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Limited Extension During Peak Tertiary Volcanism, Great Basin of Nevada and Utah

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The relative timing and magnitude of middle Tertiary extension and volcanism in the Great Basin (northern Basin and Range province) of the western United States remain controversial. To constrain the timing, we present 31 stratigraphic sections from the central part of the province, together with data from other studies in the Great Basin. Especially significant in this record of regional paleogeographic and associated tectonic conditions are thick sections of many well-dated ash flow sheets emplaced during the period of the most voluminous, or peak, volcanic activity about 31–20 Ma. From these data we make the following conclusions: (1) Extension prior to the period of peak volcanism was apparently localized. (2) Extension during peak volcanism (the ignimbrite flareup) was minor and in places possibly related to magmatic processes in the shallow crust, rather than to regional tectonic processes. Angular unconformities and interbedded epiclastic deposits within sequences of volcanic rocks from 31 to about 22–20 Ma that would manifest synvolcanic faulting, tilting, and erosion are limited. (3) In the Great Basin as a whole, major extension and peak volcanism correlate poorly in space as well as time. (4) Essentially dip-slip faults cutting the entire conformable volcanic sequence are common in the Great Basin and indicate a widespread episode of extension after peak volcanism. Southward sweeping Tertiary volcanism in the Great Basin reflects migration of the mantle magma supply that powered crustal magma systems. We suspect this migration was related to progressive southward foundering and steepening of dip of a subducting oceanic plate (after an earliest Tertiary near-horizontal configuration beneath the continental lithosphere) and consequent backflow of asthenospheric mantle into the widening wedge between the plates. In the northern Great Basin, where the sweep was rapid, we postulate that relatively small volumes of mantle-derived magma were inserted as dikes into the lower, locally extending crust which was unusually warm because of Mesozoic compressional thickening; crustal magma systems so powered were repeatedly tapped to feed modest volume eruptions of chiefly intermediate composition lava and minor silicic ash flow tuff. As the sweep stagnated in the central southern Great Basin, copious volumes of mafic magma were inserted into the crust, apparently mostly as extensive horizontal sheets, or sills, in a nonextending, uplifting crust in a state of nearly isotropic horizontal stress. These sills and the high mantle power input optimized crustal magma generation, creating huge volumes of silicic magma that vented as large volume ash flows, chiefly about 31–20 Ma. After about 22–20 Ma, the volcanic-capped plateau collapsed in a widespread network of north striking extensional faults as plate boundary compressive forces were overcome by spreading forces within the uplift. Eruption of lava again became the dominant mode of volcanism.

INTRODUCTION

Because of its long history of plate subduction, magmatism, and tectonism during the Mesozoic and into the Tertiary, western North America continues to be a focus of much attention. The northern Basin and Range province of Nevada and western Utah, hereafter referred to as the Great Basin because of the nearly coextensive area of internal drainage (Figure 1), harbors widespread calc-alkaline rocks of intermediate to silicic composition capped locally by basaltic and rhyolitic rocks. For nearly two decades [e.g., *Christiansen and Lipman*, 1972; *Noble*, 1972] this compositional transition during the Miocene in the western United States has been attributed to a shift from convergent to a younger transform plate margin, with associated crustal extension inland.

The tectonomagmatic evolution of the Great Basin differs significantly from the southern Basin and Range province [*Glazner and Bartley*, 1990], an area not considered here.

Recently, some geologists have concluded that parts of the Great Basin experienced major extension prior to the Miocene and that ". . . major [volcanic] eruptions appear to be both temporally and spatially associated with large-magnitude extension" [*Gans*, 1987, p. 1] and ". . . the onset of extensional faulting at any given latitude in the Basin and Range generally coincided with, or immediately postdated, voluminous eruptions of intermediate to silicic volcanic rocks" [*Gans et al.* 1989, p. 45] (see also *Christiansen* [1989], *Gans and Mahood*, [1989], and *Zoback et al.* [1981]). The generalization of *Gans et al.* [1989] is based upon (1) detailed study of a 15,000 km^2 area in east central Nevada (Figure 1), where of the order of 250% extension occurred concurrently with and following eruption of about 1000 km^3 of dacitic lava and minor ash flow tuff, mostly 36–35 Ma, in the early Oligocene and (2) review of work by other geologists in seven other local areas within the Basin and Range (Figure 1) which are interpreted to support the concept of synextensional magmatism.

Gans [1987] and *Gans et al.* [1989] recognized that in the San Juan and Marysvale volcanic fields (Figure 1) and even within some areas of the Basin and Range province, voluminous volcanism did not accompany substantial crustal extension. Nonetheless, *Gans* [1987] concluded that all Tertiary volcanism in the western United States is fundamentally synextensional, because of a highly mobile and actively extending lower crust and mantle lithosphere; weak coupling with the lower crust allows areas of extreme upper crustal extension to be interspersed among areas that lack normal faults at the surface. This tectonomagmatic viewpoint constitutes some departure from the conventional concept of a subduction setting of little or no extension in which intermediate composition calc-alkaline magmas are generally considered to form [e.g., *Hildreth*, 1981, Figure 15] and therefore demands close scrutiny.

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In contrast to the model of synextensional magmatism and active rifting, *Taylor et al.* [1989, p. 7771] concluded that "There is a general lack of correlation between extensional periods and volcanism" in the southeastern Great Basin. They (see also *Bartley et al.* [1988]) examined an area of about 8000 km^2 in southeastern Nevada (Figure 1) and found crustal extension to be episodic during four periods of time, as follows: prevolcanic before 32 Ma, early synvolcanic 30–27 Ma, immediately postvolcanic about 16–14 Ma, and Pliocene to Quaternary. Although the timing and amount of extension are not accurately quantifiable with respect to the entire transect, extension occurred during each period in some part of it.

Because volcanic activity was time transgressive through the Great Basin [*Cook*, 1965; *Armstrong et al.*, 1969; *Stewart and Carlson*, 1976; *Best et al.*, 1989*b*], inadequate sampling of areas in space and time could yield misleading conclusions regarding the relative timing of volcanism and extension.

The purposes of this paper are (1) to present stratigraphic data for the Tertiary of a large part of the central Great Basin, in part encompassing areas of previous studies, (2) to use stratigraphic data to demonstrate that crustal extension was episodic, not continuous, during the Tertiary, as *Taylor et al.* [1989] found in part of the province, (3) to determine the relative timing of volcanism and extension and therefore the case for passive versus active rifting, and (4) to propose an alternative tectonomagmatic model for the Tertiary of the Great Basin.

OTHER PERTINENT PREVIOUS WORK

Three decades ago, *Mackin* [1960] first conceptualized the significance and utility of Tertiary volcanic rocks, particularly datable ash flow sheets that are widespread in both time and space, in elucidating the structural evolution of the Basin and Range province. *Mackin* [1960, p. 114] noted that ". . . they provide a key (a) to such problems as whether the block faulting has been episodic in a regional sense or random in distribution in space and time, (b) to the relationship of the block faulting to eruptive activity. . . ." The possibility of two or more episodes of normal faulting in some places and lack of such faulting in others was considered [*Mackin* [1960, p. 113].

Using only basic physical characteristics and without the benefit of radiometric ages, [*Cook*, 1965], a student of Mackin, correlated, named, and determined the distribution and volume of many ash flow sheets found in the area of Figure 5. In this pioneering effort, he constructed numerous stratigraphic columns, 13 of which are included here in updated form. *Cook* [1965, p. 55] recognized local prevolcanic faulting, suggested some accompanied volcanism, but wrestled with the cause and effect relation.

In a study of an area (Figure 1) near those investigated by *Gans et al.* [1989] and *Taylor et al.* [1989] but two decades earlier, *Moores et al.* [1968] concluded that limited normal faulting occurred during the period of maximum pyroclastic activity (37–25 Ma) but was followed by greater deformation during the Miocene and Pliocene(?).

McKee et al. [1970] first pointed out that the (1) overall scarcity of sedimentary deposits in the Great Basin older than the middle Miocene, (2) widespread distribution of thin ash flow sheets, and (3) same amount of deformation of old and young Tertiary rocks in most places indicate the existence of little relief and therefore limited faulting until late in the Tertiary.

In a series of time-period maps, necessarily generalized because of the small 1:1,000,000 scale, *Stewart and Carlson* [1976] showed the lithologic character of Tertiary rocks in Nevada, thereby including much of the Great Basin. Smaller-scale time-lithologic maps of Nevada and parts of California and Utah were included. Digitized time-area summaries of these maps are shown in Figure 3*b*. In addition to illustrating the well-known ignimbrite flareup of the late Oligocene-early Miocene, these maps clearly demonstrate the sparse area of exposure of sedimentary deposits of this time period, less than in the briefer older and younger ones. Similarly scarce sedimentary deposits are disclosed in the Tertiary part of 18 stratigraphic sections in the eastern Great Basin of Utah [*Hintze*, 1988].

Zoback et al. [1981], *Eaton* [1982], *Engebretson et al.* [1984], and *Wernicke et al.* [1987] advocated concurrent crustal extension and calc-alkaline magmatism during the Tertiary. These studies will be examined in a later section.

BRIEF OUTLINE OF TERTIARY VOLCANISM IN THE GREAT BASIN

Volcanism began north of the Great Basin in the Paleocene and swept southward, entering the northern part of the province in the Eocene about 43 Ma [*Cross and Pilger*, 1978; *Best et al.*, 1989*b*], and continued a southward transgression along an arcuate, roughly east-west front into southern Nevada by Miocene time (Figures 1 and 2). Age determinations and chemical analyses [*Best et al.*, 1989*b*; see also *McKee et al.*, 1970; *McKee*, 1971; *Noble*, 1972], small-scale maps [*Stewart and Carlson*, 1976], and estimates of volumes of large and very large ash flow tuff deposits (Figure 3) show the following: (1) Until about 31 Ma most of the erupted magma was high-K andesite, dacite, and rhyolite lavas and minor

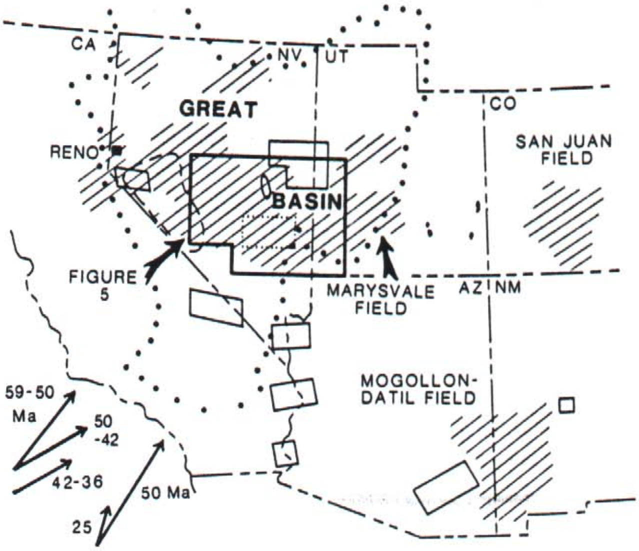

Fig. 1. Index map showing some areas (diagonal ruling; data sources from *Best et al*. [1989*b*, Figure 2] and *Best et al*. [1989*a*, Figure 1]) of southwestern United States subjected to voluminous volcanic activity during the middle Tertiary and areas of study referred to in text. Great Basin area of internal drainage is indicated by heavy dotted line (*Fenneman* [1931]; California part is not considered in this report). Late Oligocene-early Miocene (34–17 Ma) Reno-Marysvale zone in the Great Basin extends eastward from Reno, Nevada. Small solid areas between Marysvale and San Juan volcanic fields represent dioritic laccoliths emplaced 32–21 Ma [*Sullivan et al*., 1991]. Arrows off southern California coast are vectors of convergence of oceanic lithosphere (Vancouver plate) beneath continent from 59 to 36 Ma (relative speeds, indicated by arrow length, and directions 30–35 from *Stock and Molnar* [1988, Table 15]). For comparison, vectors of convergence (50–25 Ma) from *Engebretson et al*. [1985, Figure. 8] are also shown. Solid line open boxes are areas of crustal extensional reviewed by *Gans et al*. [1989], fine dotted line box by *Taylor et al*. [1989], and solid line ellipse by *Moores et al*. [1968]. Dashed line in western Nevada encloses area of early Miocene extension documented by *John et al*. [1989].

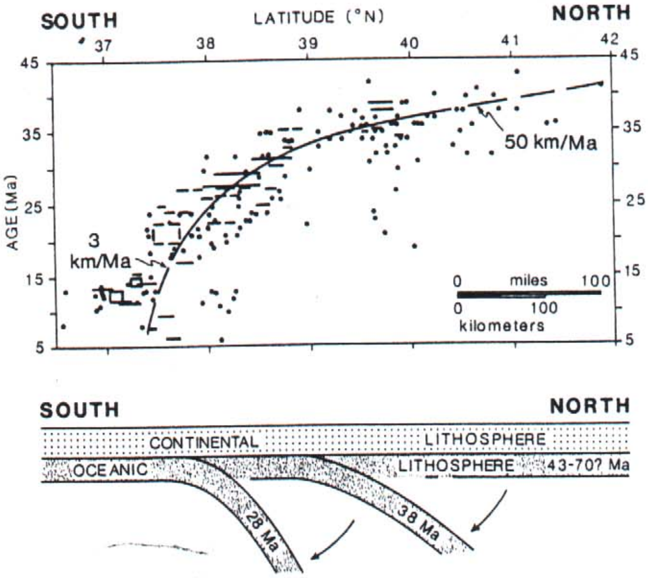

Fig. 2. Decelerating southward transgression of calc-alkaline volcanism in the Great Basin. (Top) Space-time data from *Best et al*. [1989*b*, Figures 3 and 7] in a time-latitude plane along the Nevada-Utah stateline. Sites of dated lava flows (dots) and sources of regional ash flow tuffs (lines and, where pyroclastic activity was extended in time, boxes) located on Precambrian crust have been projected onto the plane. A best fit line through the data shows that the southward sweep nearly stagnated (speed only about 3 km/m.y.) in the south central Great Basin in the Reno-Marysvale zone where the ignimbrite flareup occurred. (Bottom) A speculative and highly schematic cross-sectional model, in about the same plane as top diagram, accounting for the decelerating transgression [cf. *Lipman*, 1980]. During the Tertiary, the oceanic plate is believed to have fallen away, or foundered, progressively southward from the overlying continental lithosphere. Mafic magmas that supplied mass and thermal energy to the transgressive continental magma systems are presumed to have been generated in the southward migrating wedge of asthenospheric backflow overlying the subducting plate. Because of considerable uncertainty in the amount of east-west crustal extension since peak volcanism in the Great Basin, we have not attempted to adjust data points to a preextension configuration. Nonetheless, compensation for any amount of east-west extension makes the sweep more southwesterly through the Great Basin so the Reno-Marysvale zone is more nearly perpendicular to the direction of convergence (see Figure 1) of the oceanic plate. The foundering lip of the subducting oceanic slab in the Great Basin area is considered to have had a somewhat arcuate, subhorizontal hinge; a complex warp in the descending slab may not have existed.

pyroclastic material, chiefly rhyolitic. (2) From about 31 to about 20 Ma, similar lavas were extruded, but their volume was clearly subordinate to a much greater volume, more than 35,000 km^3, of rhyolitic and dacitic ash flow deposits. In the Great Basin, as well as other major volcanic fields in southwestern North America (Figure 4), this late Oligocene-early Miocene period represents peak volcanic activity, the "ignimbrite flareup". (3) Following about 20 Ma, ash flow volcanism, chiefly rhyolitic, waned in the Great Basin, and extrusions of lava flourished. Increasingly alkalic, especially sodic, lavas of a broader spectrum of silica concentrations were erupted [*Best et al.*, 1989*b*]. However, a well-developed bimodal compositional spectrum and true basalt (International Union of Geological Sciences classification) did not appear until after the latest Miocene, about 8–6 Ma. Most dark colored lavas containing pyroxene and locally olivine phenocrysts of pre-Pliocene age are not basalts because of their relatively high content of alkalies and silica. The inception in the Great Basin of widespread extensional faulting and creation of local basins in which erosional debris collected beginning about 17 Ma [*McKee et al.*, 1970; *Stewart and Carlson*, 1976] therefore generally predates the extrusion of basalt. A transition from orogenic (calc-alkaline) to anorogenic (rare metal) rhyolite occurred about 21 Ma [*Christiansen et al.*, 1986]. Thus tectonic and magmatic transitions in the Great Basin are only loosely correlated during Miocene time.

