Cenozoic Tectonics of the Western United States[1]

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Abstract. The Cenozoic structures of the western United States are interpreted here as being products mostly of horizontal motion of the crust. The distribution of strike-slip faulting, tensional fragmentation of the brittle upper crust or rupturing of the entire continental crust, and compression define a pattern of northwestward motion increasing irregularly southwestward toward coastal California. Hans Becker, in 1934, and S. W. Carey, in 1958, are among those who have suggested such a tectonic system.

The aggregate Cenozoic right-lateral displacement of Cretaceous and older rocks and structures by the northwest-trending strike-slip faults of coastal California is about 500 km. The greater part of this movement has occurred along the San Andreas fault, but many other faults share in it. At least six earthquakes within the past century have been accompanied by lateral displacements at the surface along faults of the San Andreas system. Successively greater offsets of successively older geologic terranes demonstrate continuing motion throughout Cenozoic time. Late Miocene materials have been displaced at least 160 km; Oligocene, at least 260 km. The present velocity of regional shear strain, about 6 cm/yr, demonstrated by geodetic resurveying in southern and central California, is about 8 times faster than the average needed to account for the total movement within the Cenozoic. The faults are in general associated with structures formed by oblique tension south of Los Angeles and with structures due to oblique compression north of that city. The opening of the Gulf of California and the Salton Trough by the oblique rifting of Baja California and the Peninsular Ranges away from mainland Mexico is the greatest of the tensional effects.

The strike-slip faults may be confined to the crust. Earthquake foci extend no deeper than 16 km. The faults end to the south in the Gulf of California, whose crustal structure is oceanic. To the north, the San Andreas turns seaward as the north-facing Gorda scarp, west in line of which in deeper water is the south-facing Mendocino escarpment, produced apparently by an inactive left-lateral oceanic fault. The continental sliver of coastal and Baja California, west of the faults of the San Andreas system, may be drifting northwestward independently over the ocean floor and the mantle, and the leading point of the sliver may have been deflected westward when it hit the Mendocino scarp on the sea floor.

East of this coastal movement system is the Basin and Range province, whose obvious Cenozoic structures are dominated by block faulting. The present ranges have formed mostly since early Miocene time, similar older ranges having been destroyed by erosion and deformation. The normal faulting, which is not associated within the region with any complementary tectonic compression, requires crustal extension as its basic cause. If the faults maintain their average 60° dips at depth, extension is half the dip-slip amount; but probably the major faults flatten downward, and the amount of extension about equals that of shallow dip-slip. Total Cenozoic extension in northern Nevada and Utah may have been 300 km. Concurrent volcanism much augmented the thinned and fragmented crust, and the volcanic terranes in turn have been fragmented by block faulting.

Right-lateral strike-slip faults trend northwestward in lanes between normal-fault maintain blocks in the southwestern part of the Basin-Range province. Cenozoic dis-

[1] A contribution to the Upper Mantle and Western Earthquake Belt Programs.

placements reach 50 km on the Las Vegas fault and 80 km on the Death Valley-Furnace Creek faults. Northeast of the strike-slip faults, ranges and basins trend north-northeastward in tension-gash orientation. Within the belt of lateral faulting, ranges undergoing active normal faulting mostly trend north-northwestward in oblique pull-apart orientation. The Sierra Nevada and Klamath Mountains have moved northwestward and rotated counterclockwise, thus moving away from the continental interior more in the north than in the south, and the extension distributed behind them has formed the Basin-Range province.

The narrow block-fault Rio Grande valley system of New Mexico and southern Colorado is structurally and topographically similar to the rift valleys of East Africa and reflects localized crustal extension. The Idaho batholith, like the Sierra Nevada batholith, is drifting northwestward as an unbroken plate. Extension east of the Idaho batholith is taken up by normal-fault fragmentation in south-central Idaho and southwestern Montana, whereas extension south of the batholith has produced a rift through the continental crust, the Snake River Plain, filled deeply by lava. Seismic velocities indicate granitic crust to be lacking in at least the western part of the plain. Right-lateral faults of the Osburn system bound the batholithic plate on the north, and the motion they represent is taken up north of them by extension forming fault troughs.

Integration of geologic and geophysical information shows that large regions of the Northwest are lava accumulations of continental crustal thickness, not old continental crust covered by lava. The volcanic terrane of northwestern Oregon and southwestern Washington forms new volcanic crust in a region which was oceanic before Cenozoic time. The volcanic terrane of southeastern Oregon, northeastern California, and northwestern Nevada fills an irregular tension rift through the Mesozoic continental crust. This rift resulted from the westward motion of the Klamath Mountains region, which was sundered from a position south of the Mesozoic terrane of northeastern Oregon and which was bent oroclinally as it moved westward in post-middle Eocene time. The Mesozoic terrane of northeastern Oregon pivoted away from the Idaho batholith to form a smaller orocline and left a triangular rift since filled by lava. Independent motion of continental crust over mantle and oceanic crust seems to be indicated. Inertial forces due to redistribution of rotational momentum among crustal fragments, mantle, and core may provide the motive power.

INTRODUCTION

The structure of the western United States is here described and interpreted in terms of a tectonic system in which the California region is moving rapidly northward past the continental interior. Structures of extremely varied superficial aspect can be viewed within the moving framework of this tectonic system as manifestations of a single pattern of continental motion. Such a tectonic system was suggested by *Becker* [1934], and the proposal was much elaborated by *Carey* [1958, pp. 334–338]. Other workers contributed important ideas. Particularly significant was the inference [*Hill and Dibblee,* 1953] of great lateral faulting, the amount decreasing with decreasing age of the offset materials. *Hamilton* [1961] and *Wise* [1963], among others, have expanded upon aspects of the tectonic system. Older reports hinting at such a pattern of deformation include those by *Gianella and Callaghan* [1934] and *Locke et al.* [1940]. We note in this paper samples of the available evidence for lateral motion in the western states and present briefly our interpretations. *Gilluly* [1963], *King* [1959], and *Eardley* [1962], writing from different viewpoints, provide other interpretations and also references to many matters which we do not discuss here.

We regard it as proved—many others do not—that the San Andreas and related faults of coastal California have an aggregate Cenozoic displacement of hundreds of kilometers. The region is now being deformed at velocities, measured geodetically, adequate to account for such offsets in a small fraction of Cenozoic time. Lesser strike-slip faults occur far inland. Spectacular as the great lateral faults are, they are but one aspect of the active deformation of the western United States. Tensional normal faults are active over broad regions, compressive folds and thrust faults over other regions, and strike-slip faults occur in both environments. In one of the two major regions in which the continental crust has been ruptured and pulled apart, new oceanic crust has formed in the void; in the other, extensive volcanism has produced a thick new crust standing at continental levels. These and allied topics are discussed in the following pages.

We do not discuss the structures formed during the Laramide orogeny, which culminated during Paleocene time throughout the eastern part of the deformed belt of the western United States, nor do we discuss the later Cenozoic deformation of the Colorado Plateau and the central Rocky Mountains.

The subdivisions of Cenozoic time are of unequal absolute length, and the disparities should be kept in mind when comparing, say, features of the long Miocene record with those of the short Pliocene one. The age of the beginning of each of the subdivisions, in millions of years, is approximately as listed below [after *Geological Society of London,* 1964]; we have added the Recent date.

QUATERNARY

Recent 0.01 Pleistocene 1.5–2

TERTIARY

Pliocene	7	Eocene	
Miocene		Late	45
Late	12	Middle	49
Middle	18–19	Early	53–54
Early	26	Paleocene	
Oligocene		Late	58.5
Late	?	Early	65
Middle	31–32		
Early	37–38		

PACIFIC MARGIN OF MESOZOIC NORTH AMERICA

The western margin of North America probably lay far from its present position, relative to the interior of the continent, in late Mesozoic time. The Franciscan formation of California was formed on the ocean floor but was overridden by the continental plates in Cretaceous time and was thickened tectonically to form an addition to the continent before the beginning of the Tertiary. Subsequent growth and deformation during Cenozoic time greatly modified the western part of the continent.

The western part of the Mesozoic continent is represented now by a belt of rocks metamorphosed and intruded by granitic plutons primarily during Late

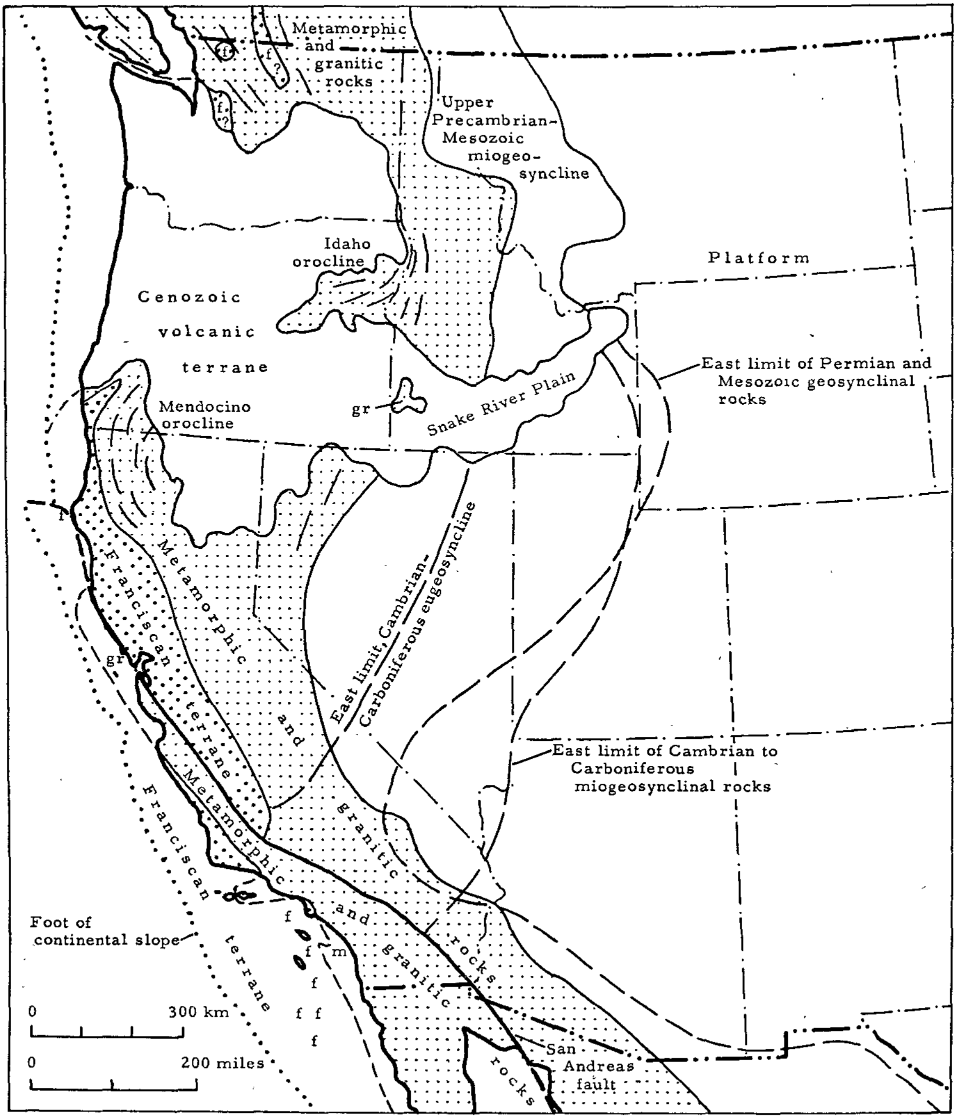

Fig. 1. Major Paleozoic and Mesozoic complexes of the western United States. Small and offshore areas of basement complexes are marked by letters: f, Franciscan terrane (and similar rocks in Washington) and gr, granitic rocks, and m, metamorphic rocks, belonging to the metamorphic-and-granitic terrane.

Jurassic and Cretaceous time. The belt trends southward across the western United States from British Columbia to Baja California and western Sonora (Figure 1) and includes the great batholiths of Idaho, the Sierra Nevada, and southern California. This belt was largely eugeosynclinal during early and middle Mesozoic time, although parts of it—as, the regions north and east of the Idaho batholith—apparently were not geosynclinal at all during the Mesozoic. Paleozoic eugeosynclinal and miogeosynclinal suites trend into the metamorphic-and-granitic terrane at a high angle in Nevada and California, and, in southern California south of the limit of all Paleozoic geosynclinal rocks, middle Precambrian plutonic basement rocks are widely exposed within the province of Mesozoic metamorphism and batholithic intrusion. The Paleozoic geosynclinal assemblages are truncated obliquely by the Pacific coast and, so far as is known, do not reappear farther south in the Americas, which poses perplexing tectonic problems and indicates that the orogenic system parallel to the present margin of the continent did not come into existence until Mesozoic time.

