

# Evolving Geographic Patterns of Cenozoic Magmatism in the North American Cordillera: The Temporal and Spatial Association of Magmatism and Metamorphic Core Complexes

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Four maps are presented here that show the location and extent of magmatic fields between eastern Alaska and northern Mexico during the successive time intervals of 55-40, 40-25, 25-10, and 10-0 Ma, and four others show the distribution of metamorphic core complexes during the same Cenozoic time intervals. The maps are based on U.S. Geological Survey and Canadian Cordilleran data bases containing about 6000 isotopic dates and extensive literature review. For nearly 60 Ma the development of metamorphic core complexes has coincided with the locus of areally extensive and voluminous intermediate-composition magmatic fields. The association is suggestive of a close link between magmatism and core complex formation, namely that magma directly and indirectly lowers the strength of the crust. Magmatism thus controls the location and timing of core complex formation. The stresses responsible may be inherited from Mesozoic crustal thickening, locally created by uplift and magmatic thickening of the crust, and imposed by the global pattern of plate motions and driving forces. Since the Miocene, rates of magmatism, extension, and core complex formation have declined. The modern Basin and Range province is not a suitable model for the situation that existed during major magmatic culminations. The singular event of early Miocene time, the merging of two large magmatic fields, extinguishing the Laramide magmatic gap, explains several disconnected observations: the hyperextension episode of the Colorado River corridor, rapid reorientation of stress patterns across much of western North America, and subsequent rapid tectonic movements in California. Magma-triggered breakup of western North America lithosphere coincided with development of the San Andreas transform system. Thermal destruction of the Laramide magmatic gap created a California "microplate" about 22 Ma ago that moved rapidly away from North America. Thus two plate tectonic processes, thermal destruction of the lithosphere "bridge" and northward growth of a transform system, interacted to produce Miocene and later tectonic patterns and events.

## INTRODUCTION

There have been many reviews of the Cenozoic magmatic evolution of the western United States [Armstrong *et al.*, 1969; McKee, 1971; Lipman *et al.*, 1971; Christiansen and Lipman, 1972; Lipman *et al.*, 1972; Armstrong and Higgins, 1973; Snyder *et al.*, 1976; Cross and Pilger, 1978; Armstrong, 1978; Coney and Reynolds, 1977; Stewart and Carlson, 1978; Christiansen and McKee, 1978; Luedke and Smith [1979a, 1979b, 1981, 1982, 1983, 1984, 1986], Luedke *et al.* [1983]; Lipman, 1980; Ewing, 1980; Smith and Luedke, 1984; Mutschler *et al.*, 1988], southeastern Alaska [Brew, 1988] and some broad overviews of the Cenozoic magmatic history of western Canada [Souther, 1967, 1970, 1977; Noel, 1979]. Nevertheless, there has never been a single presentation of the distribution of magmatic activity over the entire Cordilleran region extending from southeastern Alaska to the Mexican border (Figure 1). None of the previous reviews has been based on as large a data base as we have assembled. Our compilation for the Cenozoic is an outgrowth of work for another paper [Armstrong and Ward, 1991] that synthesized the Late Triassic to early Cenozoic (230-55 Ma) magmatic history of

the Cordilleran region and discussed the significance of those evolving magmatic patterns for the Western Interior Basin. The mandate of the first paper did not include the Cenozoic, but the abundant data on age and distribution of magmatism did not stop in the early Cenozoic. In fact, the time and space distribution of Cenozoic magmatism is richly and accurately documented. It was almost no extra effort to continue the compilation, done up to 55 Ma ago for the Western Interior Basin paper, to the present. Moreover, there were other interesting stories to tell. The maps that are central to both papers were created together from a large body of recently assembled information. Together they provide a cinematic image of evolving magmatic patterns, presented in uniform graphic style, for Late Triassic to present time. In discussing magmatism we include data from both intrusive and extrusive igneous rocks. For the Cenozoic the data base is weighted toward volcanic rocks, whereas in the Mesozoic, intrusive rocks are predominant. Where studied in detail, intrusive bodies and thick lava accumulations are coincident in time and are essentially coextensive. Distal volcanic ash layers must of course be disregarded in mapping the extent of magmatically active areas.

For many years the U.S. Geological Survey has been building a Radiometric Age Data Bank (RADB) [Zartman *et al.*, 1976]. Coverage has gradually been compiled state by state. Ward [1986, and unpublished manuscripts, 1986, 1988] recently assembled the state files for the entire

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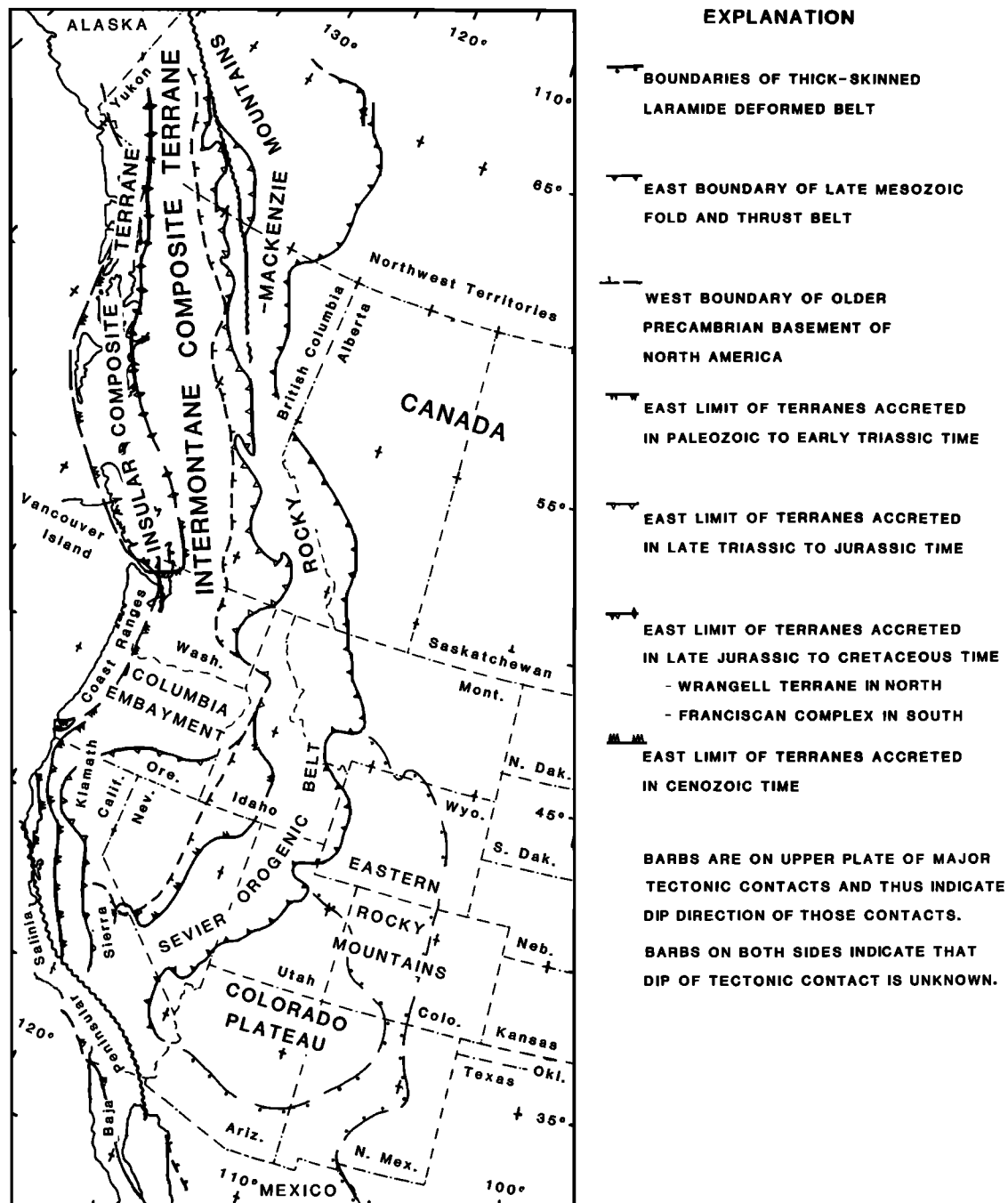


Fig. 1. Map showing tectonic belts and geographic base for Plates 1-4 [after Armstrong and Ward, 1991]. Cenozoic tectonic and magmatic features are labeled on subsequent Figures.

western United States and produced a series of computer-plotted maps showing distribution of dated rocks during a sequence of time intervals. He discussed the observed magmatic history and possible plate tectonic explanations, with particular emphasis on the Cenozoic patterns in the western United States.

The Canadian Isotopic Date Data File was converted to computer-readable form by Bentzen [1987], with support from the Geological Survey of Canada and British Columbia Ministry of Energy, Mines and Petroleum Resources, during the winter of 1986-1987. We merged the two data banks to provide reasonably comprehensive coverage for the entire North American Cordillera between Mexico and Alaska (Figure 1).

There are 11,500 age determinations plotted on the maps that we prepared spanning the last 230 Ma in the Cordillera. About 50% of those are within the 55-0 Ma time interval that we focus on here. The data presented in this paper represent a fourfold increase in the number of isotopic dates compiled since the last similar syntheses [Snyder *et al.*, 1976; Cross and Pilger, 1978], but there are certain necessary disclaimers. The data are not complete for many reasons. The intent of the compilers of RADB was to include only dates published in major journals with supporting details on analytical techniques, decay constants used, and observed consistency with other dates and geologic relationships. The Canadian file, in contrast, contains many unpublished, or grey literature, items. Some large regions,

such as northern Washington, northern British Columbia, and the Yukon, are less well studied and may not be properly represented in this type of summary. Young deposits may obscure the older record in areas such as the Intermontane Belt of British Columbia, Columbia Plateau, Snake River Plain, and Puget-Willamette Trough. Neither file is entirely up to date or complete. For example, the Canadian file on magnetic tape has been updated only to late 1984, did not have unpublished data from universities other than the University of British Columbia or from the Geological Survey of Canada, and was known to be incomplete with respect to dates for ash layers in the Western Interior Basin. The RADB was last updated in 1986. There are unknown amounts of grey literature, unpublished data, and overlooked data that result in incomplete representation of the information that exists at any time. Probably another 20-30 % could be added today to the data collection. Both large files will contain errors and misleading dates. The Canadian file has been fairly heavily edited to flag any dubious result or results giving dates for metamorphic events or partially reset dates. It is clear from study of the raw plots that the U.S. file contains many questionable items; these have been assigned to the "ash layer or dubious" category, which are shown as small dots on the maps. An effort to bring both files completely up to date and to edit them exhaustively would involve years of scholarly work and is beyond the limits of this study. This is thus only a progress report on an unending process of data generation, systematization, and synthesis. Our goal here is to describe the time and space distribution of Cenozoic magmatism and focus on the implications for Cenozoic metamorphic core complexes and continental deformation.

#### PROCEDURE

From the merged computer files [Ward, 1986; Armstrong, 1988], two series of maps were plotted using Albers equal-area conic projections: one from 46° to 67.5°N (western Canada and adjacent parts of Alaska and the western United States), and the other from 28° to 50°N (western United States and adjacent parts of Canada and Mexico). All dates used were calculated or recalculated using International Union of Geological Sciences (IUGS) conventional decay constants [Steiger and Jäger, 1977]. One pair of maps was created for each 5 Ma time interval from 225 to 0 Ma. On the original plots, distinction was made between dates for intrusive rocks and different types of extrusive rock (mafic, felsic, pyroclastic). There was also indication of dates that were no more than minimum or maximum values for the time of emplacement or those of dubious significance.

These initial figures were then used to construct histograms and composite time interval maps to decide what simplified time groupings were meaningful, with distinction based on magmatic lulls or minima and changes in geographic pattern. For the final choice of composite time intervals, a series of maps for the entire Cordillera between Mexico and Alaska was drafted (Figures 3 to 8 of Armstrong and Ward, [1991] and Plates 1-4 of this paper) showing the distribution of magmatism during each of the composite time intervals. These maps are the basis for the following discussion.

As a general rule, distal ash layers in sedimentary basins have been deemphasized. The magmatic belts shown are intended to be the areas where magmatism occurred, not the entire areas into which volcanic products were transported by Earth surface processes.

The plates are designed to show the extent of magmatism within a time interval and significant changes between and during time intervals. Single-shafted arrows facilitate the comparison of successive plates by showing the movement

of magmatic belt boundaries from the previous interval to the one being illustrated. Solid symbols show age determinations belonging to the early part of time intervals, and open symbols show the age determinations in the last 5-10 Ma of the intervals. This allows changes within any interval to be directly visualized. These within-interval changes are highlighted by larger outlined arrows. Some larger arrows are based on literature discussions of the magmatic evolution of specific areas. Where open and closed age determination symbols mingle on the maps, magmatism persisted throughout the time interval for the map. The outlines of magmatic areas on Plates 1-4 have been extensively edited to conform to literature descriptions of magmatic activity in many areas where dates are not shown.

It has not been practical to compile volumetric and petrochemical data for this review. The papers cited in the introduction contain abundant information on petrochemistry (especially Christiansen and Lipman [1972], Lipman *et al.* [1972], Luedke and Smith [1979a, 1979b, 1981, 1982, 1983, 1984, 1986], Luedke *et al.* [1983], Mutschler *et al.* [1988]). In this paper we make only passing mention of the petrochemical character of magmatic fields.

Throughout this discussion we accept the Decade of North American Geology (DNAG) time scale calibration [Palmer, 1983] as most up-to-date, accurate, and conventional. A revision of the Harland *et al.* [1982] time scale [Harland *et al.*, 1990] makes no substantial departures from the DNAG scale, in spite of an enlarged data base.

#### THE TIME INTERVALS USED FOR COMPILATION: THE CHANGING TEMPO OF MAGMATISM

Plate 1 shows the distribution of magmatism in the first time interval illustrated in this paper, from 55 to 40 Ma. On histograms of Cordilleran magmatic activity for the region north of latitude 42°N [e.g., Armstrong, 1974a; Armstrong *et al.*, 1977; Armstrong, 1988] this time interval brackets a prominent magmatic episode for which the composite name "Kamloops-Challis-Absaroka" is used. This episode began in Canada and northern Washington about 60 Ma ago, culminated over a large region at 50±1 Ma and was in decline by 45 Ma. By 40 Ma, magmatism within much of the previously active region had ceased, and a southward transgression of magmatism into the future Basin and Range Province had begun [Lipman *et al.*, 1972; Armstrong and Higgins, 1973].

The time-subdivisions of the Cenozoic after 40 Ma are somewhat arbitrary. Although magmatism is always locally episodic, the episodes blur into a continuum of magmatic activity when the whole Cordilleran region is viewed during later Cenozoic time. No comprehensive lulls punctuate the Cenozoic magmatic history. In contrast with the Mesozoic [Armstrong and Ward, 1991], the discussion of Cenozoic history relegates talk of magmatic arcs and episodes to local features and becomes dominated by description of migrating patterns of activity, time-transgressive shifts of pattern, waxing and waning magmatic loci, persistent loci, and magmatic gaps. A fine-scale episodicity has been discussed for the Cascade to Snake River Plain region [McBirney *et al.*, 1974; Armstrong, 1975], but it is not clear from the larger body of isotopic data that we reviewed how applicable those details (Columbian, 16-13 Ma; Andean 10-9 Ma; Fijian 6-3 Ma; and Cascade 1-0 Ma episodes of McBirney [1978]) are to the Cordilleran region as a whole. Priest [1989] is even skeptical of their application in the Cascades in central Oregon. There does appear to be a reduction in magmatic activity to a minimum at about 40 Ma before an increase to a weak maximum in Oligocene time (about 35-30

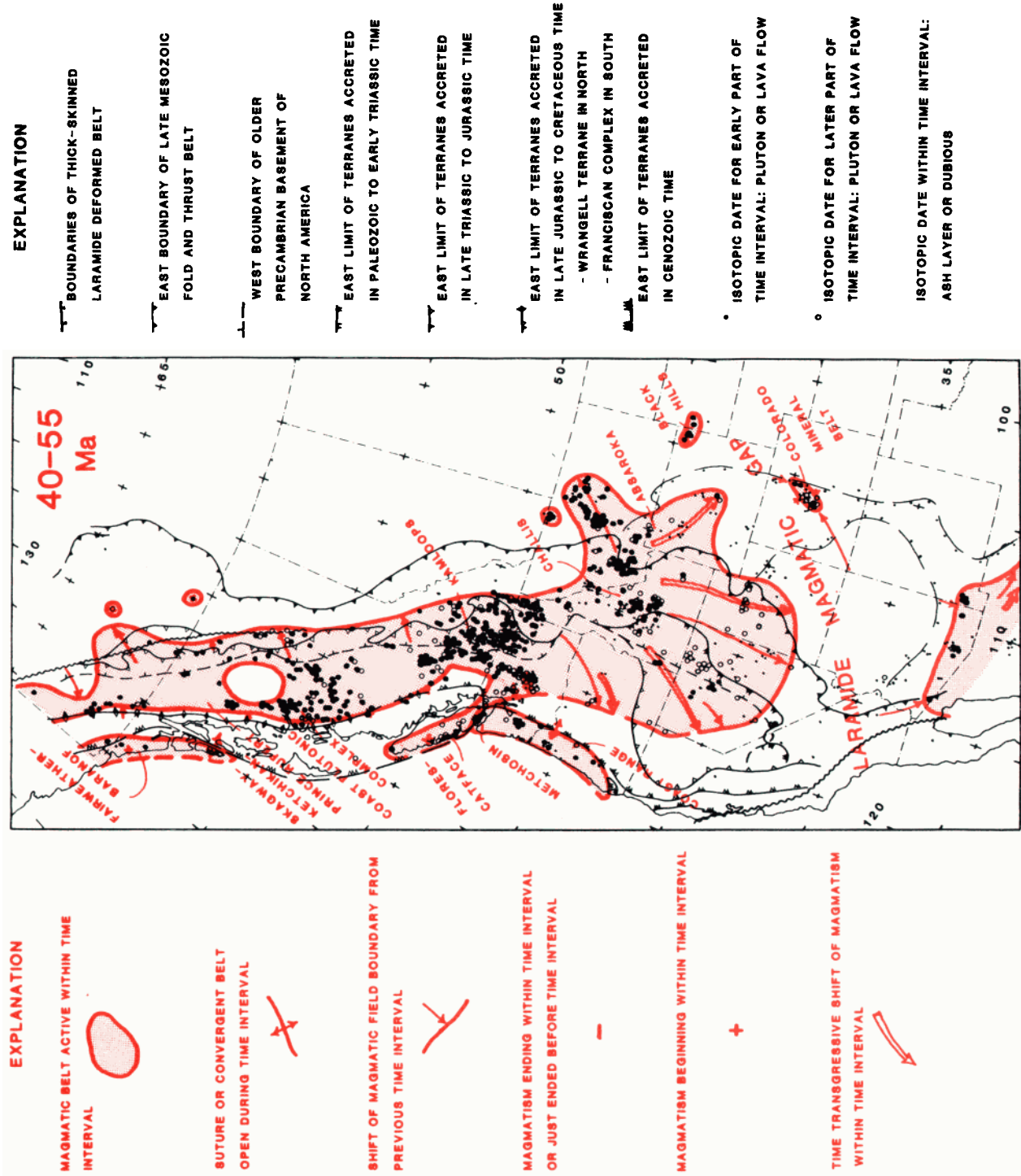
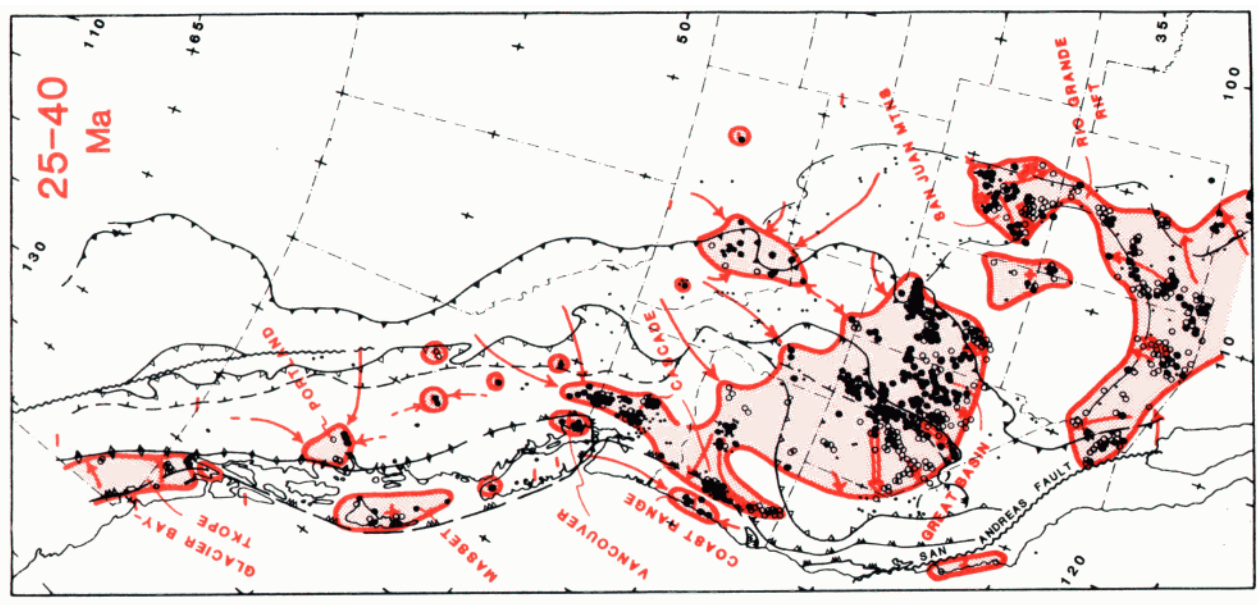
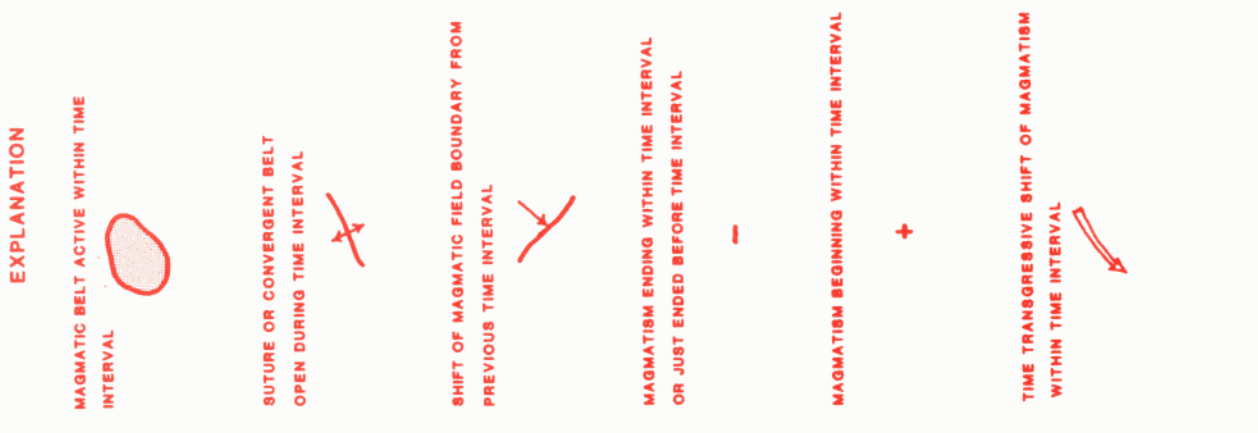


