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Cainozoic Evolution of the State of Stress and Style of Tectonism of the Basin and Range Province of the Western United States

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Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western United States

By Mary Lou Zoback†, R. E. Anderson‡ and G. A. Thompson§
† *U.S. Geological Survey, Mail Stop* 935, *Reston, Virginia* 22092, *U.S.A.*
‡ *U.S. Geological Survey, Denver, Colorado* 80225, *U.S.A.*
§ *Geophysics Department, Stanford University, Stanford, California* 94303, *U.S.A.*

Cainozoic evolution of the modern plate boundary along the western United States from subduction to a predominantly transform boundary coincided with a change from compressional to extensional deformation in the western United States. Extensional tectonism responsible for the modern Basin and Range province appears to represent a unique late-stage episode of a much longer period of extension initiated in an 'intra-arc' setting contemporaneously with calc-alkaline magmatism. Basin–range extension is distinguished from early extension on the basis of angular unconformities, differences in fault trends and spacing, and associated magmatism (basaltic). Pre-basin–range extension (i.e. extension preceding the break-up of the region into ranges resembling the modern ones) was under way locally by at least 30 Ma and is now recognized by faulted and highly tilted strata exposed in uplifted range blocks, by large regions of the crust underlain by passively emplaced subvolcanic batholiths, and by the thickness and distribution of stratigraphic units. Locally, high strain rates that accompanied early extensions of as much as 50–100% are implied. Data on preferentially orientated dyke swarms and fault slip vectors indicate a strikingly uniform WSW–ENE least principal stress orientation in the period *ca.* 20–10 Ma, during this early extension. The change from early extension to basin–range style faulting of the upper 15 km of crust, which resulted in broadly spaced ranges (25–35 km crest–crest spacing), was time-transgressive and probably not abrupt; locally both types occurred concurrently. Southern Basin and Range block faulting occurred largely in the period 13–10 Ma, in response to a stress field orientated similarly to that responsible for the early extension. In contrast, northern Basin and Range block faulting developed after 10 Ma and continues to the present in response to a stress field orientated approximately 45° clockwise to the earlier stress field. This modern stress field, with a WNW–ESE to E–W directed least principal stress, characterizes the entire modern Basin and Range province and Rio Grande rift region. The 45° change in least principal stress orientation is consistent with superposition of dextral shear associated with the development of the San Andreas transform fault. Inclusion of pre-basin–range extension may help resolve the discrepancy between estimates of 15–30% for basin–range block faulting and total extension estimates of 100–300% for the Basin and Range province.

Introduction

Characterized by a broad zone (up to 1000 km wide) of normal faulting and seismicity, high heat flow, thin crust yet high regional elevation, the Basin and Range province of the western United States is typical of areas of continental extension throughout the world (see Thompson & Burke 1974; Eaton *et al.* 1978). Most of the Basin and Range province currently lies east of the San Andreas transform fault, which forms the plate boundary between the Pacific and North American plates (figure 1). Although subduction occurs northwest of the Basin and Range province today, and does not appear to be spatially associated with the province, Cainozoic regional magmatic patterns and offshore magnetic anomaly patterns strongly suggest that subduction tectonics have had a significant role in the overall development of the Basin and Range province.

Evidence is now emerging that indicates a complex history of extensional tectonism in the Basin and Range province, which can be related to changes in stress pattern probably resulting from plate interactions along the western plate boundary of North America. In this paper we review and present new evidence on the state of stress and structural processes responsible for the extensional deformation in the Basin and Range province. Modern

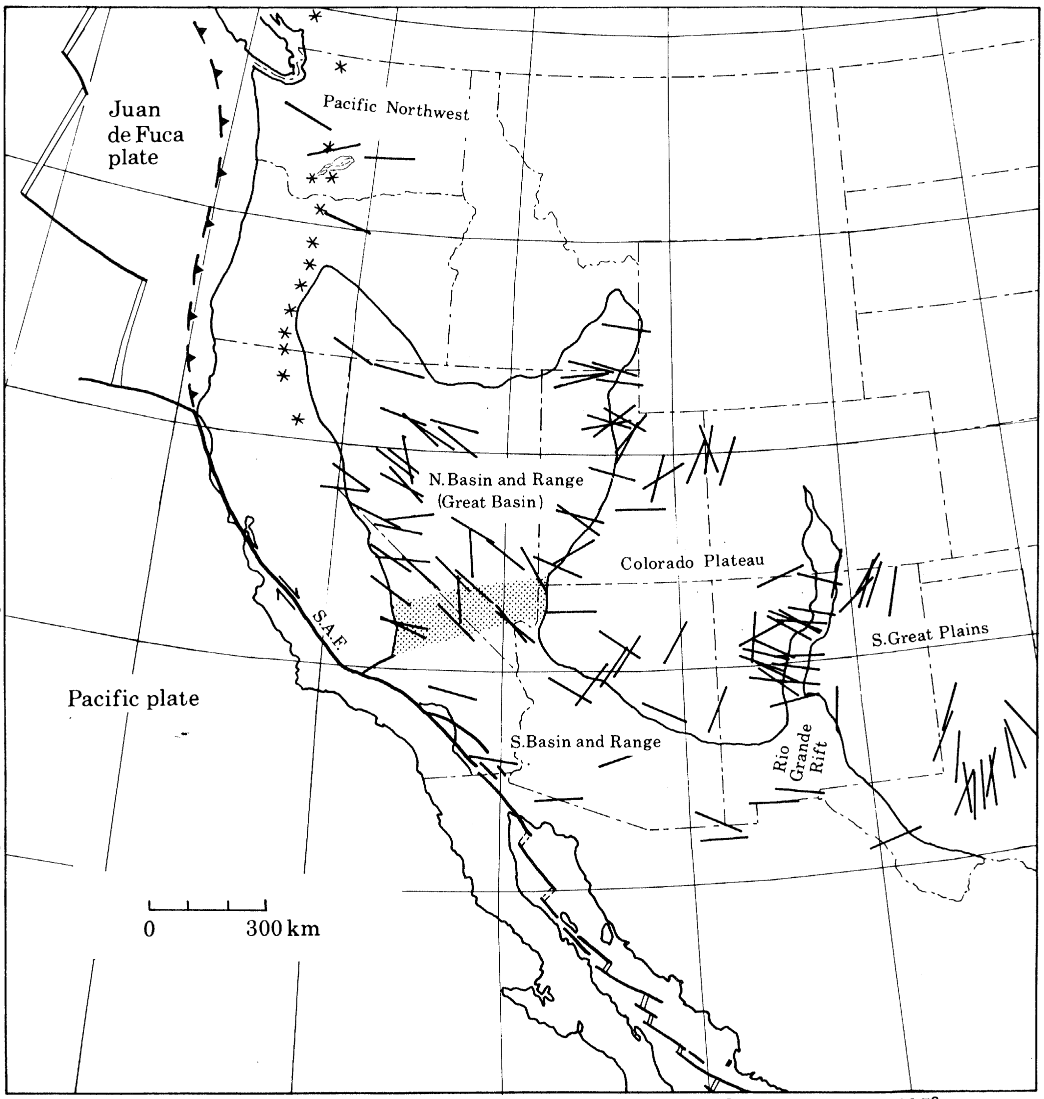

FIGURE 1. Modern least principal horizontal stress directions in the Basin and Range, Rio Grande rift and surrounding provinces (from Zoback & Zoback 1980). The shaded region in southern Nevada and Utah marks the boundary between the northern and southern Basin and Range province, after Eaton (1979*a*). The current plate boundary along the western United States consists of spreading in the Gulf of California (double line segments in southern part of map), San Andreas transform fault (S.A.F.; heavy solid line), and probable subduction zone (barbed line) along the Pacific northwest. Active Cascade andesitic volcanic chain indicated by asterisks.

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basin–range physiography is dominated by elongate ranges (length: width ratio generally 4 to 8) of regionally parallel trend separated by basins filled with Tertiary–Quaternary fluvial/pluvial sequences. Characteristic crest–crest spacing of the range blocks is 25–35 km, with the intervening basins commonly 10–20 km wide; this average basin width is approximately the thickness of the seismogenic (brittle) part of the crust (Eaton 1980). In evaluating the structural history of the Basin and Range province, it is important to distinguish between basin–range structure and extensional tectonics. Basin–range structure is generally considered to refer to the development of the modern normal fault-controlled sedimentary basins and topographic forms described above (Stewart 1978). This is the usage adopted here. Extensional tectonics, as used herein, refers to any deformation that resulted in an increase in area regardless of association with sedimentation, volcanism, plutonism or metamorphism, and regardless of physical relation to modern topographic forms. As we shall attempt to demonstrate here, extension began before the development of basin–range structure; thus, deformation responsible for modern physiography refers to a unique late-stage episode of extensional tectonism in the Basin and Range province.

We begin with a discussion of the timing, structural style, and state of stress responsible for basin–range extension. Next we provide igneous, structural and stratigraphic evidence for pre-basin–range extension along with geological evidence indicating that stress orientations were different during the earlier extension than they were during most of basin–range faulting. Contrasts in structural history coupled with present-day topographic and geomorphic differences suggest separation of the Basin and Range province into two subprovinces. In this report the boundary between the northern Basin and Range province (N.B.R.) and the southern Basin and Range province (S.B.R.) is placed at the southern boundary of the transitional zone separating the two subprovinces as defined by Eaton (1979*a*) on the basis of regional elevation and morphology (figures 1 and 2).

Basin–range extension

Age of onset of basin–range faulting

Stewart (1978) reviewed evidence pertaining to the onset of basin–range faulting from the N.B.R. and suggested that the grain of present-day topography probably did not develop before 10 Ma at the earliest. We have reviewed evidence from both the northern and southern Basin and Range sections and suggest that modern topography probably began to form earlier in the S.B.R. than in the N.B.R. (*ca.* 13 Ma compared with *ca.* 10 Ma). The data from the N.B.R. suggest oldest possible ages for the onset of basin–range faulting (as used herein) ranging from *ca.* 15 to 6.8 Ma and documented ages ranging from 10 to 7.6 Ma. Detailed site by site descriptions of these localities are included in a manuscript in preparation. The data from the S.B.R. include the results of three regional summaries (Eberly & Stanley 1978; Scarborough & Shaffiqullah 1979; Shaffiqullah *et al.* 1980), each of which indicated an age of about 13 Ma for the inception of the modern physiography. These summaries agree with specific data from three additional localities within the S.B.R. (Otton 1978; Bohannon 1979; Rehrig *et al.* 1980).

