement is generally best developed on one side of a particular complex, usually on the less steeply dipping flank of the commonly asymmetrical dome or arch (Reynolds and Rehrig, this volume). On the steeper flank, the discontinuity can be less tectonically abrupt with only very steep metamorphic gradient and little demonstrable evidence of major movement between cover and basement. In at least two complexes, several slices (or thin packets of discontinuity-bound rocks) extend across the dome or arch. Three separate slices are recognized in both the Raft River–Grouse Creek and Rincon complexes. In Raft River–Grouse Creek complex (Compton, 1972, 1975; Compton and others, 1977; Todd, this volume), the two lower slices are metamorphosed, but the upper is not. In the Rincon Mountains (Davis, this volume; Drewes, 1977), the lower slice is metamorphic Paleozoic rocks that are extremely attenuated, the middle slice is original Precambrian basement, and the upper slice is unmetamorphosed Paleozoic and Mesozoic rocks. The core in both examples is Precambrian granite, metasedimentary rocks, and lower to middle Tertiary plutons.

REGIONAL TECTONIC SETTING

The regional tectonic setting of Cordilleran metamorphic core complexes (Fig. 1) is in many ways the most puzzling aspect of the problem. This is so because no obvious regional tectonic relationship has been demonstrated to everyone's satisfaction. Nevertheless, it has become clear that the complexes are an important element in the overall architecture of the North American Cordillera.

Distribution of metamorphic rocks in western North America, excluding the cratonic Precambrian basement beneath the eastern margin of the orogen, grossly reveals two subparallel belts (King, 1969; Monger and Hutchison, 1971). The western belt is largely a metamorphic sheath below, within, and adjacent to the great belt of Cordilleran batholiths. This belt extends through the Canadian coastal plutonic complex, the Idaho batholith, and the Sierra Nevada–Peninsular Ranges batholith southward into western Mexico. An eastern belt (Coney, 1978) follows the Omineca crystalline complex of the eastern Cordillera in Canada and culminates in the Shuswap terrane of southern British Columbia to northwestern Washington (Cheney, 1977 and this volume; Fox and others, 1977). The western and eastern belts of metamorphic rocks appear to merge in the Idaho batholith (Miller and Engels, 1975), but to the south they again separate, and the eastern belt extends southward across eastern Nevada, southeastward across Arizona, then southward into Sonora. All the so-called Cordilleran metamorphic core complexes as defined here lie in the eastern belt, which extends at least from southern Canada to northern Mexico.

Most of the eastern belt developed either on or very close to the edge of the original North American Precambrian cratonic basement. In contrast, most of the western belt may have developed in magmatic arcs on oceanic crust or on crustal fragments that were subsequently accreted onto North America's continental margin (Jones and others, 1977; Monger, 1977; Dickinson, 1976; Coney, 1978). Finally, the apparent continuity of both belts does not imply historical continuity. The ages of batholiths in the western belt vary along strike, and much of the northern two-thirds of the eastern belt records a much more prolonged metamorphic history than the southern part. It is the most recent metamorphic-tectonic events of the eastern belt that we identify as characteristic of the core complexes, and these are superimposed on a diverse terrane, whose history and tectonic evolution predate the development of the core complexes.

Pre-Mesozoic Tectonic Trends

Of the 25 or so Cordilleran metamorphic core complexes currently identified, all evolved in terrane underlain by North American Precambrian continental cratonic basement, as defined by being inboard of the 0.706 $^{87}Sr/^{86}Sr$ contour line (see Fig. 1) (Armstrong and others, 1977; Kistler and Peterman, 1973). Two possible important exceptions are the Okanogan (Fox and others, 1977) and Kettle (Cheney, 1977 and this volume) complexes in Washington. In many complexes, the Precambrian age of the basement is either proved or implied by isotopic dating (Wanless and Ressor, 1975; Clark, 1973; Armstrong and Hills, 1967; Compton and others, 1977; Shakel and others, 1977), and regional relations seem to demand its presence in most of the remainder. Even when this Precambrian basement is looked at more closely, controls on evolution of metamorphic complexes are not obvious. Precambrian lithologic and structural trends, which are generally northeasterly, strike at high angles to the trend of the belt of complexes, and basement ages crossed by the belt range from greater than 2 b.y. in the north to about 1 b.y. in the south (King, 1969). The Arizona complexes may parallel a northwest trend of late Precambrian right-shear just southwest of the Colorado Plateau, but so do all other post-Paleozoic tectonic trends in that area.

From southern Nevada northward to the Selkirk complex in Idaho and Washington, the complexes lie within the thick Cordilleran miogeoclinal prism of latest Precambrian–Paleozoic age. On the other hand, in Arizona and Sonora, the complexes evolved well inboard of the Paleozoic miogeocline on what had been a thin cratonic shelf (Peirce, 1976). In contrast, the Okanogan and Kettle complexes seem to lie outboard of the Paleozoic miogeoclinal shelf edge. As a result, the complexes cannot be explained as being related to a zone of deep Paleozoic burial and thick Paleozoic sedimentary accumulation. The thickness of uppermost Precambrian–Paleozoic deposits over the eventual site of the core complexes is almost 15 km in southern Canada (Price and Mountjoy, 1970; Campbell, 1973), about 10 km in Nevada (Armstrong, 1968a), and only about 2 km in southern Arizona (Peirce, 1976).

Similarly, the distribution of the complexes varies relative to Paleozoic orogenic activity and metamorphism. The northern complexes are found in a region that was probably affected by middle and late Paleozoic Antler-Sonoma deformation and, in the case of the Shuswap complex, some Paleozoic metamorphism (Okulitch and others, 1975; Read and Okulitch, 1977; Brown and Tippett, 1978). Southward in Nevada and Arizona, the complexes lie well east or south of any profound Paleozoic thermal or tectonic events.

Relationship to Mesozoic–Early Cenozoic Trends

Latest Paleozoic–early Mesozoic time was a major transition in Cordilleran tectonic evolution (Coney, 1972, 1973a; Burchfiel and Davis, 1975). It marks inception of draping and accretion of magmatic arcs on the North American margin and the evolution of back-arc thrusting and folding inboard from the magmatic belts.

