Cenozoic Volcanism and Plate-Tectonic Evolution of the Western United States. II. Late Cenozoic

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Cenozoic volcanism and plate-tectonic evolution of the Western United States.
II. Late Cenozoic†

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CONTENTS

A major change in volcanic associations and their tectonic settings occurred in much of the Western United States during late Cenozoic time. Where this volcano-tectonic transition can be documented, an earlier orogenic and post-orogenic association of predominantly calc-alkalic andesitic rocks typical of circum-Pacific continental margin and island arcs was succeeded by fundamentally basaltic volcanism which accompanied regional normal and strike-slip faulting. The igneous fields regarded here as fundamentally basaltic include: (1) basaltic fields, (2) alkalic fields in which differentiated igneous series commonly can be related to alkali–basaltic parent magmas, and (3) bimodal associations of mafic and silicic rocks, generally basalts and high-silica rhyolites. Similar igneous fields occur in other regions of the world characterized by tectonic extension.

The nature and timing of the late Cenozoic volcano-tectonic transition in various areas of the Western United States are documented from published references. The transition began in the southeastern part of the region in latest Oligocene time and moved northwestward through Miocene, Pliocene, and Quaternary time. The inception of basaltic, alkalic, or bimodal volcanism and associated regional extension of inland areas appears to date the times at which plate-tectonic boundaries between North America and two Pacific plates underwent drastic changes. These changes resulted from collision of the East Pacific Rise with a mid-Tertiary continental-margin trench and resulting direct contact of the American and western Pacific plates along a right-lateral transform fault system. These plate-tectonic interactions have evolved continuously and have determined the volcanic and tectonic evolution of the Western United States for the last 30 million years.

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Introduction

Although volcanism has been widespread in the Western United States during most of the Cenozoic time, the types of magmas erupted and their tectonic associations have changed markedly during that time. A pattern of orogenic and postorogenic volcanism of predominantly intermediate composition, mainly calc-alkalic but grading eastward into a foreland alkalic suite, dominated the entire region during early and middle Tertiary time, as described in part I of this paper by Lipman, Prostka & Christiansen (this volume, p. 217). That volcano-tectonic system has been replaced gradually since about the beginning of the Miocene by volcanism characterized by abundant basalts associated with extensional faulting (Lipman 1970; Christiansen & Lipman 1970). We propose that the temporal and spatial changes in volcanic suites and tectonic styles resulted from progressive termination of the spreading of a segment of the East Pacific Rise and its complementary continental margin trench and subduction zone, together with the initiation and evolution of a new set of plate-tectonic interactions reflected by a complex transform system. In this paper we (1) summarize the nature of fundamentally basaltic volcanism in the Western United States, (2) discuss the late Cenozoic tectonic system, (3) attempt to document regional changes in volcanism and tectonism during late Cenozoic

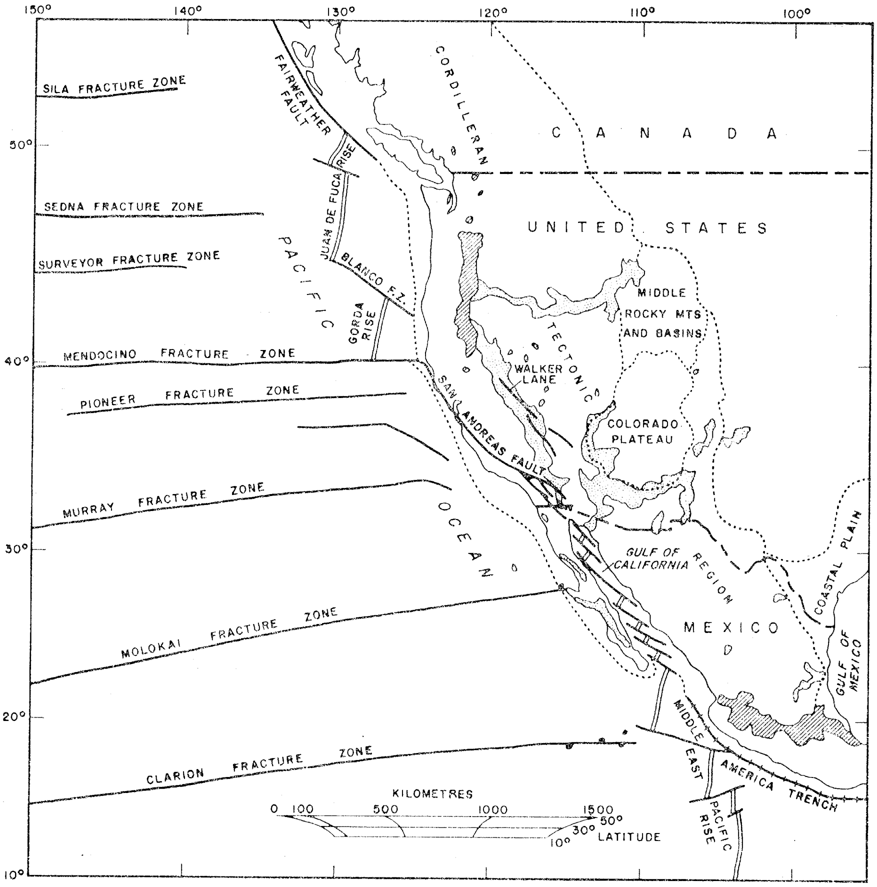

Figure 1. Quaternary volcanic fields of the Western United States and the present configuration of certain major tectonic elements. Diagonally lined areas, predominantly andesitic; stippled areas, fundamentally basaltic (see text).

time, and (4) interpret relations between the late Cenozoic volcano-tectonic system and plate-tectonic evolution of the region.

The Quaternary volcanic and tectonic framework of the region is shown in figure 1. The 'predominantly andesitic' volcanism indicated in the figure is of the same type as that described in part I of this paper by Lipman *et al.* (this volume); the 'fundamentally basaltic' volcanism of the figure includes fields of three types that are outlined immediately following. The only predominantly andesitic fields of Quaternary age in the Western United States are the Cascade Range of the Pacific Northwest and two smaller fields in northern California. A similar field forms the trans-Mexico volcanic belt. These andesitic fields both lie inland from oceanic belts of active seismicity (figure 2). The areas of fundamentally basaltic volcanism are seismically active (figure 2), but they lie within zones in which late Cenozoic deformation has been mainly by extensional normal (basin-range) faulting (figure 4). It is the evolutionary sequence from a continuous belt of predominantly andesitic volcanism associated with trench and subduction activity to the volcano-tectonic pattern of figure 1 which will be interpreted in this paper.

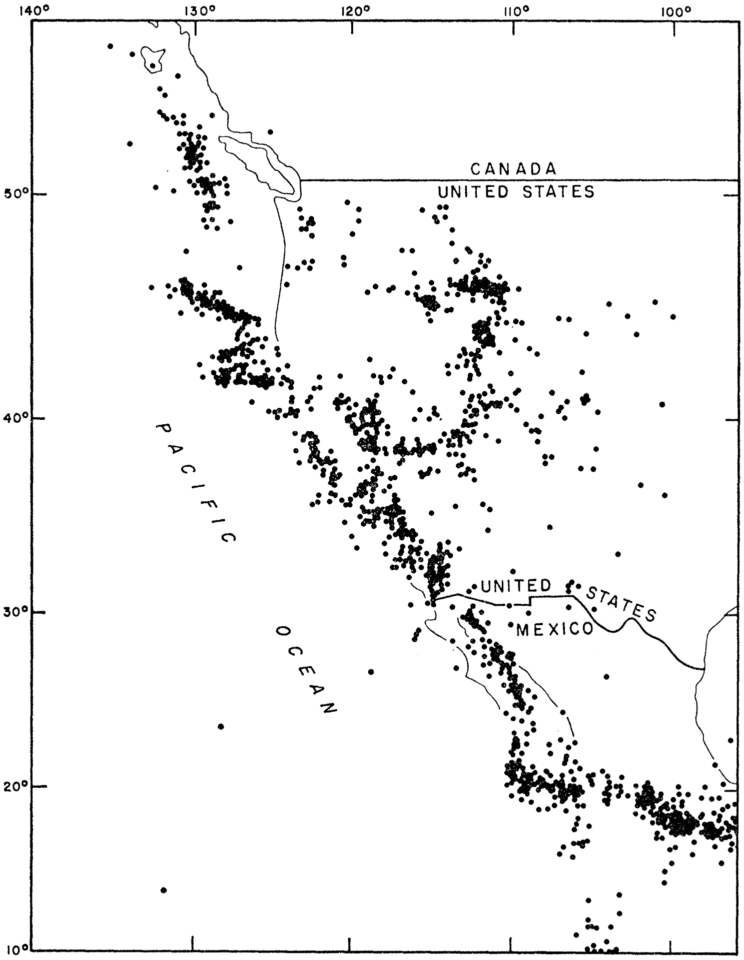

FIGURE 2. Seismicity of the Western United States, showing epicentres for the years 1961–7 from Barazangi & Dorman (1969).

Types of fundamentally basaltic continental volcanism

We have characterized the late Cenozoic volcanism in much of the Western United States as 'fundamentally basaltic' (Christiansen & Lipman 1970). Basalt is indeed common in most of these fundamentally basaltic suites but is not predominant in all of them. Also, of course, basalts occur in predominantly andesitic calc-alkalic igneous fields, such as the volcanic associations of island arcs, especially near the trenches. Such basalts, however, are subordinate to andesites in any large region of a volcanic arc. We describe here the volcanic suites embraced by the designation 'fundamentally basaltic' in terms of three types of volcanic field. Locations of areas cited as examples can be found in figure 5.

Basaltic fields

Volcanic fields in which basalt is the greatly predominant or the only type of erupted magma are present in many continental regions. In the Western United States, the great fissure-fed basaltic floods of the Northwest are most conspicuous, including the Columbia River Plateau (Waters 1955, 1961, 1962) and parts of the Oregon Plateaus (Powers 1932; Waters 1962) and the Snake River Plain (Stearns, Crandall & Steward 1938; Malde & Powers 1962; Stone 1966). In each of these great basaltic fields the basaltic lavas commonly are of one or only a few chemical types, each of which generally has a limited compositional range. The basalts of these floods are mainly of tholeiitic or high-alumina compositions although compositions differ considerably between the various fields.

A number of other volcanic fields in the Western United States contain basaltic flows and cinder cones fed by numerous central vents. Some of the volcanoes and lava fields overlap extensively, but commonly they are in small separate groups. Such a field lies along the southwestern margin of the Colorado Plateau (Hamblin & Best 1970). Most fields of this type are made up of alkali basalts (Leeman & Rodgers 1970), but tholeiites occur among them in areas near the boundaries of major tectonic provinces (e.g. Best, Hamblin & Brimhall 1966; Lipman 1969; McKee & Anderson 1971).

Differentiated basaltic and alkalic fields

Many volcanic fields similar to the separated central-vent basaltic fields contain volcanoes that have erupted a differentiated magma series, commonly related to an alkali-basaltic parent, although the alkalicity of these suites varies considerably. For example, the volcanoes of San Francisco Mountain of central Arizona (figure 5) were built up on a platform of alkali basalts by trachybasaltic, trachyandesitic, dacitic, and soda-rhyolitic lavas; progressively more silicic rocks occur in progressively smaller volumes (Robinson 1913). Many upper Cenozoic volcanic fields near the margins of the Great Basin are composed of basaltic, trachybasaltic, alkali-andesitic, trachyandesitic, and rhyolitic lavas erupted from central-vent volcanoes (see, for example, Gilbert, Christensen, Al-Rawi & Lajoie 1968; Robinson, McKee & Moiola 1968; Vitaliano 1969; Leeman & Rodgers 1970). Other fields in that region culminated with eruptions of peralkaline ash flows and lavas (Noble 1965, 1968; Noble, Chipman & Giles 1968; Christiansen & Noble 1965). Continuous compositional variation is represented in most of these differentiated alkalic fields. More silicic and alkali-rich rock types generally are less abundant than the more mafic ones in each suite, except in some of the peralkaline fields.