Modern state of stress

Modern deformation in the Basin and Range province occurs in response to a stress field with a horizontal least principal stress trending approximately WNW–ESE, as indicated by earthquake focal mechanisms and *in situ* stress measurements (Zoback & Zoback 1980). Geological stress indicators, including the alignment of volcanic feeders and detailed fault slip data, suggest a late Tertiary–Quaternary (less than 5 Ma) stress field similar to the modern one. The data from all four types of stress indicators are shown in figure 1. The stress field is reasonably consistent throughout the N.B.R. and S.B.R. and appears to continue into the Rio Grande Rift (R.G.R.). Least horizontal principal stress axes in the Colorado Plateau

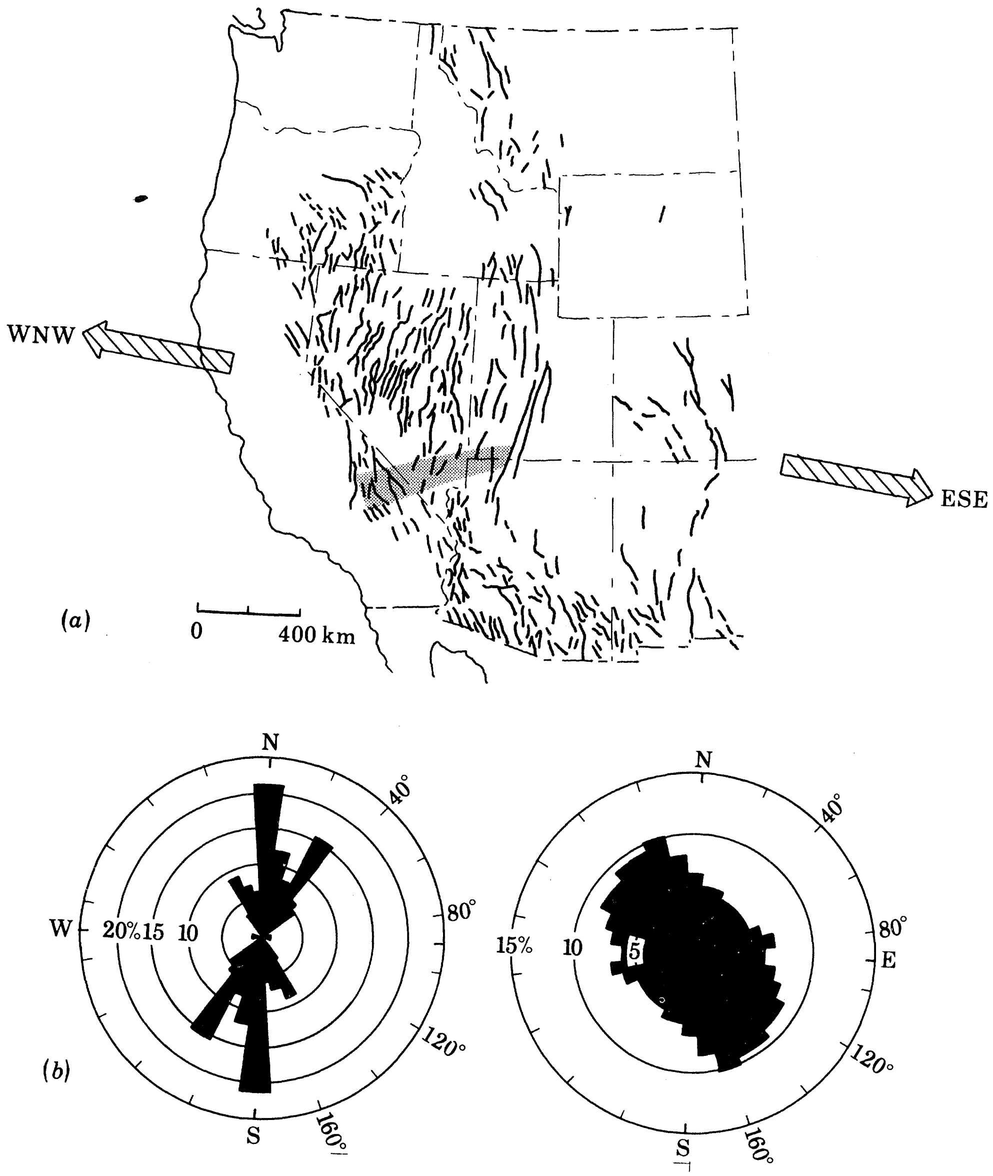

FIGURE 2. (*a*) Late Cainozoic normal fault trends in the western United States (from Thompson & Burke 1974). Large arrows indicate the approximate modern least principal stress direction for the Basin and Range province and Rio Grande rift. The shaded region is the boundary zone between the northern and southern Basin and Range province, after Eaton (1979*a*). (*b*) Rose diagrams of individual 50 km long range-front segments in the northern Basin and Range province and Rio Grande rift (left) and in the southern Basin and Range province (right). More than 500 individual segments were compiled for each area (from Eaton 1980, fig. 9.4).

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interior and in the southern Great Plains – areas that are not undergoing extension – are orientated approximately perpendicular to those in the Basin and Range province. In the Pacific northwest, least horizontal principal stress orientations are *ca.* E–W, roughly perpendicular to the trend of the trench; however, this region is currently characterized by N–S compressional tectonism (for a discussion of the regional pattern of stress in all these areas see Zoback and Zoback (1980) and Thompson & Zoback (1979)).

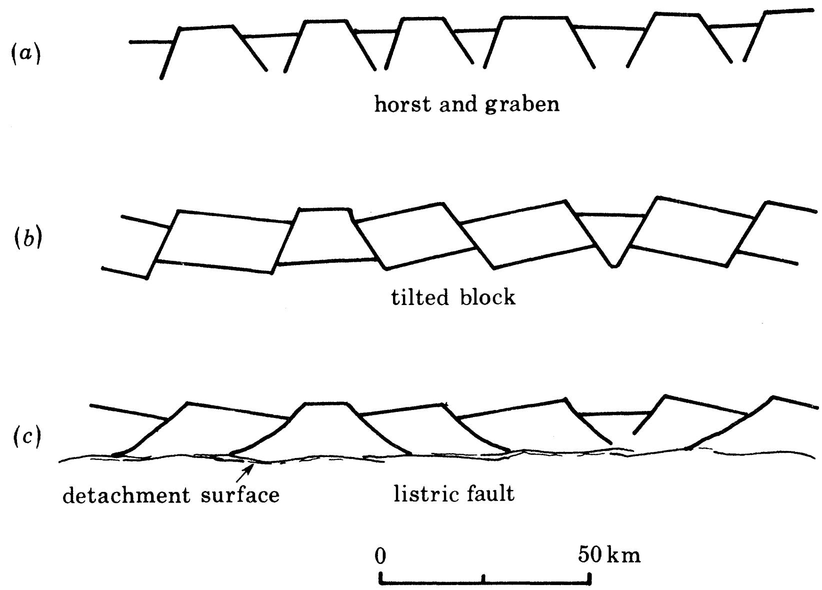

Figure 3. Generalized models of basin–range structure. Relatively small-scale faulting and tilting within major blocks is not shown. All models are inferred to merge with a ductile extending zone below the depth of brittle failure (modified from Stewart 1980). The scale is approximate, and represents both horizontal and vertical distances.

A comparison of these 'modern' least principal stress orientations with normal fault trends throughout the Basin and Range–Rio Grande rift provinces (figure 2*a*) indicates that the least principal stress is now (and probably has been throughout Quaternary time) orientated approximately perpendicular to fault trends in the N.B.R., but is orientated rather obliquely to the generally NW-trending mountain ranges in the S.B.R., as graphically illustrated by the rose diagrams of range trends in the two subprovinces (figure 2*b*). As Eaton (1979*a*, *b*) has noted, this suggests a difference in timing and/or state of stress responsible for the development of the two subprovinces. Current low levels of seismic activity and geomorphic parameters, including the paucity of Quaternary scarps and the breadth of range-bounding pediments in the S.B.R., suggest that that region has been structurally quiescent for hundreds of thousands to perhaps a few million years and is currently largely quiescent (Eaton 1980).

Nature of basin–range faulting

Three basic models have been suggested for the cross-sectional subsurface geometry of basin–range faults (figure 3; see also Stewart 1971, 1978, 1980). Faults illustrated in both the listric fault (figure 3*c*) and the tilted block (figure 3*b*) model are inferred to merge with a region of continuous or quasi-continuous strain at depth – a ductile zone below the seismogenic layer 10–15 km thick. The horst and graben model (figure 3*a*) requires a localized zone of extension

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beneath the grabens in the region where the faults intersect; Thompson (1966) and Thompson & Burke (1974) have suggested that a zone of dyke intrusion may accommodate this localized extension. Available seismological, geological, geophysical and drill-hole data do not form a basis for preferring any one of the three basic models for basin–range faulting. As a consequence, the subsurface geometry of basin–range faults remains a subject of much debate. Some of the pertinent data and interpretations are summarized in the paragraphs that follow.

Historic seismicity is concentrated in broad belts (100–150 km wide) along the margins of the N.B.R. These belts tend to surround a relatively aseismic region in the central part of the Great Basin. Earthquake focal depths are concentrated in the depth range from 5 to 16 km and there is a general absence of earthquakes below depths of about 16–20 km (Eaton 1980; Smith 1978). Thus, contemporary brittle failure of a predominantly extensional nature (Smith & Lindh 1978) appears to be restricted to the upper 20 km or so of the crust. Failure beneath this zone is aseismic, probably occurring by ductile flow and/or igneous intrusion resembling continuous or quasi-continuous strain.

Stewart (1980) examined regional tilt patterns for major range blocks within the Basin and Range and Rio Grande rift and identified broad regions of consistent tilt. These regions are commonly on the order of 200 km wide, approximately ten times the spacing of the individual ranges. Such regional tilt domains are compatible with the tilted block model (figure 3*b*) or the listric fault model (figure 3*c*) but not the horst and graben model (figure 3*a*). Although the latter model may apply in a modified sense to the internal structure of individual basins, it is difficult to reconcile in terms of regional tilts. It should be noted, however (and will be developed later), that much of the tilting seen in uplifted blocks pre-dates the block uplift on basin-range faults.

The downbending of strata on the downthrown block close to some major active normal faults in the Basin and Range province (referred to as reverse drag flexing by Hamblin (1965)) suggests that the faults decrease in dip with depth and are concave upward. Examples of such reverse drag include the Hurricane fault (Hamblin 1965) and parts of the Wasatch fault (Swan *et al.* 1980), two major faults along the eastern boundary of the Basin and Range province. In contrast, many normal faults in the province show no evidence of reverse drag in limited vertical exposures along their surface trace suggesting that (1) they are not concave surfaces, (2) the curvature is exceedingly gentle, or (3) the curvature is restricted to their deep portions only. In addition, as discussed in greater detail below, listric and associated detachment faults seen on published seismic reflexion sections generally do not penetrate into the lower 10 km (5–15 km depth) of the zone of contemporary faulting (as indicated by earthquake focal depths) and are therefore unlikely to merge with a region of continuous strain release. Drilling data pertinent to defining the subsurface geometry of faults are limited. A geothermal well in north–central Nevada intersected the main range-front fault at a depth of 2.9 km, requiring a minimum dip of 70° for that fault (Zoback 1979*a*).

The only historic major earthquake in the Basin and Range province for which the dip of the active fault plane at depth can be determined is the 1954 Fairview Peak earthquake in western Nevada ($M = 7.2$). On figure 4 the coseismic geodetically determined horizontal components of earthquake slip are compared with the focal mechanism. Selecting as the fault plane the NNW-trending focal mechanism nodal plane, which corresponds to the overall trend of ground breakage, the horizontal component of the slip vector agrees quite well with the directions of measured surface horizontal offset; this fault plane has a 62° dip. Romney

(1957) assigned a focal depth of 15 km for this event based on identification of a pP phase. Focal depths determined for the main aftershock zone were concentrated in the depth range 12–14 km (Stauder & Ryall 1967).