Plate 1. Distribution of isotopic age determinations for the time interval 40-55 Ma ago (early and middle Eocene time). Red indicates extent of magmatic activity for the time interval and time-transgressive trends in the distribution of magmatic activity.













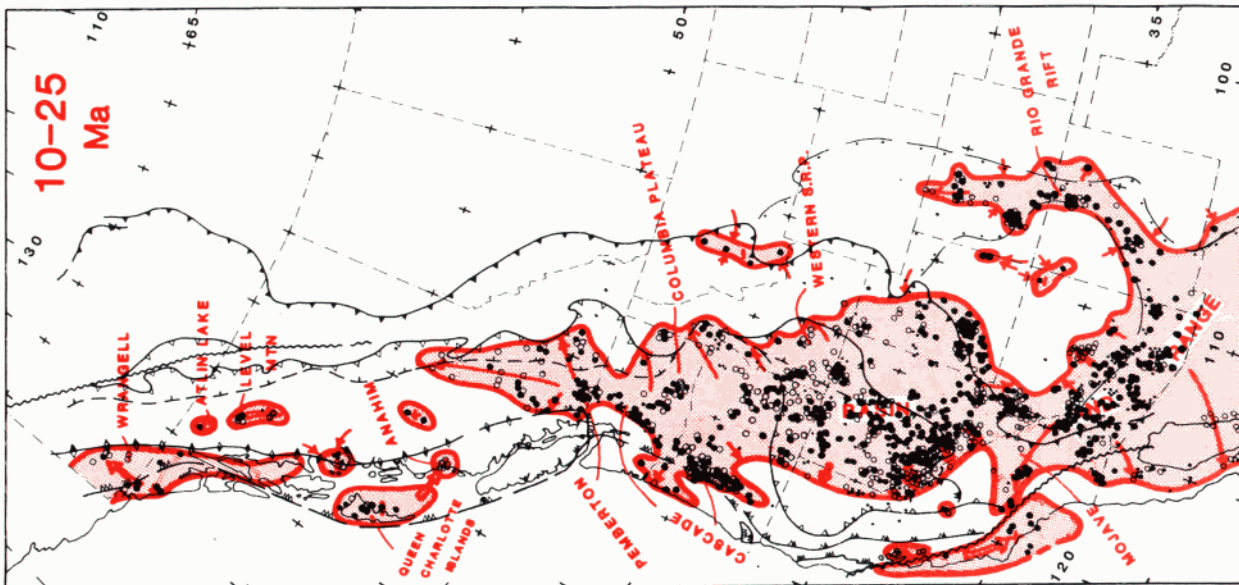
- EXPLANATION**
-  BOUNDARIES OF THICK-SKINNED LARAMIDE DEFORMED BELT
  -  EAST BOUNDARY OF LATE MESOZOIC FOLD AND THRUST BELT
  -  WEST BOUNDARY OF OLDER PRECAMBRIAN BASEMENT OF NORTH AMERICA
  -  EAST LIMIT OF TERRANES ACCRETED IN PALEOZOIC TO EARLY TRIASSIC TIME
  -  EAST LIMIT OF TERRANES ACCRETED IN LATE TRIASSIC TO JURASSIC TIME
  -  EAST LIMIT OF TERRANES ACCRETED IN LATE JURASSIC TO CRETACEOUS TIME
    - WRANGELL TERRANE IN NORTH
    - FRANCISCAN COMPLEX IN SOUTH
  -  EAST LIMIT OF TERRANES ACCRETED IN CENOZOIC TIME
  -  ISOTOPIC DATE FOR EARLY PART OF TIME INTERVAL: PLUTON OR LAVA FLOW
  -  ISOTOPIC DATE FOR LATER PART OF TIME INTERVAL: PLUTON OR LAVA FLOW
  -  ISOTOPIC DATE WITHIN TIME INTERVAL: ASH LAYER OR DUBIOUS

Plate 2. Distribution of isotopic age determinations for the time interval 25-40 Ma ago (late Eocene to latest Oligocene time). Red indicates extent of magmatic activity for the time interval and time-transgressive trends in the distribution of magmatic activity.



**EXPLANATION**

MAGMATIC BELT ACTIVE WITHIN TIME INTERVAL



SUTURE OR CONVERGENT BELT OPEN DURING TIME INTERVAL



SHIFT OF MAGMATIC FIELD BOUNDARY FROM PREVIOUS TIME INTERVAL



MAGMATISM ENDING WITHIN TIME INTERVAL OR JUST ENDED BEFORE TIME INTERVAL



MAGMATISM BEGINNING WITHIN TIME INTERVAL



TIME TRANSGRESSIVE SHIFT OF MAGMATISM WITHIN TIME INTERVAL



**EXPLANATION**

BOUNDARIES OF THICK-SKINNED LARAMIDE DEFORMED BELT

EAST BOUNDARY OF LATE MESOZOIC FOLD AND THRUST BELT

WEST BOUNDARY OF OLDER PRECAMBRIAN BASEMENT OF NORTH AMERICA

EAST LIMIT OF TERRANES ACCRETED IN PALEOZOIC TO EARLY TRIASSIC TIME

EAST LIMIT OF TERRANES ACCRETED IN LATE TRIASSIC TO JURASSIC TIME

EAST LIMIT OF TERRANES ACCRETED IN LATE JURASSIC TO CRETACEOUS TIME  
- WRANGELL TERRANE IN NORTH  
- FRANCISCAN COMPLEX IN SOUTH

EAST LIMIT OF TERRANES ACCRETED IN CENOZOIC TIME

ISOTOPIC DATE FOR EARLY PART OF TIME INTERVAL: PLUTON OR LAVA FLOW

ISOTOPIC DATE FOR LATER PART OF TIME INTERVAL: PLUTON OR LAVA FLOW

ISOTOPIC DATE WITHIN TIME INTERVAL: ASH LAYER OR DUBIOUS

Plate 3. Distribution of isotopic age determinations for the time interval 10-25 Ma ago (latest Oligocene to early late Miocene time). Red indicates extent of magmatic activity for the time interval and time-transgressive trends in the distribution of magmatic activity. Some adjustments to the magmatic patterns defined by data in the computer file have been made on the basis of maps of *Luedke and Smith* (1979a, 1979b, 1981, 1982, 1983, 1984, 1986), *Luedke et al.* [1983], *Stanley* [1987], *Guffanti and Weaver* [1988], and *Brew* [1988].

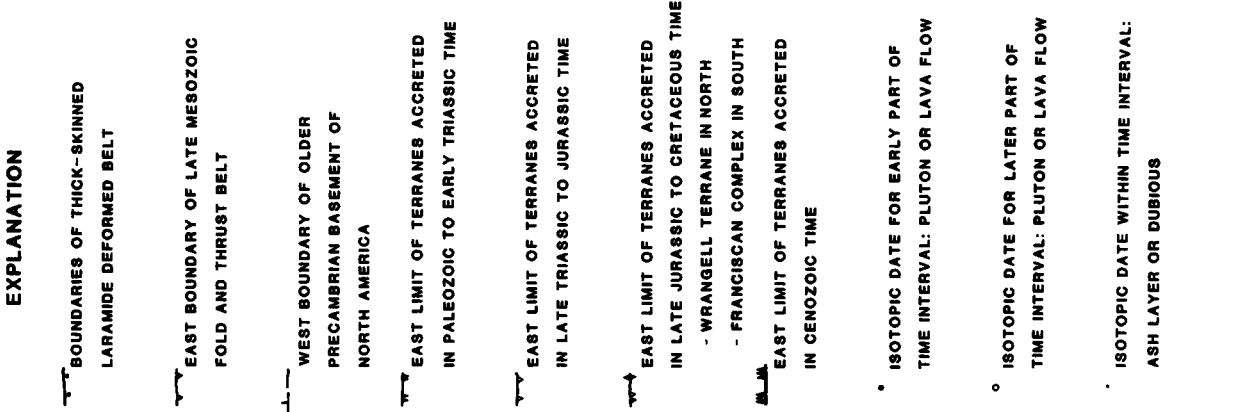
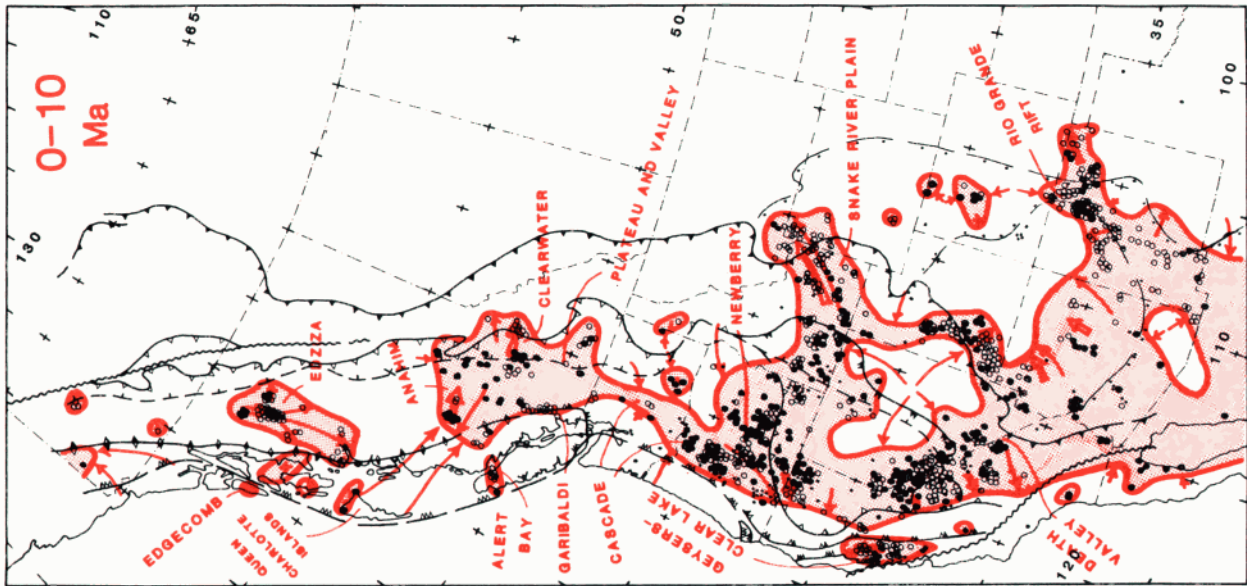
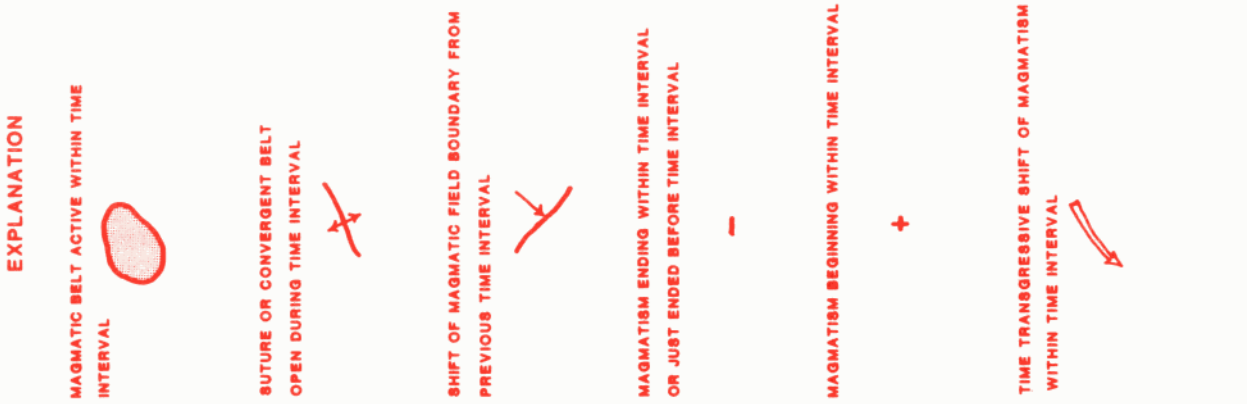


Plate 4. Distribution of isotopic age determinations for the time interval 0-10 Ma ago (late Miocene to Holocene time). Red indicates extent of magmatic activity for the time interval and time-transgressive trends in the distribution of magmatic activity. Some adjustments to the magmatic patterns defined by data in the computer file have been made on the basis of maps of *Laedke and Smith* (1979a, 1979b, 1981, 1982, 1983, 1984, 1986), *Laedke et al.* [1983], *Stanley* [1987], *Guffanti and Weaver* [1988], and *Brew* [1988].

Ma], the ignimbrite flareup, followed by a steady decline toward the end of the Cenozoic. The Oligocene maximum was previously emphasized by Gilluly [1973] because his data base was confined largely to Basin and Range latitudes. White and McBirney [1978] and Verplank and Duncan [1987] discuss the general decline since 35 Ma in the Cascade region. The voluminous basalt, erupted between 17 and 14 Ma in the Columbia Plateau region [Christiansen and McKee, 1978; Barrash and Venkatakrishnan, 1982; Barrash et al., 1983], is a local anomaly, which is also evident in increased magmatism in adjacent areas but not over the entire Cordilleran region. In the Basin and Range and Rio Grande Rift areas a lull at about 17 Ma has been reported by several workers [McKee et al., 1970; Chapin and Seager, 1975; Aldrich et al., 1986]. In many areas there is evidence of a Pliocene lull followed by accelerated magmatism during the last 2-3 Ma [McBirney et al., 1974; Armstrong, 1975; Smith and Luedke, 1984], but this is a detail not resolved in our compilation. Moreover, because rocks of very young age are difficult to date accurately by K-Ar, they are probably underrepresented in the data base.

For Plates 2 to 4 we have somewhat arbitrarily chosen time intervals of 40-25, 25-10, and 10-0 Ma. The 40-25 Ma interval captures the main episode of ash flow volcanism in the Great Basin, southern Arizona, and New Mexico and in the Eastern Rocky Mountains, as well as the establishment of the Cascade volcanic arc. Between 25 and 10 Ma the most dramatic magmatic event was the eruption of basalts in the Columbia Plateau region. Over much of the Cordillera south of the Colorado Plateau this was also the time of change from intermediate-composition ash flow to bimodal, fundamentally basalt eruptions [Lipman et al., 1971; Christiansen and Lipman, 1972]. Basin and Range and Rio Grande rifting were prominent developments that accompanied the change in magmatic style. The magmatic patterns from 10 Ma to the present are essentially those of the present day, with only evolutionary modifications.

#### REVIEW OF MAGMATIC EVOLUTION

##### *Prior to 55 Ma*

We begin this synthesis with a brief review of magmatic patterns just before 55 Ma that are discussed by Armstrong and Ward [1991]. Their figures have the same format as those presented here. A major turning point in Cordilleran tectonics occurred about 55 Ma ago. During the Mesozoic, magmatism in the Cordillera had been episodic on a scale of tens of million years and had been distributed in long linear belts parallel to the entire length of the continental margin. Between 85 and 55 Ma the behavior of U.S. and Canadian sectors departed from this simple pattern. In Canada the magmatic belt remained essentially continuous and parallel to the continental margin. A weak culmination of magmatic activity at about 80 Ma was followed by a decline to a pronounced minimum about 65 Ma, close to the Cretaceous-Tertiary boundary [Armstrong, 1988]. By 60 Ma the tempo of magmatism in the north accelerated rapidly, and at some time between 60 and 55 Ma the tectonic style north of 42° reversed dramatically, from crustal shortening that constructed the fold and thrust belt of the Rocky and Mackenzie Mountains to crustal extension and strike-slip faulting that continued to be the dominant tectonic themes through the rest of the Cenozoic [Ewing, 1980; Okulitch, 1984; Journeay, 1986; Carr, 1989].

In the United States south of 42°, the continuity of the Mesozoic magmatic belt was disrupted after 80 Ma by the Laramide magmatic gap [Armstrong, 1974b], which spread over California, Nevada, and Utah as magmatism shifted

inland to the Rocky Mountain region and greatly diminished in intensity [Coney and Reynolds, 1977]. The magmatic gap was to remain a prominent feature of Cordilleran magmatic patterns until about 22 Ma ago.

Laramide-style uplifts of basement rock in the Montana and Wyoming Rocky Mountains appear to have ceased to rise by 55 Ma. In Wyoming the uplifts are unconformably overlain by volcanic rocks and volcanoclastic sedimentary rocks of 55-50 Ma age [Dickinson et al., 1988]. Farther south, the uplifts in the Southern or Colorado-New Mexico Rocky Mountains may have continued to rise actively until somewhat later, until about 40 Ma according to Dickinson et al. [1988]. By 55 Ma the Laramide magmatic episode had virtually ended in Arizona [Damon and Mauger, 1966], had contracted to a persistent magmatic locus in central Colorado, and was waning in the Black Hills region of South Dakota and Wyoming [Shafiquillah et al., 1980; Snyder et al., 1976; Mutschler et al., 1988].

##### *40-55 Ma (Plate 1)*

The Kamloops-Challis-Absaroka volcanic episode [Armstrong, 1974a] dominates this time interval. At its culmination this magmatic belt extended from southern Idaho to Alaska. Its western magmatic front is sharp and precisely located in the Coast Plutonic Complex of British Columbia. It generally varies in composition from calc-alkaline on the west to distinctly alkaline on the east, but the chemical patterns are locally complicated [Larsen, 1940; Lipman et al., 1971, 1972; Ewing, 1981; Holder and Holder, 1988; O'Brien et al., 1991]. The curvature of the axis of the magmatic belt into central Montana is a notable feature, partly inherited from the Laramide magmatic pattern, a locus of exceptionally intense magmatism that swept northeastward from the Sierra Nevada into central Montana over the time interval 80-65 Ma [Armstrong and Ward, 1991]. After 45 Ma, magmatism in the Kamloops-Challis-Absaroka belt waned dramatically, and at the same time a southward transgression of intermediate-composition magmatism, including voluminous ash flows from calderas, began [Lipman et al., 1972; Armstrong and Higgins, 1973]. This is shown by the larger outlined arrows on Plate 1. In Alaska the name "Skagway-Ketchikan-Prince Rupert" [Brew, 1988] is used for a part of the much larger Paleogene magmatic belt.