The differentiated alkalic suites are not everywhere easily distinguished by a study of available geologic reports from the predominantly andesitic calc-alkalic suites of the contrasted volcano-tectonic assemblage, especially when chemical analyses are sparse. Reports commonly designate as 'andesite', rocks that we would separate into our two major associations. Generally we recognize alkalic suites as part of our 'fundamentally basaltic' assemblage where they overlie older distinctly calcic or calc-alkalic associations. The latter associations, however, have considerable variation in the ratio CaO/Na_2O+K_2O (top three curves of figure 3). The younger alkalic suites typically are associated with abundant basalts, not with predominant andesites although 'andesites' commonly are present in them. The bottom two curves of figure 3, representing different parts of one volcanic field (Noble *et al.* 1965), show the range of alkalicity in fundamentally basaltic associations. The greatest difficulty in making this distinction is in areas that were in the more inland and more alkalic parts of the predominantly calc-alkalic coherent suite of the dual mid-Tertiary igneous belt (see Lipman *et al.* this volume). Where such assemblages were succeeded by upper Cenozoic differentiated alkalic suites, the transition generally involved large amounts of alkalic andesites and their differentiates before finally proceeding to predominantly basaltic fields. Such a sequence, difficult to distinguish clearly in the transitional stage, seems to be represented in southern and western Arizona (see, for example, Simons 1964; Anderson & Creasey 1958), as discussed in a later section of this paper. Contrasts that help to make the distinction in some transitional suites include the abundance of light-coloured andesites and rhyodacites bearing hornblende and biotite, and the paucity of true basalts, in the more alkalic of the older fields, such as the San Juan Mountains of Colorado (Larsen & Cross 1956; Lipman, Steven & Mehnert 1970), and the predominance of dark-coloured andesites and latitic to trachyandesitic differentiates bearing augite and olivine, along with common basalts, in the younger alkalic fields, such as those of the western Great Basin and adjoining areas (see, for example, Huber & Rinehart 1967).

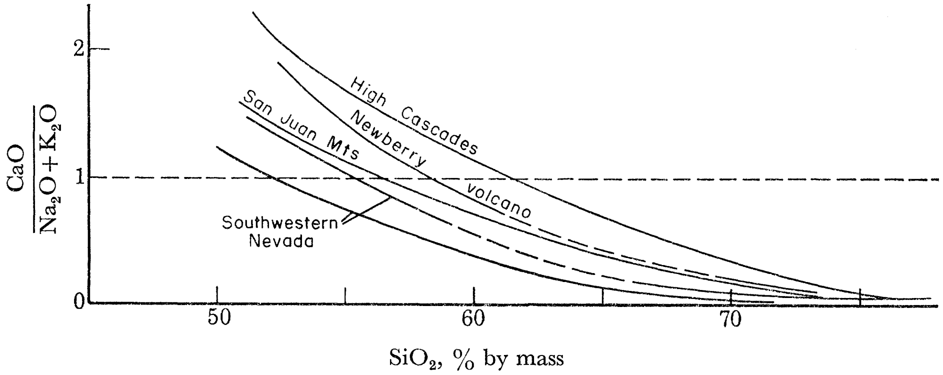

FIGURE 3. Plot of CaO/Na_2O+K_2O *vs.* SiO_2 for selected volcanic fields of the Western United States. Top three curves represent the range of alkalicity of predominantly andesitic igneous fields. The bottom two curves, from separate volcanic source areas in a single volcanic field (Noble *et al.* 1965), represent virtually the entire alkalicity range of suites regarded in this paper as fundamentally basaltic.

Bimodal basalt–rhyolite fields

The third major type of fundamentally basaltic field in the Western United States generally contains both basalt and rhyolite in abundance, but rocks of intermediate composition are sparse or lacking. Some intermediate-composition rocks in these fields represent hybrid lavas of mixed basaltic and rhyolitic parentage. Such assemblages were called bimodal by Hamilton

(1965). In many fields the basalt is predominant and the rhyolite relatively minor, as in the Miocene volcanic rocks of the San Juan Mountains of southwestern Colorado (Larsen & Cross 1956; Lipman *et al.* 1970) or the Pliocene of the Modoc Plateau in northern California (Powers 1932; Macdonald 1966). In other fields rhyolites greatly predominate over basalt, as in the Quaternary Yellowstone rhyolite plateau (Boyd 1961; Hamilton 1963*a*; R. L. Christiansen & H. R. Blank, Jr., unpubl. data 1971). Some fields in which there is a considerable compositional range in the abundant rock types, both mafic and silicic, still have relatively sparse rocks of intermediate composition. We classify as bimodal several of these fields, such as the southwestern Nevada volcanic field (O'Connor 1963; Luft 1964; Orkild 1966; Lipman 1966; Lipman, Christiansen & O'Connor 1966; Byers, Orkild, Carr & Quinlivan 1968).

We prefer in our present state of knowledge to separate specific petrogenetic theories from our thesis regarding the relations between particular volcanic suites and tectonic styles and their progressive development in the Western United States. We do believe, however, that even in bimodal fields where rhyolite is the greatly predominant erupted magma type, basalts represent the fundamental expression of deep-seated processes and that the rhyolites are related directly to the rise of basaltic magmas in the Earth's crust. For example, we regard the Yellowstone rhyolite plateau as only a portion of a much larger basalt-and-rhyolite province that includes the eastern Snake River Plain (Christiansen & Blank 1969), and basalts are the oldest, the youngest, and ultimately the most abundant phases in the volcanic evolution of any segment of that system except for the Yellowstone Plateau itself, which we presume to be incompletely developed.

The rhyolites of bimodal basalt-rhyolite fields commonly are petrologically distinct from rhyolites of calc-alkalic predominantly andesitic fields. The former commonly contain more than about 72 % silica (analyses recalculated water-free) and many contain about 76 %. In the latter, rhyolites containing more than 72 % silica are relatively sparse. Alkalies in the rhyolites of bimodal fields commonly are higher in relation to calcium, and the Na/K ratio generally is higher than in those of differentiated calc-alkalic suites. As a consequence, the alkali feldspar of rhyolites in basalt–rhyolitic associations typically is more Na-rich (commonly more sodic than $Or_{50}Ab_{50}$) than in calc-alkalic rhyolites and dacites. Also ferroaugite- and fayalite-bearing rhyolites occur only in alkalic and bimodal suites. These distinctions are used later in this paper to assign certain predominantly rhyolitic fields and granitic bodies to one or the other of our two fundamental igneous associations, but available data are not always sufficient to do so with confidence.

Complex fields

The three types of volcanic field just summarized include essentially all the volcanic rocks of the Western United States which we characterize as being 'fundamentally basaltic'. Some areas that are more complex than those just cited as examples can be regarded as combinations of the same types. For example, the Pliocene and Quaternary Jemez Mountains volcanic field of north-central New Mexico has been interpreted by Smith & Bailey (1968*a*) as comprising four separate volcanic cycles, the first and last being bimodal basalt–rhyolite sequences and the middle two being continuous differentiation series from basaltic parents; basaltic volcanism was intermittent in or around the field during each of the four cycles.

Tectonic associations of fundamentally basaltic volcanism

The tectonic associations of most fundamentally basaltic volcanic fields probably are of extensional character. Although our examples and conclusions are based on the Western United States, we feel that the conclusion could be stated even more generally. Tectonic settings of fundamentally basaltic volcanism in the Western United States are mainly of two types: (1) relatively small alkalic or bimodal igneous fields in the orogenic and volcanic foreland of predominantly calc-alkalic andesitic volcanic regions related to a continental-margin subduction zone, and (2) commonly large late Cenozoic fields in or adjacent to regions of basin-range faulting. The first type is typified by such volcanic fields as the alkalic and somewhat bimodal suite of Eocene and Oligocene age in west Texas (Lonsdale 1940; Goldich & Elms 1949; Erickson 1953; Maxwell, Lonsdale, Hazzard & Wilson 1967; Wilson, Twiss, DeFord & Clabaugh 1968) and the Quaternary basalt-rhyolite assemblage of the Newberry volcano at the east front of the Cascade Range (Williams 1935; Higgins & Waters 1968, 1970). The second type, the principal subject of this paper, is a tectonic setting of regional extension, as discussed next.

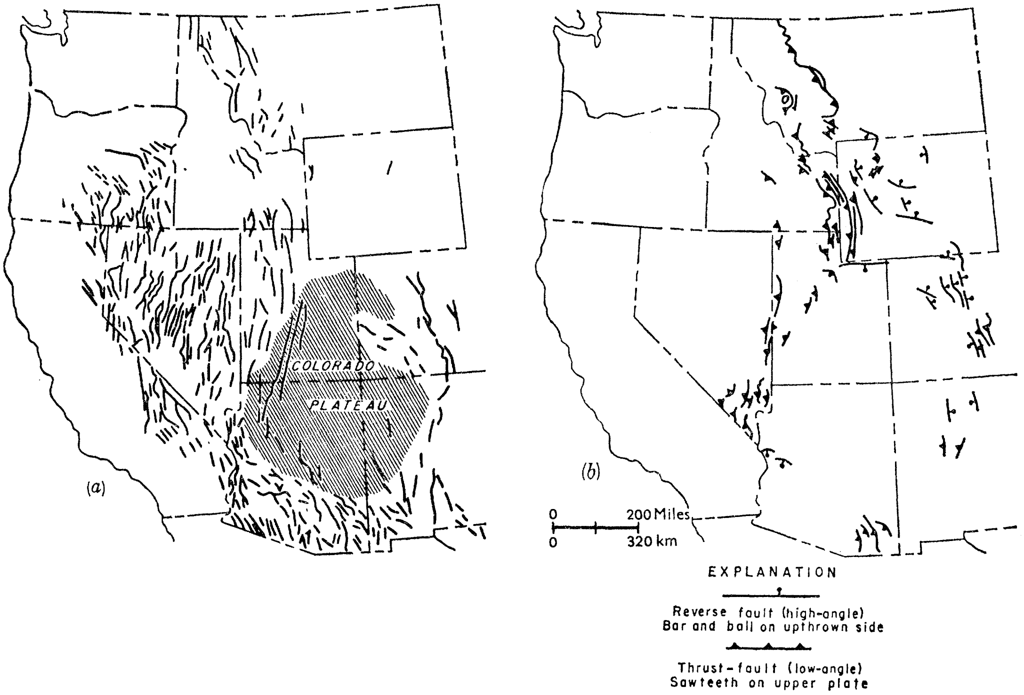

Figure 4. Late Mesozoic and Cenozoic structural framework of the Western United States. (*a*) Distribution of late Cenozoic basin-range faulting in the Western United States (from Gilluly 1963). (*b*) Distribution of Mesozoic and early Tertiary orogenic deformation in the eastern Cordilleran region (from Gilluly 1963).