A quite different view of basin–range subsurface fault geometry where major range-bounding faults merge into subhorizontal surfaces at less than 5 km depth is presented by Effimoff & Pinezich (this symposium). Their interpretations, together with additional published seismic data (McDonald 1976), seem to require that the basin-bounding range blocks move laterally

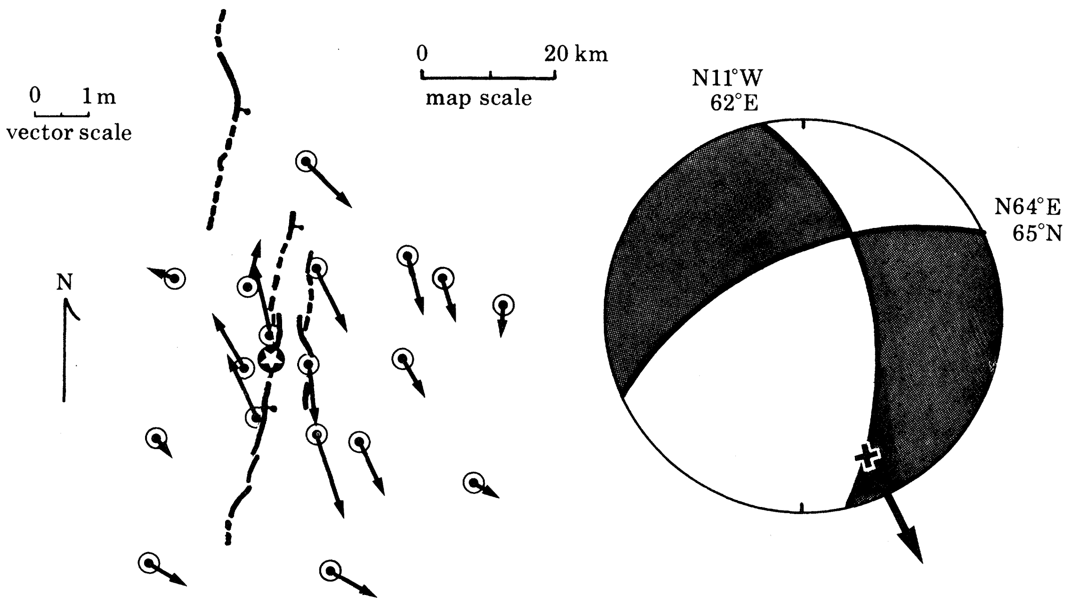

FIGURE 4. Slip associated with the 1954 Fairview Peak earthquake. Plan view on left shows surface ground breakage, epicentre (star) and geodetically determined horizontal components of slip (heavy vectors) (after Whitten 1957). The focal mechanism on the right indicates (with ×) the orientation of the preferred slip vector (after Romney (1957) and Stauder & Ryall (1966)).

apart from one another above the shallow (5 km) zone of detachment. Some seismic reflexion data suggest that detachment faults that have a 'break away' zone adjacent to one mountain mass pass beneath the adjacent mountain mass and thus provide surfaces along which the ranges could separate from one another. Structural accommodation beneath the detachment surfaces is probably extensional and must include brittle failure (evidence from earthquake foci), but its true nature is not understood.

Some faulting in the Basin and Range province, including large-scale major faulting along the margins of the N.B.R. (the Wasatch fault zone at the east margin and the Sierra Nevada frontal faults along the west margin), appears related to major through-going structures that probably cut through the lithosphere. This is suggested both by the scale of the gently back-tilted (*ca.* 2–3°) uplifted blocks bounded by these fault systems and by gravity data that indicate that the uplifted blocks are isostatically compensated. The major bounding fault along the east margin of the Rio Grande rift appears to correlate on COCORP seismic reflexion profiles with a steeply dipping (*ca.* 70°) zone of structural disruption extending through the crust (Brown *et al.* 1979). A similar structure was not found along the western margin of the rift where the boundary is more diffuse and the seismic data suggest zones of listric faulting within the upper 5 km (Cape *et al.* 1980).

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In summary, faulting responsible for modern extension in the Basin and Range province probably includes many types of faults: steep, through-going faults, faults that decrease in dip and become subhorizontal at depths of 4–5 km, and other faults that decrease in dip and merge with a subhorizontal zone of decoupling at *ca.* 15 km depth (base of seismogenic portion of crust) (see Eaton (1979*a*, *b*, 1980) and Wallace (1980*a*, *b*) for an attempt at defining a hierarchy of faulting). Extension within the ductile zone underlying the brittle faulted layer can be accommodated either by more uniform stretching or by dyke intrusion or by a combination of the two mechanisms. Either model or a combined model can be matched with realistic strain rates to the current thermal régimes of the Basin and Range lithosphere (Lachenbruch & Sass 1978).

Amount of extension

Estimates for the total amount of extension in the Basin and Range province vary widely. Extrapolations to the entire province from studies made on a single basin generally range between *ca.* 5 and 15% (see Thompson & Burke 1974; Stewart 1978). These estimates are applicable to basin–range extension (approximately the last 10 Ma) and are based on an assumption of planar faults; more extension can be accommodated by faults that flatten with depth, where the surface expression of this additional extension (reverse drag or antithetic faulting) is largely buried under basins.

A more definitive approach to estimating extension in the last *ca.* 10 Ma comes from an analysis of faulting on four major fault sets in north–central Nevada, where the range bounding faults have considerable oblique (left-lateral) components of motion (Zoback 1978, 1979*b*). By using gravity data to constrain the vertical offset along the faults, and magnetic data to constrain lateral offsets of a narrow zone of dykes (3–5 km wide) extending through the region, the total offset along each major fault set was calculated. The total extension across the region was found to be *ca.* 17–23% with a best estimate of 20%. This estimate was derived from an area that includes four major fault sets and hence provides a better average value than previous studies, which only included information from a single basin. In that both horizontal and vertical components of motion were constrained, calculation of a mean net horizontal extension direction of N 77° W, which is consistent with other evidence, provides an independent check on the extension estimate. For northeastern Nevada, I. Effimoff (oral communication, 1980) estimates a total extension of 30% based on palinspastic reconstruction of the basement structure revealed by reflexion profiling.

Examining patterns of range tilts in the Basin and Range province, Stewart (1980) used a regional approach to estimate total extension based on a geometric relation between block tilts of ranges and total extension (assuming planar faults) proposed by Morton & Black (1975). Stewart found that most ranges in the N.B.R. are tilted less than 32° with the average tilt only 15–20°, corresponding to an extension of 20–30% for the entire N.B.R. region. As mentioned above (and acknowledged by Stewart) this method includes tilts of individual blocks exposed within the ranges and therefore may not be representative of the tilt of the modern range block.

A somewhat different regional approach to estimating total extension comes from a study by Proffett (1977) of a region of extreme extension (more than 100%) in the Yerington mining district of western Nevada. On the basis of similar fault trends and related directions of tilting, Proffett suggested a continuum of deformation between this extreme extension on listric faults exposed in the range and faults bounding the modern range. A sharp angular discordance of tilts at *ca.* 11 Ma was attributed to a decrease in the rate of extension at that time. Relating the observed extension in the Yerington district to anomalously thin crust generally found along the east and west margins of the Great Basin, and citing other examples of extreme extension exposed in range blocks along the margins, Proffett used regional crustal thickness variations to estimate crustal extension of 35–100% in the western and eastern parts of the N.B.R. and 10–15% in the central part.

While generally accepting a relation between crustal thickness and total extension, we report below on data that indicate that the major part of the total extension, in at least some regions of the Basin and Range province, preceded the extensional event responsible for the modern physiography (see Elston & Bornhorst 1979). Thus, discrepancies between conservative extension estimates summarized above and estimates of total Cainozoic extension in the Basin and Range province of 100–300% (Hamilton & Myers (1966) and Hamilton (1975); based on Mesozoic palinspastic reconstructions) may arise from pre-basin–range extension, which locally was as much as 70–100%, as discussed below.

Pre-basin–range extension

In many parts of the Basin and Range province there is geological evidence of pre-basin–range extensional events. Differences in structural style and associated magmatism distinguish this early extension from the last *ca.* 7–13 Ma of basin–range extension described above. In addition, there is geological evidence that stress orientations were different during the earlier extension from what they were during most of basin–range faulting. Evidence for pre-basin–range extension is summarized in table 1 and is discussed below. Extensional tectonism followed a long period of compressional deformation and was initiated during a major change in subduction geometry beneath the western United States as inferred from spatial and temporal magmatic patterns. Regional plate tectonic and magmatic patterns in the period preceding the initiation of extensional deformation are first reviewed briefly below.

Final pulse of arc-related compressional tectonism

Throughout late Palaeozoic and Mesozoic time the western U.S. was subjected to several arc-related compressional orogenies, culminating in the development of the Sevier Mesozoic fold and thrust belt along the entire length of the Cordillera (figure 5). A subparallel batholithic belt including the Sierra Nevada probably represented the Mesozoic island arc. About 80 Ma ago, apparently due to a change in plate motions, magmatism ceased abruptly along nearly the entire length of the batholithic belt in the western U.S. (Coney 1976; Armstrong 1974). Compressional deformation (Laramide and Sevier) continued throughout late Cretaceous and early Tertiary time (*ca.* 80–40 Ma) throughout much of the region from Canada into Arizona (Armstrong 1968; Coney 1976, 1978; Davis 1980). This final episode of compressional tectonism included a new style of deformation (classic Laramide orogeny) (Coney 1976, 1978) which affected the cratonic region well inland of the fold and thrust belt and resulted in large basement uplifts bounded by thrust faults resulting from NE–SW to ENE–WSW compression (Grose 1972; Tweto 1975; Davis 1978, 1980). For the most part, calc-alkaline magmatic activity ceased along the batholithic belt and throughout the region west of the Laramide belt (Lipman *et al.* 1972; Coney 1972, 1976; Armstrong 1974; Snyder *et al.* 1976). Both the far inland extent of compressional deformation (extending 1200–1500 km inland) and this gap

