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Synextensional magmatism in the Basin and Range Province; A case study from the eastern Great Basin

ABSTRACT

An integrated structural, stratigraphic, geochronological, and geochemical investigation of Cenozoic volcanic and sedimentary rocks within a highly extended part of the eastern Great Basin sheds light on the interplay between magmatism and extensional tectonism. Tertiary rocks in east-central Nevada and west-central Utah can be divided into three broad groups: (1) 40 to 35 Ma, locally derived sequences of andesite and rhyolite lava flows and ash-flow tuffs; (2) the voluminous 35 Ma Kalamazoo volcanic rocks, including the compositionally zoned (rhyolite to dacite) Kalamazoo Tuff, crystal-rich hornblende dacite lavas, and the K-rich dacite tuff of North Creek and associated lavas; and (3) 35 to 20(?) Ma, predominantly sedimentary sequences. Crosscutting relations between faults and subvolcanic intrusions, decreasing tilts upward within the Tertiary sections, and sedimentologic evidence for rapid unroofing of deep structural levels demonstrate that rapid, large-magnitude extension in this region began at least 36 Ma during some of the earliest eruptions, was ongoing at 35 Ma during the culminating eruptions of Kalamazoo volcanic rocks, and continued after volcanism had largely ceased. These synextensional volcanic rocks constitute a high-K calc-alkaline andesite to rhyolite series, and closely resemble suites from the central Andes rather than the bimodal or alkalic suites commonly associated with continental rifts. Trace-element systematics and reconnaissance Sr and Nd isotopic data suggest that the suite formed by extensive contamination of mantle-derived basalt by crustal partial melts in the deep crust, followed by relatively minor wall-rock assimilation during fractionation from andesite to rhyolite, presumably at shallower levels. Modeling of the isotopic data suggests that the most voluminous rock type, hornblende dacite, consists of 30 to 50 percent mantle material. Thus, intrusions associated with Cenozoic volcanic rocks represent a significant addition of new mantle-derived material to the continental crust.

A comparison of the eastern Great Basin with other highly extended parts of the Basin and Range province reveals striking similarities in eruptive and extensional histories, despite important regional variations in absolute timing. These similarities are best explained by an active rifting model that invokes a flux of basaltic magma into the crust, hybridization and mixing of these magmas with crustal melts to produce intermediate magmas that differentiate in shallower magma reservoirs, and magmatically induced thermal weakening of the crust culminating in brittle failure of the upper crust and ductile flow at depth. This model helps explain (1) the close spatial and temporal association between the onset of large-magnitude extension and voluminous volcanism throughout the province; (2) the general decrease in extensional strain rates through time; (3) the typical progression of magma compositions from early, intermediate to silicic rocks to late, relatively primitive basaltic or bimodal suites; and (4) the uniform crustal thickness and the reflective mafic lower crust of the Basin and Range province.

INTRODUCTION

Between 39 and 33 Ma, large volumes of intermediate to silicic magma were erupted from several volcanic centers in east-central Nevada, covering much of the area with 1 to 2 km of lavas and tuffs. Similar short-lived yet voluminous outpourings of intermediate to silicic volcanic rocks occurred throughout the western U.S. during the middle Tertiary. Although the timing and character of volcanism varied from place to place, the shear volume of middle Tertiary magmatism and its temporal overlap with large-magnitude extension in "metamorphic core complexes" has led several authors (e.g., Coney, 1979; Elston, 1984) to treat it as a distinct orogenic event in the development of the Cordillera. The ultimate cause and regional tectonic setting of this magmatic event remain poorly understood, in part because there have been few detailed studies integrating the magmatic and structural evolution of individual volcanic fields.

Following Atwater's (1970) reconstruction of North American and Pacific plate motions, most geologists have interpreted Tertiary magmatism in the western U.S. within the context of plate tectonics. The landmark papers by Lipman et al. (1972) and Christiansen and Lipman (1972) proposed a model for Cenozoic magmatism wherein early to mid-Tertiary volcanic rocks, predominantly andesite to rhyodacite in composition, represent the remnants of a broad continental arc related to an east-dipping subduction zone beneath North America. They proposed that the change from a convergent margin to a transform boundary during northward migration of the Mendocino triple junction was accompanied by a change from calc-alkaline "subduction-related" volcanism to bimodal basalt-rhyolite or "fundamentally basaltic" volcanism that was related to the onset of Basin and Range extension. Subsequent papers by Snyder et al. (1976), Coney and Reynolds (1977), and Keith (1978) accepted this general model and related specific changes in the space-time-composition pattern of early to mid-Tertiary volcanism to variations in the dip of the subducting slab and to changing rates of convergence.

Several aspects of Tertiary magmatism in the western U.S. are not adequately explained by simple plate tectonic models. In detail, space-time patterns of volcanism bear little relation to the inferred plate margin configuration or geometry of the subducting slab. For example, in the northern Basin and Range province (Fig. 1), volcanism swept southward, nearly parallel to the continental margin, from Oregon in the Eocene to southern Nevada in the early Miocene (Armstrong, 1970; Lipman et al., 1972; Stewart and Carlson, 1976). A related problem is that the inferred mid-Tertiary "arc" of the western U.S. was much wider than any modern arc. Contemporaneous calc-alkaline volcanism extended from central Colorado to western Nevada, a present east-west distance of 1200 km that was at least 900 km prior to extension. Modern volcanic arcs at convergent plate boundaries are all less than 300 km wide (Gill, 1981). The inferred change from calc-alkaline, "subduction-related" suites to basaltic or bimodal, "extension-related" suites (Christiansen and Lipman, 1972) also appears to be oversimplified. A growing body of data suggests that a significant amount of the extension in the Basin and Range province predated the termination of subduction at any particular latitude (e.g., Coney, 1979; Zoback et al., 1981; Gans, 1981; Chamberlin, 1983) and was synchronous with voluminous calc-alkaline volcanism (Elston, 1984; Crowe, 1978; Gans and Mahood, 1984). Similarly, the switch from typical calc-alkaline to bimodal suites was highly diachronous and does not bear any obvious relation to the position of the Mendocino triple junction.

This paper will focus on the ages and compositions of volcanic rocks within a representative part of the mid-Tertiary volcanic province and look in detail at the relation between magmatism and tectonism on a more local scale. Mid-Tertiary volcanic rocks in east-central Nevada (Figs. 1 and 2) are well suited for such a study because they are well exposed, relatively fresh, and lie within an area whose structural evolution is increasingly well understood. Representative Tertiary stratigraphic sections will be described from the Egan, Schell Creek, Deep Creek, Snake, and Confusion ranges (Fig. 3) in order to illustrate variations in the ages, thicknesses, and relative proportions of different volcanic and sedimentary rock types. Emphasis is placed on how these sections relate to the local structural history and to aspects of the stratigraphic record that document concurrent faulting. The major- and trace-element compositions of fresh volcanic rocks in east-central Nevada, together with limited isotopic data, place some constraints on their petrogenesis. A review of the eruptive and extensional histories of some other highly extended parts of the Basin and Range province reveals some striking similarities to what we have documented in the eastern Great Basin, despite important regional differences in absolute timing and crustal structure. We use the combined structural, stratigraphic, geochemical, and geophysical evidence from these highly extended terranes to develop a model for synextensional magmatism in the western United States that invokes: (1) a large flux of mantle-derived basaltic magma into the crust and extensive hybridization with crustal partial melts; (2) thermal weakening of the crustal column, culminating in catastrophic failure (extension) of the elastic lid once sufficient amounts of magma had accumulated at shallow crustal levels; and (3) a transition from hybrid, predominantly dacitic-andesitic volcanism to more primitive, basaltic volcanism as the crust thinned and cooled, and the lower crust became depleted in easily melted components.

Geologic setting

The ranges in east-central Nevada and west-central Utah are underlain mostly by an upper Precambrian to Triassic sequence of sandstones, shales, and carbonates. This well-known miogeoclinal succession includes about 20 distinctive and regionally extensive formations with an aggregate thickness in excess of 13 km (Stewart and Poole, 1974; Hose and Blake, 1976). Exposures of Tertiary rocks represent less than 20 percent of the 100 × 150 km area considered in this paper and are concentrated in the northern Schell Creek Range and Antelope Range (Fig. 2).

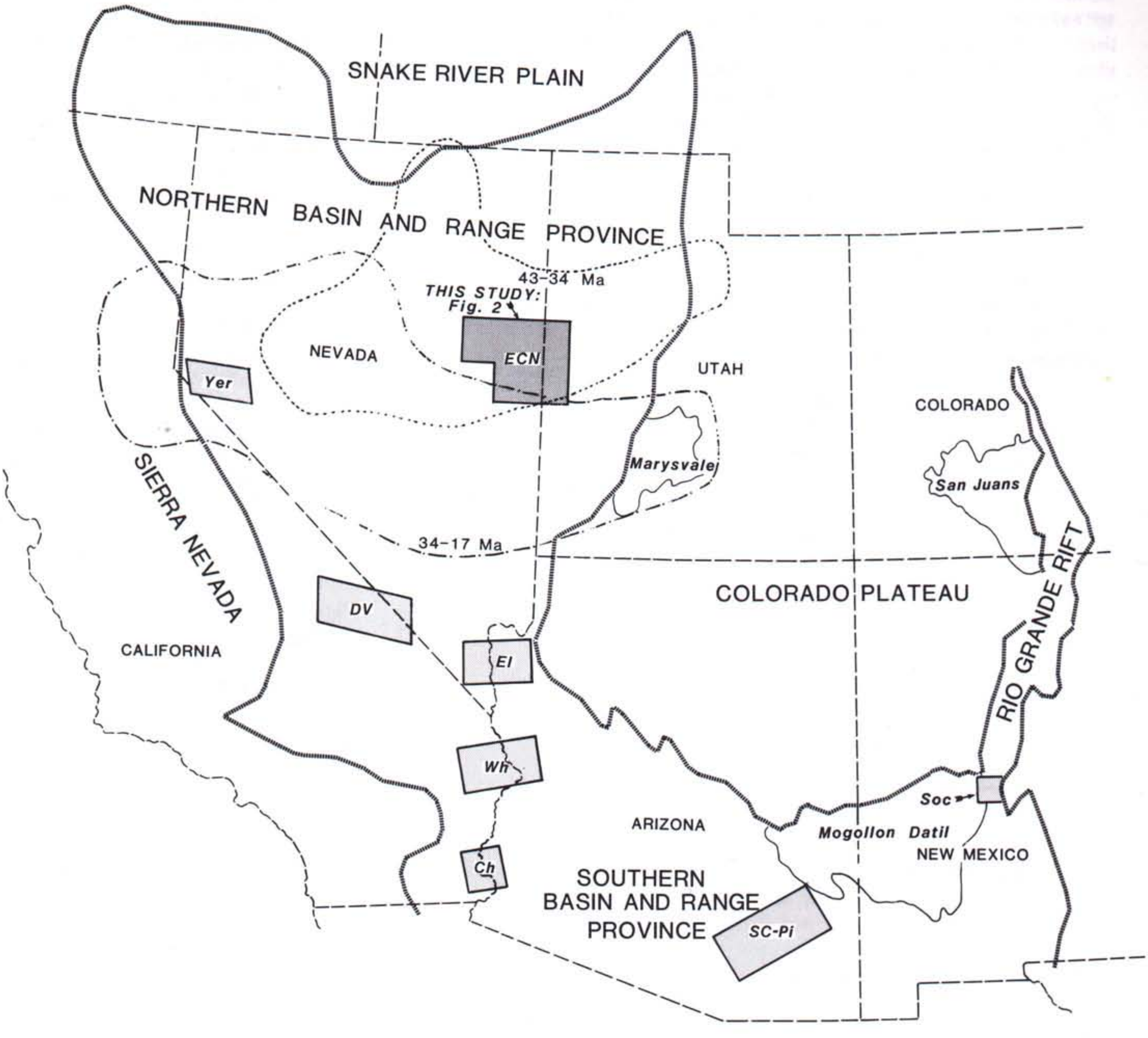


Figure 1. Index map of the Basin and Range province (outlined in heavy line) showing location of the study area in east-central Nevada and west-central Utah and locations of some other highly extended domains discussed in the text. Abbreviations: ECN—East-central Nevada (this study); Yer—Yerington; DV—Death Valley; El—Eldorado Mountains; Wh—Whipple Mountains; Ch—Chocolate Mountains; SC-Pi—Santa Catalina–Pinaleno Mountains; Soc—Socorro. Dotted and dash-dot lines show approximate distribution of 43- to 34-Ma and 34- to 17-Ma volcanic rocks, respectively, in the northern Basin and Range province (Stewart and Carlson, 1976).

Previous studies in this area have focused on its structural evolution. Imbricate high- and low-angle faults that typically place younger strata on older are the characteristic structural element. An increasing amount of evidence supports a Tertiary age and extensional origin for most of the faulting. Where Tertiary rocks are exposed, they are clearly involved in faulting and tilting; more important, the character of their basal unconformity suggests little pre-Tertiary supracrustal deformation (Armstrong, 1972; Gans and Miller, 1983). The earliest Tertiary rocks were deposited exclusively on upper Paleozoic strata and with little angular discordance, suggesting that at the time of their deposition the miogeoclinal stratigraphy was virtually intact and flat-lying. Thin discontinuous intervals of conglomerate at the base of many of the Tertiary sections typically contain only clasts of upper Paleozoic strata (Kellogg, 1964; Dechert, 1967; Gans and Miller, 1983), providing further evidence that before early Tertiary time, no major structural relief had been developed in this area. In contrast, the subsequent history of the eastern Great Basin has been marked by repeated episodes of normal faulting and large differential uplifts. As first suggested by Gans (1981, 1982) and as elaborated below, this extensional deformation began in the early Oligocene, synchronous with voluminous magmatism. The geometry and kinematics of extensional faulting across this region were described in detail by Gans and Miller (1983). Extensional strain within the upper crust is highly heterogeneous, such that regions characterized by multiple sets of rotated, imbricate, high-angle normal faults alternate with much less deformed areas. One such highly extended domain or corridor includes the northern Egan, Schell Creek, and Snake ranges (Fig. 2), across which there has been approximately 250 percent or 95 km of west-northwest–east-southeast–directed extension (Gans and Miller, 1983). The history of Tertiary volcanism and sedimentation within this corridor and the constraints it places on timing of extensional faulting are described in detail below.