STRATIGRAPHIC DATA

The 31 stratigraphic sections located and shown in Figures 5 and 6 (see also Tables 1 and 2) constitute a sample of the Cenozoic

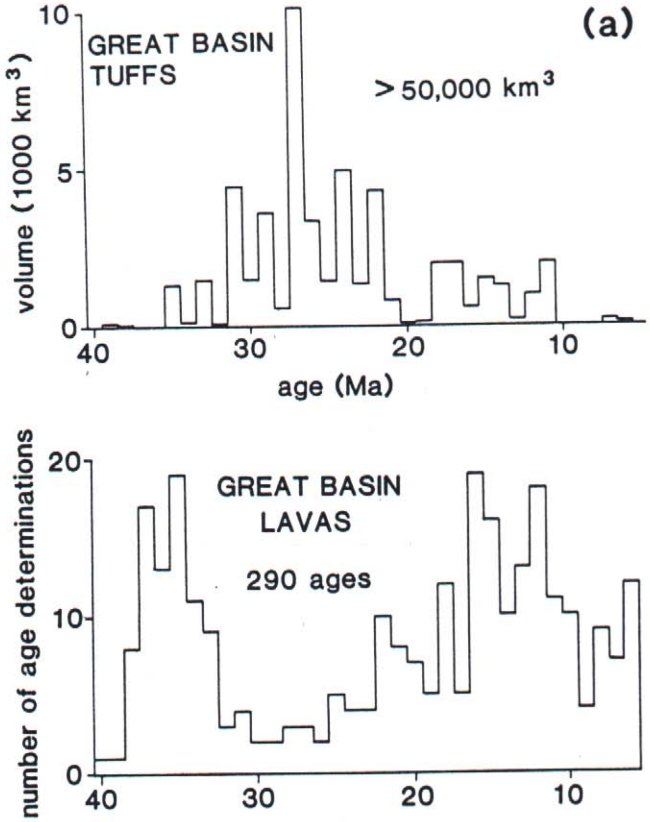

Fig. 3. Peak volcanism occurred in the Great Basin from about 31 to 20 Ma. (*a*) Volumes of dated, regionally extensive ash flow tuff sheets estimated from numerous measured sections and geologic maps are shown in top of figure and published and unpublished ages of lava flows in bottom part (both from *Best et al*. [1989*b*]). Because of sampling biases, the age histogram does not accurately portray volumes of lavas but suggests that less were extruded during peak ash flow activity than before and after. (*b*) Areas of tuff, lava, and sedimentary deposits in the Great Basin from the maps of *Stewart and Carlson* [1976] plotted in terms of total area for the map time interval divided by the duration of the time interval (43 Ma - 34 Ma = 9 m.y., etc.). Areas of lava flows and tuffs are from their smaller-scale maps of Utah and Nevada and of sedimentary deposits from the larger-scale map of Nevada (note change in scale for sedimentary deposits). These areas do not accurately represent true erupted volumes of magma in the Great Basin because of (1) variable thicknesses (some large calderas harbor as much as 2 km of tuff), (2) preferentially greater erosion and burial of older deposits, (3) voluminous extrusion of lavas in the Cascade and Snake River Plain provinces adjacent to the western and northern margins, respectively, (4) a considerable volume of ash carried downwind out of the province, and (5) regionally variable amounts of extension since volcanism. For these reasons, the area of 34–17 Ma ash flow tuff (71,000 km^2) probably underrepresents the volume of magma erupted relative to volume of extruded 17–6 Ma lava flows (area of 64,000 km^2). About one-half of the area of 34–17 Ma lava flows are in the Great Basin part of the Marysvale field. Half of the 34–17 Ma sedimentary material is associated with known calderas, making the amount possibly related to regional tectonism during this time period even less than shown and trivial compared to the amount from 17 to 6 Ma, unless it is preferentially buried in geologically recent basins.

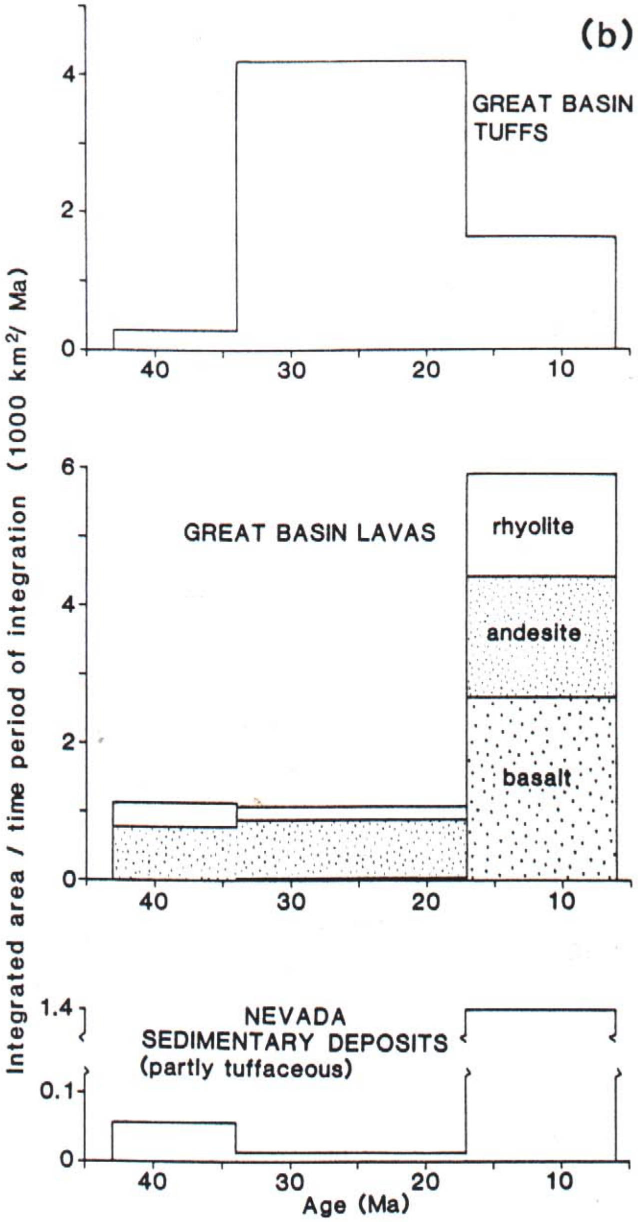

Fig. 3. (continued)

geologic record in the central Great Basin where peak volcanism with respect to the entire province occurred during the late Oligocene-early Miocene [*Best et al.*, 1989*b*]. These data furnish a regional stratigraphic framework for evaluation of the relation between extension and volcanism. Thirteen of these sections were examined by *Cook* [1965] and some in western Utah are included in the work by *Hintze* [1988]. The 31 have good chronologic constraints and were chosen to represent the longest intervals of time and the most complete sequence of ash flow sheets in a particular area. With the exception of sections 9- 13, which represent time periods of only a few million years, most cover about 10 m.y. during the peak late Oligocene-early Miocene volcanism; some sections cover a greater interval of time.

It is critically important in evaluating the timing of volcanism and regional tectonism to exclude from the data set stratigraphic sections located within recognized calderas and other magmatic centers. In such places, subsidence and postcollapse resurgence and associated faulting have produced local angular unconformities and erosional debris that could be confused with products of regional tectonic processes. Although we have avoided known large calderas, the possibility remains that the rock record in some sections has been influenced by local magmatic processes; two such sections might be numbers 18 and 26 (see discussion below and Figures 6 and 7).

Stratigraphic Record of Synvolcanic Extension

Significant synvolcanic brittle extension of the crust would produce conspicuous angular unconformities, fanning dips, and sedimentary deposits within the volcanic sequence [*Gans et al.*, 1989, Figure 18] (see also *Eaton* [1982, Figure 6C] and *Noble et al.* [1990*b*]). Slide blocks may also occur between sedimentary de-

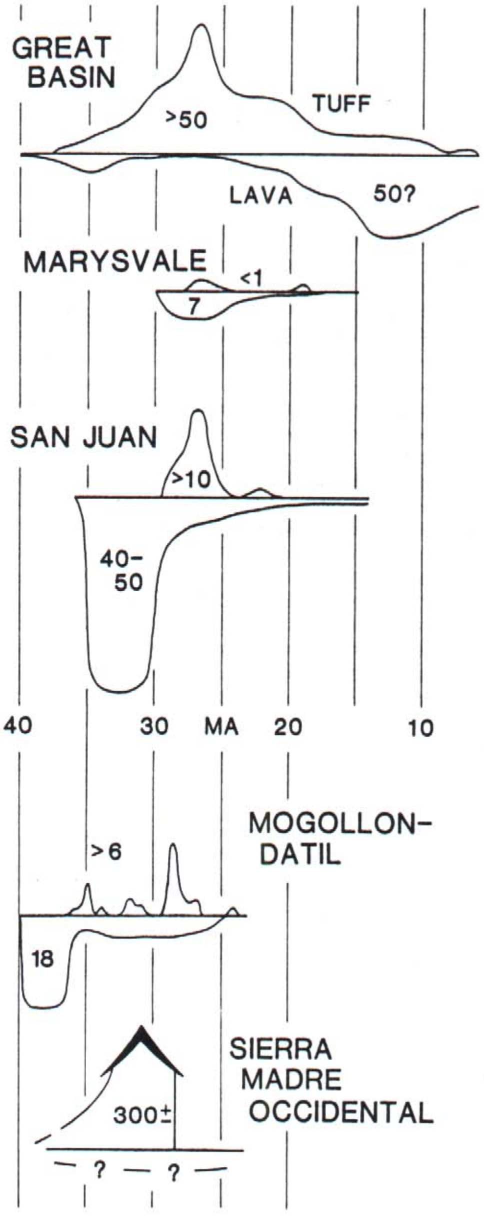

Fig. 4. Highly generalized time-volume relations of lava flow and tuff deposits in volcanic fields of the southwestern United States and Mexico (Sierra Madre Occidental [from *McDowell et al.*, 1990]). Volume estimates are in thousands of cubic kilometers (sources of data are in *Best et al.* [1989*b*, Table 1] and *Ratté et al.* [1989]). Note near coincidence in time of voluminous ash flow activity (ignimbrite flareup) in the five areas [*Noble*, 1972].

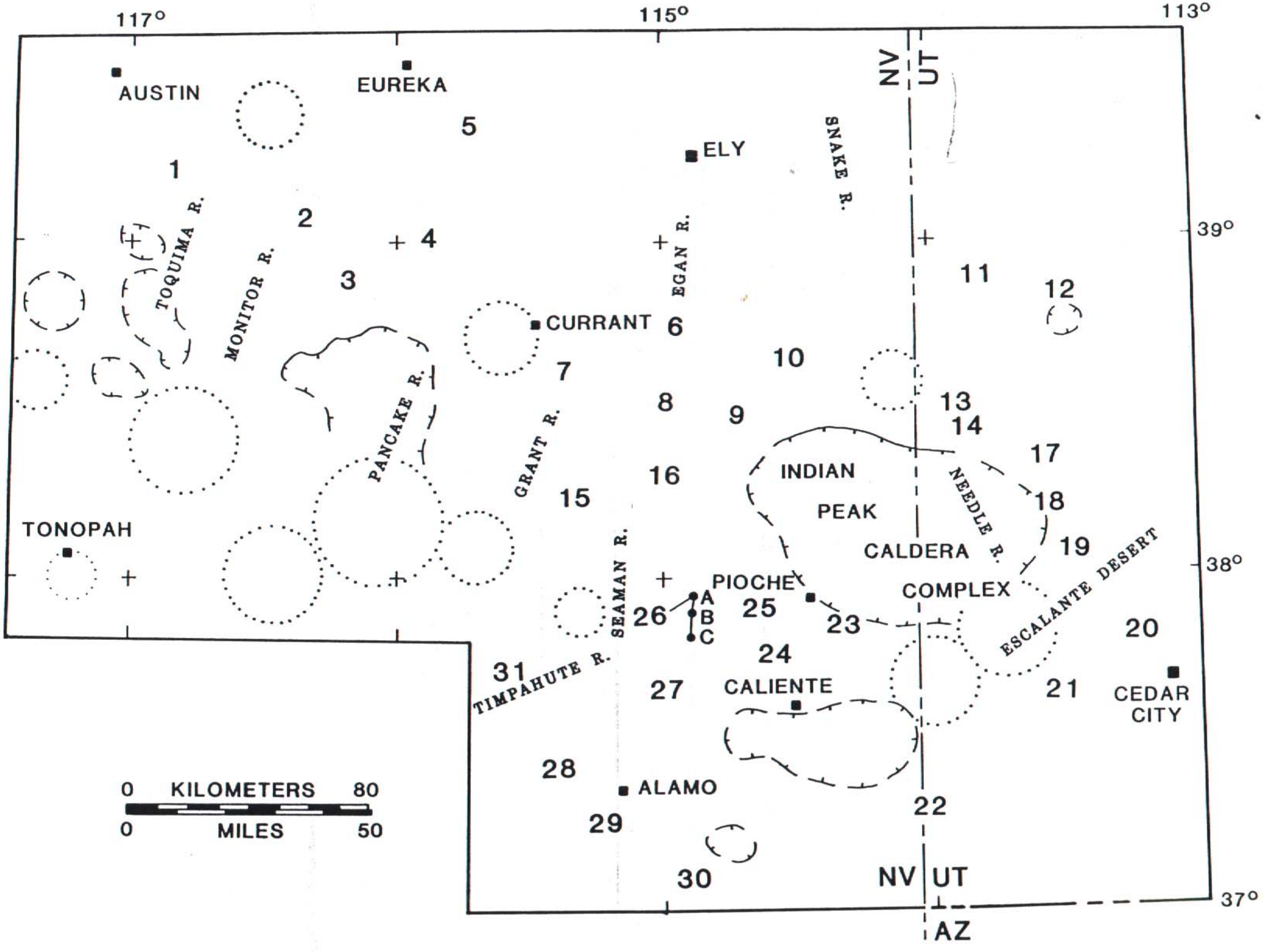

Fig. 5. Locations of stratigraphic sections shown in Figure 6. Line labeled 26-A-B-C west of Pioche is section in Figure 7. Caldera sources of major regional ash flow sheets of late Oligocene-early Miocene age are shown by ornamented lines; approximately located or indefinite sources shown by dotted circles [*Best et al.*, 1989*b*]. Latitude and longitude and references for locations are given in Table 1.