Normal faulting and associated block tilting have characterized the late Cenozoic structural pattern of much of the Western United States. Figure 4*a* (from Gilluly 1963) shows the area in which Cenozoic faults of this type were importantly developed. That this faulting is the result of regional extension is generally, though not universally accepted in modern reviews of the topic (see, for example, King 1959, p. 157; Osmond 1960, p. 258; Thompson 1960, 1966; Gilluly 1963; Cook 1966; Hamilton & Myers 1966). The history of basin-range faulting is not so widely agreed upon. Figure 4*b* shows that late Cenozoic basin-range faulting extended to include most of the eastern Cordillera which previously had undergone orogenic folding, thrusting, and block-uplifting during Mesozoic and early Tertiary time. Only the eastern part of that orogenic zone is shown in the figure, but the region of basin-range faulting as a whole is substantially similar to the Mesozoic orogenic zone. Present seismicity inland from the coastal belt is largely confined to marginal parts of the regions of late Cenozoic basin-range faulting (figure 2). Most regional syntheses agree that the basin-range normal-fault pattern developed largely during late Cenozoic time, mainly during the Miocene and Pliocene, but the times of initial basin-range faulting, both regionally and locally, are difficult to establish. Nolan (1943) concluded that this faulting has been essentially continuous through most of the region since early Oligocene time. However, more recent regional Tertiary stratigraphic studies and isotopic dating of Cenozoic volcanic rocks generally have indicated that faulting of this type did not become regionally important until Miocene time. The evidence for this conclusion is discussed for individual areas in the following section, but generally it comes from three types of relationship: (1) datable single widespread units, especially single ash-flow sheets, where they predate block faulting, spread uniformly over subsequent basins and ranges; where they post-date block faulting, they were more or less confined to the basin areas; (2) the oldest sedimentary basin deposits related to basin-range faulting give a minimum age for inception of the faulting, but they are not all easily distinguished from older basin deposits regelated to Late Cretaceous–early Tertiary orogenic structures; and (3) volcanic rocks locally have a direct relation to pertinent structures as, for example, dikes which, occupying normal faults of the basin-range system, can give a minimum age for formation of the faults.

Studies of structural patterns and of active faulting in the basin-range province have brought out the importance of strike-slip faulting in addition to simple normal faulting and block tilting. Studies of surface faulting associated with the Cedar Mountain earthquake of 1932 in western Nevada (Gianella & Callaghan 1934) showed that right-lateral offset has occurred along modern faults that lie within the Walker Lane, a major northwest trending zone of structural discontinuity (Locke, Billingsley & Mayo 1940). Longwell (1960) showed that the major right-lateral Las Vegas Valley shear zone lies along the southeastward projection of the Walker Lane, and Ekren, Rogers, Anderson & Orkild (1968) demonstrated that the Las Vegas Valley shear zone was active mainly during late Miocene and later time. Evidence of regional northwest trending right-lateral displacements along the western marginal zone of the Great Basin has been given by Albers (1967), Stewart (1967), Poole *et al.* (1967), Stewart, Albers & Poole (1968), and others. Seismic and geologic studies of faulting related to the Dixie Valley–Fairview Peak earthquake of 1954 (Tocher 1957; Romney 1957; Whitten 1957; Slemmons 1957) showed that these faults in western Nevada slipped with oblique normal and right-lateral displacement. King (1959, p. 157–158) suggested that extensional normal faulting of the Basin and Range province reflected the breakup of major blocks bounded by strike-slip faults. Shawe (1965) reviewed much of the geologic evidence to show that basin-range structure in the Great Basin represents a regional oblique-slip system in which oblique extension on north trending normal faults, partly following older structural trends, accompanied major northwest trending right-lateral and minor northeast trending left-lateral deformation.

Hamilton (1963*b*) and Hamilton & Myers (1966) proposed that the Snake River Plain of Idaho is a region of tensional thinning of the crust that resulted from relative motion of areas to the north, northwestward away from the middle Rocky Mountain region. The Snake River

Plain is within a larger region of typical basin-range faulting and represents part of the same overall system of tectonic extension.

A plate-tectonic interpretation of oblique extension by widespread basin-range faulting and more localized crustal thinning, all related to right-lateral deformation of the Western United States, is discussed in the final section of this paper.

Fundamentally basaltic volcanism of the regions of late Cenozoic basin-range faulting was similar to volcanic assemblages associated with continental extension in other parts of the world. The volcanic suites of the African rift zones and the Red Sea margins would fall within the range of examples of fundamentally basaltic volcanism in the Western United States. The major ocean basins of the world, except for the arc-trench associations of their margins, are characterized by fundamentally basaltic volcanism and by extensional and strike-slip faulting related to sea-floor spreading. Other fundamentally basaltic and bimodal assemblages are associated with continental zones that bound spreading ocean basins as, for example, the Tertiary Brito–Arctic province, in which regional extension is recorded in widespread dike swarms (Richey 1939).

Probably the fundamentally basaltic late Cenozoic volcanic activity of the Western United States has been intense in very few places at any given time. The major localities of great Pleistocene volcanic activity were the Cascade Range and several areas of voluminous caldera-forming rhyolitic ash-flow eruptions: the Jemez Mountains of northern New Mexico (Smith & Bailey 1966, 1968*a*; Smith, Bailey & Ross 1961, 1970), the Long Valley area of eastern California (Gilbert 1938; Rinehart & Ross 1954, 1964; Huber & Rinehart 1967; Smith & Bailey 1968*b*), and the Yellowstone region (Boyd 1961; Hamilton 1965; Christiansen & Blank 1969). Each of these areas is near a major late Cenozoic tectonic-province boundary. Similarly, large-scale ash-flow eruptions of Miocene and Pliocene time occurred in zones marginal to the Great Basin of Nevada, Utah and California (Armstrong, Ekren, McKee & Noble 1969), along the axis of the eastern Snake River Plain (Christiansen & Blank 1969), and in the last stages of activity of some of the major mid-Tertiary calc-alkalic rhyolitic fields when their activity was affected by an abrupt change to an extensional tectonic régime (Lipman 1970). Other fundamentally basaltic activity during the time included the major basaltic fields of the Colorado Plateau margins and the Rio Grande graben system of New Mexico and Colorado; widely scattered volcanoes in the Great Basin, in southern Arizona and New Mexico, and in marine basins in the California coastal region; and the fissure-fed basaltic floods of the Northwest.

Hamilton (1965) and Hamilton & Myers (1966) first made special note of the bimodal volcanism of the Snake River Plain–Yellowstone region and implied a close genetic relationship between that volcanism and the extensional origin of the tectonic zone they occupy.

The great tholeiitic and high-alumina flood basalts of the Columbia River and Oregon Plateaus formed immediately inland from the Cascade chain, which was a predominantly andesitic province throughout most of Cenozoic time. The feeder-dike swarms for these floods represent a considerable extension of this region, and basin-range faulting was contemporaneous along their eastern margin (Hamilton 1962, 1963*b*; Hamilton & Myers 1966; Taubeneck 1969, 1970). These plateau basalts appear to represent volcanism related to extension in the foreland of the Pacific coastal orogenic and volcanic region, perhaps analogous to that recognized recently behind some island arcs (Karig 1970).

Late Cenozoic volcano-tectonic relations in individual areas

We have recognized various igneous suites either as predominantly andesitic or fundamentally basaltic (or in a few areas as transitional) on the basis of the associations of various rock types, the sequences in which they occur, their relative volumes, and their chemistry and mineralogy. Our original recognition of these distinctions stemmed from intensive recent studies, including our own, of several volcanic fields. Similar late Cenozoic changes in volcanic associations appear to have occurred across much of the Western United States. Many practical problems, however, arise in attempting to make these distinctions from the geologic literature. Data for many areas come only from areal-mapping and mineral-deposit studies that were not importantly oriented toward understanding the volcanic rocks. For many areas there are few or no chemical analyses or isotopic ages; where such data have been published, they too often are not integrated with well-determined geological relations. In particular, the volcanic stratigraphy and relative volumes of the principal rocks generally are not known or are known only for small arbitrary areas within larger igneous fields. Our synthesis, thus, is necessarily tentative. It is clear, nevertheless, that the general picture of older predominantly calc-alkalic andesitic igneous activity, succeeded by younger fundamentally basaltic suites associated with regional normal and strike-slip faulting, applies to the region as whole. Furthermore, the data suggest a time pattern in which the volcanic and tectonic transitions occurred across the region.

Figure 5 is a map showing the times at which the transition between fundamental volcanic associations and at which the first basin-range faulting occurred in various regions. The following sections document the relations upon which figure 5 is based. The conclusions derived from these area-by-area descriptions are summarized in the final section, and some readers may wish to proceed directly to it.

Southeastern and southern region

Miocene and younger volcanic fields of west Texas, New Mexico, Colorado, and most of Arizona, as shown in figure 5, are mainly of types we include as fundamentally basaltic, but many of these Miocene fields succeed Oligocene fields of predominantly andesitic calc-alkalic type.

West Texas was in the foreland of the Late Cretaceous and early Tertiary orogenic belt and of the early and mid-Tertiary volcanic belt. A large alkalic volcanic field there of late Eocene and Oligocene age, as young as about 30 million years (Ma) (Wilson *et al.* 1968), was considered in Part I of this paper (Lipman *et al.* this volume) to be part of a coherent volcanic suite that is mainly calc-alkalic but which becomes more alkalic eastward across the eastern Cordilleran region. The sedimentary platform beneath the volcanic pile subsequently was cut by a widespread swarm of alkali-basaltic to phonolitic dikes, which locally fed surface flows, along earlier northwestward and later northward trends during an episode of extension that ultimately produced large-scale normal faulting (Dasch, Armstrong & Clabaugh 1969). The age range of dated dikes, according to Dasch *et al.* is about 23 to 18 Ma.

Mid-Tertiary volcanic rocks of the Chiricahua Mountains and surrounding areas in southeastern Arizona and southwestern New Mexico consist of an older calc-alkalic series ranging from hornblende andesite to rhyolite (Gilluly 1956; Zeller & Alper 1965; Enlows 1955; Fernandez & Enlows 1966), and younger alkali-rich high-silica rhyolitic ash-flow tuff with sodic alkali-feldspar, olivine-bearing basaltic andesites, and gravels (Enlows 1955; Gilluly 1956; Marjaniemi 1968). Calc-alkalic intrusive rocks in the area have ages between about 35 and

FIGURE 5. Ages of the transition from predominantly andesitic to fundamentally basaltic volcanism and of initial basin-range faulting in various Miocene and younger volcanic fields of the Western United States.

29 Ma (Erickson 1968). Marjaniemi (1968, 1969) reported ages of about 28 and 29 Ma for a rhyodacite flow and a rhyolite welded tuff of the older sequence, and about 25 Ma for the younger ash-flow tuff. Marjaniemi also showed that the 25 Ma old ash-flow sheet crosses three present ranges but that its distribution and thicknesses indicate basin-range faulting to have been in the early stages of development when it was emplaced. Continued development of basin-range topography has broken the continuity of the sheet.

Regional studies of Cenozoic volcanism in the upper Gila River region of western and central New Mexico by Elston, Coney & Rhodes (1968, 1970), still in progress, have led to recognition of three volcanic cycles. The first cycle, 38 to 29 Ma old, is typically calc-alkali and petrologically much like the calc-alkalic main sequence of the San Juan Mountains (see Part I of this paper). We interpret the volcanic rocks of the two younger cycles of Elston *et al.* (1970) as a bimodal assemblage of fundamentally basaltic affinities. These younger cycles erupted more alkalic rocks including rhyolitic ash-flow tuffs and alkali 'andesites' and basalts during the period from about 27 to about 21 Ma ago. Rhyolites in the younger sequence have high silica and alkali contents and sodic, commonly perthitic alkali feldspars. Closely similar rhyolites are associated with the bimodal later sequence of the San Juan Mountains. Elston *et al.* (1970) recognized basin-range faulting between about 20 and 6 Ma old, dated principally on the basis of sedimentary basin deposits including the Gila Conglomerate. As only marginal parts of the basin fill are exposed within the volcanic field, older deposits might be buried in the deeper parts of the sedimentary basins. Mapping of individual ash-flow sheets is not yet sufficiently complete to allow their use in defining palaeotopography.

A westward extension of the volcanic field of the upper Gila River region into the Blue Range area of western New Mexico and eastern Arizona also contains calc-alkalic andesites to rhyolites, overlain by high-silica rhyolites and alkali basalts and their differentiates, including a peralkaline ash-flow tuff (Ratté, Landis & Gaskill 1969). Overlying the alkali-basaltic series is the basin-filling Gila Conglomerate. An andesite from the lower sequence is about 37 Ma old; rhyolite and basaltic andesite from the upper sequence are about 25 to 23 Ma old.