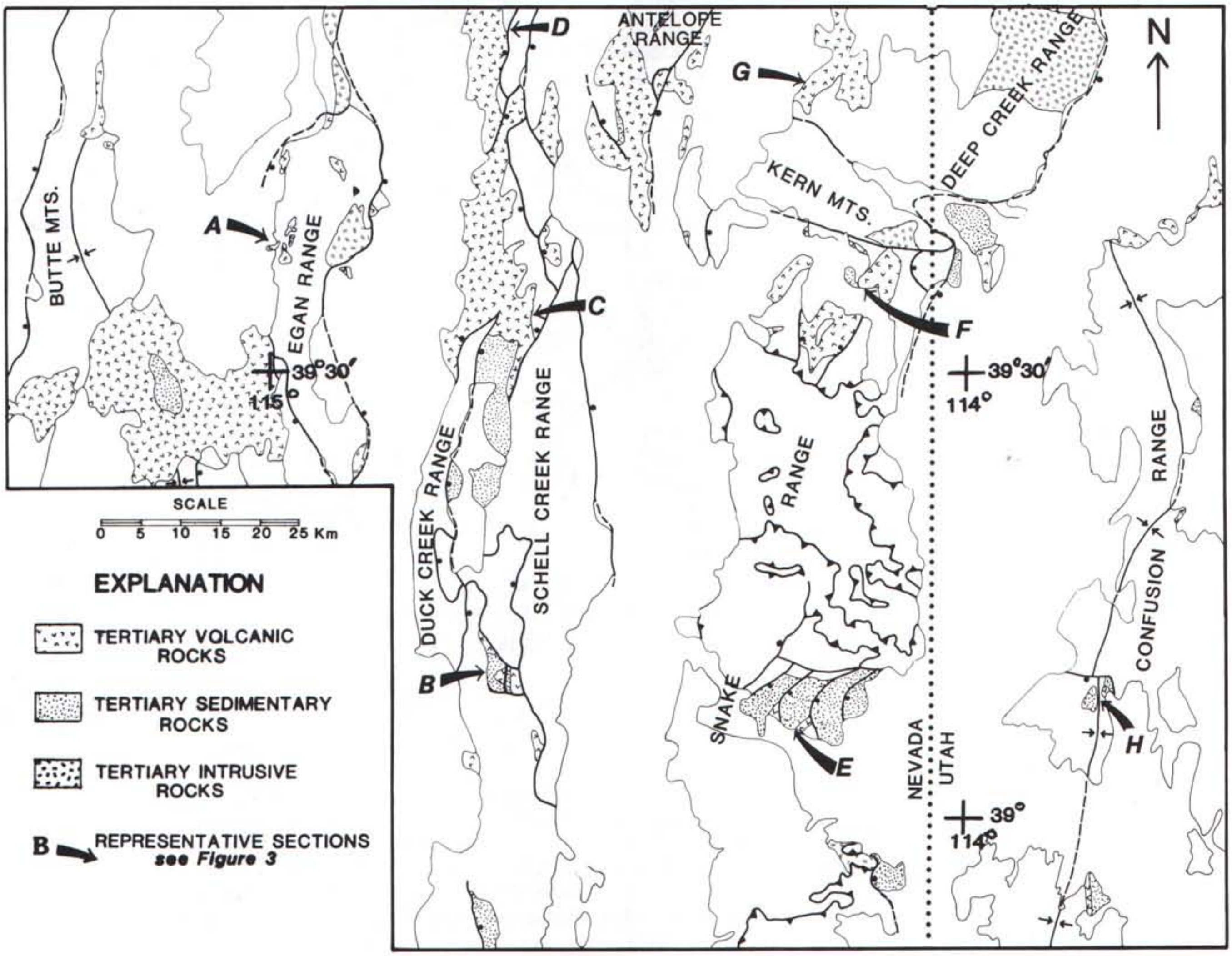


Figure 2. Simplified geologic map of east-central Nevada and westernmost Utah, showing the distribution of mid-Tertiary volcanic, sedimentary, and plutonic rocks and some prominent structural features (modified from Hose and Blake [1976], Hose [1977], and Hintze [1980]). Bold letters with arrows point to representative Tertiary sections illustrated in Figure 3.

Previous work

Early geologic studies in east-central Nevada largely overlooked the Tertiary rocks; relatively little has been published about the details of local stratigraphic successions or on the regional extents and correlations of specific units. Notable exceptions include Young (1960), Dechert (1967), and Drewes (1967), who carefully subdivided and mapped the Tertiary units in their respective map areas. Because much of the early mapping was done prior to the dissemination of many modern volcanologic concepts (e.g., Smith and Bailey, 1968) and before K/Ar dating and quantitative chemical analyses were readily available, the nature, ages, and compositions of the eruptive units were not well known. Armstrong (1970) was the first to date many of the volcanic rocks in east-central Nevada, and he concluded that the principal eruptions occurred approximately 35 Ma. Subsequent dating by McKee et al. (1976) supported this conclusion but suggested a more protracted volcanic history. In overviews of volcanism in this region, Blake et al. (1969) and Hose and Blake (1976) pointed out that Tertiary rocks in the southern and southwestern part of White Pine County were dominated by areally extensive ash-flow sheets, whereas the northern and northwestern parts of the county, including the area described in this paper, were dominated by locally derived lavas and tuffs. They called the lavas and tuffs the "Older Volcanic Rocks"; they range in age from 38 to 32 Ma, with peak activity approximately at 35 Ma. A study in the southern Antelope Range by Blake and Hose (1968) indicated that these rocks comprise a high-K calc-alkaline suite of pyroxene andesite, hornblende rhyodacite, and biotite rhyolite. The preliminary map of White Pine County by Hose and Blake (1970) identified many exposures of what they referred to as "the welded tuff of Kalamazoo Creek," an important Tertiary eruptive unit that is described in detail below.

Methods

Selected areas in the northern Egan, Schell Creek, and Snake Ranges were mapped at a scale of 1:24,000. Results of this mapping were integrated with both previously published information and our reconnaissance investigations of Tertiary rocks elsewhere in the region in order to generate the generalized stratigraphic sections in Figure 3.

A total of 24 new K-Ar ages were obtained from fresh volcanic and subvolcanic rocks in the study area and are summarized in Table 1, together with previously published geochronologic data. All older K-Ar ages have been corrected for the new decay constants (Dalrymple, 1979). Extractions for most samples were performed at Stanford University; associated isotopic analyses were performed at the Branch of Isotope Geology, U.S. Geological Survey, Menlo Park, California. A few of the K-Ar ages were obtained at the University of California, Berkeley. Potassium determinations for all samples are by flame photometry, some of which were done at Stanford; others were provided by the U.S. Geological Survey.

Approximately 40 new whole-rock X-ray fluorescence (XRF) analyses were obtained from fresh lavas and ash-flow tuffs in the study area (Table 2). Wherever possible, we analyzed fiamme separated from ash-flow tuffs in order to circumvent the bias introduced by crystal enrichment in bulk-tuff samples. The major- and trace-element XRF analyses were performed at Stanford University. In addition, instrumental neutron activation analyses and Sr and Nd isotopic analyses were performed on a small number of samples spanning the compositional range (Table 2). Neutron activation analyses were performed at Massachusetts Institute of Technology using procedures and techniques reported by Lla and Frey (1984) and Lindstrom and Korotev (1982). Isotopic ratios and concentrations of Sr and Nd were determined by isotope dilution (Hart and Brooks, 1977).

TERTIARY STRATIGRAPHY

Tertiary rocks in east-central Nevada can be conveniently divided into three distinct groups. The oldest is late Eocene to early Oligocene in age and consists of local accumulations of andesitic to dacitic lavas, rhyolitic tuffs and lava flows, and intercalated lacustrine deposits and conglomerates. These older sequences are overlain by the more voluminous 35-Ma Kalamazoo volcanic rocks (Young, 1960); in ascending order, they include the Kalamazoo Tuff (this paper), hornblende dacite lavas, and the tuff of North Creek. The youngest group ranges in age from middle Oligocene to Miocene and consists of thick local accumulations of fanglomerate and lacustrine limestone, and rare interstratified tuffs. A composite stratigraphic column summarizing typical thicknesses, geochronologic data, compositions, and mineral modes from selected units within each of the three groups is illustrated in Figure 4.

Older Andesites and Rhyolites

The oldest volcanic rocks in the study area are exposed at widely separated localities in the northern Egan Range, the central and northernmost Schell Creek Range, and southwestern Deep Creek Range (Fig. 5). They consist mostly of andesitic lavas and rhyolitic tuffs and, for the most part, represent small-volume eruptions from separate volcanic centers. In addition, most of the Tertiary granites in the study area are within the age range of this older suite of rocks and appear to represent the intrusive equivalents of the early rhyolites.

Northern Egan Range. Several large granitic plutons, scattered porphyritic dikes and small stocks, and a few small remnants of volcanic rocks in the northern Egan Range are thought to represent different levels of an early Oligocene silicic magmatic center. The Warm Springs Granite on the eastern flank of the range (Fig. 5) is an equigranular to slightly porphyritic biotite granite. It yielded a K/Ar biotite age of 37.0 ± 0.8 Ma (Armstrong, 1970) and a discordant U/Pb zircon date that is interpreted as mixing between a 36-Ma magmatic zircon component and a 1.7-Ga inherited component (Miller et al., 1988). The

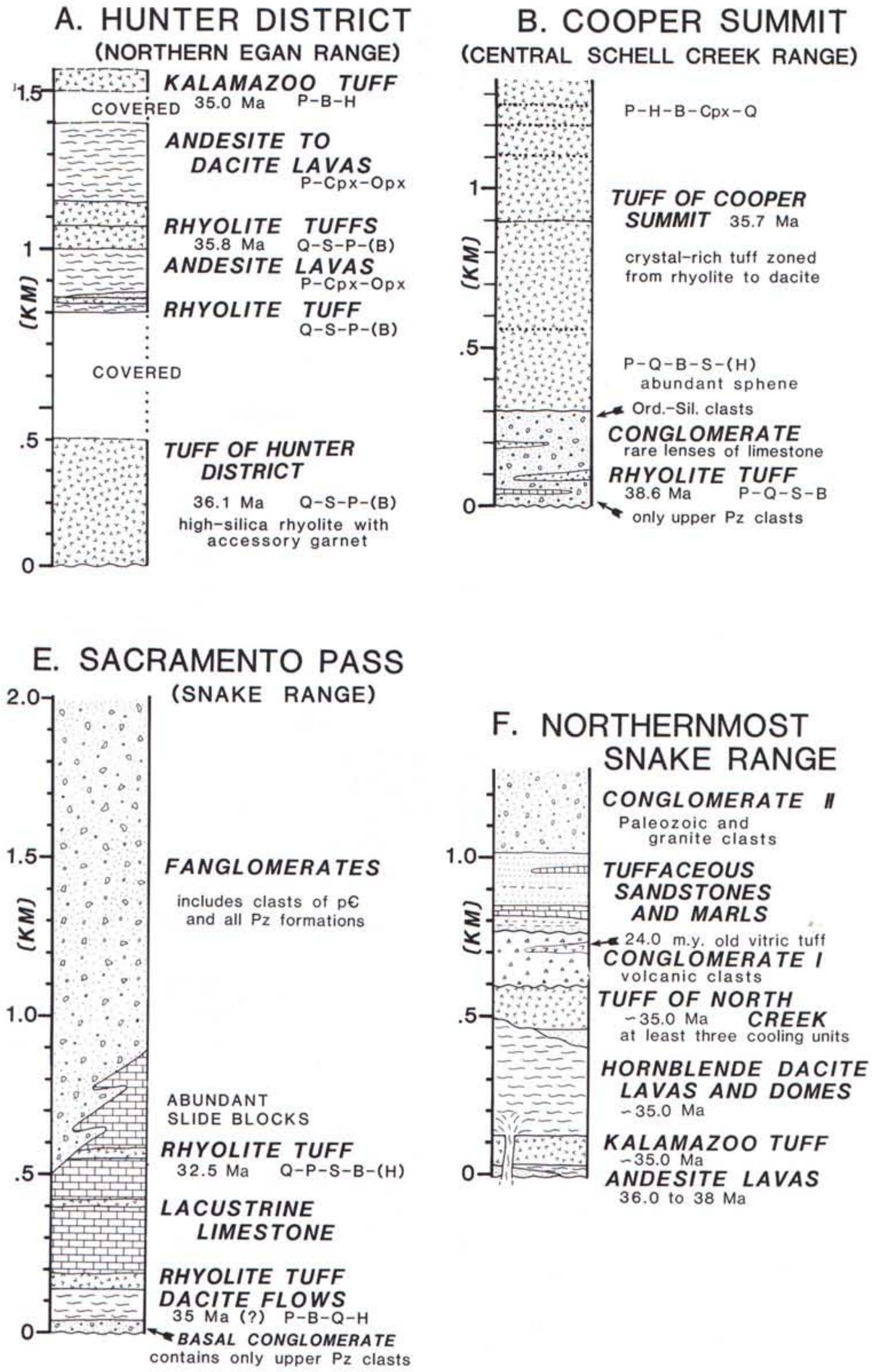
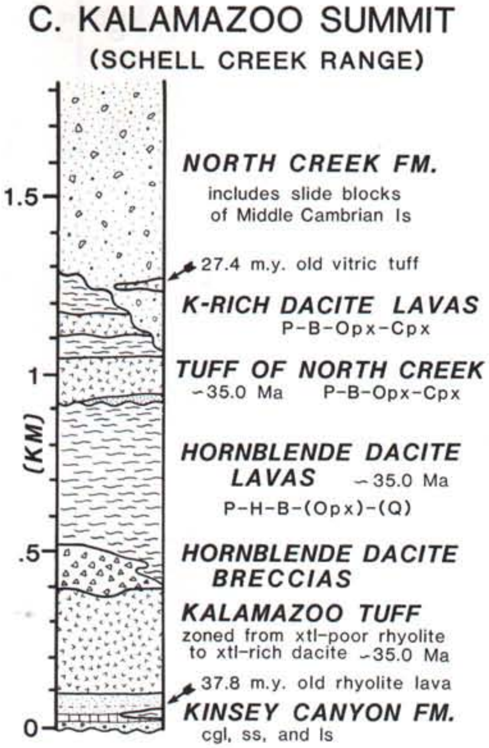
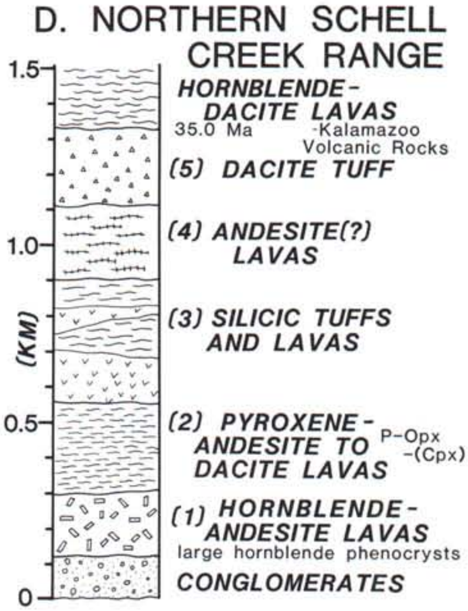
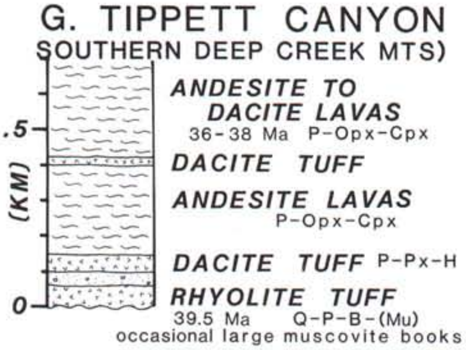
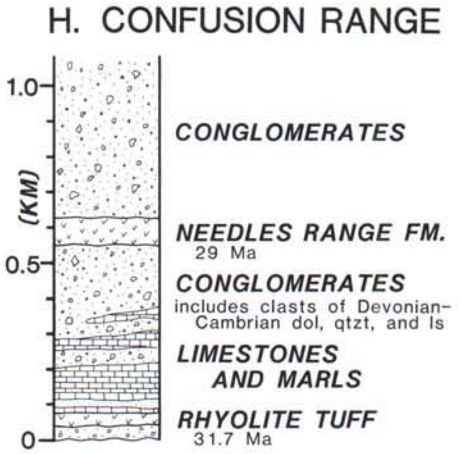


Figure 3 (this and facing page). Generalized Tertiary stratigraphic sections from the northern Egan, Schell Creek, and Snake ranges, the Deep Creek Mountains, and the Confusion Range. See Figure 2 for approximate locations.