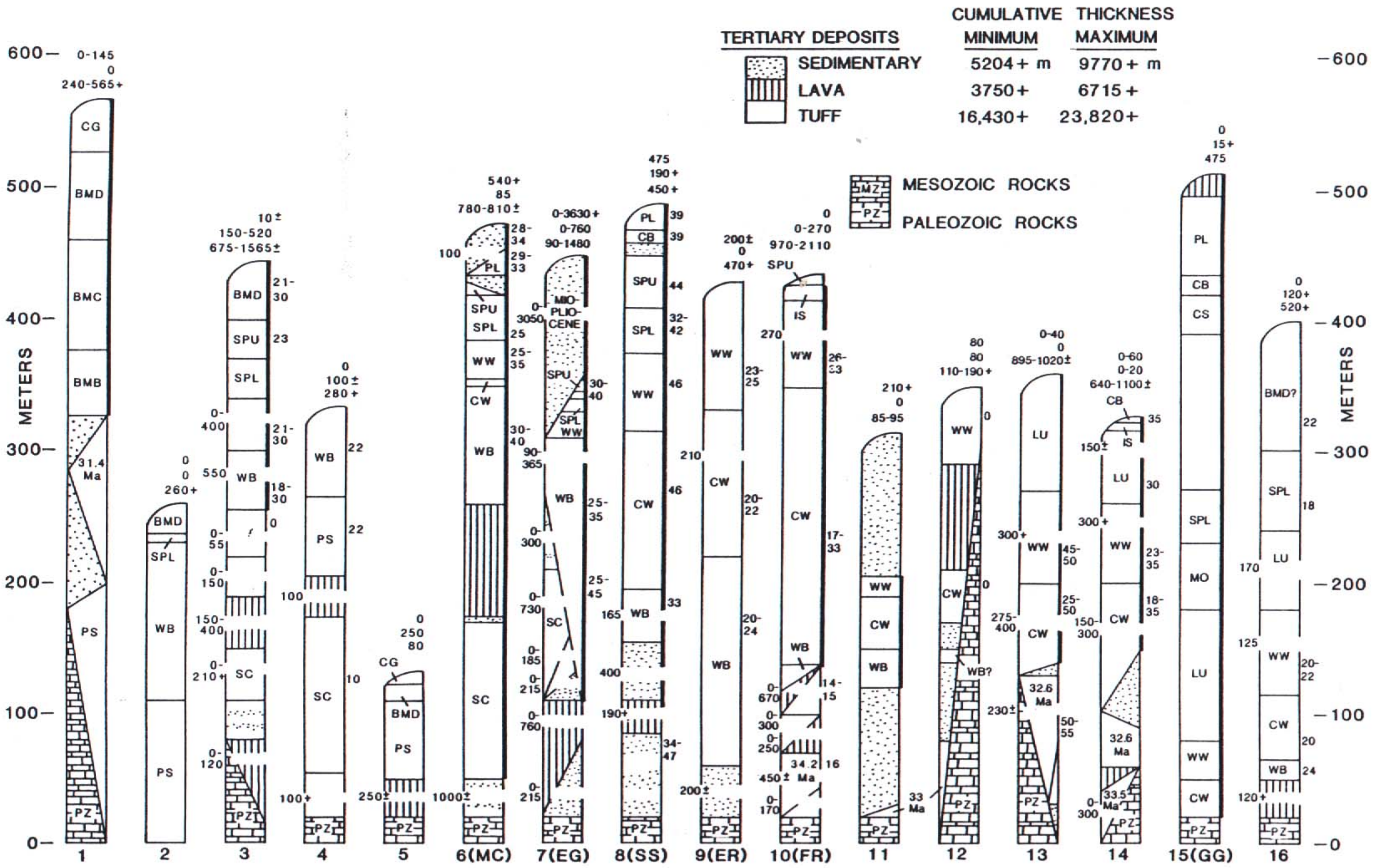

Fig. 6. Stratigraphic sections of Tertiary volcanic and sedimentary deposits whose locations are shown in Figure 5. Sections originally examined by *Cook* [1965] are identified at bottom of column in parentheses, as, for example, (MC) in section 6. Two- and three-letter designations of stratigraphic units and their isotopic ages are in Table 2. Ages in Ma of local tuff units not listed in Table 2 are shown. Most thicknesses are approximate; where too great to depict in column, the thickness (in meters) is shown on left of unit and vertical lines defining column are dashed. Sections taken from geologic maps indicate range in thickness of units if substantial variations occur. Dip angles are listed to right of unit. Heavy vertical line along right side of column indicates conformability of units on the geologic map, cross-section, or on a well-exposed hillside (see Figure 8 for section 15 and frontispiece of *Williams* [1967] for section 27). Minor pinchouts of generally less than 20 m occur over strike distances of a kilometer or so in some of these conformable sequences. In section 3, five tuff cooling units as much as 410 m thick between Shingle Pass Tuff and Windous Butte Formation pinch out entirely within 8 km; the Shingle Pass Tuff also pinches out in this same area. Wavy contact in section 18 indicates angular unconformity. Numbers at top of each column indicate cumulative thicknesses (in meters) of, from top down, Tertiary sedimentary deposits, lava flows, and ash flow tuff. Stippled pattern labeled "V" is volcanic debris deposit, and that labeled "C" is sedimentary Eocene-Oligocene Claron Formation. Cumulative total range of thickness of deposits is in meters. Nature of contact between pre-Tertiary and Tertiary deposits, whether an angular unconformity or bedding-parallel contact, was not determined where top of brick pattern is horizontal.

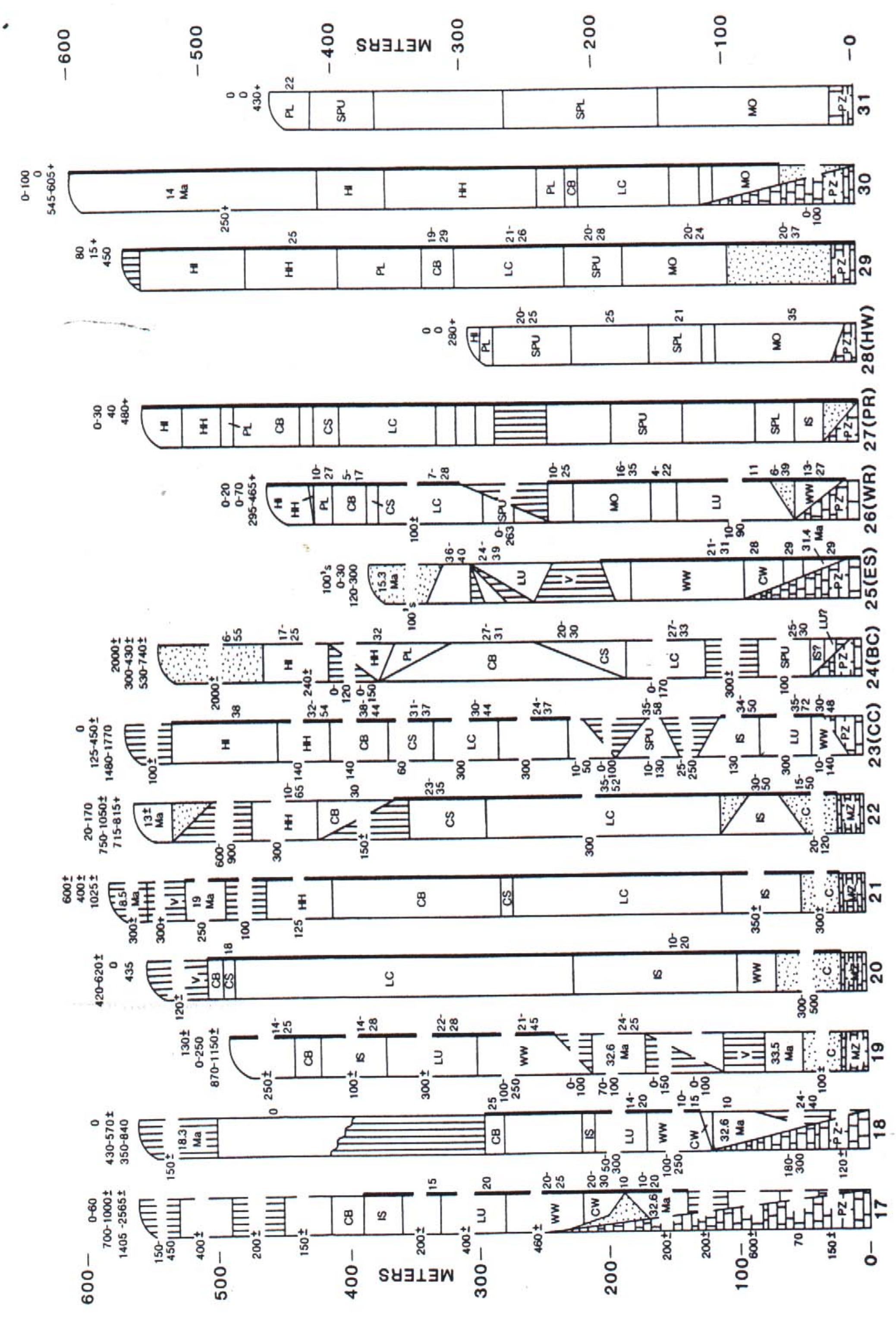

Fig. 6. (continued)

TABLE 1. Data for Stratigraphic Sections (Figures 5 and 6)

Section	Topographic Quadrangle/Reference	Latitude North	Latitude West
1	*McKee* [1976, Figures 26, 31, and 32]	39°12′	116°49′
2	Horse Heaven Mountain, Nevada	39°03′	116°18′
3	*Dixon et al.* [1972]	38°53′	116°10′
4	Moody Peak, Nevada	39°01′30″	115°51′
5	Pancake Summit, Nevada	39°19′20″	115°44′
6	Brown Knoll, Nevada; *Kellogg* [1964]	38°45′20″	114°54′20″
7	*Moores et al.* [1968] and M. G. Best (unpublished data, 1991)	38°37′30″	115°22′
8	*Kellogg* [1964] and *Best et al.* [1989*b*]	38°33′	114°56′
9	Dutch John Mountain, Nevada	38°27′30″	114°43′
10	*Loucks et al.* [1989]	38°39′	114°28′
11	Burbank Hills, Utah; L. F. Hintze (unpublished data, 1991)	38°54′20″	113°49′23″
12	*Hintze* [1974]	38°50′	113°28′
13	*Hintze and Best* [1987]	38°32′	113°55′
14	*Best and Hintze* [1980]	38°27′	113°51′
15	Water Gap NE, Nevada (see Figure 8)	38°13′30″	115°18′
16	Silver King Well, Nevada	38°19′	114°58′
17	*Abbott et al.* [1983]	38°20′	113°33′
18	*Best et al.* [1987*c*]	38°12′	113°32′
19	*Hintze et al.* (in press)	38°05′	113°27′30″
20	*Mackin and Rowley* [1976]	37°49′	113°13′
21	*Siders et al.* [1990]	37°39′	113°32′
22	Dodge Spring, Utah-Nevada; R. E. Anderson and L. F. Hintze (unpublished data, 1990)	37°19′ 37°19′	114°03′ 114°03′
23	Condor Canyon, Nevada; G. J. Axen (unpublished data, 1991)	37°51′	114°21′
24	Bennett Pass, Nevada; K. J. Burke (unpublished data, 1991)	37°45′	114°36′
25	Ely Springs, Nevada; *Taylor et al.* [1989]	37°55′	114°39′
26	White River Narrows, Nevada; *Taylor* [1989]	37°52′	115°01′15
27	Pahroc Spring, Nevada; *Williams* [1967, frontispiece]	37°40′30″	115°00′
28	Hancock Summit, Nevada	37°26′	115°22′
29	Alamo, Nevada; A. S. Jayko (unpublished data, 1990)	37°15′10″	115°13′20″
30	Delamar 3 SE, Nevada; *Swadley et al.* [1990]	37°05′	114°51′20″
31	Tempiute and Meeker Peak, Nevada	37°45′	115°36′

Where sections are composite and cover several square kilometers coordinates are only given to nearest minute. Data for sections indicated by topographic quadrangle are from unpublished work of M. G. Best and, where indicated, by other geologists.

posits, reflecting tectonic erosion of topographic highs and accumulation in lowlands. Ash flow sheets would have significant lateral variations in thickness within and between adjacent fault blocks and their lateral extent would be restricted by such blocks. Some of these features have been found in east central Nevada by *Gans et al.* [1989]. However, major angular unconformities are not present within their volcanic sections, perhaps reflecting the relatively short time interval (1–2 m.y.) during which most of the volcanic rocks in this area were erupted and their better exposure in less extended and uplifted areas.

The possibility exists that the stratigraphic sections portrayed in Figure 6 just happen to be positioned within relatively undeformed blocks in which tilting of tuff sheets was minimal. As we have not investigated log data from drill holes in present basins this possibility cannot be fully evaluated. Unextended blocks would have remained high, thus precluding sediment accumulation on them but also restricting or even preventing accumulation of ash flow material, depending, of course, on factors such as relief and thickness of the ash flow. Oldest ash flow deposits, generally older than about 31 Ma, show evidence of topographic relief but the distribution and thickness of younger sheets imply limited relief existed during their deposition (see also below).

Local Extension Before 31 Ma Prior to Peak Volcanism

Eighteen of the 31 sections include locally tuffaceous sedimentary deposits lying beneath or intercalated between the oldest volcanic units, older than about 31 Ma. The aggregate thickness of these older sedimentary deposits is roughly one half of the total Tertiary sedimentary material. These 18 sections are scattered between intervening sections in which volcanic rocks lie on a clean erosion surface cut into Paleozoic rocks. Four Tertiary sections (19–22) resting on Mesozoic sedimentary rock, all in southwestern Utah, have 100 m or more of Eocene-Oligocene continental sedimentary rock (the Claron Formation) beneath or partly intervening between the volcanic deposits. These relations suggest that as much as a few hundreds of meters of relief existed on top of pre-Tertiary rock within the central Great Basin area of Figure 5. Conglomerate containing rounded clasts only of Paleozoic rock lie between volcanic units more than about 31 Ma in sections 1, 6, 8, 11, 12, 13, 14, and 17. Most of these eight lie in the northeast part of Figure 5 and probably reflect shedding of erosional debris off a nearby highland exposing Paleozoic rocks during emplacement of volcanic rocks about 34–31 Ma. From the stratigraphic data alone it cannot be decided whether the detritus was shed off (as recently as early Oligocene?) residual topographic highs associated with Mesozoic compressional tectonism or highs produced by extensional faulting immediately preceding peak volcanism.

In the pre–31 Ma parts of the Tertiary stratigraphic sections in Figure 6, no marked angular unconformities exist. Significant variations in thickness of older sedimentary and volcanic deposits reflect deposition in topographic lows in the eroded terrane of Paleozoic strata, especially obvious in sections 1, 12, 13, 17, 18, 25, and 30.

TABLE 2. Stratigraphic Units and Ages

Symbol	Name of Unit	Age, Ma
HI	Hiko Tuff	18.6
HH	Harmony Hills Tuff	21
PL	tuff of Pahranagat Lakes	22.65
	Condor Canyon Formation	
CB	Bauers Tuff Member	22.74
CS	Swett Tuff Member	
CG	tuff of Clipper Gap	22.8
LC	Leach Canyon Formation	24 ±
	Bates Mountain Tuff	
BMD	D unit	25.11
BMC	C unit	
BMB	B unit	
	Shingle Pass Tuff	
SPU	upper	26.00
SPL	lower	26.68
IS	Isom Formation	26.96
MO	Monotony Tuff	27.31
LU	Lund Formation	27.9
WW	Wah Wah Springs Formation	29.5
CW	Cottonwood Wash Tuff	30.6
WB	Windous Butte Formation	31.37
PS	Pancake Summit Tuff	34.73
SC	Stone Cabin Formation	35.40

Ages mostly from *Best et al.* [1989*b*] and also unpublished determinations of A.L. Deino by laser fusion of single crystals for ^{40}Ar/^{39}Ar. Uncertainties in conventional K-Ar values, cited to nearest tenth of a million years, are about 3%; uncertainties in ^{40}Ar/^{39}Ar determinations, cited to nearest hundredth of a million years, are about 0.1%.