Genetic linking of the Cordilleran metamorphic core complexes to Cordilleran thrust belts has been the most persistent and persuasive argument put forward to explain the phenomena under study. The argument has manifested itself in several ways and has influenced discussion of Cordilleran tectonics in general as well as discussion of the complexes themselves. No aspect of the complexes has generated more controversy than this.

From Nevada northward, the metamorphic core complexes lie within a belt about 200 km west of the thin-skinned foreland folds and imbricate thrust faults so characteristic of the North American Cordillera and other orogens (Coney, 1976). Because this belt of metamorphic rocks lies behind the folds and thrust faults of the foreland, the belt has been termed a "hinterland." The tectonic events of the hinterland are supposed to have been deeper-seated than those of the foreland and included uplift, thermal disturbance, and remobilization. The assumption has been that the metamorphism in the hinterland accompanied the thrusting in the foreland; thus, the two responses were genetically linked. It was this assumption that so heavily influenced early models such as those of Misch (1960) and Price and Mountjoy (1970).

Paleozoic and lower Mesozoic rocks are clearly metamorphosed in Canada (Hyndman, 1968), and Paleozoic rocks are involved in Nevada (Misch, 1960). From regional relationships in Canada, some of the metamorphism is Paleozoic, and most of it is at least as old as Middle Jurassic (Wheeler and Gabrielse, 1972; Brown and Tippett, 1978). Ironically, recent work in the southern Rocky Mountains of Canada suggests that much of the polyphase deformation and metamorphism so characteristic of the Shuswap terrane is pre–Late Jurassic (Brown, 1978; Wheeler and Gabrielse, 1972) and thus *earlier* than the well-documented Late Jurassic to early Tertiary folding and thrusting to the east. Furthermore, the increasing evidence that the mylonitic metamorphism in United States core complexes is in part, at least, Tertiary (Compton and others, 1977; Cheney, this volume; Rehrig and Reynolds, 1977 and this volume; Anderson and others, this volume) and hence much *later* than Sevier or Laramide thrusting has clouded the issue of a genetic link between thrusting and metamorphism more than anything else.

In Arizona and Sonora, the complexes are not in a "hinterland" behind a thrust belt, but are in fact in the midst of a Laramide belt of deformation, although of a somewhat different character from the thin-skinned folds and thrusts of Sevier-Laramide age to the north (Davis, 1979). The deformation in the south was apparently deeper-seated and involved both basement and cover rock. Furthermore, Laramide tectonic features are clearly older than the core-complex metamorphism and deformation, which are superimposed on some postthrusting Laramide plutons and even on middle Tertiary plutons (Anderson and others, this volume; Reynolds and others, 1978; Reynolds and Rehrig, this volume). As is the case with so many other regional aspects of Cordilleran metamorphic complexes, the Arizona-Sonora examples show a major departure from relationships historically so suggestive to the north.

In Nevada—the original battleground of metamorphism and thrusting in the Cordillera—the relationships are less clear. Middle Mesozoic metamorphism has long been advocated in the hinterland (Misch, 1960) and certainly affected the Ruby Range (Howard, 1971 and this volume; Snoke, this volume) and probably the Snake Range as well. However, this is an older metamorphism and is observable only deep in the cores of some of the complexes. Superimposed on this earlier, generally steeper fabric is the later, shallow-dipping mylonitic fabric so characteristic of the complexes throughout their extent. The late metamorphism and associated deformation are at issue here. Their effects appear to be superimposed on plutons as young as middle Tertiary (Compton and others, 1977), thus much younger than the Late Jurassic to Late Cretaceous thrusting in the Sevier thrust belt of central Utah.

The assumption of a genetic link between the thrust belt and the core complexes has played another significant role in interpretations of the complexes. The argument has led the distinctive "decollement" surface and its associated mylonitization to be identified with the basal shear plane of the thrust belts (Misch, 1960). This interpretation has been variably invoked in Idaho (Hyndman and others, 1975), in Nevada and western Utah (Misch, 1960; Hose and Danes, 1973), and in Arizona (Drewes, 1976, 1978). Obviously, the thrusting would have to be of Sevier (Late Jurassic to Late Cretaceous) age in Nevada, of Sevier-Laramide age in Idaho, and of Laramide (Late Cretaceous to Eocene) age in Arizona. The fact that the decollement surface and the mylonitic deformation associated with it are now known to cut rocks as young as early to middle Tertiary in all these regions casts some doubt on this interpretation (see Fig. 5). As a result, some workers have more recently argued models of multiple thrusting (Drewes, 1976, 1978; Thorman, 1977) and/or middle Tertiary gravitational sliding on a decollement surface originally made during regional low-angle thrusting during Sevier or Laramide time (see discussion in Compton and Todd, 1979, and Crittenden, 1979). In some cases at least, these models seem geometrically difficult. Armstrong (1972), for example, has argued on geometric grounds that the decollement surface in the Snake Range of eastern Nevada is unrelated to the basal shearing plane of Sevier thrusts to the east (Fig. 3).

In any event, the debate concerns whether the characteristics so typical of the core complexes—namely, the decollement surface, the distinctive mylonitic foliated and lineated fabric, and younger-on-older "faults" in the cover—are genetically linked to regional thrusting of Mesozoic–early Cenozoic age. No one can deny deformation and even metamorphism of Sevier and/or Laramide age in some of the regions now occupied by core complexes. What is claimed is that the younger features typical of the complexes are superimposed on earlier fabrics; that the younger features are probably, for the most part, of Tertiary age; and that they are unrelated to the thrust belts at least in any direct way.

Because the core complexes are clearly, in part, of thermal origin, distribution of magmatic activity is of interest in discussing their evolution. Compilatons of Mesozoic–early Cenozoic magmatic activity reveal considerable complexity in both space and time. This activity encompasses the entire Cordillera and spreads over a far greater region than the rather narrow belt of complexes as defined here.