C. KALAMAZOO SUMMIT
(SCHELL CREEK RANGE)
1.5
1
.5
0
(KM)
NORTH CREEK FM.
includes slide blocks of Middle Cambrian ls
27.4 m.y. old vitric tuff
K-RICH DACITE LAVAS
P-B-Opx-Cpx
TUFF OF NORTH CREEK
~35.0 Ma P-B-Opx-Cpx
HORNBLENDE DACITE LAVAS ~35.0 Ma
P-H-B-(Opx)-(Q)
HORNBLENDE DACITE BRECCIAS
KALAMAZOO TUFF
zoned from xtl-poor rhyolite to xtl-rich dacite ~35.0 Ma
37.8 m.y. old rhyolite lava
KINSEY CANYON FM.
cgl, ss, and ls


D. NORTHERN SCHELL CREEK RANGE
1.5
1.0
0.5
0
(KM)
HORNBLENDE-DACITE LAVAS
35.0 Ma -Kalamazoo Volcanic Rocks
(5) DACITE TUFF
(4) ANDESITE(?) LAVAS
(3) SILICIC TUFFS AND LAVAS
(2) PYROXENE-ANDESITE TO DACITE LAVAS
P-Opx-(Cpx)
(1) HORNBLENDE-ANDESITE LAVAS
large hornblende phenocrysts
CONGLOMERATES


G. TIPPETT CANYON
(SOUTHERN DEEP CREEK MTS)
.5
0
(KM)
ANDESITE TO DACITE LAVAS
36-38 Ma P-Opx-Cpx
DACITE TUFF
ANDESITE LAVAS
P-Opx-Cpx
DACITE TUFF P-Px-H
RHYOLITE TUFF
39.5 Ma Q-P-B-(Mu)
occasional large muscovite books


H. CONFUSION RANGE
1.0
0.5
0
(KM)
CONGLOMERATES
NEEDLES RANGE FM.
29 Ma
CONGLOMERATES
includes clasts of Devonian-Cambrian dol, qtzt, and ls
LIMESTONES AND MARLS
RHYOLITE TUFF
31.7 Ma

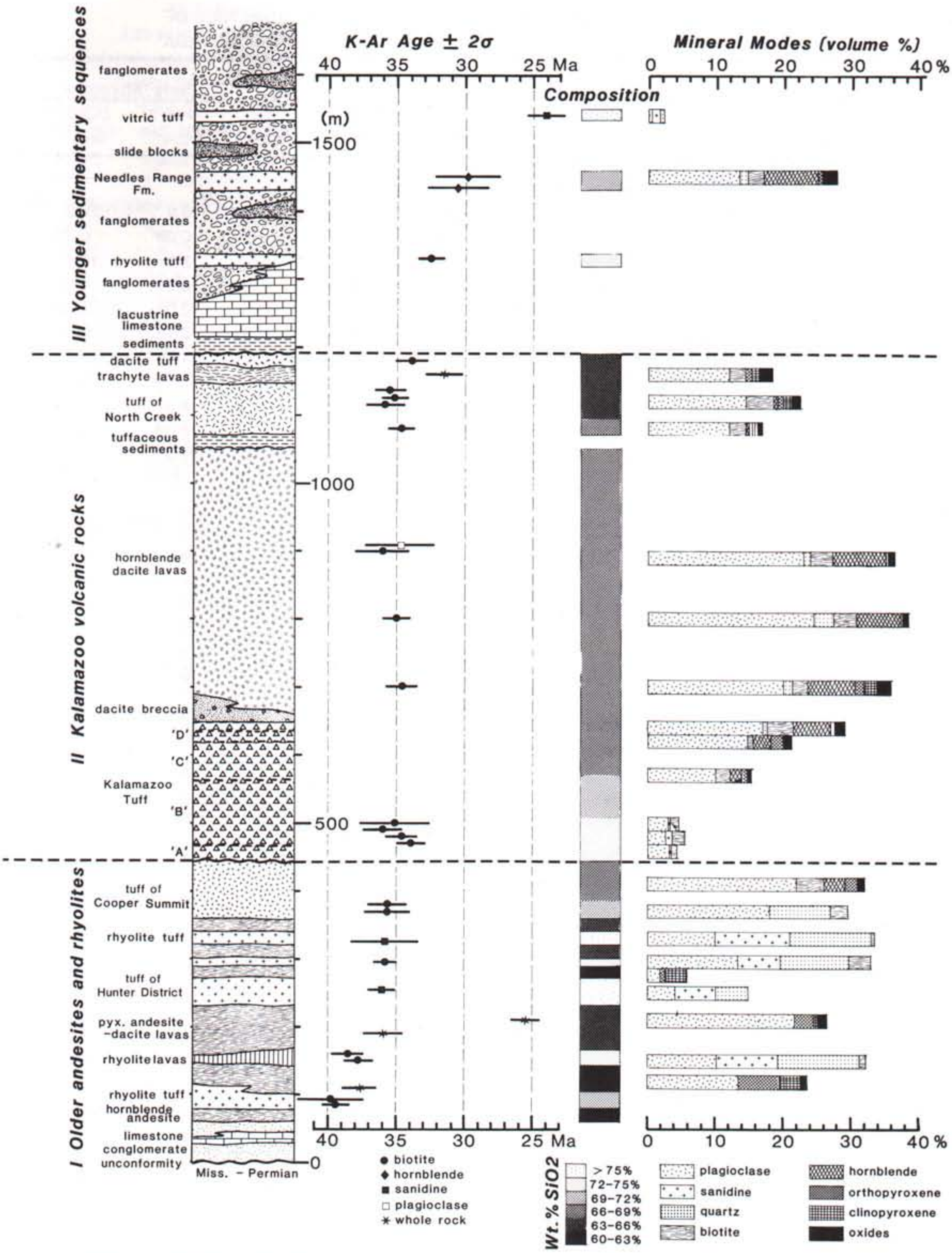


Figure 4. Schematic composite stratigraphic column for east-central Nevada summarizing the lithology, geochronology, compositions, and modes of the three principal groups of Tertiary rocks in the study area. Note that this section does not represent an actual section at a given locality, but shows the inferred relative stratigraphic positions and typical thicknesses of Tertiary units observed in different areas. K-Ar dates are from this study. Mineral modes typically averaged from point counts of several thin sections (500 to 1,000 points per section).

TABLE 2. MAJOR- AND TRACE-ELEMENT AND ISOTOPIC ANALYSES OF REPRESENTATIVE FRESH VOLCANIC ROCKS, EAST-CENTRAL NEVADA (continued)

Major elements were analyzed by wavelength-dispersive x-ray fluorescence (WDXRF) on fused discs. All major-element analyses were performed at Stanford University, except for *samples, which were analyzed by the U.S. Geological Survey at Lakewood, Colorado. The U.S.G.S. Na_2O data were multiplied by 1.05 in order to correct for a systematic difference between the two data sets. Trace elements were analyzed by WDXRF on pressed pellets at Stanford University and by instrumental neutron activation analysis (INAA) at the Massachusetts Institute of Technology. Trace-element concentrations measured by WDXRF are precise to 10 to 15 percent and those analyzed by INAA are precise to 1 to 5 percent. Measurements of isotopic ratios of Nd and Sr and concentrations of Nd, Sm, Sr, and Rb by isotope dilution (†) were performed at M.I.T. $^{87}Sr/^{86}Sr$ normalized to $^{86}Sr/^{88}Sr = 0.1194$ and reported relative to E&A $SrCO_3 = 0.70800$. $^{143}Nd/^{144}Nd$ normalized to $^{146}Nd/^{144}Nd = 0.7219$ and reported relative to BCR-1 = 0.51264. Uncertainties are 0.005 percent for $^{87}Sr/^{86}Sr$, 0.004 percent for $^{143}Nd/^{144}Nd$, 0.3 percent for Sr and Nd, and 1 percent for Sm and Rb. Under the rock type heading, d = devitrified and v = vitric.

Warm Springs pluton is cut by numerous, gently to moderately east-dipping rhyolite or granite porphyry dikes. In the western part of the pluton these dikes have sharp intrusive contacts and strongly chilled margins, whereas downsection to the east, the dikes grade into the main phase of the granite. These relationships suggest that the dikes are comagmatic with the Warm Springs pluton but were emplaced late in its crystallization history, after the western (upper) part had solidified.

Dikes of similar composition occur sporadically throughout the northern Egan Range but are particularly abundant in the vicinity of the Hunter District (Fig. 6), where they have been described in detail by Gans (1982). Here, four generations of silicic dikes can be distinguished on the basis of crosscutting relationships, modal mineralogy, and major- and trace-element chemistry. The earliest dikes are phenocryst-poor, high-silica rhyolite porphyries, easily identified by the presence of trace garnet phenocrysts. These are cut by phenocryst-rich, high-silica rhyolite porphyry dikes, which are cut in turn by dikes of low-silica rhyolite to dacite that contain conspicuous sanidine megacrysts up to 5 cm in length. The dikes in the fourth and youngest group closely resemble the second type, but are generally much fresher.

A thick sequence of steeply dipping volcanic rocks is exposed just west of the Hunter District. Although very poorly exposed, it appears to be more than 1 km thick and includes several rhyolite ash-flow tuffs and intermediate composition lavas (Section A in Fig. 3). The oldest unit (tuff of Hunter District) is an unusual high-silica rhyolite ash-flow tuff that contains sparse phenocrysts of quartz, albite, sanidine, pale-green biotite, and garnet (Fig. 4). It has a poorly defined eutaxitic texture and contains sparse carbonate lithic fragments. The three overlying tuffs are all crystal-rich rhyolites (two are high-silica) that contain no obvious lithic fragments or fiamme, but contain abundant fragments of quartz, sanidine, plagioclase, and biotite crystals in a welded ash matrix. They are interstratified with massive to blocky lavas that contain phenocrysts of plagioclase, hypersthene, augite, and rare olivine replaced by iddingsite, and range in composition from andesite to low-silica dacite. The tuff of Hunter district and the two youngest tuffs have yielded K/Ar ages of 36.1 ± 1.0, 35.8 ± 1.0, and 35.8 ± 1.3 Ma, respectively (Table 1, Fig. 4), suggesting that the entire sequence was deposited around 36 Ma. All four tuffs are inferred to have small volumes because they have not been recognized in any of the other Tertiary sections in the study area.

The close compositional, textural, and modal similarities between the four generations of rhyolite dikes in the Hunter District and the four rhyolite ash-flow tuffs (Gans, 1982) leaves little doubt that the tuffs represent the extrusive equivalents of the dikes. In addition, their age is within analytical uncertainty of the age of the Warm Springs pluton. Westward tilting of the northern Egan Range has effectively exposed a cross-sectional view of an early Oligocene silicic center, from the top of the magma chamber on the east side of the range, through the subvolcanic feeder dikes in the Hunter District, to the volcanic cover on the west side of the range. Because most of the differential uplift and tilting of the range postdates the early Oligocene intrusions, it is possible to reconstruct their original depths by using the stratigraphic depths at which they are emplaced. For example, the Warm Springs pluton intrudes upper Precambrian strata within the structurally deepest fault slice, corresponding to paleodepths of 8 to 11 km. Similarly, the dikes in the Hunter District crosscut Upper Ordovician to Upper Devonian strata at reconstructed depths of 1 to 3 km.

Conners Pass area, central Schell Creek Range. Thick sections of Tertiary volcanic and sedimentary rocks are exposed in the vicinity of Conners Pass (Fig. 5) and record some of the earliest magmatism and extensional(?) tectonism in the study area. The following stratigraphic summary is drawn largely from the detailed mapping and descriptions of Drewes (1967); minor modifications are based on our own reconnaissance field and analytical investigations. Drewes (1967) divided Tertiary rocks in the Conners Pass quadrangle into a variety of lavas, tuffs, subvolcanic intrusions, and conglomerates. Although some of the exposures that he identified as lavas and intrusions appear to be densely welded ash-flow tuff, the general stratigraphic succession of conglomerates followed by rhyolite to dacite tuffs and lavas is clearly valid. An east-dipping section of Tertiary sedimentary and volcanic rocks more than 1.5 km thick is well exposed at Cooper Summit (Section B, Fig. 3).

The lower 300 m of the Cooper Summit section consists predominantly of conglomerate. Lenses of lacustrine limestone up to 10 m thick occur near the base of the section, and thin horizons of rhyolitic ash-flow tuff and tuffaceous sediments are interstratified within the middle and upper part of the conglomerate. The conglomerate is overlain by a thick section of ash-flow tuff that we here informally refer to as the tuff of Cooper Summit. It is locally greater than 1 km thick and, with the exception of a minor cooling break, is entirely densely welded. We suspect that this accumulation may be part of an intracaldera fill sequence, but the original caldera geometry is obscured by subsequent faulting and erosion. The lowest part of the tuff is a crystal-rich, low-silica rhyolite that contains phenocrysts of quartz, plagioclase, sanidine, biotite, and trace hornblende. Small sphene crystals are conspicuous in most samples. The tuff is zoned upward to more mafic compositions and marked by the disappearance of sanidine, a decrease in the abundance of quartz, and an increase in the abundance and variety of mafic phases (Fig. 4). The upper part of the tuff is a hornblende-biotite-pyroxene dacite that superficially resembles a lava flow. The areal extent of the tuff of Cooper Summit is not well known. Hose and Blake (1976) apparently correlated welded-tuff exposures in the central Schell Creek Range (including the tuff of Cooper Summit) with what they named the Charcoal Ovens Tuff in the southern Egan Range. This correlation seems reasonable in light of their similar appearance and crystal contents, but the geochronology discussed below raises some doubts. The youngest volcanic rocks in the vicinity of Conners Pass are hornblende-dacite lavas that closely resemble the middle member of the Kalamazoo volcanic rocks described below.