Dying remnants of Laramide magmatic fields show on Plate 1 in the Black Hills (where a westward movement of activity is hinted at by a short arrow), in central Colorado (last gasp of the Laramide episode in the Colorado mineral belt), and in southern Arizona (end of the Laramide episode of Damon and Mauger [1966]). Along the southern edge of the map the Laramide activity was followed by a shift of magmatism into southwestern Texas in middle Eocene time, about 47-40 Ma ago [Wilson et al., 1968; Hoffer, 1970; Henry and McDowell, 1986]. This completed the late Mesozoic to early Cenozoic eastward sweep of magmatism noted by Coney and Reynolds [1977].

The remaining magmatic features of Plate 1 are three belts along the western margin of the continent. The southernmost is the Coast Range belt of basaltic island volcanos of Oregon and Washington [Duncan, 1982] and Metchosin belt of southern Vancouver Island [Muller, 1980; Massey, 1986]. This region was not firmly attached to North America at the time of construction of the older volcanoes (basalt accumulation spanned 62 to 41 Ma) [Duncan, 1982; McElwee and Duncan, 1984; Heller et al., 1987]. These volcanic accumulations are notable for the large and variable tectonic rotations that have accumulated during Cenozoic time [Wells and Heller, 1988]. The amount



of northward motion of the component parts of this belt with respect to North America is uncertain. A northward movement of a few hundred kilometers is suspected but difficult to quantify [Beck, 1984]. Accretion occurred in middle Eocene time, about 50-42 Ma ago [Muller, 1980; Heller and Ryberg, 1983; Armentrout, 1987].

The Flores Volcanic-Catface Intrusive belt on Vancouver Island [Carson, 1973; Isachsen, 1987; Massey and Armstrong, 1989] and the Fairweather-Baranof belt in Alaska [Brew, 1988] are continent-margin calc-alkaline magmatic belts of enigmatic tectonic setting. The 55-40 Ma magmatic rocks on Vancouver Island and in the foothills of the Cascade Range in Washington appear to be almost exactly coincident in age with the inland Kamloops-Challis-Absaroka magmatic belt. The Alaskan magmatic belt is the same, to slightly younger in age (49-39 Ma according to Brew [1988]). Cowan [1982] suggested that the Alaskan Eocene magmatic belt is offset by strike-slip faulting during later Cenozoic time from original continuity with the geologically similar Vancouver Island Eocene magmatic belt.

#### 25-40 Ma (Plate 2)

By 35 Ma [Smith et al., 1980; Priest and Vogt, 1983; Richards and McTaggart, 1976] the Cascade volcanic arc became established close to its present location in Oregon, Washington, and southern British Columbia. It remained a persistent magmatic feature for the rest of Cenozoic time, undergoing only modest shifts in position and variations in intensity [McBirney et al., 1974; Armstrong, 1975; Armstrong et al., 1985].

The southward transgression of an east-west trending belt of magmatism in Nevada and Utah is a dominant feature of Plate 2. This transgression was first documented by Armstrong et al. [1969] and Armstrong [1970] and later discussed by Lipman et al. [1972], Noble [1972], Stewart et al. [1977], and Burke and McKee [1979], among others.

Magmatic activity in the San Juan Mountains and nearby areas in Colorado and in the Basin and Range and Rio Grande rift areas of Arizona and New Mexico expanded dramatically at the same time as the Great Basin ignimbrite flareup, but the two major Oligocene magmatic fields remained separated until after 25-22 Ma by the Laramide magmatic gap. Over the time interval illustrated, the Colorado and Arizona-New Mexico magmatic fields expanded independently and eventually merged into one as the Rio Grande rift began its development. As part of this expanding activity, magmatism in southern Arizona migrated westward at 3-4 cm/a [Shafiqullah et al., 1980]. Several Colorado Plateau laccolithic centers and diatremes were emplaced, mostly later in this time interval, in an alkalic, small-volume, scattered-center magmatic field that almost linked the large southern (Arizona-Colorado) and northern (Nevada-Utah) magmatic regions [Naeser, 1971; Laughlin et al., 1986; Sullivan, 1987].

The other notable features of magmatism in the western United States on Plate 2 (25-40 Ma time interval) are the southwestern Montana locus of persistent magmatism and nearby singular magmatic spots and the area of late stage basalt and alkalic magmatism of the Oregon Coast Range [McElwee and Duncan, 1984].

In southwestern California, west of the San Andreas fault, magmatism started only at the very end of the time interval for Plate 2 and is thus more reasonably included in the next time interval to be discussed.

Oligocene magmatism in Canada and southwestern Alaska was restricted in volume and extent. A few parts of the Eocene belt remained sites of basalt eruption. These features of the map (Plate 2) are confirmed by multiple dates in most

cases [e.g., Rouse and Mathews, 1988; Ross, 1983; Mathews, 1989] but are volumetrically small. A few basalt dikes of this time interval are also found in the Vancouver area of southwestern British Columbia and on northern Vancouver Island. Granitic and lamprophyric dikes and small plutons of Oligocene to Miocene age have been reported in several studies of the Coast Mountains near and in the southeastern tip of Alaska (Portland Canal area) [Brew, 1988; Lull and Plafker, 1988].

The two larger Oligocene magmatic fields north of latitude 49°N are the Masset volcanic field (culminating 35-25 Ma), on and near the Queen Charlotte Islands [Young, 1981; Hickson, 1988], and the Glacier Bay-Tkope magmatic belt (42-24 Ma, shifting northeastward during this time interval), in southeastern Yukon, northwesternmost British Columbia and adjacent Alaska [Brew, 1988].

#### 10-25 Ma (Plate 3)

There are three highlights of this time interval: the merging of the Arizona and Nevada magmatic fields along the Colorado River corridor about 25-22 Ma ago, the eruption of basalt in the Columbia Plateau 17-14 Ma ago, and the northwards transgressive change in tectonic and magmatic behavior that affected much of the western United States at about 20-17 Ma ago [Christiansen and Lipman, 1972; Armstrong and Higgins, 1973].

The merging of the magmatic fields, a singular event of profound significance for metamorphic core complex development, was coincident with the inception of magmatism in the Mojave Desert [Armstrong and Higgins, 1973; Glazner and Bartley, 1984; Dokka and Woodburne, 1986; Dokka, 1988].

An aspect of the merged volcanic belt that has received considerable discussion is the change in volcanic composition and eruptive style from predominantly intermediate chemistry with typical ash flow eruption style to one of bimodal chemistry, predominantly basaltic eruptions. This was first discussed by McKee [1971], Lipman et al. [1971, 1972], Noble [1972], and Christiansen and Lipman [1972], and the time-transgressive pattern of this change is shown by Armstrong and Higgins [1973]. In the southernmost areas the transition occurred earliest, perhaps as early as 25 Ma ago [Crowe et al., 1979]. The change spread rapidly northward between 20 and 17 Ma, connecting with the Columbia Plateau basalt eruptions at 17 Ma. By 15-12 Ma the change to bimodal, mostly basalt magmatic style had occurred over most volcanic fields of the western United States, the principal exception being the Cascade Arc [Priest, 1989]. A brief interruption of magmatic activity at this time of changing magmatic style is recognized in several papers [McKee et al., 1970; Chapin and Seager, 1975; Aldrich et al., 1986].

Also approximately coincident with the merging of the larger magmatic fields was a magmatic episode (24-22 Ma according to Stanley [1987]) of considerable extent but modest volume on the Pacific plate, west of the San Andreas fault in southwestern California [Johnson and O'Neil, 1984; Fox et al., 1985; Stanley, 1987]. The Mojave field was presumably coextensive as well as coincident in time with this volcanic area. The two fields are interpreted to be one, split by movement along the San Andreas fault [Mathews, 1973]. Pilger and Henley [1979] and Tennyson [1989] emphasize that this magmatic event preceded the arrival of transform faulting in southwestern California. In middle Miocene time (15 Ma ago) a north migrating and expanding magmatic field appeared just northeast of the San Andreas fault in central California.

As the Basin and Range magmatic field expanded both

southeastward and westward (in step with the outward propagation of extensional strain) [Armstrong *et al.*, 1969; Armstrong, 1970; Scott *et al.*, 1971; Armstrong *et al.*, 1972], the Rio Grande Rift magmatic belt propagated northward and gradually became more narrowly focused. The last of the Colorado Plateau laccolith centers were emplaced early in the time interval of Plate 3.

In the northwestern states and southern British Columbia, eruption of basalt from fissures greatly expanded the area of magmatic activity both eastward and northward. The Columbia River Basalt of the Columbia Plateau region is the better known and most voluminous result of these eruptions [Christiansen and McKee, 1978; Hooper and Swanson, 1987], but lesser volumes of contemporaneous and younger basalt occur throughout much of the Intermontane Belt of British Columbia as older parts of the "Plateau Basalt" or "Chilcotin Basalt" [Mathews, 1988, 1989]. The Columbia River Basalt spread across the Cascades into coastal Oregon and Washington, and contemporaneous basalts were erupted as well in northern California and Nevada. The time-transgressive bimodal magmatism of the Snake River Plain began about 15 Ma ago in western Idaho at the time of the Columbia River Basalt event, and bimodal volcanism became widespread over much of eastern Oregon.

The Cascade arc continued throughout this time interval as a stable feature, stretching from Oregon to southwestern British Columbia, in virtually the same position as its Oligocene predecessor. There is disagreement as to whether Cascade magmatism was interrupted [Priest, 1989] or accelerated [McBirney *et al.*, 1974] at the time of the Columbia Plateau basalt episode. The persistent magmatic locus in Montana finally became extinct during the Miocene.

At 54°-55°N during the time interval of Plate 3 the Masset magmatic activity of the Queen Charlotte Islands diminished to near extinction. Magmatic activity shifted from the Masset centers eastward to begin the Anahim Magmatic Belt hot spot trace [Bevier *et al.*, 1979; Souther, 1986] as the Masset area itself was displaced northward on strike slip faults that parallel the continental margin [Young, 1981; Yorath and Hyndman, 1983]. Early Miocene basalts occur in the interior of British Columbia at these latitudes [Church, 1973], but they are volumetrically insignificant.

Early in the late Oligocene to late Miocene time interval of Plate 3 scattered calc-alkaline to alkaline magmatic activity continued in southeastern Alaska [Brew, 1988] and northwesternmost British Columbia. In addition, early to middle Miocene basalt has been discovered on the east shore of Atlin Lake, east of the Coast Mountains in northwestern British Columbia [Bultman, 1979; University of British Columbia (UBC), unpublished data, 1980].

After about 15 Ma, magmatism shifted northeastward to form the calc-alkaline Wrangell belt, which initially extended from Alaska southeastward across the southwestern corner of the Yukon into northwestern British Columbia [Skulski, 1988]. About 15 Ma ago a large peralkaline volcanic shield (Level Mountain) began growing in northwestern British Columbia (unpublished UBC K-Ar dating for the Geological Survey of Canada) and by 10-8 Ma that magmatic field had expanded southward into the Mount Edziza area [Souther *et al.*, 1984]. Volcanic rocks at several localities further north in the Yukon have been inferred to be Miocene [e.g., Tempelman-Kluit, 1974, 1976; Noel, 1979], but are actually Cretaceous [Grond *et al.*, 1984].

#### 0-10 Ma (Plate 4)

During the last 10 Ma there have been few major changes in the overall magmatic pattern. The areas of Quaternary magmatism are much the same as those of late Miocene time. The Basin and Range magmatic field has continued to

slowly expand. Its early "cores", in Nevada and southern Arizona, have become virtually extinct. This pattern is illustrated in Plate 4. The waning stages are typically represented by small vents erupting basanitic, nodule-bearing basalt [Wilshire and Shervais, 1975; Smith and Luedke, 1984]. Magmatism, mostly of small volume and bimodal-basaltic character, has concentrated near the expanding margins of the magmatic field. The east migrating eastern margin of the Basin and Range in Idaho, Wyoming, and northern Utah is tied to the migrating Yellowstone hot spot [Pierce *et al.*, 1988; Anders *et al.*, 1989; Westaway, 1989a, 1989b]. Elsewhere magmatism and uplift appear to advance sooner into stable areas than extensional strain, as for example along the eastern, western, and southwestern edge of the Colorado Plateau [McKee and Anderson, 1971; Best and Hamblin, 1978; Rowley *et al.*, 1978; Best *et al.*, 1980]. Rates of extensional strain declined overall during this interval [Zoback *et al.*, 1981; Eaton, 1984; Wernicke *et al.*, 1988].

A notable feature of this time is the development of the Snake River Plain, documented by Armstrong *et al.* [1975]. Silicic magmatism, followed by bimodal and basaltic eruptions, has migrated northeastward up the axis of the eastern Snake River Plain to a present locus in Yellowstone Park in northwestern Wyoming. A much weaker and parallel migration of magmatism has occurred into the Clayton-Raton area of northeastern New Mexico and southeastern Colorado [Suppe *et al.*, 1975]. Lipman [1980] has argued that this is not the end of a long-lived hot spot trace. Almost perpendicular is the trend of migration and expansion of the magmatic field that lies just east of the San Andreas fault in central western California. Activity there is currently centered in the The Geysers-Clear Lake area [McLaughlin and Donnelly-Nolan, 1981; Fox *et al.*, 1985; Stanley, 1987].

The other magmatic features south of 42°N are scattered bimodal volcanic occurrences in southwestern California and around the Gulf of California, the remnants of the central Colorado-Rio Grande rift persistent magmatic locus, and one field of peculiar extremely potassic alkaline magmas in southern Wyoming [McDowell, 1971]. In the northwestern states, the Cascade arc has persisted through the last 10 Ma, with its magmatic front migrating eastward in central Oregon [McBirney, 1978; Priest, 1989] and jumping westward in southern British Columbia [Armstrong *et al.*, 1985; Green *et al.*, 1988]. From 10 to 4 Ma the average rate of Cascade magmatism declined, reaching a minimum in Pliocene time. In Quaternary time, magmatism accelerated to current rates. The Cascade arc now extends down into northern California to virtually merge with the expanded Basin and Range magmatic field. In eastern Oregon, the area where silicic magmatism occurs has systematically contracted over the last 10 Ma into the Newberry area, just east of the Cascades [McKee *et al.*, 1976]. The younger basaltic centers in eastern Oregon are largely located in a narrow belt extending east-southeast from Newberry volcano [Guffanti and Weaver, 1988]. Two areas of late basalt eruption on the Columbia Plateau are shown on Plate 4. That field is now extinct.

In central and southern British Columbia the eruption of "Plateau" and "Valley" basalts has continued into the Holocene over an extensive region, but the volumes erupted are small [Bevier, 1983; Mathews and Rouse, 1986; Mathews, 1988, 1989]. The Anahim Belt has migrated to the Nazko area [Souther, 1984] and another vent cluster has appeared in the Clearwater area [Hickson and Souther, 1984]. These features are shown on Plate 4 by the larger outlined arrows.

A short-lived magmatic belt on northern Vancouver Island, the Alert Bay Belt, was active about 3±1 Ma ago, during the westward jump of the Cascade Belt from the Pemberton to

the Garibaldi axes [Armstrong *et al.*, 1985]. Scattered young basalt fields occur on the Queen Charlotte Islands and in southeastern Alaska. The Quaternary Edgcomb field, of bimodal chemistry, lies farthest west, close to the currently active strike-slip North American plate boundary [Kosko, 1981; Meyers and Marsh, 1981].

In northern British Columbia, Level Mountain has become extinct, and there has been an expansion of the Edziza field [Souther *et al.*, 1984] from peralkaline central volcanos to widespread small-volume basalt vents (unpublished UBC K-Ar dating for the Geological Survey of Canada). The Wrangell arc has contracted so that its activity is now entirely within Alaska [Skulski, 1988]. Scattered late Miocene to Pleistocene basalt vents occur in the southern Yukon, east of the Coast Mountains.

#### MAGMATIC CORE COMPLEXES IN TIME AND SPACE

Davis and Coney [1979], Coney [1979, 1980], Davis [1980], and Armstrong [1982] have reviewed the general characteristics of Cordilleran metamorphic core complexes. These are exposures of ductile deformed middle crust exposed in structural culminations in an extensional tectonic environment. It has been long known that the core complexes become younger southwards in the United States and occur in close association with extensive regional magmatism. The association of magmatism and large-magnitude extension was first recognized by Anderson [1971] (with discussion and reply by Thompson and Anderson [1971]), and this association with core complexes is commented on in all the reviews cited and is emphasized in recent papers by Coney [1987], Hamilton [1987], Gans [1987], Brown and Journeay [1987], Wernicke *et al.* [1987], Gans *et al.* [1989], McCarthy and Thompson [1988], Thompson and McCarthy [1990], Lachenbruch and Morgan [1990], and Lucchitta [1990]. Table 1 lists a number of core complexes or closely related areas of ductile deformation and low-angle faulting where structural and geochronometric studies have defined the age of ductile deformation associated with uplift and rapid cooling of the metamorphic rocks. This information has been obtained by U-Pb, K-Ar, fission track, and Rb-Sr dating of prekinematic, synkinematic and postkinematic igneous phases and minerals to determine crystallization ages and cooling histories. The common and long-recognized association of igneous rocks and deformation in metamorphic core complexes has often been the key to providing rocks whose ages closely bracket the times of deformation. Most of the literature cited was published within the last decade. Not listed in Table 1 are many areas where K-Ar dates have been reset but where evidence for synchronous ductile strain is lacking and areas where brittle extension has occurred but which lack exposed rocks with ductile strain.

The locations and times of ductile deformation are plotted on a series of maps (Figures 2-5), similar in format to those showing the magmatic evolution of the Cordillera between Alaska and Mexico. The point to be made is simple and emphatic. The core complexes form only within the largest magmatic belts and fields. They do not form where there is little or no magmatic activity, and there is often magmatic activity without the formation of core complexes. The figures are a graphical demonstration of the association. Extension directions for most of these metamorphic core complexes have been compiled and illustrated by Wust [1986a].

#### 40-55 Ma (Figure 2)

From central British Columbia to central Idaho all the metamorphic core complexes formed in early to middle

Eocene time, coincident with the Eocene magmatic episode. At the international boundary (49°N latitude) the area affected by ductile deformation of Eocene age is nearly as wide as the magmatic arc, extending from Cascade and Coast Mountains (Ross Lake and Bridge River areas) on the west to the eastern flank of the Shuswap Complex (Valhalla and Spokane domes) on the east.

#### 25-40 Ma (Figure 3)

Ductile extension structures of this age occur in two areas, each within major magmatic fields. The large core complexes of southern Idaho, eastern Nevada, and northwestern Utah formed synchronously with the ignimbrite transgression through Nevada. In southern Arizona, some ductile strain is reported to be as old as the time interval illustrated here, but most is immediately later.

#### 10-25 Ma (Figure 4)

Some ductile strain in the eastern Great Basin continued into this time interval, but the focus of ductile (and brittle) extension was in the Colorado River Corridor and adjacent parts of southern California and western and southern Arizona [Glazner and Bartley, 1984; Howard and John, 1987; Sherrod *et al.*, 1987; Miller and John, 1988; Davis, 1988; and Davis and Lister, 1988]. Davis and Lister [1988] infer rates of extension greater than 1 cm/a in the Whipple Mountains between 20 and 18 Ma ago. Brittle extension occurred over a much wider area [Proffett, 1977; Rowley *et al.*, 1978; Morgan *et al.*, 1986], and this is usually viewed as the main period of development of the Basin and Range structure [e.g., Eaton, 1984]. A major reorientation of regional stress in the western United States occurred 26-17 Ma ago (Eaton *et al.* [1978] give approximately 17 Ma for the time of change in the Great Basin; Wust [1986a] gives 24 Ma for the core complexes; Aldrich *et al.* [1986] give about 23 Ma for the Rio Grande rift region; Best [1988] gives 26-18 Ma for western Utah; and Ren *et al.* [1989] give 30 to 14 Ma for the eastern Great Basin). This change in stress orientation is notable in the contrast between Eocene and Oligocene metamorphic core complexes, with WNW lineations, and Miocene and younger metamorphic core complexes with WSW lineations, as shown on the compilation of Wust [1986a]. Further reorientation occurred about 10 Ma ago in the northern Basin and Range [Zoback *et al.*, 1981], probably in response to migration of the Yellowstone plume and to increased coupling to the San Andreas transform system.