Other geologists have found evidence for Tertiary faulting predating peak volcanism in the Great Basin. While it is beyond the scope of this paper to document all instances, a few examples are sufficient to characterize this period of extension. In the vicinity of the Grant and southern Egan ranges, represented by sections 6–8, the mostly epiclastic Sheep Pass Formation of Eocene to Paleocene age (to possibly late Cretaceous [*Stewart,* 1980]) records contemporaneous block faulting [*Moores et al.*, 1968; *Newman*, 1979]. Near section 8, *Kellogg* [1964] mapped a 3-km-long slide block of Paleozoic rock resting on the Sheep Pass; this block, which he presumed to have calved off the nearby ancestral Shingle Pass fault scarp, is in turn covered by tuffaceous sediments and then by lava flows, conglomerate, and finally several tuff cooling units deposited about 31–23 Ma. South of Eureka, Nevada, between sections 2 and 5 in the southern Fish Creek Range, J. Bartley (written communication, March 1990) has found what he believes to be slide masses of Paleozoic rock at the base of the Sheep Pass Formation. He has also mapped in the vicinity of section 13 numerous NNW striking, high-angle normal faults with generally small offsets that are overlain by a 32.6 Ma tuff. Just north of the area of Figure 5, deposition of the Eocene-Oligocene Elko and Indian Well formations [*Solomon et al.*, 1979; *Palmer et al.*, 1991] apparently was governed in part by local uplift via block faulting. In the Indian Well sequence, an angular discordance of about 15 exists between tuff units deposited about 36 Ma and those about 31 Ma. In the area near Pioche, Nevada, *Taylor* [1989, pp. 107–141], *Taylor et al.* [1989], and *Axen et al.* [1988] have found evidence for extensional faults which on the basis of compatible timing and similarity in geometry and kinematics, they believe constitute a southern continuation of the Oligocene extensional fault system of *Gans and Miller* [1983] and *Gans et al.* [1989] in east central Nevada that was active mostly 36–35 Ma. *Taylor* [1989, p. 139] proposed that regional extension was roughly synchronous for 200 km or more southward along strike of this fault system and that because of the southward transgression of volcanism in the Great Basin (Figure 2), extension was synvolcanic in east central Nevada but prevolcanic near Pioche.

Limited Extension About 31–22 Ma Concurrent with Peak Volcanism

Examination of the sections in Figure 6 discloses little stratigraphic evidence for significant regional tectonic extension from about 31 Ma to about 22–20 Ma in the central Great Basin when the greatest volume of magma was erupted. This lack of evidence for extension was acknowledged by *Gans et al.* [1989, p. 48]. There is a striking contrast between the expected stratigraphic sequence in a synextensional volcanic terrain [*Gans et al.*, 1989, Figure 18] and the observed sections in Figures 6 and 8.

Sedimentary material intercalated within volcanic rocks after 30.6 Ma (the time of deposition of the Cottonwood Wash Tuff) occurs only in sections 6, 8, 22, 26, and possibly 1; the maximum aggregate thickness of these sedimentary deposits, some of which might have been shed off older topographic highs, is 1% of the maximum cumulative thickness for all Tertiary sedimentary material in the 31 sections. The possibility exists, of course, that erosional debris from topographic highs produced by synvolcanic faults was continuously and virtually wholly flushed outside the central Great Basin area during emplacement of the ash flows, particularly if the region was concurrently uplifting (see below). We have no way of independently evaluating this, although fault-related angular discordances would remain.

Marked angular discordances within the post–31 Ma part of the volcanic sequence occur only in section 18 which represents a local area of early Miocene (about 22–18 Ma) extension via block faulting [Best et al., 1987*b*] that is intimately associated in space and time with quasi-bimodal magmatism.

West of Pioche, Nevada, in the Northern Pahroc Range, *Taylor* [1989, pp. 90–91], *Taylor et al.* [1989], and *Taylor and Bartley* [1988] find evidence for minor extensional faulting 30–27 Ma that produced an angular discordance of less than 10 in the volcanic sequence and an intercalated coarse sedimentary deposit as much as

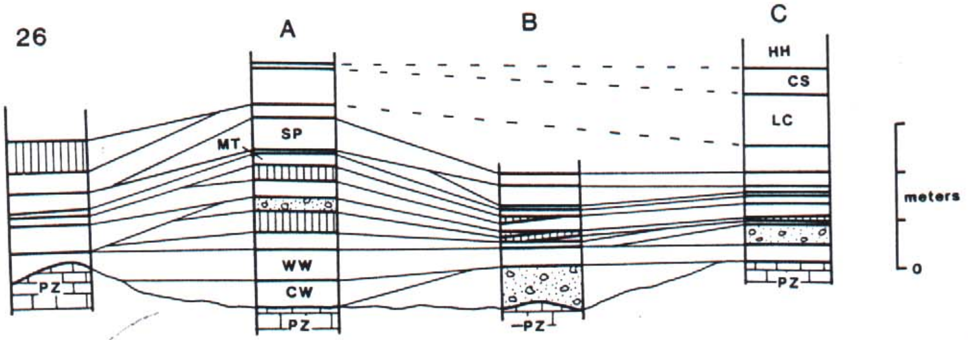

Fig. 7. Stratigraphic sections in the North Pahroc and Seaman Ranges [after *Bartley et al.*, 1988, Figure 8]. Location of sections shown in Figure 5. See Figure 6 and Table 2 for other designations.

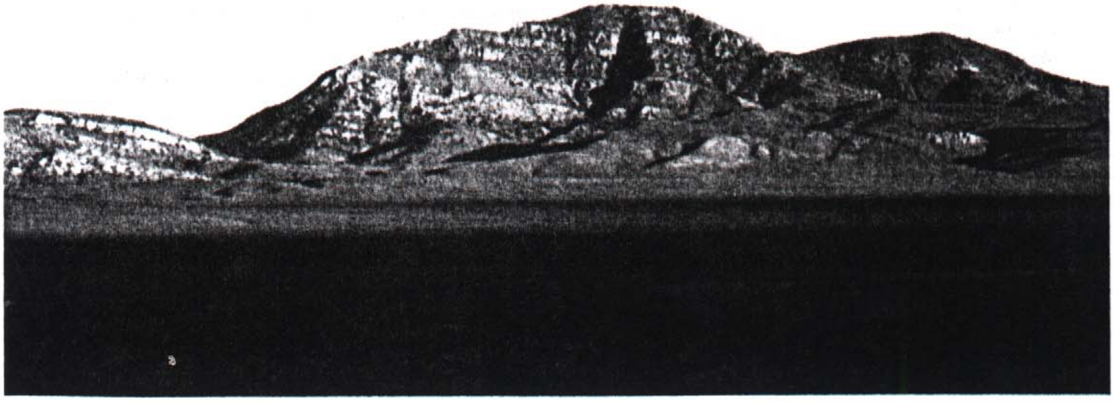

Fig. 8. View looking east at northern Golden Gate Range, section 15. A conformable sequence of nine ash flow deposits ranging in age from 30.6 to 22.74 Ma in highest hill is capped by 20.7 Ma lavas (seen on hill to south) and disconformably overlies Paleozoic carbonate strata to north exposed in low hill. Entire section is gently tilted.

60 m thick (Figure 7). Mapped faults account for considerably 1 km of extension over a distance of several kilometers. Although *Taylor* [1989, p. 91] considered the possibility that the faulting might be related to the nearby, mostly slightly older Indian Peak caldera complex [*Best et al.*, 1989*a*], we believe that it is more likely to be related to emplacement of magmas in the upper crust, or their eruption, 27–24 Ma, to form several local lava flows and ash-flow tuff sheets in this immediate area (see *Best et al.*, [1989*b*], Table R3, Petroglyph Cliff, Hancock Summit, and trachydacite tuffs). Alternatively, this extensional faulting might reflect a regional tectonic pulse of limited magnitude. In the southern Grant Range farther to the northwest, the NW striking Wadsworth Ranch fault is an oblique slip fault that dies northward from a probable caldera [*Taylor et al.*, 1989; *Bartley and Gleason*, 1990]. It cuts 31.8 Ma tuff and is cut by a large dike whose age may be about 26 Ma. Whether this fault was caused by the nearby magmatic activity is certain.

In southwestern Nevada, *Robinson and Stewart* [1984] found no indication of late Oligocene-early Miocene faulting except in the Candelaria Hills where eruption of 25–23 Ma ash flows seems to have been associated with subsidence of a local trough.

The distribution of two regional ash flow sheets (the Lund emplaced about 28 Ma and the Leach Canyon about 24 Ma) in the southeastern Great Basin are much more elongate east-west than older and younger sheets derived from nearby sources [*Best*, 1988*b*; *Best et al.*, 1989*a,b*]. Although the distribution of outflow sheets is influenced by vent position, eruption dynamics, and other factors, it is nonetheless a possibility that the dispersal of the ash flows or preservation of these sheets was influenced by east-west crustal sags, grabens, or block faults that formed concurrently with pyroclastic activity. No direct evidence for such controlling faults have been found, although such structures do locally exist in the eastern Great Basin [e.g., *Best et al.*, 1987*b*]; whether they formed because of associated magma emplacement in the upper crust cannot be ruled out.

The wide distribution of thin, generally less than 10–20 m, ash flow sheets in the Great Basin [*Best et al.*, 1989*b*] is indirect evidence that during the latest Oligocene and early Miocene little topographic relief existed and therefore little extensional faulting. For example, the correlative Nine Hill Tuff and D unit of the Bates Mountain Tuff (25.110.02 Ma [*Deino*, 1989]) extend from the western foothills of the Sierra Nevada to within 40 km of Ely, Nevada, and the tuff of Clipper Gap (22.8 Ma) crops out from 35 km southeast of Austin, Nevada, to within 8 km of the Utah stateline [*Grommé et al.*, 1972; C.S. Grommé, unpublished data, 1990].

Extension After About 22–20 Ma Postdating Peak Volcanism

Dip-slip faults that cut the entire sequence of volcanic and older rock are widespread in the Great Basin and are responsible for the characteristic topography of this part of the Basin and Range province [e.g., *Stewart*, 1978]. These faults indicate that postvolcanic deformation is both common and one of the most significant elements in the aggregate crustal extension. Major detachment faults occur in many places [e.g., *Taylor et al.*, 1989]. Some areas [e.g., *Noble et al.*, 1990*b*] have clearly been extended between times of deposition of ash-flow sheets after peak volcanism in the middle to late Miocene.

Episodic Versus Continuous Extension During the Tertiary

In southeastern Nevada, *Taylor et al.* [1989] found evidence for episodic extension, the most significant occurring before 34–32 Ma and, with loose constraints, sometime after about 22–15 Ma, depending on the area. Limited extension that was possibly related to local magmatic activity occurred in the interim. South of the area studied by *Taylor et al.* [1989], *Jayko* [1990] documented similar episodic extension and found no evidence for late Oligocene-early Miocene extension.

In the Yerington district just south of Reno, Nevada (Figures 1 and 9 [*Proffett*, 1977; *Proffett and Dilles*, 1984]), the stratigraphic record is unusually complete and entirely compatible with the interpreted episodic deformation, and its timing, in the southeastern part of Nevada. Basal clastic deposits overlain by voluminous late Oligocene silicic ash flow tuff sheets are reminiscent of many sections in eastern Nevada. The small amount of epiclastic deposits and lack of angular discordances within the 2+ km sequence of tuffs indicate relative tectonic quiescence during the period of peak regional volcanism in the Great Basin. Also recorded in the Yerington section is major extension, locally more than 100%, between about 17 and 11 Ma and therefore well after peak regional volcanism.

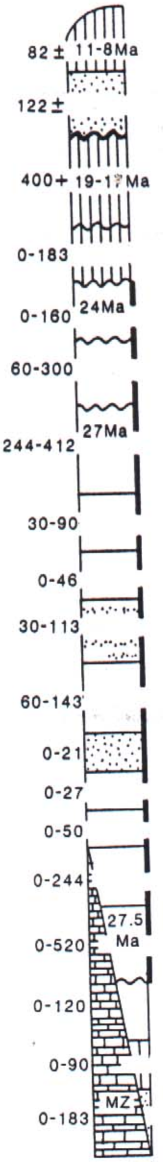

Fig. 9. Generalized stratigraphic section of rocks in the Yerington district [after *Proffett*, 1977] in format of Figure 6. Light wavy line is erosional unconformity, and heavy wavy line is angular unconformity.

The Yerington district is actually only one of 13 areas in western Nevada (Figure 1) where extensional faulting produced widespread angular unconformities after the regional peak volcanism [*John et al.*, 1989]. From about 20 to 19 Ma the style of volcanic activity shifted from eruption of silicic pyroclastic flows to intermediate composition lavas. *John et al.* [1989, Table 2] also indicated that only two of the 13 areas experienced extensional faulting during ash-flow activity, once again demonstrating that only local deformation occurred during peak volcanism in the Great Basin.

Gans et al. [1989, Figure 19] show major extension in east-central Nevada continuing for about 15 m.y. after the time about 35 Ma when widespread volcanic deposits accumulated to serve as chronotectonic markers. However, this interpretation is based [*Gans et al.*, 1989, pp. 28–29] upon sedimentary basin sequences containing only three dated ash beds which indicate lower parts are middle to latest Oligocene; upper parts have unconstrained ages.

Zoback et al. [1981, Table 1] presented data intended to "prove or support an interpretation of pre-basin-range extension" through the Oligocene and Miocene in the Great Basin. However, reliability of the cited evidence for regional tectonic extension is variable. For example, extension inferred from passively emplaced batholiths and faulting near calderas may not be related to regional tectonism. Extension in the Needle Range area of western Utah (sections 13, 14, and 17–19 in Figures 5 and 6) and in Lincoln County, Nevada (sections 23–27), was almost entirely after the early Miocene according to our data (Figure 6). *Anderson* [1983] documented interstratified early Oligocene conglomerate and tuff in several places in the eastern Great Basin as well as "Oligocene or younger" and Miocene extension. All of these data can be interpreted to conform to an episodic pattern of extension in which only a limited amount occurred during the period of most voluminous volcanism.

Wernicke et al. [1987, pp. 212–213] discussed evidence for pre-middle Miocene extension in the Great Basin. Once again, all of their data are compatible with two major episodes of extension: before and after peak late Oligocene-early Miocene volcanism. For example, they note that

> . . . in the northern Death Valley area, no normal faults of early-Miocene or Oligocene age are known, but the deposition of up to 1000 m of Oligocene and lower Miocene(?) Titus Canyon Formation . . . may record the onset of extensional tectonism in this area. The basal Titus Canyon contains lenses of non-volcanic megabreccia, above which occur fossils of early-Oligocene age. The top of the formation is overlain by volcanic rocks between 22 and 20 Ma old.

The case for continuous, significant, regional extension during the Tertiary in the Great Basin is therefore not compelling and we conclude that it was episodic (Figure 10). Locally significant extension occurred sometime before 34–32 Ma and, with loose constraints, sometime after about 22–15 Ma, depending on the area. The latter period of extension has been widespread and of major magnitude, producing the present topography of ranges and basins in the Great Basin. Limited, local extension that was possibly related to shallow crustal magmatic activity in some areas occurred in the interim, but hardly justifies, in our view, the qualifier "synextensional" in describing the accompanying volcanism.