The Rio Grande depression is a series of en echelon grabens that extends from south to north across central New Mexico and southern Colorado (Bryan 1938; Kelley 1952). It breaks across the mid-Tertiary calc-alkalic volcanic fields and contains a thick complex sedimentary fill. Basalts and mafic alkalic rocks commonly are associated with this basin fill and are widespread along the margins of the depression (Lipman 1969). Sediments as old as early Miocene are related to deposition in the basins (Galusha 1966). The Questa molybdenum deposit of northern New Mexico at the edge of the Rio Grande depression is associtaed with a high-silica alkali-rich granite, about 23 Ma old (Laughlin, Rehrig & Maugher 1969), compositionally like the rhyolites of bimodal volcanic fields.

An axis of Pliocene and Pleistocene volcanism extends across the Rio Grande depression from the Mesa de Maya and Raton Mesa region of southeastern Colorado and northeastern New Mexico, through the Jemez Mountains, to the southeastern margin of the Colorado Plateau in the Mount Taylor, Black River, and nearby volcanic fields. Basaltic, differentiated alkalic, and bimodal fields occur along this axis and are associated in a number of places with extensional normal faulting. The alkalic fields of the Navajo and Hopi regions, within the Colorado Plateau, are of Pliocene age (Williams 1936). A similar alkalic field occurs in the area of the San Rafael Swell farther north in the Colorado Plateau (Gilluly 1927).

The large composite Oligocene volcanic field of central and southern Colorado was broken up by block faulting and erosion in Miocene and later time (Steven & Epis 1968). A bimodal suite of volcanic and shallow intrusive rocks was emplaced intermittently during the time of extensional faulting. In the San Juan Mountains of southwestern Colorado the beginning of basaltic and high-silica rhyolitic eruptions can be shown to have occurred simultaneously with the first appearance of a deepening graben in the San Luis Valley to the east and of normal faulting and block tilting along the eastern margin of the San Juan Mountains (Lipman & Mehnert 1969). The youngest calc-alkalic ash-flow tuffs of the mid-Tertiary San Juan volcanic field, about 27 Ma old (Steven, Mehnert & Obradovich 1967), were deposited uniformly across the positions of later normal faults and thin eastward across the margin toward what was to become a major depositional basin in the San Luis Valley. Miocene basaltic and rhyolitic rocks as old as about 23 Ma (Lipman *et al.* 1970) lie unconformably on the tilted older ash flows and are interlayered with basin-fill gravels at the edge of the San Luis Valley. The oldest dated rhyolite of this late bimodal suite is an ash-flow tuff that was erupted from the Lake City caldera (Lipman *et al.* 1970, p. 2344). The volume and structural setting of this ash-flow eruption were comparable to those of preceding calc-alkalic rhyolitic ash flows, but the younger rhyolites have significantly higher SiO_2 and alkali contents and more sodic alkali feldspar than the older ones. This 23 Ma old rhyolite, therefore, represents the type of change that occurred in several volcanic fields that were active at the time of the transition to extensional tectonics and fundamentally basaltic volcanism.

Elsewhere in central Colorado, a change in intrusive suites is recorded in the Elk Mountains, where the bracketing ages are as young as about 29 Ma for the calc-alkalic suite and about 12 Ma for a high-silica alkali granite which is associated with a group of mafic dikes (Obradovich, Mutschler & Bryant 1969; Lipman, Mutschler, Bryant & Steven 1969). In the Thirtynine Mile volcanic field (Epis & Chapin 1968) calc-alkalic andesites were erupted from local centres during the time quartz-latitic to rhyolitic ash flows were emplaced from nearby areas up to about 34 Ma ago. These rocks are overlain above an erosional unconformity of great relief by gravels and succeeding basaltic to alkali-andesitic flows, the basal flow of which is about 19 Ma old (Epis & Chapin 1968). Other Miocene and younger volcanic fields of central Colorado are all of basaltic or bimodal types and include the Grand Mesa, White River–Flat Tops, and Hahns Peak areas, having ages between about 10 and 24 Ma (Mutschler & Larson 1969; Strangway, Larson & York 1969). In Middle Park, basalts shown on figure 5 as an eastern extent of the White River field overlie lower and middle Miocene basin deposits which lie in turn on calc-alkalic intermediate-composition volcanic rocks largely of Oligocene age (Izett 1966).

The highly alkalic volcanic rocks of the Leucite Hills, Wyoming, are about 1 Ma old (Bradley 1964, pp. 57–58).

Miocene and younger volcanic rocks of south-central Arizona are mainly basalts, olivine-bearing alkali andesites, and silicic ash-flows, small lava flows and domes, and ash beds (D. W. Peterson 1960, 1968, 1969; N. P. Peterson 1962; Willden 1964; Simons 1964; Bikerman & Damon 1966; Percious 1968; Sheridan 1968; Sheridan & Fodor 1969; Sheridan & Stuckless 1969; Krieger 1969). In terms of the criteria by which we have distinguished our two major volcano-tectonic associations the lower part of this section seems to be a somewhat alkalic suite transitional between the two. These rocks are associated in a number of areas with coarse fluvial basin deposits that may be related to the inception of basin-range fault topography. Locally these rock types are as old as latest Oligocene and unconformably overlie lower to middle Tertiary calc-alkalic igneous rocks. The oldest rocks in the upper sequence commonly are alkalic olivine andesites or latites. In the Roskruge Mountains 'basaltic andesite' as old as about 24 Ma overlies a granodiorite pluton about 34 Ma old (Bikerman 1968; Damon 1968). Similarly, in the Tucson area, the oldest alkali andesites are at least as old as 25 Ma (Bikerman & Damon 1966; Percious 1968). Damon & Mauger (1966) relate the younger suite to basin-range faulting. An association of olivine andesites, gravels, and quartz latites to rhyolites east of Tucson yielded ages between about 20 and 26 Ma (Creasey & Kistler 1962; Damon & Bickerman 1964; Krieger 1969). This association in its lower part is predominantly andesitic and in its upper parts, especially to the north, is bimodal and basaltic. One bimodal composite dike of andesite and rhyolite has been described (Simons 1963). This field seems to represent a more protracted transition between predominantly andesitic and fundamentally basaltic volcanism than do most other areas.

In a general way the geologic map of Arizona (Wilson, Moore & Cooper 1969) shows widespread upper Tertiary and Quaternary basaltic rocks in the Gila Bend region (indicated in figure 5 as the Miocene and younger volcanic field of that region) to overlie older Tertiary volcanic and intrusive rocks of diverse compositions, at least in part of intermediate calc-alkalic types. In the Ajo mining district (Gilluly 1946), intermediate to silicic calc-alkalic volcanic rocks, dikes, and stocks of late Cretaceous or early Tertiary age are overlain unconformably by a thick fanglomerate related to topography that predated present basins and ranges. The fanglomerate is interlayered with and overlain by hornblende-biotite andesites whose descriptions suggest that they are like our earlier calc-alkalic suite. These andesites are overlain uncoformably by younger volcanic rocks that are principally latites and olivine-bearing alkali andesites, typical of the suite we regard as a differentiated alkali-basaltic association in other areas. These younger volcanic rocks locally overlie conglomerates that were deposited in basins closely related to the present fault-block topography. An andesitic suite near the southwestern corner of Arizona has an age range of 26 to 29 Ma and is overlain by a sedimentary sequence as old as 23 Ma that includes abundant fanglomerate and probably indicates beginning of basin-range faulting (Olmsted 1968).

The late Cenozoic volcanic stratigraphy in the Verde River–San Francisco Mountain–Mount Hope region of west-central Arizona is substantially similar to that described for southern Arizona. Most of the volcanic rocks of west-central Arizona are latites, trachyandesites, and basalts of latest Oligocene or earliest Miocene to Quaternary age and are associated with abundant gravels (Anderson & Creasey 1958; Lehner 1958; Krieger 1965). These rocks lie on an eroded surface that was tilted slightly and broken by small faults (Anderson & Creasey 1958, pp. 78–79). Basin-filling sediments and intercalated latitic and minor basaltic volcanic rocks began accumulating by about 19 Ma ago; eruption of trachyandesitic to basaltic rocks continued through Miocene and Pliocene into Quaternary time, along with major modification by normal faulting and block tilting, mainly during Pliocene time (McKee & Anderson 1971).

Tertiary volcanic rocks in the lower Colorado River region (Schrader 1909; Ransome 1923; Longwell 1963) are mainly basalts, olivine-augite andesites, latites, and rhyolites similar to Miocene and younger rocks of Arizona referred to previously. Rocks of this sequence have been dated between about 18 and 5 Ma (Armstrong 1970; R. E. Anderson, written communication 1971). Also present are shallow intrusive diorites and granites that range in age from about 16 to 12 Ma (Anderson 1969; Armstrong 1970).

Great Basin and its bounding areas

Numerous maps show the distributions of various Cenozoic volcanic and shallow intrusive rock types in southeastern California, but little petrography and almost no systematic chemical or geochronological work have been done on them. Dibblee (1967*a*) noted that the oldest fossiliferous deposits in the western Mojave Desert are late Miocene and that they overlie widespread rhyolitic tuffaceous sediments and local piles of silicic volcanic rocks. Interlayered basalt flows are abundant locally. We regard this part of the section as a bimodal basalt-rhyolite assemblage. Dibblee (1967*a*, p. 111) pointed out that deposition of these sediments, tuffs, and volcanic rocks was in persistent basins between fault-bounded ranges. Both normal and right-lateral faults appear to account for this topography (Dibblee 1967*a*, p. 115). Unroofed, generally quartz-latitic intrusive rocks locally underlie the bimodal section unconformably. Evernden, Savage, Curtis & James (1964) dated a welded tuff associated with the late Miocene fossils in the upper part of the bimodal section as about 15 Ma old. Turner, Curtis, Berry & Jack (1970) suggested that rhyolites and andesites at the base of the section, probably predating the transition between our main volcanic assemblages, are offset from the Pinnacles volcanic field about 280 km to the northwest across the San Andreas fault. Their published age of the Pinnacles field is about 23 Ma, or early Miocene. Although quite indirect, this proposal provides about the best guess available for the lower bracketing age of the volcanic transition in the western Mojave Desert.

The Tertiary volcanic sequence of the western Mojave region contains a major anomaly from our point of view. The bimodal volcanic assemblage associated with basin-filling sediments is in turn overlain in several areas by local volcanic piles or cut by intrusions of calc-alkalic andesitic rocks, mainly of early Pliocene age, in the southern Sierra Nevada (or Tehachapi Mountains) (Dibblee 1967*a*), in the Lava Mountains (Smith 1964), and in the Lane Mountain area (McCulloh 1952). These three localities are indicated as andesitic on figure 5. The only published systematic chemical or petrologic study of Tertiary volcanic rocks in the Mojave Desert is that by Smith (1964) of the Lava Mountains, clearly showing the Pliocene andesites there to be a typical calc-alkalic assemblage.

The only dated Tertiary fossiliferous sequence known from the eastern Mojave Desert is of Miocene age (Bassett & Kupfer 1964, p. 22). Pumice associated with these beds is about 12 Ma old (Evernden *et al.* 1964). The rocks containing these fossils are basin-fill sediments associated with rhyolitic and basaltic rocks. Byers (1960) published descriptions and chemical analyses of similar rhyolites and basalts in a nearby area. Mapping in the eastern Mojave Desert (Dibblee 1964, 1966; Dibblee & Bassett 1966*a*, *b*; Dibblee 1967*b*–*d*) shows that the Tertiary basin-filling sediments associated with basalts and rhyolites overlie a volcanic sequence of varied but predominantly intermediate composition, but the ages have not been established. Hewett (1956) noted a similar section in a large area just to the north, astride the California–Nevada border.

Quaternary volcanic rocks of the eastern and western Mojave Desert and surrounding areas are mainly alkali basalts erupted from numerous scattered vents (Parker 1959, 1963; Dibblee 1967; Wise 1969; Smith & Carmichael 1969).