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AN INTERPRETATION OF PRE-BASIN–RANGE EXTENSION

locality or region (numbers keyed on figure 7)	evidence	period or age/Ma	references
	igneous terrains		
1. northern trough, central Nevada	inferred passively emplaced batholith beneath fault-rotated cogenetic volcanic rocks	early Oligocene	Gilluly & Masursky (1965), Burke & McKee (1979)
2. southern trough, central Nevada	inferred passively emplaced batholith beneath fault-rotated cogenetic volcanic rocks	30–22	Riehle *et al.* (1972), Vitaliano & Vitaliano (1972), Burke & McKee (1979), Ekren *et al.* 1974, 1976
3. northern Nye County, Nevada	inferred passively emplaced batholith beneath fault-rotated cogenetic volcanic rocks	30–25	Ekren *et al.* (1974, 1976)
4. central Nye County, Nevada	fault-rotated volcanic strata and widespread passively emplaced coeval plutons	24–15	Ekren *et al.* (1971), Anderson (1978)
5. southern Nye County, Nevada	form and internal structure of caldera; extensional faulting southwest of caldera	11	Cornwall & Kleinhampl (1964), Byers *et al.* (1976*a*, *b*)
6. Lincoln County, Nevada	fault styles and trends internal to mountain ranges	28–10	Ekren *et al.* (1977)
7. Eldorado Mts, Nevada	unconformities and fault kinematics	15–11	Anderson (1971), Anderson *et al.* (1972)
8. southwestern Utah	unconformities and fault kinematics	20–10(?)	R. E. Anderson, unpublished data
9. Needles Range, Utah	fault-rotated volcanic strata and cogenetic shallow intrusive masses	Oligocene	Conrad (1969), Best (1976), Grant (1979)
10. east Tintic Mts, Utah	extensional faulting and intrusion during volcanism	39–31	Morris & Anderson (1962), Morris & Mogensen (1978)
11. Oquirrh Mts, Utah	shape of hypabyssal extensions from buried batholith	Eocene–early Oligocene	Moore (1973)
12. Picacho Peak, Arizona	early fault-related strata tilting	20–15	Shafiqullah *et al.* (1976)
13. southeastern Arizona	inferred tectonic régime of mid-Tertiary batholith	mid-Tertiary	Banks (1977), Creasey *et al.* (1977)
14. southwestern New Mexico	cauldron shapes, fault-related stratal tilting, passive emplacement of subvolcanic batholith	40–20	Chapin & Seager (1975), Seager (1975), Elston (1976), Elston & Bornhorst (1979), Chamberlin (1978)
15. Vulture Mtns, Arizona	fault-related stratal tilting accompanying volcanism	18–16	Rehrig *et al.* (1980)
	sedimentary and mixed sedimentary–volcanic terrains		
16. Elko, Nevada	post-faulting unconformities	early Oligocene	Solomon *et al.* (1979)
17. west-central Nevada	faulting accompanying sedimentation	12.5–8	Gilbert & Reynolds (1973)
18. east-central Nevada	faulting penecontemporaneous with sedimentation	late Cretaceous(?) to early Oligocene	Fouch (1979), Newman (1979)
19. northwest of Las Vegas, Nevada	fault trends and styles and inferred age (no known igneous activity)	possibly late Tertiary	Longwell (1945) (age reinterpreted)
20. east of Las Vegas, Nevada	faulting accompanying sedimentation	Miocene	Anderson (1973), Bohannon (personal communication, 1980)
21. central–western Utah	faulting accompanying sedimentation	Oligocene and Miocene	Anderson (1980 and unpublished data)
22. Thomas Range	fault-related sedimentation and stratal tilting	late Eocene(?) and Miocene	Lindsey (1979*a*, *b*), R. E. Anderson (unpublished data)
23. western Arizona	fault-related sedimentation, strata rotation, unconformities	28(?)–17(?)	Eberly & Stanley (1978), Shafiqullah *et al.* (1980)
24. southeasternmost California	palaeotopography and distribution of fault-related sediments	Oligocene	Crowe (1978)

in calc-alkaline magmatic activity have been attributed to the effects of continued, but very low-angle, subduction along the western plate boundary (see, for example, Coney 1976; Coney & Reynolds 1977; Dickinson & Snyder 1978; Cross & Pilger 1978; Lipman 1980) drawing from the modern analogy of effects above the shallowly dipping segments of the Andean Benioff zone (Stauder 1975).

Support for the shallow slab model comes from a spatial and temporal analysis of K–Ar dating of calc-alkaline magmatism across the S.B.R., where magmatic activity did not cease entirely but is seen to have swept rapidly eastward during Laramide deformation. Coney & Reynolds (1977) have interpreted these data in terms of a subducting slab of variable dip by

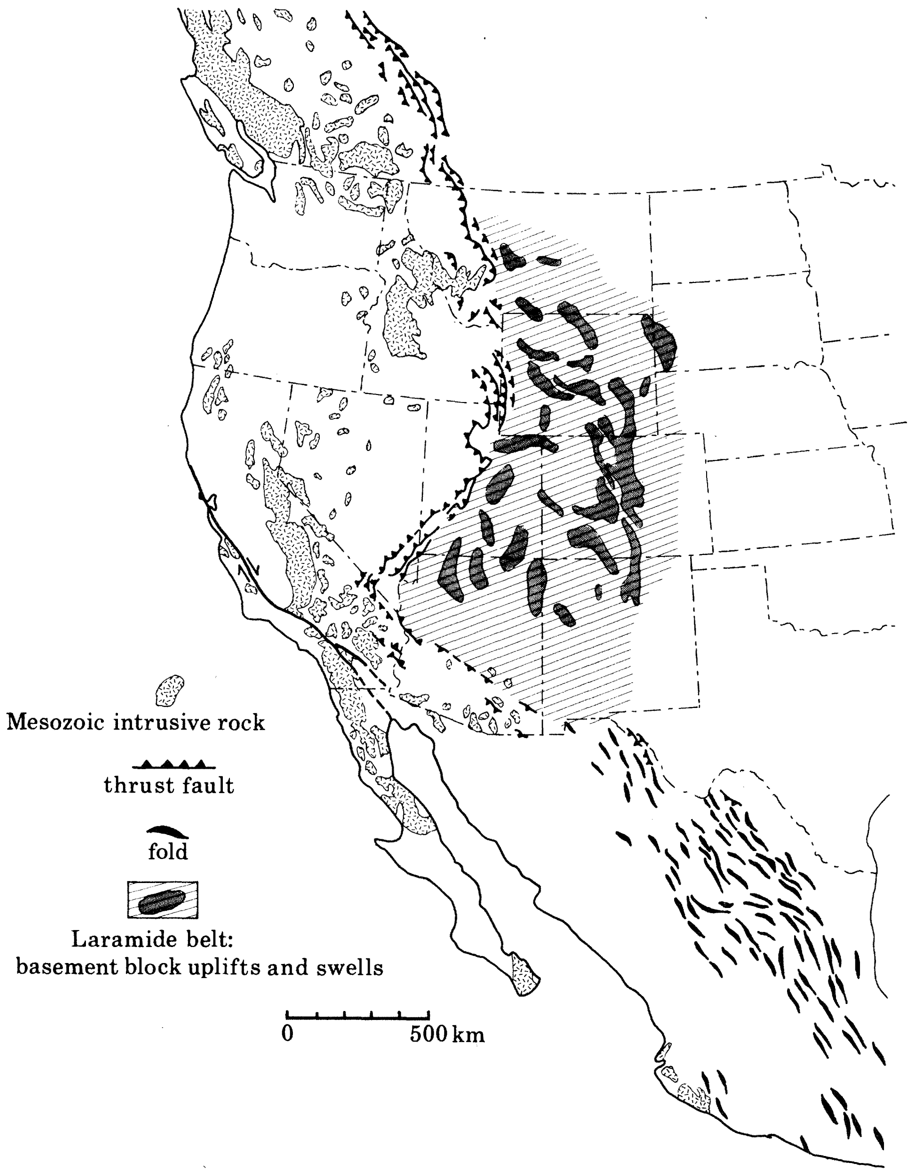

Figure 5. Mesozoic intrusive rocks and late Mesozoic and earliest Cainozoic deformational belts in western North America. Thrust faults are both Sevier and Laramide in age. The batholithic belt probably represents the roots of a calc-alkaline magmatic arc. Modified from Stewart (1978).

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fixing the magma-producing zone at 150 km depth. They infer a minimum dip of *ca.* 10° for the subducting slab at 40 Ma and attribute the shallow slab to rapid overriding by the North American plate, accompanying a high rate of convergence. Dickinson & Snyder (1978) accept this shallow subduction model and attribute the far-inland Laramide deformation to mechanical effects on the overriding plate of the overlapped underlying plate; that is, a régime in which the subducted plate scrapes horizontally beneath the surficial plate. Regional NE–SW compression inferred from the structures produced during late Cretaceous – early Tertiary deformation (see, for example, Davis 1978, 1980) is consistent with reconstructions indicating a rapid NE-trending convergence between the North American and Farallon plates (Coney 1978; Cross & Pilger 1978). This convergence was probably very nearly perpendicular to the trench at 80 Ma as inferred from the northwest trend of the youngest batholiths within the Sierra Nevada belt (Evernden & Kistler 1970).

Magmatic setting for early extension

Between 40 and 50 Ma ago, compressional tectonism came to an end probably as a result of a major worldwide reorganization of plate motions as evidenced in the Pacific plate by the 40 Ma bend in the Hawaiian–Emperor seamount chain (Coney 1972, 1978). The igneous history of the western U.S. from mid-Eocene to Miocene is summarized in figure 6*a*. As can be seen, there is a generally west to southwest 'return sweep' of calc-alkaline volcanism filling the magmatic Laramide gap. This return sweep of calc-alkaline magmatic activity was an intense period of volcanism variously referred to as the 'ignimbrite flare-up' (Lipman *et al.* 1972; Noble 1972) and the 'mid-Tertiary orogeny' (Damon 1964). As discussed below much of the extensional tectonism occurred concurrently with calc-alkaline magmatism, hence the tectonism may be considered 'intra-arc' deformation analogous to the initial or 'arc-splitting' stage of back-arc spreading as envisaged by Karig (1971).

Some time between 20 and 30 Ma ago the Farallon–Pacific ridge, which had been producing the subducting plate, collided with the trench, and relative motions were such that the San Andreas transform began to develop (Atwater 1970; Atwater & Molnar 1973). By about 20 Ma, calc-alkaline magmatism in the S.B.R. was replaced by basaltic volcanism, and a fairly well developed calc-alkaline magmatic arc had formed along the western edge of the N.B.R. (figure 6*b*). The southern extent of this arc was controlled by the location of the Mendocino triple junction. Hence the arc shortened as the San Andreas transform lengthened. Thus the widespread initiation of basaltic volcanism throughout the N.B.R. at about 17 Ma and in the S.B.R. some time between 20 and 30 Ma (often cited as the initiation of extension) took place in a back-arc setting in the N.B.R. and a back-transform setting in the S.B.R. (Eaton 1979*a*). As discussed earlier, much of the modern Basin and Range physiography did not develop until after 10 Ma, whereas evidence discussed below indicates that extensional tectonism began throughout the province long before the initiation of basaltic volcanism.

Evidence of early extension

We have reviewed published and new unpublished evidence for early extensional tectonics in the Basin and Range province. The data are summarized in table 1 from areas whose locations are indicated in figure 7. A detailed site-by-site description of the geological evidence for extension is part of a manuscript in preparation.