Relation Between Extension and Volcanism in Space and Time in the Great Basin

Because of the southward transgressive sweep of volcanism in the Great Basin (Figure 2), datable markers are not everywhere

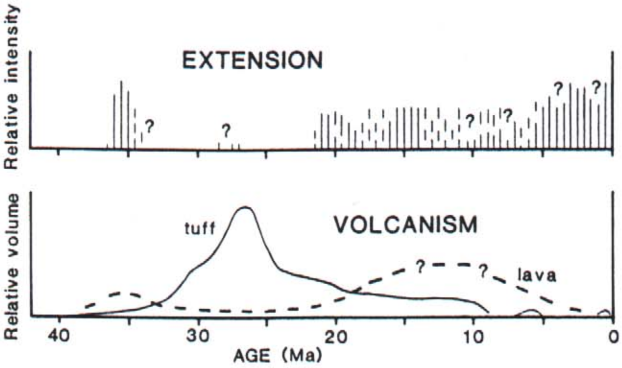

Fig. 10. Schematic timing of diachronous extension and volcanism for the entire Great Basin. Generalized relative volumes of volcanic rocks are based on Figure 3 and essentially represents an integrated picture of volcanism along a north (older) to south (younger) section through the Great Basin.

present to delineate all details of the timing and intensity of extension. Despite this inadequacy, our perspective of how extension and volcanism are related in space and time in the Great Basin differs significantly from conclusions drawn by some other geologists.

Our interpretation of what we consider to be representative data in the Great Basin is that a period of limited extension, and possibly even regional tectonic quiescence, prevailed from at least as early as about 31 Ma and lasted until roughly 22–20 Ma, essentially coinciding with the period of maximum, voluminous volcanism that was manifest in maximum pyroclastic activity (Figure 10). Local extension occurred before this tectonic lull and ignimbrite flareup but widespread extension, including major detachment faulting in places, afterwards. On a province-wide scale, maximum extension and the most voluminous volcanism are poorly correlated, not only in time but also in space (Figure 11*a*). In the Great Basin, volcanism was dominated by extrusion of lavas at 43–34 and 17–6 Ma [*Stewart and Carlson,* 1976] during extension (Figure 10). However, there is little spatial correlation between areas of lava-dominant volcanism and highly extended terranes (Figure 11*b*). Some areas of older and younger volcanism have, as yet, no documented major detachment faults. Extended areas do not everywhere manifest volcanism.

On the basis of available information, it thus appears that extension and volcanism during the Tertiary in the Great Basin were not closely coupled processes; this lack of close coupling was also suggested by *Bartley et al.* [1988], *Taylor* [1989], and *Taylor et al.* [1989].

PREVIOUS TECTONOMAGMATIC MODELS

If extension and volcanism are loosely coupled on a province-wide basis, then simple, end-member models of passive and active continental rifting, such as proposed by *Sengor and Burke* [1978], are difficult to apply in the Great Basin.

Gans et al. [1989, pp. 47–48] recognized that significant supracrustal extension did not occur in some large, middle Tertiary eruptive centers in the southwestern United States, such as the San Juan volcanic field in Colorado, parts of the Mogollon-Datil volcanic field in New Mexico, and much of the Oligocene to Miocene ash flow tuff province in the central Great Basin. They asked why these areas did not extend and if there was anything fundamentally different about the magmatism. It is beyond the scope of this paper to consider details of the large San Juan and Mogollon-Datil fields. But we consider next whether there is anything fundamentally different in the Great Basin between Tertiary volcanism associated in space and time with major extension, as in the east central Nevada area studied by *Gans et al.* [1989] and *Feeley and Grunder* [1991], and volcanism not accompanied by extension. As a test, we compare time-compositional properties of the east central Nevada field with the Indian Peak volcanic field [*Best et al.*, 1989*a*]; the latter field surrounds the Indian Peak caldera complex (Figure 6), was created by episodic eruptions about 32–27 Ma, and has little evidence for concurrent extension.

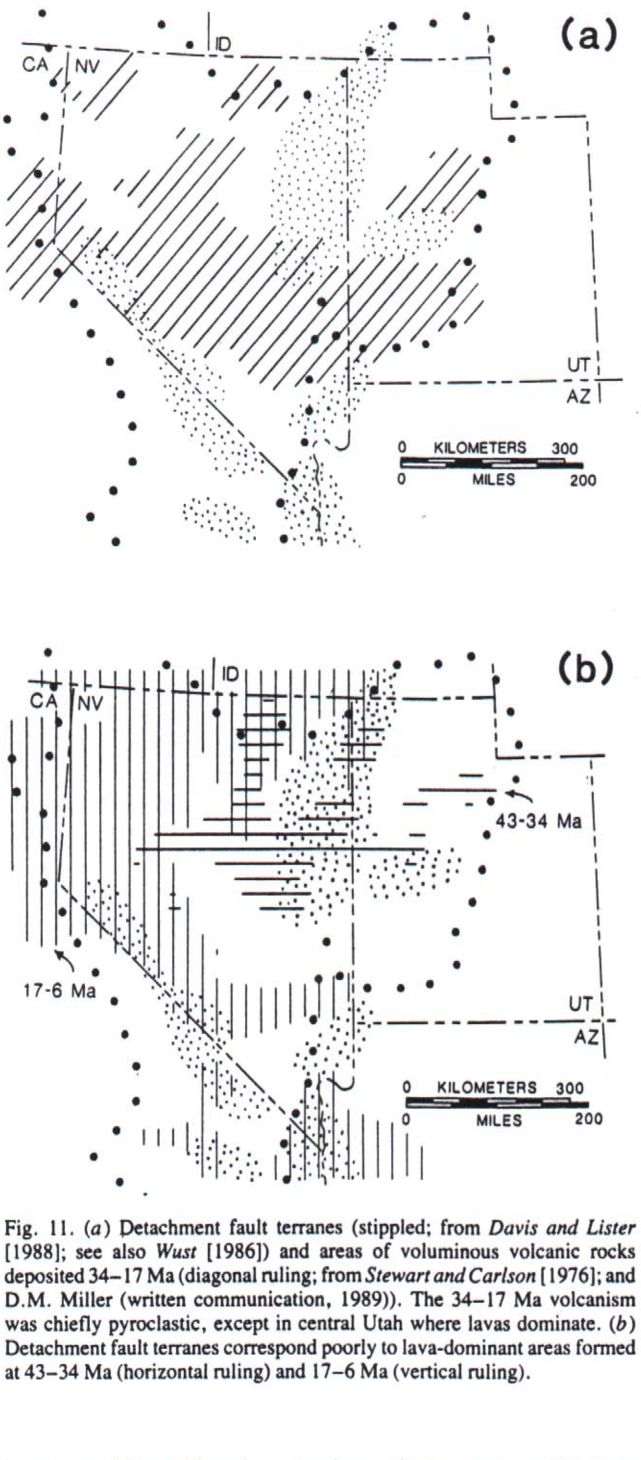

Fig. 11. (*a*) Detachment fault terranes (stippled; from *Davis and Lister* [1988]; see also *Wust* [1986]) and areas of voluminous volcanic rocks deposited 34–17 Ma (diagonal ruling; from *Stewart and Carlson* [1976]; and D.M. Miller (written communication, 1989)). The 34–17 Ma volcanism was chiefly pyroclastic, except in central Utah where lavas dominate. (*b*) Detachment fault terranes correspond poorly to lava-dominant areas formed at 43–34 Ma (horizontal ruling) and 17–6 Ma (vertical ruling).

The Indian Peak field, like others in the Great Basin formed during peak volcanic activity [*Best et al.*, 1989*b*], was created by eruption of thousands of cubic kilometers of silicic ash flows and only minor andesitic through rhyolitic lavas from a localized magma system, now marked by a large caldera complex [*Best et al.*, 1989*a*]. Figure 12 demonstrates that few contrasts exist between the

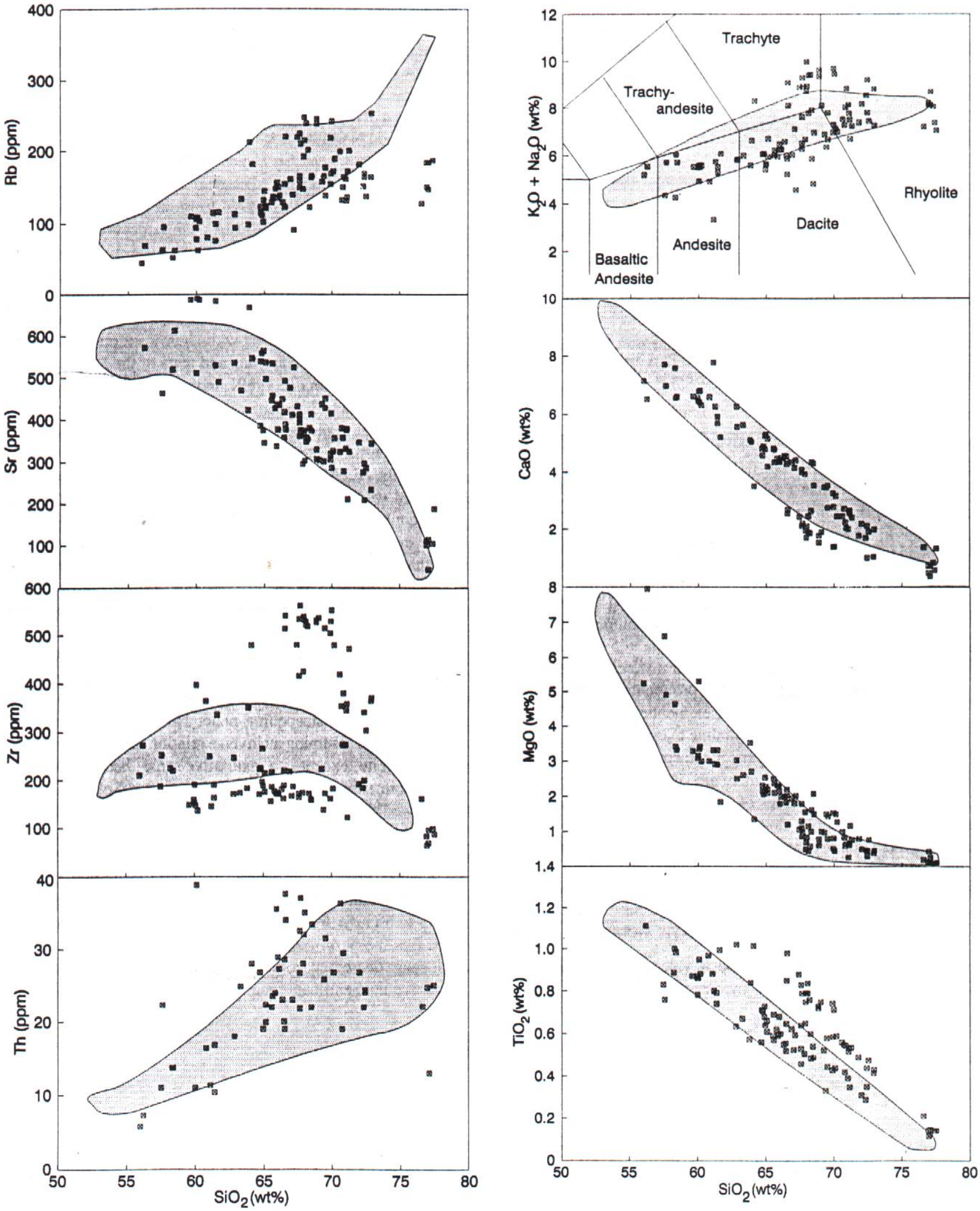

Fig. 12*a*. Comparison of compositions of volcanic rocks in the east central Nevada and Indian Peak volcanic fields. Shaded area represents samples from the east central Nevada field [*Gans et al.*, 1989; *Feeley and Grunder*, 1991] and squares represent the Indian Peak field [*Best et al.*, 1989, also unpublished data, 1991]. IUGS classification in upper left.

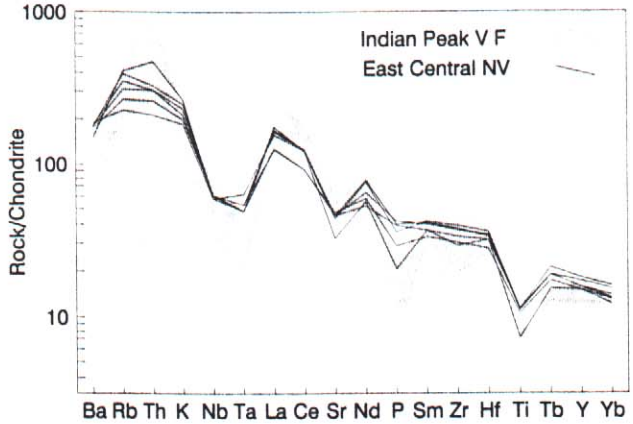

Fig. 12*b*. Chondrite normalized [*Thompson*, 1982] trace element patterns for lava flows with less than 65% SiO_2. Indian Peak field ruled; lines are representative analyses from the east central Nevada field.

compositions of the broadly calc-alkaline magmas erupted in this field and the east central Nevada field. One notable difference is the late eruption in the Indian Peak field of pl+cpx+opx trachyte to trachydacite ash flows forming the Isom Formation. Although the last eruptions in the east central Nevada field were also of relatively alkaline magmas, they do not have high concentrations of Zr, Ti, and incompatible elements like the Isom [*Christiansen et al.*, 1988]. Moreover, the late dacites in the east central Nevada field contain more biotite than pyroxene. Figure 12*b* compares the trace element patterns for intermediate composition (65% SiO_2) lava flows from the two regions. Again, no major differences are apparent. Andesites from both fields display pronounced depletions of Nb, Ta, and Ti compared to adjacent elements; such patterns are typical of subduction-related calc-alkaline magmatic suites.

Although no major contrasts exist in the compositional nature of volcanism in the two test areas, there are significant differences in the relative volumes and modes of eruption (Figure 13). Voluminous pyroclastic eruptions dominated in the Indian Peak field, whereas a lesser volume of erupted magma, mostly lava, formed the smaller east central Nevada field. Such contrasts, however, merely reflect temporal variations in the Great Basin as a whole.

ALTERNATIVE TECTONOMAGMATIC MODEL

Fundamental properties of Great Basin volcanism and tectonism during the Tertiary which must be incorporated into an interpretive model include (1) southward decelerating sweep of calc-alkaline, subduction-related volcanism (Figure 2), (2) coincidence in space and time of most voluminous volcanism with the area where the sweep slowed and stagnated in the southern Great Basin 34–17 Ma, forming the Reno-Marysvale volcanic zone (Figure 1), (3) decreased speed of convergence between oceanic Farallon-Vancouver and continental North American plates through the Tertiary [*Stock and Molnar*, 1988; see also *Engebretson et al.*, 1985]; the north velocity component (parallel to plane of Figure 2) at 45N and 38N probably decreased about threefold from the earliest Paleocene to latest Eocene, while no significant change occurred in the east component; during this time, the direction of movement of the oceanic plate shifted to more easterly (Figure 1), (4) most voluminous volcanism dominantly pyroclastic, i.e., the "ignimbrite flare-up" (Figure 3), (5) most voluminous volcanism in the Great Basin not associated in space and time with significant crustal extension (the same was true of the San Juan and parts of the Mogollon-Datil volcanic fields [*Gans et al.*, 1989]. In the Sierra Madre Occidental in Mexico, there is little sedimentary material and angular discordance in the central plateau, which is as much as 3 km above sea level, although the eastern and western margins are cut by many normal faults (F. McDowell, personal communication, March 1990)), and (6) extension and volcanism during the Tertiary not closely coupled in space and time.