#### 0-10 Ma (Figure 5)

Areas where ductile strain of this age is documented are few and nearly all are in the Death Valley to Salton Sea region of southern California [Hodges *et al.*, 1987; Asmerom *et al.*, 1990]. Rates of extension over the entire Basin and Range are inferred to be much less than earlier in the Miocene [Zoback *et al.*, 1981; Wernicke *et al.*, 1988].

#### DISCUSSION

The association of magmatism and core complexes leads to the deduction that magmatism is a necessary precondition to the formation of metamorphic core complexes, because it leads to elevated geotherms and a consequent weakening of the entire lithosphere so that extension may occur. The effects of heat on lithosphere strength were emphasized by Burchfiel and Davis [1975], Cross and Pilger [1978], and Davis [1980] and are discussed more recently by Lipman *et al.* [1986], Lynch and Morgan [1987], and Gaudemer *et al.* [1988].

TABLE 1. Times of Ductile Deformation in Metamorphic Core Complexes

No.	Locality	Time of Ductile Deformation	Reference
<i>Canada</i>			
1	Nulki	<58 Ma	R. Friedman and R. L. Armstrong, (unpublished U-Pb dating, 1990)
2	Coast Plutonic Complex	51 Ma	van der Heyden [1989]
3	Tatla Lake	56-47 Ma	Friedman and Armstrong [1988]
4	Valhalla	59-52 Ma	Parrish et al. [1988]
5	Okanagan	60-47 Ma 52-47 Ma	Parrish et al. [1988] Templeman-Kluit and Parkinson [1986]
6	Bridge River	45-40 Ma	Monger et al. [1984] and Potter [1986]
<i>Washington</i>			
7	North Cascades	~45 Ma	Babcock et al. [1984]
8	Okanogan Dome	~48, <65 Ma	Hansen and Goodge [1988]
9	Kettle Dome	Late Cretaceous to Eocene	Cheney [1980] and Rhodes and Cheny [1981]
10	Newport fault-Spokane Dome	48-45 Ma and Price [1983], >50 Ma  Eocene	Miller [1971], Harms Armstrong et al. [1987], Bickford et al. [1985], and Rhodes and Hyndman [1988] Rehrig et al. [1987]
<i>Northern and Central Idaho</i>			
11	Bitterroot Range	46-44 Ma  57?-49-46 Ma	Garmezy and Sutter [1983] Hyndman and Myers [1988]
12	Pioneer Mountains	52-42 Ma ~40 Ma <68, >40 Ma  45-48 Ma and 36-33 Ma	Chase et al. [1983] Wust [1986b] O'Neill and Pavis [1988] Silverberg [1990]
<i>Central and Northern Nevada</i>			
13	Wood Hills	56-47 Ma	Thorman and Snee [1988]
14	Ruby Mountains	26-24 Ma 45-20 Ma 45-23 Ma	Dokka et al. [1986] Dallmeyer et al. [1986] Snoke and Miller [1988]
15	Snake Range	36-<24 Ma	Lee et al. [1987] and Miller et al. [1988]
<i>Southern Idaho and Northern Utah</i>			
16	Albion Range	34-17 Ma 30-15 Ma	Armstrong [1976] Snoke and Miller [1988]
17	Raft River Mountains-Grouse Creek Range	50?-20 Ma ~25 Ma	Compton et al. [1977] Todd [1980]
<i>Southern Nevada to Death Valley</i>			
18	Mineral Ridge	~17 Ma	McKee [1983]
19	Trappman Hills	~14 Ma	McKee [1983]
20	Bullfrog Hills	~11 Ma	McKee [1983]
21	Grapevine-Panamint	11-7 Ma  12-<5 Ma	Glazner and Bartley [1984] M.W. Reynolds et al. [1986]

TABLE 1. (continued)

No.	Locality	Time of Ductile Deformation	Reference
<i>Southern California and Southwestern Arizona</i>			
22	Colorado River Corridor	22-17 Ma	Howard and John [1987]
23	Whipple Mountains	22-19 Ma 19-16 Ma 20-18 Ma	Howard et al. [1990] Anderson et al. [1988] Davis and Lister [1988]
24	Rawhide Mountains	26-16 Ma 16-10 Ma	Davis [1988] Shackelford [1980]
25	Big Maria Mountains	20-16 Ma	Hamilton [1982]
26	Central Mojave	20 Ma  22-17 Ma	Glazner and Bartley [1984] Dokka [1988, 1989]
<i>Salton Sea Area</i>			
27	Yuba Desert	<6 Ma	Isaac et al. [1986]
28	Peninsular Range	<24, >5 Ma	Engel and Schultejan [1984] and Schultejan [1984]
<i>Southern Arizona</i>			
29	South Mountain	25-20 Ma	S.J. Reynolds et al. [1986]
30	Pinaleno	≤25 Ma	Glazner and Bartley [1984]
31	Rincon	28-24 Ma	Glazner and Bartley [1984]
32	Catalina	21-17 Ma 25-20 Ma 24-16 Ma	Anderson et al. [1988] Reynolds et al. [1986] Dickinson and Shafiqullah [1989]
33	Bullard fault	35-22 Ma 25-17 Ma	Davy et al. [1989] Reynolds and Spencer [1985]

A much longer list of areas of crustal extension or low-angle faulting could be compiled, as, for example by Glazner and Bartley [1984], but such information would only diffuse the focus of this paper on the metamorphic core complexes.

The cross reference numbers are plotted on Figures 2-5, as appropriate. There is not enough room on the figures to include either names or times of ductile deformation.

Magmatism does not of itself necessarily cause convergence or extension. That depends mostly on the far-field plate tectonic forces acting on a region [Molnar and Atwater, 1978; Chase, 1978; Cross and Pilger, 1982] and inherited topography and crustal thickness (as reviewed by Dewey [1988]). Magmatism may contribute to uplift and crustal thickening and, consequently, favor extension but is not alone decisive. Magmatic heating allows deformation to occur. During the Mesozoic there was abundant magmatism without large-scale extension. The Cordilleran region was evidently under compression (maximum principal stress generally east-west) and once weakened by heating, failed in convergent style [Burchfiel and Davis, 1975; Allmendinger and Jordan, 1981]. The maximum principal stress axis in the upper crust has apparently been vertical during most of Cenozoic time, starting in northern areas about 55 Ma ago, and migrating southward through the western United States by about 40 Ma ago. Extension has occurred wherever and whenever weakness prevailed. After about 30 Ma ago the growth of the San Andreas transform [Atwater, 1970; Dickinson, 1981] system added further complication to Cordilleran tectonic and magmatic patterns but did not

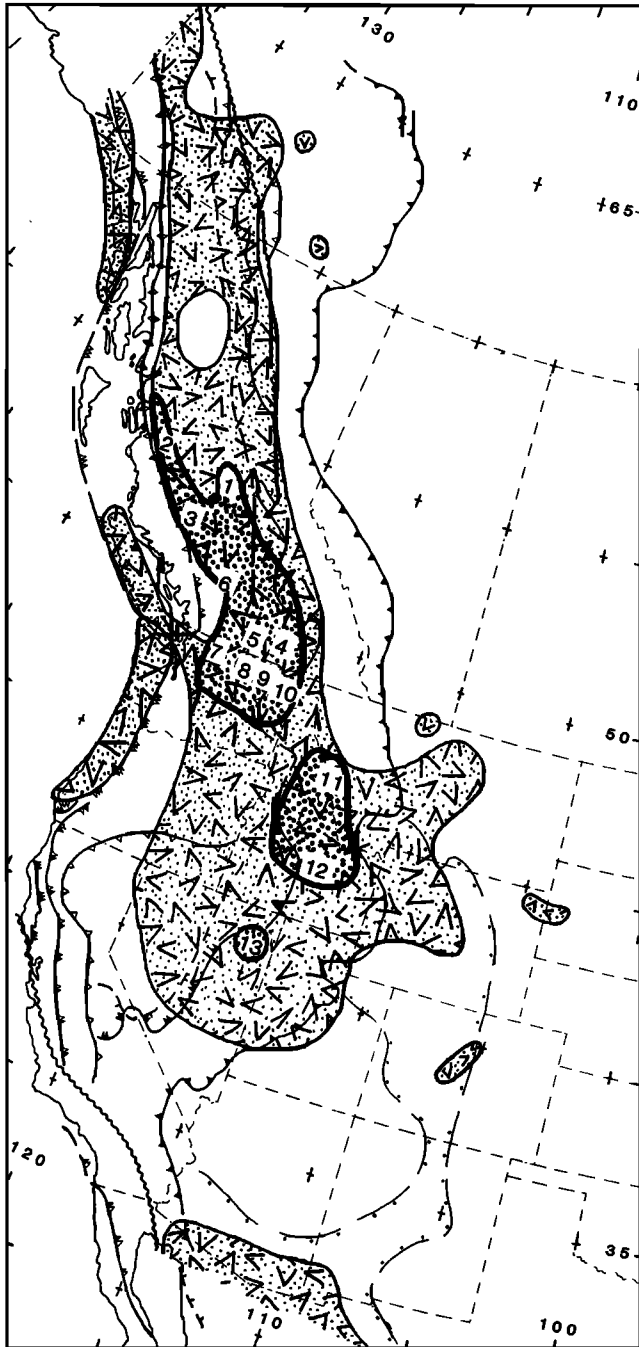


Fig. 2. Magmatic belts and location of ductile deformation in Cenozoic metamorphic core complexes for the time interval 40-55 Ma ago (early and middle Eocene time). The core complexes occur in the areas shown by a darker pattern. The numbers in those areas are keyed to the complexes listed in Table 1.

fundamentally change the extensional tectonic regime. The explanations for magmatism and stress within the Cordilleran lithosphere may be interrelated but must also be somewhat independent of one another.

**BURNING THE LITHOSPHERE BRIDGE**

The rapid production of core complexes of amazing extent in the Colorado River corridor has been commented on by many workers, often in puzzlement [Davis, 1980; Glazner and Bartley, 1984; Howard and John, 1987; Miller and John,

1988; Davis, 1988; Davis and Lister, 1988]. Why is this phenomena so extremely developed in this particular area and at one certain time, about 20-18 Ma ago? Contemplation of the maps showing changing patterns of magmatic activity provides an explanation that further elaborates on the theme that cold lithosphere is strong and areas of a magmatically sustained steep geothermal gradient are thoroughly weak. The unique circumstance that began the time of hyperextension is the merging of Arizona and Nevada magmatic fields at about 25-22 Ma, first documented by Armstrong and Higgins [1973]. This created a new

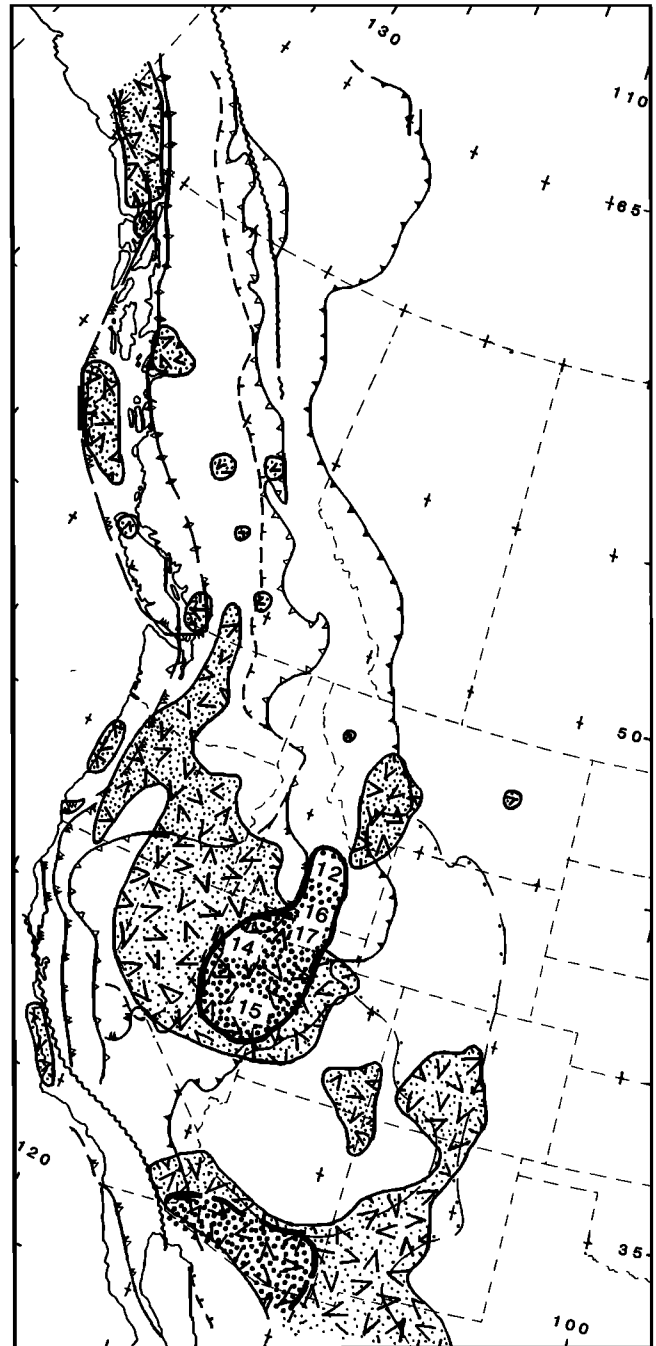


Fig. 3. Magmatic belts and location of ductile deformation in Cenozoic metamorphic core complexes for the time interval 25-40 Ma ago (late Eocene to latest Oligocene time). The core complexes occur in the areas shown by a darker pattern. The numbers in those areas are keyed to the complexes listed in Table 1.

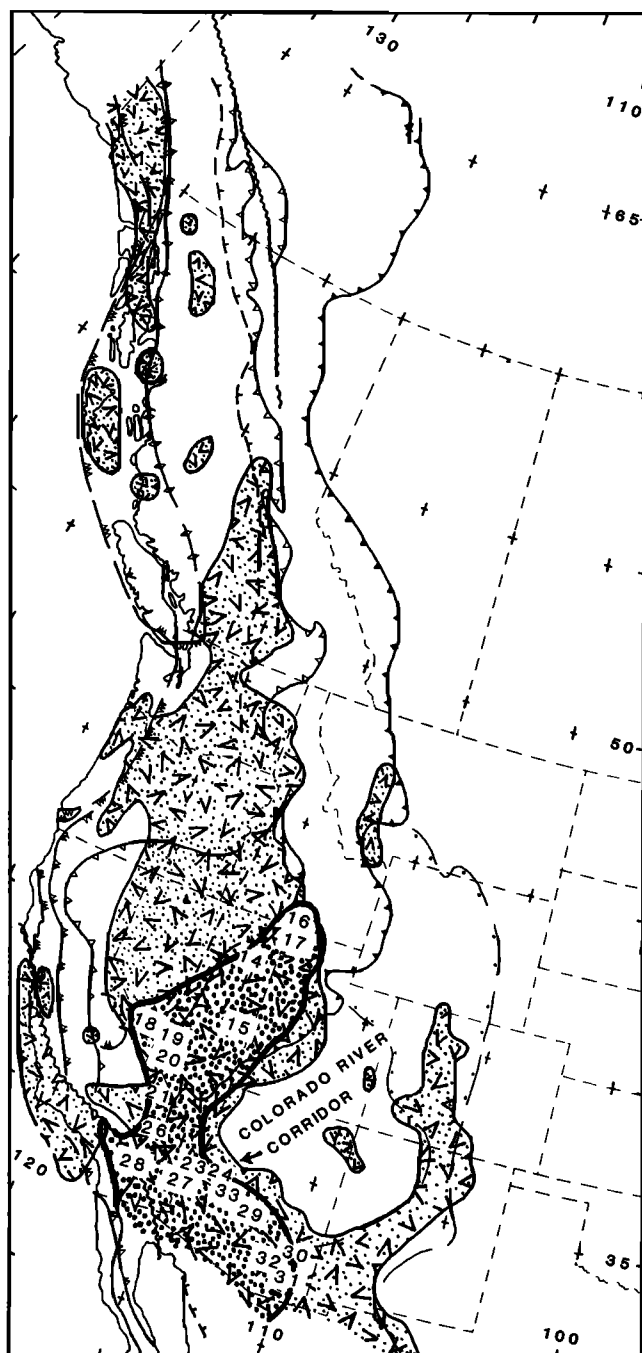


Fig. 4. Magmatic belts and location of ductile deformation in Cenozoic metamorphic core complexes for the time interval 10-25 Ma ago (latest Oligocene to early late Miocene time). The core complexes occur in the areas shown by a darker pattern. The numbers in those areas are keyed to the complexes listed in Table 1.

tectonic regime, a continuous magmatic belt from Mexico to Canada for the first time since about 80 Ma ago. Until about 22 Ma the Laramide magmatic gap remained as a "bridge" of cold lithosphere constraining extension in adjacent areas. When that bridge ceased to exist (referred to above as "burning the bridge"), the constraint was removed. Extension of unusual rate and magnitude followed linkage of the magmatic fields within a few million years, and continued for several million years, until the previously accumulated stresses were accommodated and a new steady

state with forces resisting plate motion was achieved. In early to middle Miocene time California became a separate microplate, able to rotate and move away from North America at rates that may have approached several centimeters per year. It is noteworthy that large tectonic rotations in the Transverse Ranges occurred during middle Miocene time [Hornafius *et al.*, 1986] and that the last episode of accretion of the Franciscan Complex, in the King Range area, occurred just after middle Miocene time [McLaughlin *et al.*, 1982]. These events coincided with the brief time interval during which California was a rapidly

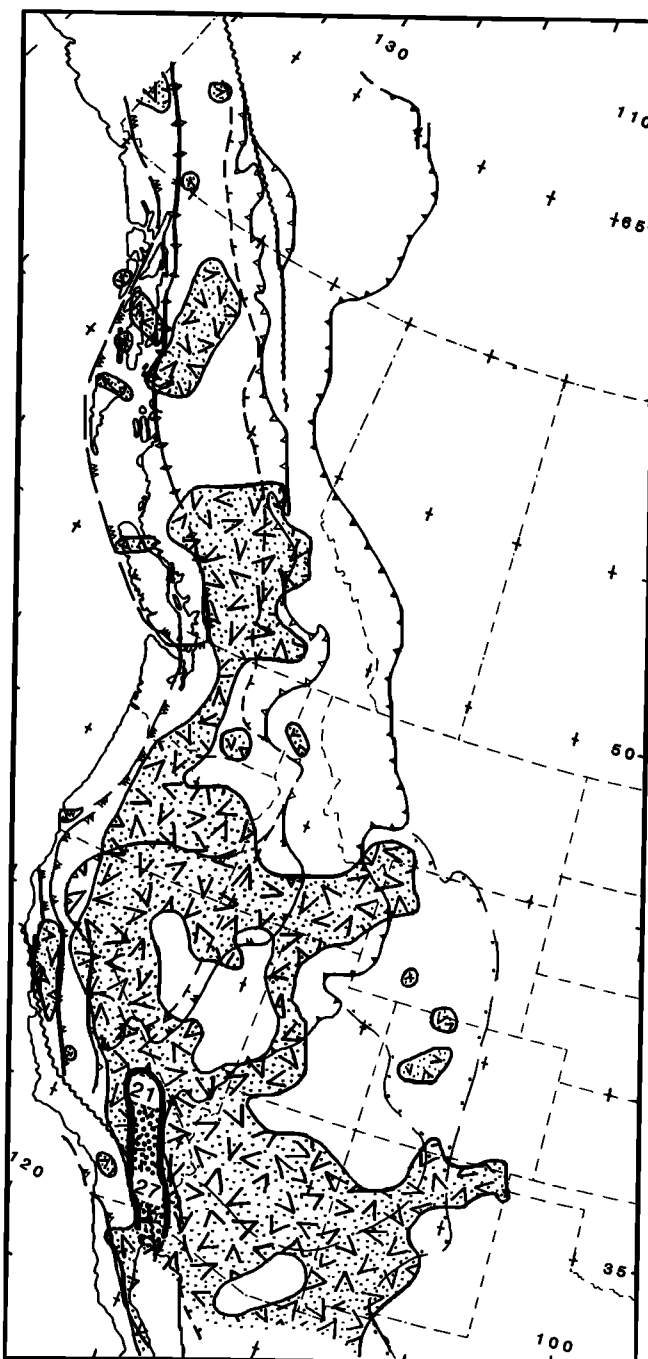


Fig. 5. Magmatic belts and location of ductile deformation in Cenozoic metamorphic core complexes for the time interval 0-10 Ma ago (late Miocene to Holocenetime). The core complexes occur in the areas shown by a darker pattern. The numbers in those areas are keyed to the complexes listed in Table 1.

westward moving microplate. Paleomagnetic measurements cannot detect purely longitudinal motion, but reconstruction of the intersection of the Mendocino Fracture Zone with the edge of the continent must take these westward displacements of California into account [e.g., *Stock and Molnar*, 1988].