Existing geochronology suggests that most of the Tertiary rocks in the Conners Pass area are latest Eocene to early Oligocene. We obtained a K/Ar biotite age of 38.6 ± 1.3 Ma from a rhyolite tuff near the base of the conglomerates. The tuff of Cooper Summit yielded K/Ar biotite ages of 37 ± 10 percent (Drewes, 1967), 35.7 ± 0.7 (Armstrong, 1970a), and 35.7 ± 1.2 Ma (Table 1). These ages are significantly older than the 32.8 ±

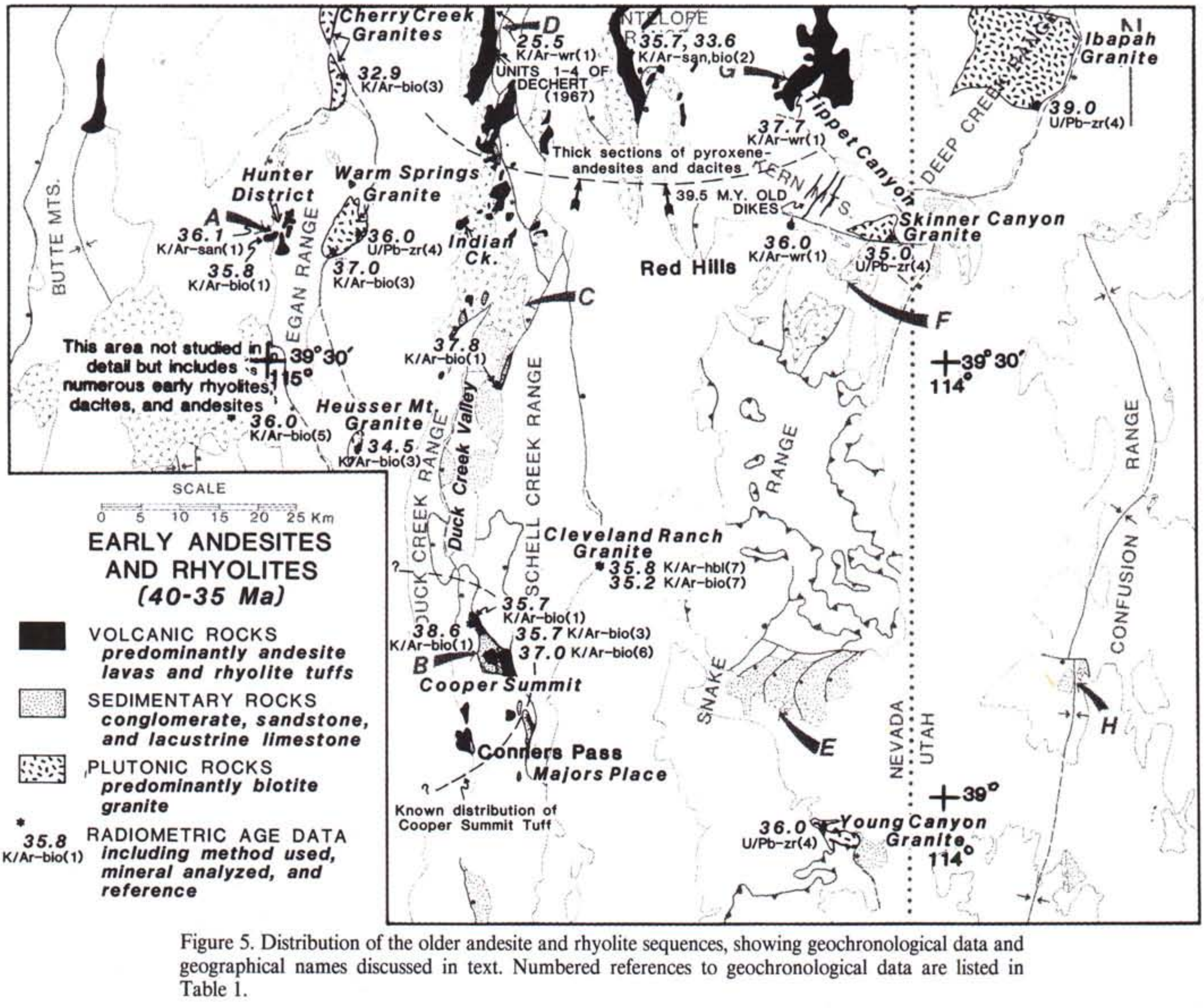


Figure 5. Distribution of the older andesite and rhyolite sequences, showing geochronological data and geographical names discussed in text. Numbered references to geochronological data are listed in Table 1.

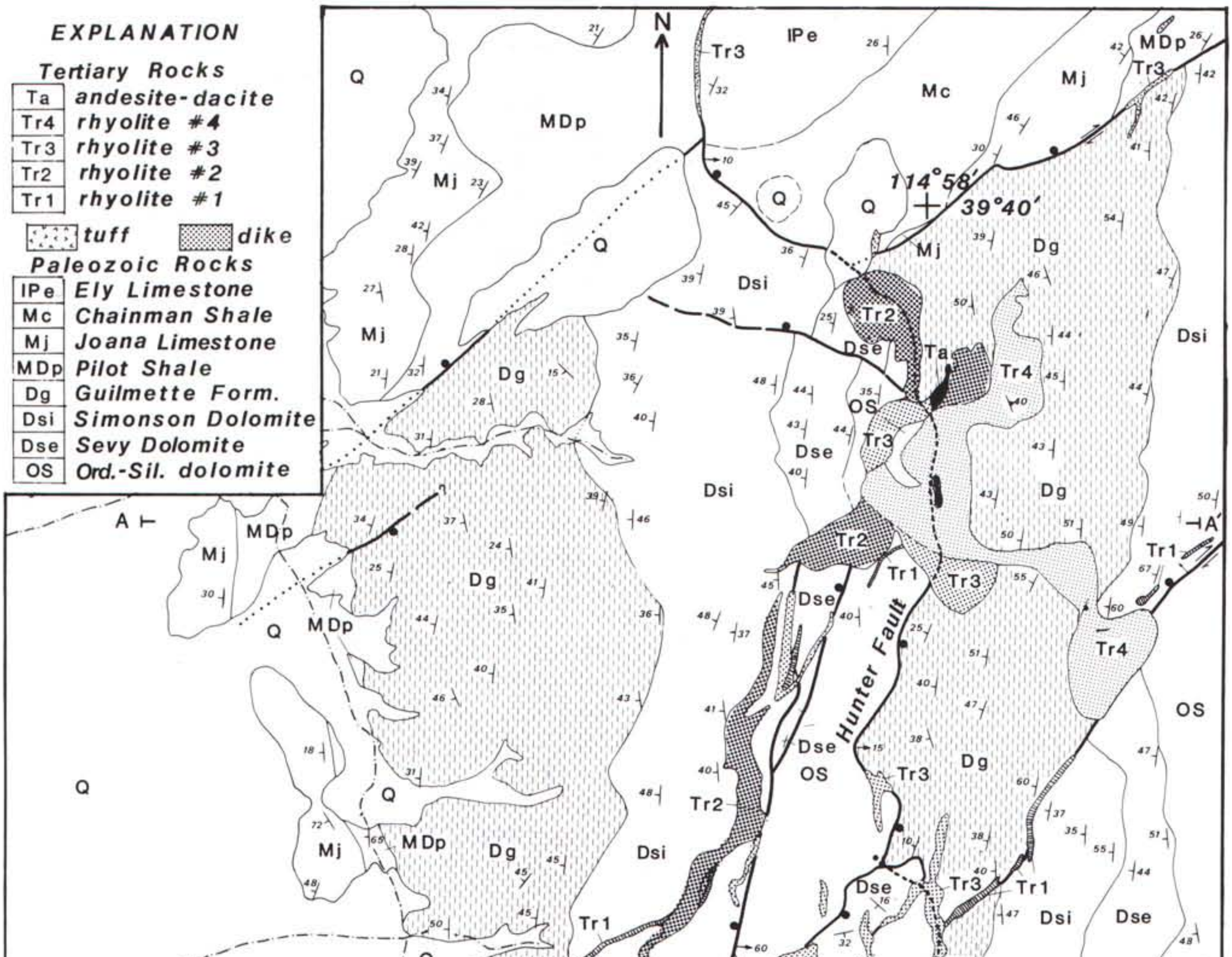


Figure 6. Geologic map and cross section of the Hunter district in the northern Egan Range. Simplified from Gans (1982).

1.1 Ma age (K/Ar sanidine) obtained for the Charcoal Ovens Tuff (McKee et al., 1976), suggesting that they are two different tuffs, or that the sanidine date is spuriously young. If the correlation of the youngest hornblende-dacite lavas with similar lavas to the north is valid, then most of the Tertiary rocks in the Conners Pass area must predate eruption of the Kalamazoo volcanics rocks.

Northernmost Schell Creek Range. Some of the thickest and best-exposed sequences of volcanic rocks in east-central Nevada occur in the northern Schell Creek Range (Fig. 2). Although most of these rocks belong to the Kalamazoo volcanic rocks described below, older sedimentary and volcanic rocks are also present (Fig. 5) and appear to thicken markedly toward the north. Their ages and compositions are poorly known but appear to be similar to the early andesites and rhyolites exposed elsewhere in the study area.

Discontinuous intervals of conglomerate and lacustrine limestone, collectively known as the Kinsey Canyon Formation (Young, 1960), are the oldest Tertiary rocks in the northern Schell Creek Range (Section C in Fig. 3). This sedimentary sequence is up to 250 m thick and typically passes upward from a basal conglomerate that contains clasts derived from post-Devonian strata (Young, 1960; Dechert, 1967), into lacustrine limestones, marls, and shales. Volcaniclastic sandstones and reworked ash falls and pumice falls are commonly interstratified in the upper part of the section.

The Kinsey Canyon Formation is locally overlain by and interstratified with an assortment of lavas and tuffs that predate the Kalamazoo volcanic rocks. Included in this group are unit 1A of Young (1960) and units A and 1–4 of Dechert (1967). The total thickness of these older volcanic rocks locally exceeds 1 km (Dechert, 1967) but is highly variable, consistent with their local derivation from separate volcanic centers. South of Schellbourne Pass, they include brown-weathering andesitic(?) lavas overlain by crystal-rich rhyolite lavas and tuffs. We have obtained a K/Ar biotite age of 37.8 ± 1.0 Ma from one such rhyolite lava intercalated within the upper part of the Kinsey Canyon Formation in the vicinity of Bird Creek (sample DC-1 in Table 1). Similar rhyolite lavas and domes are exposed on the west flank of the Duck Creek Range and at the mouth of Indian Creek (Fig. 5). These early rhyolites in the Schell Creek Range have modal and chemical compositions that closely resemble the rhyolites in the northern Egan Range (Fig. 4).

As emphasized by Dechert (1967), the volcanic stratigraphy in the northern Schell Creek Range changes at about the latitude of Schellbourne Pass. North of Schellbourne pass, the Kalamazoo Tuff is not present and the Tertiary sections consist largely of intermediate composition lavas (Section D, Fig. 3). Dechert (1967) divided these volcanic rocks into five numbered map units, which he described in ascending order as: (1) 0 to 250 m of dark gray andesite lavas containing large hornblende phenocrysts; (2) 0 to 500 m of hypersthene "basalt" lavas, (3) 0 to 800 m of rhyolitic to andesitic(?) tuffs and flows, (4) 0 to 300 m of intermediate(?)-composition flows, and (5) 0 to 500 m of dacitic(?) tuff. Neither the ages nor compositions of these units are well known. Dechert (1967) concluded that at least the first four were depositionally overlapped by and hence older than the Kalamazoo Tuff. We dated a hydrated glass concentrate from one of the hypersthene-rich lavas of unit 2 but obtained a spuriously young age of 25.5 Ma. Limited analytical data from these "basalts" suggest that they are actually andesite to low-silica dacite lavas, containing approximately 25 percent phenocrysts of plagioclase, pyroxene, and Fe-Ti oxides (Fig. 4). They closely resemble the better dated pyroxene-andesite to dacite lavas in the southwestern Deep Creek Range and may have been derived from the same volcanic center.

Southwestern Deep Creek Range. A 500- to 700-m-thick sequence of Tertiary volcanic rocks disconformably overlies Permian strata in the southwestern part of the Deep Creek Range (Rodgers, 1987). In the vicinity of Tippett Canyon (Section G, Fig. 3; Fig. 5), the basal eruptive unit is an unusual rhyolite ash-flow tuff with 10 to 20 percent crystals of quartz, plagioclase, biotite, and rare euhedral muscovite books up to 2 cm in diameter. We have not found muscovite included within pumice lapilli, so it is unclear whether it is magmatic or was picked up as accidental fragments during emplacement of the tuff. The muscovite-bearing Tungstonia Granite (Best et al., 1974) is exposed just south of the tuff and might have generated muscovite-rich gravels and soils. However, this would not explain the absence of other granitic detritus as lithic fragments, which are generally rare and appear to consist exclusively of upper Paleozoic carbonate, sandstone, and chert. Gans et al. (in preparation) identified a swarm of rhyolite to dacite porphyry dikes within the Tungstonia Granite that contain books of muscovite and represent likely feeders for the tuff. It is possible that the magmas engulfed significant volumes of Tungstonia granite and that the muscovite represents a refractory phase. Indeed, this explanaation seems likely given the absence of sanidine in the tuff (which would be expected to coexist with muscovite as a phenocryst). Muscovite from the dikes, and both muscovite and biotite from the tuff, yielded disturbed $^{40}Ar/^{39}Ar$ spectra but indistinguishable total-gas ages of 39.5, 39.6, and 39.5 Ma, respectively (Gans et al., in preparation). This late Eocene age and a 39.8-Ma age reported by McKee et al. (1976) for a rhyolite exposed 25 km to the north are the oldest ages obtained from Tertiary volcanic rocks in the study area.

The muscovite-bearing tuff is overlain by several hundred meters of mafic lavas and thin, locally derived, intermediate-composition tuffs. The lavas and tuffs range in composition from silicic andesite at the base to low-silica dacite toward the top of the section, and contain 20 to 30 percent phenocrysts of plagioclase, augite, hypersthene, and Fe-Ti oxides (Fig. 4). We have obtained ages of 37.7 ± 1.2 and 36.0 ± 1.3 Ma on groundmass concentrates from two different fresh, devitrified lava flows. These earliest Oligocene lavas closely resemble the early pyroxene andesites and dacites in the northernmost Schell Creek Range and may be derived from the same volcanic center. In both the northern Red Hills and along the southern flank of the Kern

Mountains (Fig. 5), they are depositionally overlain by the basal member of the Kalamazoo volcanic rocks.