The main result of this magmatic activity was the eventual emplacement of a massive Cordilleran batholith system comprising the Canadian coastal plutonic complex, the Idaho batholith, and the Sierra Nevada–Peninsular Ranges batholith in California and western Mexico (King, 1969). These bodies are not all the same age. Furthermore, with the exception of the Idaho batholith, all are well west of the belt of metamorphic core complexes.

Lesser plutonic bodies extend eastward across the Cordillera into, and even east of, the core complex belt. In Canada, the Omineca crystalline belt has plutons of Late Jurassic and Cretaceous ages (Gabrielse and Reesor, 1974), most of which clearly crosscut the metamorphic fabrics typical of the Shuswap terrane (Hyndman, 1968).

In the United States, the Washington and Idaho complexes are superimposed on, or certainly co-existent with, the main batholith belt (Miller and Engels, 1975). Farther south, in Nevada, the complexes lie well east of the batholith belt, but well within a field of scattered Jurassic to Late Cretaceous plutons. These eastern plutons are perhaps best explained as scattered intrusions parasitic to the main batholith belt. They were emplaced where they are either by generation from deeper levels

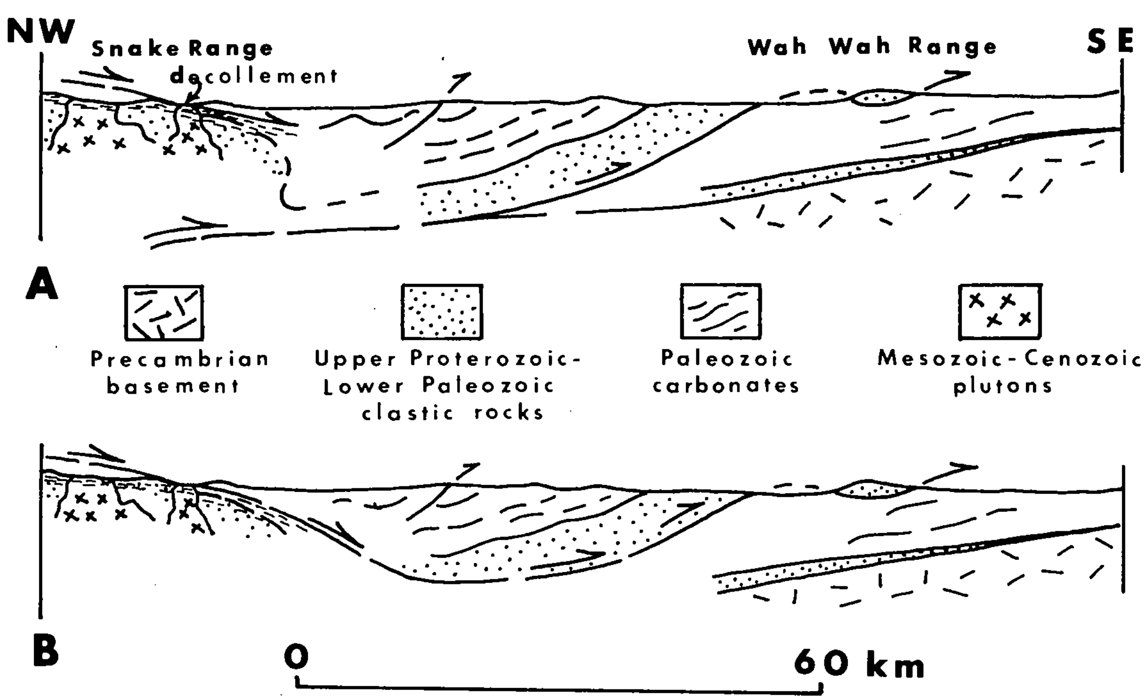


Figure 3. Two contrasting interpretations of structure from the Snake Range, Nevada, to the Wah Wah Range, Utah, based on a section by Armstrong (1972). (A) Deep-seated thrust-fault model showing basal Sevier thrust in Wah Wah Range rooting beneath the Snake Range. This interpretation was favored by Armstrong. The Snake Range decollement is not connected to the Sevier thrust faults, but is interpreted as a Tertiary denudation fault (Armstrong, 1971) off the Snake Range core complex. (B) Shallow thrust-fault model that connects the Snake Range decollement with Sevier thrust faults to the east. This interpretation was favored by Hose and Danes (1973).

of the subducted slabs or because of transient variable dips in these slabs. The Arizona and Sonora complexes are within a broad belt of mainly Late Cretaceous–ezrly Tertiary (Laramide) scattered magmatic activity that swept inboard from the Cretaceous Peninsular Ranges batholith along the coast after 80 m.y. B.P. (Silver and others, 1975; Coney and Reynolds, 1977).

In summary, Mesozoic–early Cenozoic magmatic arc activity spread over the entire Cordillera at one time or another, including the narrow belt of core complexes. Most of the volume of plutons was emplaced well west of the belt of core complexes. Finally, with the possible exception of the Omineca crystalline belt in Canada, no unique or distinct pre–middle Tertiary magmatic trend coincides with the belt of complexes, either in space or in time.

Relation to Middle Cenozoic Tectonic Trends

Between about 55 and 20 m.y. B.P., a very complex pattern of post-Laramide magmatic activity spread over the entire southern Cordillera (Armstrong, 1974; Coney and Reynolds, 1977; Noble, 1972; Lipman and others, 1971). The activity was characterized by enormous outbursts of caldera-associated ignimbrites and the emplacement of shallow plutons. This massive thermal disturbance reset radiometric ages over thousands of square kilometres and also caused much low-angle normal faulting (Rehrig and Heidrick, 1976; Anderson, 1971). The ignimbrite flare-up is very important because the core complexes seem to have evolved just prior to and during the ignimbrite outburst (Coney, 1974, 1978). What is puzzling, however, is that the magmatic activity covered a region far wider than that of the core-complex belt itself.