#### COMMENTS ON EXPLANATIONS FOR MAGMATISM

The abundant literature on Cenozoic magmatism and faulting in the Cordilleran region is full of explanations for the phenomena observed, and the truth probably incorporates many of the proposed processes. In this section we comment on the various proposals and the observations that they explain.

Large magmatic belts parallel to the continental margin are conventionally viewed as magmatic arcs of Andean style. *Hamilton* [1969] and *Dickinson* [1970] emphasized this and they were hardly the first to recognize the similarity. It can be found in much earlier papers, for example, by *Daly* [1933] and *Stille* [1940]. This is a traditional first-order view, supported by study of modern arcs, and generally accepted today for the Cascades. *Lipman et al.* [1971, 1972] so liked this idea that they proposed double magmatic arcs (one normal and one cryptic, without surface expression of subduction), based on volcanic chemistry, for the early Cenozoic. *Burchfiel and Davis* [1975], *Snyder et al.* [1976], *Cross and Pilger* [1978], *Leeman* [1982b], and many other authors further support the magmatic arc viewpoint but usually in the simpler form of a single slab being subducted under the Cordilleran region. *Lipman* [1980], likewise, now advocates a single-slab model.

Extension within active arcs is a common observation [*Healey*, 1962; *Tobisch et al.*, 1986; *Smith et al.*, 1987], and is not incompatible with subduction [*Molnar and Lyon-Caen*, 1988; *Sébrier et al.*, 1988]. In fact, subduction of older crust may even create trench suction and cause within-arc and back arc extension [*Dewey*, 1980; *Cross and Pilger*, 1982; *Burchfiel and Royden*, 1982]. Back arc extension has been emphasized in discussions of the Great Basin by *Scholz et al.* [1971], *Thompson and Burke* [1974], *Stewart* [1978], *Cross and Pilger* [1978], *Davis* [1980], and *Eaton* [1980] and in many later papers.

The Laramide magmatic gap is usually explained by a change from normal (> 30° dip of downgoing plate) to a shallowly descending plate, as in modern nonvolcanic sectors of the Andes [*Snyder et al.*, 1976; *Coney and Reynolds*, 1977; *Dickinson and Snyder*, 1978; *Keith*, 1978].

The closely related theme of control of magmatic patterns by details of absolute and relative velocity of convergent plates and the age and shape of the subducted plate (changing rate of subduction, migration of flexures, segmentation of the downgoing plate, subduction of aseismic ridges or fracture zones, growth of accretion wedges, etc.) is further developed in numerous papers [e.g., *Vogt*, 1973; *Dickinson*, 1973, 1979; *Cross and Pilger*, 1978, 1982; *Coney*, 1978; *Pilger and Henley*, 1979; *Dewey*, 1980; *Wells et al.*, 1984; *Page and Engebretson*, 1984; *Elston* 1984; *Glazner and Schubert*, 1985; *Verplanck and Duncan*, 1987; *Guffanti and Weaver*, 1988].

Since *Hamilton* and *Myers* [1966] and *Atwater* [1970], many discussions invoke the effects of the enlarging San Andreas transform fault system, distributed shear [*Lipman et al.*, 1971, 1972; *Noble*, 1972; *Suppe et al.*, 1975; *Stewart*, 1978; *Zoback and Thompson*, 1978; *Livaccari*, 1979; *Pilger and Henley*, 1979; *Coney*, 1987], relaxed compression [*Scholz et al.*, 1971; *Thompson*, 1972; *Stewart*, 1978; *Coney*, 1987], and the enlarging slab window created by change from subduction to strike slip along the Pacific

Margin (hinted at by *Scholz et al.* [1971] and explicitly invoked by *Best and Hamblin* [1978], *Dickinson and Snyder* [1979a], *Lipman* [1980], *Seager et al.* [1984], and *Fox et al.* [1985]). This latter idea would not seem to be applicable to Eocene magmatism and core complex formation and so cannot be a general explanation for crustal extension. *Thorkelsen and Taylor* [1989] present unconstrained speculation that a north-migrating Eocene slab window did exist under southern British Columbia, but this does not fit observed magmatic patterns.

Other authors argue in a more general way for the importance of oblique convergence, which may be partitioned into subduction and strike slip components [*Jarrard*, 1986a, 1986b], with consequences that are similar to the San Andreas-Basin and Range interaction. This has been used to explain the Eocene events north of 42°N [*Ewing*, 1980; *Price and Carmichael*, 1986] and many details of Cordilleran history [*Page and Engebretson*, 1984; *Engebretson et al.*, 1985; *Wells and Heller*, 1988].

Migrating triple junctions, especially the Mendocino triple junction of the evolving San Andreas transform fault system, are given special emphasis in numerous papers [*Coney*, 1976, 1987; *Snyder et al.*, 1976; *Dickinson and Snyder*, 1979b; *Ingersoll*, 1982; *Glazner and Supplee*, 1982; *Zandt and Furlong*, 1982; *Glazner and Bartley*, 1984; *Johnson and O'Neil*, 1984; *Fox et al.*, 1985; *Ward*, 1986]. A few papers assign importance to overriding of the East Pacific Rise by North America [*Menard*, 1960; *Cook*, 1966; *Damon*, 1971] (and more recently, *Gough* [1984] and *Wilson* [1988]), but most marine geologists view the Rise as an entirely passive feature that has no existence between offset active segments [*Atwater*, 1970]. These mechanisms for uplift and magmatism would be applicable only for the last 30 Ma of the nearly 60 Ma duration of magmatism associated with extension and core complexes and only from California southward.

Explanations using the northward migration of subducted rise and triple junctions are most attractive and suitable for features of the magmatic and tectonic history that migrate northward (e.g., ages of low-angle faulting in the southwestern United States discussed by *Glazner and Bartley* [1984] and the switchoff of arc magmatism in California discussed by *Snyder et al.* [1976]), in step with the migration of the triple junction, and moving eastward with the velocity expected for the subducted ridge.

Another factor responsible for magmatic fields is deep mantle plumes [*Armstrong et al.*, 1975; *Suppe et al.*, 1975; *Leeman*, 1982a; *Iyer*, 1984; *Brandon and Goles*, 1988; *Westaway*, 1989a, 1989b]. These are invoked not only for their magmatic contribution but also as significant plate driving forces by *Matthews and Anderson* [1973] and *Smith and Sbar* [1974]. Some authors envision a more generalized large-scale mantle upwelling as important [*Thompson*, 1972; *Smith*, 1978; *Eaton et al.*, 1978; *Best and Hamblin*, 1978; *Gough*, 1986], and this overlaps conceptually with the slab-window and subducted ocean ridge explanations, being only a little more vague as to the specific physical cause of the upwelling. Mantle upwelling is generally prescribed as the explanation of the bimodal, predominantly basalt magmatic association closely linked with crustal extension [*Christiansen and Lipman*, 1972; *Leeman*, 1982b]. Magma volumes in purely extensional continental regimes above upwelling mantle, apart from areas blamed on deep and energetic plumes, are generally small. The rhyolite component is attributed to extreme fractionation of primary basalt or melting of lower crust by heat from the mantle-derived basalt. As the system wanes nodule-bearing basanite becomes common [*Smith and Luedke*, 1984; *Wilshire and Shervais*, 1975].

Propagating fractures and lineament controls have been advocated as an alternative to plume traces by *Smith* [1978], *Christiansen and McKee* [1978], and *Lipman* [1980], but many deeply rooted fractures are not associated with magmatism and fracture alone would seem inadequate as the cause of a thermal perturbation capable of generating large amounts of magma.

Thick crust, inherited from Mesozoic orogenesis, was suggested as one of the controls on extension and core complex formation by *Armstrong* [1972] and recently by *Coney and Harms* [1984], *Coney* [1987], *Brown and Journeay* [1987], *Malavielle* [1987], and *Gaudemer et al.* [1988]. This can be only a partial explanation for core complex location and nucleation. It provides a simple explanation for locally higher crustal temperatures and local forces favorable to extension. But a magmatic trigger and suitable regional stresses are also necessary to explain the association we observe between magmatism and core complexes and their large strains.

The interplay of magmatism and crustal extension is emphasized in recent discussions of the geophysical images of extensional orogens [*Klemperer et al.*, 1986; *Potter et al.*, 1986; *Allmendinger et al.*, 1987; *McCarthy et al.*, 1987; *McCarthy and Thompson*, 1988; *de Voogd et al.*, 1988; *Valasek et al.*, 1989; *Thompson and McCarthy*, 1990]. Magma in these interpretations plays multiple roles: space filling and magma inflation of the lower crust solves volume and isostatic problems, and recently emplaced horizontal intrusive sheets may be the lower crust layers imaged as horizontal reflectors of seismic energy. A flat Moho, apparently undisturbed beneath intensely faulted upper crust, is a puzzling observation in all the extensional orogens that have been studied. The lower crust must be extremely ductile, and what more suitable material to redistribute by flow, than magma, or rocks softened by injection of magma? This carries the view of conditions in the roots of core complexes a step beyond the recognition that lower crust strength is reduced by heating. When magma accumulates in abundance in the lower crust its strength must virtually disappear. *de Voogd et al.* [1986] present evidence that magma sheets are present today in the Death Valley region, where the youngest ductile extension structures are found. Weak lower crust is a conclusion dictated by core complex geometry [*Block and Royden*, 1990] and seismic reflectors in the crust and mantle [*Reston*, 1990].

#### SUMMARY AND CONCLUSIONS

The complex and changing pattern of magmatic evolution of the North American Cordillera requires a multifaceted explanation. In this paper we have presented evidence, in the form of maps showing the localities where isotopic dating has been done, and from that data, and extensive literature review, we have outlined the magmatic fields that existed during four successive time intervals (55-40, 40-25, 25-10, and 10-0 Ma). We have not attempted to explain these patterns in terms of a specific plate motion model, nor have we dealt with any of the detailed questions of petrogenesis. Our emphasis has been on the association of magmatism and metamorphic core complexes and the implications of that association.

Early Cenozoic magmatic patterns were inherited from the late Mesozoic. After approximately 80 Ma the continuous magmatic belt that lay parallel to the continent margin broke up into two belts, separated by a Laramide magmatic gap that linked California to the cratonic interior of North America. Orogenic compression continued between Mexico and Alaska until 55 Ma, creating the last stages of the fold and thrust belt (from Montana northward and from southern

Arizona into Mexico) and most of the thick-skinned, basement-uplift structures in the Eastern Rocky Mountains (between Montana and New Mexico). Magmatism declined to a minimum at about the Cretaceous-Tertiary boundary.

During the early and middle Eocene a distinct magmatic culmination, peaking at 50 Ma, formed the Kamloops-Challis-Absaroka belt north of 42°. Its southern end curved into cratonic parts of Montana, mimicking a Late Cretaceous to Paleocene magmatic trend. Along the continent margin an oceanic basaltic island chain formed and was synmagmatically accreted in Oregon, Washington, and southern British Columbia and magmatism occurred near the edge of the continent from the foothills of the Cascades in Washington to Alaska. In Colorado and the Black Hills region and in southern Arizona, Laramide magmatic belts waned and shifted somewhat eastward during this time interval.

During late Eocene to late Oligocene time, magmatic activity in the north shifted into Cascade arc and Great Basin fields. Several continent margin magmatic fields persisted from Vancouver Island northward, and inland there was scattered basaltic magmatism. Magmatic fields in Arizona-New Mexico and the San Juan Mountains regions expanded and merged along the future trend of the Rio Grande rift. The large southern and northern magmatic fields were almost connected by scattered magmatic centers across the Colorado Plateau.

In latest Oligocene through most of Miocene time the most notable magmatic development was the merging of the large northern and southern magmatic fields into one continuous and vigorous magmatic belt extending from Mexico to Canada. Farther north, magmatism occurred in scattered fields of hot spot or within-plate character and in the Wrangell arc. The flood basalt episode of the Columbia Plateau occurred, the Snake River Plain magmatic transgression began, and the Cascade arc persisted in place. Magmatism rapidly spread over much of California southwest of the San Andreas fault, Colorado Plateau activity declined and Rio Grande rift activity became more focused on modern patterns. After the merger of the two major magmatic fields, about 22 Ma ago, there has been both a general decline in the amount of magmatic activity and a change in most areas to the bimodal, predominantly basaltic, petrochemical association.

Time relationships suggest a link between merging of the two large magmatic fields, the consequent tectonic and magmatic effects in the Great Basin, and the subsequent eruption of the basalts of the Columbia Plateau. The northward propagation of accelerated rifting and change in magma petrochemistry reached the northwestern United States just at the moment the voluminous basalt eruptions began (17 Ma). The plateau basalt event cannot be the cause of the other phenomena because it is the last to occur. If it has an independent origin (e.g., plume breakout [*Morgan*, 1981; *Richards et al.*, 1989; *Loper*, 1989] or meteorite impact [*Alt et al.*, 1988]) the timing must be pure coincidence. We cannot explain how the northward propagation of new tectonic and magmatic patterns could cause, or trigger, a localized episode of plateau basalt volcanism. We only observe the sequence of events and offer that observation as a topic for future speculation.

Since late Miocene time, magmatism has been much like modern patterns. In the north, the Wrangell arc has shrunk into Alaska. Several continent margin and within-plate fields have waxed and waned. Small-volume hot spot and back arc predominantly basaltic magmatism has occurred over much of southern British Columbia. The Cascade arc persisted from Canada to northern California, while back arc activity in the United States has diminished to little more



than the eastern plateaus of Oregon. The Snake River Plain has continued to expand eastward. Magmatic activity has tended to be localized on the margins of the Basin and Range and Colorado Plateau provinces. In southwestern California a continent margin magmatic belt has moved northwestward to The Geysers-Clear Lake area.

Since nearly 60 Ma ago, the development of metamorphic core complexes has followed the locus of the largest voluminous intermediate composition magmatic fields. The association is suggestive of a close, necessary link between magmatism and crustal extension of sufficient magnitude to produce the structures associated with these complexes. The logical inference is that the emplacement of magma into the crust raises crustal temperatures, and, moreover, its very presence lowers the strength of the crust. Thus existing stresses are allowed to deform the crust. Magmatism thus explains the location and timing of core complex formation. The stresses may be inherited (magmatically or orogenically thickened crust) or immediately created (magmatic inflation, uplift above anomalous mantle) or imposed by the global pattern of plate motions and driving forces (the logical recourse when local explanations are inadequate). The interplay of magmatism and crustal extension is emphasized in numerous papers cited above. Since the Miocene, the rates of magmatism, extension, and core complex formation have declined. The thickened and magma-impregnated crust of earlier Cenozoic time has now collapsed, one of the extensional driving forces is neutralized by the collapse, and the crust has become stronger. The modern Basin and Range Province is not a suitable model for the situation that existed during local magmatic culminations. There must have been a much shallower brittle-ductile transition in the crust of the developing core complexes than exists today. Our sympathies for a rheological model for core complex times would thus lie more with the model of a brittle zone overlying a ductile zone in the crust (pure shear models of *Thompson and Burke* [1974] and *Eaton* [1980]) (graphically displayed by *Davis and Lister* [1988] as a melting chocolate bar (Mars™) in a frying pan) than with the idea that discrete low angle faults penetrate the entire crust to root in mantle asthenosphere (simple shear model of *Wernicke* [1981, 1985]. *Wernicke* [1990] now also favors a large degree of compensation within weak crust.

The singular event of early Miocene time, the merging of magmatic fields, explains several disconnected observations. The time and place of the hyperextension episode of the Colorado River corridor are explained by the coincidence of magmatism and the release of a tectonic constraint, the thermal destruction of the Laramide magmatic gap. This eliminated the cooler and consequently stronger lithosphere "bridge" that had connected California to central North America for the previous 50-60 Ma. The dramatic change in plate boundary conditions resulted in early Miocene reorientation of stress patterns across much of western North America. California was freed to move rapidly westward as an independent microplate. Within western California this precipitated dramatic tectonic movements - rotation of Transverse Ranges crustal blocks, rapid basin development, and a late episode of subduction in the northern Coast Ranges. The merger of magmatic fields and the magmatic flareup in southern California came before the onset of transform faulting in southwestern California [*Pilger and Henley*, 1979; *Tennyson*, 1989]. The rapid westward motion of California coincided with development of the San Andreas transform system. Northward migration of the southern magmatic field may have been linked to the northward migration of the Mendocino triple junction, but the southward migration of the northern magmatic field was certainly not. The two plate tectonic processes, transform

growth and magmatic breakup of western North America, interacted. Miocene tectonics were not simply a consequence of the growing transform system and triple junction migration. Tectonic models that focus on the development of the San Andreas system as the singular explanation of continental margin geology are missing half the story!

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#### REFERENCES

- Aldrich, M.J., Jr., C.E. Chapin, and A.W. Laughlin, Stress history and tectonic development of the Rio Grande rift, New Mexico, *J. Geophys. Res.*, **91**, 6199-6211, 1986.
- Allmendinger, R.W., and T.E. Jordan, Mesozoic evolution, hinterland of the Sevier orogenic belt, *Geology*, **9**, 308-313, 1981.
- Allmendinger, R.W., K.D. Nelson, C.J. Potter, M. Barazangi, L.D. Brown, and J.E. Oliver, Deep seismic reflection characteristics of the continental crust, *Geology*, **15**, 304-310, 1987.
- Alt, D., J.M. Sears, and D.W. Hyndman, Terrestrial maria: The origins of large basalt plateaus, hotspot tracks and spreading ridges, *J. Geol.* **96**, 647-662, 1988.
- Anders, M.H., J.W. Geissman, L.A. Piety, and J.T. Sullivan, Parabolic distribution of circumeastern Snake River Plain seismicity and latest Quaternary faulting: Migratory pattern and association with the Yellowstone hotspot, *J. Geophys. Res.*, **94**, 1589-1621, 1989.
- Anderson, J.L., A.P. Barth, and E.D. Young, Mid-crustal Cretaceous roots of Cordilleran metamorphic core complexes, *Geology*, **16**, 366-369, 1988.
- Anderson, R.E., Thin skin distension in Tertiary rocks of southeastern Nevada, *Geol. Soc. Am. Bull.*, **82**, 43-58, 1971.
- Armentrout, J.M., Cenozoic stratigraphy, unconformity bounded sequences, and tectonic history of southwestern Washington, in *Selected Papers on the Geology of Washington*, edited by J.E. Schuster, *Bull. Wash. Div. Geol. Earth Resour.*, **77**, 291-320, 1987.
- Armstrong, R.L., Geochronology of Tertiary igneous rocks, eastern Basin and Range province, western Utah, eastern Nevada, and vicinity, U.S.A., *Geochim. Cosmochim. Acta*, **34**, 203-232, 1970.
- Armstrong, R.L., Low-angle (denudation) faults, hinterland of the Sevier orogenic belt, eastern Nevada and western Utah, *Geol. Soc. Am. Bull.*, **83**, 1729-1754, 1972.
- Armstrong, R.L., Geochronometry of the Eocene volcanic-plutonic episode in Idaho, *Northwest Geol.*, **3**, 1-15, 1974a.
- Armstrong, R.L., Magmatism, orogenic timing, and orogenic diachronism in the Cordillera from Mexico to Canada, *Nature*, **247**, 348-351, 1974b.