Studies of Miocene and younger volcanic rocks of southwestern Utah and the adjacent part of southeastern Nevada include those by Callaghan (1939), Cook (1957, 1965), Blank (1959, 1963), Mackin (1960*a*), Williams (1960), Dolgoff (1963), and Noble (1968). K/Ar dating studies are those of Bassett, Kerr, Schaeffer & Stoenner (1963), Armstrong (1970), and Blank & McKee

(1969). The lower part of the Tertiary volcanic section of the region from the St George Basin east to the high plateaux and west into Nevada comprises mainly calc-alkalic andesites, rhyodacites, and rhyolites that range in age from about 30 Ma to about 20 Ma and are cut by approximately contemporaneous and immediately succeeding intermediate-composition shallow intrusions. In the high plateaux, overlying these calc-alkalic igneous rocks, are high-silica rhyolites as old as about 20 Ma. Farther southwest silicic ash-flow tuffs about 18 Ma old and younger have more restricted distributions than the older units and include several centres of peralkaline volcanic activity. Mackin (1960*a*, *b*) and Cook (1965) suggested that the entire history of Cenozoic volcanism and basin-range faulting were contemporaneous. However, as far as volcanic units older than about 20 Ma are concerned, the data upon which the conclusion is based are unconvincing (see Cook 1965, p. 54). The older stratigraphic units whose changes in thickness were supposed to be pertinent to the question of contemporaneous faulting contain many separate ash-flow cooling units and include volcanic piles that certainly were of local origin. In particular, a well-documented correlation of several individual ash-flow cooling units in the age range of 24 to 21 Ma shows that they are widespread across a region now broken by many fault-block ranges and have no consistent thickness variations that would indicate even incipient formation of these or similar ranges. By contrast, single ash-flow cooling units about 18 Ma old and younger show restricted distributions along the trends of basin-range structures that suggest that they were erupted early during the time of basin-range faulting. Basalts are common above these younger ash-flow tuffs and locally are interlayered with them (Tschanz & Pampayen 1961). The uppermost Tertiary and Quaternary volcanic rocks of southwestern Utah and southeastern Nevada are mainly basaltic.

The large volcanic field of southwestern Nevada has been discussed by Cornwall (1962), Cornwall & Kleinhampl (1964), Noble, Anderson, Ekren & O'Connor (1964), Noble *et al.* (1965), Christiansen, Lipman, Orkild & Byers (1965), Christiansen & Noble (1965), Lipman *et al.* (1966), Lipman (1966), Noble, Chipman & Giles (1968), Kistler (1968), Byers *et al.* (1968), Marvin, Byers, Mehnert & Orkild (1970). This large composite volcanic field consists mainly of voluminous rhyolitic to peralkaline ash-flow tuffs related to large collapse calderas, local rhyolitic lavas and bedded tuffs in the source areas of the large ash-flows, and widely scattered alkali-basaltic to trachyandesitic volcanic centres (see, for example, Luft 1964). The major activity of this volcanic field extended from about 16 Ma to about 6 Ma ago. Distributions, thickness variations, and direct structural relations of various units in the sequence show that normal faults were active intermittently during the time the sequence was erupted (see, for example, Ekren *et al.* 1968). A single small calcic andesite-rhyodacite pile of local origin occurs within the field (Poole, Carr & Elston 1966). The bimodal volcanic assemblage overlies widespread intermediate-composition lavas and breccias as young as about 18 Ma old (Anderson & Ekren 1968) which are the youngest part of a calc-alkalic volcanic sequence that extends northward into central Nevada and back in age into the Oligocene (Marvin *et al.* 1970). Extensive ash-flow tuffs of this older sequence extend unbroken across regions of subsequent major basin-range faults.

Post-Oligocene volcanic rocks of eastern California from the Death Valley region (Noble 1941; Drewes 1963) to the Coso Range–Inyo Mountains region (Hall & MacKevett 1962; Ross 1970), mainly constitute a bimodal suite, largely of Pliocene and Pleistocene age but probably including some Miocene rocks. The volcanic rocks are mainly rhyolitic pyroclastics, small flows, and breccia-and-flow complexes; and basalts, trachyandesites, and related alkali-basaltic differentiates. Small andesite bodies have been noted locally. These rocks are interlayered with alluvial and other basin-filling sediments clearly related to deposition in basin-range fault valleys. There are few places in this eastern California region where the young bimodal assemblage clearly overlies dated mid-Tertiary volcanic rocks. In the Death Valley area certain rhyolitic tuffs, basalts, and sediments have been correlated tentatively with Oligocene deposits (T. P. Thayer, *in* Noble 1941, p. 956), but the basis of the correlation is unstated. A complex volcanic field southwest of Death Valley has not been studied and is not shown on figure 5.

The age of initial basin-range faulting in the Death Valley region requires special discussion because a thick lower Oligocene sequence of gravels and other sedimentary rocks in the mountains east of northern Death Valley has been cited as evidence that basin-range faulting began as early as early Oligocene time (Stock & Bode 1935, p. 578; Nolan 1943, p. 183; Gilluly 1963, p. 157). The presence of several megabreccia masses of local derivation at the base of, and within these sediments, is the main evidence cited for the conclusion. However, it was noted in the course of detailed studies by Reynolds (1969), and from our own reconnaissance nearby, that all mapped normal faults in the area are younger than these Oligocene beds. Furthermore, some of the materials in the gravels are not of local derivation. Certain distinctive granitic cobbles must have come from areas more than 65 km away, probably from the other side of Death Valley (Reynolds 1969). Death Valley is now a fault trough more than 1 km deep. The lower Oligocene unit is overlain unconformably by heterogeneous, partly tuffaceous fluvial and lacustrine sediments that were deposited in fault basins roughly in the positions of the present basins. These basic-fill sediments are overlain in turn by ash-flow tuffs of the southwestern Nevada volcanic field which are about 15 Ma old and younger. We follow Reynolds's interpretation that the Oligocene sediments of the northern Death Valley area were deposited on a terrain of high initial relief that was folded and faulted during Late Cretaceous or early Tertiary time; deposition of the Oligocene strata resulted in progressive reduction of topographic relief. The megabreccia masses were related to landsliding from nearby topographic highs but not necessarily to normal faulting (M. W. Reynolds, written communication 1971).

Robinson *et al.* (1968) showed that in the Silver Peak area, near the California–Nevada border, volcanism was active during deposition of the Esmeralda formation in fault-bounded basins that essentially coincide with present basins. The Esmeralda deposits are of late Miocene to late Pliocene age. The interlayered and overlying volcanic materials are mainly rhyolitic and trachyandesitic tuffs and flows associated with basalts and andesites; together they appear to form a somewhat alkalic bimodal assemblage. Air-fall tuffs in this sequence are as old as about 13 Ma. The basin deposits and interlayered volcanic rocks unconformably overlie older calc-alkalic rocks, including an ash-flow tuff about 22 Ma old that was emplaced across the fault margins of later basin and range blocks. Similarly, in the Owens Valley–Mono Lake region, just to the northwest (Gilbert 1938, 1941; Gilbert *et al.* 1968; Huber & Rinehart 1967) basin formation, postdating eruption of rhyolitic ash flows dated as about 22 Ma old and younger andesitic breccias, was accompanied by the eruption of latites, alkalic andesites, trachyandesites, trachybasalts, and rhyolites ranging in age from about 12 million to a few thousand years.

A large Oligocene calc-alkalic volcanic field in central and northeastern Nevada is capped by widespread lower Miocene quartz-latitic to rhyolitic ash-flows, the great extent of which across present basins and ranges indicates that their eruption largely predated basin-range faulting (Blake, Hose & McKee 1969; McKee & Silberman 1970; Armstrong *et al.* 1969; Armstrong

1970). Volcanic activity in this field diminished greatly in middle Miocene time, about 20 Ma ago (McKee, Noble & Silberman 1970). Volcanism resumed about 16 Ma ago but was of quite different type, consisting mainly of widespread basalt to basaltic-andesite flows, small rhyolite flows and domes, and peralkaline ash-flow tuffs (McKee & Silberman 1970; Armstrong 1970; McKee *et al.* 1970). Normal faulting became active throughout the region during the period of this late volcanism. In the Jarbidge area of northern Nevada, Coats (1964) showed that Eocene tuffs and sediments are overlain unconformably by a bimodal volcanic sequence of Miocene and younger age. Evernden *et al.* (1964) dated a rhyolite in the lower part of the mainly rhyolitic upper sequence as about 15 Ma old. Coats (1964, p. M 23) regarded at least most of the normal faults of the area to be of late Miocene age.

Armstrong *et al.* (1969) made the interesting observation that silicic volcanic rocks of the Great Basin of Nevada and adjacent Idaho, Oregon, California, and Utah seem to be oldest in a 'core area' in the north-central part of the region and became progressively younger outward from this 'core' towards the margins of the Great Basin. Armstrong (1970) later extended this concept to the late mafic rocks as well. We would suggest that several effects may have combined to form the pattern that they noted. First, there are few old dates north of their 'core area' because the entire northern part of their study area is covered by upper Miocene and younger volcanic rocks of the Snake River plain and Oregon plateaux provinces, but Eocene and Oligocene rocks reappear north of this younger volcanic cover. Secondly, as was noted in part I of this paper (Lipman *et al.*, this volume, p. 217), the most active region of calc-alkalic volcanism seemed to move southward from Eocene through Oligocene time and in the northern region became restricted to areas farther west during the Oligocene; these changes probably resulted from changes in the geometry of subduction during early and middle Tertiary time. This trend, in combination with the first point noted above, may be reflected in the pattern of ages illustrated by Armstrong *et al.* (1969) for the times from about 40 to about 20 Ma ago. Thirdly, we visualize in the same way as did Armstrong *et al.*, the progressive restriction of both basin-range normal faulting and basaltic and bimodal volcanism toward marginal parts of the Great Basin during the time from about 16 Ma ago to the present.

In the central Sierra Nevada, Miocene calc-alkalic rhyolitic ash-flows as young as about 20 Ma and younger andesitic breccias and lava flows represent a continuation of volcanism that began during the Oligocene (Dalrymple 1963, 1964). Slemmons (1966, p. 203), summarizing studies of the central Sierran volcanism, showed that these upper andesites probably include rocks as young as early Pliocene. These calc-alkaline volcanic rocks are overlain unconformably by latites, succeeded by basalts, alkali andesites, and minor rhyolites. The latites are as old as about 9 Ma (Dalrymple 1964). Slemmons (1966, p. 201) stated that uplift of the Sierra Nevada tilted fault block had already begun at the time of the early latite eruptions but that it took place mainly, along with basin-range faulting in the area just east, during later Pliocene and Pleistocene time. Christensen (1966) regarded uplift as mainly postdating the early latite eruptions.

The volcano-tectonic transition is well displayed in the Virginia City–Steamboat Springs area, north of Carson City in western Nevada (Thompson 1956; Thompson & White 1964). Rhyolitic ash-flow tuffs about 23 Ma old (Evernden & James 1964) that extend across later basin-range structures are overlain by calc-alkalic andesites. The uppermost andesites are interlayered with basal sediments of the Truckee Formation, which Thompson & White (1964, p. A 32, A 39–40) interpreted as having accumulated in the precursors of the present basin-range valleys. Alkali-olivine basalts and alkali andesites are interlayered with the main part of the Truckee formation, and a bimodal alkali basalt-rhyolite sequence locally overlies it. A fossil flora dates basin-fill deposits in westernmost Nevada that grade into the Truckee as middle Pliocene (Axelrod 1958). Potassium-argon dating of interlayered volcanic materials indicates an age of about 6 Ma (Evernden & James 1964).