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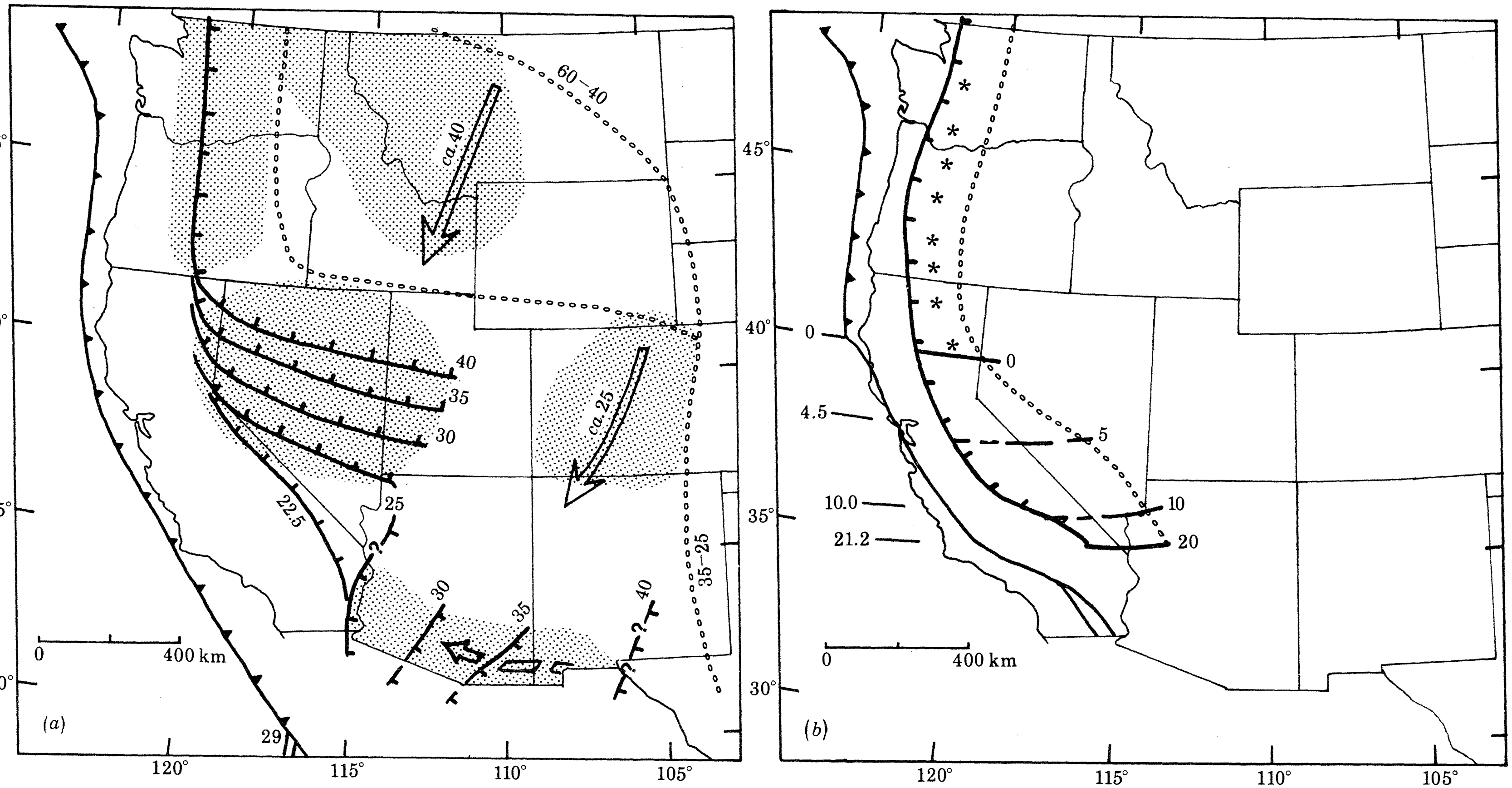

FIGURE 6. Cainozoic migration of calc-alkaline magmatism, after Snyder *et al.* (1976) and Dickinson & Snyder (1978). Hachured lines represent the westernmost extent of calc-alkaline magmatism, small circles represent the easternmost extent. (*a*) Middle Tertiary time (*ca.* 40–20 Ma); numbers indicate dates in megayears. Shaded areas represent magmatic loci defined by Snyder *et al.* (1976). The transform boundary was initiated in this time interval, probably about 29 Ma when the ridge (double line at bottom of figure) first intersected the trench off Baja, California. (*b*) Late Cainozoic time (*ca.* 20–0 Ma). Numbers offshore indicate (in megayears) the northward migration of triple junction (after Atwater & Molnar 1973). Numbers inland indicate (in megayears) the southernmost extent of calc-alkaline magmatism (after Snyder *et al.* 1976). Asterisks represent volcanoes of the Cascade volcanic chain, the modern andesitic 'arc'.

The most widespread evidence for early extension in the Basin and Range province is seen in well exposed uplifted range blocks that are composed of strata that are cut by, and tilted on, normal- or oblique-slip faults that predate uplift of the ranges. Proof that the range uplift is younger is seen in the truncation of old faults with distinct trends by young range-bounding faults with different trends or in strata related to the basin–range event deposited unconformably on older faulted and tilted strata. In some parts of the province these geological relations

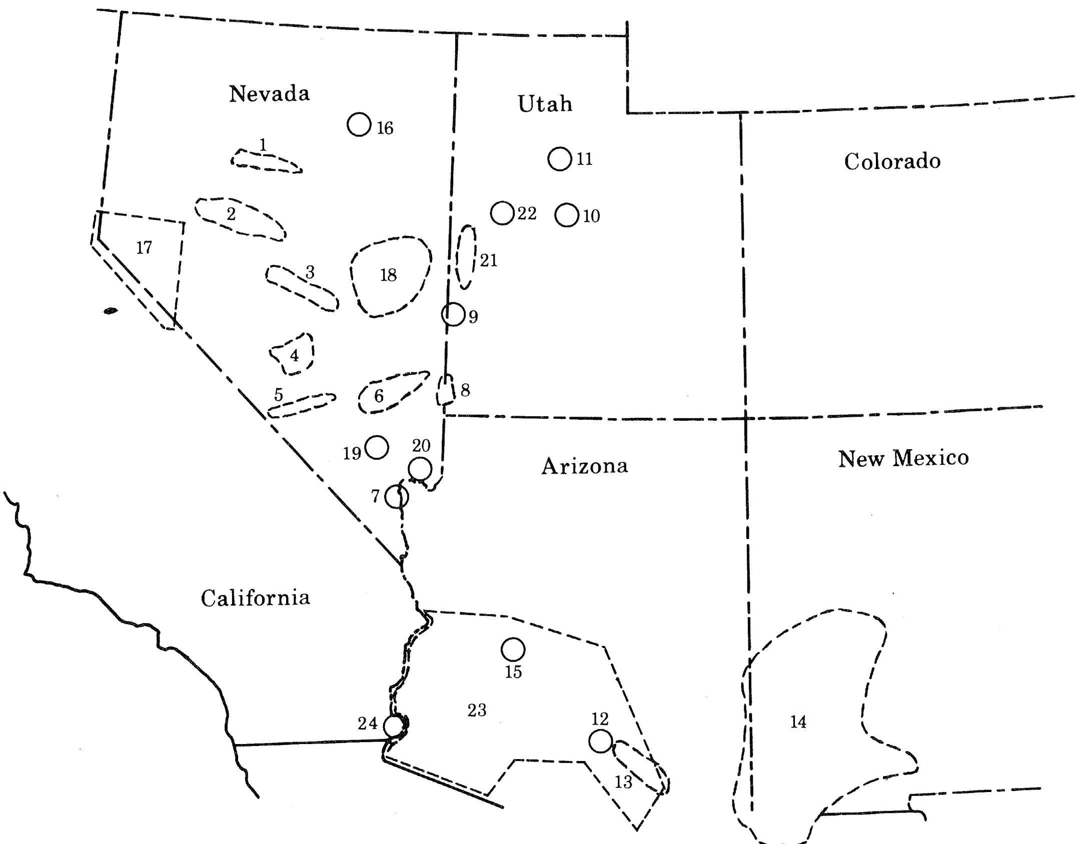

FIGURE 7. Localities where early extensional tectonism (pre-basin–range faulting) can be identified or inferred. Numbers refer to entries in table 1; solid circles represent localities and broken outlines represent regions.

exposed in the ranges are supported by gravitational, seismic and drill-hole data from the adjacent basins. Over areas of thousands of square kilometres the faulting and stratal tilting are closely associated with coeval volcanic eruptions of calc-alkaline composition. In many of these areas the volcanic rocks are homoclinally tilted on cogenetic systems of normal and transverse faults that combine to resemble growth faults. We interpret such structures as indicative of extension during the development of major calc-alkaline volcanic fields of Cainozoic age.

The magnitude of stratal offset and tilting on the early structures varies greatly. In numerous well studied areas the early event accounts for extension of much greater magnitude than the basin–range faulting event, as evidenced by early rotations to steep angles (locally overturned) on cogenetic systems of listric, transverse and detachment faults (see, for example, Anderson 1971, 1980; Chamberlin 1978).

Evidence for early extension also comes from preferentially orientated middle to late Cainozoic dyke swarms. Also, field, petrological, geochemical, isotopic and gravitational data combine to suggest that major Cainozoic calc-alkaline volcanic fields of western North America are underlain by steep-walled, passively emplaced subvolcanic batholiths (Lipman *et al.* 1978; Elston & Bornhorst 1979). As Elston (1976, p. 98) noted, estimates of total extension in the Basin and Range province must include that associated with such plutons that probably exist beneath cauldron complexes. He estimated that as much as one-third of southwestern New Mexico is underlain by such plutons, and we estimate that a similar proportion of central Nevada is also thus underlain.

In sedimentary and mixed sedimentary–volcanic terrains, evidence for early extension comes from the thickness and distribution of stratigraphic units as well as from the existence of coarse clastic strata within the sedimentary section. Stratal tilts of these units often indicate subsequent extensional deformation, suggesting, at least locally, several phases of extensional tectonism pre-dating the development of basin–range structure.

Additional evidence of early extension, though controversial, is found in areas where structures commonly referred to as metamorphic core complexes occur. It has been suggested that these terrains form a semi-continuous belt along the western Cordillera, from southern Canada to northwestern Mexico (Davis & Coney 1979). Typical elements of the 'core complexes' include (1) lineated mylonitic gneisses and related rocks forming the core, (2) uplifts (often domal) in which these mylonitic 'core' rocks are exposed, and (3) low-angle detachment faults that flank the terrains.

Currently the origin of the 'core complexes' is a subject of controversy and debate. Some workers (Davis & Coney 1979; Eaton 1980; Rehrig & Reynolds 1980) have suggested a genetic relation between the mylonitization of the crystalline rocks and the higher level detachment (décollement) faulting resulting from profound regional extension. Evidence for the genetic interpretation includes the association of Lower to middle Tertiary granitic plutons with some of the complexes and the similar orientations of mylonitic lineations and slip directions of low-angle detachment faulting in places involving rocks as young as Miocene (Reynolds 1980). In this view, supra-crustal extension by detachment faulting is believed to be a response to deeper, more ductile extension by mylonitic flow and intense intrusive activity. The doming (a result of megaboudinage (Davis & Coney 1979) or differential isostatic uplift (Rehrig & Reynolds 1980)) aids in detachment faulting by attenuation of units over the crest of developing domes and/or by producing slopes down which allochthonous units can move.

Evidence from perhaps the best dated 'metamorphic core complex' terrain, the Whipple–Bucksin–Rawhide Mountains, southeastern California and western Arizona, disputes a genetic relation between mylonitization, detachment faulting and doming. There, Miocene (*ca.* 26–17 Ma) detachment faulting crosscuts the more steeply dipping mylonitic front and has been demonstrated, through stratigraphic and radiometric evidence, to postdate significantly the mylonitization event (which probably occurred some time between 70 and 50 Ma (Davis *et al.* 1979; Shackelford 1980)). In addition, the Miocene extension of upper-plate units appears to have been unaccompanied by regional and coeval extensional phenomena in the crystalline rocks of the lower plate and hence has been interpreted as gravity sliding on a regional scale. In this region, doming appears to be a temporally, spatially and kinematically separate event that *post*dates both the earlier mylonitization and younger detachment faulting.