Other areas. Many of the Tertiary volcanic rocks in the central Egan Range and Butte Mountains (Fig. 2) are inferred to belong to the older andesite and rhyolite suite, although their ages and compositions are poorly known. Work by Feeley et al. (1988) suggests that volcanic rocks in the central Egan Range include both two-pyroxene andesite and hornblende-biotite dacite lavas and domes. Hose and Blake (1976) also reported many rhyolite dome complexes from this area. A reconnaissance of Tertiary sections in the Illipah area of the northern White Pine Range (just west of Fig. 2) identified a consistent stratigraphic succession of: (1) discontinuous intervals of prevolcanic conglomerate up to 100 m thick, (2) up to 500 m of andesitic lavas, (3) 50 to 250 m of tuffaceous sediment and fanglomerate, and (4) two thin crystal-poor rhyolite tuffs that cap the sections and have been correlated with the ~24.0-Ma Bates Mountain Tuff and the tuff of Clipper Gap (Gromme et al., 1972; Hose and Blake, 1976). The lavas near the base of the section include abundant two-pyroxene and olivine-bearing basaltic andesites (e.g., samples WP-1 and WP-3 in Table 2) and constitute the most mafic compositions we have identified in east-central Nevada. Groundmass concentrates from two of these lavas yield ages of 34.1 and 35.7 Ma (Table 1). These ages are within analytical uncertainty of most of the other volcanic rocks in east-central Nevada and do not resolve whether the lavas are age equivalent to the older andesite and rhyolite sequences elsewhere or synchronous to postdating eruption of the Kalamazoo volcanic rocks.

KALAMAZOO VOLCANIC ROCKS

The name Kalamazoo Volcanics was first used by Young (1960) for a sequence of volcanic rocks exposed in the Kalamazoo Creek area of the north-central Schell Creek Range. We suggest redefining the term Kalamazoo volcanic rocks to encompass three areally extensive members that correspond approximately to Young's (1960) units 1 thru 6 and Dechert's (1967) units B thru E. The basal member we herein name the Kalamazoo Tuff. Overlying the Kalamazoo Tuff are hornblende dacite lavas and an ash-flow tuff that we informally call the tuff of North Creek. Complete sections of all three members are well exposed in the vicinity of Kalamazoo Summit in the northern Schell Creek Range (Fig. 7 and Section C in Fig. 3). These three units represent a large proportion of the total volume of volcanic rocks in the study area, and we describe each of them in detail below.

Existing geochronology for the Kalamazoo volcanic rocks is summarized in Table 1. We have determined K-Ar ages of 34.0 ± 1.1 and 34.6 ± 1.2 Ma on biotite from two different samples of glassy Kalamazoo Tuff. These ages, together with previously determined K-Ar biotite ages of 36.0 ± 1.4 (Armstrong, 1970a) and 35.1 ± 2.6 (McKee et al., 1976), yield a weighted mean age of 34.7 ± 0.7 Ma for the tuff. Two K-Ar biotite ages of 34.6 ± 1.2 and 35.0 ± 1.2 Ma were obtained from vitrophyric and devitrified samples of the hornblende dacite lavas, similar to the 36.1 ± 2.6 Ma and 34.8 ± 2.0 Ma ages obtained by McKee et al. (1976) from the same unit, yielding a weighted mean age of 34.9 ± 0.8 Ma. Finally, four samples of the tuff of North Creek yielded K-Ar biotite ages of 35.9 ± 1.3, 34.7 ± 1.1, 35.2 ± 1.0, and 35.5 ± 1.1 Ma, for a weighted mean of 35.2 ± 0.6 Ma. Armstrong (1970a) also dated this tuff and obtained a somewhat younger age of 32.6 ± 1.5 Ma on a biotite concentrate. The simplest interpretation of these K-Ar ages is that all three members of the Kalamazoo volcanic rocks were erupted over a few hundred thousand years or less at ca. 35.0 Ma.

Kalamazoo Tuff

Distribution, volume, and source area. The Kalamazoo Tuff is the most areally extensive ash-flow tuff in east-central Nevada. Its distinctive compositional and mineralogical zonation, well-developed eutaxitic texture, and abundant carbonate lithic fragments distinguish it from all other eruptive units in east-central Nevada. Exposures of the Kalamazoo Tuff are concentrated in the north-central Schell Creek Range but occur throughout an elliptically shaped area that extends 140 km from the Butte Mountains to the Confusion Range (Fig. 8). It generally occurs at or near the base of exposed Tertiary sections, resting disconformably on either upper Paleozoic strata or the early Oligocene andesites, rhyolites, and sedimentary sequences described above. Complete sections as thick as 350 m are well exposed in its type area in the headwaters of Kalamazoo Creek (Fig. 7).

Several problems are encountered in estimating the volume of Kalamazoo Tuff. Foremost is that the present areal extent of the tuff does not reflect its original area, but has been expanded by later extensional tectonism. The Kalamazoo Tuff was erupted relatively early in the extensional history of this region, such that most of its north-south–trending outcrops (Fig. 8) represent the upper parts of tilted fault blocks rather than remnants of a continuous subhorizontal sheet. Palinspastic reconstruction of most of the 250 percent or 95 km west-northwest–east-southeast-extension estimated by Gans and Miller (1983) across this region restores the elliptical outcrop pattern of the Kalamazoo Tuff to a nearly circular distribution approximately 45 km in diameter. It is noteworthy that numerous other Oligocene to early Miocene ignimbrites in the Basin and Range province are also elongate in an east-west direction (e.g., Gromme et al., 1972; Glazner et al., 1986) and may similarly reflect large magnitudes of subsequent extension. Failure to correct for this obviously leads to overestimation of erupted volumes.

Additional uncertainties in estimating the volume of Kalamazoo Tuff stem from the fact that only a small fraction of the original sheet is exposed. Erosion has stripped much of the tuff from the ranges, and 50 percent of its present area lies buried beneath younger basin-fill deposits. The tuff appears to have been erupted over a surface of relatively low relief, because extreme local variations in its thickness are uncommon. Complete sections

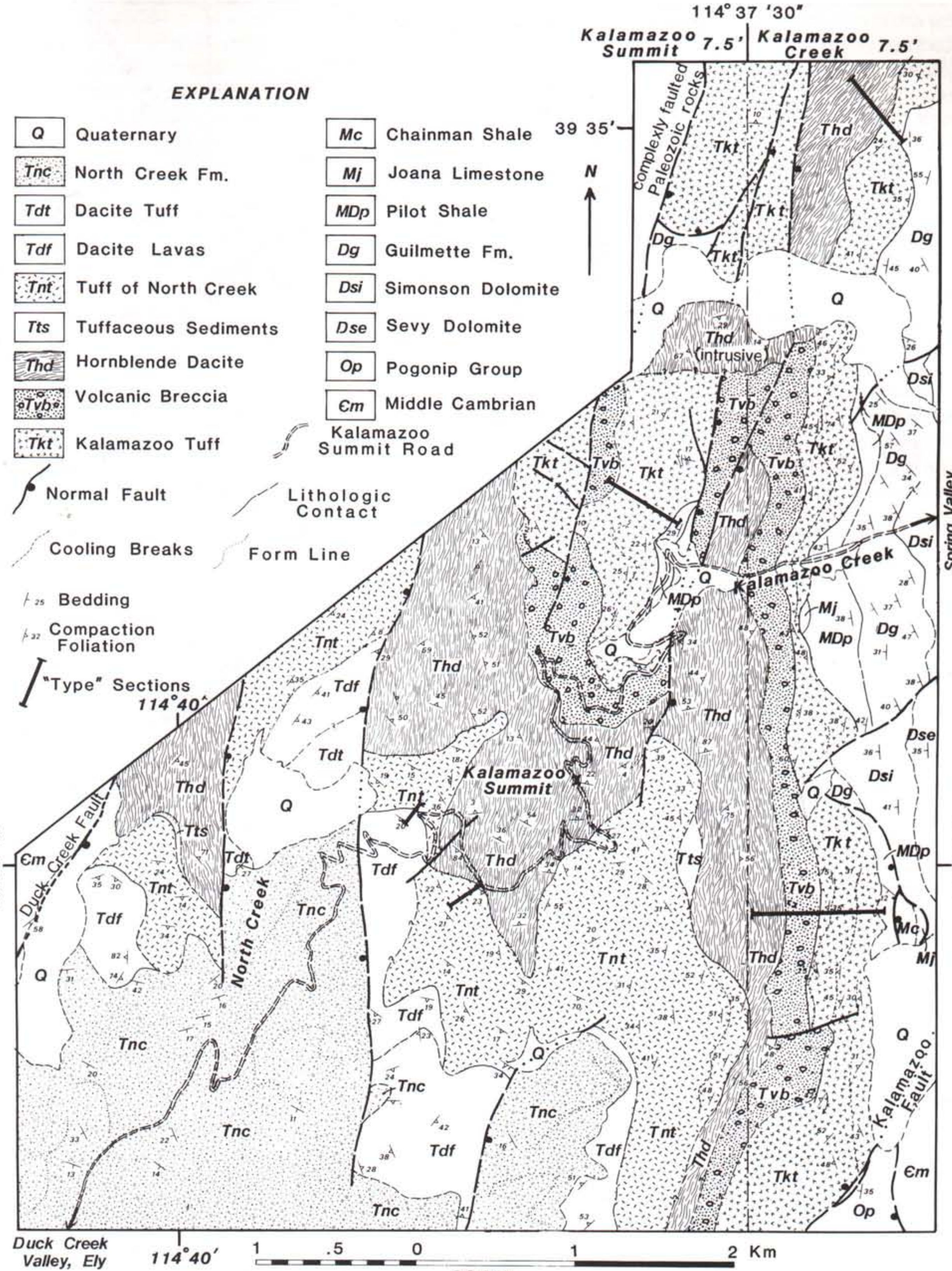


Figure 7. Geologic map of the Kalamazoo Summit region, showing the location of the type sections of the Kalamazoo volcanic rocks. Mapping by P. B. Gans (1982–1983, unpublished data) and Young (1960).

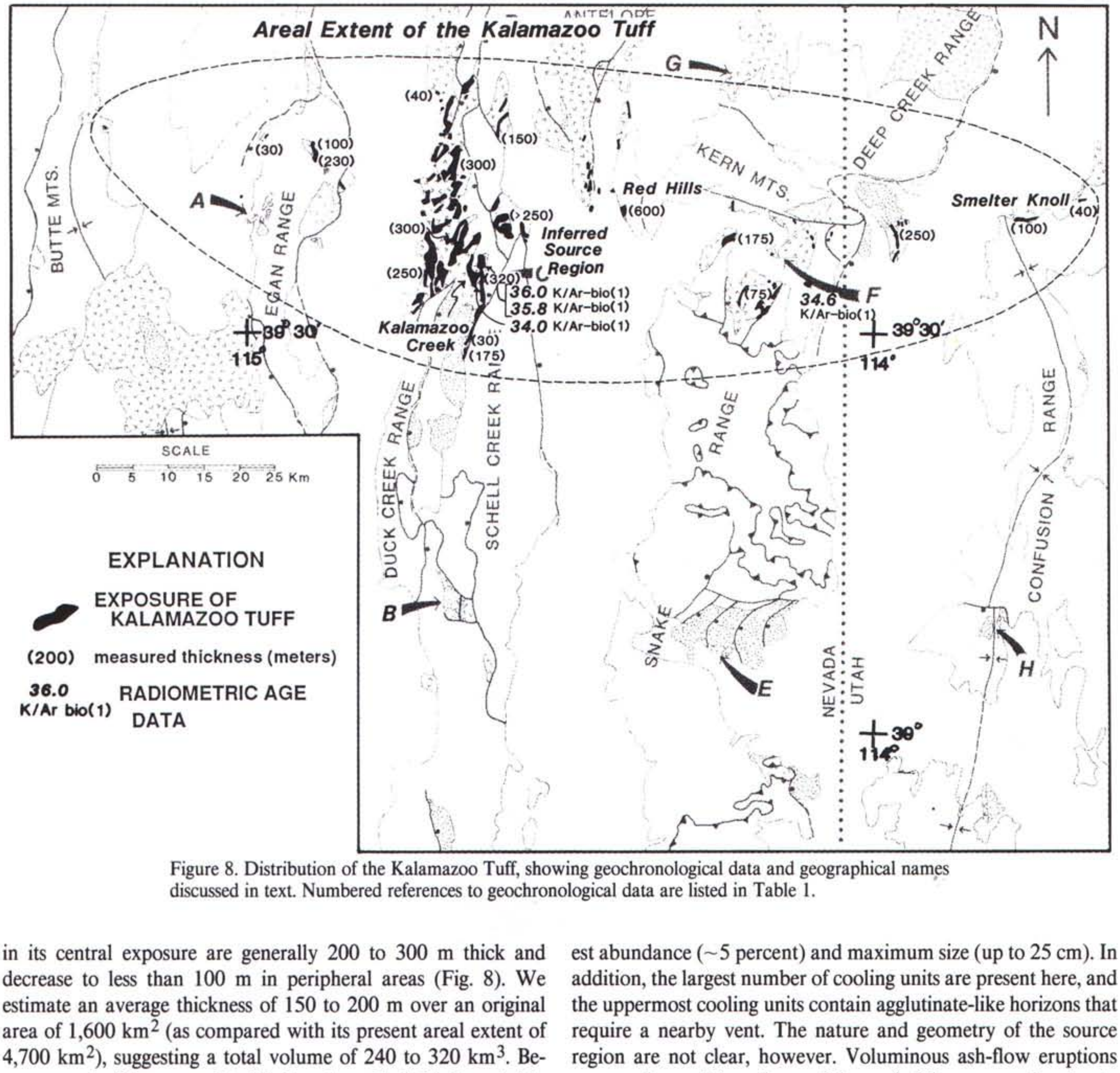


Figure 8. Distribution of the Kalamazoo Tuff, showing geochronological data and geographical names discussed in text. Numbered references to geochronological data are listed in Table 1.

in its central exposure are generally 200 to 300 m thick and decrease to less than 100 m in peripheral areas (Fig. 8). We estimate an average thickness of 150 to 200 m over an original area of 1,600 km^2 (as compared with its present areal extent of 4,700 km^2), suggesting a total volume of 240 to 320 km^3. Because much of the exposed tuff is densely welded, this is probably close to the volume of erupted magma. If thick sections of Kalamazoo Tuff ponded within an as yet unrecognized caldera (see discussion below), its volume may be closer to 500 km^3. In some of the thicker, centrally located exposures (e.g., the north fork of Kalamazoo Creek; Fig. 7), the tuff grades upward into agglutinate-like horizons of poorly vesiculated pumice bombs akin to the overlying lavas, suggesting that it never had a thick, nonwelded upper part in these areas. However, erosion may have removed significant volumes of nonwelded tuff from distal outcrops and from co-ignimbrite fall deposits.