In Late Cretaceous time (Fig. 4A), a well-established magmatic arc terrane extended from Canada southward through the Idaho–Sierra Nevada–Peninsular Ranges batholiths into western Mexico (Coney, 1976, 1978; Armstrong, 1974). After 80 m.y. B.P., this Laramide magmatic activity swept rapidly eastward (Coney and Reynolds, 1977) across the southern Cordillera, then extinguished north of Arizona, except for very scattered activity (Fig. 4B). In Arizona and New Mexico (Coney and Reynolds, 1977) and in Mexico (Clark and others, 1978), the eastward sweep did not extinguish and reached nearly 800 km inboard by Eocene time (Fig. 4C). At about the same time, the entire Pacific Northwest erupted violently with Challis-Absaroka volcanism and shallow plutonism (Armstrong, 1974). This started a rapid return sweep of magmatic activity back across the western United States toward the continental margin. The return sweep was responsible for the vast ignimbrite flare-up (Fig. 4D) across Idaho, Washington, and Oregon; Utah and Nevada; New Mexico and Arizona; and all of central and northern Mexico (Coney and Reynolds, 1977). Only the Colorado Plateau was spared. By 15 to 20 m.y. B.P., the magmatic activity reached the coast and formed the Cascade magmatic arc trend in the Pacific Northwest, but transformed to a widespread bimodal basalt and rhyolite phase associated with basin-range faulting eastward and southward (Lipman and others, 1971) (Fig. 4E). There is considerable evidence, at least in the United States, that the core complexes developed during this massive return sweep of magmatic activity between 55 and 15 m.y. Furthermore, some evidence suggests that the complexes north of the Snake River Plain evolved during the Eocene Challis-Absaroka outburst (Reynolds, 1977, oral commun.; Cheney, this volume); likewise, those south of the Snake River Plain evolved during the Oligocene–early Miocene ignimbrite flare-up there (Coney, 1978).

The post-Laramide to middle Tertiary is a most puzzling time (Coney, 1978). The events clearly followed Laramide com -ressive deformation, and they seem to have begun by widespread erosion and beveling of Laramide landscapes (Epis and Chapin, 1975). Within the belt of core complexes, the relationship to the ignimbrites is often dramatic. In southern Arizona, some volcanic ranges are made up of vast ignimbrite sheets whose radiometric ages are essentially the same as cooling ages in metamorphic rocks within the adjacent core complex. Just why the core complexes should be restricted to such a narrow belt within this widespread panorama of ignimbrite eruption is not obvious.

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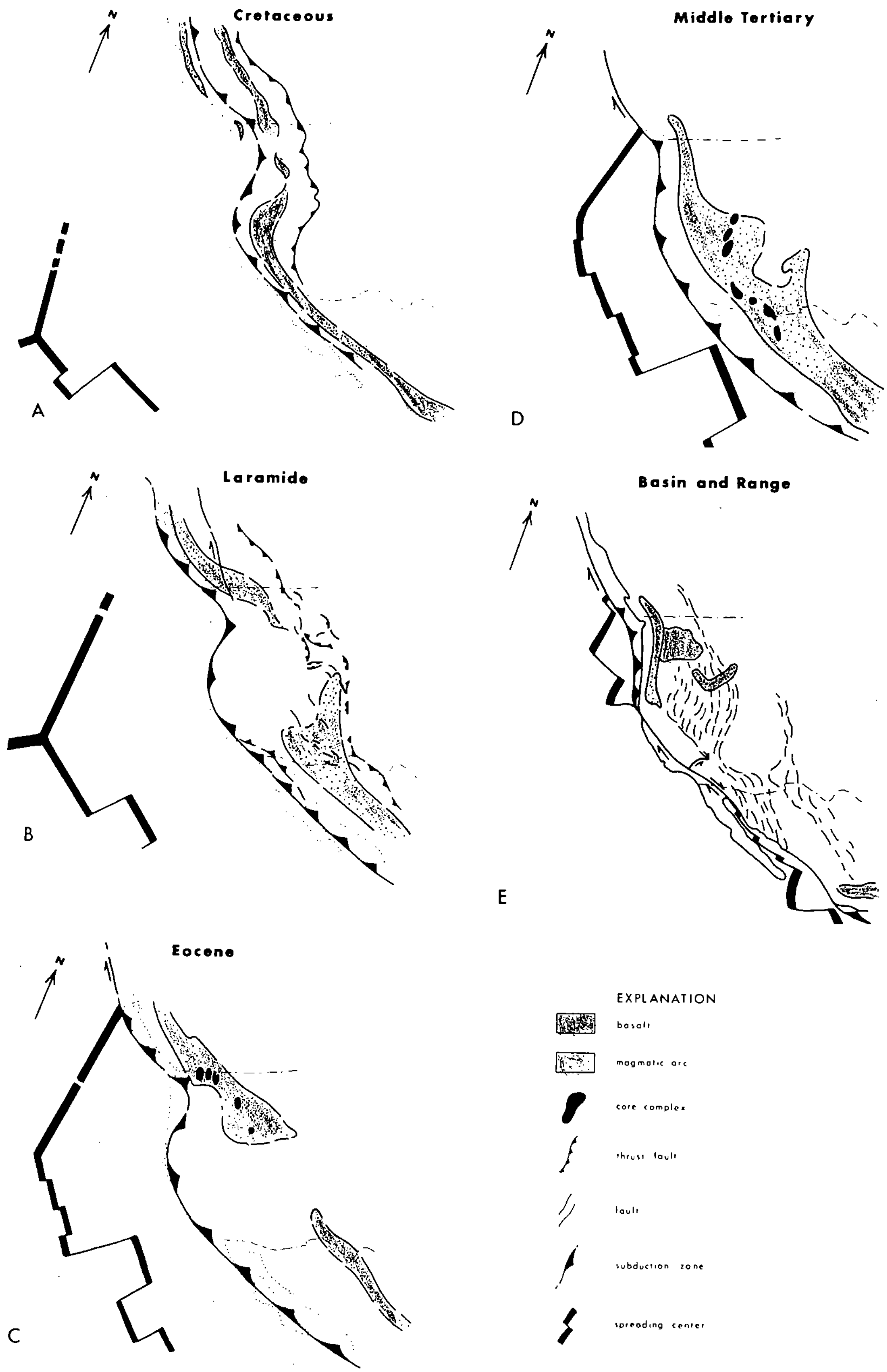


