

Chapter I

CORDILLERAN METAMORPHIC CORE COMPLEXES:

AN OVERVIEW

by

Peter J. Coney

INTRODUCTION

Cordilleran metamorphic core complexes are a group of usually domal or arch-like, isolated uplifts of anomalously deformed, metamorphic and plutonic rocks, overlain by a tectonically detached and distended unmetamorphosed cover. The features (see Figure 1-1) are scattered in a sinuous string along the axis of the eastern two-thirds of the North American Cordillera from southern Canada to northwestern Mexico. To date, over 25 of them are known and it is significant that over half of them have been recognized only since 1970. They are, without question, the newest and most controversial addition to the recognized architecture of the eastern two-thirds of the Cordillera since the discovery, in the early 1960s, of the Tertiary calderas and their associated vast ignimbrite sheets. During the past 10 years, considerable debate has centered on them, and they have been termed metamorphic core complexes (Coney, 1973a, 1976, 1978, 1979; Davis and Coney, 1979; Crittenden et al., 1978).

The first hint of the existence and potential significance of these complexes was from the early efforts of Peter Misch and his students who began work in the Great Basin in the 1950s. Misch (1960) discovered and emphasized scattered occurrences of a major sub-horizontal dislocation plane or "décollement, as it was called, separating an unmetamorphosed Paleozoic miogeoclinal cover from a usually metamorphosed substratum. He found this repeatedly

in many ranges along and west of the Utah-Nevada border about 200 kms west of the already known low-angle, east-verging Mesozoic thrust faults in central Utah.

To Misch (1960) the most important element of the eastern Nevada structural province, or hinterland, was the "décollement." This discontinuity was seen to separate Precambrian basement and metamorphosed late Precambrian-early Paleozoic sediments from an overlying unmetamorphosed allochthon. The type area for this regional décollement was the Snake Range of east-central Nevada. Misch reasoned that the décollement and the associated shearing and metamorphism along it were produced during mid-Mesozoic orogeny. He felt 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 basal shearing-off plane, or décollement, 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 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 décollement (or abscherung zone) and contrasted this domain of recumbent folds and planar fabrics to a less deformed, brittle suprastructure above.

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 and gravitationally spread eastward, propelling 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.

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" faults (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 eastern Nevada and western Utah (Roberts and Crittenden, 1973; Hose and Danes, 1973). Hose and Danes, for example, interpreted

the décollement 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 Figure 3-B). This cover terrane slid eastward to become the superficially telescoped older on younger thrust faults of central Utah.

This sets the stage for developments, mostly after 1970, which were to cast considerable confusion over the simplicity and beauty of the early models. Early workers noted certain data and relationships which were either troublesome or inconsistent with existing models. Damon (Damon and others, 1963; Mauger and others, 1968) found very young mid-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 Tertiary modifications of a mainly Mesozoic tectonic history, or as isolated events of only local significance. In some cases, the local importance was adequately emphasized, but the regional significance was not appreciated by others. The consensus seemed to be that these were minor Tertiary modifications of a basically Mesozoic tectonic regime of metamorphism and low-angle thrusting.

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 mid-Tertiary time was a possible explanation for the "regional décollement" of the eastern Nevada hinterland. Using geochronology and field relations, he reinterpreted existing published geologic mapping and structure sections. His results suggested that the extensional younger on older faults, which cut well-dated mid-Tertiary volcanic rocks as well as associated sedimentary rocks and flatten at depth to merge with the décollement plane were, at least in part, as young as the Tertiary volcanics they cut. The implication was clear. The décollement surface was, in part at least, mid-Tertiary in age and possibly had only little or perhaps nothing to do with Sevier age 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 décollement in the southern Snake Range were progressively reset to younger ages as one approached the décollement. The ages decrease to about 18 m.y. at the discontinuity. They concluded that the most recent

movement, at least 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 mid-Tertiary low-angle gravity sliding of unmetamorphosed cover rocks off metamorphic basement on a décollement surface. At about the same time this author heard (Crittenden, pers. comm., 1972) that Todd (1973), working in the Raft River-Grouse Creek range, had found that allochthonous sheets of Paleozoic cover rocks had moved off a metamorphic basement onto middle-to-late Tertiary sediments. 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 mid-Tertiary pluton.

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

We owe our readers an explanation of the term Cordilleran metamorphic core complex. There has been objection to the name and widespread wonderment about its meaning. The name was coined, quite accidentally, by me in 1973 (Coney, 1973a, p. 723) in reference to the Shuswap metamorphic complex and its relationship to the Canadian Rocky Mountain foreland thrust belt. I am quite sure it was an unconscious reference to the term "metamorphic core zone" used by Canadian workers (Wheeler and others, 1972) to describe the eastern Omineca crystalline belt in the Canadian Cordillera. Since then, the term has been applied by myself and others to the many metamorphic terranes and related features found southward in the Cordillera as they were recognized or re-evaluated. If for no other reason, the term has stuck because the complexes seemed so distinctively peculiar and hitherto not properly recognized that they needed a special name. For example, the metamorphic-plutonic basement terrane so typical of the complexes can be thought of as a "core" terrane. I make no apology for the term Cordilleran metamorphic core complex. It has proven useful for many of us and it simply indicates that, although variety exists, the objects so identified have a considerable commonality as to physical features and age.

CHARACTERISTICS

The metamorphic complexes 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 lithologies, 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.

Two distinct domains characterize the complexes (Fig. 2). These are a metamorphic-plutonic basement terrane or core zone, and an overlying or adjacent unmetamorphosed cover. Separating the two is a sharp discontinuity, or zone, marking rapid or abrupt change in lithology and structure. Rarely do lithology and structural fabric 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. Quite frequently, the complexes stand prominently in topography as the highest mountains in their respective regions. They are usually recognized from afar, the low-sweeping domal profile distinctive on the horizon.

The metamorphic basement is characterized by a low-dipping foliation whose attitude usually conforms to the overall domal or arch-like 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 stretching over a distance of 400 km in southern Arizona and Sonora, for example, it is almost universally about N60°E (Davis, 1980). Northward the lineation is more variable, but it tends to be either east-west or northwest-trending (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 is usually shallow, rarely exceeding 20° to 30°. Both the foliation and lineation are usually described as "cataclastic," but seem to involve recrystallization, particularly in quartz, as well as cataclasis (Todd, 1980; Reynolds and Rehrig, 1980). The rocks are best described as mylonitic gneiss. Strain is extreme, and axial ratios of mineral elongations and occasional stretched pebble conglomerates, can attain 8:2:1 (Coney, 1974; Compton, 1980; Compton et al., 1977; Davis, 1980). The overall strain picture is one of maximum shortening and flattening perpendicular to the sub-horizontal foliation plane and maximum extension parallel to the lineation (Compton, 1980). The direction of maximum elongation is

Figure 1-1

Distribution and general regional tectonic setting of Cordilleran Metamorphic Core Complexes. Metamorphic core complexes - solid black; major batholiths - X pattern; Sevier frontal thrust belt - solid barbed line; Laramide thrust faults - open barbed lines; Early to Middle Tertiary mainly ignimbrite volcanic rocks - V-pattern; Strontium 87/Strontium 86 .706 line - heavy dark, dashed line; numbered metamorphic core complexes as follows: 1. Frenchman's Cap; 2. Thor-Odin; 3. Pinnacles; 4. Valhalla; 5. Okanagan; 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 Mountain-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.