The source of the Kalamazoo Tuff is inferred to be near Kalamazoo Creek; this is where lithic fragments reach their greatest abundance (~5 percent) and maximum size (up to 25 cm). In addition, the largest number of cooling units are present here, and the uppermost cooling units contain agglutinate-like horizons that require a nearby vent. The nature and geometry of the source region are not clear, however. Voluminous ash-flow eruptions commonly result in collapse of the roof of the magma chamber to form a caldera (Smith and Bailey, 1968), and ash-flow tuffs with volumes similar to the Kalamazoo Tuff are known to have formed calderas with diameters of 10 to 20 km (Smith, 1979; Lipman, 1984). In older, highly disrupted volcanic terrains such as east-central Nevada, the original topographic expression is unlikely to be evident, but the presence of a cauldron can still be inferred by using a variety of sedimentological and structural criteria recently summarized by Lipman (1984). Applying these criteria, we find little or no evidence for the existence of a caldera related to the eruption of Kalamazoo Tuff. None of the exposed sections of Kalamazoo Tuff are as thick as most known intracaldera fill accumulations (typically >1 km). The thickest sections are generally less than 350 m thick, and even these often have partial cooling breaks defined by several vitrophyres. An exception is a poorly exposed section (no top exposed) in the southern Red Hills, which may be as much as 650 m thick (Clark, 1985). Thicknesses appear to gradually decrease away from the thickest sections rather than decreasing abruptly, as would be expected at a caldera margin. No intercalations of coarse lithic debris (caldera collapse breccias) have yet been identified within the Kalamazoo Tuff, and no faults or dikes have been identified that are clearly related to a ring-fracture system. A large hypabyssal dacite intrusion that intrudes the Kalamazoo Tuff at the north end of the Snake Range might represent a cogenetic intrusion, but complete sections of the tuff in this area are thinner and contain fewer and smaller lithics than sections farther to the west. Given the distribution of Kalamazoo Tuff and the location of its thickest sections (Fig. 8), it is conceivable that a source cauldron may be largely buried beneath the north end of Spring Valley.

Cooling units, lithic content, and mineralogy. The Kalamazoo Tuff is a composite sheet (Smith, 1960) that includes at least four cooling units. In ascending order, these are informally named A, B, C, and D. Only B and C are widespread; A and D are restricted largely to the headwaters of Kalamazoo Creek (Fig. 7). Thick sections of the tuff in the central part of its distribution area typically lack major cooling breaks between units, whereas more distal sections have pronounced cooling breaks.

Units A and B are both crystal-poor tuffs with relatively large fiamme (pumice lapilli flattened by welding) and abundant carbonate lithic fragments. Unit B is the most widespread of the four cooling units, occurring in all outcrops of the tuff and representing two thirds of its exposed volume. It attains a maximum thickness of 200 m and typically grades upward from a 0.5- to 3-m-thick, poorly exposed, nonwelded base to a cliff-forming, partly to densely welded vitrophyre as much as 40 m thick, to a thick, pink or red weathering, densely welded, and devitrified upper part. Distal exposures of unit B locally have internal cooling breaks marked by the occurrence of two or more vitrophyres. Fiamme in B are typically 2 to 10 cm in diameter but locally exceed 40 cm in diameter and 8 cm in thickness. Lithic fragments constitute up to 5 percent of the basal vitrophyre, decreasing upward in both size and abundance. They consist predominantly of fossiliferous limestone, shale, and chert derived from upper Paleozoic formations, but also include minor andesite and rare coarse-grained granodiorite. Sedimentary lithic fragments are commonly altered and preferentially weathered, leaving distinctive white pockmarks that resemble vapor-phase cavities on outcrop surfaces.

Units C and D have a markedly different appearance from A and B. They contain more crystals, fewer and smaller lithic clasts, and much smaller fiamme (typically 1 to 3 cm). However, because only a partial cooling break occurs between B and C, and mineralogical and compositional changes appear to be gradational, there is little doubt that all four units are comagmatic. Unit C weathers rust brown and has a strong, platy parting. In many specimens, its pyroclastic nature is obvious only in thin section. It is generally less than 150 m thick and is largely restricted to the middle third of the elliptical distribution of the Kalamazoo Tuff. Eutaxitic texture is more obvious in unit D. It appears to represent a series of thin ash flows emplaced in rapid succession, separated by fine-grained basal layers (Sparks et al., 1973). The upper part of D in the Kalamazoo Creek area (Fig. 7) includes horizons of agglutinate that consist largely of poorly vesiculated vitrophyric bombs.

Both the abundance and the relative proportions of phenocrysts change upward within the Kalamazoo Tuff (Fig. 4). Fiamme in unit A and in the basal part of unit B contain approximately 5 percent phenocrysts of plagioclase (3 percent), biotite (1.5 percent), and sanidine (0.7 percent), together with trace amounts of hornblende, Fe-Ti oxides, apatite, and zircon. The crystallization sequence appears to be hornblende followed by biotite and plagioclase followed by sanidine. The abundance of crystals increases upward within the tuff and is accompanied by the disappearance of sanidine, appearance of pyroxene, and increasing proportions of hornblende relative to biotite. Vitrophyric bombs in unit D have 20 to 25 percent phenocrysts of plagioclase (15 percent), hornblende (5 percent), biotite (2 percent), Fe-Ti oxides (0.5 percent), quartz (0.5 percent), and pyroxene (<0.5 percent), similar to the modes of the overlying hornblende dacite lavas (Fig. 4).

Hornblende dacite lavas

Distribution, volume, and source area(s). Crystal-rich hornblende dacite lavas, together with associated breccias and shallow intrusions, constitute the most voluminous rock types in the area. Their distribution resembles that of the Kalamazoo Tuff, with a similar east-west dimension but an even greater north-south extent (Fig. 9). Although it is possible that the more peripheral exposures of hornblende dacite may include some unrelated lavas, their consistent stratigraphic position, together with limited geochemical and geochronological data, suggest that they are comagmatic. The hornblende dacite lavas typically overlie the Kalamazoo Tuff or the older andesites and rhyolites, and are often the youngest eruptive unit exposed in any given area. Because their age, modal mineralogy, and composition closely resemble the last-erupted portion of the Kalamazoo Tuff, we believe the two are genetically related.

The massive, monotonous character of the hornblende dacite lava sequences makes it difficult to evaluate their attitude and to detect faults within many of the sections. Despite these difficulties, we estimate that a few sections, with no exposed tops, in the northernmost Schell Creek Range, northern Egan Range, and northernmost Snake Range are 600 to 1,000 m thick, and that complete sections elsewhere typically range from 100 to 400 m. We conservatively estimate the total volume of erupted hornblende dacite magma to be approximately 500 km^3.

The hornblende dacite lavas were apparently erupted from numerous vents distributed over a broad area. Subvolcanic intrusions and domes of hornblende dacite that texturally and compositionally closely resemble the lavas have been identified from such widely scattered localities as the northernmost Snake Range, the Kalamazoo Summit area of the northern Schell Creek Range, and the Hunter district in the northern Egan Range. Thin, poorly exposed, north-south–trending dacite porphyry dikes occur sporadically throughout all the ranges in the study area and appear to represent feeders for the lavas and domes. These dikes are generally somewhat altered but have approximately the same modal proportions as the lavas. The large volume and broad areal extent of hornblende dacite lavas and their vents (Fig. 9) indicate that much of the area was underlain by a dacitic magma body of batholithic dimensions.

Textural variations and modal mineralogy. Most of the hornblende dacite shown in Figure 9 occurs as lava flows. These lavas commonly have well-developed flow laminations defined by platy partings and the alignment of tabular minerals, but many are devoid of internal fabric. Most are completely devitrified and weather purplish gray, lavender, or reddish brown due to oxidation and variable amounts of vapor-phase alteration. Dark vitrophyre is locally preserved at the bases of some flows and on the margins of domes.

Intervals of volcanic breccia up to 150 m thick locally intervene between the Kalamazoo Tuff and the overlying hornblende dacite lavas. These breccias are typically monolithologic, containing angular clasts of hornblende dacite (mineralogically identical to the lavas) as large as 1 m in diameter in an ashy or pumiceous matrix. They are poorly stratified and include both clast- and matrix-supported varieties. The matrix locally has a primary compaction foliation defined by flattened pumice fragments. The breccias are well exposed in the Kalamazoo Summit area (Fig. 7), where they interfinger laterally with the hornblende dacite lava and also grade upward into the autobrecciated basal parts of the lavas. These breccias are block-and-ash flows, lahars, and pumiceous pyroclastic flows associated with emplacement of the hornblende dacite lavas.

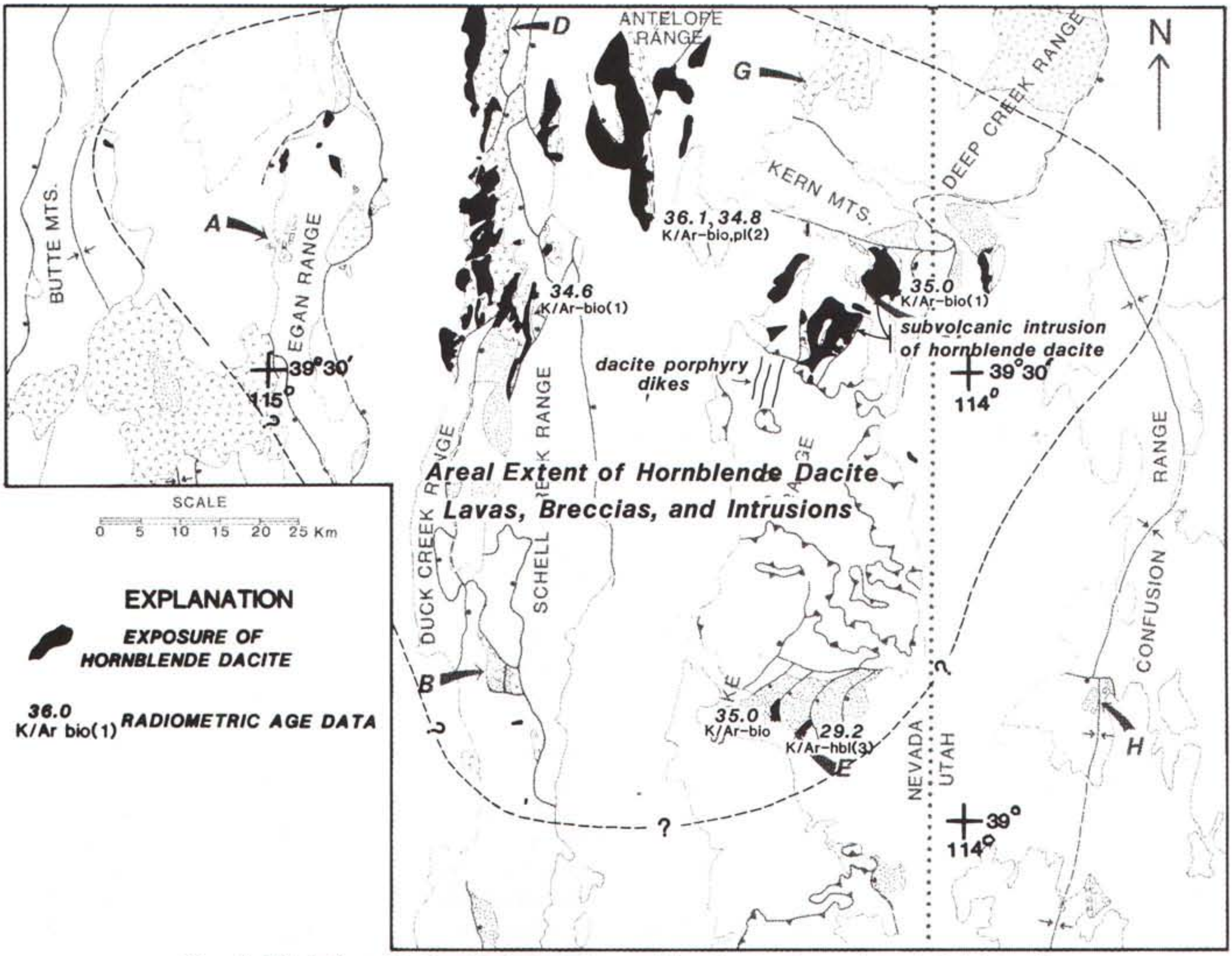


Figure 9. Distribution of the hornblende dacite lavas and breccias, showing geochronological data and geographical names discussed in text. Numbered references to geochronological data are listed in Table 1.

In addition to the lavas and breccias, some of the hornblende dacite depicted in Figure 9 occurs as subvolcanic intrusions. An especially large intrusion is exposed in the low area between the northern Snake Range and the Kern Mountains. Although it is cut by the youngest set of east-dipping normal faults and is difficult to distinguish from dacite lavas that overlie the Kalamazoo Tuff, we estimate that this single(?) intrusion must have originally been at least 10 km across. It has approximately the same phenocryst abundances as the lavas, but a somewhat coarser, microcrystalline groundmass. The scattered exposures of Kalamazoo Tuff in this area occur as steeply tilted roof pendants in the intrusion.

The hornblende dacite typically contains 35 to 40 percent phenocrysts, including 20 to 25 percent plagioclase, 6 to 8 percent hornblende, 2.5 to 3.5 percent biotite, 0.5 to 2 percent quartz, 1 percent Fe-Ti oxides, and 0.2 to 3.0 percent pyroxene (Fig. 4). These proportions closely resemble the last-erupted portion of the Kalamazoo Tuff, suggesting that the two are closely related. The large phenocrysts, high crystal contents, and predominance of hornblende among the mafic phases distinguish these lavas from other intermediate lavas in east-central Nevada. Plagioclase phenocrysts up to 1 cm across are commonly sieve textured and strongly zoned. Hornblende and biotite phenocrysts appear to have crystallized relatively early. The amount of quartz is highly variable, but is generally most abundant in the lower part of the dacite sections. Quartz occurs both as isolated subhedral to rounded/embayed phenocrysts(?) and as xenocrystic(?) polycrystalline aggregates as large as 3 cm. Hypersthene and lesser augite, occurring either as isolated euhedral crystals or cognate polycrystalline aggregates, are commonly rimmed by hornblende.

Tuff of North Creek

Distribution, volume, and source area. The tuff of North Creek is the youngest and volumetrically least significant member of the Kalamazoo volcanic rocks. Its areal distribution and age overlap with that of the older two members, but its modal composition and geochemistry are distinct. The tuff is exposed in two principal areas: (1) east of North Creek at the north end of Duck Creek Valley in the Schell Creek Range, and (2) along the southern and eastern margins of the Kern Mountains (Fig. 10). In many of the exposed sections, the tuff is separated from the underlying hornblende dacite lavas by a thin interval of pale-green water-laid tuff and tuffaceous sandstone. It is overlain, typically along a pronounced angular unconformity, by the younger sedimentary and volcanic sequences described below.

Too little of the tuff of North Creek is preserved to accurately assess its volume, but it appears to be considerably smaller than the Kalamazoo Tuff. A few sections are as much as 150 to 200 m thick, but most are between 30 and 100 m. Using its present distribution as a guide, and correcting for subsequent extension, we infer that its original extent was less than 25 km across and that its total volume was probably less than 50 km^3. The source area for the tuff of North Creek is not known. The thickness is too variable to provide any regional thickening trends, and like the Kalamazoo Tuff, none of the exposed sections are as thick as typical intracaldera fills. Although horizons that are choked with accidental lithic fragments of hornblende dacite have been identified, they do not appear to be caldera collapse breccias, because they are most common in the basal part of the tuff and occur throughout its distribution area. Perhaps the vent for the tuff of North Creek is also hidden beneath the north end of Spring Valley.