Much of the belt metamorphosed and intruded by granitic rocks during late Mesozoic time must have had a crust of continental thickness by the beginning of the Mesozoic. Precambrian plutonic basement rocks are widely exposed within the Mesozoic crystalline belt in southern California and southwestern Arizona. Elsewhere, upper Paleozoic strata, for example, contain such shallow-water fossils as fusulinids, even in the western part of the crystalline belt in many localities, showing deposition upon a crust that was thick and presumably continental. Many of the Mesozoic eugeosynclinal rocks were similarly deposited in shallow water, although it is quite possible that other strata formed at oceanic depths. In any case, great orogenies welded the various rocks of the belt into a mass whose crustal structure probably was everywhere continental by early Late Cretaceous time.

West of the metamorphic-and-granitic belt there is on the present continent a terrane of late Mesozoic deep-water deposits apparently formed on oceanic crust. In coastal and offshore California, this terrane consists of the eugeosynclinal and generally nonmetamorphosed Franciscan formation of Upper Jurassic, Lower Cretaceous, and (locally only?) lower Upper Cretaceous rocks. The Franciscan is dominated by graywackes derived from metamorphic source rocks and deposited by turbidity currents in deep water [*Bailey et al.*, 1964, pp. 5, 36]. The character of the associated cherts and rare limestones indicates deposition probably at oceanic depths [*Bailey et al.*, pp. 67, 77]. About one-tenth of the Franciscan consists of volcanic rocks, among which tholeiites are much dominant over high-alumina basalts and more silicic rocks [*Bailey et al.*, pp. 41, 55, Table 4], and this dominance of tholeiite over high-alumina basalt is consistent with an ocean-floor environment rather than an island-arc one. (See, for example, *Nicholls* [1965].) No basement is exposed beneath the Franciscan, but tectonic inclusions within it and xenoliths in the ultramafic intrusions into it are of more metamorphosed rocks of Franciscan types, and also eclogites, and do not include any rocks of continental basement types [*Bailey et al.*, 1964, p. 143]. Isostatic considerations make it unlikely that a continental basement could have been depressed to the oceanic depths required for deposition of the Franciscan formation. The Franciscan apparently formed on the ocean floor either as turbidite fans at the base of the continental slope or as abyssal-plain turbidite deposits farther seaward [cf. *Heezen et al.*, 1966].

Seismic data do not require that any granitic basement be present beneath the Franciscan. *Cameron* [1961] deduced a crustal structure in an area in the northern Coast Ranges of 3 km of material of $V_p = 5.1$ km/sec, above a 5.95-km/sec layer extending to a depth of 24 km, and a lower-crust 6.93-km/sec layer extending to the Mohorovicic discontinuity at 29 km. *Bailey et al.* [1964, p. 143] suggested that the top 3 km represents unconsolidated sediments, the next 21 km is Franciscan, and the basal 5 km is basalt. *Eaton* [1963, pp. 5804–5805] analyzed several seismic-refraction lines to infer an unlayered crust, about 20 km thick and having $V_p = 5.6$ km/sec, in the San Francisco area; he concluded that all, or most of, this crust represented the Franciscan and attributed the low velocity to the lack of strong metamorphism of even the deeper Franciscan.

The contact in northwestern California between the Klamath Mountains part of the metamorphic-and-granitic terrane and the Franciscan formation is a great overthrust fault, marked by a thick zone of phyllonite and followed discontinuously by sheets of serpentine [*Irwin*, 1960, p. 60 and plate 1]. At the south end of the Klamath Mountains, the overthrust rises in the overriding plate, turns southward in the eastern part of the Coast Ranges, and carries Sacramento Valley facies of uppermost Jurassic, Lower Cretaceous, and lower Upper Cretaceous strata (which depositionally overlie the Klamath crystalline terrane) over the correlative and very different Franciscan terrane of the core of the Coast Ranges. The valley facies consists of nonmetamorphosed and relatively undeformed marine clastic strata, apparently the products of sedimentation on the continental shelf. Part of the overthrust separating Franciscan and valley facies was described by *Brown* [1964]. West of the Franciscan core of the northern Coast Ranges is a coastal belt of rocks of the same general age span as both Franciscan and valley facies and intermediate in lithology between the contrasted facies [*Irwin*, 1960, pp. 42–43; *Bailey et al.*, 1964, pp. 138–142]. One possible interpretation is that the strata of this coastal belt were deposited between the Franciscan and valley facies on the outer part of the continental shelf and that they were carried tectonically across the Franciscan on the forward part of the same overthrust as that known to bound the Franciscan on the east; if this interpretation is correct, the overthrust displacement is at least 120 km.

The Franciscan formation probably lies beneath a great overthrust in the central and southern Coast Ranges also. Thus, east of the San Andreas fault at the latitude of Monterey Bay, the valley facies of Cretaceous strata forms a great anticline separated from the underlying core of Franciscan formation by an overthrust followed discontinuously by serpentine sheets. (See *Jennings and Strand* [1959].) Farther south, the overthrust sinks in the overriding block, and pre-Late Cretaceous crystalline rocks are in contact with the Franciscan. The trace of the contact is displaced far northwestward on the southwest side of the San Andreas fault. *Trask* [1926] is among those who have recognized its overthrust character there.

We interpret these relationships to show that the continent, as it existed in Late Cretaceous time, slid over the ocean floor along an overthrust fault whose trace was near the base of the continental slope. The overridden terrane—the ocean-floor Franciscan formation—was intensely deformed, and parts of it were forced downward to crustal depths on the order of 30 km (see *Ernst* [1965]), then churned back to shallower depths. *Gilluly* [1963], among others, has suggested, as do we, that North America is now sliding across the Pacific floor, and a modern analog of the Franciscan may now be forming on the ocean floor west of the continent.

The Franciscan-equivalent terrane of southwestern Oregon (there assigned to the Myrtle group, Dothan formation, and other units) probably lies beneath the same great overthrust fault. (See *Bailey and Jones* [1965], *Irwin* [1964], and *Peck and Wells* [1961]; see also comments by *Dott* [1965].) A similar interpretation of the overthrusting of continent upon ocean floor can be made for northwestern Washington, where Franciscan-like strata of Jurassic and Cretaceous ages, and glaucophane schists, are in fault contact with the crystalline rocks of the Northern Cascades and of the Puget Sound region. This interpretation can be made from data published by *Misch* [1966], who reaches, however, a very different conclusion, and from the geological map of Washington [*Huntting et al.*, 1961].

Analogous explanations can be made for New Zealand and Japan. Thus, the Permian-Jurassic Torlesse group of New Zealand is composed of deep-water graywackes and tholeiites like those of the Franciscan of California. The Torlesse has been overridden from the west by continental metamorphic rocks and by shallow-water correlatives of the Torlesse, and ultramafic sheets have been injected along and near much of the overthrust contact. Consistent with the interpretation that there is no pre-Mesozoic continental crust beneath the deep-water facies of the Torlesse, the crustal column at Wellington consists of about 2 km of low-velocity sediments, 8 km of material (Torlesse?) with $V_p = 6.0$ km/sec, and 8 km of material (Torlesse plus?) with $V_p = 6.2$, above 8.0-km/sec mantle [*Eiby*, 1958, Figure 5]. By contrast, the old continental crust at Auckland has a typical continental velocity distribution.

SAN ANDREAS FAULT SYSTEM

Coastal California is laced by the numerous right-lateral strike-slip faults of the San Andreas fault system, which trends northwestward subparallel to the coast as a belt 60–200 km wide (Figures 2 and 5). The through-going San Andreas fault is the most active single structure. The strike-slip faults of the San Andreas system are arranged somewhat en echelon, stepping to the right, although there is considerable anatomosing. The faults trend a little more westerly than does the coast.

Character of faults. The active strike-slip faults are typically marked by aligned valleys, bays, and other topographic depressions, where hilly or mountainous terrane is crossed. *Crowell* [1962, p. 7] described the rift-valley features of the San Andreas fault: 'The rift consists almost everywhere of a broad shallow trough filled with fault landforms, such as scarps, slice ridges, sag ponds, shutter ridges, and offset streams. . . . Abundant fault scarplets face either direction along the fault. . . . Some scarps are the result of strike slip in

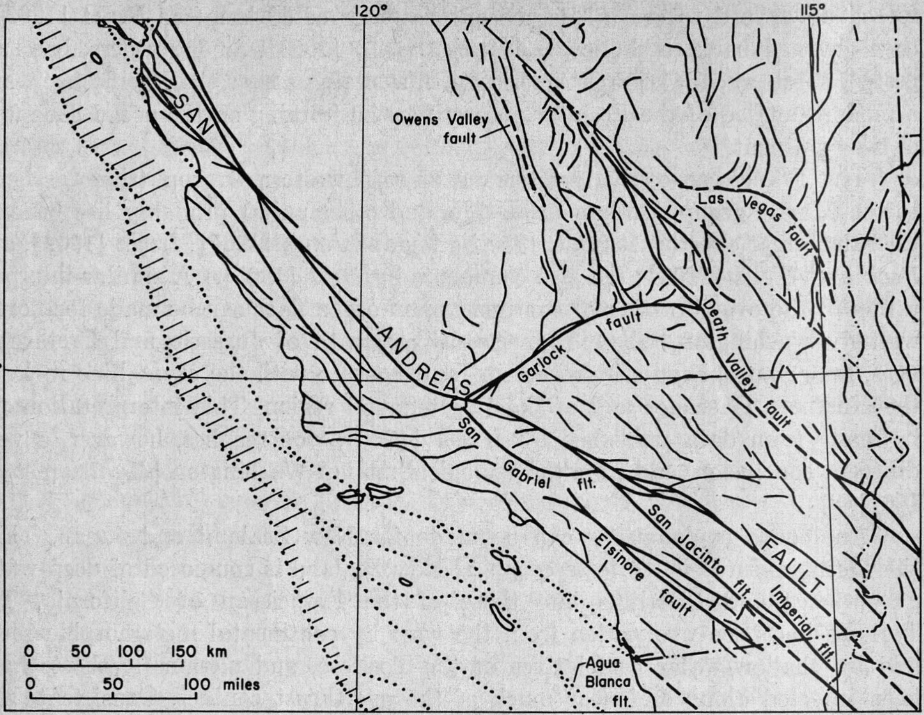

Fig. 2. Map of central and southern California and adjacent regions, showing faults active in middle and late Cenozoic time. Heavy lines, strike-slip faults; dashed where inferred; dotted beneath the sea, where faults are inferred from topographic alignments. Light lines are mostly normal faults (east of the San Andreas fault) and thrust faults (west of the San Andreas) but include strike-slip faults. Continental slope shown by diagonal ruling. Adapted from *Cohee* [1961] and other sources.

irregular topography . . . , so that transected hills have been moved sideways against valleys.'

The rift valleys are developed where topography is offset in a rising region and displaced streams are entrenched along the faults; most of the rift valleys are not tectonic depressions. On more level ground, the traces are generally conspicuous lines as seen from the air, with sag ponds, low scarps, and gently rumpled topography aligned along them, and with drainage lines offset (Figure 3).

Some minor faults of the San Andreas system are single breaks, but most of the major faults are zones as much as a few kilometers wide of anastomosing nearly parallel breaks of varying age. Some breaks are moving now but others have been long inactive. Gouge and breccia are typically present along the faults, but mylonite and blastomylonite have been exposed along others. Slivers between adjacent breaks are of rocks and deposits of all ages from middle Precambrian to Pleistocene; many slivers include rocks with no counterparts outside the fault zones for long distances in either direction. The faults are generally expressed at the surface as thrust faults where they mark the base of steep high mountain

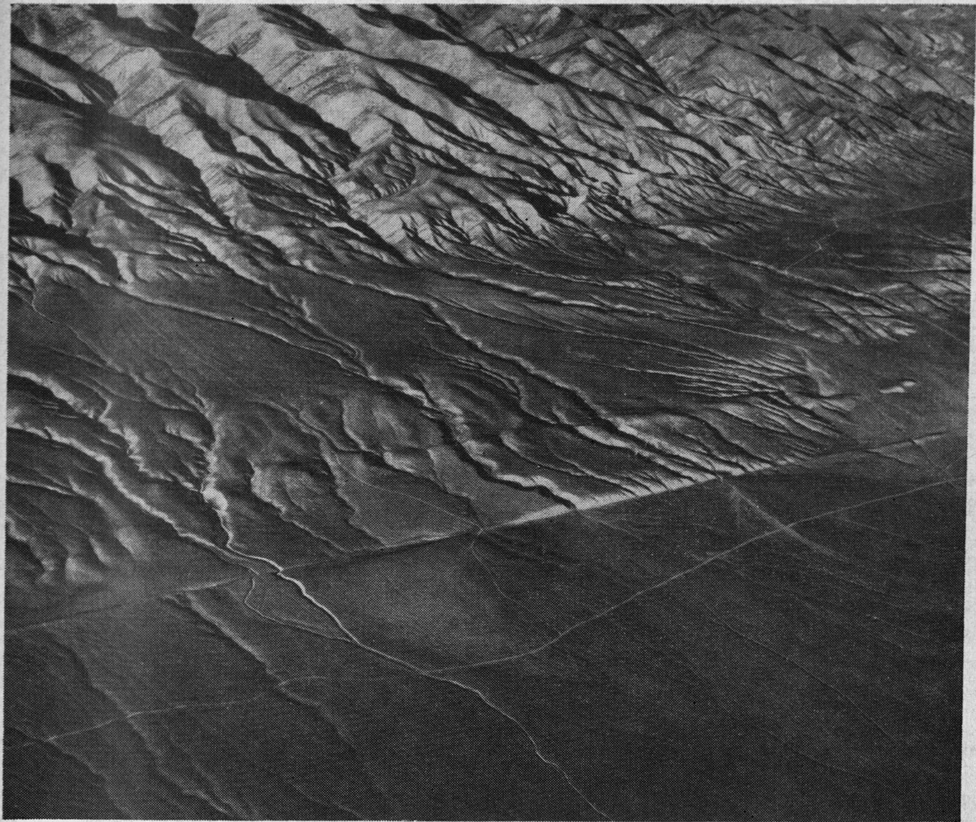

Fig. 3. Aerial view eastward across the San Andreas fault in the Carrizo Plain to the Temblor Range, west of the southern part of the Great Valley of California. The active right-lateral fault trace (foreground) displaces successively older drainages across the unconsolidated alluvium by successively greater amounts. See *Dibblee* [1962] for a description of this sector. Aerial photograph copyright by *John S. Shelton;* reproduced by permission.

fronts, but presumably they become vertical at shallow depth. These and other features of the fault zones are described by *Allen* [1965], *Crowell* [1952*a,* 1962], *Wallace* [1949], and *Waters and Campbell* [1935], among others.