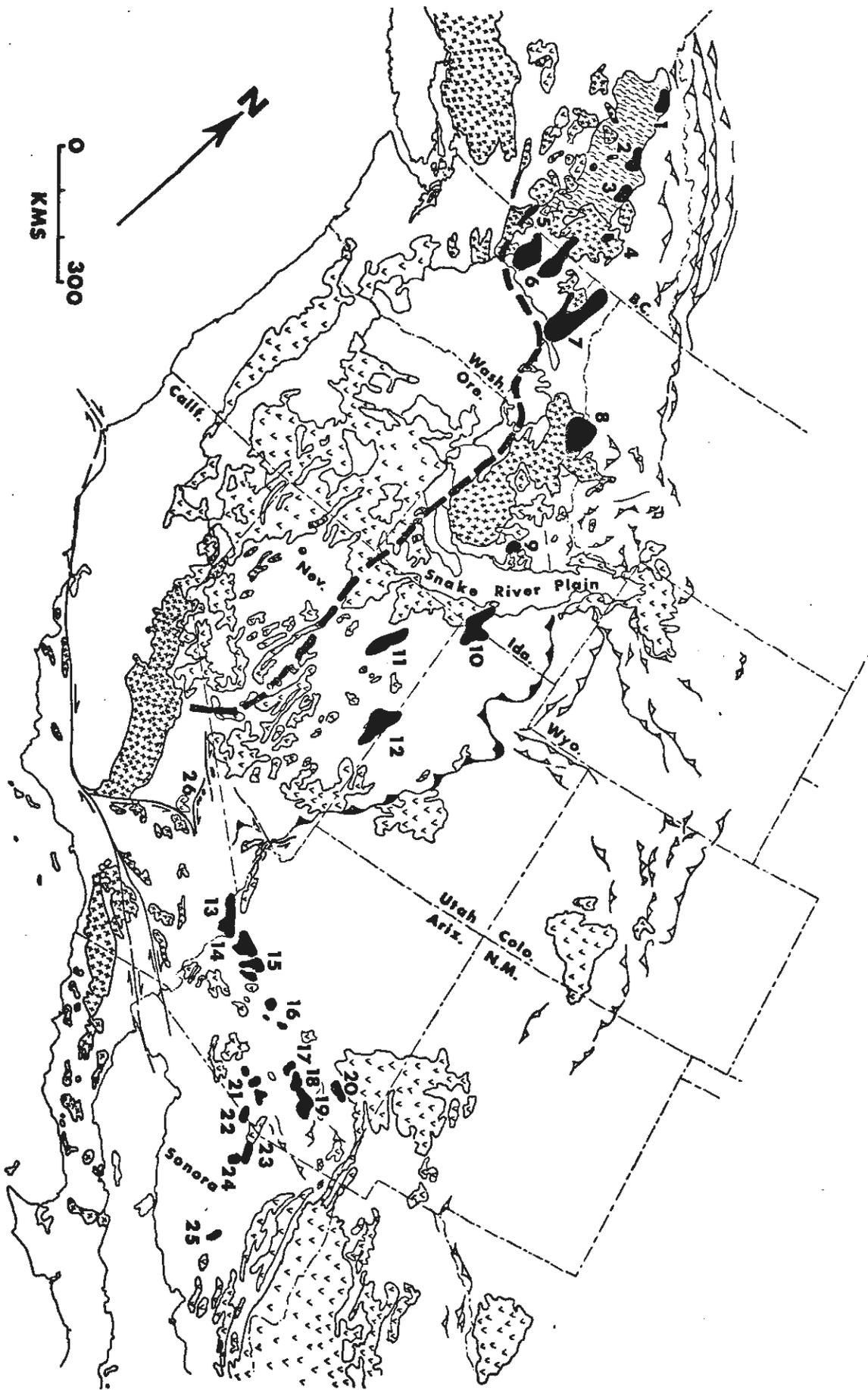
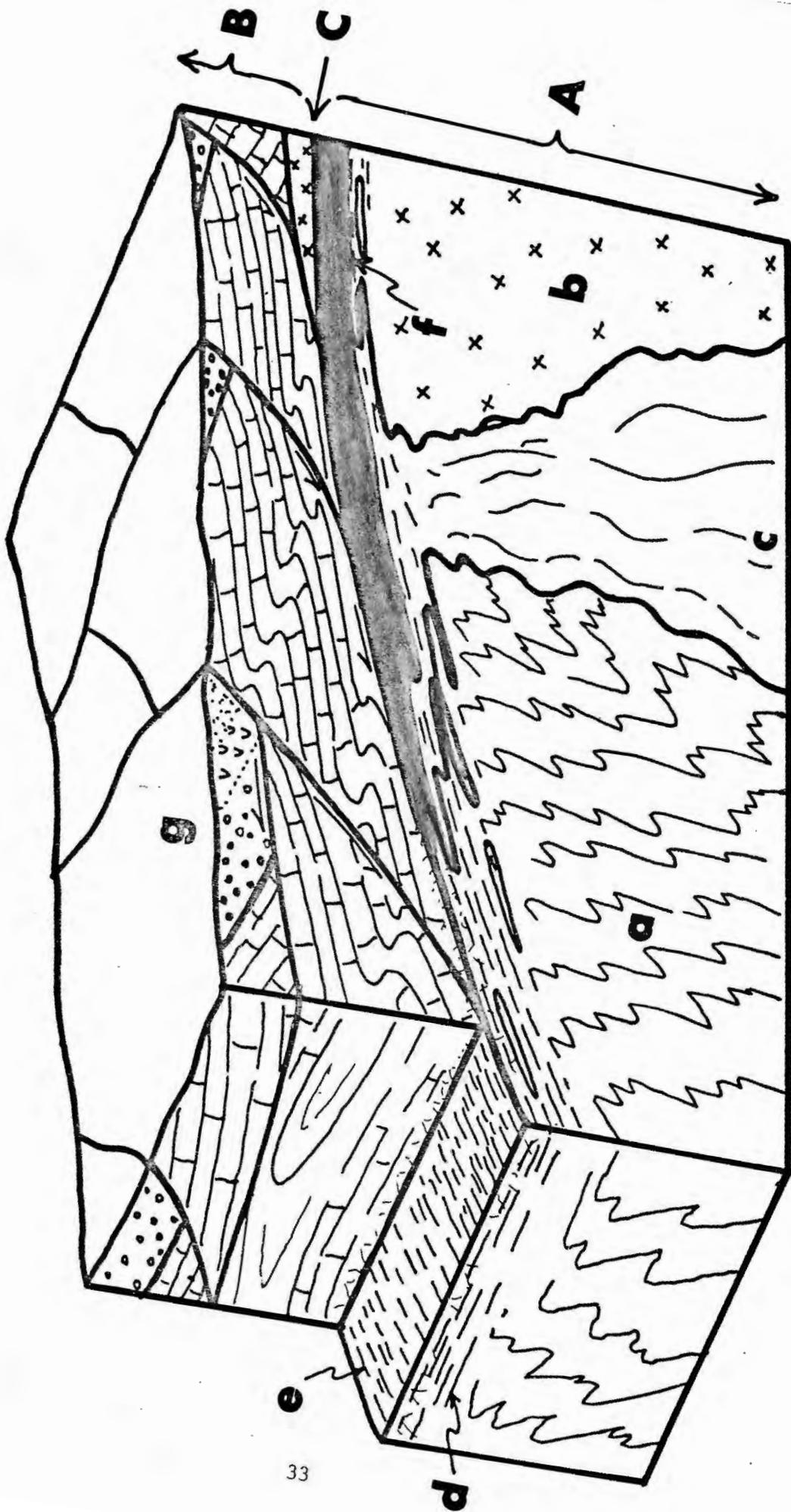


Figure 1-2

Schematic structural block diagram of typical domains of Cordilleran metamorphic core complexes. A-basement terrane; B-cover terrane; C-décollement zone; a-older metasediments; b-older pluton; c-younger pluton (Early to Middle Tertiary); d-"cataclastic" foliation; e-"cataclastic" lineation; f-marble tectonite (black); g-Early to Middle Tertiary sediments and volcanics.



frequently described as sub-parallel to minor recumbent flattened, and attenuated fold axes. There are also cases known (where lithology is favorable) of minor folds within the gneiss which suggest preferred vergence and simple shear in the same direction as the lineation. The inferred directions of movement are not universally northeast or east but form large domains which oppose one another over large regions (See discussion in Chapter 3 by Davis and Hardy). Davis has also found small late-stage normal faults whose strike is perpendicular to the lineation (Davis and others 1975; Davis, 1975, 1977, 1980). These faults seem to be the result of progression from ductile behavior to brittle failure. On the fault surfaces are slickensides whose bearing is sub-parallel to the lineation.

In those complexes where erosion has cut deeply into the uplifts, the above-mentioned foliated and lineated fabric can sometimes be seen to diminish downward into an earlier, usually steeper metamorphic fabric, or sometimes into a more homogeneous plutonic fabric (Coney, 1974; Todd, 1980; Reynolds and Rehrig, 1980). In some cases the superimposed mylonitic zone is only tens of meters thick. The deeper, earlier metamorphic fabrics are often quite complex and record poly-phase deformations and complex history (Reesor, 1970; Hyndman, 1968; Miller, 1980). The distinctive mylonitic foliation and lineation are therefore superimposed on either an earlier metamorphic fabric or on homogeneous plutonic fabrics.

The protoliths of the metamorphic basement are extremely variable both in lithology and in age. This is a point that cannot be overemphasized. In most cases, several protoliths exist in a single complex. At one place or another, the protoliths include proven older Precambrian metasedimentary basement (Reynolds and Rehrig, 1980), older Precambrian plutons which intrude into the metasediments (Banks, 1980; Compton and others, 1977; Shakel and others, 1977), Late Precambrian sedimentary rocks, Paleozoic sedimentary rocks (Misch, 1960; Howard, 1971; Thorman, 1970), probably Mesozoic sedimentary rocks (Rehrig and Reynolds, 1980; Hyndman, 1968), Laramide age plutonic rocks (Anderson and others, 1980), and even early to mid-Tertiary plutonic rocks (Reynolds and Rehrig, 1980; Keith and others, 1980). All of the above protoliths have had 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 and 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 "décollement" as it is often called, is subparallel or exactly parallel to the underlying mylonitic and gneissic fabric. This zone of brecciation is very distinctive and sometimes extends into non-mylonitic older basement. But it is always found below the décollement zone.

Granitic plutons are extremely common in the basement terrane. They are of special interest since some are described as of the two-mica garnet-bearing type (Chappell and White, 1976; Best and others, 1974; Miller and Engels, 1975). Other than the plutons, pegmatitic and migmatitic rocks are common, as are other late-stage differentiates and leucocratic phases. These smaller bodies usually form sheet-like or lensoid masses and fine stringers. These smaller bodies are frequently sub-parallel to the foliation, but can also cross it. Some have the mylonitic fabric superimposed on them, while others do not. The larger plutons are usually quite homogeneous at deeper levels, but usually progressively acquire the characteristic foliation and lineation approaching the décollement. The plutonic pegmatitic and migmatitic bodies never cross the décollement, and are frequently abruptly terminated at the décollement. In a few cases for which documentation is just emerging, even the largest plutons are apparently gigantic sill-like masses emplaced at or just below, and sub-parallel to the level of the décollement surface (Banks, 1980; Keith and others, 1980).

Metamorphic grade in the basement terrane is quite variable, but is usually moderate to high. In many complexes, the older and deeper metamorphic grade was quite high, and kyanite-sillimanite-andalusite are not uncommon (Reesor, 1970; Armstrong, 1968; Compton and others, 1977). The younger "cataclasis" presumably formed at more moderate conditions.

The overlying cover terrane consists of unmetamorphosed rocks separated from the metamorphic-plutonic core by the décollement, or by a zone of very steep metamorphic gradient. In many cases, very little of this superficial covering terrane remains at the surface since it has frequently been largely stripped away by erosion. Commonly, the only remnants are isolated "klippen," as they are usually termed, scattered around the margins of the complex.

Like the basement terrane, lithology and age of the cover rocks are highly variable. In one complex or another, the cover rocks consist of slivers of original Precambrian basement (Davis 1980; Drewes, 1977), late Precambrian sedimentary rocks, Paleozoic sedimentary rocks (Coney, 1974; Compton and others, 1977; Thorman, 1970), probable Mesozoic sedimentary rocks (Rehrig and Reynolds, 1980), and Tertiary volcanic and sedimentary rocks

(Davis and others, 1977, 1980). All of the above rocks can be demonstrated to have moved relative to the basement terrane along the décollement including, it is to be emphasized, Early to Mid-Tertiary volcanic rock and associated Tertiary sedimentary rocks (Davis et al., 1977; Davis et al., 1980).

In those complexes where sufficient cover terrane is preserved to make observations, structures in the cover 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). At times, the entire cover terrane can take on the character of a mega-breccia. It is extremely rare that faulting of any kind penetrates into the basement below the basal décollement. In other words, the décollement marks a discontinuity of extreme ductility contrast--brittle above, ductile below.