Cooling units, lithic content, and mineralogy. Thicker sections of the tuff of North Creek have two and, locally, three cooling units separated by partial to complete breaks. The different cooling units are too similar and their exposures are too widely scattered to correlate them from section to section. In the Kalamazoo Summit area, the tuff has one or two thin vitrophyres near its base overlain by a thick section of reddish-brown weathering, densely welded, devitrified tuff; locally the section is capped by an additional vitrophyre. On the southern flank of the Kern Mountains, the cooling breaks appear to be more evenly spaced, and a larger proportion of the tuff is vitrophyric.

Lithic fragments are more abundant in the tuff of North Creek than in the Kalamazoo Tuff and, in contrast to the latter, are almost entirely dacite. Most of the tuff contains only a few percent lithic fragments, 0.5 to 4 cm in diameter, although the basal part of the tuff locally contains as much as 30 percent lithic fragments up to 15 cm in diameter, and lithic-rich horizons occur sporadically throughout the section. The tuff has a well-developed eutaxitic texture containing about 30 percent fiamme, 2 to 10 cm in diameter.

Fiamme from the tuff of North Creek contain 17 to 21 percent phenocrysts, including 12 to 14 percent plagioclase, 3 to 4 percent biotite, 1.5 to 2.5 percent pyroxene, 1.0 percent Fe-Ti oxides, and less than 1 percent hornblende (Fig. 4). These percentages appear to remain relatively constant throughout the tuff and overlap with the modes in overlying trachytic lavas. The predominance of biotite+pyroxene among the mafic phases contrasts with most other intermediate composition rocks in east-central Nevada, which contain either anhydrous assemblages (2 pyroxenes + olivine) or hornblende + biotite, and is compatible with its more alkalic character. The ratio of clinopyroxene to orthopyroxene averages 2:1, but is variable. The tuff locally contains large anhedral grains and aggregates of quartz that we suspect are xenocrystic. In devitrified parts of the tuff, biotite is commonly replaced by iron oxides.

The tuff of North Creek is overlain by up to 50 m of intensely flow folded trachytic lavas in its type area at the north end of Duck Creek Valley (Fig. 7). Their mineralogy and composition closely resemble that of the tuff, suggesting that they are related. The 31.5 ± 1.4 Ma K-Ar age (Table 1) of these lavas is significantly younger than our preferred 35 Ma age for the tuff, and we suspect it is spuriously young, as a stratigraphically higher crystal-poor tuff in this same area yielded a K/Ar biotite age of 33.9 ± 1.1 Ma (Fig. 4, Table 1).

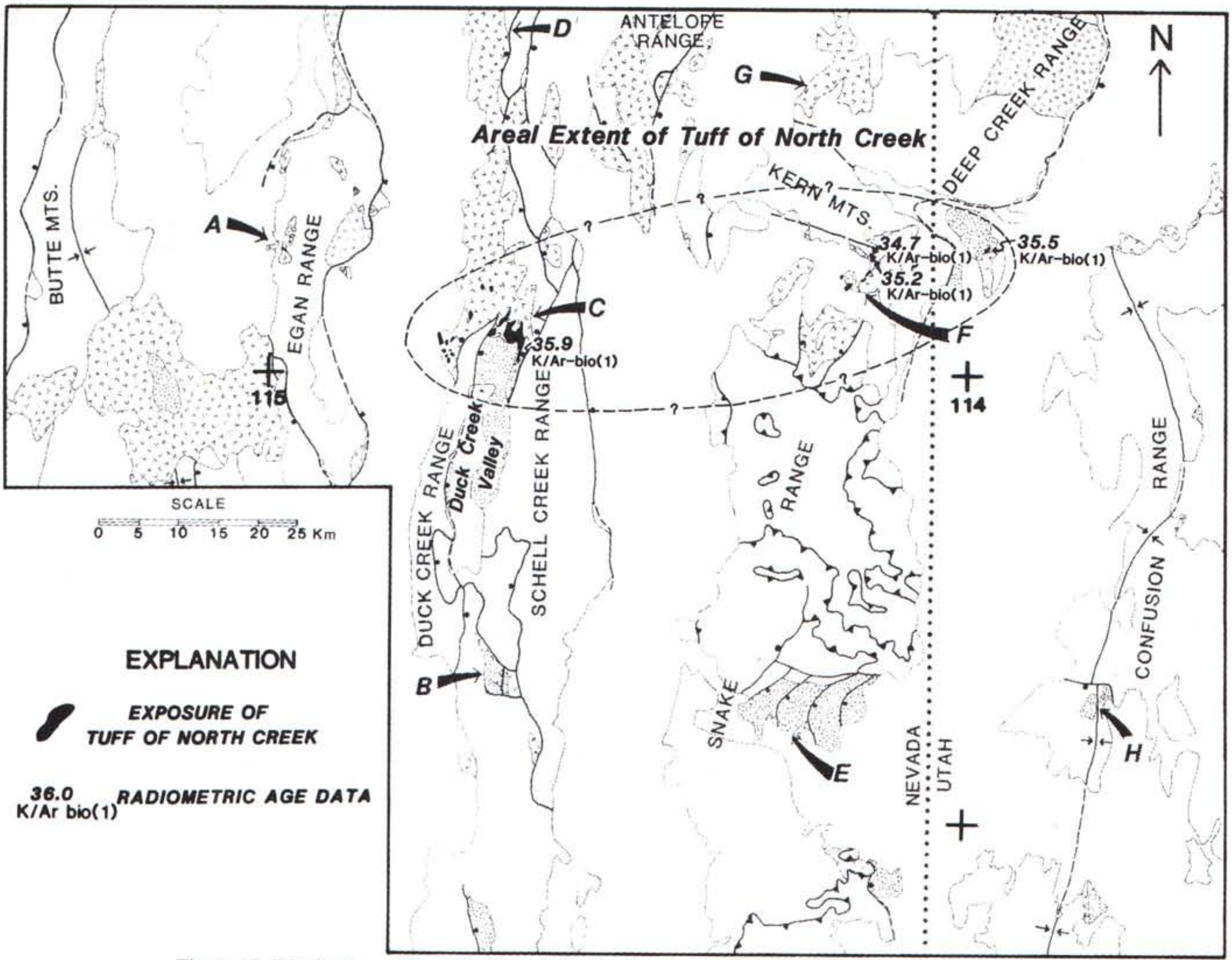


Figure 10. Distribution of the tuff of North Creek, showing geochronological data and geographical names discussed in text. Numbered references to geochronological data are listed in Table 1.

YOUNGER SEDIMENTARY AND VOLCANIC SEQUENCES

Thick sections of predominantly sedimentary rocks overlie Oligocene volcanic rocks in various parts of White Pine County and were grouped together by Hose and Blake (1976) into the "younger sedimentary and volcanic rocks." Here, we summarize stratigraphic and geochronological data from five of the better studied sections of these rocks (Fig. 11).

Duck Creek Valley

Duck Creek Valley is an asymmetric graben within the Schell Creek Range, bounded on the west by a major east-dipping normal fault, the Duck Creek fault, and on the east by the smaller, west-dipping Kalamazoo fault (Young, 1960) (Figs. 7 and 10). It is underlain by a thick, gently west-dipping section of conglomerates, sandstone, and monolithologic breccia, named the North Creek Formation by Young (1960). The base of this sequence unconformably overlies Kalamazoo volcanic rocks at the northern end of the valley, whereas farther south, along the eastern side of Duck Creek Valley, stratigraphically higher levels within the formation apparently onlap strata as old as Middle Cambrian (Fig. 2). The maximum thickness of the North Creek Formation is unknown but probably exceeds 1 km. It grades upward from conglomerates containing only clasts of volcanic rocks into conglomerates containing clasts derived from the whole spectrum of Paleozoic formations. Locally, large monolithologic breccia sheets derived from the Middle Cambrian occur within the upper part of the formation. A vitric tuff near the base of the North Creek Formation yielded a zircon fission-track age of 27.4 Ma (Anderson, 1983), but the upper age limit of the formation is not known.

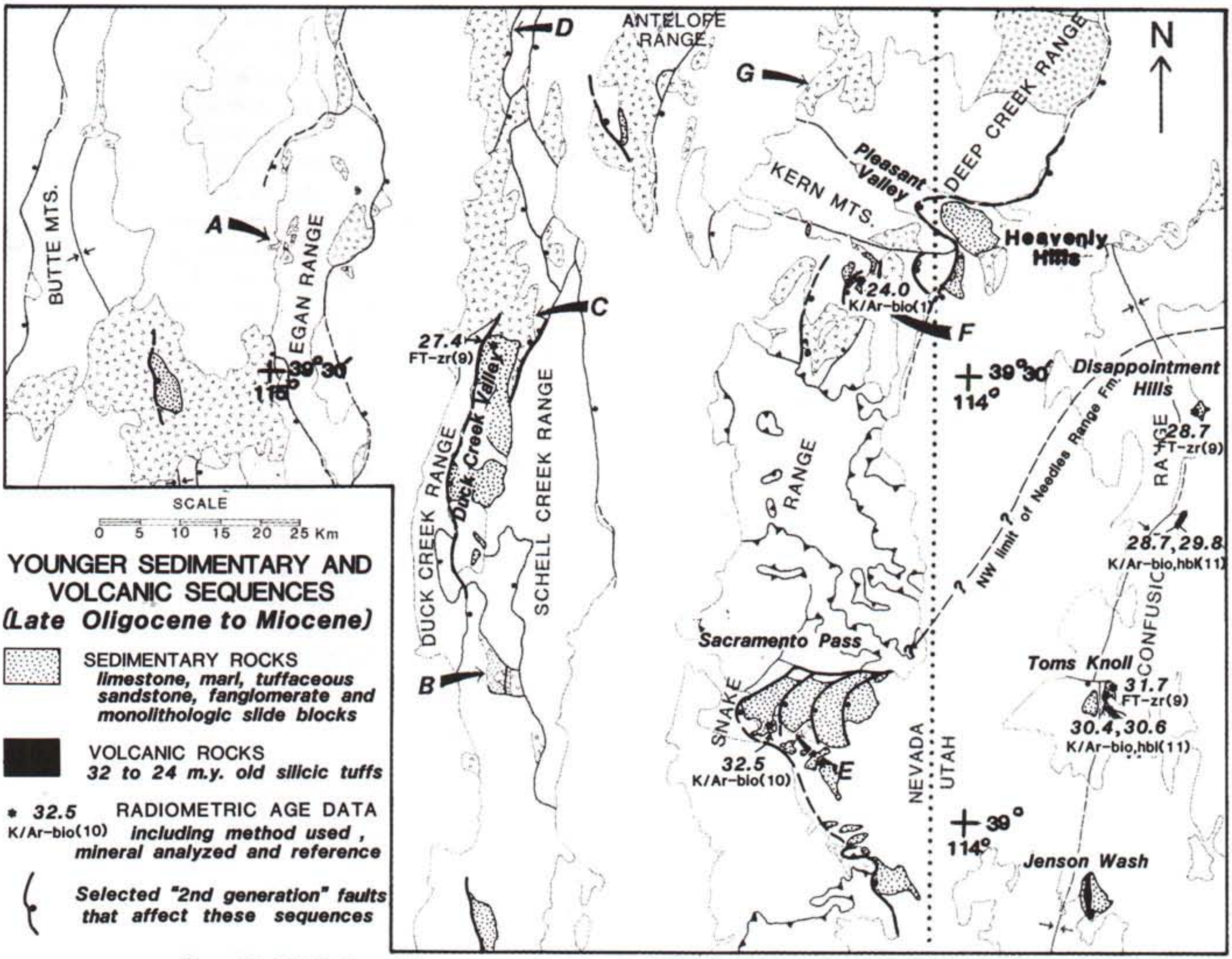


Figure 11. Distribution of the younger sedimentary and volcanic sequences, showing existing geochronological data and geographical names discussed in text. Numbered references to geochronological data are listed in Table 1.

Sacramento Pass

Sacramento Pass forms an east-west–trending low area between the northern and southern parts of the Snake Range. The 2- to 3-km-thick Tertiary section of sedimentary and volcanic rocks (Section E in Fig. 3) has been described by Hose and Whitebread (1981) and Grier (1983, 1984); here we summarize their principal findings.

The depositional base of the Tertiary section is exposed only in two small areas east of Sacramento Pass. At both localities, a well-rounded and well-sorted red conglomerate a few tens of meters thick unconformably overlies Pennsylvanian strata and contains only clasts derived from upper Paleozoic formations. The conglomerate is overlain by up to 200 m of hornblende-biotite dacite lavas followed by a thin rhyolitic ash-flow tuff. The volcanic rocks are overlain by a 300- to 800-m-thick sequence of fresh-water limestone, marl, and minor tuffaceous sandstone. Detailed sedimentological and petrological work by Grier (1984) indicates that this sequence was deposited in an ephemeral playa lake and includes facies that range from lagoonal to offshore. Lacustrine deposits are overlain by, and interfinger with, coarse conglomerates that exceed 1500 m in thickness. Spectacular monolithologic slide blocks up to 1 km in length are intercalated within the upper part of the lacustrine deposits and lower part of the fanglomerates. They include variably brecciated Cambrian to Devonian units that apparently peeled off of active fault scarps and slid into the Tertiary basin. Conglomerates consist mainly of braided-stream and debris-flow deposits that record encroachment of ancient alluvial fans across the playa lake. Pebble imbrications and interfingering relations within the fanglomerates suggest predominantly northeast-directed paleocurrent directions (Grier, 1984). The conglomerates contain clasts of Paleozoic limestone, dolomite, and quartzite, Tertiary volcanic rocks and lacustrine limestone, metamorphosed upper Precambrian quartzite and schist, and Mesozoic granite and granodiorite. The latter two clast types closely match lithologies currently exposed in the northern part of the southern Snake Range and indicate that 7 to 9 km of structural relief had been developed at the time of their deposition. Clasts of highly tectonized metasedimentary and plutonic rocks such as are widespread beneath the northern Snake Range décollement are mostly absent, but have been identified in the upper part of the easternmost fault block exposed in Sacramento Pass (E. L. Miller, 1986, personal communication) and in correlative conglomerates along the eastern flank of the northern Snake Range.

The exact age and correlation of the basal volcanic rocks in Sacramento Pass is not entirely clear. Armstrong (1970) obtained an age of 28.5 Ma on a hornblende + biotite concentrate from one of the lavas, and McKee et al. (1976) obtained a K/Ar biotite age of 21.9 Ma from the overlying rhyolitic tuff (Table 1). We believe that these ages are spuriously young, however, in that the samples are hydrothermally altered. A 35-Ma age from a fresher lava was reported by E. H. McKee (oral communication, 1971, *in* Hose and Blake [1976]), but only the approximate sample location is known. We prefer this latter age for the basal volcanic rocks at Sacramento Pass because a thin rhyolitic pumice fall intercalated within the slide-block–bearing horizons near the top of the lacustrine limestone sequence yielded a K/Ar biotite age of 32.5 Ma (Grier, 1984). The overlying fanglomerates are not dated, but correlative units in the Confusion Range (described below) are, at least in part, older than 29 Ma.