Historical observations. Direct observation indicates that the coastal region of California is being deformed actively by horizontal shift as the ocean side moves relatively northwestward past the continental interior. Right-lateral offsets at the surface of various faults of the San Andreas system have occurred during earthquakes of 1857, 1868, 1906, 1934, 1940, and 1956, and probably (records are ambiguous) of 1836 and 1838 [*Biehler et al.,* 1964; *Richter,* 1958, pp. 473–487; *Shor and Roberts,* 1958]. Probably the greatest of these offsets were those of the San Andreas fault itself. In 1857, 300 or 400 km of the San Andreas fault in southern California slipped several meters, with maximum displacements of 10 meters [*Oakeshott,* 1964; *Wallace,* 1949, p. 799], and, in 1906, about 450 km of the fault in northern California was offset several meters. Hundreds of lesser historic earthquakes along the faults of the San Andreas system have not been accompanied by surface faulting.

Geodetic data demonstrate that the offsets during the major earthquakes release part of the shear strain accumulated at remarkably rapid rates over regions extending far from the faults. Thus, permanent strain accompanying the 1940 offset of the Imperial fault was of elastic-rebound type and decreased exponentially outward to almost nothing in a distance of less than 30 km on each side of the fault [*Whitten,* 1955, Figure 2]. Regional distributed motion, without further slipping along the fault, has continued, the amount of accumulated shear strain increasing gradually westward from far inland; points 60 km southwest of the fault moved 0.5–1.2 meters northwestward relative to points an equal distance northeast of it between 1941 and 1954 [*Whitten,* 1956, Figure 3]. The average post-earthquake strain rate across the 120 km broad belt was about 6 cm/yr. A 250-km sector of the San Andreas fault, passing through San Francisco, has slipped since the 1906 earthquake at an average rate of about 2 cm/yr, along a single fault trace in some places and across a zone centered on a trace in others [*Meade,* 1965, pp. 217–226]. Total displacement across a broader zone in this sector has been much larger: a point 25 km southwest of the fault moved more than 3 meters northwestward, 6 cm/yr, relative to a point 50 km northeast of the fault between post-earthquake 1906 and 1962 [*Meade,* 1965, Figure 3 and Table 1]. The triangulation network extending south from the latitude of San Francisco, in a zone 70 km wide across the Coast Ranges, underwent regional right-lateral shear strain with an apparent net strain of nearly 1 meter between surveys of 1951 and 1963 [*Pope et al.,* 1966], at an average rate of about 7 cm/yr. The elastic-rebound characteristics of the catastrophic displacements during earthquakes indicate that the total fault displacement over thousands of years will probably nearly equal the regional strain, and hence that the long-term average fault-motion rate in California is near 6 cm/yr. The southern California sector of the San Andreas fault did not slip by a geodetically determinable amount in the interval between the 1930's and 1950's [*Meade,* 1965, pp. 228–229]; the broadly distributed motion in southern California, north of the Imperial sector, apparently has not yet been determined.

Extrapolation of these geodetically determined rates indicates regional shear motion proceeding at about 60 km/m.y. Such a rate is far faster than is needed to account for any deformation proposed in this paper. Conversely, if such strain rates have characterized any substantial parts of the geologic past, deformation of the magnitude proposed here must have occurred. Severe earthquakes accompanying surface strike-slip faulting are to be expected every few decades along faults of the San Andreas system.

The geodetic baseline of a few decades is so short that any extrapolation over geologic epochs might be open to serious challenge. To establish a somewhat longer baseline for estimating the recent rate of displacement along major strike-slip faults, we studied aerial photographs along nearly 600 km of the Denali fault in central and eastern Alaska. Most surficial deposits, except for active flood plains and talus slopes, show right-lateral offsets throughout this length of the fault, the displacement increasing with age of the material.[2] Clear topographic offsets reach 30 km. Moraines and other deposits of the last major glaciation occur in many areas along the fault [see *Karlstrom et al.*, 1964] and provide an approximate time datum about 10,000 years old [*Péwé et al.*, 1965, p. 361]. These deposits typically are offset about 60 meters and locally 150 meters, so that the average rate of slip along the fault is about 6 cm/yr, or about the same as the present rate of strain accumulation in coastal California.

Minor earthquakes along the San Andreas fault occur from the surface to a maximum depth of about 16 km [*Bolt*, 1965]. There is thus no seismological evidence for the existence of the fault in even the uppermost part of the mantle.

Geologic evidence for displacements. The San Andreas and some other strike-slip faults show right-lateral offsets of stream channels, valleys, and other Quaternary erosional and depositional features, the amount of offset increasing with age of the feature (Figure 3). Even very young deposits are offset and much deformed (Figure 4). For information regarding the total displacement along the faults, however, one must go to displaced rock provinces far older than the modern landscape. The San Andreas juxtaposes completely unlike rock assemblages in most places where middle Tertiary and older rocks are present along it. Matching of offset rock suites and contacts demonstrates right-lateral displacements of hundreds of kilometers. *Hill and Dibblee* [1953] suggested displacements increasing with age of Quaternary, Tertiary, and upper Mesozoic materials; many of their suggestions have been confirmed by newer data.

Post-Miocene displacement along the San Andreas fault has been at least 160 km. This displacement is shown particularly clearly by the relationships described by *Dibblee* [1962] for the Carrizo Plain area, west of the southern part of the Great Valley. Lower, middle, and upper Miocene strata directly adjoin the fault on both sides, but the sharply juxtaposed rocks are of totally different assemblages. The Miocene sequence along the west side of the fault is a thick nonmarine section of sands and fanglomerates, derived from a granitic source east of the fault. There is, however, no possible source in the outcrop or subcrop region east of the fault now, and the nearest granitic rocks not covered by marine Miocene strata are 30 km to the southeast. The correlative Miocene

[2] *St. Amand* [1957] and others concerned with the great strike-slip faults of Alaska have assumed that the Denali fault connects with the Lynn Canal of southeastern Alaska via the Kluane Lake trench of Yukon Territory, which is known to mark a great fault separating different pre-Teritary complexes throughout the region. We found, however, that there is no lateral offset detectable on aerial photographs along this line east of the Nabesna River within eastern Alaska, along the north side of the Nutzotin Mountains. Instead, the active strike-slip fault zone of Recent displacement diverges southward from this line in the Nutzotin Mountains and is traceable as far as Beaver Peak at the northeast side of the Wrangell Mountains, beyond which snow and ice cover and the extreme youth of surficial deposits mask its course within eastern Alaska. This active strike-slip fault projects southeastward toward the St. Elias Mountains of southeastern Alaska; therefore we assume that it connects with the very active Fairweather fault, which *Tocher* [1960] found to have been offset right-laterally as much as 6 meters during the great earthquake of 1958. This apparent continuity of the Denali and Fairweather faults has considerable significance in the interpretation of the Cenozoic tectonics of Alaska.

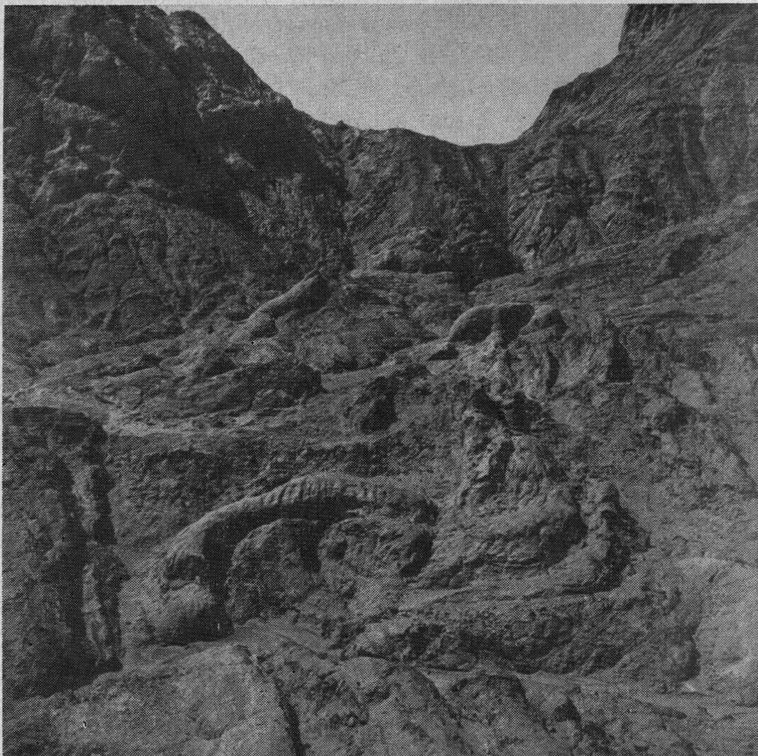

Fig. 4. Unconsolidated middle(?) Pleistocene alluvium, folded isoclinally about steeply plunging fold axes near the San Andreas fault. View northwestward near Painted Canyon in the Mecca Hills, southeastern California; the active trace of the San Andreas is just over the hill to the left. The area was studied by *Hays* [1957].

section along the east side of the fault is deep-water-marine sandstone and clay shale, and high in this section just east of the fault is very coarse slide breccia of granite, marble, and schist, derived from southwest of the fault. The nearest possible source of such basement rocks, without a cover of Miocene rocks, is 130 km to the northwest.

The evidence for displacement along the San Andreas fault in southern California has been synthesized ably by *Crowell* [1962], who has himself done much of the fieldwork in critical terranes. Crowell found that a distinctive suite of rocks of Precambrian, Paleozoic, Mesozoic, and Cenozoic ages occurs in only two areas in southern California: along the northeast side of the San Andreas fault in the Orocopia Mountains (100 km north of the Mexican border) and far to the northwest on the other side of the same fault in the San Gabriel Mountains (between the San Gabriel and San Andreas faults). Among the rocks of the suites in both areas are Precambrian anorthosite (including ilmenitic, magnetitic, and apatitic rocks), blue-quartz syenite, and varied polymetamorphic rocks; Paleozoic(?) metasedimentary rocks; Mesozoic granitic and migmatitic rocks; and nonmarine Oligocene volcanic and sedimentary rocks containing borates. The distinctive assemblage has no counterpart elsewhere along the fault; therefore its presence in the blocks adjacent to opposite sides of the San Andreas fault is convincing evidence for separation by strike-slip faulting. The right-lateral strike-slip displacement on the San Andreas fault since Oligocene time has been about 210 km.

The San Gabriel fault is itself another right-lateral fault in the San Andreas fault system, so that the 210-km displacement represents that from one side of the system to a large sliver within the system. The total displacement is greater. Middle Eocene marine strata of distinctive facies occur in the Orocopia Mountains (and nowhere else in southeastern California) and also in the Lockwood Valley area (on the southwest side of the San Andreas fault, near the junction of the Garlock fault and west of the San Gabriel fault). The Lockwood area contains also Oligocene clastic rocks and evaporites similar to those of the Orocopia Mountains. The crystalline rocks of the Lockwood area are of types present also in the Orocopias, but they do not include the unique Precambrian rock types of the Orocopia and San Gabriel mountains, although polymetamorphic rocks of probable Precambrian age are present. As *Crowell* [1962] concluded, the Eocene and Oligocene strata of the Orocopia and Lockwood areas demonstrate a probable offset of 260 km since the Oligocene—210 km between the Orocopia and San Gabriel mountains, 50 km more between the San Gabriels and Lockwood Valley. As Lockwood and Orocopia basement complexes are not sufficiently similar to warrant correlation, the total displacement may be greater than 260 km by an amount of pre-middle Eocene displacement (on a fault passing south of the San Gabriel Mountains) not defined by the data noted.