Cross and Pilger [1978] and *Lipman* [1980, Figure 14.6] suggested that the southward sweep of volcanism in the Great Basin was related to progressive steepening and foundering of the subducting oceanic lithosphere beneath the continental lithosphere (Figure 2) as the rate of plate convergence diminished in the Tertiary. Mafic, mantle-derived magmas that thermally powered and provided mass to the migrating continental magma systems were associated in some way with the southward growing asthenospheric wedge overlying the steepening plate. However, *Glazner* [1983] cautioned against assuming an inverse relation between slab dip and convergence rate, except in a qualitative sense, because of a study of 17 modern subduction zones by *Tovish and Schubert* [1978]. They showed that for 12 zones, dips are 45°–80° for convergent velocities less than about 10 cm/yr but 5°–30° for five slabs where velocities are 10–11 cm/yr. For comparison, during the Tertiary of western North America, *Engebretson et al.* [1985] found that from 26°N to 42°N latitude the total convergent velocity decreased from about 15 to 5 cm/yr from 50 to 25 Ma. *Stock and Molnar* [1988] showed that the north component of velocity for about the same latitude range decreased from about 10 to 3 cm/yr from 68 to 42 Ma. Thus we see no significant inconsistency between the geophysical

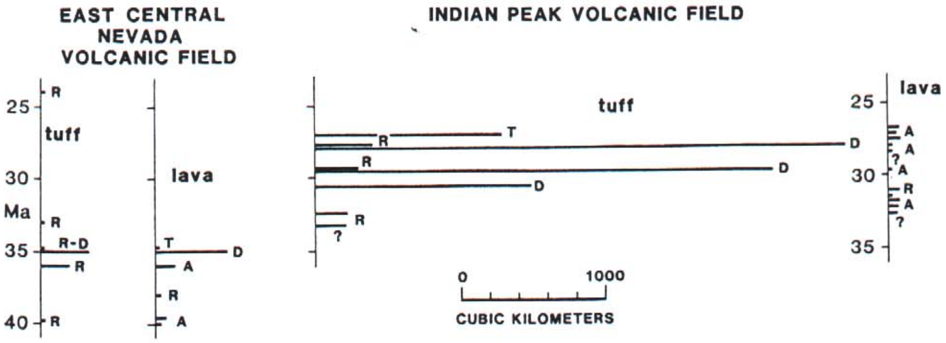

Fig. 13. Comparison of rock volumes in synextensional east central Nevada volcanic field and nonextensional Indian Peak volcanic field. Volumes for units in east central Nevada field taken from *Gans et al.* [1989, Figure 4] by scaling thicknesses of minor units against thickness of two major tuff and lava units of cited volume. Data for Indian Peak field from *Best et al.* [1989*a*]; timing and volumes of lava extrusions are schematic and time of inception of volcanism is uncertain but close to 33 Ma. A, andesite; D, dacite; T, trachyte; R, rhyolite.

data and the proposed model of a foundering and steepening slab (Figure 2).

Further dynamic considerations of middle Tertiary volcanism nd tectonism in the Great Basin can be viewed with respect to the late Cenozoic evolution of the central Andes, also a site of shallow subduction of oceanic lithosphere.

The Altiplano-Puna of western South America is a high plateau ranging from 3.5 to 4.7 km in elevation and extending from about 200 to 600 km inland from the trench [*Froidevaux and Isacks*, 1984; *Isacks*, 1988]. Episodic tectonic shortening during the late Cretaceous and Cenozoic [*Noble et al.*, 1990*a*] produced a crust about 70 km thick that is capped by a relatively thin veneer of volcanic deposits, including at least 10,000 km^3 of latest Miocene to Pleistocene ash flow tuff [*de Silva*, 1989*a*]. Some large-volume tuff sheets are of crystal-rich dacite, whereas contemporaneous andesitic lavas are volumetrically subordinate, as in the late Oligocene-early Miocene of the Great Basin [*de Silva*, 1989*b*; *Christiansen and Best*, 1989]. Since major compressional faulting in the late Miocene, the plateau block has been tectonically relatively inert and current shallow (65 km) seismicity is very limited [*Froidevaux and Isacks*, 1984]; only local minor compressional and extensional faulting has occurred (*Jordan et al*. [1983]; but see *Moore and Wernicke* [1988]). *Isacks* [1988] concluded that significant post-late Miocene uplift was a consequence of crustal thickening associated with crustal shortening of the order of 100 km as well as thermal thinning of the mantle lithosphere related to convective transport of heat from the underlying wedge of asthenospheric mantle. Although the horizontal force perpendicular to a plateau such as the Altiplano-Puna can be constant during plate convergence, lateral variations in crustal thickness and density across it can modify the ientations of principal stresses so that stress states are locally orizontally isotropic or conducive to extensional or strike-slip faulting [*Molnar and Lyon-Caen*, 1988; *England and Houseman*, 1989]. North and south of the Altiplano-Puna, mean elevation is less, crust is thinner, and andesitic rocks dominate over ash flows. *Isacks* [1988, p. 3228] concluded

> There is no evidence for major crustal rifts that might result if large amounts of material were injected into the crust as dikes. The physiographic characteristics of the [Altiplano-Puna] plateau thus indicate that substantial magmatic contributions would have to be in the form of sill-like intrusions or horizontally distributed underplating of material rather than large vertical dikelike intrusions.

In the area that became the Great Basin, compressional episodes occurred during the Paleozoic and Mesozoic [*Stewart*, 1980] and in the eastern part shortening of 104–135 km occurred 150–50 Ma [*Levy and Christie-Blick*, 1989]. The amount of associated crustal thickening was probably variable; quantification is problematic and depends upon uncertain assumptions [*Sonder et al*., 1987; *Gans*, 1987; *Coney and Harms*, 1984]. Mesozoic granitic intrusions are widely scattered [*Barton et al.*, 1988], particularly in southeastern Nevada and western Utah, but local bodies of two-mica granite are thought to be related to thickened crust [e.g., *Armstrong*, 1983; *Lee and Christiansen*, 1983] and seem to be associated in some way with highly extended terranes [*Anderson*, 1988].

The cause of local extension that occurred in the early Oligocene is uncertain but possibly was related to gravitationally unstable thickened crust or to momentary relaxation of compressional force as the speed of plate convergence started to diminish after about 50 Ma. Volcanism accompanying this episode was dominated by extrusions of lava (Figure 10). Mantle-derived magmas may have invaded the crust as dikes; only the more evolved magmas leaked to the surface [*Glazner and Ussler*, 1988] and before very large volumes of magma were produced (Figure 14).

During the late Oligocene-early Miocene, significant changes

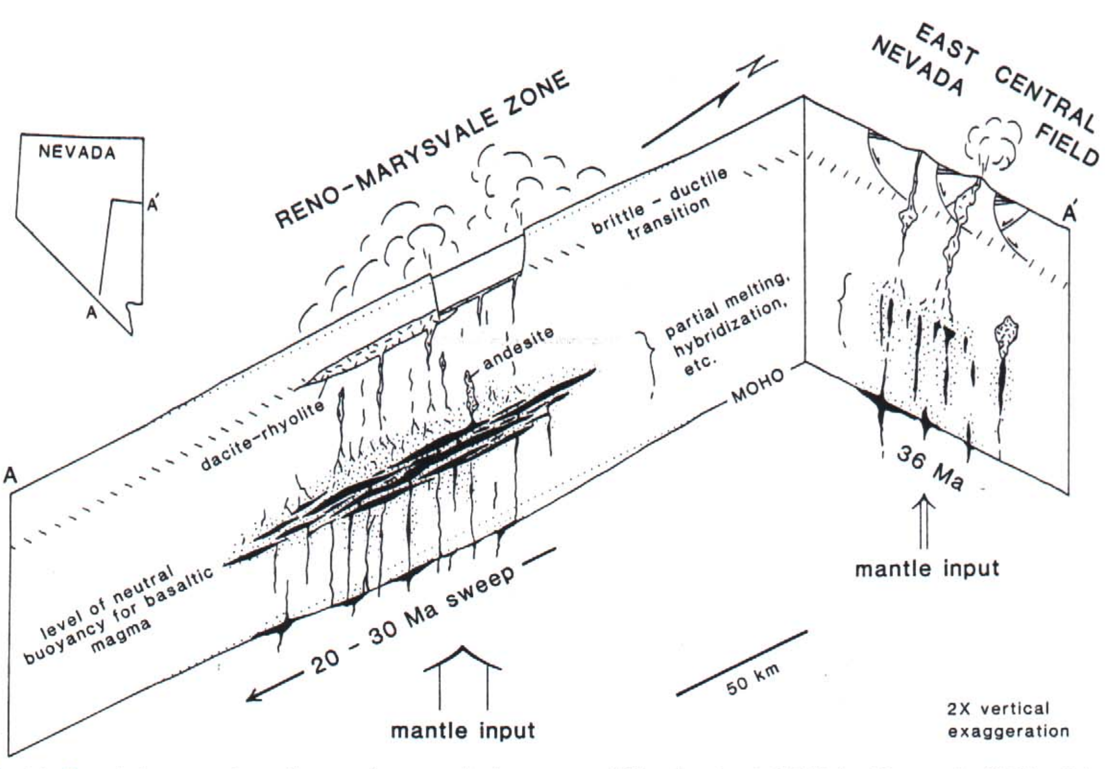

Fig. 14. Speculative comparison of magmatic systems in the east central Nevada volcanic field [after *Gans et al*., 1989] and the Reno-Marysvale zone where peak volcanism in the Great Basin occurred. Large input of mantle-derived basaltic magma stagnating as sills at a level of neutral buoyancy spawned large silicic magma bodies in the Reno-Marysvale zone. Smaller mantle magma input in the extending east central Nevada crust formed dikes and smaller silicic magma bodies. Dotted lines for crust in Reno-Marysvale zone is a 50-km-thick reference thickness to show that intruded mantle-derived magma thickened and elevated crust.

occurred in plate tectonic and crustal processes that we believe had a profound magmatic and tectonic effect in the Great Basin. As the southward sweeping mantle magma supply to the crust nearly stagnated in the south central Great Basin, as much as an order of magnitude more mantle-derived mafic magma might have been inserted into the crust, compared to the region of faster sweep to the north. This greater mantle magma input into the Reno-Marysvale zone is reflected in the contrasting volumes of the erupted, more evolved magma between the northern (43–34 Ma) and south central Great Basin (34–17 Ma) (Figure 10). The ascending basaltic magma may have been trapped at midcrustal density discontinuities where the magma had neutral buoyancy [*Glazner and Ussler*, 1988].

If such a large volume of mantle-derived magma was emplaced as dikes into the lower crust in the Reno-Marysvale zone, it would be expected to be accomodated by extension. But according to our data, extension was limited during peak volcanism. We do not yet have requisite trace element and isotopic data to evaluate approximately how much mantle-derived magma must have been emplaced into the crust to produce the extrusive volume of volcanic rock in the Reno-Marysvale zone [cf. *Riciputi and Johnson*, 1990]. Nonetheless, a crude estimate can be made using the numerical model of *Feeley and Grunder* [1991] and assuming similar proportions of crust and mantle components were involved because volcanic rock compositions are similar (see section on Previous tectonomagmatic models). In an area of about 150 km^2 in the Egan Range northwest of Ely, Nevada, *Feeley and Grunder* [1991] concluded that to produce about 40 km^3 of volcanic rock (mostly lava flows, average thickness 0.27 km) at least 4.5–9 km of basalt was added to the crust, ignoring that involved in crustal melting. In the whole Reno-Marysvale zone, at least 35,000 km^3 of rock (which does not include an untold volume of air fall tuff outside the zone) is spread over an area of roughly 80,000 km^2 (compensated for an estimated 50% east-west crustal extension) for an average thickness of 0.44 km. This would imply that 7.3–14.7 km of basalt was added to the crust in the zone. If this basalt was injected as vertical dikes through 20 km of the lower crust, which is probably an excessive depth interval, each one km^2 cross-sectional vertical column of lower crust would contain dikes 0.37–0.73 km in width, for a horizontal extension of 37–73%. If the assumptions and approximations in this model are reasonable, then diking should have been manifest in brittle extension of the upper crust. However, our stratigraphic data allow for only limited extension, in all probability less than this calculated range.

Entrapment of a large volume of magma in the crust without accompanying horizontal extension is possible if the intrusions are subhorizontal sheets, or sills; the crust simply inflates vertically. Independent evidence for such sheets in the Great Basin is, however, only circumstantial.

It is commonly assumed that horizontal intrusive sheets require that the least principal stress be vertical. Unfortunately, the state of stress in the Great Basin during the time of most voluminous volcanism is difficult to evaluate directly. The speed of plate convergence had diminished prior to, and perhaps continued to decrease during, early peak volcanism, reducing the magnitude of the compressional force on the continent and thus favoring extensional conditions due to gravitational instability of previously thickened crust [*England and Houseman*, 1989, Figures 1b and 1c]. *Bartley* [1990] suggested that a north-south component of "active spreading" associated with the peak volcanism might have been superposed on the crustal stress field otherwise controlled by buoyancy forces in a thickened crust. East-west vertical dikes emplaced during peak volcanism are sparse regionally; a few in the Marysvale, Utah, area are J- and T-shaped [*Anderson*, 1986], suggesting local horizontally isotropic stress rather than a minimum principal stress north-south [*Best*, 1988*a*]. Local, limited synvolcanic extension west of Pioche, Nevada [*Taylor et al.*, 1989], indicates an east-west to northeast-southwest minimum principal stress. Indirectly, such information suggests a more or less isotropic state of stress in the Great Basin that varied slightly from place to place and possibly in time as well. Deviatoric states of variable orientation resulted, but nowhere were magnitudes sufficient to produce major deformation. This interpretation is reminiscent of the contemporary state in the Altiplano-Puna of South America discussed above. Mantle-derived basaltic magmas might have initially ascended into the lower crust in the Reno-Marysvale corridor as vertical dikes. But continued copious injection of mafic magma, ascent to a level of neutral buoyancy, and consequent swelling against the wall rock could have increased the horizontal principal stresses until the vertical stress became least, in which situation sills formed and grew repeatedly as long as the mafic magma supply lasted (for further mechanical arguments see *McCarthy and Thompson* [1988, p. 1370] and *Shaw* [1980, pp. 229–230]).

Reorientation of principal stresses during diking is even more likely in a crust under more or less isotropic stress if the effect of thermal expansion of the wall rock is considered; the horizontal thermal stress normal to the vertical dike can exceed the ambient deviatoric stress [*Tucotte and Schubert*, 1982, p. 87; see also *Etheridge*, 1983].

Rinehart et al. [1979] found seismic evidence for a sill at a depth of about 20 km beneath the Rio Grande rift. The sill has a thickness of 0.6–1.2 km if the magma is wholly liquid and a lateral extent of at least 1700 km^2. They conclude that although the rift has formed in an extensional stress regime since late Oligocene, the contemporary state appears to be compressive(σ_1 horizontal north-south) or possibly hydrostatic. *Howard* [1991] reported intrusions of mafic rock exposed over a large area of Arizona and southeastern California that were emplaced as horizontal sheets. *Goodwin et al.* [1989] interpreted prominant seismic reflectors in the subsurface of west central Arizona as horizontal mafic sheets.

Thus, although we have no direct evidence for widespread sills of Tertiary mafic rock in the lower crust in the Reno-Marysvale zone (Figure 14), their existence seems likely and could be tested by appropriate seismic investigations [*Goodwin et al.*, 1989]. In a lower crust under more or less isotropic stress and still relatively warm, and therefore weak, due to Mesozoic thrusting [*Glazner and Bartley*, 1985; *Sonder et al.*, 1987; *Gaudemer et al.*, 1988], conditions for silling of mafic magma intruded at a high rate at a level of neutral buoyancy seem especially favorable.