In the northern Sierra Nevada, the Miocene and younger history is basically similar to that in the central Sierra Nevada and the Carson City region (Durrell 1959, 1966). As to the south, lower Miocene and Oligocene rhyolites are abundant and are as young as about 20 Ma (Dalrymple 1964). They overlie widespread older andesitic breccias and flows. Andesitic mudflow breccias and volcaniclastic conglomerates overlie the rhyolites and may include younger rocks than comparable andesites in the central Sierra. Their upper age limit is uncertain but is probably early or middle Pliocene (Durrell 1959). Basalts flooded the area, probably in late Pliocene time (Durrell 1959, p. 179), just before uplift of the Sierra Nevada block by large-scale normal faulting. Sediments accumulated in numerous fault-block basins formed during this uplift.

Northwestern region

Upper Cenozoic volcanic rocks of western Montana are poorly known except in the area near Helena. Most of the volcanic rocks of the Helena–Deer Lodge area are either Cretaceous in age and related to the slightly younger Boulder batholith or are of early Eocene age and overlie the batholith. However, eruption of local small bodies of rhyolite, probably of late Miocene or Pliocene age (Ruppel 1963, pp. 52–60), overlapped graben formation represented by coarse Miocene sedimentary rocks in the Divide basin mapped by H. W. Smedes (Steven *et al.* 1971). Most volcanic rocks in southwestern Montana are Eocene to lower Miocene (Scholten, Keemon & Kupsch 1955; Lowell 1965). They appear to be an extension of the Challis volcanic field to the west, at least in part, and to predate a regional unconformity found in areas farther east at the base of the upper Miocene. Basin deposits older than this unconformity appear to be largely in the successors of basins found in the Late Cretaceous–early Tertiary orogeny; upper Miocene and overlying deposits appear to be related to renewed faulting, block tilting, and regional uplift after an interval of quiescence (Robinson 1960, 1961). Basalts in the valley of the Yellowstone River near Livingston, Montana, are of early Pliocene age (Bush 1968) and overlie upper Miocene and lower Pliocene sediments that may be related to block faulting.

The Columbia River and Oregon plateaux adjoin the Cascade range on the east. The plateau region and its uplifts preserve a record of varied Miocene and younger volcanic activity. The lower Miocene rocks of the plateau region, included in the John Day formation, are mainly silicic ash deposits that accumulated downwind from the contemporaneous calc-alkalic volcanoes of the western Cascades (Merriam 1901; Hay 1963; Peck 1964; Peck *et al.* 1964). High-silica alkali-rich rhyolitic ash-flows and local trachyandesite and rhyolite lavas are interlayered with these ashes in the western part of the plateau region (Hay 1963; Peck 1964; Fisher 1966; Swanson & Robinson 1968) and appear to form a somewhat alkalic, bimodal volcanic foreland suite erupted from source areas east of the main early Miocene volcanic chain of the western Cascades.

A major change in the volcanism of this region occurred in early or middle Miocene time with the eruption of the lower part of the plateau basaltic sequence. Eruption of basalts of the Columbia River Plateau extended from about 21 Ma to about 12 Ma ago or less according to Gray & Kittleman (1967). Taubeneck (1969, 1970) showed that eruption of these lavas through thousands of generally north- to northwest-trending dikes accompanied regional tectonic extension comparable in time, trend, and structural mechanics to the normal faulting of the Basin–Range province. Furthermore, extensional faulting contemporaneous with the Columbia River Basalt occurred widely in the area to the east (Hamilton 1962; Taubeneck 1969, 1970). Local intermediate to silicic volcanism around the margins of the Columbia River Plateau was contemporaneous with and followed the basaltic eruptions (Thayer & Brown 1966).

Basin-range faulting of late Miocene to Quaternary age accompanied the generally basaltic to bimodal volcanism of the Oregon plateaux (Fuller 1931; Waters 1962; Donath 1962; LeMasurier 1968; Walker & King 1969). In fact, these plateaux commonly are regarded as a largely basalt-covered northern extension of the Basin–Range province. Volcanic vents of the region commonly are alined along range-bounding faults. In the Modoc Plateau, the southwestern part of the Oregon plateaux province, predominantly andesitic activity ended in late Miocene or early Pliocene time and normal faulting became active, accompanied by the eruption of rhyolitic ash-flows and high-alumina basalts as well as by accumulation of basin-filling sediments (Russell 1928; Powers 1932; Macdonald 1966).

Christiansen & Blank (1969) interpret the eastern Snake River Plain (its northeast-trending portion) and the Yellowstone Plateau as having evolved progressively and as constituting parts of an integral volcano-tectonic system of Pliocene and Quaternary age. The origin of the system was in the region south of Boise (figure 5), during early Pliocene time (Malde & Powers 1962). Probably the system evolved as tensional rifting opened the region northeastward along the axis of the Plain (Hamilton & Myers 1966). According to Christiansen & Blank, large granitic bodies, emplaced periodically high in the crust, each successively northeast of the preceding one, vented to produce voluminous ash-flow eruptions and large calderas. During the time that each of these successive rhyolitic complexes was active, tholeiitic and high-alumina basalt were erupted in surrounding areas. With the crystallization of each large granitic body, more alkali-rich basaltic lavas were erupted through it and eventually filled a regional subsidence trough along the axis of the extinct rhyolitic caldera complexes. The Yellowstone Plateau is a rhyolitic region at the northeast end of the system marking the youngest stage in this continuously evolving system. The area of the eastern Snake River Plain as shown on figure 5 is the downwarped axis of older rhyolitic activity, since flooded by younger basalts. The probable early Pliocene age of the origin of this system dates the beginning of extension on the eastern Snake River Plain axis.

The Cascade range has been a nearly continuously active calc-alkalic andesitic chain through most of Cenozoic time and continues the history outlined in part I of this paper (Lipman *et al.*, this volume, p. 217) virtually to the present. In the southern Cascade Range Lydon (1968) showed that eruption of a calc-alkalic andesite breccia, that is the southernmost unit related to the Cascades, took place in the area south of Mount Lassen as recently as about 3 Ma ago. Mount Lassen itself is the only Cascade volcano that has had major eruptive activity in this century and is indicated in figure 5 by an age of 'less than zero' for the volcanic transition, which is to say that the transition has not yet extended north of that latitude in the Cascade range.

Coastal California

The volcanic fields of coastal California are not in their original spatial relationship to contemporaneous fields farther east because of large right-lateral displacement on the San Andreas and related faults. The details of these relations are not examined here, but the fundamentally basaltic character of most of the coastal volcanism is noted.

Late Cenozoic volcanism of southern California and its tectonic significance were discussed by Hawkins (1970). Previous studies in that region are those by Shelton (1954, 1955), Yerkes (1957) and Eaton (1958). Some of the Tertiary volcanic rocks of this region represent submarine eruptions and shallow intrusions. The oldest rocks of the suite are late Oligocene, about 28 Ma old, in Baja California, Mexico (McFall 1968; Hawkins 1970). Volcanic rocks in the Jacumba, Murietta and Channel Islands–Los Angeles Basin region, however, are younger than about 20 Ma. Hawkins (1970) shows that they represent a suite of basalts and somewhat alkalic differentiates of parental basaltic magmas. Their eruption was essentially coincident with folding, subsidence of the Los Angeles Basin and California borderland, and regional faulting in Miocene and later time. Volcanism was particularly active during the earlier stages of that deformation in middle Miocene time, but younger Miocene, Pliocene, and Quaternary volcanism are recorded locally.

Volcanic rocks of the southern and central Coast Ranges (Taliaferro 1943) generally were similar to those of southern California. Basalts are abundant, including distinctly alkalic types. Also abundant in the sequence are dark-coloured, probably alkali-rich andesites and lesser silicic differentiates. The volcanic rocks are mainly of middle and late Miocene age (Taliaferro 1943; Turner 1970) and are interlayered in a number of places with marine sedimentary rocks that were deposited in increasingly isolated basins formed by Coast Range folding and faulting. Others are subaerial volcanic fields. A volcanic sequence probably representing a differentiated alkali-basaltic series is present in the Quien Sabe field, probably of mid-Miocene age (Bailey & Myers 1942; Taliaferro 1948; Leith 1949). Marine basaltic and differentiated more silicic rocks in the Santa Cruz Mountains as old as about 23 Ma (Turner 1970) are interlayered with lower Miocene marine sedimentary rocks (Cummings, Touring & Brabb 1962). Basalts, alkali andesites, and rhyolites of the Berkeley Hills–Santa Clara Valley area appear to form the northernmost volcanic field in the California coastal region east of the San Andreas fault that we would regard as fundamentally basaltic. The bulk of that field is of Pliocene age (Taliaferro 1951). Potassium–argon dating of volcanic rocks of the Berkeley Hills and vicinity yielded ages of about 12 to about 5 Ma (Evernden *et al.* 1964). This volcanism was approximately contemporaneous with predominantly intermediate-composition calc-alkalic volcanism of the Sonoma volcanic field north of San Francisco Bay (Weaver 1949), although a K/Ar age as young as about 3 Ma was obtained there by Evernden & James (1964). Calc-alkalic volcanism of Pleistocene age occurred in the Clear Lake region farther north (Anderson 1936). The calc-alkalic igneous rocks of Sutter Buttes are as young as about 1.5 Ma (Williams 1929; Evernden *et al.* 1964).

It seems significant that, although tectonism has been almost continuous since late Mesozoic time in the California coastal region, major strike-slip faulting on the San Andreas and related faults, region uplift, termination of major thrusting, and formation of certain major structures such as the Los Angeles basin may have occurred largely or entirely in late Cenozoic time (Crowell 1962; Yeats 1968; Page 1970*b*; Ernst 1970; Hawkins 1970; Atwater 1970), the time of active volcanism mainly of fundamentally basaltic character. That volcanism was most intense regionally during the earlier stages of the late Cenozoic coastal tectonism. The significance of the calc-alkali fields of the northern part of the region will be considered separately in the interpretive summary.

SUMMARY AND PLATE-TECTONIC INTERPRETATION

We have attempted to show in the preceding sections that a fundamental change in the nature of igneous activity in the Western United States corresponded closely with evolution of a new extensional tectonic régime. Part I of this paper (Lipman *et al.*, this volume, p. 217) showed that at least until late Oligocene time the volcanism of the Western United States was predominantly andesitic and formed two belts of calc-alkalic igneous rocks that extended parallel to the continental margin, each belt increasing eastward in the K_2O/SiO_2 ratio. The eastern belt extended to a foreland of highly alkalic volcanic fields of fundamentally basaltic type. Plate-tectonic models based independently upon sea-floor magnetic anomaly patterns require the presence of a continental-margin trench and subduction zone along the entire Pacific margin of North America during the time that this volcanic pattern prevailed. The interpretation offered in part I of this paper was that the wide zone of early and middle Tertiary volcanism of the Western United States was related to the evolution of a low-dipping imbricate subduction zone under the continental margin from latest Cretaceous to late Oligocene time.

In parts of the continent which had undergone deformation and calc-alkalic igneous activity during Mesozoic to middle Cenozoic time, northwest-trending right-lateral faults eventually dominated the late Cenozoic tectonic pattern in areas relatively near the continental margin, and normal faults oriented roughly northerly and controlled to some extent by older structures produced oblique extension of inland areas. The change in tectonic pattern began near the end of the Oligocene in southern New Mexico and Arizona, and the locus of this change migrated northwestward across the Western United States and probably southeastward into Mexico. As the region of oblique opening widened, the igneous activity changed to several types of fundamentally basaltic volcanism such as occur in other regions of major extension in the world.