The terrane metamorphosed and intruded by granitic rocks during late Jurassic and Cretaceous time generally lies to the east of the Franciscan belt of correlative nonmetamorphosed rocks. The central 500 km of the San Andreas fault in coastal California, however, juxtaposes Franciscan on the east against metamorphic-and-granitic terrane on the west, and this crystalline terrane in turn gives way westward to another belt of Franciscan (Figure 1). The granitic rocks yield radiometric ages younger than the fossil ages of most of the Franciscan, and yet the Franciscan is nowhere intruded. As *Hill and Dibblee* [1953] emphasized, it appears probable that the long narrow belt of crystalline rocks along the west side of the San Andreas fault has been displaced relatively northwestward about 500 km from an initial position on strike to the south of the Sierra Nevada. (A few geologists have proposed vertical offsets of tens of kilometers to explain such changes across the San Andreas fault, which they regard as having little, if any, strike-slip displacement. There is much evidence to indicate, however, that the needed complexes are not available at depth, even if such vertical offsets had occurred, and there is no topographic or structural evidence to suggest that any such vertical offsets have occurred. Another interpretation was made by *Bailey et al.* [1964, pp. 160–163], who speculated that the Franciscan east of the San Andreas fault might have formed in a rift through the continental crust, produced when the granitic terrane west of the fault moved obliquely away from the rest of the continent; among the objections to this hypothesis is that it provides no explanation for the otherwise identical Franciscan west of the San Andreas.) As was noted previously, the contact on both sides of the San Andreas fault between Franciscan on the west and crystalline rocks on the east is probably a regional overthrust fault; folding of this contact may have complicated the pattern of apparent offset by the San Andreas fault.

There are numerous other right-lateral faults within the San Andreas system of coastal California and northern Baja California. Several of these faults are marked on Figure 2 and some are identified by name. Faults inferred from the submarine topography to be present on the continental shelf are also shown. (See *Emery* [1960, Figure 68] for another interpretation of offshore faults.) Several of the onshore faults have undergone lateral offsets during earthquakes, and some of these faults, as well as others, display clear physiographic evidence of repeated late Quaternary displacements. Others are apparently inactive, and valleys along them may be due more to erosion of the fault zones than to primary rift topography. Many of the strike-slip faults juxtapose different rock suites, and displacements of the order of a few kilometers to a few tens of kilometers can be argued to have occurred along some of them. The Agua Blanca fault, which crosses Baja California just south of the area shown on Figure 2, offsets Quaternary gravels about 5 km and crystalline bedrock probably about 20 km [*Allen et al.*, 1960, pp. 467–469]. The San Gabriel fault offsets Eocene and Oligocene strata about 50 km [*Crowell*, 1962] and upper Miocene beds about 30 km [*Crowell*, 1952*b*], and one branch of the fault displaces middle Pliocene strata 6 km [*Shepard*, 1962]. The Hayward fault, east of the San Andreas fault near the north edge of Figure 2, underwent right-lateral offset probably during two nineteenth-century earthquakes, and it is currently slipping at a slow rate without major earthquakes [*Radbruch et al.*, 1966]. A fault west of the San Andreas in central California offsets distinctive facies of upper Miocene and Pliocene strata at least 18 km [*Durham*, 1965].

The broad San Jacinto fault zone of anastomosing breaks shows abundant evidence of Quaternary right-lateral and vertical offsets [*Jahns*, 1954] and has produced many recorded earthquakes, although only one has been accompanied by surface faulting [*Biehler et al.*, 1964]. Quaternary gravels are offset right-laterally at least 2½ km; and stream courses, almost 1 km. The total horizontal displacement along the fault, as determined by offsets of a mylonite zone, metasedimentary rocks, and a number of distinctive granitic plutons, is about 25 km [*Sharp*, 1964, 1965].

Faulting, uplift, and subsidence. The faults of the San Andreas system lace through uplifts and downwarps whose boundaries are to a considerable extent independent of the faults. Thus, the San Andreas fault trends within the sea-level lowlands of the Salton Trough to San Gorgonio Pass, where it rises to cross obliquely through the Transverse Ranges, via passes that include three with altitudes of about 2000 meters. (See *Allen* [1957] for uncertainties regarding fault connections and nomenclature in the complex San Gorgonio sector.) Several other faults of the San Andreas system reach about 2500 meters within the

Transverse Ranges. Thence, the San Andreas descends to trend with very slight obliquity through the young uplifts and downwarps of the Coast Ranges. (*Christensen* [1965] discussed aspects of this problem for central California.) Similarly, the Elsinore and San Jacinto faults cross obliquely through the Peninsular Ranges. The strike-slip faults locally bound the rising and falling masses and tend to crop out as steep reverse faults where they lie at the foot of high steep slopes [*Allen,* 1965], but commonly the faults rise and fall with the regional uplifts and depressions.

It thus appears that on a regional scale, uplift and subsidence are independent of the faulting. The Transverse Ranges represent an overprint across the San Andreas system, as though the process of uplift of the ranges is unrelated to the mechanism of strike-slip faulting. Perhaps the uplifts are due to changes in depth of the Mohorovicic discontinuity as material is added to the base of the crust in one place and removed in another, either by vertical or horizontal transport. (Related suggestions have been made by *Gilluly* [1963] and others.)

The upper limit of horizontal offset of topographic features is at least 25 km and may be 75 km. The smaller value is established by the lengths of continuous-slope segments of San Andreas rift valleys along the north flank of the Transverse Ranges, where nondisrupted drainage is almost perpendicular to the fault. The larger value represents the possible offset of the San Bernardino Mountains from the San Gabriel Mountains.

The San Bernardino Mountains form the eastern part of the east-trending Transverse Ranges; and the San Gabriels, the central part. The San Andreas and related faults trend west-northwestward along the southern flank of the San Bernardinos, cross obliquely through the pass separating the mountain blocks, and trend along the northern flank of the San Gabriels. The geometry of the blocks permits the speculation that the San Bernardino Mountains have been offset along the San Andreas about 75 km from the San Gabriel Mountains. Reconstruction before such an offset juxtaposes the southeast corners of the two mountain masses and brings into continuity the regions now higher than 1500 meters in the eastern parts of each. Inherent in such an interpretation is the assumption that isostatic bowing, following and consequent upon the offset of the thick crust of the ranges, caused extension of the San Gabriel uplift to the north and of the San Bernardino uplift to the south of the San Andreas line of rupture. If this rationale is valid, consideration of the offsets of late Cenozoic materials along the San Andreas fault and other faults in the Transverse Ranges would date the initial mountain system as largely late Miocene. It is, of course, alternatively possible that the apparent offset of the two mountain masses is illusory and is only the result of irregularities in uplift due, perhaps, to the position of the faults.

If the San Bernardino Mountains have been offset 75 km from the San Gabriels, it follows that thickened crustal sections, although formed independently of the strike-slip faults, once formed are carried along by the faults.

Gulf of California. The right-lateral faults of the San Andreas system trend longitudinally into the Gulf of California, and submarine rift topography and earthquake epicenters indicate that the fault system trends along the gulf. *Carey* [1958], *Hamilton* [1961], *Rusnak and Fisher* [1964], *Rusnak et al.* [1964], and others have shown that the gulf probably was opened by the oblique tensional rifting of Baja California away from mainland Mexico. The deep-water gap across the mouth of the gulf in the direction of rifting, from Cape San Lucas to the geologically similar coast of Jalisco and Nayarit, is about 450 km wide, which defines the total offset on the motion system since the intrusion during Late Jurassic and Cretaceous time of the chain of batholiths near the western margin of the continent. The Gulf of California and its northward extension, the Salton Trough, formed where the previous continental crust was thinned and ruptured. (Older hypotheses of downwarping or downfaulting as an origin of the gulf are disproved by the thinness of continental crust in the northern part of the gulf and by the absence of such crust in the southern part.) Consistent with this pattern of oblique tension, Baja California and its northward continuation, the Peninsular Ranges of southern California, bear thin little-deformed sections of Upper Cretaceous and Cenozoic strata. By contrast, the correlative rocks of the Transverse Ranges and Coast Ranges to the north occur in extremely variable sections in local basins and display repeated folding and thrust faulting along axes oblique at low angles to the San Andreas. The strike-slip motion has generally had a tensional component south of Los Angeles but may have had a compressional component north of it, although *Christensen* [1965] showed that much of the Pliocene and Pleistocene deformation in the central Coast Ranges could be accounted for by vertical motion without horizontal compression.

THE ENDS OF THE SAN ANDREAS FAULT SYSTEM

The strike-slip faults of the San Andreas system appear to be limited to the continental crust and do not appear to affect the mantle over which Baja California and coastal California are sliding northwestward. This interpretation, if correct, has profound implications regarding the mechanism of deformaton.

Southern terminus. The faults of the San Andreas system vanish southeastward into the Gulf of California and northwestward into the submarine continental shelf. In both directions much can be inferred about their behavior from the submarine topography (Figure 5) [*Rusnak et al.,* 1964; *Shepard and Emery,* 1941]. The geometry of submarine scarps, ridges, and basins in the Gulf of California indicates that it has been deformed by right-lateral en echelon faults and by northwestward extension, the proportion of the extension to the faulting increasing southward as the gulf widens and deepens [*Rusnak et al.,* 1964, pp. 72–73]. The extension has been accompanied by the formation, presumably by processes of basaltic volcanism and intrusion, of new oceanic crust across the gap left by the sundered continent, because the crustal structure of the deeper part of the gulf is oceanic, like that of the east Pacific rise. The crust of the shallower part of the gulf is of continental type but is very thin [*Phillips,* 1964, p. 90]. Thick sedimentation in the northern part of the gulf and along the mainland side have there obscured the tectonic topography.

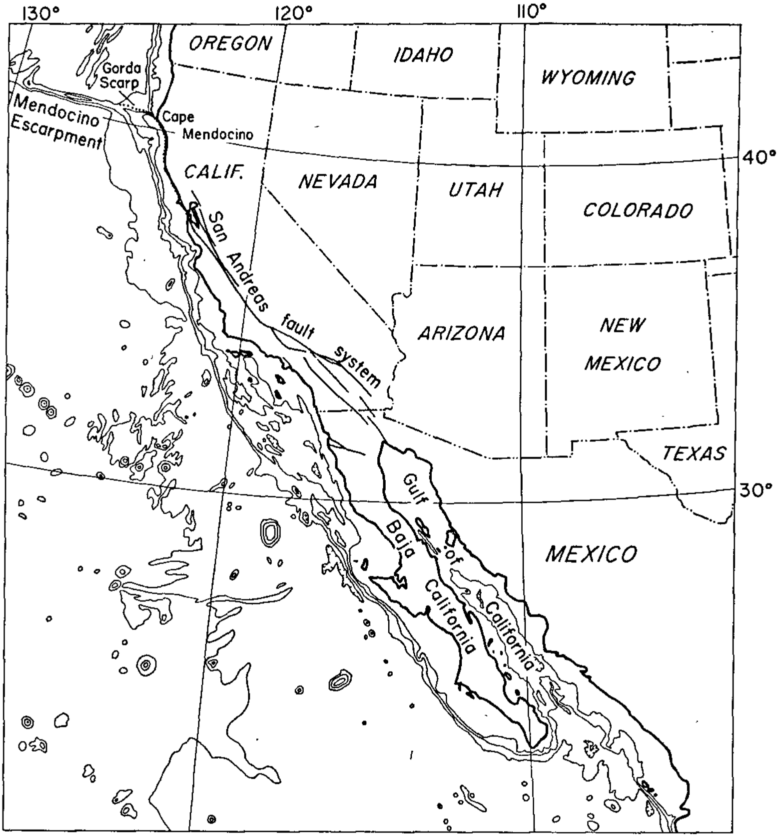

Fig. 5. Submarine topography west of California and Mexico. Contour interval 1 km. Generalized from a compilation by Philip B. King [*Goddard,* 1965].

The rift topography of the Gulf of California ends at the mouth of the gulf along a line trending southeastward from the tip of Baja California to mainland Mexico. Apparently Baja California has moved northwestward away from the mainland, and the gulf has formed as a tension rift in its lee, and the motion has been limited to the continental plate. *Menard* [1960] and others have speculated that the Gulf of California opened as Baja California was carried passively away from the mainland by mantle convection currents whose axis of divergence trends northward into the gulf from the east Pacific rise. If this were true, rift topography should be also present south of the mouth of the gulf, and none is known to be present there. It appears instead that the rift in the continental plate is due to the motion of part of that plate over the mantle.