- Armstrong, R.L., Episodic volcanism in the central Oregon Cascade Range, Confirmation and correlation with the Snake River Plain, *Geology*, 3, 356, 1975.
- Armstrong, R.L., The geochronometry of Idaho, *Isochron/West*, 15, 1-33, 1976.
- Armstrong, R.L., Cenozoic igneous history of the U.S. Cordillera from 42° to 49° N latitude, *Mem. Geol. Soc. Am.*, 152, 265-282, 1978.
- Armstrong, R.L., Cordilleran metamorphic core complexes — From Arizona to southern Canada, *Annu. Rev. Earth Planet. Sci.*, 10, 129-154, 1982.
- Armstrong, R.L., Mesozoic and Early Cenozoic magmatic evolution of the Canadian Cordillera, in, *Processes in Continental Lithospheric Deformation*, edited by S.P. Clark, B.C. Burchfiel, and J. Suppe, *Spec. Pap. Geol. Soc. Am.* 218, 55-91, 1988.
- Armstrong, R.L., and R.E. Higgins, K-Ar dating of the beginning of Tertiary volcanism in the Mojave Desert, California, *Geol. Soc. Am. Bull.*, 84, 1095-1100, 1973.
- Armstrong, R.L., and P. Ward, Late Triassic to earliest Eocene magmatism in the North American Cordillera: Implications for the Western Interior Basin, *Geol. Assoc. Can. Spec. Pap.*, in press, 1991.
- Armstrong, R.L., E.B. Ekren, E.H. McKee, and D.C. Noble, Space-time relations of Cenozoic silicic volcanism in the Great Basin of the western United States, *Am. J. Sci.*, 267, 478-490, 1969.
- Armstrong, R.L., H. Dick, and C.J. Vitaliano, K-Ar dates and strontium isotope initial ratios of some Cenozoic volcanic rocks from west-central Nevada, *Isochron/West*, 3, 23-28, 1972.
- Armstrong, R.L., W.P. Leeman, and H.E. Malde, K-Ar dating, Quaternary and Neogene volcanic rocks of the Snake River Plain, Idaho, *Am. J. Sci.*, 275, 225-251, 1975.
- Armstrong, R.L., W.H. Taubeneck, and P.O. Hales, Rb-Sr and K-Ar geochronometry of Mesozoic granitic rocks and their Sr isotopic composition, Oregon, Washington and Idaho, *Geol. Soc. Am. Bull.*, 88, 397-411, 1977.
- Armstrong, R.L., J.E. Muller, J.E. Harakal, and K. Muchlenbachs, The Neogene Alert Bay Volcanic Belt of northern Vancouver Island, Canada: Descending-plate-edge volcanism in the arc-trench gap, *J. Volcanol. Geotherm. Res.*, 26, 75-97, 1985.
- Armstrong, R.L., R.R. Parrish, P. van der Heyden, S.J. Reynolds, and W.A. Rehrig, Rb-Sr and U-Pb geochronometry of the Priest River Metamorphic complex - Precambrian X basement and its Mesozoic-Cenozoic plutonic-metamorphic overprint, northeastern Washington and northern Idaho, in, *Selected Papers on the Geology of Washington*, edited by J.E. Schuster, *Bull. Wash. Div. Geol. Earth Resour.*, 77, 15-40, 1987.
- Asmerom, Y., J.K. Snow, D.K. Holm, S.B. Jacobsen, B.P. Wernicke, and D.R. Lux, Rapid uplift and crustal growth in extensional environments: An isotopic study from the Death Valley region, California, *Geology*, 18, 223-226, 1990.
- Atwater, T., Implications of plate tectonics for the Cenozoic tectonic evolution of western North America, *Geol. Soc. Am. Bull.*, 81, 3513-3536, 1970.
- Babcock, R.S., P. Misch, and R.L. Armstrong, Geochemistry of the crystalline core of the North Cascades Range (abstract), *Eos Trans. AGU*, 65, 328-329, 1984.
- Barrash, W., and R. Venkatakrishnan, Timing of late Cenozoic volcanic and tectonic events along the western margin of the North American plate, *Geol. Soc. Am. Bull.*, 93, 977-989, 1982.
- Barrash, W., J. Bond, and R. Venkatakrishnan, Structural evolution of the Columbia Plateau in Washington and Oregon, *Am. J. Sci.*, 283, 897-935, 1983.
- Beck, M.E., Jr., Has the Washington-Oregon Coast Range moved northward?, *Geology*, 12, 737-740, 1984.
- Bentzen, A., Report on the establishment of a computer file of radiometric dates, *Geol. Fieldwork 1986, Pap. 1987-1*, p. 441, B. C. Minist. of Energy Mines and Petrol. Resour., Victoria, 1987.
- Best, M.G., Early Miocene change in direction of least principal stress, southwestern United States: Conflicting inferences from dikes and metamorphic core-detachment fault terranes, *Tectonics*, 7, 249-259, 1988.
- Best, M.G., and W.K. Hamblin, Origin of the northern Basin and Range province: Implications from the geology of its eastern boundary, *Mem. Geol. Soc. Am.*, 152, 313-340, 1978.
- Best, M.G., E.H. McKee, and P.E. Damon, Space-time-composition patterns of the late Cenozoic mafic volcanism, southwestern Utah and adjoining areas *Am. J. Sci.*, 280, 1035-1050, 1980.
- Bevier, M.L., Regional stratigraphy and age of Chilcotin Group basalts, south-central British Columbia, *Can. J. Earth Sci.*, 20, 515-524, 1983.
- Bevier, M.L., R.L. Armstrong, and J.G. Souther, Miocene peralkaline volcanism in west-central British Columbia — Its temporal and plate tectonic setting, *Geology*, 7, 389-392, 1979.
- Bickford, M.E., B.P. Rhodes, and D.W. Hyndman, Age of mylonitization in the southern Priest River Complex, northern Idaho and northeastern Washington (abstract), *Geol. Soc. Am. Abstr. Programs*, 17, 341-342, 1985.
- Block, L. and L.H. Royden, Core complex geometries and regional scale flow in the lower crust, *Tectonics*, 9, 557-567, 1990.
- Brandon, A.D., and G.G. Goles, A Miocene subcontinental plume in the Pacific Northwest: Geochemical evidence, *Earth Planet. Sci. Lett.*, 88, 273-283, 1988.
- Brew, D.A., Late Mesozoic and Cenozoic igneous rocks of southeastern Alaska — A synopsis, *U.S. Geol. Surv. Open File Rep.*, 88-405, 29 pp., 1988.
- Brown, R.L., and J.M. Journeay, Tectonic denudation of the Shuswap metamorphic terrane of southeastern British Columbia, *Geology*, 15, 142-146, 1987.
- Bultman, T.R., Geology and tectonic history of the Whitehorse trough west of Atlin, British Columbia, Ph.D. thesis, 284 pp., Yale Univ., New Haven, Conn., 1979.
- Burchfiel, B.C., and G.A. Davis, Nature and controls of Cordilleran orogenesis, western United States: Extensions of an earlier synthesis, *Am. J. Sci.*, 275-A, 363-396, 1975.
- Burchfiel, B.C., and L. Royden, Carpathian foreland fold and thrust belt and its relation to Pannonian and other basins, *Bull. AAPG*, 66, 1179-1195, 1982.
- Burke, D.B., and E.H. McKee, Mid-Cenozoic volcano-tectonic troughs in central Nevada, *Geol. Soc. Am. Bull.*, 90, Part 1, 181-184, 1979.
- Carr, S.D., Implications of Early Eocene Ladybird granite in the Thor-Odin—Pinnacles area, southern British Columbia, *Pap. Geol. Surv. Can.*, 89-1E, 69-77, 1989.
- Carson, D.J.T., The plutonic rocks of Vancouver Island, British Columbia: Their petrography, chemistry, age and emplacement, *Pap. Geol. Surv. Can.*, 72-44, 70 pp., 1973.
- Chapin, C.E., and W.R. Seager, Evolution of the Rio Grande Rift in the Socorro and Las Cruces areas, *Field Conf. Guidebook N. M. Geol. Soc.*, 26th (Las Cruces County) 297-319, 1975.
- Chase, C.G., Extension behind island arcs and motions relative to hot spots, *J. Geophys. Res.*, 83, 5385-5387, 1978.
- Chase, R.B., M.E. Bickford, and E.C. Arruda, Tectonic implications of Tertiary intrusion and shearing within the Bitterroot dome, northeastern Idaho batholith, *J. Geol.*, 91, 462-470, 1983.
- Cheney, E.S., Kettle dome and related structures of northeastern Washington, *Mem. Geol. Soc. Am.*, 153, 463-483, 1980.
- Christiansen, R.L., and P.W. Lipman, Cenozoic volcanism and plate tectonic evolution of the western United States, II, Late Cenozoic, *Philos. Trans. R. Soc. London, Ser. A.*, 271, 249-284, 1972.
- Christiansen, R.L., and E.H. McKee, Late Cenozoic volcanic and tectonic evolution of the Great Basin and Columbia Intermontane regions, *Mem. Geol. Soc. Am.*, 152, 283-311, 1978.
- Church, B.N., Geology of the Buck Creek Area, in *Geological Exploration and Mining in British Columbia 1972*, pp. 353-363, British Columbia Department of Mines and Petroleum Resources, Victoria, 1973.
- Compton, R.R., V.R. Todd, R.E. Zartman, and C.W. Naeser, Oligocene and Miocene metamorphism, folding, and low-angle faulting in northwestern Utah, *Geol. Soc. Am. Bull.*, 88, 1237-1250, 1977.
- Coney, P.J., Plate tectonics and the Laramide orogeny, *Spec. Publ. N. M. Geol. Soc.*, 6, 5-10, 1976.
- Coney, P.J., Mesozoic-Cenozoic Cordilleran plate tectonics, *Mem. Geol. Soc. Am.*, 152, 33-50, 1978.
- Coney, P.J., Tertiary evolution of Cordilleran metamorphic core complexes, in *Cenozoic Paleogeography of the Western United States*, pp. 15-28, Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., 1979.
- Coney, P.J., Cordilleran metamorphic core complexes: An overview, *Mem. Geol. Soc. Am.*, 153, 7-31, 1980.
- Coney, P.J., The regional tectonic setting and possible causes of Cenozoic extension in the North American Cordillera, in *Continental Extensional Tectonics*, edited by M.P. Coward, J.F.

- Dewey, and P.L. Hancock, *Geol. Soc. Spec. Publ. London*, 28, 177-186, 1987.
- Coney, P.J., and T. Harms, Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression, *Geology*, 12, 550-554, 1984.
- Coney, P.J., and S.J. Reynolds, Cordilleran Benioff zones, *Nature*, 270, 403-406, 1977.
- Cook, K.L., Rift system in the Basin and Range Province, *Pap. Geol. Surv. Can.*, 66-4, 246-279, 1966.
- Cowan, D.S., Geological evidence for post-40 m.y. B.P. large-scale northwestward displacement of part of southeastern Alaska, *Geology*, 10, 309-313, 1982.
- Cross, T.A., and R.H. Pilger, Jr., Constraints on absolute motion and plate interaction inferred from Cenozoic igneous activity in the western United States, *Am. J. Sci.*, 278, 865-902, 1978.
- Cross, T.A., and R.H. Pilger, Jr., Controls of subduction geometry, location of magmatic arcs, and tectonics of arc and back-arc regions, *Geol. Soc. Am. Bull.*, 93, 545-562, 1982.
- Crowe, B.M., J.C. Crowell, and D. Krummenacher, Regional stratigraphy and K-Ar ages of Cenozoic volcanic rocks of southeastern California, *Am. J. Sci.*, 279, 186-216, 1979.
- Dallmeyer, R.D., A.W. Snoke, and E.H. McKee, The Mesozoic-Cenozoic tectonothermal evolution of the Ruby Mountains, East Humboldt Range, Nevada: A Cordilleran metamorphic core complex, *Tectonics*, 5, 931-954, 1986.
- Daly, R.A., *Igneous Rocks and the Depths of the Earth*, 598 pp., McGraw-Hill, New York, 1933.
- Damon, P.E., The relationship between late Cenozoic volcanism and tectonism and orogenic-epirogenic periodicity, in *The Late Cenozoic Glacial Ages*, edited by K.K. Turekian, pp. 15-35, Yale University Press, New Haven, Conn., 1971.
- Damon, P.E., and R.L. Mauger, Epirogeny-orogeny viewed from the Basin and Range province, *Trans. Soc. Min. Eng. AIME*, 235, 99-112, 1966.
- Davis, G.A., Problems of intraplate extensional tectonics, western United States, in *Continental Tectonics, Stud. Geophys.*, pp. 84-95, U.S. National Academy of Sciences, Washington, D.C., 1980.
- Davis, G.A., Rapid upward transport of mid-crustal mylonitic gneisses in the footwall of a Miocene detachment fault, Whipple Mountains, southeastern California, *Geol. Rundsch.*, 77, 191-209, 1988.
- Davis, G.A., and G.S. Lister, Detachment faulting in continental extension; Perspective from the southwestern U.S. Cordillera, in editors, *Processes in Continental Lithospheric Deformation*, edited by S.P. Clark, B.C. Burchfiel, and J. Suppe, *Spec. Pap. Geol. Soc. Am.*, 218, 133-159, 1988.
- Davis, G.H., and P.J. Coney, Geologic development of the Cordilleran metamorphic core complexes, *Geology*, 7, 120-124, 1979.
- Davy, P., G. Guérin, and J.-P. Brun, Thermal constraints on the tectonic evolution of a metamorphic core complex (Santa Catalina Mountains, Arizona), *Earth Planet. Sci. Lett.*, 94, 425-440, 1989.
- de Voogd, B., L. Serpa, L. Brown, E. Hauser, S. Kaufman, J. Oliver, B.W. Troxel, J. Willemin, and L. A. Wright, Death Valley bright spot: A mid-crustal magma body in the southern Great Basin, California, *Geology*, 14, 64-67, 1986.
- de Voogd, B., L. Serpa, and L. Brown, Crustal extension and magmatic processes: COCORP profiles from Death Valley and the Rio Grande rift, *Geol. Soc. Am. Bull.*, 100, 1550-1567, 1988.
- Dewey, J.F., Episodicity, sequence, and style at convergent plate boundaries, *Geol. Assoc. Can. Spec. Pap.*, 20, 553-573, 1980.
- Dewey, J.F., Extensional collapse of orogens, *Tectonics*, 7, 1123-1139, 1988.
- Dickinson, W.R., Relations of andesites granites and derivative sandstones to arc-trench tectonics, *Rev. Geophys.*, 8, 813-860, 1970.
- Dickinson, W.R., Widths of modern arc-trench gaps proportional to past duration of igneous activity in associated magmatic arcs, *J. Geophys. Res.*, 78, 3376-3389, 1973.
- Dickinson, W.R., Cenozoic plate tectonic setting of the Cordilleran region in the United States, in *Cenozoic Paleogeography of the Western United States*, pp. 1-13, Pacific Section, Society of Economic Paleontologists and Mineralogists, Bakersfield, Calif., 1979.
- Dickinson, W.R., Plate tectonic evolution of the southern Cordillera, *Ariz. Geol. Dig.*, 14, 113-135, 1981.
- Dickinson, W.R., and M. Shafiquallah, K-Ar and F-T ages for syntectonic mid-Tertiary volcanosedimentary sequences associated with the Catalina core complex and San Pedro trough in southern Arizona, *Isochron/West*, 52, 15-27, 1989.
- Dickinson, W.R., and W.S. Snyder, Plate tectonics of the Laramide orogeny, *Mem. Geol. Soc. Am.*, 151, 355-366, 1978.
- Dickinson, W.R., and W.S. Snyder, Geometry of subducted slabs related to San Andreas transform, *J. Geol.*, 87, 609-627, 1979a.
- Dickinson, W.R., and W.S. Snyder, Geometry of triple junctions related to San Andreas transform, *J. Geophys. Res.*, 84, 561-572, 1979b.
- Dickinson, W.R., M.A. Klute, M.J. Hayes, S.U. Janecke, E.R. Lundin, M.A. McKittrick, and M.D. Olivares, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region, *Geol. Soc. Am. Bull.*, 100, 1023-1039, 1988.
- Dokka, R.K., Synthesis of middle and late Cenozoic tectonic history of the Mojave Desert block (abstract), *Geol. Soc. Am. Abstr. Programs*, 20, 156, 1988.
- Dokka, R.K., The Mojave extensional belt of southern California, *Tectonics*, 8, 363-390, 1989.
- Dokka, R.K., and M.O. Woodburne, Mid-Tertiary extensional tectonics and sedimentation, central Mojave Desert, California, *Publ. Geol. Geophys. Tectonics Sediment*, 1, 55 pp., Louisiana State Univ. at Baton Rouge, 1986.
- Dokka, R.K., M.J. Mahaffie, and A.W. Snoke, Thermochronologic evidence of major tectonic denudation associated with detachment faulting, northern Ruby Mountains-East Humboldt Range, Nevada, *Tectonics*, 5, 995-1006, 1986.
- Duncan, R.A., A captured island chain in the Coast Range of Oregon and Washington, *J. Geophys. Res.*, 87, 10,827-10,837, 1982.
- Eaton, G.P., Geophysical and geological characteristics of the crust of the Basin and Range province, in *Continental Tectonics, Stud. Geophys.*, pp. 96-113, U.S. National Academy of Sciences, Washington, D.C., 1980.
- Eaton, G.P., The Miocene Great Basin of western North America as an extending back-arc region, *Tectonophysics*, 102, 275-295, 1984.
- Eaton, G.P., R.R. Wahl, H.J. Prostka, D.R. Mabey, and M.D. Kleinkopf, Regional gravity and tectonic patterns: Their relation to late Cenozoic epeirogeny and lateral spreading in the western Cordillera, *Mem. Geol. Soc. Am.*, 152, 51-91, 1978.
- Elston, W.E., Subduction of young oceanic lithosphere and extensional orogeny in southwestern North America during mid-Tertiary time, *Tectonics*, 3, 229-250, 1984.
- Engelbreton, D.C., A. Cox, and R.G. Gordon, Relative motions between oceanic and continental plates in the Pacific Basin, *Spec. Pap. Geol. Soc. Am.*, 206, 59 pp., 1985.
- Engel, A.E.J., and P.A. Schultejan, Late Mesozoic and Cenozoic tectonic history of south central California, *Tectonics*, 3, 659-675, 1984.
- Ewing, T.E., Paleogene tectonic evolution of the Pacific Northwest, *J. Geol.*, 88, 619-638, 1980.
- Ewing, T.E., Petrology and geochemistry of the Kamloops Group volcanics, British Columbia, *Can. J. Earth Sci.*, 18, 1478-1491, 1981.
- Fox, K.F., Jr., R.J. Fleck, G.H. Curtis, and C.E. Meyer, Implications of the northwestwardly younger age of the volcanic rocks of west-central California, *Geol. Soc. Am. Bull.*, 96, 647-654, 1985.
- Friedman, R.M., and R.L. Armstrong, Tatla Lake Metamorphic Complex: An Eocene metamorphic core complex on the southwestern edge of the Intermontane Belt of British Columbia, *Tectonics*, 7, 1141-1166, 1988.
- Gans, P.B., An open-system, two-layer crustal stretching model for the eastern Great Basin, *Tectonics*, 6, 1-12, 1987.
- Gans, P.B., G.A. Mahood, and E. Schermer, Synextensional magmatism in the Basin and Range Province; a case study from the Eastern Great Basin, *Spec. Pap. Geol. Soc. Am.*, 233, 58 pp., 1989.
- Garnezy, L., and J.F. Sutter, Mylonitization coincident with uplift in an extensional setting, Bitterroot Range, Montana-Idaho (abstract), *Geol. Soc. Am. Abstr. Programs*, 15, 578, 1983.
- Gaudemer, Y., C. Jaupart, and P. Tapponnier, Thermal control on