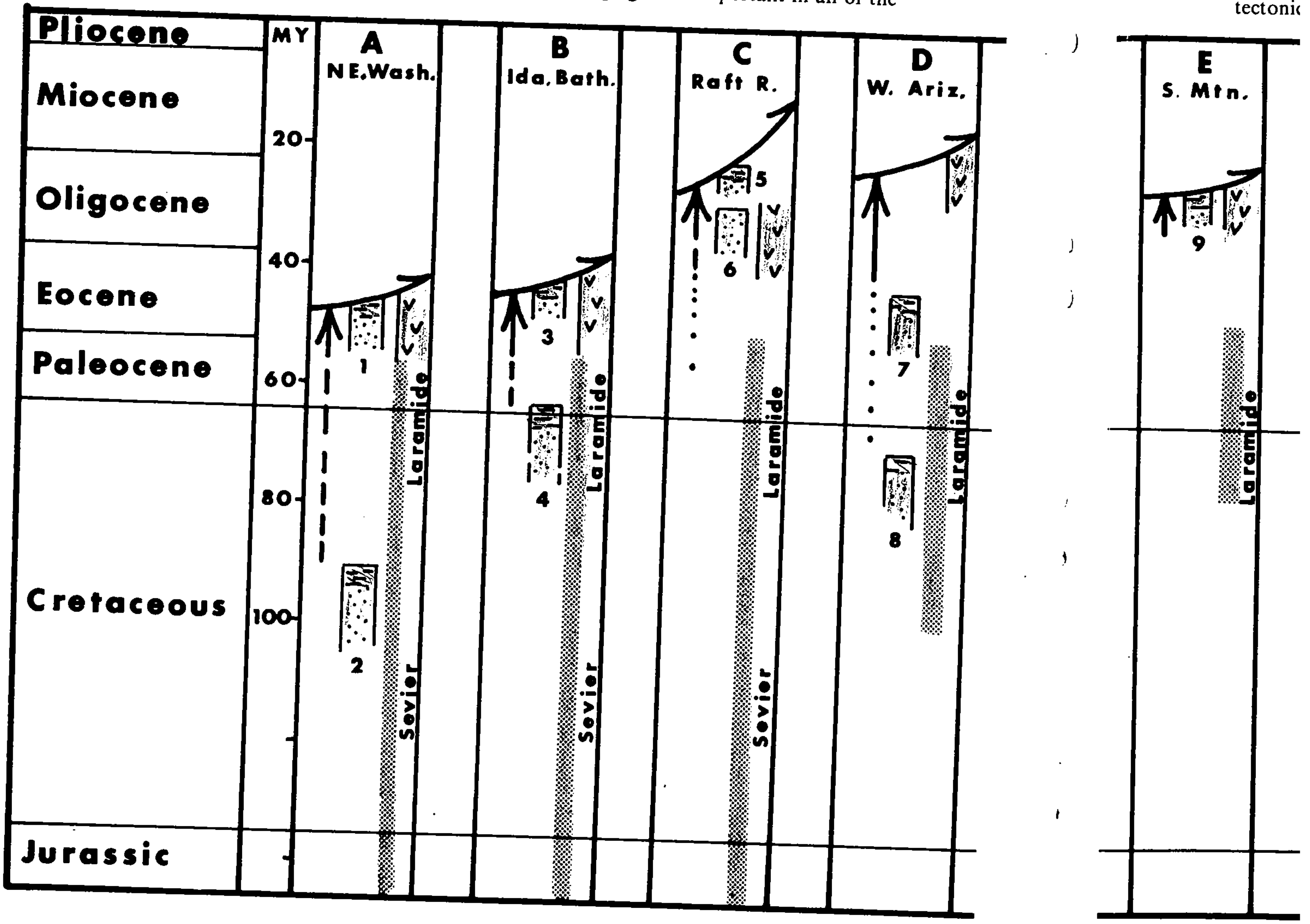
Figure 4. Major features of Cordilleran tectonic evolution since Early Cretaceous time (from Coney, 1978).

Relationship to Late Cenozoic Tectonic Trends

One relationship on which almost all workers are agreed is that late Tertiary basin-range faulting seems to postdate most core-complex activity (Fig. 4E). In many areas, the steep block faulting clearly cuts metamorphic rocks, the decollement, or cover rocks (Coney, 1974; Eberly and Stanley, 1978). It is worth noting, however, that all the complexes south of the Snake River Plain occur within a region that was affected by this block faulting.

TECTONIC SIGNIFICANCE

The tectonic significance of Cordilleran metamorphic core complexes has been much debated during the past 20 yr. Before their significance can be fully understood it is necessary to recognize two distinct, and perhaps largely unrelated, aspects of their history. The first aspect is the earlier (mostly Mesozoic) history of many of the complexes, particularly those from western Arizona northward. The second aspect is the early to middle Tertiary history that is emerging as so important in all of the



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complexes, at least from northeastern Washington southward into Mexico. In my view, much of the confusion surrounding the complexes has been due to a lack of full appreciation of these younger Tertiary features and interpretation of these features to results of Mesozoic events. It was in relation to this that the full significance of the Arizona and Sonora examples emerged. This happened because they are not in the tectonic setting of the hinterland behind the Mesozoic thrust belts, which are so characteristic of the setting of those complexes to the north. The fact that the Arizona and Sonora complexes so remarkably resembled the younger aspects of the northern complexes lent support to the growing recognition of the importance of the Tertiary events throughout the belt.

In other words, there is considerable evidence that much of the metamorphism, deformation, and thermal disturbance so characteristic of Cordilleran metamorphic core complexes is of early to middle Tertiary age (Fig. 5). In many complexes, particularly those northward from Arizona, these mainly Tertiary features were superimposed on mainly Mesozoic metamorphic and deformational effects of the thrust-belt hinterland; however, most of the characteristic mylonitic fabrics, the decollement zones, and the chaotic structures in the cover rocks are, in part at least, the result of early to middle Tertiary tectonics.