Northern terminus. The San Andreas fault trends northwestward through southern California, approaching the coast at a low angle. It reaches the coast at San Francisco, and from there to Cape Mendocino the fault trends along the shoreline, being exposed across headlands but otherwise being hidden beneath the coastal waters. The northernmost such headland exposure is across Point Delgado, a few kilometers north of the fortieth parallel. Beyond Delgado, the fault apparently arcs to the west and becomes the submarine Gorda scarp. This curve is shown by submarine rift topography, the beheading of a submarine canyon, and a smoothly arcuate canyon that opens at the base of the scarp [*Shepard and Emery,* 1941, pp. 38–42; *Shepard,* 1957]. Epicenters of distinctive Franciscan-continental-crust earthquakes, generated within 10 km of the surface, extend along the Gorda scarp [*Cameron,* 1961]. This north-facing scarp is about 1.5 km high and has an average slope of about 30° [*Krause et al.,* 1964, Figure 3]. We infer from the onshore geology that the Gorda scarp bounds a continental block formed of Franciscan terrane; consistent with this inference, dredge hauls from the crest of the scarp at a depth of about 2 km and about 110 km offshore included serpentine [*Krause et al.,* 1964, pp. 248–249]. The San Andreas fault thus swings westward from a coastal trend to one directly offshore and displaces the continental margin directly seaward; the Gorda scarp is developed along the margin of the higher standing continental plate.

The north-facing Gorda scarp is directly continuous with the south-facing Mendocino escarpment, which begins at the foot of the continental slope (Figure 5) and continues westward for something like 2500 km. The crossover occurs where the depth of the continental slope south of the Gorda scarp becomes greater than the depth of the crest of the Mendocino escarpment. The Mendocino structure apparently marks a *left*-lateral strike-slip fault, probably inactive, along which a distinctive pattern of magnetic anomalies and the westward-sloping ocean floor have been displaced about 1150 km [*Vacquier et al.,* 1961]. The near-shore part of the Mendocino escarpment is marked by a submarine ridge, which stands 2 to 2.5 km above the ocean floor to the south but only about 1 km above the floor to the north, and is formed of basalt [*Krause et al.,* 1964, Figure 4 and pp. 247–248].

The San Andreas fault thus turns directly seaward at the point at which the south-facing Mendocino escarpment projects into the continent. San Andreas and Mendocino displacements are in opposite senses; hence they cannot be part of a single motion system. The San Andreas is highly active; the Mendocino, apparently inactive. These anomalies, and the other features of the San Andreas-Gorda structure, are easily accounted for if the continental plate west of the San Andreas fault is riding over the crust of the Pacific Ocean basin. The narrow continental slice west of the San Andreas has been drifting northwestward, past interior and northern California, throughout Cenozoic time, and its point may have been deflected westward as it encountered the south-facing Mendocino escarpment on the ocean floor. About 100 km of displacement along the San Andreas has postdated this encounter, the balance having occurred before the coastal strip reached the escarpment. The inception of the Eel River basin, which trends northwestward just north of Cape Mendocino, in the late Miocene [*Ogle,* 1953] may have been due to deformation resulting from the initial impinging of the San Andreas sliver against the Mendocina scarp. Deformation of the Eel River basin has continued to the present.

Significance. The San Andreas fault system thus appears to end both to the northwest and to the southeast where the continental crust ends at the Pacific margin. The fault system may be restricted to the continental plate, which is moving independently over the mantle and the oceanic crust. The very shallow depth (0–16 km) of San Andreas minor earthquakes [*Bolt,* 1965] is consistent with this interpretation.

BASIN AND RANGE PROVINCE

East of the San Andreas fault system and the Sierra Nevada is the broad Basin and Range province (Figure 6), whose obvious major middle and late Cenozoic structures are the normal faults bounding each of the many mountain blocks on one or both sides. There are also, however, important strike-slip and oblique-slip faults within the province, and the structure of the region seems best interpreted in terms of oblique, right-lateral extension.

Basin-Range faulting. Each young mountain block in the province is bounded on one or both sides by zones of dip-slip normal faults, which are irregular in plan and do not offset drainage lines. Basin and range blocks are typically each between 10 and 20 km wide. Ranges generally stand 500 to 1200 meters above the alluvial fill of flanking basins, but extreme local topographic relief exceeds 3000 meters. Some faults pass along strike into folds along which the ranges rise abruptly from the basins, and presumably the faults pass downward into folds also [*Von Huene et al.,* 1963, pp. 65, 72]. The bounding faults mostly dip 40° to 80° basinward [*Gilluly,* 1928]. If the average near-surface dip of about 60° continues to a depth at which opposed major faults intersect, the major fault blocks can be viewed as horizontal prisms less than 15 km deep. *Moore* [1960] concluded, however, from the general concavity in plan of most range fronts that the faults actually flatten at depth; if he is correct, the limiting depth of normal faulting is less than 10 km. *Hamblin* [1965] reached a similar conclusion regarding the character of normal faults in the Colorado Plateau, on the basis of the geometry of associated folding.

Basin-Range faulting began during Eocene time and is continuing. Most of the present ranges were formed by faulting since early Miocene time, older ranges having been destroyed by erosion and deformation. (See, for example, *Cook* [1965] and *Ekren et al.* [1966].) Faults are now active in various parts of the province, including the extreme margins, the Sierra Nevada on the west and the Wasatch Mountains on the east, but the region of greatest Pliocene and Quarternary faulting is that of eastern California north of the Garlock fault, from the Sierra Nevada to the Black Mountains. In this triangular region, bedrock ranges, with high steep frontal scarps relatively little modified by erosion (Figure 7), have twice the area of the intervening basins. In most of the rest of the province north of about the thirty-fifth parallel, basins and ranges have about equal areas, but south of that parallel, where the ranges have been still more eroded, basin fill has about twice the area of bedrock ranges, and frontal scarps are generally not recognizable.

The geometry of the tilted normal-fault blocks requires regional extension as the basic cause of faulting. *Carey* [1958], *Lombardi* [1964], and *Thompson*

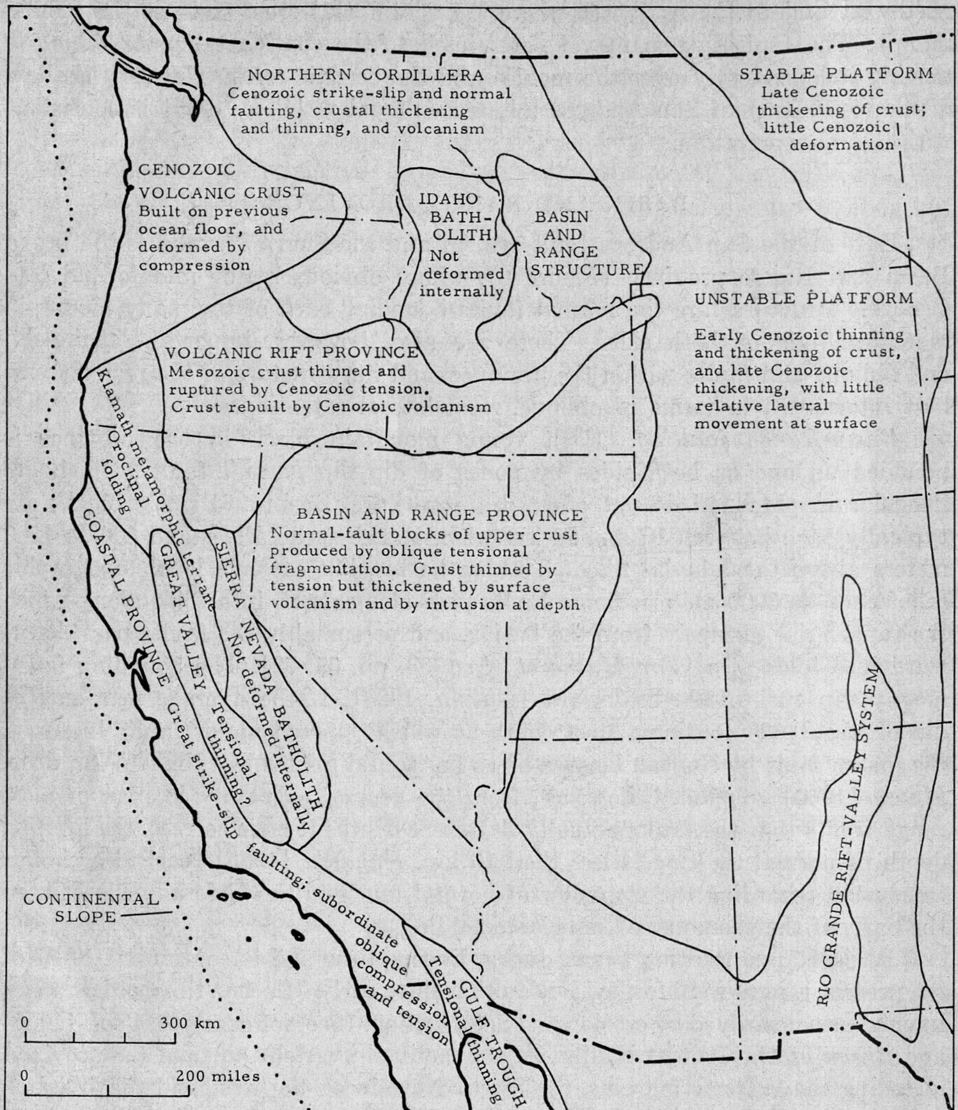

Fig. 6. Cenozoic tectonic provinces in the western United States. Most deformation is interpreted as being due to the northwestward movement of California relative to the continental interior. The proportions of oblique tension, oblique compression, and direct strike-slip motion vary widely, but all major movement is in the same right-lateral sense and increases from the stable interior toward the coast.

[1959] are among those who have emphasized this relation. A fault dipping 60° requires 1 km of horizontal extension for each 2 km of dip-slip; if the faults do indeed flatten downward, the amount of extension needed approaches that of the dip-slip produced. There are perhaps 25 major range-bounding faults in the section across the Basin-Range province along the fortieth parallel [cf. *Cohee,*

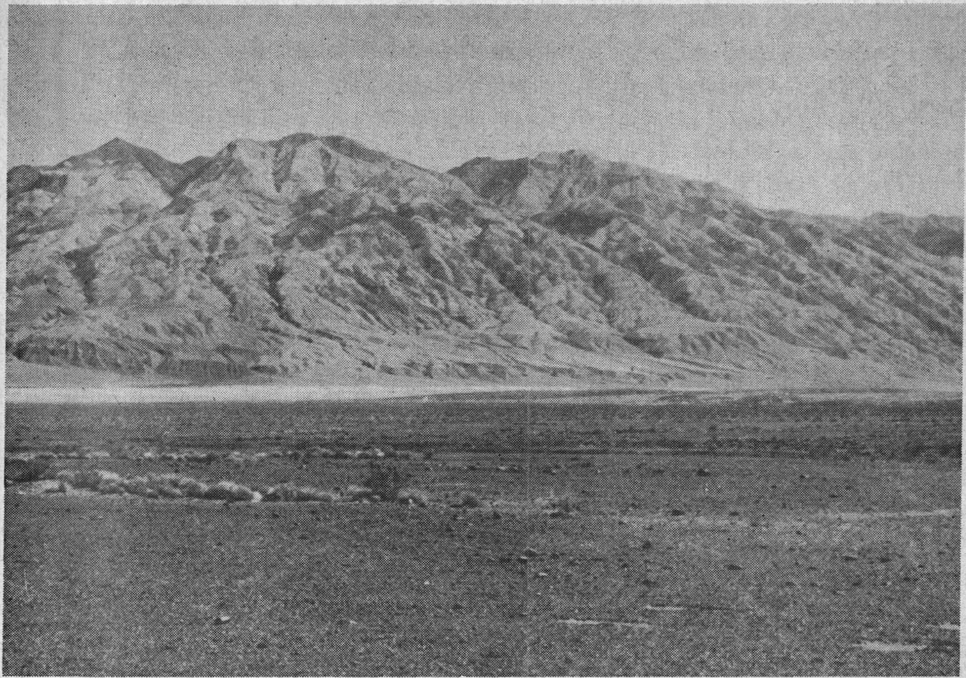

Fig. 7. The west face of the southern Panamint Range, eastern California. This is one of the highest (1700 meters) of the very young fault scarps bounding Basin-Range blocks; a large part of the faulting must have occurred within Pleistocene time. Subordinate scarps break the alluvial fans below the main mountain front scarp.

1961]. If we assign to each of these faults an average dip-slip displacement of 4 km, the crustal extension indicated by them is between 50 and 100 km. These faults represent only the last third or half of the period of Cenozoic normal faulting; therefore, if the recent rate of extension has been similar to that of the earlier part of the era, the total Cenozoic extension is within the range 100–300 km. The larger value represents nearly half the present width of the province.

The brittle fracturing which produces the fault blocks is limited to the upper part of the crust, and we visualize the faults as giving way downward to horizontal laminar flow. As we discuss in sequel, Cenozoic volcanism has added much new material to the crust, rebuilding it as tension has thinned and fragmented it.