In some areas, detailed structural analysis of cover rocks reveals structures ranging from minor folds to slickensides on faults, or on the décollement surface itself, that can be interpreted to reflect movement of cover rocks down present dips of the décollement 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, while in other cases they are sub-parallel. Also, these earlier basement fabrics, including the mylonitic foliation and lineation, are re-deformed, usually brittlely, into geometries consistent with the movement picture derived from the cover (Coney, 1974). This late movement seems to have been associated with intense brecciation seen in both cover rocks and in basement terrane just below the décollement. Water was abundant, evidenced by clastic dikes and chloritic and hematitic fillings in the pervasive fractures.

The amount of extension in the cover terrane is often dramatic. In several complexes, attenuation of original stratigraphy is extreme (Compton and others, 1977; Todd, 1980; Davis, 1975) and lithologic units once very high in the original cover sequence have been brought down into contact with the décollement surface. In some cases, the stratigraphic separation is well over 2 km. It is not uncommon to find Tertiary rocks, the youngest of the original cover, brought down in tectonic contact with the basement terrane.

In many of the complexes, particularly in southern Arizona-Sonora, part of the cover sequence is an early to mid-Tertiary continental sequence composed of conglomerate, fanglomerate, sandstone, siltstone, lacustrine units, and evaporitic deposits (Pashley, 1966). These sedimentary rocks are often red and frequently associated regionally (usually below) with well-dated early to mid-Tertiary volcanics (Armstrong, 1972). All these rocks are

usually tilted to high angles. These distinctive continental sediments are so consistently found in association with the complexes in Arizona that they suggest a genetic link.

The sediments are usually very thick, and can attain several kilometers. 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-lined basement rocks occur.

These distinctive Early to Middle Tertiary sediments and volcanics commonly extend over wide regions beyond the core complexes. They are particularly well preserved in southern Arizona and in southeastern California and southern Nevada. They are inevitably tilted to high angles and show conclusive evidence of deformation by listric normal growth faults. These listric normal faults can frequently be shown to flatten with depth and merge into a décollement-like zone placing the Tertiary rocks directly on crystalline basement. This relationship and geometry was first recognized by Anderson (1971, 1977, 1978) in the Lake Meade region and later extended into Arizona by Rehrig and Heidrick (1976), Eberly and Stanley (1978), Scarborough and Peirce (1978) and Shafiqullah and others (1978).

Quite remarkably, the direction of strike in these tilted sequences over thousands of square kms. is regionally perpendicular to the direction of lineation in the mylonitic gneiss core terrane of the complexes themselves. In other words, the movement picture derived from the faulted sediments and volcanics is the same as that derived from the mylonitic gneiss in the core complexes. This is in spite of the fact that there is usually evidence that the listric normal faulting is younger than the mylonitic gneiss. For a more complete discussion of these relationships see Chapter 3 by Davis and Hardy in this report.

The décollement, or dislocation surface is perhaps the most distinctive aspect of the core complexes thus far recognized (Misch, 1960; Coney, 1974; Whitebread, 1968; Nelson, 1966; Davis and others, 1980; Miller, 1972). Although variations exist, the general characteristics of the décollement are so remarkably similar from one complex to another that the feature is instantly recognized.

In some areas, the décollement is located quite close to either the Precambrian-Phanerozoic unconformity or in horizons directly above thick Late Precambrian-Early Paleozoic quartzite-siltstone sequences. If carbonates lie below the décollement

they are usually metamorphosed and attenuated and intensely deformed into a marble tectonite rarely over several tens of meters thick (Misch, 1960; Nelson, 1966; Coney, 1974; Whitebread, 1968). Davis (1980) has referred to this tectonite band as a metamorphic carapace. Unmetamorphosed Paleozoic carbonates can directly overlie their metamorphosed equivalents below the décollement. Where the basement is composed of plutonic rocks, the décollement usually lies directly above them and the plutons never cross the décollement. A remarkable example in the southern Snake Range of eastern Nevada (Whitebread, 1968), has a Jurassic pluton as basement. This pluton is overlain along a clearly tectonic low-dipping planar surface by up to 30 meters of marble tectonite. The décollement 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 décollement (Lee and others, 1970; Armstrong, 1972; Coney, 1974).

The décollement surface is locally very sharp and clearly visible in topography. It is generally polished and has slickensides, and rock directly below can have the aspect of a fused paste or welded small clast-sized breccia.

Rocks near the décollement, both above and below, are usually brecciated and show extensive alteration (Reynolds and Rehrig, 1980). 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 micro-breccia aspect.

The décollement is typically 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, 1980). On the other, steeper side, the discontinuity can be less sharp or tectonically abrupt with only very steep metamorphic gradient and little, if any, evidence of major relative movement between cover and basement demonstrable. In at least two complexes, several slices, or thin packets of discontinuity-bound rocks, are found extending 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 (Compton, 1972, 1975; Compton, 1972, 1975; Compton and others, 1977; Todd, 1980), the two lower slices are metamorphosed, but the upper is not. In the Rincon Mountains (Davis, 1980, Drewes, 1977), the lowest slice is metamorphic Paleozoic rocks 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 and metasediments and early to middle Tertiary plutons.

Are the complexes basically classic gneiss domes (Escola, 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 arch-like geometry, steep metamorphic gradient, etc. 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 no more than 4 km in a wavelength of as much as 50 km, giving an amplitude-wavelength ratio of .08--a fact reflected in the universal low-dipping foliation which rarely exceeds 20° to 30° (e.g., 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, 1975) where amplitude--wavelength ratios are .25-.5 or more. Third, it has been emphasized earlier in this paper that the cataclastic foliation and lineation so characteristic of the complexes in many cases actually seems 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 deep mobility characteristic of an "infrastructure" 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. Perhaps the main difference is that the Tertiary aspects Cordilleran core complexes evolved in a regional non-compressional, perhaps even extensional tectonic setting, whereas domes characteristic of other orogens did not. In fact, it is the overwhelming evidence for pervasive extension in basement fabric, structures in the cover and along the décollement, that dominates all characteristics of Cordilleran metamorphic core complexes. For a more complete discussion of the gneiss dome concept see Chapter 2 of this report.

REGIONAL TECTONIC SETTING

The regional tectonic setting of Cordilleran metamorphic core complexes is portrayed on the 1:1,000,000 tectonic map accompanying this report. (Map 1-1) To date, no specific regional tectonic relationship of the complexes has been demonstrated to everyone's satisfaction. Regardless, 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 sub-parallel belts (King, 1969; Monger and Hutchison, 1971). A 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 batholith southward into western Mexico. An eastern belt (Coney, 1978) follows the Omineca crystalline complex of the eastern Cordillera in Canada, culminating in the Shuswap terrane of southern British Columbia which extends into north-eastern Washington (Cheney, 1977, 1980; Fox and others, 1977). southward across Nevada, southeastward across Arizona, then southward into Sonora. All of the so-called Cordilleran metamorphic core complexes as defined here lie in this eastern belt, extending at least from southern Canada to northern Mexico.

Most of the eastern belt developed either on or very close to the edge of 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, either recently or subsequently accreted against North America's continental margin (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 variable pre-core complex history and tectonic evolution.

Pre-Mesozoic Tectonic Trends

Of the 25-odd Cordilleran metamorphic core complexes currently identified, all evolved in terrane underlain by North American Precambrian continental cratonic basement as defined by the $.706^{87}\text{Sr}/^{86}\text{Sr}$ line (see Fig. 1) (Armstrong and others, 1977; Kistler and Peterman, 1973). Two possible exceptions are the Okanagan (Fox and others, 1976) and Kettle (Cheney, 1977, 1980) complexes in Washington which appear to lie west of proven North American Precambrian basement. In most complexes, the Precambrian basement is either proven or implied by isotopic dating (Wanless and Ressor, 1974; Clark, 1973; Armstrong and Hills, 1976; Compton and others, 1977; Shakel and others, 1977); and regional relations seem to demand its presence in most of the remainder. Looking more closely at this Precambrian basement, 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 two billion years in the north to

about one billion in the south (King, 1969). The Arizona complexes may parallel a northwest-southeast trend of late Precambrian right-shear just southwest of the Colorado Plateau, but so do all other post-Paleozoic tectonic trends.

From southern Nevada northward, all the complexes lie within the thick Cordilleran latest Precambrian-Paleozoic miogeoclinal prism. In Arizona and Sonora, on the other hand, the complexes evolved well inboard of the Paleozoic miogeocline on what had been a thin cratonic shelf (Peirce, 1976). As a result, relating the complexes to a zone of deep Paleozoic burial and thick Paleozoic deposition over the eventual site of the core complexes is unlikely. Paleozoic cover varies from almost 15 km in southern Canada, to about 10 km in Nevada, to only 2 km in southern Arizona.

Similarly, distribution of the complexes with respect to Paleozoic orogenic activity and metamorphism is variable. The northern complexes are found in a region that probably suffered mid- and late-Paleozoic Antler-Sonoma deformation and, in the case of the Shuswap complexes, 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, 1973a; Burchfield and Davis, 1976). It marks inception of draping and accretion of magmatic arcs on the North American margin and the evolution of arc-rear thrusting and folding inboard from the magmatic belts.

Genetic linking of 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 concept 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 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). This belt of metamorphic rocks has been termed a "hinterland" behind the thrust faults where more deep-seated tectonics is supposed to have taken place with associated uplift, thermal disturbance, and remobilization. The assumption has been that the metamorphism accompanied the thrusting and was

thus genetically linked to it. It was this position that so heavily influenced early models such as those of Misch (1960) and Price and Mountjoy (1970).