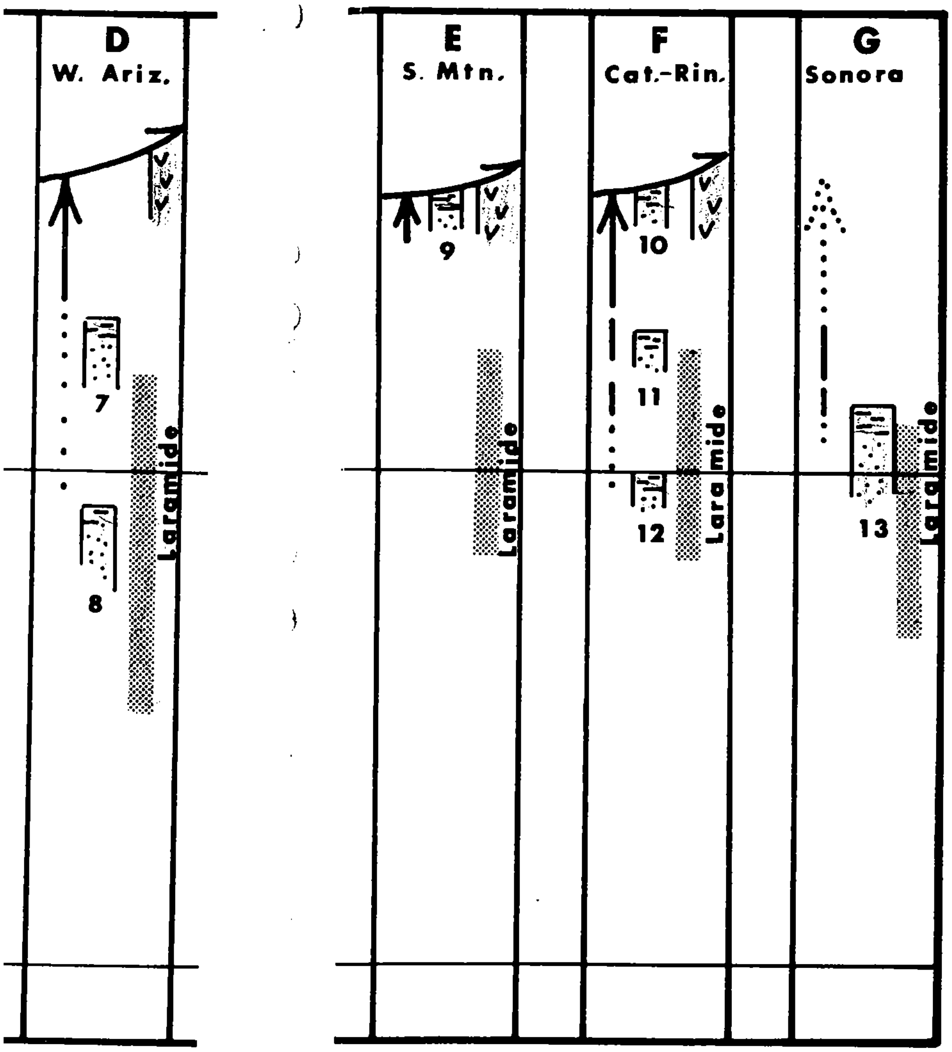

Figure 5 (facing pages). Age relationships in selected Cordilleran metamorphic core complexes. Columns as follows: A, northeastern Washington (Selkirk complex); B, Idaho batholith (Bitterroot complex); C, Albion–Raft River–Grouse Creek complex; D, western Arizona (Harcuvar complex); E, South Mountains complex south of Phoenix, Arizona: F, Catalina-Rincon complex near Tucson, Arizona; G, Sonora, Mexico. Stipple pattern is for age range of plutonic rocks with dash pattern at top signifying mylonitic gneissic fabric superimposed on the pluton: V pattern is age range of lower to middle Tertiary volcanic rocks in vicinity of each complex; vertical heavy arrow represents possible age limits for formation of overprinted mylonitic gneissic fabrics superimposed on the plutons and other basement terranes. Subhorizontal heavy barbed arrow is approximate older age limit on movement of cover rocks over basement terrane on "decollement" surfaces. In many places, this movement could be younger than indicated, but it can usually be shown to be older than latest Tertiary basin-range faulting. Vertical light stipple bands in each column are approximate durations of major compressional Sevier and/or Laramide deformation in thrust belts east of, or in vicinity of, respective core complexes. Numbered plutons as follows: 1, Silver Point quartz monzonite (Miller, 1972); 2, middle Cretaceous plutons (Miller and Engels, 1975); 3, Eocene plutons (S. J. Reynolds and W. A. Rehrig, 1979, oral communs.); 4, Bitterroot lobe of Idaho batholith (Chase and others, 1978); 5, Red Butte pluton (Compton and others, 1977); 6, Immigrant Pass pluton (Compton and others, 1977); 7, muscovite granite (Rehrig and Reynolds, this volume); 8, Tank Pass pluton (Rehrig and Reynolds, this volume); 9, South Mountains pluton (Reynolds and Rehrig, this volume); 10, Catalina granite (Shakel and others, 1977); 11, Wilderness granite (Shakel and others, 1977; Keith and others, this volume); 12, Leatherwood granite (Keith and others, this volume); 13, Sierra Mazatan (Anderson and others, this volume).

In the Shuswap complex of southern Canada, something on the order of 40,000 km^2 of metamorphic rock are exposed. It is the largest of all the Cordilleran metamorphic core complexes, and in the original conception of the problem, it was the type example and the source of the name (see my "Introduction" to this volume). As outlined earlier, studies indicate that some of the metamorphism is as old as Paleozoic and much of it is at least as old as Jurassic (Okulitch and others, 1975; Read and Okulitch, 1977; Brown and Tippett, 1978; Wheeler and Gabrielse, 1972; Hyndman, 1968). There are dated Upper Jurassic to middle Cretaceous plutons that crosscut metamorphic rocks (Gabrielse and Reesor, 1974).