Right-lateral strike-slip faults. The known major strike-slip structures are west of a line trending northwest across Nevada and mostly are right-lateral faults that strike northwestward within valley systems. The extent of lateral faulting is known best across southern Nevada and adjacent California, where right-lateral offsets of tens of kilometers are demonstrable on two major strike-slip fault zones, Death Valley and Las Vegas (Figure 2). These faults are largely concealed beneath the alluvial fill of structural basins, and this concealment, as well as the complexity of structures older than the strike-slip faulting, has delayed their recognition and interpretation.

The Death Valley fault (or Death Valley-Furnace Creek fault) locally offsets drainage and alluvial features right-laterally and is marked by fault trenches and sag ponds [*Curry,* 1938; *Noble and Wright,* 1954, p. 157; *Wright and Troxel,* 1966, p. 857]. As the facies in the upper Precambrian and Paleozoic strata of the region strike generally south-southwestward at a high angle to the fault zone, it is possible to define the total displacement by stratigraphic studies. *Stewart* [1966] has done this by means of a study of three upper Precambrian and Lower Cambrian formations. Isopachs and facies features of each of the formations are offset 80 km right-laterally between the Funeral Range (east of the intersection of the Death Valley fault and the Furnace Creek fault, which is the unlabeled fault shown in Figure 2 branching southeastward from the Death Valley fault near the Nevada state line) and the Panamint Range (west of the Death Valley fault). This is the horizontal displacement on the Death Valley fault alone north of the fault intersection but on both faults together south of the intersection. Stewart believes that the fault displacement gives way to oroclinal folding northwestward and perhaps southeastward also. The offset of isopachs of Ordovician strata also is consistent with such a displacement [*R. J. Ross, Jr.,* 1964, Figure 12].

Wright and Troxel [1966, Figure 3] presented an isopach map of the total thickness of upper Precambrian strata in the southern Death Valley region. The isopachs based on their assumption that the Death Valley and Funeral Creek faults have no significant lateral offsets define a sharp trough along the fault system. Their 14 data points east of the faults show clearly the regional southwestward trend of isopachs; but they have only 2 points between the Death Valley and projected Furnace Creek faults, and only one point west of the Death Valley fault, so that the south*east* trends they assume for these blocks are in no way demonstrated. We recontoured their data points assuming continuity of southwestward trends through the faulted region and found right-lateral offsets of about 50 km each on the Furnace Creek and Death Valley faults to be suggested by their data. This total of about 100 km of movement is in reasonable agreement with the 80 km found by Stewart a little farther north on the basis of more complete data.

Faults of the Death Valley zone are exposed in the region south of the Garlock intersection in such ranges as the Avawatz, Soda, and Old Dad [*Jahns and Wright,* 1960]. *Grose* [1959] described the Soda Mountains faults as forming a zone several kilometers wide consisting of through-going and branching faults marked by brecciation, subhorizontal slickensides, slivers of rocks which in many places differ from those of either wall, reversals of apparent throw, and en echelon structures indicating right-lateral transport.

The Death Valley fault zone passes (dashed line on Figure 2) through a region in which northwest-trending faults separate contrasted terranes [*Bishop,* 1964] to connect with faults mapped by Hamilton (unpublished data) in the Big Maria, Little Maria, and Riverside mountains (along the southeastern part of the fault zone within California), where right-lateral faults are spread through a zone at least 20 km wide. Single faults in this part of southeastern California have right-lateral displacements of 2–15 km each and an aggregate displacement probably of about 50 km. Straight canyons trending southeastward through the Dome Rock Mountains and nearby ranges in southwestern Arizona along strike from these mapped faults in southeastern California presumably mark the same faults.

The Las Vegas fault [*Albers,* 1964; *Burchfiel,* 1965; *Longwell,* 1960; and maps by *Longwell et al.,* 1965, plates 1 and 5] trends northwestward across a region whose early Tertiary and older structures strike northward to northeastward, so that the gross displacements along the fault seem apparent even though the fault itself is hidden beneath the alluvial fill of broad valleys. Isopachs of two Ordovician formations appear to be offset at least 40 km [Ross and C. R. Longwell, in *R. J. Ross, Jr.,* 1964, pp. 88–93]. The great overthrust sheet that carries Cambrian carbonates over Jurassic strata in the Muddy Mountains northeast of the Las Vegas fault apparently is offset about 50 km to the Spring Mountains on the southwest side. (We draw the major fault to pass south of Frenchman Mountain, the stratigraphy and structure of which we regard as belonging beneath the overthrust sheet, rather than to pass north of Frenchman Mountain as some have done; but faults may be present on both sides.) Various belts of thrust faults west of the trace of the overthrust are offset like amounts if right-lateral drag is added to abrupt displacements, but the offset on the Las Vegas fault itself decreases northwestward as progressively more of the deformation is taken up by oroclinal drag. There may be no surface faulting at all along the northwest part of the structure. The faulting largely postdates the early Miocene [*Ekren et al.,* 1966]. The Las Vegas fault has not yet been mapped southeast of the limit drawn on Figure 2, but structural alignments suggest that it continues far into Arizona.

The Las Vegas fault projects north-northwestward as the vague and generally alluviated 'Walker Lane,' a zone separating ranges whose trend is mostly northward, northeast of the fault, from ranges whose dominant trend is northwestward, southwest of the fault. Numerous small rifts and fissures formed during a 1932 earthquake show by their en echelon pattern and by the right-lateral offsets on some of them general right-lateral displacement along one sector of the lane [*Gianella and Callaghan,* 1934]. Several pre-Tertiary structures and stratigraphic units have been offset about 20 km right-laterally within the zone, the largest single fault accounting for 16 km of this total [*Nielsen,* 1965].

During the Owens Valley, California, earthquake of 1872, a right-lateral fault broke the alluvium east of the foot of the Sierra Nevada normal-fault scarp with horizontal offsets reaching 5 meters, and a normal fault broke the alluvium between the lateral fault and the mountain front [*Bateman,* 1961]. Correlation of a granitic pluton [*D. C. Ross,* 1962] and of a dike swarm [*Moore and Hopson,* 1961] across Owens Valley, from the Sierra Nevada on the west to the Inyo Mountains on the east, demonstrates that the total Cenozoic strike-slip offset within the valley can be no larger than 25 km and may be much smaller. (Pluton and dikes trend northwestward, oblique at a low angle to the fault, and there is ambiguity as to their proper projections to the fault. And if extension has accompanied the downdropping of Owens Valley, one effect of this extension would be to minimize the apparent displacement of any northwest-striking right-lateral structure.) No detectable deformation of a triangulation network in Owens Valley occurred between surveys of 1934 and 1956 [*Meade,* 1965, p. 232].

Oblique tensional fragmentation. The Basin-Range province is undergoing tension with an east-west component and also right-lateral shear along northwest-trending structures; therefore it is obvious that the total motion is oblique extension. Such oblique motion has been observed in displacements accompanying earthquakes and is also shown by patterns of late Cenozoic faulting.

A zone of faults offset at the surface during earthquakes of 1903, 1915, 1932, 1934, and July, August, and December of 1954 curves northward, parallel to the larger Basin and Range fault blocks, from the northern part of the Walker Lane in western Nevada. The character of offset during these earthquakes changes northward along this zone, from dominantly right-lateral strike-slip in the southern part to dominantly dip-slip in the north [*Shawe,* 1965]. The geometry of these faults indicates that right-lateral and block faulting are closely related. The results of the December 1954 earthquakes are best known [*Whitten,* 1957]. Oblique-slip faults broke the surface in a zone 80 km long in the central part of the north-trending zone. Releveling and retriangulation of a survey network established shortly before the earthquakes showed that absolute vertical movement was largely downward, locally exceeding 2 meters; absolute uplift was no greater than 0.1 meter. Plan displacement was oblique: the faults trend east of north, but points on the west side moved north-northwest, and points on the east side moved south-southeast. Blocks on opposite sides of the fault moved obliquely apart and, as Whitten emphasized, this pulling apart created a void into which the downdropped block collapsed.

A north-trending scarp 80 km long formed in Sonora during an earthquake in 1887; faulting was oblique, with dip-slip and right-lateral offsets each reaching 6 or 7 meters [*Gianella,* 1960]. The net direction of transport down the dipping fault was north-northwestward. Oblique slip is also shown along the Black Mountains facing Death Valley [*Hill and Troxel,* 1966].

Normal faulting as a result of oblique extension is displayed with particular clarity in the Saline Valley region, between the northwest-trending Owens Valley and Death Valley faults in eastern California [*Lombardi,* 1964; see map compiled by *Jennings,* 1958]. Saline Valley has a topographic closure of 1200 meters —exceeded by fault troughs elsewhere in the world probably only by Lakes Tanganyika and Baikal—and lies 3000 meters below the crest of the Inyo Range which bounds it on the west. Between Saline Valley and Death Valley is a mountainous region 30–40 km wide, which is broken by numerous subparallel normal faults that trend north-northeastward, face in either direction to define horsts, grabens, and tilted blocks 1–10 km wide, and have dip slips of 100–2000 meters. These north-northeast faults constitute a tension-gash system of jostled blocks in a region undergoing both extension and right-lateral shear.

The active young fault blocks of eastern California north of the Garlock fault—the Sierra Nevada, White-Inyo-Argus, Panamint, and Black mountain blocks, and the basins between them—strike mostly north-northwestward, oblique at a low angle to the general northwestward trend of the regional strike-slip faults. The basins thus have orientations fitting a pattern of oblique extension as the ranges are pulled apart in a northwesterly direction, leaving the basins as narrow parallelograms which collapsed into the tensional voids. *Burchfiel and Stewart* [1966] presented such an explanation for Death Valley in particular. (Lake Baikal in southeastern Siberia, the deepest closed-basin continental fault trough in the world, apparently bears a similarly oblique relationship to regional strike-slip faults, in this case left-lateral.)

The over-all pattern of basins and ranges throughout the province can be interpreted in similar terms. In Utah and Nevada northeast of the strike-slip Las Vegas fault and its Walker Lane continuation, the structural blocks trend mostly north-northeastward. There are no known strike-slip faults within this terrane, and the blocks make a gross pattern of tension gashes in a system under northwesterly right-lateral shear. Southwest of the Las Vegas fault, in eastern and southeastern California, and southwest of the projected trend of this fault through southwestern Arizona, the blocks are mostly oriented northwestward parallel to the general trend of the strike-slip faults within this terrane. The amount of shear in this southwestern region has been much greater than in the northeastern one, although the cross-strike extension has been similar in both regions, and the blocks are parallel to the direction of shear.

Left-lateral faults. The Garlock fault arcs eastward across southern California from the San Andreas fault (Figure 2). The Garlock shows abundant physiographic evidence of Quaternary left-lateral movement, and its total Cenozoic offset, as shown by the displacement of a distinctive broad swarm of dikes [*Smith,* 1962] and of a northwest-trending fault system [*Michael,* 1966] is about 70 km. The Garlock and Death Valley faults merge and mutually deflect each other [*Jahns and Wright,* 1960], but the Garlock does not continue east beyond the Death Valley zone, nor does it appear farther southeast in a position offset along the Death Valley fault. South of the Garlock is the Mojave Desert block of generally old, low mountain blocks, largely buried by basin deposits in the west. North of the Garlock fault is a region of high and exceedingly active fault-block ranges, the Sierra Nevada, Argus, Panamint (Figure 7), and Black Mountains. The Garlock thus has the position and relative offset required by the explanation that the block faulting to the north is due to crustal extension, because the fault marks the south end of the currently stretching mass, although the total amount of lateral displacement is too large to be accounted for by this mechanism alone. The aggregate topographic height of the major range-front scarps north of the Garlock fault is 7 or 8 km; if the bedrock relief is twice the topographic relief, at most 15 km of extension could have accompanied the formation of the present ranges. Strike-slip displacement due to this process would increase westward.

There are other northeast-trending left-lateral faults in southern California.

Some have been interpreted to have large horizontal displacements, and others are known to have only small displacements. These left-lateral faults may generally represent offsets between blocks being jostled by drag within the regional right-lateral northwest-trending shear system.

New volcanic crust. Pre-Tertiary rocks are exposed along about half of any traverse across the Basin and Range province south of about the thirty-seventh parallel; but they are exposed along only between one-third and one-eighth of any traverse across the wider part of the province farther north. The remainder of the exposures is of Cenozoic volcanic rocks and sedimentary deposits. Pre-Tertiary rocks are known to occur beneath much of this younger material, of course, but the crust obviously has been much augmented by volcanism. Faulting and volcanism have gone on concurrently. Tensional extension and thinning of the crust, and normal-fault fragmentation of its brittle upper part have been accompanied by the building of new crust by volcanism, and the new volcanic crust in turn has been stretched and broken.

Isotopic age determinations on Nevada volcanic rocks show that late Eocene and Oligocene volcanics are widespread in the northeastern quarter of the state, that early and middle Miocene rocks are widespread in most parts of the state, and that late Miocene and early Pliocene volcanic rocks are largely limited to a belt along the southwest border [*Schilling,* 1965]. Later Pliocene and Quaternary volcanics are of relatively minor abundance. If the abundance of volcanic rocks correlates in a broad way with the amount of regional extension in the province, the extension occurred largely during the 30 m.y. between middle Eocene and late Miocene time, although continuing extension has also occurred. This timing coincides with that deduced for the formation of most of the volcanic rift province of southeastern Oregon and northeastern California and for the formation of the Mendocino and Idaho oroclines.