Huppert and Sparks [1988] concluded that mafic magma intruded as sills, compared to dikes, provides a more promising situation for extensive and geologically rapid melting of crustal rocks. As large "ponds" of silicic crustal magmas formed, subsequent batches of mafic magma ascending into the lower crust were buoyantly blocked and stagnated, which led to further heating and melting and large-scale mixing of mafic and silicic magmas [*Best et al.*, 1989*a*; *Feeley and Grunder*, 1991]. Because of the prewarmed crust, the depth interval over which partial melting occurred was possibly greater relative to normal crust as well as the proportion of melt produced and the potential amount of mixing. Thus generation of dacite-rhyolite magma was maximized in this regime of large mantle input where the lower crust was already relatively warm.

According to the calculations of *Huppert and Sparks* [1988, p. 621], ". . . melting occurs in the thermal boundary layer and simultaneous crystallization must occur in the interior of the melt layer as *it forms* . . . large volumes of crystal-rich magma could be generated in a source region in very short time periods." As shown by *Best et al.* [1989*a,b*] much of the pyroclastic material erupted during the period of most voluminous volcanism in the Great Basin was crystal-rich dacite of the Monotony type. Such vast volumes (individual eruptions as much as 3000 km^3) of dacite magma imply large mantle input. Gravitational instability of huge magma bodies of presumed sill form (Figure 14) ultimately led to eruption and associated caldera collapse.

Eruptions of the very large volume Monotony-type ash flows in the Reno-Marysvale zone, chiefly 31–27 Ma, were succeeded by widespread venting of trachytic ash flows of the Isom type, mostly 27–23 Ma [*Best et al.*, 1989*b*; *Christiansen and Best*, 1989]. Preliminary interpretations of compositional data suggest [*Christiansen et al.*, 1988; *Best et al.* [1989*a*] that these unusual, high-temperature calc-alkaline magmas were created by fractionation of pyroxene from mafic parents with limited involvement with silicic crust. This interpretation is compatible with our envisaged massive input of mantle-derived magma into the crust along the Reno-Marysvale corridor where the Isom magmas eventually evolved.

Buoyancy of the Great Basin lithosphere stemming from Mesozoic compression and resultant crustal thickening and heating was greatly augmented during Tertiary magmatism and foundering of the subducting oceanic plate beneath the continental lithosphere. Thermal erosion of the lithosphere as hotter asthenosphere moved in under it added another component of buoyancy that no doubt culminated in optimum conditions for extensional collapse of the elevated crust [*England and Houseman*, 1989; *Molnar and Lyon-Caen*, 1988]. Yet another factor allowing for crustal extension after peak volcanism was progressive shut off of subduction after about 28 Ma [e.g., *Stock and Molnar*, 1988] along the continental margin, greatly reducing, if not effectively eliminating, compressive force against the continent. This ongoing extensional event probably had a diachronous, but difficult to date, inception and has occurred in separate domains at different times; it has been obviously more widely distributed and more pervasive throughout, and beyond, the Great Basin area than the prepeak volcanic extensional episode [*Wernicke et al.*, 1987; *Levy and Christie-Blick*, 1989].

The shift to a widespread state of lithospheric extension has allowed extrusion of basaltic lavas only since approximately the middle Miocene. Complete thermal erosion of the lithospheric mantle and replacement by asthenosphere has apparently occurred locally in the Great Basin [*Fitton et al.*, 1988]. Only since peak volcanism can the Great Basin possibly qualify as an example of an active rift, but its evolution has been so complex through the Tertiary that simplistic rift models are difficult to apply [*Bartley*, 1990].

In the Oligocene-early Miocene Marysvale field just east of the Great Basin (Figure 1), volcanism was dominated by extrusion of lava flows, rather than ash flows. Can this contrast be reconciled in our dynamic model? It is probably no coincidence that the eastern limit of Mesozoic-earliest Tertiary thrusting and presumed crustal thickening roughly separates the Marysvale field from the Great Basin [e.g., *Levy and Christie-Blick*, 1989]. The lower crust beneath the Marysvale field was probably not warmed prior to major volcanism as was the crust beneath the Great Basin because of little crustal thickening associated with thrusting. Presumably, the underlying mantle lithosphere was also cooler and apparently less mantle-derived magma invaded the crust at the eastern end of the Reno-Marysvale zone. Consequently, less thermal energy was available to power crustal magma systems, and silicic pyroclastic eruptions were subordinate to eruption of andesitic lava. Likewise, only after an enormous amount of mafic magma was emplaced in the San Juan crust did large caldera-forming silicic magma systems develop there [*Lipman*, 1975].

CONCLUSIONS

Tertiary extension in the Great Basin was interrupted during the late Oligocene-early Miocene by a largely ignored or unrecognized period of virtual tectonic quiescence during which time the most voluminous volcanism in the Great Basin occurred. Maximum extension and maximum volcanism in the Great Basin appear to be largely mutually exclusive in space and time. Extension during the peak volcanism, or ignimbrite flareup, was so limited that the concept of "synextensional volcanism" is hardly appropriate. The expected stratigraphic record for synextensional volcanism [*Gans et al.*, 1989, Figure 18] is strikingly different from the observed record in the middle Tertiary (Figure 6).

An older episode of extension before peak volcanism, probably in the early Oligocene about 36 Ma, was apparently mostly localized in eastern Nevada. More widespread postpeak extension in the Great Basin was associated in time with lava dominant volcanism (Figure 10), but spatial correspondence is poor (Figure 11). As Taylor et al. previously concluded [e.g., *Taylor et al.*, 1989], for a local area, volcanism and extensional faulting were not correlative in space and time through most of the Tertiary of the Great Basin.

First-order tectonomagmatic properties of the Great Basin in the middle Tertiary can be related to plate interactions. As the speed of oceanic-continent convergence diminished, the subducting plate is presumed to have dropped away from the continental plate and assumed a steepening dip, causing a decelerating southward sweep of volcanic activity through the Great Basin. As the sweep nearly stagnated in the south central Great Basin in the Reno-Marysvale corridor in the late Oligocene-early Miocene, we postulate that a copious volume of mantle-derived magma lodged as horizontal sheets in the lower crust in a nearly isotropic state of stress that was previously warmed by Mesozoic crustal thickening. These optimal conditions produced huge silicic magma bodies that erupted thousands of cubic kilometers of pyroclastic material, chiefly crystal-rich dacite (Monotony type).

Lava dominant volcanism before and after this ignimbrite flareup was associated with a crust in a state of extension with a lower mantle input. Such conditions engendered smaller, "leaky" crustal magma systems which did not mature into huge, sill-fed, Monotony-type systems.

Simplistic models of active versus passive rifting are inappropriate to the complexly evolving Great Basin during the Tertiary.

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REFERENCES

Abbott, J.T., M.G. Best, and H.T. Morris, Geologic map of the Pine Grove-Blawn Mountain area, Beaver County, Utah, U.S. Geol. Surv. *Misc. Invest. Map, I-1479*, 1983.

Anderson, J.J., Geologic map of the Circleville Mountain quadrangle, Beaver, Piute, and Garfield counties, Utah, *Map 80*, Utah Geol. Mineral Surv., Salt Lake City, 1986.

Anderson, J.L., Core complexes of the Mojave-Sonoran Desert: Conditions of plutonism, mylonitization, and decompression, in *Metamorphism and Crustal Evolution of the Western United States*, edited by W.G. Ernst, pp. 502–525, Prentice-Hall, Englewood Cliffs, N.J., 1988.

Anderson, R.E., Cenozoic structural history of selected areas in the eastern Great Basin, Nevada-Utah, *U.S. Geol. Surv. Open File Rep.*, 83–504, 1983.

Armstrong, R.L., Cordilleran S- and I-type granites, Indicators of lithosphere thickness, *Geol. Assoc. Can. Annu. Meet. Program*, *8*, A3, 1983.

Armstrong, R.L., E.B. Ekren, E.H. McKee, and D.C. Noble, Space-time relations of Cenozoic silicic volcanism in the Great Basin of the western United States, *Am. J. Sci.*, *267*, 478–490, 1969.

Axen, G.J., P.R. Lewis, K.J. Burke, K.G. Sleeper, and J.M. Fletcher, Tertiary extension in the Pioche area, Lincoln County, Nevada, in *Cordilleran Section Field Trip Guidebook*, edited by D.L. Weide and M.L. Faber, pp. 3–5, Geological Society of America, Boulder, Colo., 1988.

Bartley, J.M., Changing Tertiary extension directions in the Dry Lake Valley area, Nevada, and a possible dynamic model, in *Compressional and Extensional Structural Styles in the Northern Basin and Range*, Geological Society of Nevada, Reno, pp. 35–39, 1990.

Bartley, J.M., and G. Gleason, Tertiary normal faults super imposed on Mesozoic thrusts, Quinn Canyon and Grant Ranges, Nye County, Nevada, *Mem. Geol. Soc. Am.*, 176, pp. 195–212, 1990.

Bartley, J.M., G.J. Axen, W.J. Taylor, and J.E. Fryxell, Cenozoic tectonics of a transect through eastern Nevada near 38 N latitude, in *Cordilleran Section Field Trip Guidebook*, edited by D.L. Weide and M.L. Faber, pp. 1–2, 6–20, Geological Society of America, Boulder, Colo., 1988.

Barton, M.D., D.A. Battles, G.E. Debout, R.C. Capo, J.N. Christensen, S.R. Davis, R.B. Hanson, C.J. Michelsen, and H.E. Trim, Mesozoic contact metamorphism in the western United States, in *Metamorphism and Crustal Evolution of the Western United States*, edited by W.G. Ernst, pp. 110–178, Prentice-Hall, Englewood Cliffs, N.J., 1988.

Best, M.G., Early Miocene change in direction of least principal stress, southwestern United States: Conflicting inferences from dikes and metamorphic core-detachment fault terranes, *Tectonics*, *7*, 249–259, 1988a.

Best, M.G., Easterly trending Oligocene to early Miocene (30–20 Ma) paleotopography and other geologic features, southeastern Great Basin, *Geol. Soc. Am. Abstr. Programs, 20*, 143, 1988b.

Best, M.G., and L.F. Hintze, Geology of the Sawtooth Peak quadrangle, Beaver County, Utah; *U.S. Geol. Surv. Misc. Field Stud. Map, MF-1152*, 1980.

Best, M.G., S.K. Grant, L.F. Hintze, J.G. Cleary, A. Hutsinpiller, and D.M. Saunders, Geologic map of the Indian Peak (southern Needle) Range, Beaver and Iron counties, Utah, *U.S. Geol. Surv. Misc. Invest. Map, I-1795*, 1987a.

Best, M.G., H.H. Mehnert, J.D. Keith, and C.W. Naeser, Miocene magmatism and tectonism in and near the southern Wah Wah Mountains, southwestern Utah, *U.S. Geol. Surv. Prof. Pap. 1433-B*, 29–47, 1987b.

Best, M.G., H.T. Morris, R.W. Kopf, and J.D. Keith, Geologic map of the southern Pine Valley area, Beaver and Iron Counties, Utah, *U.S. Geol. Surv. Misc. Invest. Map, I-1794*, 1987c.

Best, M.G., E.H. Christiansen, and R.H. Blank, Jr., Oligocene caldera complex and calc-alkaline tuffs and lavas of the Indian Peak volcanic field, Nevada and Utah, *Geol. Soc. Am. Bull.*, *101*, 1076–1090, 1989a.

Best, M.G., E.H., Christiansen, A.L. Deino, C.S. Grommé, E.H. McKee, and D.C. Noble, Eocene through Miocene volcanism in the Great Basin of the western United States, *Mem. N. M. Bur. Mines Miner. Resour. 47*, 91–133, 1989b.

Christiansen, E.H., and M.G. Best, Compositional contrasts among middle Cenozoic ash-flow tuffs of the Great Basin, western United States in *Continental Magmatism*, Bull. N. M. Bur. Mines Miner. Resour., *131*, 51, 1989.

Christiansen, E.H., M.F. Sheridan, and D.M. Burt, The geology and geochemistry of Cenozoic topaz rhyolites from the western United States, *Spec. Pap. Geol. Soc. Am.*, *205*, 82 pp., 1986.

Christiansen, E.H., M.G. Best, and J.D. Hoover, Petrology of a trachytic tuff from a calc-alkaline volcanic center: The Oligocene Isom tuff, Indian Peak volcanic field, Utah and Nevada, *Eos Trans. AGU*, *69*, 1494, 1988.

Christiansen, R.L., Volcanism associated with post-Laramide tectonic extension in the western U.S., in Continental Magmatism, *Bull. N. M. Bur. Mines Miner. Resour.*, 131, 51, 1989.

Christiansen, R.L., and P.W. Lipman, Cenozoic volcanism and plate tectonic evolution of the western United States, II, Late Cenozoic, *Philos. Trans. R. Soc. London, Ser. A*, *271*, 249–284, 1972.

Coney, P.J., and T.A. Harms, Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression, *Geology*, *12*, 550–554, 1984.

Cook, E.F., Stratigraphy of Tertiary volcanic rocks in eastern Nevada, *Rep. Nev. Bur. Mines*, *11*, 61 pp., 1965.

Cross, T.A., and R.H. Pilger, Jr., Constraints on absolute motion and plate interaction inferred from Cenozoic igneous activity in the western United States, *Am. J. Sci.*, *278*, 865–902, 1978.

Davis, G.A., and G.S. Lister, Detachment faulting in continental extension: Perspectives from the southwestern U.S. Cordillera, *Spec. Pap. Geol. Soc. Am.*, *218*, 133–160, 1988.

Deino, A.L., Single crystal ^{40}Ar/^{39}Ar dating as an aid in correlation of ash flows: Examples from the Chimney Spring/New Pass Tuffs and the Nine Hill/Bates Mountain Tuffs of California and Nevada, in Continental Magmatism, *Bull. N. M. Bur. Mines Miner. Resour.*, 131, 70, 1989.

de Silva, S.L., Petrology and petrogenesis of ignimbrites from the central Andes, in Continental Magmatism, *Bull. N. M. Bur. Mines Miner. Resour.*, 131, 68, 1989.

de Silva, S.L., Altiplano-Puna volcanic complex of the central Andes, *Geology*, *17*, 1102–1106, 1989b.

Dixon, G.L., D.C. Hedlund, and E.B. Ekren, Geologic map of the Pritchards Station quadrangle, Nye County, Nevada, *U.S. Geol. Surv. Misc. Invest. Map*, *I-728*, 1972.

Eaton, G.P., The Basin and Range Province: Origin and tectonic significance, *Annu. Rev. Earth Planet. Sci.*, *10*, 409–440, 1982.

Engebretson, D.C., A. Cox, and G.A. Thompson, Correlation of plate motions with continental tectonics: Laramide to Basin-Range, *Tectonics*, *3*, 115–119, 1984.

Engebretson, D.C., A. Cox, and R.G. Gordon, Relative motions between oceanic and continental plates in the Pacific Basin, *Spec. Pap. Geol. Soc. Am.*, *206*, 59 pp., 1985.

England, P., and G. Houseman, Extension during continental convergence, with application to the Tibetan Plateau, *J. Geophys. Res.*, *94*, 17,561–17,579, 1989.

Etheridge, M.A., Differential stress magnitudes during regional deformation and metamorphism: Upper bound imposed by tensile fracturing, *Geology*, *11*, 231–234, 1983.

Feeley, T.C., and A.L. Grunder, Hybridization of crust and mantle melts during early phases of extension: The Egan Range volcanic complex, eastern Nevada, *Contrib. Mineral Petrol.*, in press, 1991.

Fenneman, N.M., *Physiography of Western United States*, 534 pp., McGraw-Hill, New York, 1931.