In Canada, Paleozoic and lower Mesozoic rocks are clearly metamorphosed (Hyndman, 1968), and in Nevada Paleozoic rocks are involved (Misch, 1960). From regional relationships in Canada, some of the metamorphism is Paleozoic and most of it is at least as old as mid-Jurassic (Wheeler and Gabrielse, 1972; Brown and Tippett, 1978). Ironically, recent work in the southern Rocky Mountains of Canada suggests that much of the complex poly-phase deformation and metamorphism so characteristic of the Shuswap terrane is pre-late Jurassic (Brown, 1978; Wheeler and Gabrielse, 1972), 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 Tertiary (Compton and others, 1977; Cheney, 1980; Reynolds and Rehrig, 1977, 1980; Anderson and others, 1980) and hence much later than Sevier or Laramide thrusting has clouded the issue of 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). Here deformation was apparently more deep-seated, involving both basement and cover rock. Furthermore, the metamorphism and deformation associated with most of the complexes is clearly younger than Laramide tectonic features and is superimposed on post-thrusting Laramide plutons and even on some mid-Tertiary plutons (Anderson and others, 1980; Reynolds and Rehrig, 1980). 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 relations are less clear. An older, mid-Mesozoic, metamorphism has long been advocated in the hinterland (Misch, 1960); and certainly exists in the Ruby Range (Howard, 1971, 1980; Snoke, 1980), and probably in the Snake Range as well. As stated earlier, however, this is an older metamorphism exposed deep in the cores of some of the complexes. Superimposed on this earlier, generally steeper fabric is the shallow-dipping late "cataclastic" fabric so characteristic of the complexes throughout their extent. This late metamorphism and associated deformation are at issue here. That event appears to

be superimposed on plutons as young as Early to Middle Tertiary (Compton and others, 1977), thus much younger than the late Jurassic to late Cretaceous thrusting in the Sevier thrust belt to the east in central Utah.

The thrust belt-core complex concept has played another significant role in interpretations of the complexes. The concept has led to identification of the distinctive "décollement" surface and its associated cataclasis with the basal shearing-off plane of the thrust belts (Misch, 1960). This interpretation has been variably invoked in Idaho (Hyndman and others, 1975), Nevada-western Utah (Misch, 1960; Hose and Danes, 1973), and in Arizona (Drewes, 1976, 1978). Obviously, the age of shearing-off would have to be of Sevier age in Nevada, of Sevier-Laramide age in Idaho, and of Laramide age in Arizona. The fact that the décollement surface and the "cataclastic" 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 concept (See Fig. 5). As a result, some workers have more recently argued models of multiple thrusting (Drewes, 1976, 1978; Thorman, 1977) and/or mid-Tertiary gravitational sliding on a décollement surface originally made during regional low-angle thrusting during Sevier or Laramide time (see discussion in Compton and others, 1979 and Crittenden, 1979). These models seem in some cases at least geometrically difficult. Armstrong (1972), for example, has argued on geometric grounds that the décollement surface in the Snake Range of eastern Nevada is unrelated to the basal shearing-off plane of Sevier age thrusts to the east (Fig. 3).

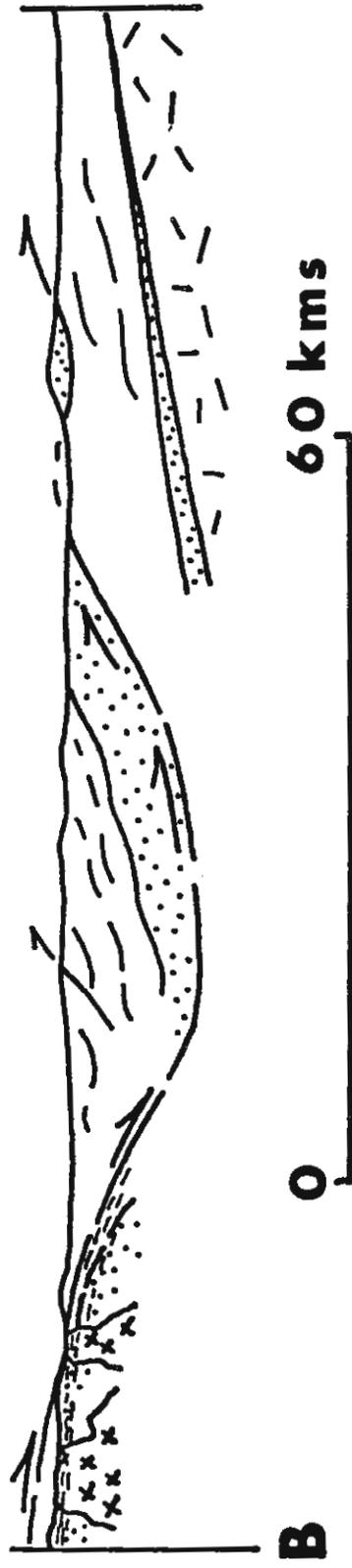
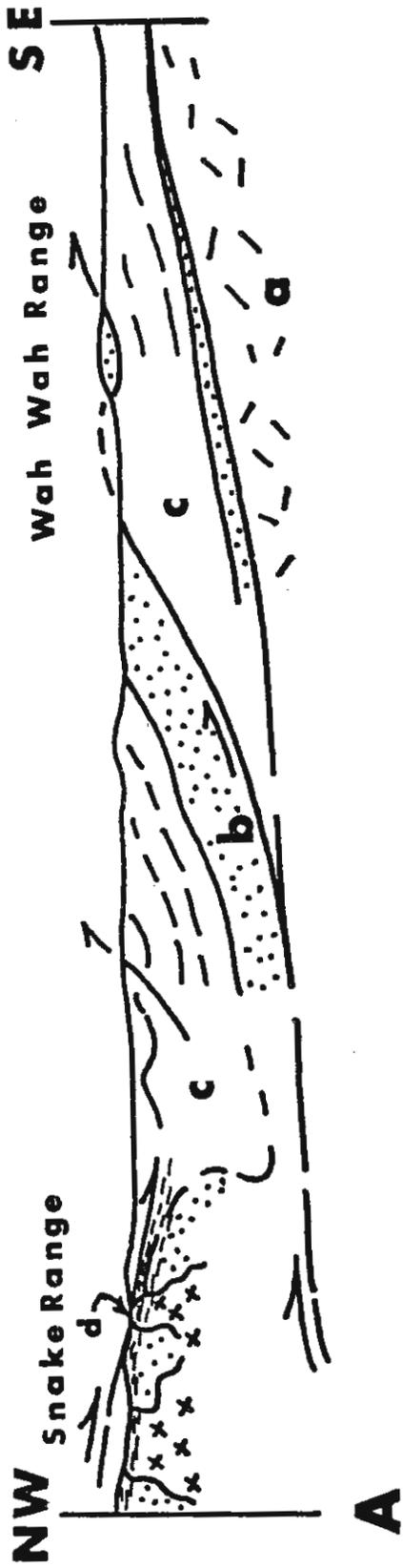
In any event, the debate concerns whether the characteristics so typical of the core complexes, namely the décollement surface, the distinctive mylonitic or "cataclastic" foliated and lineated fabric, and younger on older "faults" in the cover, are genetically linked to regional thrusting of Mesozoic-early 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 argued is that the younger features typical of the complexes are superimposed on earlier fabrics: that the younger features are probably, for the most part, Tertiary in age; and that they are seemingly unrelated to the thrust belts at least in any direct way.

Since the core complexes are clearly, in part, of thermal origin, distribution of magmatic activity is of interest in discussing their evolution. Compilations 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

Figure 1-3

Two contrasting interpretations of structure from the Snake Range, Nevada to the Wah Wah Range, Utah based on a section by Armstrong, 1972. Figure 3A - deep-seated thrust fault model showing basal Sevier thrust in Wah Wah Range rooting beneath the Snake Range. This interpretation was favored by Armstrong. Figure 3B - shallow thrust fault model which connects the Snake Range décollement is not connected to the Sevier thrust faults to the east. This interpretation was favored by Hose and Danes, 1973. In Fig. 3A the Snake Range décollement is not connected to the Sevier thrust faults, but is interpreted as a Tertiary denudation fault (Armstrong, 1972) off the Snake Range core complex. a-Precambrian basement; b-Upper Proterozoic-Lower Cambrian clastic rocks; c-Paleozoic carbonates; d-Snake Range décollement. X-pattern-Mesozoic-Cenozoic plutons.



the Canadian coastal plutonic complex, the Idaho batholith, and Sierra Nevada-Peninsula 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 cross-cut the metamorphic fabrics typical of the Shuswap terrane (Hyndman, 1968).

In the United States, the Washington-Idaho complexes are superimposed on, or certainly co-existent with, the main batholith belt (Miller and Engels, 1975). Further 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 plutons are perhaps best explained as scattered intrusions parasitic to the main batholith belt which were produced either from deeper levels of the descending slabs or from transient variable dips in these slabs. The Arizona-Sonora complexes are within a broad belt of mainly late Cretaceous-early Tertiary scattered Laramide magmatic activity which swept inboard from the Cretaceous peninsular 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 core complex belt. 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-Early-Middle Tertiary magmatic trend coincides with the belt of complexes, either in space or in time.

Relation to mid-Cenozoic Tectonic Trends

Starting about 55 m.y.b.p. and extending to about 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). It 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 kilometers, and also caused much low-angle normal faulting. This enigmatic phenomenon is very important because the core complexes seem to have evolved just prior to and during the outburst (Coney, 1974, 1978). What is puzzling, however, is that the outburst 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-Peninsula batholiths into western Mexico (Coney, 1976, 1978; Armstrong, 1974). After 80 m.y., 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-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 which eventually swept back toward the continental margin, becoming the vast ignimbrite flare-up (Fig. 4D) across Idaho-Washington-Oregon, Utah-Nevada, New Mexico-Arizona, and all of central and northern Mexico (Coney and Reynolds, 1977). Only the Colorado Plateau was spared. By 15-20 m.y. ago, the outburst reached the coast, formed the Cascade magmatic arc trend in the Pacific Northwest, but transformed to a widespread bimodal basalt-rhyolite phase associated with Basin and Range rifting 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 retrograde 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, pers. comm., 1977; Cheney, 1980); likewise, those south of the Snake River Plain evolved during the Oligocene-early Miocene ignimbrite flare-up there (Coney, 1978).