Rio Grande rift-valley system. A narrow belt of middle and late Cenozoic normal-fault ranges and grabens trends northward for 750 km from south-central New Mexico to central Colorado, across the unstable platform of the western interior states (Figure 6). Most of the belt consists of a single series of aligned troughs, bordered on one or both sides by normal-fault ranges whose dimensions are similar to those of the blocks in the Basin and Range province. The main series of troughs is followed by the Rio Grande in New Mexico. Several other troughs lie parallel to the main system in southern New Mexico. Volcanic eruptions have been widespread along the belt. The Rio Grande rift-valley system is similar structurally and topographically to parts of the rift-valley systems of East Africa.

STRUCTURE NORTH OF VOLCANIC RIFT PROVINCE

The Basin and Range province grades northward into the volcanic terrane (discussed in a subsequent section) of northeastern California and southern Oregon and Idaho. The middle and late Cenozoic structures of the southeastern part of the region north of this volcanic terrane (Figure 6) are similar to those of the eastern part of the Basin and Range province and are dominated by dip-slip normal faults. (Strike-slip displacements have been hypothesized by several geologists, who have not, however, described offset units.) These normal-fault structures are developed east of the Idaho batholith, which has remained almost unbroken by at least late Cenozoic faults [*Hamilton,* 1963*a*]. Many of the normal faults in southwestern Montana utilized very early Tertiary (Laramide) fault and bedding structures as planes of easy slip, and, because such structures extend no deeper than a few kilometers, it is apparent that the surface pattern of faulting here is controlled partly by shallow structures rather than by fundamental crustal directions [*Myers and Hamilton,* 1964].

Earthquakes accompanying normal faulting at the surface in the block-faulted region, as in the Basin and Range province, probably result from gravitational collapse following crustal extension. Thus the Hebgen Lake earthquake of 1959 in southwestern Montana was accompanied by as much as 7 meters of subsidence on dip-slip normal faults, but there was almost no compensating elevation above prior altitudes [*Myers and Hamilton,* 1964].

A zone of right-lateral faults trends west-northwestward from western Montana, near the northeast corner of the Idaho batholith, across northern Idaho. Large upwarps, major folds and faults, and mineralized areas are offset about 25 km, mostly along one structure, the Osburn fault [*Wallace et al.,* 1960; *Hobbs et al.,* 1965, pp. 73–83]. Large drag effects along the various faults all show the same right-lateral sense of movement. The faulting occurred some time between middle Cretaceous and late Miocene or early Pliocene time.

Structures such as those noted fit an explanation of rifting of the continental crust. The Idaho batholith appears to be drifting slowly northwestward as an unbroken mass, in the lee of which the Snake River depression has been produced by tensional thinning and rupturing of the crust. Distributed tension east of the batholith is represented by the normal faulting of southwestern Montana and east-central Idaho. West of the southern part of the massive batholith, Pliocene and Pleistocene north-trending normal-fault blocks have formed mostly by slipping along the steeply dipping foliation planes of the gneissic rocks bordering the batholith [*Hamilton,* 1962]: the amount of northwestward motion continues to increase west of the batholith. The batholithic plate is bounded on the north by the Osburn fault system.

The extension represented by the normal faults east of the batholith and south of the projection of the Osborn fault system is apparently taken up by another normal-fault system on the north side of the Osburn faults farther west. The Osburn fault system is not known to reach the basement crystalline terrane of northeastern Washington. Two south-trending fault troughs, the Rocky Mountain Trench in northwestern Montana and the Purcell Trench in northern Idaho, end at the Osburn fault system, so these trenches may have formed by normal faulting due to tensional extension of the region north of the Idaho batholith.

The Rocky Mountain Trench and troughs aligned with it form a great linear depression that is nearly continuous from northwestern Montana to east-central Alaska, and possibly on to the Bering Sea. Pre-Tertiary structures and units are truncated against the trench on a regional scale. The trench is partly filled with variably deformed lower and middle Tertiary deposits in many sectors and contains great shear zones in older rocks. Strike-slip faulting has long been one of the mechanisms proposed for the trench, and considerable debate has centered on this interpretation [*Aho,* 1959; *Leech,* 1962; *North and Henderson,* 1954].

Superposition of successive normal-fault blocks with diverse trends has occurred in many parts of the Basin and Range province and in the structurally similar terrane of southwestern Montana and east-central Idaho. An example in southwestern Montana (illustrated by Figure 8) was described by *Myers and Hamilton* [1964, p. 95]. The youngest major elements are the west-trending Centennial Mountains and Centennial Valley; the range front is a precipitous scarp, generally about 800 meters high. The Centennial family of structures are being extended eastward across the southern part of the Madison Valley and Madison Range, which trend south-southeastward. The frontal scarp of the Madison Range is somewhat higher than that of the Centennial Mountains, but

Fig. 8. Aerial view southwestward from the Madison Range to the Centennial Mountains, southwestern Montana, showing three sets of superimposed basin-and-range structures with diverse trends. The youngest range is the precipitous Centennial Mountains, which form the wall across the distance. Of intermediate age is the Madison Range of the foreground and left middle distance. Truncated by both Madison and Centennial structures is an old, but post-Oligocene, basin which trends across the Gravelly Range in the right middle distance; an upraised segment of the basin forms the low area along the crest of the Centennial Mountains right of center.

it has been much more deeply eroded, attesting to its generally greater age, although the two ranges have overlapped in age. Still older is a southwest-trending synclinal graben, almost destroyed by erosion, which is truncated at high angles by both Madison and Centennial structures. This old graben was developed partly in Oligocene rocks, so the entire sequence represented in the three fault systems has developed during Miocene, Pliocene, and Quarternary time. Older than all these structures is a very early Tertiary (Laramide) uplift of Precambrian basement rocks, along the crest of which the Madison Valley was later developed.

CENOZOIC VOLCANIC CRUST

Northwestern Oregon and southwestern Washington are formed of Cenozoic rocks, which may represent new continental crust built by Cenozoic volcanism and sedimentation upon what was oceanic crust at the end of the Mesozoic. All known and projected occurrences of pre-Tertiary rocks lie east of this region (compare Figures 1 and 6). The rock and structural belts of the Klamath Mountains of northwestern California and southwestern Oregon, last metamorphosed during late Mesozoic time, curve through an arc of 90°, from a northwest strike in California to a northeast one in Oregon (Figure 1). The structural trend projects northeastward across the volcanic terrane of Oregon, and pre-Tertiary rocks are exposed in northeastern Oregon, on strike, with easterly to northeasterly trends. In west-central Idaho, another arc carries the structures through north to northwestward trends, as the pre-Tertiary belts swing toward northwestern Washington.

That pre-Tertiary continental crust is lacking in northwestern Oregon and southwestern Washington is also indicated by geophysical information. Both seismic-refraction [*Dehlinger et al.*, 1965] and deep-resistivity [*Cantwell et al.*, 1965; *Cantwell and Orange*, 1965] data show that there is probably no 'granitic' crust present, the thick crust being volcanic instead.

Mendocino and Idaho oroclines. The arcs of pre-Tertiary rocks of the Klamath Mountains and of northeastern Oregon and western Idaho were termed the 'Mendocino Orocline' and the 'Idaho Orocline,' respectively, by *Carey* [1958], who attributed the arcs to folding in plan of an initially straighter orogenic system. Paleomagnetic data support his interpretation. The paleomagnetic declination of lower and middle Eocene volcanic rocks in western Oregon, which strike east-northeastward parallel to the northern limb of the Mendocino orocline, trends east-northeast [*Cox*, 1957] or east [*Bromery*, 1965]. This declination, far clockwise from that expected for nonrotated Eocene rocks, is as required by Carey's theory if all the rotation of the orocline postdates the middle Eocene. The Miocene lavas about the southern half of the Idaho orocline show an apparent counterclockwise rotation of about 20° in paleomagnetic declination, and so about one-third of the rotation of that orocline apparently occurred within Pliocene and Quarternary time [*Watkins*, 1965].

If a substantial part of the folding of the two oroclines has indeed occurred within Cenozoic time, the rocks of the new volcanic crust should show the effects of compression as they were squeezed between the northward-moving Mendocino orocline and the relatively stable terrane of northern Washington. The late Cenozoic tectonic pattern is consistent with this requirement. The Tertiary rocks are deformed by folds [e.g., *Waters,* 1955] and at least in the Coast Ranges by thrust faults [e.g., *Snavely et al.,* 1958, pp. 84–93], which trend northeastward in Oregon and northwestward in Washington. The same structural trends probably mark the older Tertiary rocks beneath the upper Cenozoic volcanic rocks of the north-trending Cascade Range [*Peck et al.,* 1964, Figure 27].

Deformation in plan has been extreme in the Olympic Mountains, the northwesternmost part of the Cenozoic volcanic terrane. The Olympics consist of a core, 80 km wide and 100 km long, trending west-northwestward, of highly deformed Eocene and Oligocene volcanic rocks and volcanic sediments [*Danner,* 1955; *Drugg,* 1958; *Gower,* 1960; *Huntting et al.,* 1961]. Tectonically overlying the core on all sides, except the west, is an envelope of similar but less deformed rocks of Paleocene, Eocene, Oligocene, and early Miocene ages [*Brown et al.,* 1960; *Cady and MacLeod,* 1963; *Cady and Tabor,* 1964]. As core and envelope rocks are correlative, the 1-km-thick shear zone [*Gower,* 1960] that separates them must represent a post-early Miocene fault of great displacement, apparently either an overthrust or a strike-slip fault, the fault itself having been severely deformed by still later tectonism.

Early Tertiary rocks crop out primarily in the Coast Ranges, which trend northward completely across the western edge of the volcanic terrane. The northward trend of the ranges and the lack of extreme deformation except in the Olympic Mountains at their north end are difficult to reconcile with the oroclinal-compression concept. The consistent northward direction of current transport indicated by middle Eocene sediments in west-central Oregon [*Snavely et al.,* 1964, Figure 6] suggests that, if post-Eocene rotation has occurred there, it has not been differential within that region. The Miocene volcanoes and plutons of the ancestral Cascade system bridge northward across the volcanic terrane east of the Coast Ranges, from the Sierra Nevada of northern California to the pre-Tertiary terrane of northern Washington [e.g., *Snavely and Wagner,* 1963, Figure 16], and again this is difficult to explain in terms of extensive north-south compression.

We argue in the next section, however, that the motion of the Klamath terrane relative to Idaho has been westward rather than northwestward, as envisaged by Carey, although we agree with him that the Mesozoic crystalline terrane was relatively straight at the beginning of Tertiary time. We picture the Coast Ranges as having swung with the Klamaths, the rifts in the lee of each having filled progressively with younger volcanic materials. This concept accounts better for the data from what we term the volcanic rift province and encounters no serious obstacle in the information from the Coast Ranges and Cascades.

Taubeneck [1966] argued against rotation of the Idaho orocline, but those of his data which are relevant are in fact consistent with rotation. His arguments are primarily against the occurrence of strike-slip faulting along the southeastward projection of the 'Olympic-Wallowa lineament' in easternmost Oregon and west-central Idaho. Some of these arguments are quite valid, but they afford no test of either our explanation or Carey's explanation, because neither proposes strike-slip faulting there. Taubeneck's case against rotation is based primarily on his data on the orientation of late Miocene and (?) early Pliocene dikes in a great swarm in northeastern Oregon, southeastern Washington, and adjacent Idaho. (His data have yet to be published and are not as complete as he infers. Thus, no such dike swarm exists in a large part of west-central Idaho in which his Figure 1 shows it to be present [*Hamilton,* 1963*b*, p. 11].) The azimuth of the dikes is generally about 350° in Oregon but swings to 335° in Washington; the change corresponds with the axis of the Idaho orocline and, hence, is consistent with a post-Miocene age for a small part of the rotation.

VOLCANIC RIFT PROVINCE

If the Mendocino and Idaho oroclines are now connected beneath the Cenozoic volcanic rocks of southeastern Oregon by a continuous belt of pre-Tertiary metamorphic rocks, the oroclinal-folding concept would require that the Sierra Nevada and Klamath terranes have moved approximately 600 km northwestward relative to the interior states. Strike-slip faults with this aggregate displacement, however, would have to pass through the southern part of the Basin and Range province, and enough is known about this southern region to indicate that little more than 150 km of offset can be attributed to strike-slip faults within it. The known strike-slip motion in the Basin and Range province and the other evidence, such as that noted in the preceding section, nevertheless suggest that the arcs are indeed oroclinal folds. The relationships are easily explained if the volcanic terrane of northeastern California and southern Oregon and Idaho has been built upon a stretched and ruptured pre-Tertiary crust (compare Figures 1 and 6).