Confusion is added to the core complex problem by the recognition that many of the complexes (particularly those north of the Snake River Plain) are structural domes that contain high-grade metamorphic or migmatic rocks formed during a Jurassic–Cretaceous compressional regional metamorphism and deformational event (DeWitt 1980). Many of these terrains show no evidence for any kind of Tertiary deformation. It is likely, however, (and has been suggested independently by several different authors, Bally *et al.* (1966), Armstrong (1972, 1968) and Royse *et al.* (1975)) that basal detachment surfaces accommodating extension by listric faulting are inherited from décollement surfaces (thrust soles) developed during this earlier compressional régime.

Age of early extension

Available evidence does not permit determination of a unique age for the onset of extensional tectonism throughout the Basin and Range province. In fact, the data suggest that extension started in different places at different times. The pre-basin–range extensional events summarized in table 1 range from early Tertiary to about 10 Ma ago. The youngest examples represent deformation that immediately precedes basin–range faulting. Also, the ages summarized in table 1 represent the oldest *recognized* extensional event at each locality, not the oldest *possible* extensional event. In areas where chronological evidence for a pre-basin–range extensional event exists, there is generally a measurable span of geological time between that event and the youngest locally or regionally established age of prior compressional tectonics. In any particular area it is very difficult to establish the time of inception of extension because the details of early structures are commonly modified or greatly blurred by erosion or the overprint of young structures, or are buried by strata related to the young deformation. It is generally equally difficult to date accurately the last episode of compression.

Mechanics of early extension

Processes and mechanisms responsible for early extension remain ambiguous, as subsequent deformation has left detailed evidence of this extension available only locally. However, the available data suggest several fundamental factors that must be incorporated into models for crustal extension: (1) emplacement of steep-walled plutonic bodies, (2) supra-crustal extension by listric faulting over the plutonic bodies, (3) development of and tectonic denudation off structural domes, (4) major gravity sliding, possibly toward basins created by contemporaneous major high-angle normal faults.

State of stress between 20 and 10 Ma ago

Miocene deformation in the period *ca.* 20–10 Ma appears characterized by a fairly uniform WSW–ENE least principal stress orientation, as inferred from the trend of dyke swarms, the orientation of uniform fault slip vectors, and the direction of stratal tilt of rocks involved in extensional deformation (figure 8; table 2; see also Eaton 1979*a*). The data include dyke trends along a 300 km NNW-trending rift zone in northern Nevada, the trend of the graben of the western Snake River Plain, and directions of feeder dykes for the Columbia River Basalt Group – all features that formed contemporaneously, approximately 14–17 Ma ago (Christiansen & McKee 1978; Zoback & Thompson 1978).

The most striking features of this Miocene stress field are its apparent uniformity throughout the entire western United States and its apparent continuation inland almost to the Rocky Mountain front. While, during Miocene time, most of this region was in a back-arc setting (see figure 8), the San Andreas transform had already begun to develop. Much of the S.B.R. was therefore in a back-transform setting; despite this, the uniformity of stress field persists. The generally WSW–ENE least principal stress direction is perpendicular to the inferred NNW trend of the trench. This WSW–ENE extension represents a fundamental reversal from earlier compression (late Cretaceous – early Tertiary time) to extension in the same direction.

Table 2. Miocene least principal stress orientations inferred from dyke trends

number	location	least principal stress orientation	period or age/Ma	References
1.	Oatman 35.07° N, 114.37° W	N 40° E	Miocene?	Ransome (1923), Rehrig & Heidrick (1976)
2.	Castaneda Hills 34.42° N, 113.92° W	N 40° E	12–15	I. Lucchitta (personal communication, 1979)
3.	Vulture Mountains 33.8° N, 112.9° W	N 85° E	15.3–17.8	Rehrig & Heidrick (1976)
4.	Castle Dome 33.1° N, 114.1° W	N 55° E	Miocene?	Rehrig & Heidrick (1976)
5.	Ajo 32.47° N, 112.75° W	N 50° E	Miocene	Gilluly (1946), Luedke & Smith (1978*a*)
6.	Mineral Mountain 33.1° N, 111.2° W	N 65° E	Miocene	Rehrig & Heidrick (1976)
7.	Klondyke 32.9° N, 110.35° W	N 75° E	latest Oligocene or Miocene	Rehrig & Heidrick (1976)
8.	Silver Bell 32.4° N, 111.6° W	N 75° E	24?	Rehrig & Heidrick (1976)
9.	Papago Indian Res. 32.2° N, 111.38° W	N 72° E	9.7	Keith (1976)
10.	Oro Blanco 31.5° N, 111.4° W	N 55° E	Miocene?	Rehrig & Heidrick (1976)
11.	Knight Peak 32.37° N, 108.33° W	N 46° E	10–16+	Ballman (1960), Luedke & Smith (1978*a*)
12.	Cedar Grove Mountains 31.95° N, 108.05° W	N 35° E	10–16+	Bromfield & Wrucke (1961), Luedke & Smith (1978*a*)
13.	Truth or Consequences 33.08° N, 107.15° W	N 41° E	Miocene?	Kelley & Silver (1952)
14.	Magdalena 34.37° N, 107.37° W	N 80° E	Miocene? > 9	Tonking (1957), Jicha (1958)
15.	Socorro–Catron Co. 34.33° N, 108.08° W	N 60° E	Miocene? > 9	Willard (1957), Willard & Givens (1958)
16.	Spanish Peaks 37.62° N, 104.88° W	N 8° W	22–25	Muller & Pollard (1977), Stormer (1972)
17.	Telluride 37.71° N, 107.89° W	N 60° E	16.2	Steven *et al.* (1974)
18.	N of Glenwood Springs 39.9° N, 107.25° W	N 40° E	13.4	Bass & Northrop (1963), Luedke & Smith (1978*b*)
19.	S of Steamboat Springs 40.2° N, 106.95° W	N 40° E	8	Larson *et al.* (1975), Luedke & Smith (1978*b*)
20.	Northern Routt Co. 40.8° N, 107.1° W	N 40° E	8.1–11.5	Buffler (1967), Luedke & Smith (1978*b*)

Marked regional angular unconformities in the S.B.R. revealed by drilling, stratigraphic and seismic reflexion studies (Eberly & Stanley 1978; Shaffiqullah *et al.* 1980) developed at about 13 Ma and have been interpreted as marking the initiation of a major event of block-style, graben-forming faulting. This block-faulting event continued to at least 10 and possibly 6.5 Ma (see earlier discussion of onset of basin–range structure). The bulk of the deformation, however, is believed to have occurred in the period 13–10 Ma in the S.B.R. (Eberly & Stanley

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1978). Thus, the general NW-trending structural grain in the S.B.R. probably developed largely under the widespread, consistently orientated 20–10 Ma Miocene stress field.

Clockwise change in stress orientation

Comparison of the Miocene least principal stress orientation before 10 Ma with the modern one indicates a clockwise change of roughly 45° since that time (figure 9) (Zoback & Thompson 1978; Eaton *et al.* 1978; Eaton 1979*a*, *b*). The rose diagram of range trends in the S.B.R. and

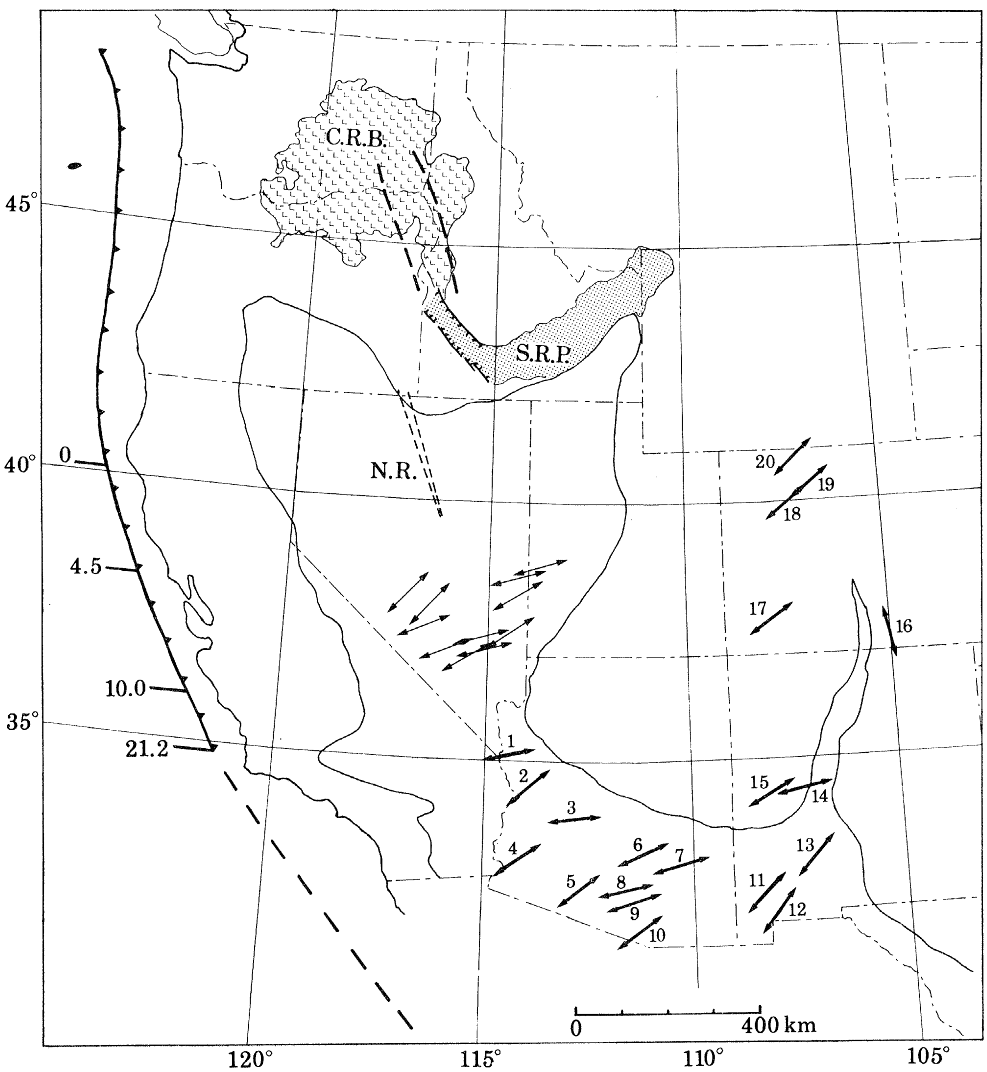

Figure 8. Miocene (*ca.* 20–10 Ma) extensional tectonism. The NNW-trending zone of rifting in the north includes a broad zone of feeder dyke swarms (heavy broken lines) for the Columbia River basalts (C.R.B.), western graben of the Snake River Plain (S.R.P.), and the Nevada rift (N.R.) (short broken lines). The modern Basin and Range and Rio Grande rift province is outlined. Light arrows in southern Nevada are Miocene extension directions inferred from fault trends and stratal tilts within ranges (from Anderson and Ekren, 1977). Heavy arrows are Miocene least principal stress directions inferred from dyke trends. Small numbers refer to table 2. Numbers along subduction zone (barbed line) show the southern extent of subduction (in megayears; see figure 6*b*). Broken lines offshore indicate the probable trend of subduction zone now replaced by the transform fault.