Fitton, J.G., D. James, P.D. Kempton, D.S. Ormerod, and W.P. Leeman, The role of lithospheric mantle in the generation of late Cenozoic basic magmas in the western United States, *J. Petrol.*, *Special Lithosphere Issue*, 331–349, 1988.

Froidevaux, C., and B.L. Isacks, The mechanical state of the lithosphere in the Altiplano-Puna segment of the Andes, *Earth Planet. Sci. Lett.*, *71*, 305–314, 1984.

Gans, P.B., An open-system, two-layer crustal stretching model for the eastern Great Basin, *Tectonics*, *6*, 1–12, 1987.

Gans, P.B., and G.A. Mahood, The interplay between Cenozoic extension and magmatism in the Basin and Range province, in Continental Magmatism, *Bull. N. M. Bur. Mines Miner. Resour.*, 131, 101, 1989.

Gans, P.B., and E.L. Miller, Style of mid-Tertiary extension in east-central Nevada, *Spec. Stud. Utah Geol. Miner. Surv.*, *59*, 107–160, 1983.

Gans, P.B., G.A. Mahood, and E. Schermer, Synextensional magmatism in the Basin and Range province: a case study from the eastern Great Basin, *Spec. Pap. Geol. Soc. Am.*, *233*, 58 pp., 1989.

Gaudemer, Y., C. Jaupart, and P. Tapponnier, Thermal control on post-orogenic extension in collision belts, *Earth Planet. Sci. Lett.*, *89*, 48–62, 1988.

Glazner, A.F., Paleoconvergence rates determined from K$_2$O/SiO$_2$ ratios in magmatic rocks and their application to Cretaceous and Tertiary tectonic patterns in southwestern North America: Discussion, *Geol. Soc. Am. Bull.*, *94*, 1032, 1983.

Glazner, A.F., and J.M. Bartley, Evolution of lithospheric strength after thrusting, *Geology*, *13*, 42–45, 1985.

Glazner, A.F., and J.M. Bartley, Contrasting Cenozoic tectonomagmatic histories of the northern and southern Basin and Range, *Geol. Soc. Am. Abstr. Programs, 22*, 25, 1990.

Glazner, A.F., and W. Ussler III, Trapping of magma at midcrustal density discontinuities, *Geophys. Res. Lett., 15*, 673–675, 1988.

Goodwin, E.B., G.A. Thompson, and D.A. Okaya, Seismic identification of basement reflectors: the Bagdad reflection sequence in the Basin and Range Province-Colorado Plateau transition zone, Arizona, *Tectonics, 8*, 821–831, 1989.

Grommé, C.S., E.H. McKee and M.C. Blake, Jr., Paleomagnetic correlations and potassium-argon dating of middle Tertiary ash-flow sheets in the eastern Great Basin, Nevada and Utah, *Geol. Soc. Am. Bull., 83*, 1619–1638, 1972.

Hildreth, W., Gradients in silicic magma chambers: Implications for lithospheric magmatism, *J. Geophys. Res., 86*, 10153–10192, 1981.

Hintze, L.F., Preliminary geologic map of The Barn quadrangle, Millard County, Utah, *U.S. Geol. Surv. Misc. Field Stud. Map, MF–633*, 1974.

Hintze, L.F., Geologic history of Utah, *Brigham Young Univ. Geol. Stud. Spec. Publ. 7*, 202 pp., 1988.

Hintze, L.F., and M.G. Best, Geologic map of the Mountain Home Pass and Miller Wash quadrangles, Millard and Beaver Counties, Utah, and Lincoln County, Nevada, *U.S. Geol. Surv. Misc. Field Stud. Map, MF-1950*, 1987.

Hintze, L.F., S.K. Grant, C.L. Weaver, and M.G. Best, Geologic map of the Blue Mountain-Lund area, Beaver and Iron counties, Utah, *U.S. Geol. Surv. Misc. Invest. Map*, in press.

Howard, K.A., Intrusion of horizontal dikes: Tectonic significance of middle Proterozoic diabase sheets widespread in the upper crust of the southwestern United States, *J. Geophys. Res., 96*, in press, 1991.

Huppert, H.E. and R.S.J Sparks, The generation of granitic magmas by intrusion of basalt into continental crust, *J. Petrol., 29*, 599–624, 1988.

Isacks, B.L., Uplift of the central Andean Plateau and bending of the Bolivian orocline, *J. Geophys. Res., 93*, 3211–3231, 1988.

Jayko, A.S., Shallow crustal deformation in the Pahranagat area, southern Nevada, *Mem. Geol. Soc. Am.*, 176, 213–236, 1990.

John, D.A., R.E. Thomason, and E.H. McKee, Geology and K-Ar geochronology of the Paradise Peak mine and the relationship of pre-Basin and Range extension to early Miocene precious metal mineralization in west-central Nevada, *Econ. Geol., 84*, 631–649, 1989.

Jordan, T.E., B.L. Isacks, R.W. Allmendinger, J.A. Brewer, V.A. Ramos, and C.J. Ando, Andean tectonics related to geometry of subducted Nazca plate, *Geol. Soc. Am. Bull., 94*, 341–361, 1983.

Kellogg, H.E., Cenozoic stratigraphy and structure of the southern Egan Range, Nevada, *Geol. Soc. Am. Bull., 75*, 949–968, 1964.

Lee, D.E., and E.H. Christiansen, The granite problem as exposed in the southern Snake Range, Nevada, *Contrib. Mineral. Petrol., 83*, 99–116, 1983.

Levy, M., and N. Christie-Blick, Pre-Mesozoic palinspastic reconstruction of the eastern Great Basin (western United States), *Science, 245*, 1454–1462, 1989.

Lipman, P.W., Evolution of the Platoro caldera complex and related volcanic rocks, southeastern San Juan Mountains, Colorado, *U.S. Geol. Surv. Prof. Pap., 852*, 128 pp., 1975.

Lipman, P.W., Cenozoic volcanism in the western United States: Implications for continental tectonics, in *Studies in Geophysics: Continental Tectonics*, pp. 161–174, National Academy of Sciences, Washington, D. C., 1980.

Loucks, M.D., D.G. Tingey, M.G. Best, M.G., E.H. Christiansen, and L.F. Hintze, Geologic map of the Fortification Range, Lincoln and White Pine Counties, Nevada, *U.S. Geol. Surv. Misc. Invest. Ser. Map, I-1866*, 1989.

Mackin, J.H., Structural significance of Tertiary volcanic rocks in southwestern Utah, *Am. J. Sci., 258*, 81–131, 1960.

Mackin, J.H., and P.D. Rowley, Geologic map of the Three Peaks quadrangle, Iron County, Utah, *U.S. Geol. Surv. Geol. Quad. Map, GQ–1297*, 1976.

McCarthy, J., and G.A. Thompson, Seismic imaging of extended crust with emphasis on the western United States, *Geol. Soc. Am. Bull., 100*, 1361–1374, 1988.

McDowell, F.W., D.A. Wark, and G. Aguirre-Diaz, The Tertiary ignimbrite flareup in western Mexico, *Geol. Soc. Am. Abstr. Programs, 22*, 66, 1990.

McKee, E.H., Tertiary igneous chronology of the Great Basin of western United States—Implications for tectonic models, *Geol. Soc. Am. Bull., 82*, 3497–3502, 1971.

McKee, E.H., Geology of the northern part of the Toquima Range, Lander, Eureka, and Nye Counties, Nevada, *U.S. Geol. Surv. Prof. Pap., 931*, 49 pp., 1976.

McKee, E.H., D.C. Noble, and M.L. Silberman, Middle Miocene hiatus in volcanic activity in the Great Basin area of the western United States, *Earth Planet. Sci. Lett., 8*, 93–96, 1970.

Molnar, P., and H. Lyon-Caen, Some simple physical aspects of the support, structure, and evolution of mountain belts, *Spec. Pap. Geol. Soc. Am., 218*, 179–207, 1988.

Moore, A., and B. Wernicke, Extensional deformation of the southern Peruvian Altiplano, *Eos Trans. AGU, 69*, 466, 1988.

Moores, E.M., R.B. Scott, and W.W. Lumsden, Tertiary tectonics of the White Pine-Grant Range region, east-central Nevada, and some regional implications, *Geol. Soc. Am. Bull., 79*, 1703–1726, 1968.

Newman, G.W., Late Cretaceous(?)-Eocene faulting in the east central Basin and Range, in *Basin and Range Symposium and Great Basin Field Conference*, edited by G.W. Newman and H.D. Goode, pp. 167–173, Rocky Mountain Association of Geologists and Utah Geological Association, Denver, Colo., 1979.

Noble, D.C., Some observations on the Cenozoic volcano-tectonic evolution of the Great Basin, western United States, *Earth Planet. Sci. Lett., 17*, 142–150, 1972.

Noble, D.C., E.H. McKee, T. Mourier, and F. Megard, Cenozoic stratigraphy, magmatic activity, compressive deformation, and uplift in northern Peru, *Geol. Soc. Am. Bull., 102*, 1105–1113, 1990a.

Noble, D.C., S.I. Weiss, and E.H. McKee, Style, timing, distribution, and direction of Neogene extension within and adjacent to the Goldfield section of the Walker Lane structural belt, *Eos Trans. AGU, 71*, 618–619, 1990b.

Palmer, H.C., W.D. MacDonald, and A. Hayatsu, Volcanic sources and structural evolution of ash flow tuffs of the Indian Well Formation, northeast Nevada, *J. Geophys. Res., 96*, 2185–2202, 1991.

Proffett, J.M., Cenozoic geology of the Yerington district, Nevada, and implications for the nature and origin of Basin and Range faulting, *Geol. Soc. Am. Bull., 88*, 247–266, 1977.

Proffett, J.M., and J.H. Dilles, Geologic map of the Yerington district, Nevada, *Map 77*, Nev. Bur. of Mines and Geol., Reno, 1984.

Ratté, J.C., S.M. Cather, C.E. Chapin, W.A. Duffield, W.E. Elston, W.C. McIntosh, Eocene-Miocene Mogollon-Datil volcanic field, New Mexico, *Mem. N. M. Bur. Mines Miner. Resour., 46*, 43–120, 1989.

Riciputi, L.R., and C.M. Johnson, Nd- and Pb-isotope variations in the multicyclic central caldera cluster of the San Juan volcanic field, Colorado, and implications for crustal hybridization, *Geology, 18*, 975–978, 1990.

Rinehart, E.F., A.R. Sanford, and R.M. Ward, Geographic extent and shape of an extensive magma body at midcrustal depths in the Rio Grande Rift near Socorro, New Mexico, in *Rio Grande Rift: Tectonics and Magmatism*, edited by R.E. Reicker, pp. 237–251, AGU, Washington D.C., 1979.

Robinson, P.T., and J.H. Stewart, Uppermost Oligocene and lowermost Miocene ash-flow tuffs of western Nevada, *U.S. Geol. Surv. Bull., 1557*, 53 pp., 1984.

Sengor, A.M.C., and K. Burke, Relative timing of rifting and volcanism on earth and its tectonic implications, *Geophys. Res. Lett., 5*, 419–421, 1978.

Shaw, H.R., The fracture mechanisms of magma transport from the mantle to the surface, in *Physics of Magmatic Processes*, edited by R.B Hargraves, pp. 201–264, Princeton University Press, Princeton, N.J., 1980.

Siders, M.A., P.D. Rowley, M.A. Shubat, G.E. Christenson, and G.L. Galyardt, Geologic map of the Newcastle quadrangle, Iron County, Utah, *U.S. Geol. Surv. Geol. Quad. Map, GQ–1690*, 1990.

Solomon, B.J., E.H. McKee, and D.W. Anderson, Stratigraphy and depositional environments of Paleocene rocks near Elko, Nevada, in *Cenozoic Paleogeography of the western United States*, edited by J.M. Armentrout, M.R. Cole, and H. Terbest, Jr., pp. 75–88, Society of Economic Paleontologists and Mineralogists, Tulsa, Okla., 1979.

Sonder, L.J., P.C. England, B.P. Wernicke, and R.L. Christiansen, A physical model for Cenozoic extension of western North America, in Continental Extensional Tectonics, edited by M.P. Coward, J.F. Dewey, and P.L. Hancock, *Geol. Soc. Spec. Publ. London, 28*, pp. 187–201, 1987.

Stewart, J.H., Basin and Range structure in western North America—a review, in Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, edited by R.B. Smith and G.P. Eaton, *Mem. Geol. S. Am., 152*, 1–31, 1978.

Stewart, J.H., Geology of Nevada, *Spec. Publ. 4*, 136 pp., Nev. Bur. of Mines and Geol., Reno, 1980.

Stewart, J.H., and J.E. Carlson, Cenozoic rocks of Nevada, *Map 52*, Nev. Bur. of Mines and Geol., Reno, 1976.

Stock, J., and P. Molnar, Uncertainties and implications of the late Cretaceous and Tertiary position of North America relative to the Farallon, Kula, and Pacific plates, *Tectonics, 6*, 1339–1384, 1988.

Sullivan, K.R., B.J. Kowallis, and H.H. Mehnert, Isotopic ages of igneous intrusions in southeastern Utah: Evidence for a mid-Cenozoic Reno-San Juan magmatic zone, *Brigham Young Univ. Geol. Stud., 37*, in press, 1991.

Swadley, W.C., W.R. Page, R.B. Scott, and E.H. Pampeyan, Preliminary geologic map of the Delamar 3SE quadrangle, Lincoln County, Nevada, *U.S. Geol. Surv. Open File Rep. 90-221*, 1990.

Taylor, W.J., Geometry of faulting, timing of extension and their relation to volcanism, near 38°N latitude, eastern Nevada, Ph.D. thesis, 204 pp., Univ. of Utah, Salt Lake City, 1989.

Taylor, W.J., and J.M. Bartley, Stratigraphy and structure of the North Pahroc and eastern Seaman Ranges, in *Cordilleran Section Field Trip Guidebook*, edited by D.L. Weide and M.L. Faber, pp. 5–6, Geological Society of America, Boulder, Colo., 1988.

Taylor, W.J., J.M. Bartley, D.R. Lux, and G.J. Axen, Timing of Tertiary extension in the Railroad Valley-Pioche transect, Nevada: Constraints from ^{40}Ar/^{39}Ar ages of volcanic rocks, *J. Geophys. Res., 94*, 7757–7774, 1989.

Thompson, R.N., Magmatism of the British Tertiary volcanic province, *Scot. J. Geol., 18*, 49–107, 1982.

Tovish, A., and G. Schubert, Island arc curvature, velocity of convergence, and angle of subduction, *Geophys. Res. Lett., 5*, 329–332, 1978.

Turcotte, D.L., and G. Schubert, *Geodynamics: Applications of continuum physics to geological problems*, 450 pp., John Wiley and Sons, New York, 1982.

Wernicke, B.P., R.L. Christiansen, P.C. England, and L.J. Sonder, Tectonomagmatic evolution of Cenozoic extension in the North America Cordillera, in Continental Extensional Tectonics, edited by M.P. Coward, J.F. Dewey, and P.L. Hancock, *Geol. Soc. Spec. Publ. 28*, p. 203–221, 1987.

Williams, P.L., Stratigraphy and petrography of the Quichapa Group, southwestern Utah and southeastern Nevada, Ph.D. thesis, 139 pp., Univ. of Wash., Seattle, 1967.

Wust, S.L., Regional correlation of extension directions in Cordilleran metamorphic core complexes, *Geology, 14*, 828–830, 1986.

Zoback, M.L., R.E. Anderson, and G.A. Thompson, Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western United States, *Philos. Trans. R. Soc. London, Ser. A, 300*, 407–434, 1981.

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