- post-orogenic extension in collision belts, *Earth Planet. Sci. Lett.*, **89**, 48-62, 1988.
- Gilluly, J., Steady plate motion and episodic orogeny and magmatism, *Geol. Soc. Am. Bull.*, **84**, 499-514, 1973.
- Glazner, A.F., and J.M. Bartley, Timing and tectonic setting of Tertiary low angle normal faulting and associated magmatism in the southwestern United States, *Tectonics*, **3**, 385-396, 1984.
- Glazner, A.F., and G. Schubert, Flexure of the North American lithosphere above the subducted Mendocino fracture zone and the formation of east-west faults in the Transverse Ranges, *J. Geophys. Res.*, **90**, 5405-5409, 1985.
- Glazner, A.F., and J.A. Supplee, Migration of Tertiary volcanism in the southwestern United States and subduction of the Mendocino fracture zone, *Earth Planet. Sci. Lett.*, **60**, 429-436, 1982.
- Gough, D.I., Mantle upflow under North America and plate dynamics, *Nature*, **311**, 428-433, 1984.
- Gough, D.I., Mantle upflow tectonics in the Canadian Cordillera, *J. Geophys. Res.*, **91**, 1909-1919, 1986.
- Green, N.L., R.L. Armstrong, J.E. Harakal, J.G. Souther, and P.B. Read, Eruptive history and K-Ar geochronology of the late Cenozoic Garibaldi volcanic belt, southwestern British Columbia, *Geol. Soc. Am. Bull.*, **100**, 563-579, 1988.
- Grond, H.C., S.J. Churchill, R.L. Armstrong, J.E. Harakal, and G.T. Nixon, Late Cretaceous age of the Hutshi, Mount Nansen, and Cammacks groups, southwestern Yukon Territory and northwestern British Columbia, *Can. J. Earth Sci.*, **21**, 554-558, 1984.
- Guffanti, M. and C.S. Weaver, Distribution of late Cenozoic volcanic vents in the Cascade Range: Volcanic arc segmentation and regional tectonic considerations, *J. Geophys. Res.*, **93**, 6513-6529, 1988.
- Hamilton, W.B., The volcanic central Andes: A modern model for the Cretaceous batholiths and tectonics of western North America, in Proceedings of the Andesite Conference, *Bull. Oreg. Dep. Geol. Miner. Ind.*, **65**, 175-184, 1969.
- Hamilton, W.B., Structural evolution of the Big Maria Mountains, northeastern Riverside County, southeastern California, in *Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada*, edited by E.G. Frost and D.L. Martin, pp. 1-27, Cordilleran Publishers, San Diego, Calif., 1982.
- Hamilton, W.B., Crustal extension in the Basin and Range Province, southwestern United States, in *Continental Extension Tectonics*, edited by M.P. Coward, J.F. Dewey, and P.L. Hancock, *Geol. Soc. Spec. Publ. London*, **28**, 155-176, 1987.
- Hamilton, W.B., and W.B. Myers, Cenozoic tectonics of the western United States, *Rev. Geophys.*, **4**, 509-549, 1966.
- Hansen, V.L., and J.W. Goode, Metamorphism, structural petrology, and regional evolution of the Okanagan complex, northeastern Washington, in *Metamorphism and Crustal Evolution of the Western United States, Rubey Volume VII*, edited by W.G. Ernst, 233-270, Prentice Hall, Englewood Cliffs, N. J., 1988.
- Harland, W.B., A.V. Cox, P.G. Llewellyn, C.A.G. Pickton, A.G. Smith, and R. Walters, *A Geologic Time Scale*, 128 pp., Cambridge University Press, Cambridge, 1982.
- Harland, W.B., R.L. Armstrong, L.E. Craig, A.G. Smith, and D.G. Smith, *A Geologic Time Scale, 1989*, 263 pp., Cambridge University Press, Cambridge, 1990.
- Harms, T.A., and R.A. Price, The Newport fault: Eocene crustal stretching, necking and listric normal faulting in NE Washington and NW Idaho (abstract), *Geol. Soc. Am. Abstr. Programs*, **15**, 309, 1983.
- Healy, J., Structure and volcanism in the Taupo volcanic zone, New Zealand, in *The Crust of the Pacific Basin, Geophys. Monogr. Ser.*, vol. 6, edited by G. A. MacDonald and H. Kuno, pp. 151-157, AGU, Washington, D.C., 1962.
- Heller, P.L., and P.T. Ryberg, Sedimentary record of subduction to forearc transition in the rotated Eocene basin of western Oregon, *Geology*, **11**, 380-383, 1983.
- Heller, P.L., R.W. Tabor, and C.A. Suczek, Paleogeographic evolution of the United States Pacific Northwest during Paleogene time, *Can. J. Earth Sci.*, **24**, 1652-1667, 1987.
- Henry, C.D., and F.W. McDowell, Geochronology of magmatism in the Tertiary volcanic field, Trans-Pecos Texas, in J.G. Price et al., editors, *Igneous Geology of Trans-Pecos Texas, Guideb. 23*, pp. 99-122, Bureau of Economic Geology University of Texas at Austin, 1986.
- Hickson, C.J., Structure and stratigraphy of the Masset Formation, Queen Charlotte Islands, British Columbia, *Pap. Geol. Surv. Can.*, **88-1E**, 269-274, 1988.
- Hickson, C.J., and J.G. Souther, Late Cenozoic volcanic rocks of the Clearwater-Wells Gray area, British Columbia, *Can. J. Earth Sci.*, **21**, 267-277, 1984.
- Hodges, K.V., J.D. Walker, and B.P. Wernicke, Footwall structural evolution of the Tucki Mountain Detachment system, Death Valley region, southeastern California, in *Continental Extension Tectonics*, edited by M.P. Coward, J.F. Dewey, and P.L. Hancock, *Geol. Soc. Spec. Publ. London*, **28**, 393-408, 1987.
- Hoffer, J.M., Petrology and mineralogy of the Campus Andesite pluton, El Paso, Texas, *Geol. Soc. Am. Bull.*, **81**, 2129-2136, 1970.
- Holder, R.W., and G.A.M. Holder, The Colville batholith: Tertiary plutonism in northeast Washington associated with graben and core-complex (gneiss dome) formation, *Geol. Soc. Am. Bull.*, **100**, 1971-1980, 1988.
- Hooper, P.R., and D.A. Swanson, Evolution of the eastern part of the Columbia Plateau, in *Selected Papers on the Geology of Washington*, edited by J.E. Schuster, *Bull. Wash. Div. Geol. Earth Resour.*, **77**, 197-217, 1987.
- Hornafius, J.S., B.P. Luyendyk, R.R. Terres, and M.J. Kamerling, Timing and extent of Neogene tectonic rotation in the western Transverse Ranges, California, *Geol. Soc. Am. Bull.*, **97**, 1476-1487, 1986.
- Howard, K.A., and B.E. John, Crustal extension along a rooted system of imbricate low-angle faults: Colorado River extensional corridor, California and Arizona, in *Continental Extensional Tectonics*, edited by M.P. Coward, J.F. Dewey, and P.L. Hancock, *Geol. Soc. Spec. Publ. London*, **28**, 299-311, 1987.
- Howard, K.A., J.E. Nielson, J.K. Nakata, and H.G. Wilshire, Uplended crustal slabs and low-angle extensional faults in the Colorado River extensional corridor: Geologic map of the Mohave Mountains area, western Arizona (abstract), *Geol. Soc. Am. Abstr. Programs*, **22**, 30, 1990.
- Hyndman, D.W., and S.A. Myers, The transition from amphibolite-facies mylonite to chloritic breccia and role of the mylonite in formation of Eocene epizonal plutons, Bitterroot dome, Montana, *Geol. Rundsch.*, **77**, 211-226, 1988.
- Ingersoll, R.V., Triple-junction instability as cause for late Cenozoic extension and fragmentation of the western United States, *Geology*, **10**, 621-624, 1982.
- Isaac, S., T.K. Rockwell, and G. Gastil, Plio-Pleistocene detachment faulting, Yuha Desert region, western Salton Trough, northern Baja California (abstract), *Geol. Soc. Am. Abstr. Programs*, **18**, 120, 1986.
- Isachsen, C.E., Geology, geochemistry, and cooling history of the Westcoast Crystalline Complex and related rocks, Meares Island and vicinity, Vancouver Island, British Columbia, *Can. J. Earth Sci.*, **24**, 2047-2064, 1987.
- Iyer, H.M., A review of crust and upper mantle structure studies of the Snake River Plain-Yellowstone volcanic system, A major lithospheric anomaly in the western U.S.A., *Tectonophysics*, **105**, 291-308, 1984.
- Jarrard, R.D., Relations among subduction parameters, *Rev. Geophys.*, **24**, 217-284, 1986a.
- Jarrard, R.D., Terrane motion by strike-slip faulting of forearc slivers, *Geology*, **14**, 780-783, 1986b.
- Johnson, C.M., and J.R. O'Neil, Triple junction magmatism: a geochemical study of Neogene volcanic rocks in western California, *Earth Planet. Sci. Lett.*, **71**, 241-262, 1984.
- Journeay, J.M., Stratigraphy internal strain and thermotectonic evolution of northern Frenchman Cap dome: exhumed duplex structure, Omineca hinterland, SE Canadian Cordillera, Ph.D. thesis, 350 pp., Queens Univ. at Kingston, Ont., 1986.
- Keith, S.B., Paleosubduction geometries inferred from Cretaceous and Tertiary magmatic patterns in southwestern North America, *Geology*, **6**, 516-521, 1978.
- Klemperer, S.L., T.A. Hauge, E.C. Hauser, J.E. Oliver, and C.J. Potter, 1986, The Moho in the northern Basin and Range province, Nevada, along the COCORP 40°N seismic reflection transect, *Geol. Soc. Am. Bull.*, **97**, 603-618, 1986.
- Kosco, D.G., The Edgcombe volcanic field, Alaska: An example of tholeiitic and calc-alkaline volcanism, *J. Geol.*, **89**, 459-477, 1981.
- Lachenbruch, A.H., and P. Morgan, Continental extension,

- magmatism and elevation: Formal relations and rules of thumb, *Tectonophysics*, 174, 39-62, 1990.
- Larsen, E.S., The petrographic province of central Montana, *Geol. Soc. Am. Bull.*, 51, 887-948, 1940.
- Laughlin, A.W., M.J. Aldrich, Jr., M. Shafiqullah, and J. Husler, Tectonic implications of the age, composition, and orientation of lamprophyre dikes, Navajo volcanic field, Arizona, *Earth Planet. Sci. Lett.*, 76, 361-374, 1986.
- Lee, J., E.L. Miller, and J.F. Sutter, Ductile strain and metamorphism in an extensional tectonic setting: a case study from the northern Snake Range, Nevada, U.S.A., in *Continental Extensional Tectonics*, edited by M.P. Coward, J.F. Dewey, and P.L. Hancock, *Geol. Soc. Spec. Publ. London*, 28, 267-298, 1987.
- Leeman, W.P., Development of the Snake River Plain-Yellowstone Plateau Province, Idaho and Wyoming: An overview and petrologic model, in *Cenozoic Geology of Idaho*, *Bull. Idaho Bur. of Mines and Geol.*, 26, 155-177, 1982a.
- Leeman, W.P., Tectonic and magmatic significance of strontium isotopic variations in Cenozoic volcanic rocks from the western United States, *Geol. Soc. Am. Bull.*, 93, 487-503, 1982b.
- Lipman, P.W., Cenozoic volcanism in the western United States: Implications for continental tectonics, in *Continental Tectonics, Stud. in Geophys.*, pp. 161-174, U.S. National Academy of Sciences, Washington, D. C., 1980.
- Lipman, P.W., H.J. Prostka, and R.L. Christiansen, Evolving subduction zones in the western United States, as interpreted from igneous rocks, *Science*, 174, 821-825, 1971.
- Lipman, P.W., H.J. Prostka, and R.L. Christiansen, Cenozoic volcanism and plate tectonic evolution of the western United States, I, Early and Middle Cenozoic, *Philos. Trans. R. Soc. London, Ser. A*, 271, 217-248, 1972.
- Lipman, P.W., H.H. Mehnert, and C.W. Naeser, Evolution of the Latir volcanic field, northern New Mexico, and its relation to the Rio Grande rift, as indicated by potassium-argon and fission track dating, *J. Geophys. Res.*, 91, 6329-6345, 1986.
- Livaccari, R.F., Late Cenozoic tectonic evolution of the western United States, *Geology*, 7, 72-75, 1979.
- Loper, D.E., On the endogenous production of episodic flood basalts (abstract), *Geol. Soc. Am. Abstr. Programs*, 21, 93, 1989.
- Lucchitta, I., Role of heat and detachment in continental extension as viewed from the eastern Basin and Range Province in Arizona, *Tectonophysics*, 174, 77-114, 1990.
- Luedke, R.G., and R.L. Smith, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Arizona and New Mexico, *U.S. Geol. Surv. Misc. Invest. Ser. Map, I-1091 A*, 1979a.
- Luedke, R.G., and R.L. Smith, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Colorado, Utah, and southwestern Wyoming, *U.S. Geol. Surv. Misc. Invest. Ser. Map, I-1091 B*, 1979b.
- Luedke, R.G., and R.L. Smith, Map showing distribution, composition, and age of late Cenozoic volcanic centers in California and Nevada, *U.S. Geol. Surv. Misc. Invest. Ser. Map, I-1091 C*, 1981.
- Luedke, R.G., and R.L. Smith, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Oregon and Washington, *U.S. Geol. Surv. Misc. Invest. Ser. Map, I-1091 D*, 1982.
- Luedke, R.G., and R.L. Smith, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Idaho, western Montana, west-central South Dakota, and northwestern Wyoming, *U.S. Geol. Surv. Misc. Invest. Ser. Map, I-1091 E*, 1983.
- Luedke, R.G., and R.L. Smith, Map showing distribution, composition, and age of late Cenozoic volcanic centers in the western conterminous United States, *U.S. Geol. Surv., Misc. Inv. Series, Maps I-1523*, 1984.
- Luedke, R.G., and R.L. Smith, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Alaska, *U.S. Geol. Surv. Misc. Invest. Ser. Map, I-1091 F*, 1986.
- Luedke, R.G., R.L. Smith and S. L. Russell-Robinson, Map showing distribution, composition, and age of late Cenozoic volcanics and volcanic rocks of the Cascade Range and vicinity, northwestern United States, *U.S. Geol. Surv. Misc. Invest. Ser. Map, I-1507*, 1983.
- Lull, J.S., and G. Plafker, Geochemistry and petrography of lamprophyre dike rocks in the Coast Mountains, southeastern Alaska, *U.S. Geol. Surv. Circ.*, 1016, 169-173, 1988.
- Lynch, H.D., and P. Morgan, The tensile strength of the lithosphere and the localization of extension, in *Continental Extensional Tectonics*, edited by M.P. Coward, J.F. Dewey, and P.L. Hancock, *Geol. Soc. Spec. Publ. London*, 28, 53-65, 1987.
- Malavielle, J., Extensional shearing deformation and kilometer-scale "a"-type folds in a Cordilleran metamorphic core complex (Raft River Mountains, northwestern Utah), *Tectonics*, 6, 423-448, 1987.
- Massey, N.W.D., Metchosin Igneous Complex, southern Vancouver Island: Ophiolite stratigraphy developed in an emergent island setting, *Geology*, 14, 602-605, 1986.
- Massey, N.W.D., and R.L. Armstrong, The Eocene Flores volcanics — Transform-fault volcanism on Vancouver Island (abstract), *Geol. Soc. Am. Abstr. Programs*, 21, 112, 1989.
- Mathews, W.M., Neogene geology of the Okanagan Highland, British Columbia, *Can. J. Earth Sci.*, 25, 725-731, 1988.
- Mathews, W.H., Neogene Chilcotin basalts in south-central British Columbia: Geology, ages, and geomorphic history, *Can. J. Earth Sci.*, 26, 969-982, 1989.
- Mathews, W.H., and G.E. Rouse, An Early Pleistocene proglacial succession in south-central British Columbia, *Can. J. Earth Sci.*, 23, 1796-1803, 1986.
- Mathews, V., III, Pinnacles-Neenach correlation — A restriction for models of the origin of the Transverse Ranges and the Big Bend in the San Andreas fault, *Geol. Soc. Am. Bull.*, 84, 683-688, 1973.
- Mathews, V., III and C.E. Anderson, Yellowstone convection plume and breakup of the western United States, *Nature*, 243, 158-159, 1973.
- McBirney, A.R., Volcanic evolution of the Cascade Range, *Annu. Rev. Earth Planet. Sci.*, 6, 437-456, 1978.
- McBirney, A.R., J.F. Sutter, H.R. Naslund, K.G. Sutton, and C.M. White, Episodic volcanism in the central Oregon Cascade Range, *Geology*, 2, 585-589, 1974.
- McCarthy, J., and G.A. Thompson, Seismic imaging of extended crust with emphasis on the western United States, *Geol. Soc. Am. Bull.*, 100, 1361-1374, 1988.
- McCarthy, J., G. Fuis, and J. Wilson, Crustal structure of the Whipple Mountains, southeastern California: A refraction study across a region of large continental extension, *Geophys. J. R. Astron. Soc.*, 89, 119-124, 1987.
- McDowell, F.W., K-Ar ages of igneous rocks from the western United States, *Isochron/West*, 2, 1-16, 1971.
- McElwee, K.R., and R.A. Duncan, Punctuated volcanism in Oregon's Coast Range (abstract), *Eos Trans. AGU*, 65, 330, 1984.
- McKee, E.H., Tertiary igneous chronology of the Great Basin of western United States — Implications for tectonic models, *Geol. Soc. Am. Bull.*, 82, 3497-3502, 1971.
- McKee, E.H., Reset K-Ar ages: Evidence for three metamorphic core complexes, western Nevada, *Isochron/West*, 38, 17-20, 1983.
- McKee, E.H., and C.A. Anderson, Age and chemistry of Tertiary volcanic rocks in north-central Arizona and relation of the rocks to Colorado Plateaus, *Geol. Soc. Am. Bull.*, 82, 2767-2782, 1971.
- McKee, E.H., D.C. Noble, and M.L. Silberman, Middle Miocene hiatus in volcanic activity in the Great Basin area of the western United States, *Earth Planet. Sci. Lett.*, 8, 93-96, 1970.
- McKee, E.H., N.S. MacLeod, and G.W. Walker, Potassium-argon ages of late Cenozoic silicic volcanic rocks, southeast Oregon, *Isochron/West*, 15, 37-41, 1976.
- McLaughlin, R.J., and J.M. Donnelly-Nolan (Eds.), Research in The Geysers-Clear Lake geothermal area, northern California, *U.S. Geol. Surv. Prof. Pap.*, 1141, 259 pp., 1981.
- McLaughlin, R.J., S.A. Kling, R.Z. Poore, K. McDougall, and E.C. Beutner, Post-middle Miocene accretion of Franciscan rocks, northwestern California, *Geol. Soc. Am. Bull.*, 93, 595-605, 1982.
- Menard, H.W., The East Pacific Rise, *Science*, 132, 1737-1746, 1960.
- Meyers, J.D., and B.D. Marsh, Geology and petrogenesis of the Edgcombe volcanic field, SE Alaska: The interaction of basalt and sialic crust, *Contrib. Mineral. Petrol.*, 77, 272-287, 1981.
- Miller, E.L., P.B. Gans, J.E. Wright, and J.F. Sutter, Metamorphic history of the east-central Basin and Range Province: Tectonic setting and relationship to magmatism, in *Metamorphism and*