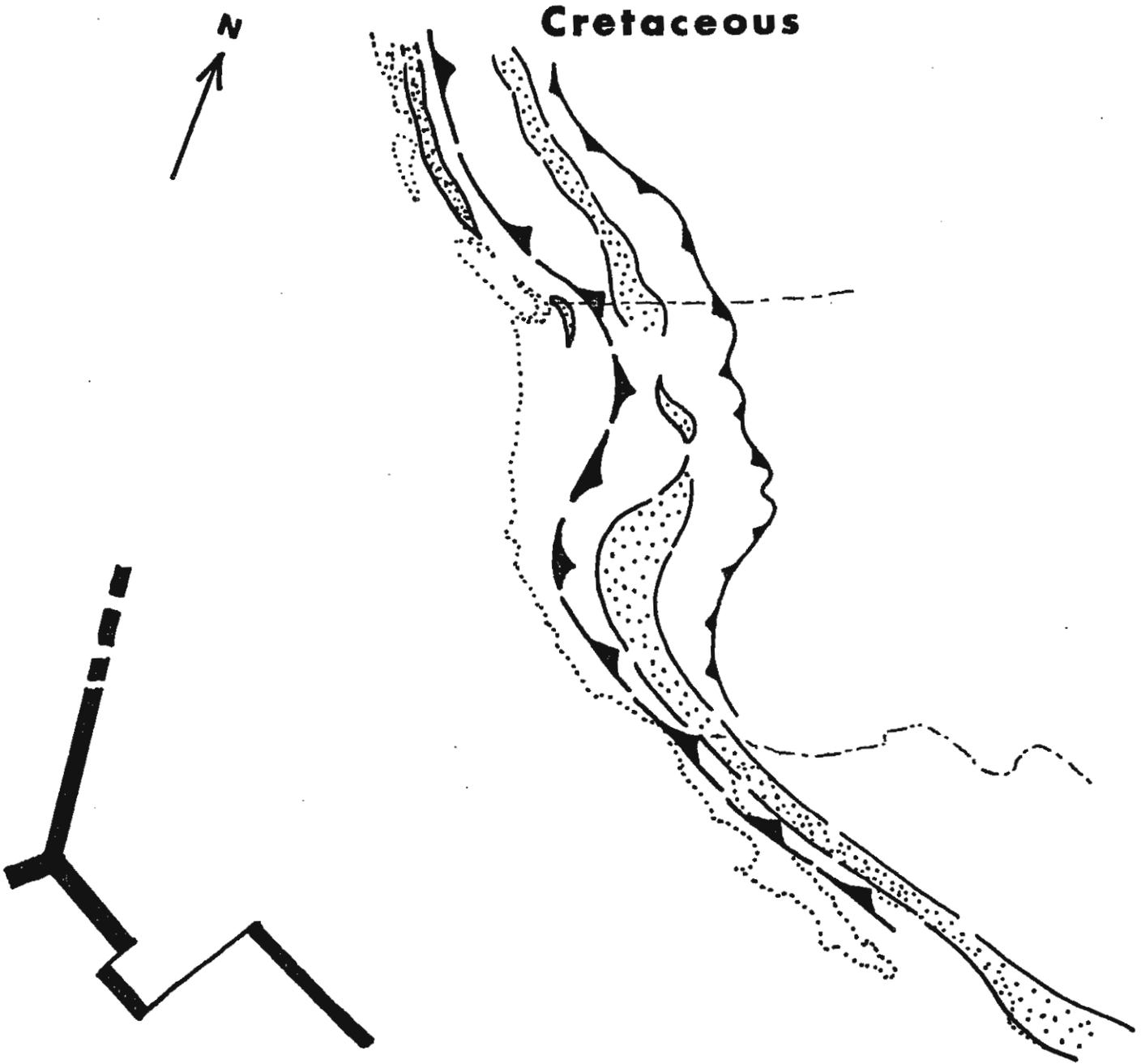
The post-Laramide to middle Tertiary is a most puzzling time (Coney, 1978). The events which took place are clearly post-Laramide compressive deformation and they seem to have begun by widespread erosion and beveling of Laramide landscapes (Epis and Chapin, 1975). Within the belt of core complexes, the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

Relationship to Late Cenozoic Tectonic Trends

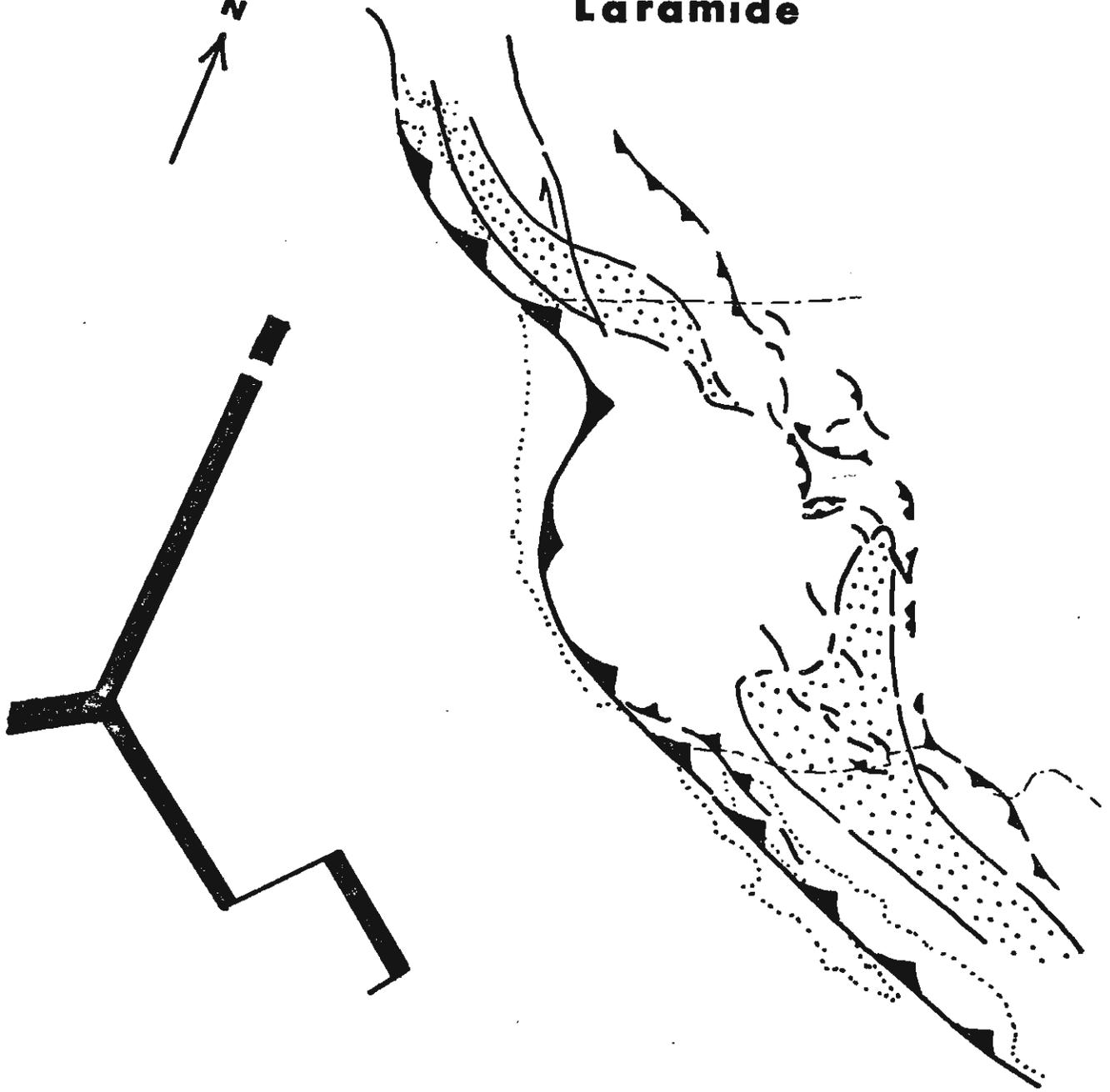
One relationship on which almost all workers are agreed is that post 15-18 m.y. Basin and Range faulting seems to post-date most core complex activity (Fig. 4E). In many areas, the steep