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N.B.R. (figure 2*b*) suggests development of the S.B.R. under a stress field similar to that in the Miocene and development of basin–range structure in the N.B.R. under a stress field comparable with the modern one. Available data on the timing of development of basin–range structure discussed above (*ca.* 13–10 Ma in the S.B.R., after 10 Ma in the N.B.R.) suggest that this clockwise change in stress orientation occurred in late Miocene time at about 10 Ma.

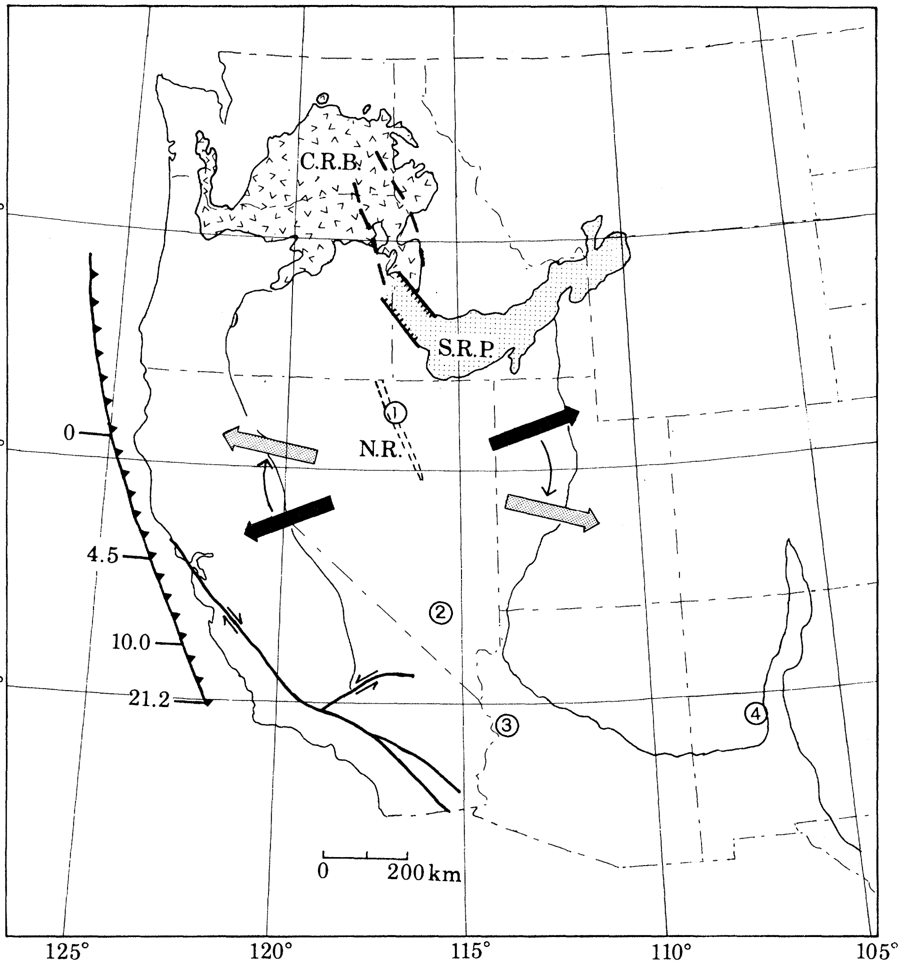

FIGURE 9. Clockwise change in least principal stress direction *ca.* 10 Ma ago in the Basin and Range province. Lightly stippled arrows indicate the modern direction. Circled numbers refer to localities mentioned in text where change in stress orientation can be documented locally. All other symbols as in figure 8.

In addition to the differences in range trend, detailed studies in numerous areas support this clockwise change in stress orientation and help to constrain its timing. The previously mentioned NNW-trending rift that formed 14–17 Ma ago in north-central Nevada (figure 9, site 1) has been segmented subsequently by prominent ENE-trending range-front faults; these nearly orthogonal ENE-trending faults now have large components of vertical offset across them (greater than 3–4 km in places) (Zoback & Thompson 1978; Zoback 1979*b*). This ENE direction represented a transform direction in Miocene time, and the present major vertical offset and extension along this ENE trend required a clockwise change of the least principal stress orientation. This change can be dated as before 6 Ma (age of a basalt flow which flowed down a graben valley) and after 14 Ma (age of the youngest flows capping the surrounding ranges) (Zoback & Thompson 1978).

In southern Nevada and southwestern Utah (figure 9, site 2), Anderson & Ekren (1977) describe regional evidence for a clockwise change in least principal stress orientation based on major extensional deformation now exposed within the modern ranges, a deformation that occurred on faults having generally NNW trends. The modern ranges in this region (which developed largely after 10 Ma) were blocked out along N to NNE trends.

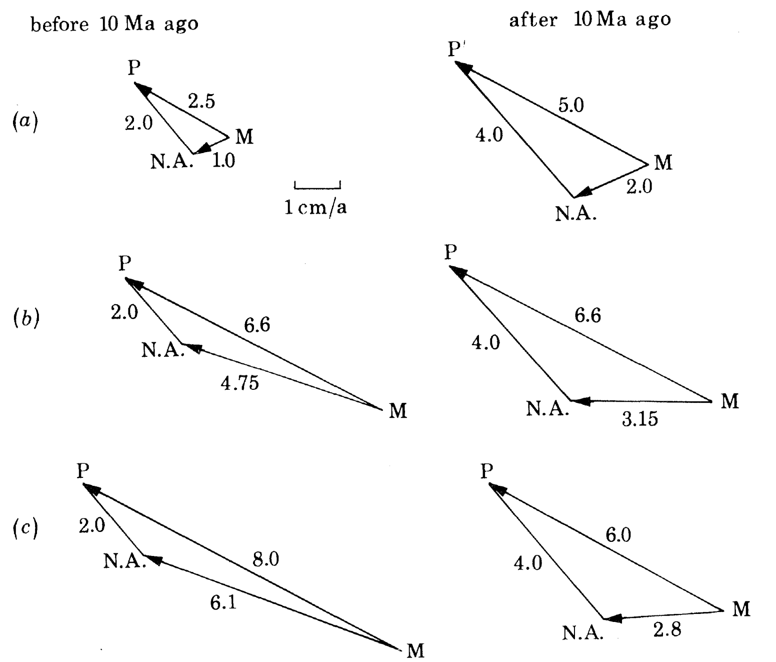

FIGURE 10. Possible velocity triangles capable of producing a *ca.* 10 Ma change in rate of relative motion between the Pacific (P) and North American (N.A.) plate along the San Andreas fault (fixed azimuth N 40° W). Plates identified at heads of vectors. Pacific–mantle (M) motion inferred from the Hawaiian seamount chain (Clague & Jarrard 1973; Minster & Jordan 1978). (*a*) Trivial case: absolute velocity azimuths for Pacific and North American plate remain constant, thus all rates must double. (*b*) Pacific absolute velocity (azimuth and rate) remains constant; North American absolute motion slows and changes direction. (*c*) Pacific absolute velocity is reduced; North American absolute velocity also reduced and changes direction.

In the S.B.R. region, studies in the Castaneda Hills in western Arizona (figure 9, site 3) reveal a contrast between NW to NNW-trending rhyolite dykes and similarly trending listric faults and younger NNE-trending basaltic dykes; these features indicate that the clockwise change occurred between 14 and 7 Ma ago (I. Lucchitta, personal communication, 1979). Evidence for the stress change can also be found along the western margin of the Rio Grande rift, in the Puertecito area (figure 9, site 4), where mid-Miocene (*ca.* 15 Ma) NNW-trending basaltic dykes were being intruded while nearly parallel normal faults were developing (Tonking 1957; Jicha 1958). The dykes and faults both track a broad regional 5–10° variation in trend, possibly reflecting a regional variation in least principal stress orientations. Currently these faults exhibit oblique-normal slip with a component of right-lateral offset consistent with a clockwise change of the least principal stress orientation. Here the change is only constrained to be after mid-Miocene.

In summary, the evidence suggests a clockwise change in least principal stress orientation that occurred at approximately 10 Ma, possibly nearly synchronously over a broad region. Such a clockwise change is mechanically consistent with the superposition of right-lateral shear on the Miocene 'back-arc' stress field. As the San Andreas transform had begun to form well before the change in stress orientation (sometime between 20 and 30 Ma) this stress change may indicate when significant coupling had developed between the Pacific and North American plates. Interestingly, plate reconstructions suggest a very low rate of relative motion between the Pacific and North American plates initially, with a marked acceleration at about 10 Ma (Atwater & Molnar 1973).

The geometry of relative motion vectors can constrain models to explain this acceleration of Pacific–North American motion at about 10 Ma (figure 10). Several scenarios are possible. If the azimuth of velocity of the Pacific Plate remains fixed as indicated by the Hawaiian 'hot spot' then both a doubling (from 2.5 to 5.0 cm/a) of Pacific plate absolute velocity and an increase in North American absolute velocity (actually also a doubling in speed if North American azimuth stays fixed) are required (figure 10*a*). A major increase in Pacific plate absolute motion has been suggested on the basis of K–Ar dating along the seamount chain; however, this increase is believed to have occurred between 20 and 25 Ma ago (Clague & Jarrard 1973). Thus, if Pacific plate velocity (azimuth and rate) has remained constant (6.6 cm/a) over the last 20 Ma, the acceleration requires the North American plate to *slow down* and move in a more westerly direction (as opposed to a northwesterly direction before 10 Ma) (figure 10*b*). Currently the North American plate moves in west-southwesterly direction (Minster & Jordan 1978); this would therefore require a clockwise change in the azimuth of absolute motion of North America in the last 10 Ma. Systematic northeast migration of silicic volcanism along the Snake River Plain after 10 Ma ago has been cited as a possible hot-spot trace defining absolute motion of North America (see Morgan 1972; Suppe *et al.* 1975). Despite abundant volcanism near the older (southwest) end of the Snake River Plain, no systematic pattern of migration of volcanism before 10 Ma ago has been identified; there is therefore no basis for inferring absolute motion before 10 Ma ago. It should be noted, however, that interpretation of the Snake River Plain as a hot-spot trace ignores the existence of a symmetric and nearly synchronous counterpart of northwest-migrating silicic volcanism in Oregon (MacLeod *et al.* 1976). A third possibility, a decrease in the absolute velocity of the Pacific plate about 10 Ma suggested by data of Clague & Jarrard (1973, Fig. 5, p. 1144), is shown in figure 10*c*. As the detailed absolute velocity history of these plates remains unresolved, it is impossible to determine which of these effects may be responsible for the apparent change in rate at 10 Ma between the Pacific and North American plates.