The concept of basin-range faulting as a regional oblique extension with opening mainly in a northwest–southeast line was utilized by Atwater (1970) in an important plate-tectonic interpretation of the evolution of western North America and the northeastern Pacific. Her interpretation is based largely upon the pattern of sea-floor magnetic anomalies produced by late Cretaceous and Cenozoic sea-floor spreading in the northeastern Pacific. Up to a point, her discussion is similar to that of McKenzie & Morgan (1969) in showing that the magnetic anomaly pattern itself requires that an ancestral East Pacific Rise was once continuous through the Pacific and that large portions of an *eastern* Pacific plate (the inappropriately named Farallon plate) must have been consumed by subduction at a trench that once existed along the west coast of North America. There also must have been a relative motion of the American and *western* Pacific plates such that the East Pacific Rise and the American plate approached one another and eventually intersected (figure 6*a*, *b*). As they did so, the portions of the spreading oceanic rise and continental-margin trench that collided were mutually annihilated, their function of accommodating relative motions of the Farallon and American plates no longer being required. In their place a transform fault system was established in order to accommodate relative motions between the western Pacific and American plates (figure 6*c*). The principal expression of this transform structure in the McKenzie–Morgan and Atwater models is the San Andreas fault zone of coastal California. Continued convergence of the Pacific and American plates produced a pair of triple junctions between the separated trench segments and the San Andreas fault zone. The triple junctions migrated relatively northwestward and southeastward from their initial point of intersection to their present positions near Cape Mendocino in northern California and the mouth of the Gulf of California in central Mexico. Present plate motions show that for at least some period of late Cenozoic time the Pacific and American plates have not merely approached but also have moved past one another in a right-lateral sense. The geologically most reasonable models would include this sense of relative motion back in time at least to the initial intersection of the rise and trench, so that the late Oligocene point of initial intersection would have moved northwestward some hundreds of kilometres relative to the American plate. Atwater's model goes beyond that of McKenzie & Morgan in showing that the relative motion between the Pacific and American plates during late Cenozoic time was distributed over a wide zone of the western portion of the American plate by oblique rifting rather than being concentrated entirely within transform faults bounding the plates.

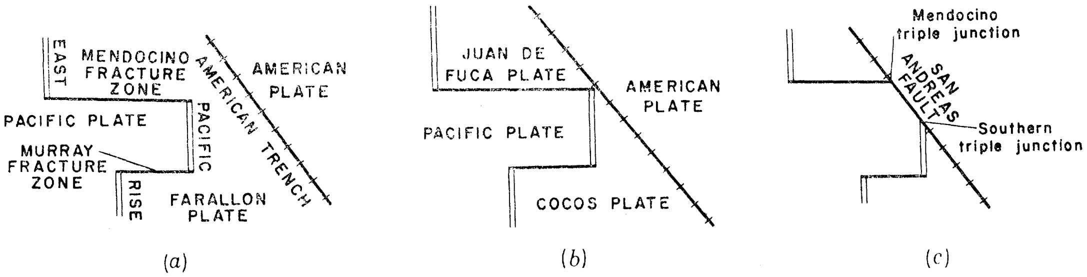

FIGURE 6. Diagrammatic representation of plate-tectonic relations between North America and the eastern Pacific ridge-trench system (based on McKenzie & Morgan 1969). (*a*) Before ridge-trench collision. (*b*) Initial ridge-trench collision. (*c*) Evolution of transform faults and triple junctions after initial collision.

The times at which fundamental changes in volcanism and tectonism occurred in the Western United States were approximately those to be expected from Atwater's model, in terms of the motion of the northern triple junction. The continental data thus support the interpretation of plate motions based upon sea-floor magnetic data and help to establish the times at which the various plates interacted in different regions. As far as we know, not enough data are available for the appropriate regions of Mexico for one to follow the corresponding southern triple junction southeastward to its present position at the mouth of the Gulf of California.

The relations between plate motions and the associations of different igneous suites and changing tectonic régimes are summarized in figure 7. The maps of this figure are plotted on a base adapted from Atwater (1970), which is a Mercator projection based upon the pole of relative rotation between the American and Pacific plates (Morgan 1968). This projection orients structures systematically with respect to the primary horizontal plate motions; the San Andreas and related transform faults, approximating small circles about the pole of relative rotation, lie close to the parallels of the projection; directions of direct opening are along meridians; and oblique extension can occur along obliquely oriented structures. Deformation of areas east of the San Andreas fault zone by basin-range faulting is not restored in these maps. Some distortions of angular relationships, therefore, are present on the maps showing the older features. Figure 8, based on the time relations summarized in figure 5, is plotted from the projection of figure 7 and interprets the progression of the triple junction along the continental margin during late Cenozoic time.

According to Atwater (1970), initial intersection of the East Pacific Rise with the American trench can be shown, from disrupted sea-floor magnetic anomalies and abrupt slowing of the spreading rate, to have occurred in the region between the Pioneer and Murray fracture zones at about the time of anomaly 9 (figure 7*a*), about 30 Ma ago according to the time scale of Heirtzler *et al.* (1968). Figures 7*a* and 8 indicate that the ridge-trench collision occurred at the continental margin in northern Mexico. Atwater points out that a time lag of several million years may have intervened after the initial intersection because of the necessity to cool the oceanic plate before deformation could occur within the continental block. Otherwise, all deformation resulting from the plate interactions would have occurred at the plate boundary, a zone where the lithospheric thickness was effectively zero at the time of intersection. Thus,

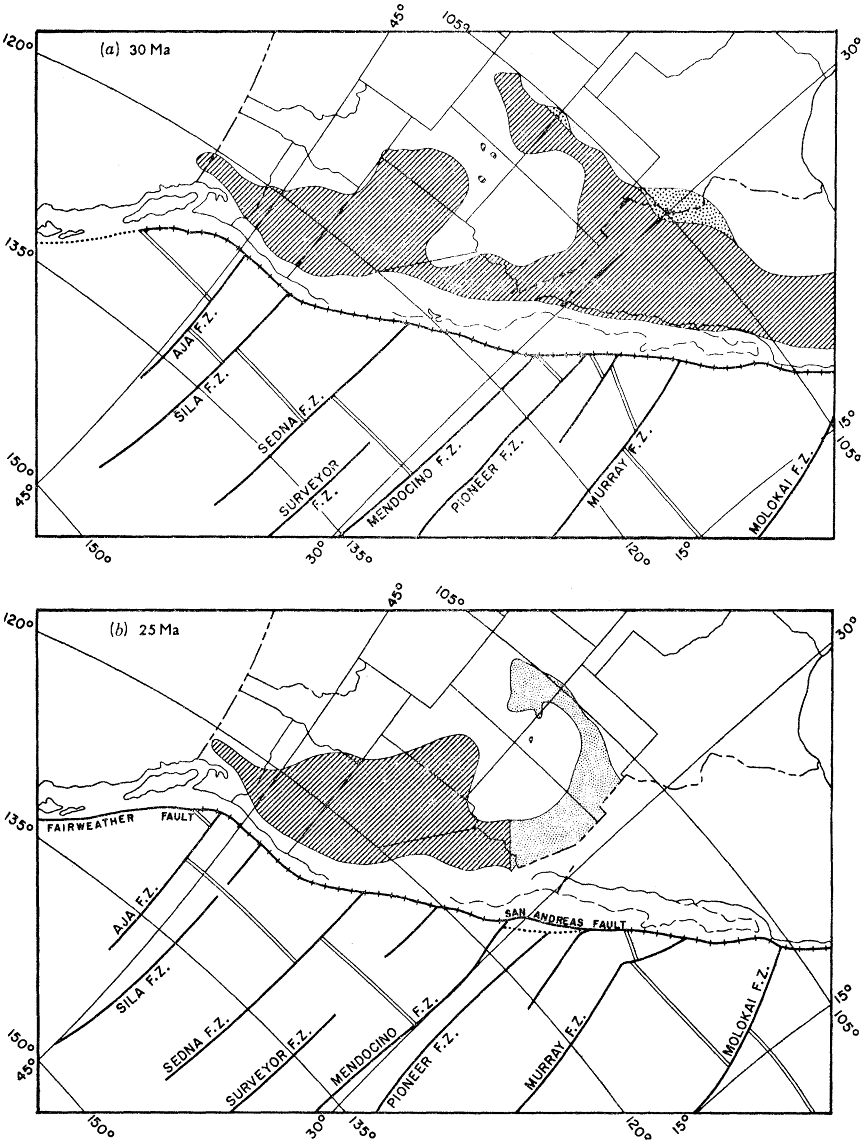

FIGURE 7. Igneous associations and plate-tectonic elements of the Western United States and eastern Pacific at various times during the late Cenozoic (base maps adapted from Atwater 1970). FZ, fracture zone; double line, spreading ridge; hatched line, trench; dotted line, stable continental margin; dashed lines, paleo-positions of modern coastlines and boundaries; diagonally lined area, predominantly andesitic volcanism; heavily stippled area, mid-Tertiary foreland alkalic volcanism; lightly stippled area, fundamentally basaltic volcanism.

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according to Atwater's model, the first appreciable effects of the ridge-trench collision should have been impressed within the North American continent sometime between about 30 and 25 Ma ago. This time lag may be partly responsible for the uppermost Oligocene and lower Miocene volcanic rocks of Arizona and New Mexico, which seem to represent a more protracted transition between predominantly andesitic and basaltic or bimodal suites than in areas farther north.

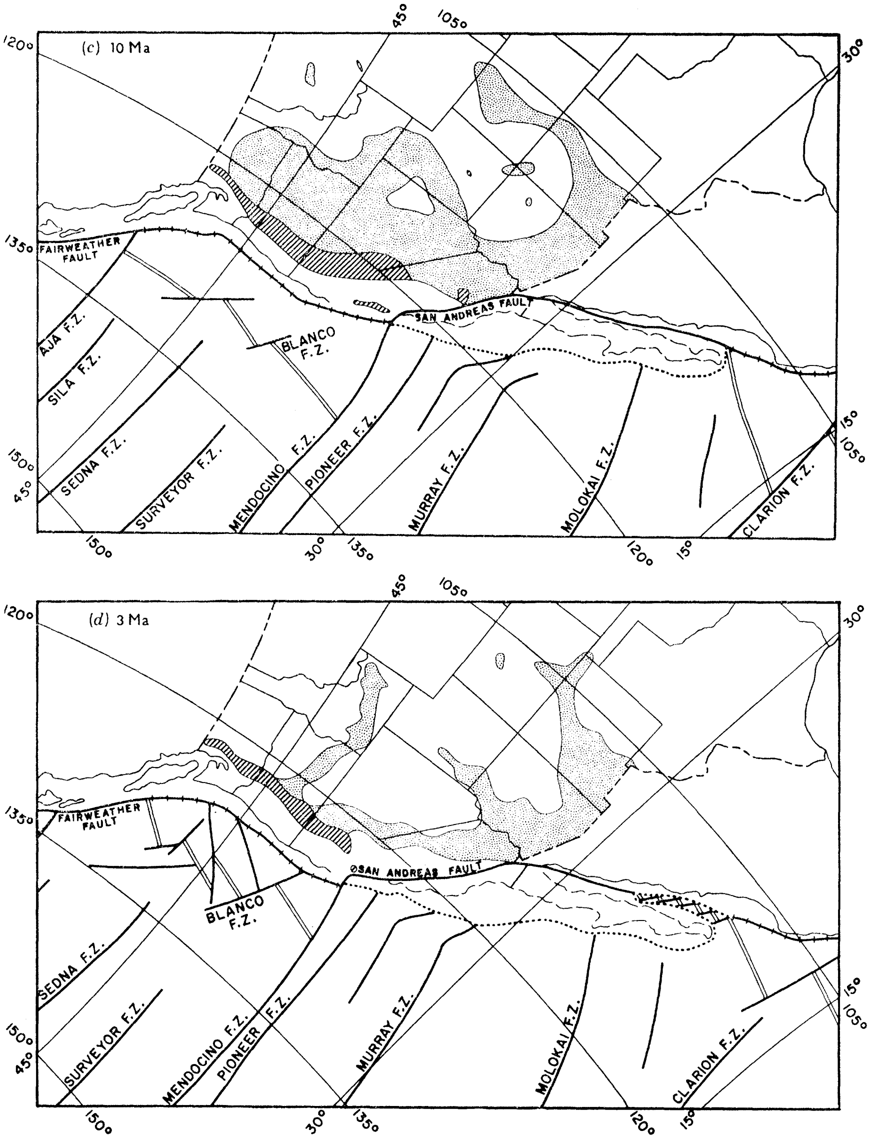

Figure 7. For legend see facing page.