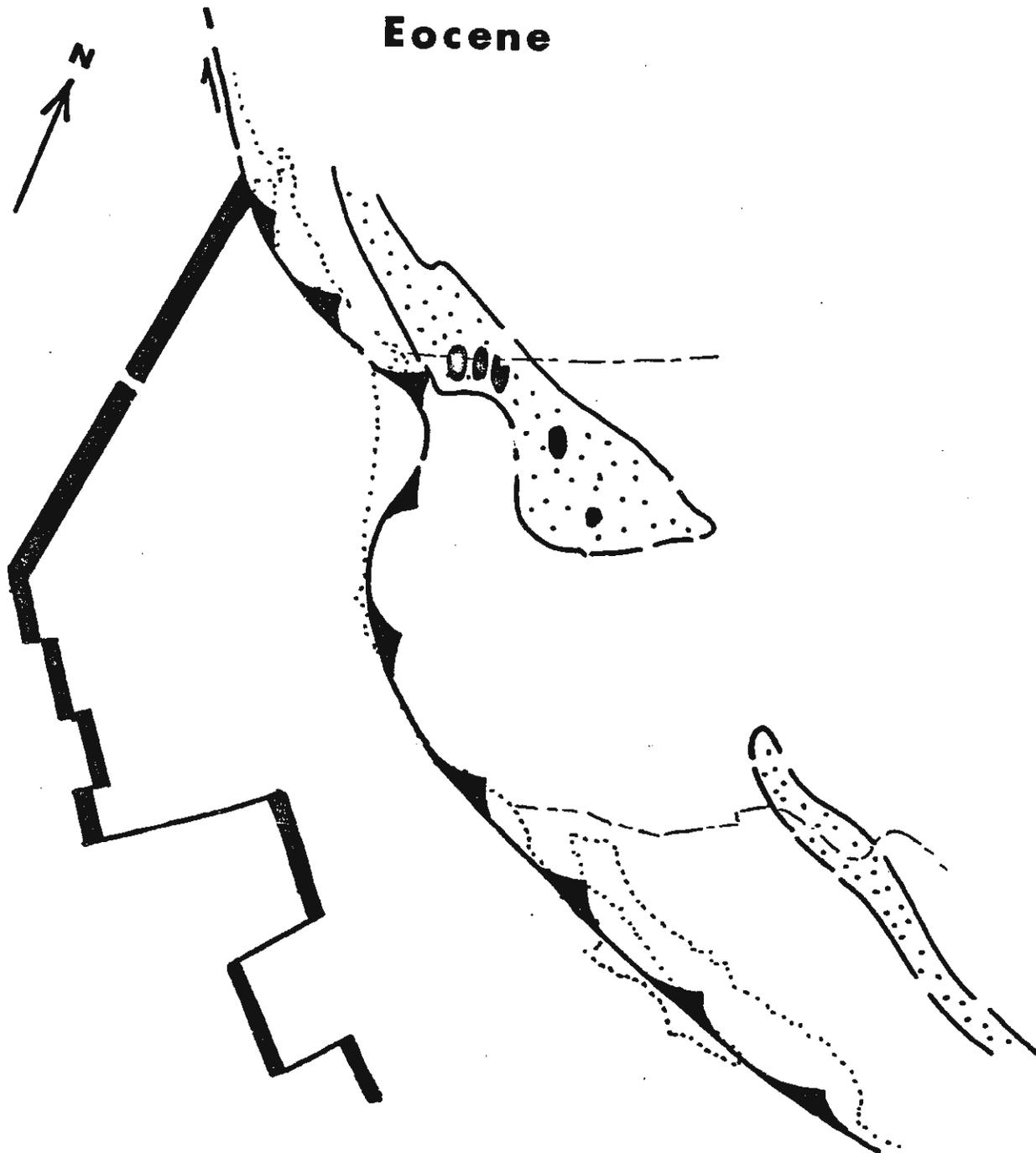
Figure 1-4

Major features of Cordilleran tectonic evolution since Early Cretaceous time. A-Cretaceous; B-Laramide; C-Eocene; D-Middle Tertiary; E-Late Tertiary. In all figures heavy stipple-magmatic arc terranes; heavy barbed line - subduction zones; light barbed lines - thrust faults. Core complexes in solid black on figures C and D. Heavy black lines west of North America are approximate positions of Pacific spreading centers at times indicated from Coney (1978).

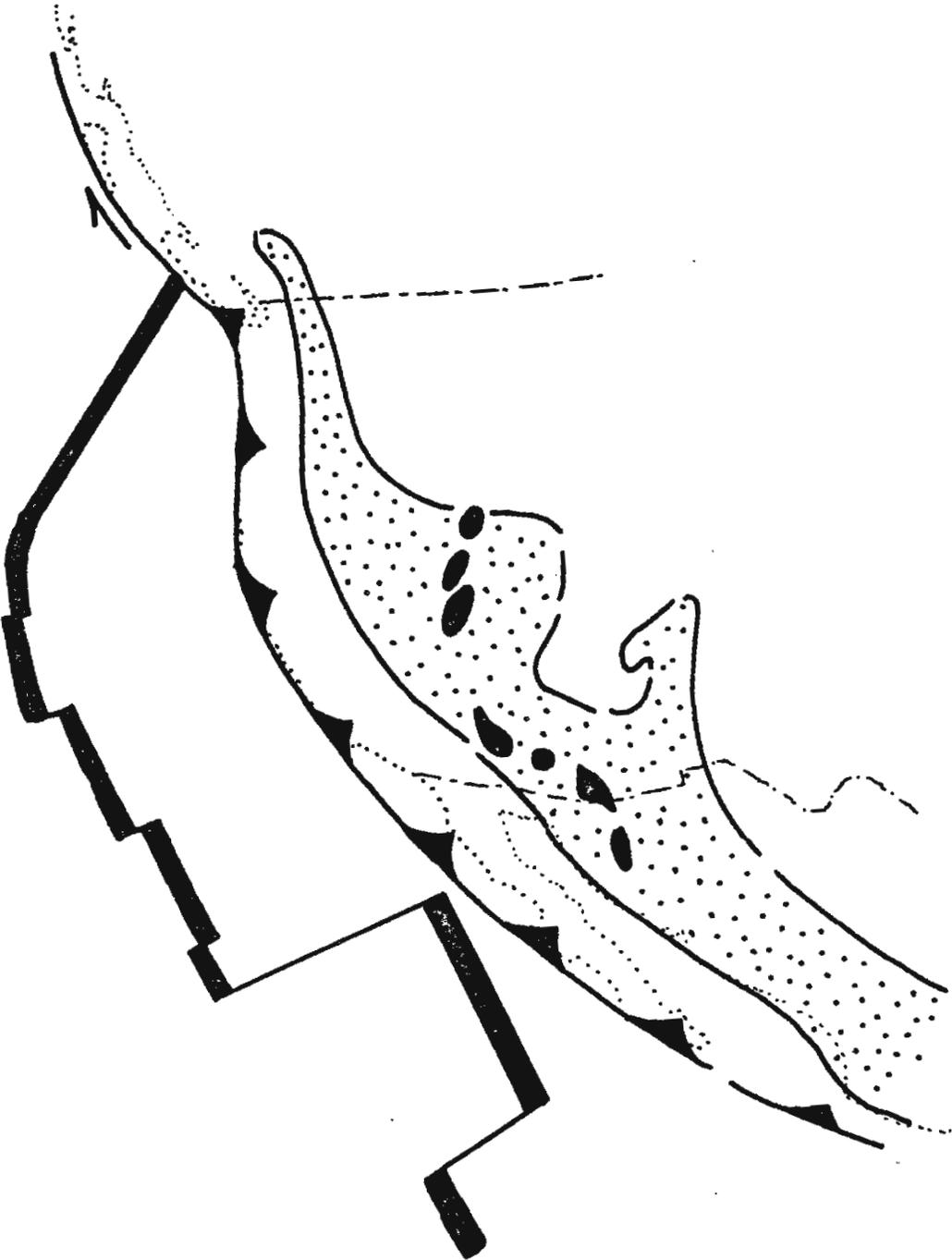


Laramide

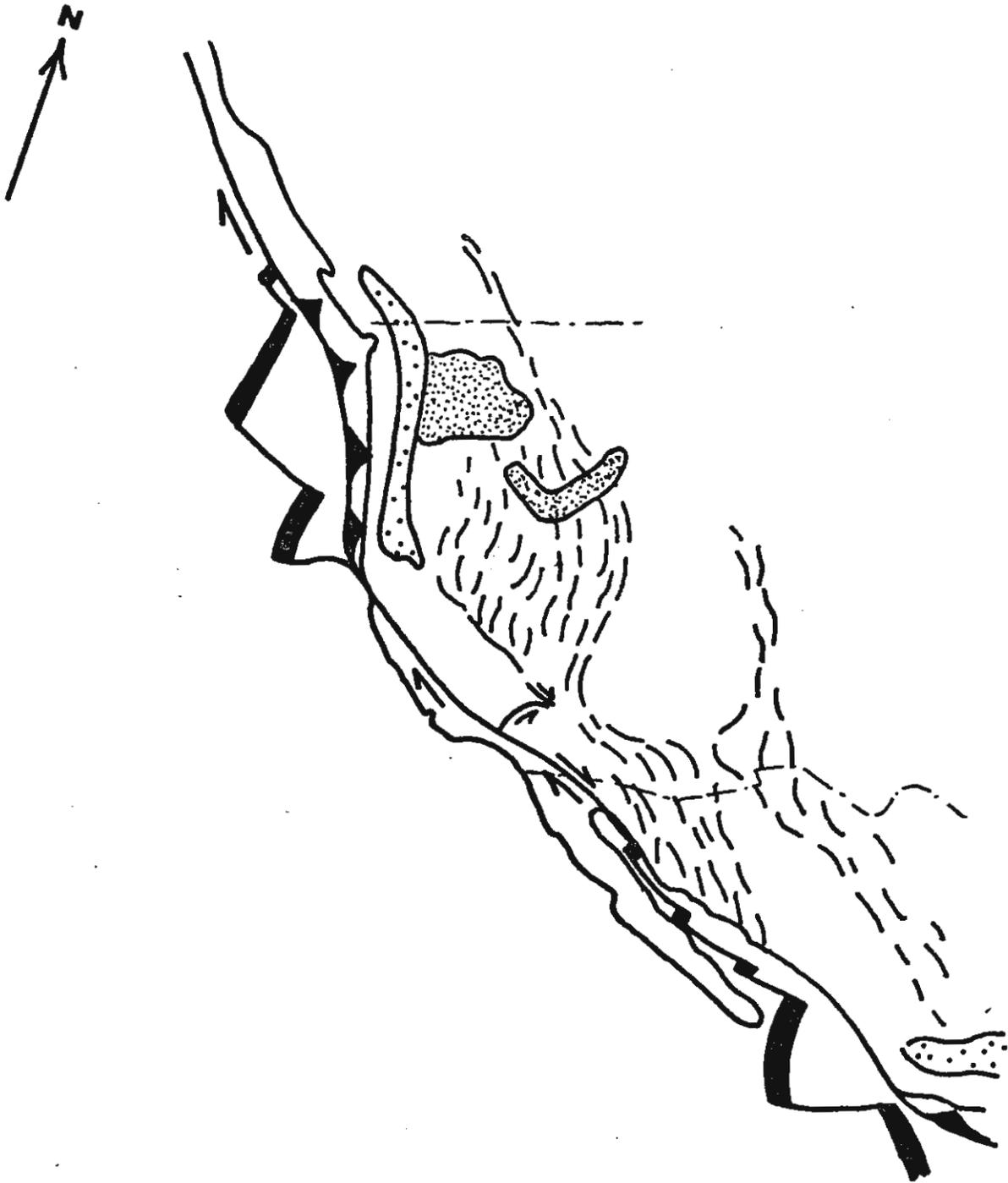




Middle Tertiary



Basin and Range



block faulting clearly cuts metamorphic rocks, the décollement, or cover rocks (Coney, 1974; Eberly and Stanely, 1978).

TECTONIC SIGNIFICANCE

The tectonic significance of Cordilleran metamorphic core complexes has been much debated during the past 20 years. 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 experienced by many of the complexes, particularly those from western Arizona northward. The second aspect is the Early to Middle Tertiary history which is emerging as so important in all of the 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 assignment of these features to results of events of Mesozoic age. In this regard, the full significance of the Arizona-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-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 Early to Middle Tertiary in 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 but much, if not all, of the characteristic "cataclastic" or mylonitic fabrics, décollement zones, and chaotic structures in cover rocks are, in part at least, the result of Early to Middle Tertiary tectonics.