Discussion

Cainozoic evolution of the stress field

Major changes in the regional stress field affecting the western United States have occurred in Cainozoic time, possibly concomitantly with inferred major changes in plate interaction along the plate boundary. A reversal from compression to extension in a similar direction occurred within a convergent plate setting.

Late Cretaceous – early Tertiary time was a period of wholesale shortening of the crust; in the western United States the compression direction was orientated between NE–SW and E–W.

Classic Laramide (late Cretaceous – early Tertiary) deformation reaching 1200–1500 km inland was largely non-magmatic and occurred behind a roughly NW-trending trench, probably during a period of rapid convergence and low angle subduction (Dickinson & Snyder 1978). As a modern analogue, non-magmatic 'back-arc compression' is currently observed along low-angle segments of the subducting Nazca plate beneath northern and central Peru (Stauder 1975).

The onset of extensional tectonism is difficult to date, but locally may have followed soon (less than 10 Ma) after the end of compressional tectonics (*ca.* 50–40 Ma ago). The subduction geometry during Eocene – early Miocene time (*ca.* 40–20 Ma ago) is obscure. The broad zone of calc-alkaline magmatism (in places more than 400 km wide) that filled the Laramide magmatic gap cannot be used as a basis for inferring the geometry of subduction. By about 20 Ma ago a well developed calc-alkaline magmatic arc had formed along the western margin of the N.B.R. Thus, the period 40–20 Ma ago represents a period of transition between low-angle subduction (possibly extending 1200 km inland with a dip of *ca.* 10°) to steep (*ca.* 40°) subduction after 20 Ma ago, and as Eaton (1979*b*) pointed out, this evolution from the low-angle *Chilean* to the steeper *Marianas* mode of subduction of the Farallon plate accompanied the change from a compressional to extensional state of stress. Early extensional tectonism described above was initiated within the broad magmatic arc (as inferred from associated calc-alkaline magmatism) probably around 30 Ma ago and hence may be considered convergence-related intra-arc extension (Eaton 1979*a*, *b*; Elston & Bornhorst 1979).

By early Miocene time (*ca.* 20 Ma ago) a uniform 'back-arc extensional' stress field had been established throughout most of the western United States. The least principal stress direction was WSW–ENE, approximately perpendicular to the trend of the trench, thus representing a reversal from convergence-related compression to convergence-related intra-arc and back-arc extension in the same direction after Laramide time. The San Andreas transform had begun to develop before 20 Ma ago, yet the Miocene stress pattern appears uniform both in the 'back-arc' and 'back-transform' setting.

At approximately 10 Ma, a 45° clockwise change in least principal stress orientation occurred. Most of the basin–range structure in the N.B.R. developed under this new stress field. The clockwise rotation is consistent with superposition of right-lateral shear along the western plate boundary related to an advanced stage of development of the San Andreas transform. Increased coupling of dextral shear probably triggered the change in stress orientations. This increased coupling may have resulted from one, or a combination, of the following effects: (1) elongation of the San Andreas transform to a 'critical' length (see Christiansen & McKee 1978), (2) an acceleration of relative motion between the Pacific and North American plates at approximately 10 Ma (Atwater & Molnar 1973), or (3) greater normal stress, hence increased friction along the San Andreas fault, possibly due to a small change in the pole of rotation. The WNW–ESE directed extension continues to the present time. Continued extensional tectonism in a back-transform setting may be related to development of a gradually growing slab-free region beneath that part of the continental block adjacent to the San Andreas transform while subduction continues north and south of the transform (Dickinson & Snyder 1975, 1979). Dickinson & Snyder attribute basin–range extensional tectonism and bimodal volcanism to the upwelling of hot asthenosphere replacing the volume of mantle formerly occupied by the subducted slab of lithosphere (see Stewart 1978; Best & Hamblin 1978).

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Comparison of styles: pre-basin–range and basin–range extension

The difference between modern basin–range extension and examples of earlier extension depend largely on the scale (thickness) of the zone of brittle deformation, the inferred strain rates and the associated magmatism. In the recognized areas of local great extension, large stratal tilts (commonly 30–70°, in places more than 90°) were apparently produced by shallow brittle deformation (probably the uppermost 5 km) on closely spaced (about 1 km) listric normal faults. Local topographic relief remained low (*ca.* 100–200 m?), because of the close fault spacing, but some areas of widespread sedimentation suggest broader basins, which may have been locally fault bounded. This early extensional tectonism occurred contemporaneously with calc-alkaline magmatism. In contrast, basin–range extension as defined herein is commonly associated with basaltic and bimodal basalt–rhyolite volcanism. The deformation results from block faulting that penetrates the upper 15 km (seismogenic) portion of the crust and produces elongate ranges with a characteristic spacing of 25–35 km. On average, gentle tilts (less than 15° and often less than 10°) are associated with the uplifted range blocks (Stewart 1980). Strain rates for basin–range deformation are in the range 1.8–2.7 %/Ma (20–30 % extension in approximately 10 Ma), whereas local strain rates for early extensional events have been reported as high as 12 %/Ma (107 % in *ca.* 6.5 Ma for early faulting in Yerington) (Proffett 1977), 19 % Ma (100 % in *ca.* 4 Ma) (Anderson 1971; Anderson *et al.* 1972) and 22 %/Ma (more than 50 % in 2 Ma) (Dokka 1979, and personal communication, 1980).

The contrast in depth penetration of faulting between pre-basin–range and basin–range extension is well demonstrated in regions where listric normal faults bounding highly tilted strata exposed in ranges are crosscut by range-bounding faults that differ in trend by as little as 15°. Development of the range-bounding faults at such a small angle to existing pervasive listric faulting clearly demonstrates that the earlier listric faults were unable to accommodate the strain related to basin–range extension and new, deeper penetrating (modern range-bounding) faults were required.

Major tear (strike-slip) faulting (e.g. along the Las Vegas shear zone (Longwell 1974) and the Lake Mead shear zone (Anderson 1973; Bohannon 1979)) accompanying earlier extension suggests localized large (50–100 %) extensional events possibly related to magmatic intrusions. Major pre-basin–range detachment faulting spatially associated with gneiss domes (so-called 'metamorphic core complexes') has also been correlated with significant thermal incursions in the crust; however, other examples of pre-basin–range detachment faulting (Whipple–Buckskin–Rawhide region) (Davis *et al.* 1979) clearly require a gravity sliding mechanism. Regional consistency of transport directions of detachment faulting and the orientation of dyke trends of associated volcanism indicate that the detachment faulting occurred in response to extensional tectonism controlled by a fairly uniform stress field.

The shallow level of early extensional deformation, the widespread occurrence of steep-walled caldera complexes, as well as the tremendous volumes of calc-alkaline magmatism characterizing pre-basin–range extension, suggest a thermal régime that contrasts with the modern one. Massive intrusion of the crust within a broad zone over a 10–20 Ma period beginning *ca.* 40 Ma ago probably resulted in an exceptionally hot and thermally weakened lithosphere. Major extension within the Basin and Range province may have occurred during this pre-basin–range extension period. The changeover to basin–range extension with faulting penetrating the upper

10–15 km of crust suggests an overall cooling of the crust facilitating tapping of subcrustal magma systems responsible for the associated basalt and bimodal basalt–rhyolite magmatism (see Elston & Bornhorst 1979; Rehrig *et al.* 1980).

As discussed above, much of the early extension took place in a stress field with the least principal stress orientated WSW–ENE. The changeover to basin–range structure with major block faulting in a seismogenic 'brittle' layer 10–15 km thick began in the S.B.R. about 13 Ma ago, probably in the WSW–ENE stress field. Development of the modern basin–range physiography in the N.B.R. took place after 10 Ma and, in places, after 7 Ma under a stress field similar to the modern one with a least principal stress orientated WNW–ESE. Hence, the clockwise change in stress orientation which probably occurred around 10 Ma ago does not coincide province-wide with the initiation of basin–range type faulting; however, sparse presently available data suggest that this clockwise change may be correlated with the end of the earlier style of extensional tectonism.

Exceptions to the general distinction of pre-basin–range and basin–range extension presented here have been reported. Chamberlin (1978) found evidence in the Lemitar Range in the Rio Grande rift that shallow thin-skin style deformation characterized by large tilts may recur after basin–range block faulting has been initiated. Such younger thin-skin deformation may possibly correspond to local shallow intrusive activity. In addition, Proffett (1977), in his previously mentioned study in the Yerington mining district in western Nevada, proposed a continuum of deformation between early extension (beginning *ca.* 18 Ma ago) producing large tilts exposed within the range and the main faults bounding the present range on the basis of similar fault trends and sense of tilts. A sharp angular discordance of tilts (at *ca.* 11 Ma) was attributed to a major decrease in strain rate. Recent mapping of J. H. Stewart (personal communication, 1980) in an area just southwest of Yerington suggests instead that progressive tilting during eruption of andesites (*ca.* 18–12 Ma ago) was followed by fluvial deposition over a surface of low relief (12–9 Ma) and initiation of block faulting (basin–range faulting) *ca.* 9 Ma ago.

Summary

Extensional tectonism in the western U.S. has affected a region of thermally weakened lithosphere inherited from a long history of subduction and magmatism. Early extension (beginning about 30 Ma ago) formed largely in an intra-arc and later back-arc setting and was directed perpendicular to the trend of the trench. Pre-basin–range extension (i.e. extension preceding the break-up of the region into ranges resembling the modern ones) is now recognized by thin skin style deformation characterized by highly tilted strata rotated on closely spaced listric normal faults currently exposed in uplifted range blocks, by large regions of the crust underlain by passively emplaced subvolcanic batholiths, and by the thickness and distribution of stratigraphic units. Data on preferentially orientated dyke swarms and fault slip vectors indicate a strikingly uniform WSW–ENE least principal stress orientation for the period *ca.* 20–10 Ma, during this early extension. Locally, high strain rates that accompanied extensions as great as 50–100% are implied.

Currently active extensional tectonism is part of the basin–range block faulting event responsible for the modern physiography. Basin–range extension is distinguished from early extension on the basis of angular unconformities, differences in fault trends and spacing, and associated magmatism. The change from early extension to basin–range style faulting was

time-transgressive and probably not abrupt; locally both types occurred concurrently. S.B.R. block faulting occurred largely in the period 13–10 Ma, in response to a stress field orientated similarly to that responsible for the early extension. In contrast, N.B.R. block faulting developed after 10 Ma and continues to the present in response to a stress field orientated approximately 45° clockwise to the earlier stress field. This modern stress field, with a WNW–ESE to E–W directed least principal stress, characterizes the entire Basin and Range province and Rio Grande rift region. The 45° change in least principal stress orientation is consistent with superposition of dextral shear associated with the development of the San Andreas transform.

Modern extension in the Basin and Range province occurs as brittle deformation in the upper 15 km of the crust and is probably matched by ductile deformation and/or magmatic intrusion at lower levels. This brittle deformation probably occurs on a complex hierarchy of faults including high-angle and listric faults, and produces gently tilted fault blocks. Total extension in the N.B.R. associated with the faulting event after 10 Ma has been estimated at 15–30%. Inclusion of pre-basin–range extension may help to resolve the discrepancy between these estimates and values of 100–300% suggested by Hamilton & Myers (1966), Hamilton (1975) and Proffett (1977) (see also Elston & Bornhorst 1979).

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