In any event, the conclusion reached by some workers that much of the metamorphism in the Shuswap terrane is at least as old as Jurassic is of considerable importance for the Price and Mountjoy model relating the metamorphic hinterland to the Rocky Mountain thrust belt to the east. Their model invokes a mobile infrastructure that buoyantly rose and propelled the thrusts to the east, largely by gravity. This model has difficulties because if the metamorphism is of Jurassic age, then most of it was over before the thrusting began. Because the metamorphic hinterland exposes rocks once deeply buried and subjected to temperatures of 600 °C and pressures approaching 4 kb, a postmetamorphic uplift of 10 km or more is demanded. An uplift of this magnitude, particularly over a region as large as the Shuswap complex, is not easy to explain. I have argued elsewhere (Coney, 1979) that this massive uplift is perhaps explained as being due to crustal telescoping in the thrust belt and resulting crustal thickening in the region of the hinterland mostly during Sevier-Laramide deformation. The uplift may have been also influenced by Mesozoic translation, collision, and accretion and by telescoping of exotic terranes against the Cordilleran margin (Jones and others, 1972, 1977; Monger, 1977; Dickinson, 1976; Coney, 1978). Furthermore, some of these events may offer an explanation for the pre–Late Jurassic metamorphism and deformation of growing concern in Cordilleran tectonics.

There are also many early Tertiary (mostly Eocene) K-Ar apparent ages associated with scattered shallow plutons and a widespread resetting of isotopic clocks (Fox and others, 1977). Unfortunately, the age of the apparent later arching in the three distinctive "gneiss domes" and in the narrow belt of late mylonitization along the eastern margin of the complex is not precisely known. The mylonitization is, however, apparently the youngest of the metamorphic fabrics (Reesor, 1970). In most ways, the late domes and the zone of east-dipping mylonitization most resemble those features characteristic of the complexes to the south considered here to be mainly Tertiary in age.

To what degree Tertiary features similar to those found in the complexes southward in the United States and northwestern Mexico have been superimposed on the results of mainly Mesozoic events described above is not yet known. It seems, however, that much of the gross metamorphic and structural character of the Canadian Shuswap core complex has an origin in earlier Cordilleran tectonic history. The later early Tertiary history is still not fully documented or evaluated.

A similar model of crustal telescoping and upift of the hinterland can be applied in the United States at least as far south as southern Nevada, but telescoping and resulting uplift were probably less there and mostly confined to the area of the Sevier orogeny in middle Cretaceous time (Armstrong, 1968a). The age of the older core-complex metamorphism is not well-controlled; it has traditionally been described as simply "mid-Mesozoic" (Misch, 1960; Armstrong and Hansen, 1966; Armstrong, 1968a; Howard, 1971 and this volume; Snoke, this volume), but may be as old as Jurassic (Compton and Todd, 1979). Superimposed on, or at least late in the history of, this earlier metamorphism are the shallow-dipping mylonitic fabrics, associated decollements, and related deformation of unmetamorphosed cover rocks. These late features appear to be, in part at least, superimposed on plutons as young as early to middle Tertiary age in the Raft River–Grouse Creek Mountains, Kern Mountains, and Ruby Mountains (Compton and others, 1977; Best and others, 1974; Snoke, this volume; Todd, this volume), and similar relationships are emerging in northeastern Washington (Cheney, this volume; Miller, 1972; Reynolds and Rehrig, 1978, oral commun.) and in the Idaho batholith (Chase and others, 1978). These events have reset K-Ar apparent ages to as young as 18 m.y. along the Snake Range decollement (Lee and others, 1970; Armstrong, 1972). They have produced field relationships such as "klippen" of Paleozoic rocks over middle to upper Tertiary sedimentary rocks in the Raft River–Grouse Creek Mountains (Todd, 1973 and this volume) and low-angle normal faults in middle Tertiary volcanic rocks (Armstrong, 1972). Coney (1974) inferred that minor structures in rocks associated with the Snake Range decollement were consistent with Armstrong's (1972) model of Tertiary denudational faulting in the Nevada hinterland. All of these features clearly predate late Tertiary basin-range faulting (Coney, 1974).

In Arizona and Sonora, the metamorphic core complexes are clearly of early to middle Tertiary age. In southwestern Arizona, an older Mesozoic metamorphism is overprinted by mylonitic gneissic fabrics in several complexes (Rehrig and Reynolds, 1977 and this volume), but several of the complexes of southeastern Arizona and Sonora are not complicated by widespread and complex pre-Tertiary metamorphism and deformation like those complexes to the north. More important, as already mentioned, the complexes here are not in a hinterland behind a thrust belt of any age but, instead, are partly in a belt of mainly brittle, deep-seated, basement-cored thrust uplifts of Laramide age accompanied by scattered Laramide plutons. Furthermore, the typical core complex fabrics and related decollements are superimposed on plutons ranging in age from about 55 m.y. in Sonora (Anderson and others, 1977 and this volume) to as young as 26 m.y. in the South Mountains near Phoenix (Reynolds and Rehrig, this volume; Reynolds and others, 1978). In the Catalina-Rincon complex near Tucson, a complicated history of plutonism, deformation, and metamorphism is recorded, but most workers now agree that features typical of the core complexes throughout the Cordillera are superimposed on plutonic rock as young as at least 50 m.y. (Shakel and others, 1977; Keith and others, this volume). From structural analysis, Davis (1975) inferred Tertiary movement of cover rocks down decollement surfaces in the Rincon Mountains.

It cannot be denied that the later, mainly Tertiary, overprint so characteristic of Cordilleran metamorphic core complexes was perhaps influenced by the preceding Mesozoic history. This is particularly true of the complexes in Nevada and northward into southern Canada. Exactly what the influence was, however, has been difficult to identify. Low-angle faults, some certainly of younger-on-older type, undoubtedly formed in the hinterland during Mesozoic time. They may have served to localize the Tertiary decollements. The Mesozoic metamorphism and deformation have already been mentioned. Perhaps one important influence was the Mesozoic uplift of the hinterland produced from crustal thickening behind the telescoping thrust belts to the east. This would permit the later thermal culminations and associated plutons of early to middle Tertiary age to likewise rise higher before being frozen in a reactive endothermic Phanerozoic cover. In any event, the typical location of the core complexes along the hinterland behind the thrust belt can hardly be a fortuitous accident. Even in Arizona and Sonora where the above relationships did not hold, the structurally and thermally battered ground inherited particularly from Laramide events could have prepared a weakened basement conducive to concentrating the Tertiary events.