In the Shuswap complex of southern Canada something on the order of 40,000 km² of metamorphic rock are exposed. It is the largest of all the Cordilleran metamorphic core complexes and in the original conception of the problem was the type example and the source of the name. As outlined earlier, studies indicate some of the metamorphism is as old as Paleozoic and much of it is at least as old as Jurassic (Okulitch and others, 1975; Reed and Okulitch, 1977; Brown and Tippett, 1978; Wheeler and Gabrielse, 1972; Hyndman, 1968). There are dated Upper Jurassic to Middle Cretaceous plutons which cross-cut metamorphic rocks (Gabrielse and Reesor, 1974). There are also many Early Tertiary

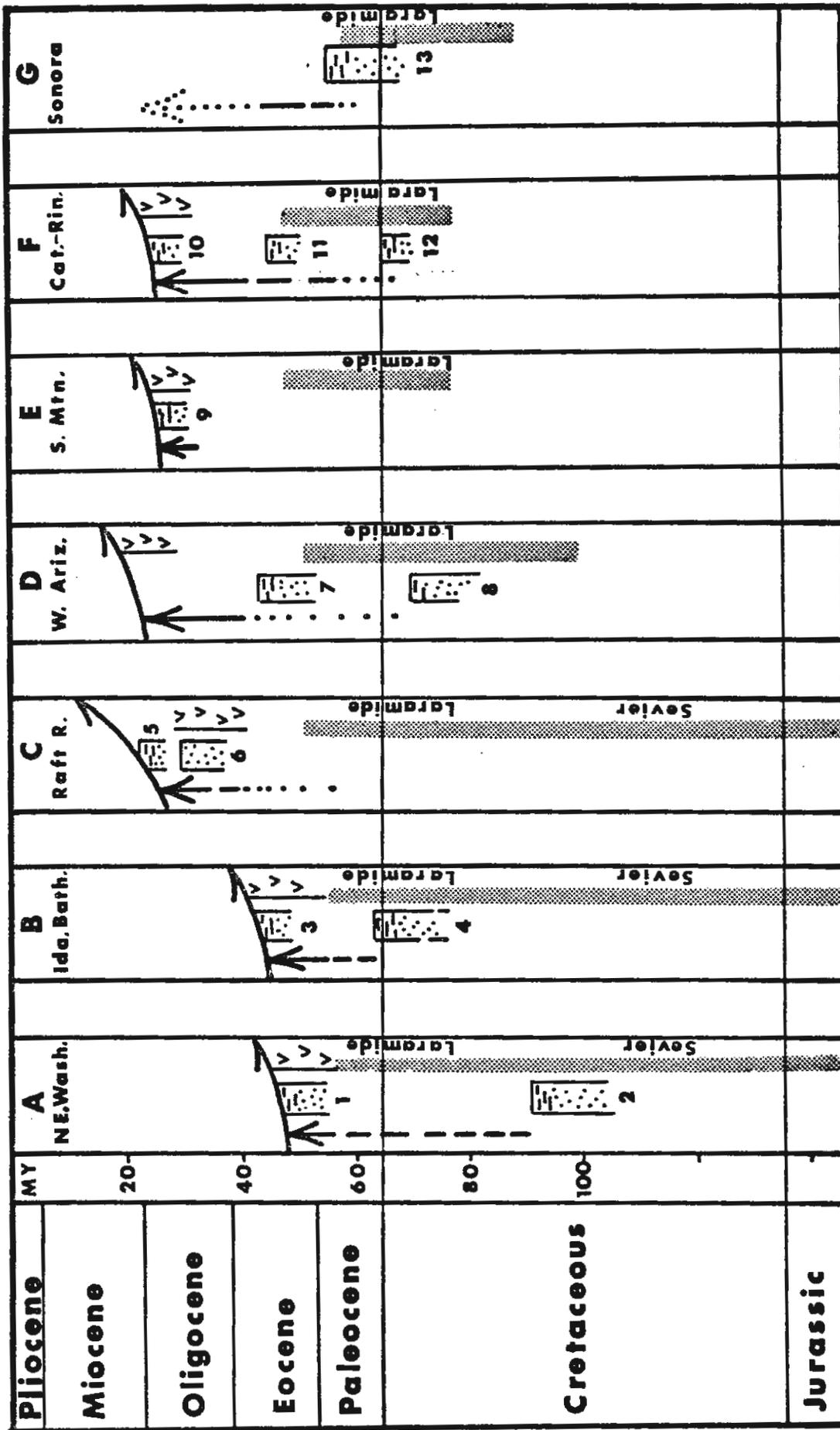
(mostly Eocene) K-Ar apparent ages associated with scattered shallow plutons and a widespread resetting of isotopic clocks (Fox and others, 1977). Unfortunately, the age of the apparent later arching seen in the three distinctive "gneiss domes," and the narrow belt of late "cataclasis" along the eastern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

As a result of field work in northeastern Washington carried out in connection with this project, and building on earlier work by Reynolds, we have demonstrated that the Purcell trench, or fault zone, is the eastern margin of the Selkirk metamorphic core complex. This zone is a 30° east-dipping mylonitic front and is very similar, although off-set to the east, to the described east-dipping mylonitic zone along the east side of the Shuswap complex. Southward the Purcell mylonitic front terminates near Lake Coeur d'Alene and is apparently complexly transformed into the right-lateral Lewis and Clark fault zone which extends east-southeast to the north end of the east-dipping, north-trending Bitterroot mylonite zone in Idaho-Montana. The evidence in Montana and Idaho suggests the system is in part Early Tertiary in age and part of the core complex process.

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. This model invokes a mobile infrastructure which buoyantly rose and propelled the thrusts to the east largely by gravity. This model has difficulties because the assignment of a Jurassic age to the metamorphism implies that most of the metamorphism was over before the thrusting began. Since the metamorphic hinterland exposes rocks once deeply buried and subjected to temperatures of 600°C and pressures approaching 4 kb, a post-metamorphic uplift of 10 kms 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 best explained as being due to crustal telescoping in the thrust belt and resulting crustal thickening in the region of the hinterland during Sevier-Laramide time. To what degree Tertiary features similar to those found in the complexes southward in 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

Figure 1-5

Age relationships in selected Cordilleran metamorphic core complexes. Column A-Northeastern Washington (Selkirk complex); B-Idaho Batholith (Bitterroot complex); C-Albion-Raft River-Grouse Creek complex; D-Western Arizona (Harcuvar complex); E-South Mountain complex south of Phoenix, Arizona; F-Catalina-Rincon complex near Tucson, Arizona; G-Sonora, Mexico. In all columns stipple pattern is for age range of plutonic rocks with dash pattern at top signifying mylonitic gneisses ("cataclastic") fabric superimposed on the pluton; V-pattern is age range of Early to Middle Tertiary volcanic rocks in vicinity of each complex; the vertical heavy arrow represents the possible age limits for formation of the overprinted mylonitic gneissic ("cataclastic") fabrics superimposed on the plutons and other basement terranes. The sub-horizontal heavy barbed arrow is the approximate older age limit on the movement of cover rocks over the basement terrane on "décollement" surfaces. In many cases this movement could be younger than indicated, but in most cases it can be shown to be older than latest Tertiary Basin and 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-Mid Cretaceous plutons (Miller and Engels, 1975); 3-Eocene plutons (Reynolds and Rehrig, pers. comm., 1979); 4-Bitterroot lobe of Idaho Batholith (Chase and others, 1978); 5-Red Butte pluton (Compton and others, 1977); 6-Imigrant Pass pluton (Compton and others, 1977); 7-muscovite granite (Rehrig and Reynolds, 1980); 8-Tank Pass pluton (Rehrig and Reynolds, 1980); 9-South Mountain pluton (Reynolds and Rehrig, 1980); 10-Catalina granite (Shakel and others, 1977); 11-Wilderness granite (Shakel and others, 1977; Keith and others, 1980); 12-Sierra Mazatan, (Anderson and others, 1980).



earlier Cordilleran tectonic history. The later Early Tertiary history is still not fully documented or evaluated.

A similar model of crustal telescoping and uplift of the hinterland can be applied southward in United States at least as far as southern Nevada, but telescoping and resulting uplift was probably less and mostly confined to mid-Cretaceous Sevier orogeny 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, 1968b; Howard, 1971, 1980; Snoke, 1980), but may be as old as Jurassic (Compton et al., 1979). Superimposed on, or at least late in the history of, this earlier metamorphism are the shallow-dipping late mylonitic fabrics, associated décollements 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 Raft River-Grouse Creek Mountains, Kern Mountains, and Ruby Mountains (Compton and others, 1977; Best and others, 1974; Snoke, 1980; Todd, 1980), and similar relationships are emerging in north-eastern Washington (Cheney, 1980; Miller, 1972; Reynolds and Rehrig, pers. comm., 1978) 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 décollement (Lee and others, 1970; Armstrong, 1972). They have produced field relationships such as "klippen" of Paleozoic rocks over Middle to Late Tertiary sediments in Raft River-Grouse Creek Mountains (Todd, 1973, 1980) and low-angle normal faults in mid-Tertiary volcanic rocks (Armstrong, 1972). Coney (1974) inferred that minor structures in rocks associated with the Snake Range décollement were consistent with Armstrong's (1972) model of Tertiary denudational faulting in the Nevada hinterland. All of these features are clearly pre-Late Tertiary Basin and Range faulting (Coney, 1974).

In Arizona and Sonora, the metamorphic core complexes are clearly Early to Middle Tertiary in age. In southwestern Arizona an older Mesozoic metamorphism is overprinted by mylonitic gneissic fabrics in several complexes (Rehrig and Reynolds, 1977, 1980), but for the most part the complexes of 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 in part in the midst of a belt of deep-seated basement cored thrust uplifts of Laramide age accompanied by scattered Laramide plutons. Furthermore, the typical core complex fabrics and related décollement are superimposed on plutons ranging in age from about 55 m.y. in Sonora (Anderson and others, 1977, 1980) to as young as 25 m.y. at South Mountain near Phoenix (Reynolds and Rehrig, 1980). 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, 1980). Davis (1975) inferred Tertiary movement of cover rocks down décollement surfaces in the Rincon Mountains based on structural analysis. Finally, all these features are clearly pre-Basin and Range block faulting.

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 décollements. The earlier Mesozoic metamorphism and deformation has 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 near perfect tracking 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 from particularly Laramide events could have prepared a weakened basement conducive to concentrating the Tertiary events.