Termination of major activity in the foreland volcanic field of west Texas occurred about 30 Ma ago; the area subsequently was broken by extensional fractures, in some of which basaltic dikes were emplaced by about 23 Ma ago. By 25 Ma ago the entire region of the Western United States southeast of a line from central Colorado to the mutual boundary of California, Arizona and Mexico had undergone the transition to fundamentally basaltic volcanism and basin-range faulting; areas northwest of the line still had active fields of predominantly andesitic volcanism and had not yet been broken by regionally extensive basin-range faults (figure 7*b*).

By about 10 Ma ago areas southeast of a line from southwestern Idaho through central Nevada, to central California had undergone the volcano-tectonic transition, and predominantly andesitic calc-alkalic volcanism was largely restricted to areas near the continental margin northwest of that line (figure 7*c*). As noted previously, the belt of calc-alkalic predominantly andesitic volcanism in the northwest had narrowed considerably by Miocene time,

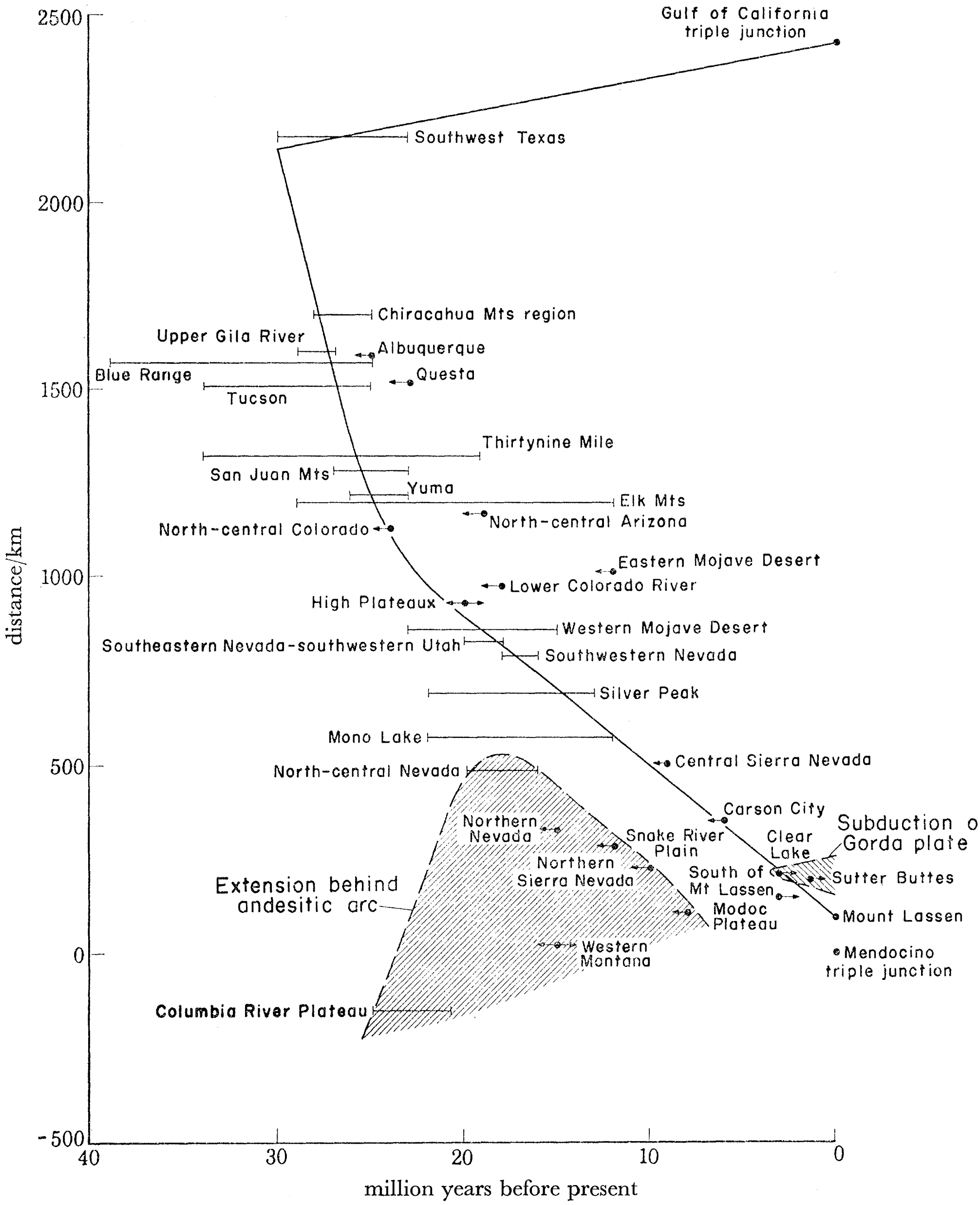

FIGURE 8. Time of volcano-tectonic transition in different areas of the Western United States, from figure 5, projected perpendicularly to the San Andreas fault in figure 7 and plotted as a function of the distance of the areas southeast of the present Mendocino triple junction. Portions of volcanic fields lying to the left of the curve are predominantly andesitic (except in shaded area), to the right are fundamentally basaltic (except in shaded area). Shaded areas are discussed in text.

and a bimodal basalt-rhyolite suite was being erupted from a volcanic foreland along its eastern margin. In early or middle Miocene time, however, eruption of the tholeiitic flood basalts of the Columbia River Plateau began, accompanying tectonic extension of a large region east of the Cascades. By middle Miocene time basin-range structure was not confined to areas southeast of the belt of calc-alkalic volcanism, but had encroached far northward behind the continental-margin arc, perhaps in analogy to regions of extension found behind several western Pacific island arcs. This extension and related basaltic volcanism, represented by a shaded area on figure 8, continued through the rest of Miocene and Pliocene time, but most of the younger activity was in the region of the Oregon plateaux, south of the Columbia River plateau. The region of extension behind the Cascade arc appears to represent a connexion through the continental plate between the relative motions north of the Juan de Fuca ridge and those south of the Mendocino fracture zone. As the relative motions north and south of the Juan de Fuca plate were accommodated by growing regions of tectonic extension in the 'soft' boundary zone of the American plate (Atwater 1970), the diminishing Juan de Fuca plate became partially coupled to the American plate through this connecting extensional zone behind the arc.

An apparent anomaly existed at about the time of figure 7*c* in the western Mojave region, where calc-alkalic predominantly andesitic volcanism was active in several areas. The reason for the existence of these calc-alkalic fields is not clear in terms of our general interpretation, but it might be noted that the petrography of the andesites indicates unusual disequilibrium between the magmas and their phenocrysts (Smith 1964). Possibly these andesites represent a mixed-magma sequence as is found in some bimodal provinces. Alternatively, the andesites might be related to oblique subduction of the subplate between the Blanco and Mendocino fracture zones as is suggested later for the younger calc-alkalic fields of the northern Coast Ranges and Great Valley of California.

By about 3 Ma ago the Gulf of California was open and the line of separation between contrasting volcano-tectonic associations extended northeastward from the northern triple junction, then located near Point Arena on the California coast (figure 7*d*). With opening of the Gulf, basin-range extension appears to have become largely restricted to inland areas northwest of the upper end of the Gulf; most faults in the basin-range province south of the Colorado Plateau became inactive in latest Cenozoic time (Gilluly 1937). A trench still existed along the coast north of Point Arena, and predominantly andesitic calc-alkalic volcanism was active in the region south of Mount Lassen, the southernmost active volcano of the Cascade Range. The small calc-alkalic fields of northwestern California, the Sonoma, Clear Lake, and Sutter Buttes, are south of the southern end of contemporaneous Cascade-northern Sierra calc-alkalic volcanism and may have been related to oblique subduction of the constricted but still active part of the Juan de Fuca plate between the Mendocino and Blanco fracture zones. These small fields are separated on figure 8 from those used to trace the movement of the triple junction. Inactivity of the Clear Lake and Sutter Buttes fields during the last million years or so may be related to disruption of the spreading ridge system by a developing connexion between the San Andreas fault and the Blanco fracture zone during that time (Moore 1970).

At the present time, the triple junction is situated near Cape Mendocino. An actively spreading oceanic rise still exists north of the Mendocino fracture zone west of the continental margin, but the complementary trench has been largely filled by sediments (Silver 1969). Volcanism probably has not occurred along the Gorda Ridge for about the last 100000 years

(Moore 1970). Although no Benioff-type seismic zone is identifiable beneath the present continental margin, some subduction may still be occurring along this margin (Silver 1969); small differences in assumptions about the relative motions of the plates involved result in large differences in the computed vector sum which indicates the relative amounts of strike-slip and underthrusting of the eastern oceanic plate relative to the continental margin. The Cascade Range appears to be nearing a state of extinction although a few volcanoes there have been active in the past two centuries and several have had major Holocene activity. Thus a plate-tectonic interpretation of the region off the coasts of northern California, Oregon, and Washington in which the underthrusting plate is becoming smaller, increasingly fragmented, and partially coupled to the American plate, is consistent with apparent waning of continental-margin volcanism and the progressive growth of basin-range structures behind the arc.

It should be emphasized that the viewpoint from which our conclusions stem contrasts with the hypothesis stated in some interpretations of the late Cenozoic in the Western United States that the East Pacific Rise has been overridden by North America and that its presence beneath the region has caused certain geological and geophysical anomalies (see, for example, Cook 1966; Gilluly 1969). In the plate-tectonic view, the high regional heat flow, anomalous upper mantle seismic velocities, and fundamentally basaltic volcanism of the Western United States can be thought of as effects, not causes, of regional extension.

The deformation of the American plate over such a wide zone during late Cenozoic time appears to be a function of its preceding stress and thermal history. The volcanic and tectonic zones related to plate convergence during Miocene and early Tertiary time were unusually wide and complex in the Western United States segment of the American cordillera. This wide zone appears to have been related to progressive flattening and imbrication of the bounding subduction zone. The widely spread-out, gently dipping subduction system must have been supported by a downgoing Farallon plate of substantial size. It was noted previously that the region affected by basin-range extension in late Cenozoic time was virtually the same as that which underwent orogenic deformation during late Mesozoic and early Cenozoic time. As the size of the remnant of the Farallon plate west of the United States, the Juan de Fuca plate, decreased after the initial ridge-trench collision, it perhaps was able to support only a less complex subduction zone which again steepened to form the narrower belts of continental-margin andesitic volcanism of later Cenozoic time. Distribution of the newly established relative motions associated with Pacific–American plate interaction inland from the San Andreas transform system was restricted to the zone which previously had been uplifted, folded, and heated. Blocks such as the Colorado Plateau that had remained undeformed and had relatively little igneous activity during earlier episodes of convergence remained relatively rigid during the succeeding episode of oblique rifting.

Termination of subduction probably resulted in regional uplift of the Western United States. The presence of a deep-seated slab of lithosphere no longer in dynamic equilibrium with subduction but being heated, and possibly undergoing phase changes, may have caused this uplift. The present high elevations of the Colorado Plateau and Wyoming basin as well as the high average elevations of areas of late Cenozoic extensional faulting such as the southern Rocky Mountains and the Basin–Range province and its bounding ranges, the Sierra Nevada and Wasatch Range, may result from these adjustments. A similar interpretation, although on a smaller scale may be implicit in the ideas of Ernst (1970) and Page (1970*a*, *b*) if late Cenozoic uplift of the California Coast Ranges is related to the termination of subduction.

The ideas upon which this paper is based were first presented in preliminary form at the Penrose Conference of the Geological Society of America in 1969 on 'the meaning of the new global tectonics for magmatism, sedimentation, and metamorphism in orogenic belts', and later at the Cordilleran Section of the Geological Society of America in 1970. Discussions with participants in those meetings greatly helped us in the formulation presented here. In particular we wish to thank Warren Hamilton, William R. Dickinson and Tanya Atwater for their stimulating encouragement as well as their challenges to our developing ideas.

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