Are the complexes basically classic gneiss domes (Eskola, 1949)? This question is often asked. Certainly, some show certain characteristics of classic gneiss domes, particularly the extreme stretching across the top, the overall domal or archlike geometry, and the steep metamorphic gradient. There are, however, certain difficulties. First, the actual doming is apparently a late feature superimposed on the metamorphic fabric of the basement. Second, the actual structural relief on the domes is not particularly great. For example, the amplitude of most of the domes is not more than 4 km in a wavelength of as much as 50 km; this gives an amplitude/wavelength ratio of 0.08—a fact reflected in the universal low-dipping foliation that rarely exceeds 20° to 30° (for example, see Drewes, 1977). This is considerably less structural relief than that usually depicted in classic gneiss domes or in experimental or theoretical modeling (Ramberg, 1972; Dixon, 1976) where amplitude/wavelength ratios are 0.25

to 0.5 or more. Third, it has already been emphasized in this paper that the mylonitic foliation and lineation so characteristic of the complexes in many cases actually seem to diminish and even disappear downward in the basement terrane. This argues for rigidity of this terrane in some cases since Precambrian time (Compton and others, 1977). It also argues against the deep-seated mobility that is characteristic of an "infrastructure" and usually cited as an essential ingredient of classic gneiss domes.

In any event, some workers in the Cordillera have found it useful to informally and tentatively reject the classic gneiss-dome concept if for no other reason than to aid objectivity and identification of the real characteristics of the Cordilleran complexes.

The evidence for extension in and adjacent to the complexes is extremely compelling. It was first acknowledged in the cover terranes (Armstrong, 1972; Anderson, 1979; Coney, 1974; Davis, 1973, 1975; see also Davis and others, this volume). Only more recently has it been proposed in the basement itself as manifested in the mylonitic foliation and lineation.

The work of George Davis (1973, 1975, 1977, Davis and others, 1975) in the Catalina-Rincon complex in Arizona first suggested this basement extension as a major aspect of core-complex evolution. Davis has subsequently (1977 and this volume; Davis and Coney, 1979) expanded these observations into the provocative concept that the complexes are in fact megaboudins. This concept is similar to recent interpretations of the Death Valley turtlebacks (Wright and others, 1974; Burchfiel and Stewart, 1966). Whatever they are, the evidence is that they were produced by extension and tectonic denudation. This is certainly the case with the cover terranes. Another early suggestion for regional extension was recognition of northwest-trending dikes cutting middle Tertiary plutons in southern Arizona (Rehrig and Heidrick, 1976). These dikes are oriented perpendicular to the lineation in the core complexes (Reynolds and Rehrig, this volume). This extension has also been recognized outside or adjacent to the main core-complex belt in areas of low-angle listric normal faults that cut middle Tertiary volcanic and sedimentary rocks but are cut by basin-range faults (Anderson, 1971; Eberly and Stanley, 1978; Rehrig and Heidrick, 1976; Davis and others, this volume).

It is remarkable how many of the complexes are characterized by lower to middle Tertiary granitic plutons. The late mylonitic fabrics are superimposed on many of these plutons, and evidence suggests that they were cooling and still partly mobile at the time of at least the earlier phases of the deformation recorded in the complexes. The granitic plutons precede, then become intimately associated with a massive thermal disturbance that is mainly of Eocene age (Fig. 4C) in the Pacific Northwest (Armstrong, 1974) and of late Eocene to middle Miocene age (Fig. 4D) in the south (Lipman and others, 1971). This vast ignimbrite flare-up has been interpreted as the result of the collapse and return (westward) sweep of a previously flattened Laramide Benioff zone during Eocene through Miocene time (Coney and Reynolds, 1977). A significant number of granitic plutons, particularly the earlier ones, are of the garnet-bearing two-mica type; this fact suggests a genetic association between the rock type and the evolution of the complexes. Perhaps the earlier two-mica plutons were generated during the late Laramide period of maximum flattening of the Benioff zone when Farallon lithosphere was essentially plated beneath North American lithosphere.

The belt of complexes has the character of an irregular, elongate and sinuous, large-scale pull-apart zone extending the length of the Cordillera at least from southern Canada into northwestern Mexico. The only large-scale phenomenon the zone seems to be associated with is the region that lies above the flattened or low-dipping Laramide (Late Cretaceous) Benioff zone which steepened and collapsed during early to middle Tertiary time. The evolution of the metamorphic core complexes as either separate distinct phases or as a continuum, probably endured 30 to 40 m.y. between about 55 and 15 m.y. B.P. in early to middle Tertiary time.

Just why the complexes formed when they did is not clear. The process began during Farallon–North America plate convergence at least 10 to 30 m.y. before even initial contact between the Pacific and North America plates and resulting growth of the San Andreas–Basin and Range transformtranspressive rifting (Fig. 4). They did not form behind a magmatic arc; they formed within a magmatic arc. But this magmatic arc was a very special one, perhaps the result of extreme flattening of the Laramide Benioff zone followed by its massive collapse and the resulting return sweep of arc activity across the Cordillera from the Pacific Northwest southward into Mexico. The thermal upwelling and instability implied in such a model gives at least an intuitive rationale for all that transpired.

The marriage of these petrologic, structural, and regional tectonic arguments has been productive, and the suggested relationships make the complexes appear more comprehensible and less confusing. There are, however, major issues still outstanding that need clarification and new insight as the contents of this volume point out. The relationships proposed here certainly provide a model to test by further detailed work in the individual complexes. I hope that such work is stimulated by the contents of this volume.

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