Snake River Plain. The broad depression of the Snake River Plain (Figure 1) trends southwestward across eastern Idaho and northwestward across the western part of the state. The plain is about 80 km wide and stands 600–1000 meters below the general level of the flanking highlands, from which rise many of the highest peaks of the northern Rocky Mountains. The depression is filled deeply by upper Cenozoic volcanic rocks and subordinate sediments. The plain and highlands are in approximate isostatic equilibrium (the Bouguer gravity, as shown by *Woollard and Joesting* [1964], correlates with regional altitude in the appropriate way), so that the plain cannot be underlain by a depressed crustal section like that of the surrounding highlands but must instead have a thinner or denser crust. Seismic-refraction data indicate that the second alternative is correct: low-velocity ('granitic') continental crust is probably wholly lacking beneath at least the western part of the plain, which has a thick but high-velocity ('basaltic') crust [*Hill and Pakiser,* 1963].

The western part of the Snake River Plain is bounded on both sides by zones of northwest-trending faults of small vertical displacements [*Malde et al.,* 1963]; we infer from the straightness and continuity of these faults that they are likely to be dominantly strike-slip features, although data to test this interpretation are not yet available. Most of the eastern part of the plain is bounded by downwarps; the high fault blocks trending toward the plain from both sides lose relief as they approach it and disappear beneath its surface, without deforming it with cross trends. The east end of the plain is bounded by the dip slopes of the Centennial Mountains on the north and the Teton Range on the southeast; these ranges face outward on deep fault troughs (Figure 8) and are the most active fault blocks in the region.

Such features all fit the interpretation that the Snake River Plain is a lava-filled tension rift formed in the lee of the northwestward-drifting plate of the Idaho batholith. The continental plate has probably been completely sundered in the western part of the plain but only thinned by tension in the eastern part. The tension has been oblique in the northwest-trending western half of the plain, where strike-slip faults may be present, but has been direct in the northeast-trending eastern half of the plain, where the flanking highlands sag smoothly toward the depression. The Centennial and Teton blocks which bound the eastern end of the plain may be sliding gravitationally into it, causing the collapse of the grabens beyond.

The exposed volcanic rocks of the Snake River Plain and of its high northeast end, the Yellowstone Plateau, form a bimodal assemblage of low-alkali olivine basalt and rhyolite. Vents that produced the contrasted types have been closely associated in some periods and at some places, indicating that the basalt and rhyolite may share a common origin. Such occurrences and possible modes of formation of both rock types from mantle sources were discussed by *Hamilton* [1965].

Southeastern Oregon and northeastern California. The volcanic rocks of southeastern Oregon and northeastern California are like those of the new continental terranes of the Snake River Plain and of northwestern Oregon and southwestern Washington and may have formed similarly on thinned continental crust or on subcontinental materials in tension rifts through the crust. The Bouguer-gravity decrease between the Klamath Mountains and the volcanic province of the southern Cascade Range in northern California may indicate that the southern Cascades consist of a surface pile, 6 to 10 km thick, of relatively light volcanic and plutonic rocks, resting on a dense basaltic crust [*LaFehr*, 1965].

Figures 6 and 9 illustrate the interpretation that the pre-Tertiary rocks of southwestern Oregon were much closer to those of northeastern Oregon before oroclinal folding and separation of the segments of the belt. Similarly, the Idaho batholith is interpreted as having been much closer to the Sierra Nevada batholith than it is at present.

ROLE OF BATHOLITHS

The mechanical strength of the great Mesozoic batholiths of western North America apparently much influenced the Cenozoic deformation of their regions.

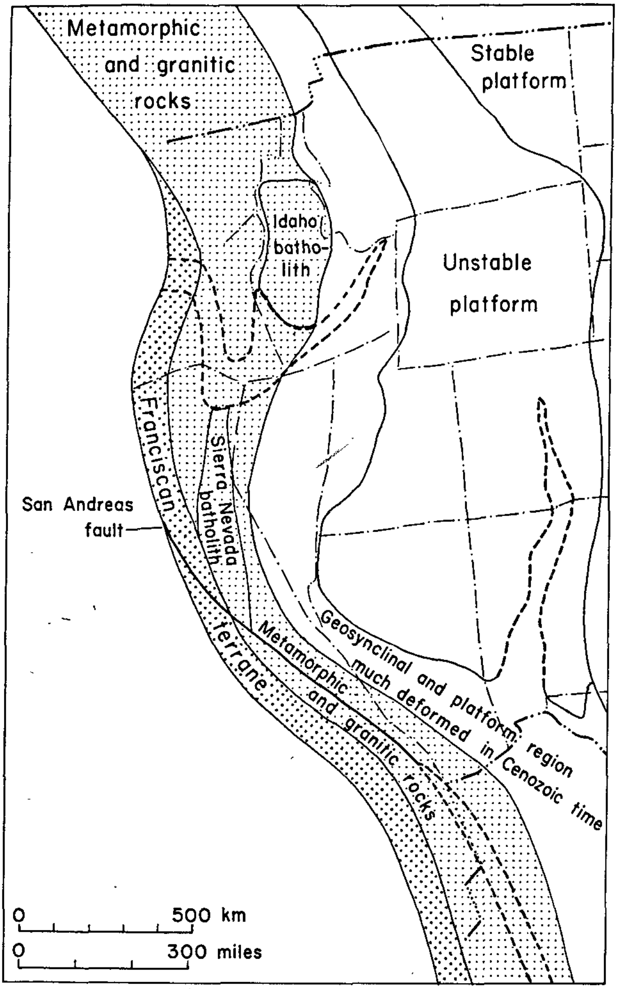

Fig. 9. Paleogeologic map of the western United States at the beginning of Tertiary time. The distortion of state and national boundaries (compare with Figures 1 and 6) represents deformation during Cenozoic time. Of the strike-slip faults, only the position of the San Andreas is marked. Boundaries of potential rift zones are marked by heavy dashed lines.

The largest unbroken mountain masses in the western states, the Sierra Nevada and the mountains of central Idaho, are carved from those parts of the batholithic belt (Figure 1) which contain the highest proportion of granitic rocks and the smallest proportion of metamorphic rocks. The fault zone bounding the Sierra Nevada block on the east cuts obliquely through the batholithic belt, which curves northeastward from the northern Sierra and southeastward from the southern Sierra, but the fault zone approximates the eastern limit of almost continuous granitic rocks within the belt. The crystalline belt contains a higher proportion of metamorphic rocks east of the fault zone and is broken into numerous large and small basin-and-range blocks. The continuous batholithic terrane stands as the Sierra Nevada block, a west-tilted block 600 km long bounded on the east by normal faults, which resisted the fragmentation that produced the normal faults. Similarly, the massive Peninsular Ranges of southwestern California and Baja California are formed of almost continuous batholithic rocks, which here form the west part of the crystalline belt; the east part, in southeastern California and western mainland Mexico, contains abundant metamorphic rocks and is broken into many fault blocks. The large basin-and-range fault blocks striking northwestward into central Idaho abruptly lose structural relief and vanish as they intersect the Idaho batholith. Other young fault blocks lie north, west, and east of the batholith, but none of consequence break it [*Hamilton*, 1962]. The Coast Range of British Columbia is another massive mountain block formed largely of batholithic rocks. These and other aspects of batholithics are discussed elsewhere [*Hamilton and Myers*, 1966].

The major batholithic masses of the western United States have drifted as unbroken plates as diverse tension features formed in their lees. The Basin and Range province opened behind the Sierra Nevada batholith; the Gulf of California, behind the southern California-Baja California batholith; and the Snake River Plain and a region of faulting of basin-range type, behind the Idaho batholith. This dependence of very broad elements of western structure upon the position of old crystalline masses provides some of the evidence that body forces within the crust cause the complex deformation of the western part of the continent.

MECHANISM

We have interpreted the Cenozoic structure of the western United States in terms of great mobility of the continental crust. The Sierra Nevada-Klamath Mountains region has moved northwestward and rotated counterclockwise, obliquely away from the continental interior, so that the westward component of movement increased northward; between moving and stable regions, the Basin and Range province has formed by the fragmentation of the continental crust by distributed oblique tension. The crust of the Basin and Range province has been much augmented by Cenozoic volcanism. Farther north, volcanism has built new crust to fill the rift left where the Klamath sector of pre-Tertiary continental crust has pulled far away from its original position. Central Idaho has moved northwestward by a lesser amount, producing normal faulting and continental rifting in its lee. The new volcanic crust of northwestern Oregon and southwestern Washington has been deformed by compression. Coastal California and Baja California are drifting rapidly northwestward, separated from the rest of California by the right-lateral faults of the San Andreas system and from mainland Mexico by the tension rift of the Gulf of California. All these motions are continuing, because faulting and warping are now in progress in all these provinces. The pattern is chaotic in detail but is broadly one in which northwestward displacements increase southwestward toward Baja California and coastal California.

The east Pacific rise trends northward toward the mouth of the Gulf of California. *Menard* [1964, chapter 6] and others have speculated that the rise marks an axis of mantle-convection divergence, which trends along the Gulf of California, thence beneath the western United States and back into the Pacific basin in the vicinity of Cape Mendocino. Such effects as the rifting of the Gulf of California and the fragmentation of the Basin and Range province are ascribed to the divergence of convective flow. There is, however, no region of active tension through which the axis of the hypothetical convection current can be postulated to leave the continent to the northwest; if such an axis enters the continent from the south, it ends beneath the continent. The dominant direction of motion of the California coastal region is northwestward, parallel to the axis of the postulated convection cell and perpendicular to the expected direction of flow. Convection alone provides no means by which the crust can move over the mantle, and yet such motion is suggested by the behavior of the San Andreas fault and Baja California. The chaotic pattern of deformation defies explanation in terms of simple divergence. Convection in the mantle might account for part of the motion of the crust but certainly cannot account for all of it.

If our interpretations are basically correct, fragments of the continental plate are drifting independently over the mantle and oceanic crust: continental pieces are not being carried passively upon moving mantle material. Either gravity or inertia can be called upon to provide the moving force. *Rusnak and Fisher* [1964] invoke gravity with a blister hypothesis. They speculate that western North America is raised by the bulging mantle, the onshore continuation of the east Pacific rise, and that the crust on the west flank of the bulge is sliding down the very slight slope into the Pacific basin The stretching of the Basin and Range province can be explained in these terms, and structural irregularities can be ascribed to a variety of local causes within such a scheme. Many features, however, such as the northwestward motion of coastal California and Baja California, seem inexplicable in terms of the blister hypothesis alone. Further, the motion along the San Andreas fault at least has been going on since early Tertiary time, and yet the uplift of the western United States is largely a late Miocene, Pliocene, and Quarternary phenomenon.

Inertial forces dependent on the earth's rotation provide perhaps another possible mechanism. The earth's core is fluid, so that it must be possible for the rotational velocities and axial orientations of core and mantle to change interdependently, as in nested gyroscopes, the sum of the products of angular momentums and moments of inertia remaining constant. (Wandering of the magnetic dipole axis, polarity reversals, changes in the length of day, and other anomalies might find partial explanations in such a phenomenon.) The moon is part of the earth's inertial system, so that its orbital parameters can also change interdependently with rotational changes in the earth. As the mantle changes in either axial orientation or angular velocity, differential motion of crust over mantle or within the mantle would result wherever stress exceeded strength. The western United States is characterized by high heat flow and by low seismic velocity and rapid attenuation of seismic energy in the upper mantle [*Pakiser and Zietz*, 1965]; presumably the upper mantle here is weak, even partly molten, and it is this that permits relatively free sliding about of the crust above. The particularly large displacement of the California coastal region might be facilitated by some other property; for example, if there is a serpentine layer at the top of the oceanic mantle, reduction of strength of this material by partial dehydration during heating [cf. *Raleigh and Paterson,* 1965], as it was depressed beneath the continent, might permit easy slipping in a zone whose horizontal width is determined by the appropriate depth temperature interval of the eastward-deepening layer.

It is of course possible that the deformation of the western United States and the overriding of the oceanic crust are due to a complex combination of mechanisms of mantle motion and of gravitational and inertial displacements of the continental crust.

CONTINENTAL DRIFT

The deformation of the western United States represents one sort of continental drift: masses of continental crust have moved hundreds of kilometers relative to one another. Our discussion has been limited to the internal deformation of the western part of the continent. This internal deformation may be superimposed on more extensive motion of North America as a whole, as there are grounds for arguing that the entire continent moved westward, and rotated slightly clockwise, as though about a pivot near the east coast, during at least the early part of Cenozoic time. Deformation in the western United States appears to be coincident areally with a particularly weak uppermost mantle, which is not present east of the Rocky Mountains [e.g., *Pakiser and Zietz,* 1965]; therefore the motion of the entire continent is probably mechanically quite different from the internal deformation of its western part. It can be argued either that the entire continent is drifting with the uppermost mantle, both being uncoupled from the deeper mantle, or that the continent is being carried passively on a mantle whose motion extends to great depth. It appears likely that in any case continental drift involves several different processes, which may be related only obscurely.

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