The evidence for large-scale Tertiary extension in and adjacent to the complexes is extremely compelling. It was first acknowledged in the cover terranes (Armstrong, 1972; Anderson, 1971; Coney, 1974; Davis, 1973, 1975; see also Davis and others, 1980). Only more recently has it been proposed in the basement itself as manifested in the mylonitic foliation and lineation. It was certainly the work of George Davis (1975, 1973, 1977a, 1977b) in the Catalina-Rincon complex in Arizona that first suggested this basement extension as a major aspect of core complex evolution. Davis has subsequently (1977, 1980; Davis and Coney, 1979) expanded these observations into the provocative concept that the complexes are in fact mega-boudins. 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 mid-Tertiary

plutons in southern Arizona (Rehrig and Heidrick, 1976). These dikes are oriented perpendicular to the lineation in the core complexes (Reynolds and Rehrig, 1980). This extension has also been recognized outside or adjacent to the main core complex belt in areas of low-angle pre-Basin and Range listric normal faults which cut Middle Tertiary volcanic and sedimentary rocks (Anderson, 1971; Eberly and Stanley, 1978; Rehrig and Heidrick, 1976; Davis and others, 1980).

It is remarkable how many of the complexes are characterized by Early to Middle Tertiary granitic plutons. The late cataclastic 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 which 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 retrograde sweep of a flattened Laramide Benioff zone during Eocene through Miocene time (Coney and Reynolds, 1977). A significant enough number of granitic plutons, particularly the earlier ones, are of the two-mica garnet-bearing type to suggest a genetic association between this 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.

Since 1970, the situation surrounding the core complexes has become one of considerable controversy and heated debate. In the process, some discoveries have been made and there have been some new insights into Cordilleran tectonics. Considerable confusion yet prevails and there is still substantial, justifiable disagreement. The most important aspect of the recent work is certainly the suspicion and realization that there had been a strongly manifested and enigmatic Tertiary overprint superimposed on the region. The overprint is most clearly recognized in young K-Ar apparent age dates from basement rocks and in the listric normal faulting and décollement zones characteristic of the unmetamorphosed cover terranes of the complexes. This activity followed Mesozoic thrusting and preceded Basin and Range block faulting, and was more or less contemporaneous with widespread Tertiary ignimbrite eruptions. This created a strange image of tectonic response not easily understood then or even today.

In retrospect, the following developments proved significant:
1) Publication of Armstrong's (1972) views on Tertiary denudational

faulting in the Nevada hinterland and subsequent tests which supported his views (Coney, 1974; Todd, 1973), 2) Discovery of the large number of, and great extent of, metamorphic complexes in Arizona and recognition of their Tertiary age (Davis, 1973). Also important was the realization that these metamorphic culminations in Arizona were not in a hinterland behind a thrust belt of any age. This cast suspicions on the presumed genetic link between the northern complexes and the thrust belts to the east, 3) Finally, the realization that most of the known complexes throughout the Cordillera had very similar lithologies and structures suggested a common origin.

It is quite remarkable how serendipitously the present stage of knowledge evolved. It is also instructive to note how scattered early work, which were seeds of what was to come, went largely unnoticed and have only recently flowered to significance and appreciation, albeit still not completely understood. Such work includes Anderson's (1971) study of Tertiary listric normal faulting south of Lake Mead and a number of early studies in Arizona and in the Nevada hinterland (for example see Damon and others, 1963; Drewes, 1964; Moores and others, 1968).

It will be obvious to all readers that considerable controversy still exists and there are major problems surrounding the complexes which need to still be resolved. This is only normal for a new and complicated large-scale tectonic feature. At the same time, this situation adds to the excitement and clearly indicates need for continued study. A number of novel and somewhat contrasting models have been recently proposed to explain the new data surrounding the complexes and there are certainly more to follow. This is also only natural and need not be taken too seriously at this time.

The major contribution of all the recent work is to signal an anomalous petro-tectonic assemblage, now recognized from southern Canada to northwestern Mexico, which has an almost certain Early to Middle Tertiary evolutionary history. The evidence seems to indicate that a significant part of this assemblage was produced by extensional tectonics and that, whatever the process was, it post-dates Sevier-Laramide compressional thrusting and pre-dates Late Tertiary Basin and Range extensional block faulting. It has clearly been superimposed on and confused with earlier, mainly Mesozoic tectonic events.

The most important controversy still remaining is the origin and significance of the mylonitic gneiss fabrics so characteristic of the basement cores of the complexes. Without question, the dramatic resemblance of these fabrics to those produced along deep-seated thrust faults in other parts of the world is an obstacle to what might be called a new consensus. Some workers

have concluded that even this aspect of the complexes was produced by Tertiary regional extension, but other workers conclude that the metamorphic basement and all its fabrics are significantly older than the upper-plate dislocations and listric normal faulting and genetically unrelated to them. As has been mentioned earlier in this chapter, many prefer to relate the metamorphism and the mylonitic fabrics to earlier periods of major Sevier-Laramide compressional tectonics and would even argue that most of the décollement and the upper-plate structures date from these earlier deformations as well.

As of this writing the main interpretations of the origin and significance of Cordilleran metamorphic core complexes can be summarized as follows:

1. The complexes are mainly Jurassic to Sevier-Laramide (mostly Mesozoic) in age. The metamorphic basement terranes are a deep-seated infrastructure (gneiss domes) and the décollements are simply bedding-plane thrust faults both of which are genetically related to Sevier-Laramide foreland thrust faulting. This is the classic interpretation of the complexes and of the Cordilleran hinterland. Most who take this view acknowledge minor later Tertiary disruption and local gravity slides along the earlier fault planes, but prefer to minimize their importance. This position is perhaps best represented by the early work of Misch (1960), Hose and Danes (1973), and Roberts and Crittenden (1973).
2. The complexes are mainly Early to Middle Tertiary in age. In this view both the mylonitic fabrics and late metamorphism and the décollements and listric normal faulting are genetically related to Early-Middle Tertiary mainly extensional tectonics and post-date Sevier-Laramide compressional tectonics. Those who take this position acknowledge an older metamorphic and structural history recorded in most of the complexes as certainly of mainly Mesozoic origin, but feel it is significantly overprinted by the Tertiary events. This is the new position that began to emerge after 1970 and has been particularly emphasized in the publications of Davis and Coney (1979), Coney (1979) and Rehrig and Reynolds (1980).
3. The complexes are truly hybrid and of both Sevier-Laramide and Early-Middle Tertiary age. In this view all the basement fabrics including the later mylonitic fabrics are of compressional origin, such as deep-seated thrust faults, and mainly related to Sevier-Laramide events, or perhaps to some late-Laramide "compressional" event. The décollements and listric normal faulting in the cover terrane are acknowledged as Tertiary, but genetically unrelated to the earlier basement terrane. In this view the co-linearity

of the basement lineation and its interpreted movement picture and the movement picture derived from upper plate structures is purely accidental. This position has been particularly emphasized most recently by Davis and others (1980).

As has been mentioned earlier most are agreed that most of the dislocation and décollement, particularly the listric normal faulting in cover rocks, clearly brittlely disrupt the more ductile mylonitic basement fabrics (Coney, 1974). Where the upper plate structures include Tertiary rocks all will have to agree that some of this late brittle deformation is Tertiary in age. It is to be emphasized that this relationship of involvement of Tertiary rocks has been demonstrated in the majority of the complexes. The main dilemma is whether the earlier mylonitic basement fabrics, in spite of being clearly older, are genetically related or totally unrelated to the later brittle Tertiary events.

Those who choose to genetically relate the two terranes emphasize the co-linearity in kinematics of the two terranes and also emphasize the fact that the mylonitic fabrics are superimposed on young rocks, particularly the Tertiary plutons emplaced in the basement terrane. As has been discussed earlier, many of these plutons are rather well dated as early Tertiary and some appear to be as young as middle Tertiary. Those who choose to not genetically relate the two terranes emphasize the age differences and contrast in mechanical behavior. The co-linearity in kinematics is thus a fortuitous accident.

Perhaps the trap is in what might be called argument based on classic geologic reasoning from age data. If all the mylonitic basement is mainly as old as some of the older Tertiary plutons affected and if all of the brittle deformation is younger than the youngest cover rocks, we are seemingly dealing with two separate and presumably unrelated events. If the mylonitic fabrics are as old and as young as the age-range in affected Tertiary plutons and if the listric normal faulting is a growth faulting and as old and as young as the age-range in Tertiary sediments and volcanics affected, the seemingly separate events could overlap and merge into a continuum of deformation ranging from Eocene to Late Miocene in age.

This is not the place to attempt to resolve the genetic dilemma surrounding Cordilleran metamorphic core complexes. Our main concern in this report is to present the distribution, character, and geologic-tectonic setting and history of these enigmatic and newly recognized features in the North American Cordillera. Hopefully this will provide a base upon which the

assessment of their economic as well as scientific potential can be carried out. There is clearly much work yet to do. It is particularly obvious that much more work needs to be done on the petrology, structure, and geochronology of the basement terranes of the complexes. There is also much need for detailed sedimentologic and stratigraphic studies in the Tertiary sediments and volcanics of the cover terrane to better document its role in the core complex process. Similarly, the plutonic manifestation of the complexes warrants much detailed petrologic and geochemical study. This is particularly true of the so-called "two-mica" granites which are so common in the core complex belt.

If the evidence for extension is recognized and acknowledged, the belt of complexes takes on the character of an irregular, elongate and sinuous large-scale pull-apart terrane extending the length of the Cordillera at least from southern Canada into northwestern Mexico. The only large-scale phenomenon it seems to be associated with is the region that lies above the first flattened, low-dipping, Laramide Benioff zone which then steepened and collapsed during Early to Middle Tertiary time. The entire metamorphic core complex process, as either separate distinct phases or as a continuum, probably endured 30 to 40 m.y. between about 55 m.y. and 15 m.y. in Early to Middle Tertiary time.

Just why this apparent extension on a regional scale occurred when it did is not entirely clear. It certainly began during Farallon-North America plate convergence at least 10 to 30 m.y. before even initial contact between Pacific and North America plates and resulting growth of the San Andreas-Basin and Range transform-transpressive rifting (Fig. 4). It did not take place behind a magmatic arc; it took place within a magmatic arc. But this magmatic arc was a very special one, perhaps the result of extreme flattening of Laramide Benioff zones followed by a massive collapse and resulting retrograde 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.