- Crustal Evolution of the Western United States, Rubey Volume VII*, edited by W. G. Ernst, pp. 649-682, Prentice-Hall, Englewood Cliffs, N.J., 1988.
- Miller, F.K., The Newport fault and associated mylonites, northeastern Washington, *U.S. Geol. Surv. Prof. Pap.*, 750 D, 77-79, 1971.
- Miller, J.M.G., and B.E. John, Detached strata in a Tertiary low-angle normal fault terrane, southeastern California: A sedimentary record of unroofing, breaching, and continued slip, *Geology*, 16, 645-648, 1988.
- Molnar, P., and T. Atwater, Interarc spreading and Cordilleran tectonics as alternates related to the age of subducted oceanic lithosphere, *Earth Planet. Sci. Lett.*, 41, 330-340, 1978.
- Molnar, P., and H. Lyon-Caen, Some simple physical aspects of the support, structure, and evolution of mountain belts, *Spec. Pap. Geol. Soc. Am.*, 218, 179-207, 1988.
- Monger, J.W.H., P. van der Heyden, and J.F. Mustard, Evolution of the eastern Coast Mountains, near Lillooet, southwestern British Columbia (abstract), *Eos Trans. AGU*, 65, 330, 1984.
- Morgan, P., W.R. Seager, and M.P. Golombek, Cenozoic thermal, mechanical and tectonic evolution of the Rio Grande rift, *J. Geophys. Res.*, 91, 6263-6276, 1986.
- Morgan, W.J., Hotspot tracks and the opening of the Atlantic and Indian oceans, in *The Sea*, vol. 7, edited by C. Emiliani, pp. 443-487, J. Wiley and Sons, New York, 1981.
- Muller, J.E., Chemistry and origin of the Eocene Metchosin Volcanics, Vancouver Island, British Columbia, *Can. J. Earth Sci.*, 17, 199-209, 1980.
- Mutschler, F.E., E.E. Larson, and R.M. Bruce, Laramide and younger magmatism in Colorado - New petrologic and tectonic variations on old themes, *Colo. Sch. Mines Q.*, 82(4), 1-47, 1988.
- Naeser, C.W., Geochronology of the Navajo-Hopi diatremes, Four Corners area, *J. Geophys. Res.*, 76, 4978-4985, 1971.
- Noble, D.C., Some observations on the Cenozoic volcano-tectonic evolution of the Great Basin, western United States, *Earth Planet. Sci. Lett.*, 17, 142-150, 1972.
- Noel, G.A., Cenozoic rocks in western Canadian Cordillera of British Columbia and Yukon Territory, *Geol. Surv. Can. Open File 659*, 39 pp., 1979.
- O'Brien, H.E., A.J. Irving, and I.S. McCallum, Eocene potassic magmatism in the Highwood Mountains, Montana: Geology, petrology and geochemistry, *Spec. Pap. Geol. Soc. Am.*, in press, 1991.
- Okulitch, A.V., The role of the Shuswap Metamorphic Complex in Cordilleran tectonism: A review, *Can. J. Earth Sci.*, 21, 1171-1193, 1984.
- O'Neill, R.L., and T.L. Pavlis, Superposition of Cenozoic extension on Mesozoic compressional structures in the Pioneer Mountains metamorphic core complex, central Idaho, *Geol. Soc. Am. Bull.*, 100, 1833-1845, 1988.
- Page, B.M., and D.C. Engebretson, Correlation between the geologic record and computed plate motions for central California, *Tectonics*, 3, 135-155, 1984.
- Palmer, A.R., The Decade of North American Geology 1983 geologic time scale, *Geology*, 11, 503-504, 1983.
- Parrish, R.R., S.D. Carr, and D.L. Parkinson, Eocene extensional tectonics and geochronology of the southern Omineca Belt, British Columbia and Washington, *Tectonics*, 7, 181-212, 1988.
- Pierce, K.L., W.E. Scott, and L.A. Morgan, Eastern Snake River Plain neotectonics: Faulting in last 15 Ma migrates along the outward from the Yellowstone "hotspot" track (abstract), *Geol. Soc. Am. Abstr. Programs*, 20, 463, 1988.
- Pilger, R.H., Jr., and T.L. Henley, Pacific-North American plate interaction and Neogene volcanism in coastal California, *Tectonophysics*, 57, 189-209, 1979.
- Potter, C.J., Origin, accretion, and postaccretionary evolution of the Bridge River terrane, southwest British Columbia, *Tectonics*, 5, 1027-1041, 1986.
- Potter, C.J., W.E. Sanford, T.R. Yoos, E.I. Prussen, R.W. Keach, II, J.E. Oliver, S. Kaufman, and L.D. Brown, COCORP deep seismic reflection traverse of the interior of the North American Cordillera, Washington and Idaho: Implications for orogenic evolution, *Tectonics*, 5, 1007-1025, 1986.
- Price, R.A., and D.M. Carmichael, Geometric test for Late Cretaceous-Paleogene intracontinental transform faulting in the Canadian Cordillera, *Geology*, 14, 468-471, 1986.
- Priest, G.R., Volcanic and tectonic evolution of the Cascade volcanic arc, 44° 00' 00" to 44° 52' 30" N, *U.S. Geol. Surv. Open File Rep.*, 89-178, 430-489, 1989.
- Priest, G.R., and B.F. Vogt (Eds.), Geology and geothermal resources of the central Oregon Cascade Range, *Spec. Pap. Oregon Geol. Miner. Ind.*, 15, 123 pp., 1983.
- Proffett, J.M., Jr., Cenozoic geology of the Yerington district, Nevada, and implications for the nature and origin of Basin and Range faulting, *Geol. Soc. Am. Bull.*, 88, 247-266, 1977.
- Rehrig, W.A., S.J. Reynolds, and R.L. Armstrong, A tectonic and geochronologic overview of the Priest River Crystalline Complex, northeastern Washington and northern Idaho, in: Selected Papers on the Geology of Washington, edited by J.E. Schuster, *Bull. Wash. Div. Geol. Earth Resour.*, 77, 1-14, 1987.
- Ren, X., B.J. Kowallis, and M.G. Best, Paleostress history of the Basin and Range province in western Utah and eastern Nevada from healed microfracture orientations in granites, *Geology*, 17, 487-490, 1989.
- Reston, T.J., The lower crust and extension of the continental lithosphere: Kinematic analysis of BIRPS deep seismic data, *Tectonics*, 9, 1235-1248, 1990.
- Reynolds, M.W., L.A. Wright, and B.W. Troxel, Geometry and chronology of Late Cenozoic detachment faulting, Funeral and Grapevine Mountains, Death Valley, California (abstract), *Geol. Soc. Am. Abstr. Programs*, 18, 175, 1986.
- Reynolds, S.J., and J.E. Spencer, Evidence for large-scale transport on the Bullard detachment fault, west-central Arizona, *Geology*, 13, 353-356, 1985.
- Reynolds, S.J., M. Shafiqullah, P.E. Damon, and E. DeWitt, Early Miocene mylonitization and detachment faulting, South Mountains, central Arizona, *Geology*, 14, 283-286, 1986.
- Rhodes, B.P., and E.S. Cheney, Low-angle faulting and the origin of Kettle dome, a metamorphic core complex in northeastern Washington, *Geology*, 9, 366-369, 1981.
- Rhodes, B.P., and D.W. Hyndman, Regional metamorphism, structure, and tectonics of northeastern Washington and northern Idaho, in *Metamorphism and Crustal Evolution of the Western United States, Rubey Volume VII*, edited by W.G. Ernst, pp. 271-295, Prentice-Hall, Englewood Cliffs, N.J., 1988.
- Richards, M.A., R.A. Duncan, and V.E. Courtillot, Flood basalts and hot spot tracks: Plume heads and tails, *Science*, 246, 103-107, 1989.
- Richards, T.A., and K.C. McTaggart, Granitic rocks of the southern Coast Plutonic Complex and northern Cascades of British Columbia, *Geol. Soc. Am. Bull.*, 87, 935-953, 1976.
- Ross, J.V., The nature and rheology of the Cordilleran upper mantle of British Columbia: Inferences from peridotite xenoliths, *Tectonophysics*, 100, 321-357, 1983.
- Rouse, G.E., and W.H. Mathews, Palynology and geochronology of Eocene beds from Cheslatta Falls and Nazko areas, central British Columbia, *Can. J. Earth Sci.*, 25, 1268-1276, 1988.
- Rowley, P.D., J.J. Anderson, P.L. Williams, and R.J. Fleck, Age of structural differentiation between the Colorado Plateaus and Basin and Range provinces in southwestern Utah, *Geology*, 6, 51-55, 1978.
- Scholz, C.H., M. Barazangi, and M.L. Sbar, Late Cenozoic evolution of the Great Basin, western United States, as an ensialic interarc basin, *Geol. Soc. Am. Bull.*, 82, 2979-2990, 1971.
- Schultejann, P.A., The Yaqui Ridge antiform and detachment fault: Mid-Cenozoic extensional terrane west of the San Andreas fault, *Tectonics*, 3, 677-691, 1984.
- Scott, R.B., R.W. Nesbitt, E.J. Dasch, and R.L. Armstrong, A strontium isotope evolution model for Cenozoic magma genesis, eastern Great Basin U.S.A., *Bull. Volcanol.*, 35-1, 1-26, 1971.
- Seager, W.R., M. Shafiqullah, J.W. Hawley, and R.F. Marvin, New K-Ar dates from basalts and the evolution of the southern Rio Grande rift, *Geol. Soc. Am. Bull.*, 95, 87-99, 1984.
- Sévrier, M., J.L. Mercier, J. Macharé, D. Bonnot, J. Cabrera, and J.L. Blanc, The state of stress in an overriding plate situated above a flat slab: The Andes of central Peru, *Tectonics*, 7, 895-928, 1988.
- Shackelford, T.J., Tertiary tectonic denudation of a Mesozoic-early Tertiary(?) gneiss complex, Rawhide Mountains, western Arizona, *Geology*, 8, 190-194, 1980.
- Shafiqullah, M., P.E. Damon, D.J. Lynch, S.J. Reynolds, W.A. Rehrig, and R.H. Raymond, K-Ar geochronology and geologic

- history of southwestern Arizona and adjacent areas, *Ariz. Geol. Soc. Dig.*, 12, 201-260, 1980.
- Sherrod, D.R., L.G. Pickthorn, R.M. Tosdal, M.J. Grubensky, and R.D. Koch, Major early Miocene extensional deformation in southwestern Arizona and southeastern California (abstract), *Geol. Soc. Am. Abstr. Programs*, 19, 841, 1987.
- Silverberg, D. S., Denudation rates and timing of diachronous Paleogene Extension in south-central Idaho (abstract), *Geol. Soc. Am. Abstr. Programs*, 22, 330, 1990.
- Skulski, T., The origin and setting of anomalous arc magmatism in the Wrangell Volcanic Belt, southwest Yukon, *Yukon Geol.*, 2, 88-98, 1988.
- Smith, G.A., L.W. Snee, and E.M. Taylor, Stratigraphic, sedimentologic, and petrologic record of late Miocene subsidence of central Oregon High Cascades, *Geology*, 15, 389-392, 1987.
- Smith, J.G., M.S. Sawlan, and A.C. Katcher, An important lower Oligocene welded-tuff marker bed in the western Cascade Range of southern Oregon (abstract), *Geol. Soc. Am. Abstr. Programs*, 12, 152, 1980.
- Smith R.B., Seismicity, crustal structure, and intraplate tectonics of the interior of the western Cordillera, *Mem. Geol. Soc. Am.*, 152, 111-144, 1978.
- Smith, R.B., and M.L. Sbar, Contemporary tectonics and seismicity of the western United States with emphasis on the intermountain seismic belt, *Geol. Soc. Am. Bull.*, 85, 1205-1218, 1974.
- Smith, R.L., and R.G. Luedke, Potentially active volcanic lineaments and loci in western conterminous United States, in *Explosive Volcanism: Inception, Evolution, and Hazards*, pp. 47-66, U.S. National Academy Press, 1984.
- Snoke, A.W., and D.M. Miller, Metamorphic and tectonic history of the northeastern Great Basin, in *Metamorphism and Crustal Evolution of the Western United States, Rubey Volume VII*, edited by W.G. Ernst, pp. 606-648, Prentice-Hall, Englewood Cliffs, N.J., 1988.
- Snyder, W.S., W.R. Dickinson, and M.L. Silberman, Tectonic implications of space-time patterns of Cenozoic magmatism in the western United States, *Earth Planet. Sci. Lett.*, 32, 91-106, 1976.
- Souther, J.G., Acid volcanism and its relationship to the tectonic history of the Cordillera of British Columbia, Canada, *Bull. Volcanol.*, 30, 161-176, 1967.
- Souther, J.G., Volcanism and its relationship to recent crustal movements in the Canadian Cordillera, *Can. J. Earth Sci.*, 7, 553-568, 1970.
- Souther, J.G., Volcanism and tectonic environments in the Canadian Cordillera — A second look, *Geol. Assoc. Can. Spec. Pap.*, 16, 3-24, 1977.
- Souther, J.G., The Ilgachuz Range a peralkaline shield volcano in central British Columbia, *Pap. Geol. Surv. of Can.*, 84-1A, 1-10, 1984.
- Souther, J.G., The western Anahim Belt: Root zone of a peralkaline magma system, *Can. J. Earth Sci.*, 23, 895-908, 1986.
- Souther, J.G., R.L. Armstrong, and J. Harakal, Chronology of the peralkaline, late Cenozoic Mount Edziza Volcanic Complex, northern British Columbia, Canada, *Geol. Soc. Am. Bull.*, 95, 337-349, 1984.
- Stanley, R.G., Implications of the northeastward younger age of the volcanic rocks of west-central California: Alternative interpretation, *Geol. Soc. Am. Bull.*, 98, 612-614, 1987.
- Steiger, R.H., and E. Jäger, Subcommittee on geochronology: Convention on the use of decay constants in geo- and cosmochronology, *Earth Planet. Sci. Lett.*, 36, 359-362, 1977.
- Stewart, J.H., Basin-range structure in western North America: A review, *Mem. Geol. Soc. Am.*, 152, 1-31, 1978.
- Stewart, J.H., and J.E. Carlson, Generalized maps showing distribution, lithology, and age of Cenozoic igneous rocks in the western United States, *Mem. Geol. Soc. Am.*, 152, 263-264, 1978.
- Stewart, J.H., W.J. Moore, and I. Zietz, East-west patterns of Cenozoic igneous rocks, aeromagnetic anomalies, and mineral deposits, Nevada and Utah, *Geol. Soc. Am. Bull.*, 88, 67-77, 1977.
- Stille, H., *Einführung in den Bau Amerikas*, 717 pp., Gebrüder Borntraeger, Berlin, 1940.
- Stock, J. and P. Molnar, Uncertainties and implications of the Late Cretaceous and Tertiary position of North America relative to the Farallon, Kula, and Pacific plates, *Tectonics*, 7, 1339-1384, 1988.
- Sullivan, K., Isotopic ages of igneous intrusions in southeastern Utah: Relation to space-time-composition patterns of Cenozoic igneous activity in Nevada, Utah and Colorado (abstract), *Geol. Soc. Am. Abstr. Programs*, 19, 337, 1987.
- Suppe, J., C. Powell, and R. Berry, Regional topography, seismicity, Quaternary volcanism and the present-day tectonics of the western United States, *Am. J. Sci.*, 275-A, 397-436, 1975.
- Tempelman-Kluit, D.J., Reconnaissance geology of Aishihik Lake, Snag and part of Stewart River map-areas, west-central Yukon, *Pap. Geol. Surv. Can.*, 73-41, 97 pp., 1974.
- Tempelman-Kluit, D.J., The Yukon Crystalline Terrane: Enigma in the Canadian Cordillera, *Geol. Soc. Am. Bull.*, 87, 1343-1357, 1976.
- Tempelman-Kluit, D., and D. Parkinson, Extension across the Eocene Okanagan crustal shear in southern British Columbia, *Geology*, 14, 318-321, 1986.
- Tennyson, M.E., Pre-transform early Miocene extension in western California, *Geology*, 17, 792-796, 1989.
- Thompson, G.A., Cenozoic Basin Range tectonism in relation to deep structure, *Int. Geol. Congr.*, XXIV, Sec. 3, 84-90, 1972.
- Thompson, G.A., and R.E. Anderson, Thin skin distension in Tertiary rocks of southeastern Nevada: Discussion and Reply, *Geol. Soc. Am. Bull.*, 82, 3529-3536, 1971.
- Thompson, G.A., and D.B. Burke, Regional geophysics of the Basin and Range Province, *Annu. Rev. Earth Planet. Sci.*, 2, 213-238, 1974.
- Thompson, G.A., and J. McCarthy, A gravity constraint on the origin of highly extended terranes, *Tectonophysics*, 174, 197-206, 1990.
- Thorkelson, D.J., and R.P. Taylor, Cordilleran slab windows, *Geology*, 17, 833-836, 1989.
- Thorman, C.H., and L.W. Snee, Thermochronology of metamorphic rocks in the Wood Hills and Pequop Mountains, northeastern Nevada (abstract), *Geol. Soc. Am. Abstr. Programs*, 20, 18, 1988.
- Tobisch, O.T., J.B. Saleeby, and R.S. Fiske, Structural history of continental volcanic arc rocks, eastern Sierra Nevada, California: A case for extensional tectonics, *Tectonics*, 5, 65-94, 1986.
- Todd, V.R., Structure and petrology of a Tertiary gneiss complex in northwestern Utah, *Mem. Geol. Soc. Am.*, 153, 349-383, 1980.
- Valasek, P.A., A.W. Snoke, C.A. Hurich, and S.B. Smithson, Nature and origin of seismic reflection fabric, Ruby-East Humboldt metamorphic core complex, Nevada, *Tectonics*, 8, 391-415, 1989.
- van der Heyden, P., U-Pb and K-Ar geochronometry of the Coast Plutonic Complex, 53°N to 54°N, British Columbia, and implications for the Insular-Intermontane superterrane boundary, Ph.D. thesis, 392 pp., Univ. of B. C., Vancouver, 1989.
- Verplanck, E.P., and R.A. Duncan, Temporal variations in plate convergence and eruption rates in the Western Cascades, Oregon, *Tectonics*, 6, 197-209, 1987.
- Vogt, P.R., Subduction and seismic ridges, *Nature*, 241, 189-191, 1973.
- Ward, P.L., Volcanism and plate tectonics of the western United States (abstract), *Eos Trans. AGU*, 67, 1226, 1986.
- Wells, R.E., and P.L. Heller, The relative contribution of accretion, shear, and extension to Cenozoic tectonic rotation in the Pacific Northwest, *Geol. Soc. Am. Bull.*, 100, 325-338, 1988.
- Wells, R.E., D.C. Engebretson, P.D. Snavely, Jr., and R.S. Coe, Cenozoic plate motions and the volcano-tectonic evolution of western Oregon and Washington, *Tectonics*, 3, 275-294, 1984.
- Wernicke, B., Low-angle normal faults in the Basin and Range Province: Nappe tectonics in an extending orogen, *Nature*, 291, 645-648, 1981.
- Wernicke, B., Uniform-sense normal simple shear of the continental lithosphere, *Can. J. Earth Sci.*, 22, 108-125, 1985.
- Wernicke, Brian, The fluid crustal layer and its implications for continental dynamics, in *Exposed Cross-Sections of the Continental Crust*, edited by M. H. Salisbury and D. M. Fountain, pp. 509-544, Kluwer, Dordrecht, 1990.
- Wernicke, B.P., R.L. Christiansen, P.C. England, and L.J. Sonder, Tectonomagmatic evolution of Cenozoic extension in the North American Cordillera, in *Continental Extensional Tectonics*, edited by M.P. Coward, J.F. Dewey, and P.L. Hancock, *Geol. Soc. Spec. Publ. London*, 28, 203-221, 1987.

- Wernicke, B., G.J. Axen, and J.K. Snow, Basin and Range extensional tectonics at the latitude of Las Vegas, Nevada, *Geol. Soc. Am. Bull.*, 100, 1738-1757, 1988.
- Westaway, R., Deformation of the NE Basin and Range Province: The response of the lithosphere to the Yellowstone plume?, *Geophys. J. Int.*, 99, 33-62, 1989a.
- Westaway, R., Northeast Basin and Range province active tectonics: An alternative view, *Geology*, 17, 779-783, 1989b.
- White, C.M., and A.R. McBirney, Some quantitative aspects of orogenic volcanism in the Oregon Cascades, *Mem. Geol. Soc. Am.*, 152, 369-388, 1978.
- Wilshire, H.G., and J.W. Shervais, Al-augite and Cr-diopside ultramafic xenoliths in basaltic rocks from western United States, *Phys. Chem. Earth*, 9, 257-272, 1975.
- Wilson, J.A., P.C. Twiss, R.K. DeFord, and S.E. Clabaugh, Stratigraphic succession, potassium-argon dates, and vertebrate faunas, Vieja Group, Rim Rock Country, Trans-Pecos Texas, *Am. J. Sci.*, 266, 590-604, 1968.
- Wilson, J.T., Convection tectonics: Some possible effects upon the Earth's surface of flow from the deep mantle, *Can. J. Earth Sci.*, 25, 1199-1208, 1988.
- Wust, S.L., Regional correlation of extension directions in Cordilleran metamorphic core complexes, *Geology*, 14, 828-830, 1986a.
- Wust, S.L., Tertiary extensional detachment system with westward vengeance, exposing brittle-to-ductile transition, Pioneer structural complex, central Idaho (abstract), *Geol. Soc. Am. Abstr. Programs*, 18, 201, 1986b.
- Yorath, C.J., and R.D. Hyndman, Subsidence and thermal history of Queen Charlotte Basin, *Can. J. Earth Sci.*, 20, 135-159, 1983.
- Young, I.F., Structure of the western margin of the Queen Charlotte Basin, British Columbia, M.Sc. thesis, 380 pp., Univ of B. C., Vancouver, 1981.
- Zandt, G. and K.P. Furlong, Evolution and thickness of the lithosphere beneath coastal California, *Geology*, 10, 376-381, 1982.
- Zartman, R.E., J.C. Cole, and R.F. Marvin, User's guide to the Radiometric Age Data Bank (RADB), *U.S. Geol. Surv. Open File Rep.*, 76-674, 77 pp., 1976.
- Zoback, M.L., R.E. Anderson, and G.A. Thompson, Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western United States, *Philos. Trans. R. Soc. London, Ser. A*, 300, 407-434, 1981.
- Zoback, M.L., and G.A. Thompson, Basin and Range rifting in northern Nevada: Clues from a mid-Miocene rift and its subsequent offsets, *Geology*, 6, 111-116, 1978.

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