Confusion Range

The Confusion Range forms a broad syncline or structural trough, with Triassic and uppermost Permian strata preserved in the core and progressively older strata exposed toward the limbs (Hose, 1977). Limited exposures of Tertiary conglomerate, lacustrine limestone, sandstone, and minor intercalated ash-flow tuff occur at widely scattered localities in the Confusion Range (Section H in Fig. 3; Fig. 11) and have been described in detail by Anderson (1983). Stratigraphic and radiometric data summarized below indicate that these Tertiary sections are correlative to the thick sedimentary sequence in the Sacramento Pass area.

Rhyolite tuff containing phenocrysts of sanidine, quartz, plagioclase, and biotite occurs near the base of Tertiary sections at Jenson's Wash and Tom's Knoll (Fig. 11). One sample yielded a zircon fission-track age of 31.7 ± 1.0 Ma (Anderson, 1983), within analytical uncertainty of the 32.5 ± 0.5 Ma K-Ar age for a similar rhyolite tuff in the Sacramento Pass section (Table 1). Overlying the rhyolite tuff are variable thicknesses of intercalated conglomerate and lacustrine limestone. Of particular interest is the clast content of the conglomerates; we have identified clasts of most of the Paleozoic formations, including abundant boulders up to 1 m in diameter of the Ordovician Eureka Quartzite, Ordovician Pogonip Group, and Upper Cambrian Notch Peak Formation. These formations are not exposed anywhere in the immediate vicinity, and pebble imbrications consistently indicate transport from the west or northwest; therefore, the logical source for these clasts is the Snake Range. We suggest that these conglomerates are correlative with the younger conglomerates in Sacramento Pass. At Jenson's Wash and Tom's Knoll, the conglomerates are overlain by a distinctive, crystal-rich ash-flow tuff that is zoned from a biotite rhyolite at its base to hornblende dacite at its top. Samples of the tuff from various localities in the Confusion Range (Fig. 11) yielded radiometric ages that range from 28.7 to 30.6 Ma (Marvin and Cole, 1978; Anderson, 1983) (Table 1). The tuff was correlated by Marvin and Cole (1978) with the ~29 Ma Needles Range Formation (Best et al., 1973). In the Disappointment Hills and at Jenson's Wash, additional thick sections of conglomerate with clast contents and pebble imbrication directions similar to the lower beds stratigraphically overlie the Needles Range Formation.

Northernmost Snake Range

Kalamazoo volcanic rocks and associated shallow intrusions constitute most of the Tertiary rocks in the northernmost Snake Range. Poorly exposed younger sedimentary rocks crop out in a few of the low hills and washes north of the main east-west road (Gans et al., in preparation). Westward tilts decrease upward within the sedimentary section, from 35° to 10°. The sedimentary sequence is at least 500 m thick and consists of three distinct members (Section F in Fig. 3). The lowest member is a conglomerate containing well-rounded and well-sorted clasts of Kalamazoo volcanic rocks and fewer upper Paleozoic rocks. This member interfingers with and is overlain by a section of tuffaceous sandstones, marls, and lacustrine limestone. The highest unit consists of coarse, poorly sorted conglomerate that contains a wide variety of lithotypes: unmetamorphosed middle and upper Paleozoic carbonates, chert, and quartzites, foliated marbles and phyllites derived from metamorphosed Paleozoic formations, a highly distinctive two-mica granite with phenocrystic muscovite, and Tertiary volcanic rocks. The metamorphic and plutonic clast types are exposed only in the Kern Mountains to the north, and their presence in this conglomerate records the unroofing of both the Tertiary Skinner Canyon Granite and the Cretaceous Tungstonia Granite.

A distinctive, 10-m-thick, crystal-poor ash-flow tuff occurs locally near the top of the lower conglomerate. It consists almost entirely of partially welded glass shards, with less than 5 percent small crystals of plagioclase, quartz, sanidine, and biotite, and rare dacite lithic fragments. This tuff has a much lower crystal content than any other eruptive unit in east-central Nevada and has yielded a K/Ar sanidine age of 24.0 ± 1.3 Ma (Table 1). Recent paleomagnetic work on this tuff (C. S. Gromme, 1988, personal communication), together with its age and crystal content, suggest that it may be correlative with the tuff of Clipper Gap (Gromme et al., 1972), thereby greatly increasing the known areal extent of this remarkable unit.

Pleasant Valley

The Kalamazoo volcanic rocks in the Heavenly Hills are overlain by a thick section of sedimentary rocks that underlie most of Pleasant Valley (Fig. 11). These rocks were first described by Nelson (1966) and have been subsequently studied by Rodgers (1987) and Gans et al. (in preparation). The postvolcanic section consists of 50 to 100 m of lacustrine limestone and tuffaceous sandstone overlain by a conglomerate with a clast content and appearance similar to the younger conglomerate in the northernmost Snake Range. The total thickness of conglomerate is unknown due to poor exposure and the likelihood of repetition by faulting, but is certainly greater than 1 km.

The entire Tertiary section dips westward and lies in the hanging wall of a major east-dipping normal fault that circumscribes Pleasant Valley. The Kalamazoo volcanic rocks dip 50° to 70° and rest disconformably on Permian strata. The sedimentary sequence overlies the volcanic rocks with an angular unconformity of $\sim 20°$ and has westward tilts that decrease upward, from 40° to 15°. No constraints exist on the age of the sequence except that it is younger than 35 Ma. We suspect it is in part Oligocene and correlative with the northernmost Snake Range section because it has similar lithologies and appears to be syntectonic with the youngest faults.

RELATIVE TIMING OF FAULTING AND VOLCANISM

Onset of extensional faulting

The best constraints on the inception of extensional faulting in east-central Nevada come from the northern Egan Range and from the central Schell Creek Range. Structural and stratigraphic relations in these two areas indicate that the earliest normal faults had begun to move by about 36 Ma, synchronous with eruption of some of the earliest volcanic rocks. Although we cannot rule out even older faulting, the character of the basal Tertiary unconformity across this region argues that it would have had to have been relatively minor (see discussions in Armstrong [1972] and Gans and Miller [1983]).

The structural style in the northern Egan Range is typical of many of the ranges in east-central Nevada and closely resembles what Proffett (1977) so elegantly documented at Yerington, Nevada. Thin slices of steeply west-dipping upper Precambrian to Permian strata are separated by low-angle faults that displace hanging walls eastward with respect to footwalls. Gans (1982) and Gans and Miller (1983) argued that the low-angle faults in the Egan Range originated as imbricate, east-dipping, high-angle normal faults that rotated to lower angles as they moved. In the vicinity of the Hunter District (Fig. 6), 36-Ma rhyolite porphyry dikes intrude and locally cut a gently east-dipping normal fault with more than 1 km of displacement (the Hunter fault), suggesting that the onset of major extensional faulting predated or was synchronous with this early episode of rhyolitic volcanism (Gans, 1981, 1982). The steep westward dips of the comagmatic volcanic rocks, together with the fact that some of the structurally controlled dikes have sheared margins, indicate that faulting and tilting continued after volcanism had ceased.

There is little evidence for major faulting within the central Schell Creek Range prior to or synchronous with deposition of the Tertiary rocks. A few small-displacement, younger-on-older faults were shown by Drewes (1967) to be depositionally overlapped and/or intruded by the youngest dacites, but in general, Tertiary strata were deposited only on upper Mississippian to Permian strata and appear to be fully involved in the faulting and tilting (cf. Armstrong, 1972). The clast lithotypes of Tertiary conglomerates, however, record the unroofing of deep structural levels from adjacent areas. For example, the conglomerate that underlies the 36-Ma tuff of Cooper Summit contains only upper Paleozoic clasts at its base but includes clasts of Ordovician to Devonian dolomite and quartzite toward the top (Drewes, 1967; Fig. 3). South of Highway 50, near Majors Place, an apparently correlative interval of conglomerate contains clasts of Middle Cambrian to Ordovician limestone, Lower Cambrian quartzite, and granite, and is there overlain by hornblende-dacite lavas presumed to be 35 m.y. old. As pointed out by Drewes (1967), some of these clasts are foreign to the central Schell Creek Range and were probably derived from the Snake Range to the east. The occurrence of clasts derived from Ordovician and perhaps Lower Cambrian formations in conglomerates interstratified with and overlain by latest Eocene to early Oligocene volcanic rocks requires that adjacent areas (probably the southern Snake Range) had been uplifted as much as 7 km and were eroding at this time. Although the actual faults responsible for this earliest Oligocene differential uplift are not exposed, they are inferred to be normal faults related to the earliest phases of extensional tectonism.

Faulting associated with the Kalamazoo volcanic rocks

Several lines of evidence indicate that extensional faulting was ongoing at the time of, and immediately prior to, the eruption of the Kalamazoo volcanic rocks. The angular discordance between the Kalamazoo Tuff and underlying strata is generally less than 15°, but stratigraphic relations beneath this unconformity suggest that significant structural relief was developed after deposition of the older Tertiary sequences and prior to the eruption of the tuff. Older sedimentary and volcanic sequences were deposited almost exclusively on Upper Pennsylvanian and Permian strata, whereas the Kalamazoo Tuff, in some areas, overlies sections of these older Tertiary rocks that are as thick as 1 km but, in other areas, rests directly on Paleozoic strata as old as Upper Devonian. For example, in the vicinity of Kalamazoo Summit, the unconformity beneath the Kalamazoo Tuff cuts abruptly downsection northward, from early Tertiary sedimentary rocks that overlie Pennsylvanian limestone to Lower Mississippian and Upper Devonian strata (Fig. 7). This represents nearly 1 km of stratigraphic relief across a horizontal distance of less than 8 km. Farther north near Muncy Creek, the Kalamazoo Tuff may overlap a normal fault that places Upper Permian strata on Ordovician strata (Dechert, 1967). It is noteworthy that many of the areas where the Kalamazoo Tuff rests directly on the pre-Tertiary basement are also areas where the oldest Paleozoic strata occur beneath the Tertiary unconformity. These areas likely represent horsts or the up-ended parts of gently tilted fault blocks where earlier Tertiary sequences and uppermost Paleozoic strata were erosionally stripped prior to deposition of the Kalamazoo Tuff. Although some of this pre-Kalamazoo Tuff structural relief may be related to Mesozoic folding and faulting(?), the fact that it appears to be greater than the relief overlapped by the older Tertiary strata and that it occurs across relatively short horizontal distances argues that some of this structural relief is a consequence of the early Oligocene extensional faulting.

Only in a few areas is it possible to infer angular unconformities and upward decreasing tilts within the Kalamazoo volcanic rocks that would suggest syndepositional growth faulting. However, most sections are dominated by hornblende dacite lavas from which it is difficult to get reliable attitudes. In the vicinity of Kalamazoo Summit, gently south-dipping sections of the tuff of North Creek overlie unconformably a predominantly west-dipping section of Kalamazoo Tuff and hornblende-dacite lavas and domes (Fig. 7). Here, an east-dipping fault repeats the Tertiary unconformity and the lower two members of the Kalamazoo volcanic rocks, but appears to die out upward and southward, because it offsets only slightly the overlying tuff of North Creek. In the area between the Snake Range and Kern Mountains, most complete sections of the Kalamazoo volcanic rocks are conformable, but in one area, a thick section of moderately west-dipping tuff of North Creek overlies a section of hornblende dacite lavas and Kalamazoo Tuff that appears to dip more steeply.

A final piece of evidence for faulting concurrent with the eruption of the Kalamazoo volcanic rocks comes from the north end of the Snake Range. Previous workers (e.g., Nelson, 1966; Hose and Blake, 1976) concluded that the volcanic rocks in this area largely postdate the faulting in the upper plate of the northern Snake Range décollement and locally rest depositionally directly on marble of the lower plate. Recent mapping by Gans et al. (in preparation) suggests that relations are more complicated. Kalamazoo Tuff typically dips moderately to steeply westward and rests depositionally only on uppermost Mississippian to Permian strata, suggesting that the amount of faulting prior to its deposition was minor. However, a large subvolcanic intrusion of hornblende dacite (Fig. 9), of age and composition indistinguishable from the hornblende dacite lavas, appears to postdate a large proportion of the extensional faulting. In map pattern, the intrusive contact truncates both down-to-the-east and down-to-the-west normal faults, some of which have stratigraphic throws in excess of 5 km (e.g., Pennsylvanian on Middle Cambrian). Roof pendants of the intrusion include steeply tilted sections of Kalamazoo Tuff that dip downward into subhorizontal intrusive contacts. The dacite intrusion is almost certainly displaced by the latest movement on the northern Snake Range décollement; the youngest east-dipping normal faults imbricate the intrusion together with the overlying tuff of North Creek, but do not appear to offset the décollement along strike.

Faulting associated with the younger sedimentary and volcanic sequences

By the time the younger sedimentary and volcanic sequences were deposited, extensional faulting was underway throughout east-central Nevada. These sequences typically include coarse clastic debris and monolithologic slide blocks that record uplift and erosion of some of the deepest exposed structural levels. They commonly overlap older normal-fault mosaics, yet are themselves affected by the youngest normal-fault systems. In many areas, tilts decrease upward within the sections, suggesting that deposition was synchronous with faulting and tilting.

Duck Creek Valley. Structural and stratigraphic relations reviewed by Anderson (1983) and Gans et al. (1985) suggest that the North Creek Formation represents the syntectonic basin fill that accumulated in Duck Creek Valley during movement on the Duck Creek and Kalamazoo faults. Dips within the formation generally decrease upward, and it locally contains large monolithologic breccias derived from formations as old as Middle Cambrian (Young, 1960). It overlies the Kalamazoo volcanic rocks along a pronounced angular unconformity at the northeast end of Duck Creek Valley and depositionally overlaps an earlier set of gently dipping normal faults farther south in the Schell Creek Range (see Fig. 2 in Gans et al., 1985). The 27.4-Ma vitric tuff near the base of the formation constrains this earlier episode of extensional faulting in the Schell Creek Range area to have occurred prior to the latest Oligocene and suggests that the youngest basin-bounding faults may have begun to move by this time. Because there is no upper age constraint on the North Creek Formation, the timing of movement on the youngest system of normal faults is poorly known. Locally, there is evidence for Quaternary movement on the range-bounding faults.

Sacramento Pass and Confusion Range. Grier (1983) concluded that the Tertiary sedimentary rocks in Sacramento Pass were deposited in a basin that was localized between an area undergoing rapid, large-magnitude extension to the north and an area of lesser extension to the south. She inferred that the northern margin of the basin was a strike-slip fault, whereas the southern and western margins were major normal faults. At least three down-to-the-east normal faults subsequently cut the basin fill and tilted bedding 30° to 50° westward. These faults are curved in plan view and merge with a west-northwest–trending, sinistral(?) fault on the southern flank of the northern Snake Range (Fig. 11) that is thought to represent an original lateral ramp in the Snake Range décollement (Gans and Miller, unpublished data). The amount of faulting older than the volcanic rocks at the base of the section is difficult to assess due to the limited exposures of pre-Tertiary basement, but was probably minor, given the clast content of the basal conglomerate. Active faulting during deposition of the sequence is indicated by the occurrence of monolithologic breccia sheets and clasts derived from rocks as old as upper Precambrian. The basin itself appears to have undergone relatively little syndepositional tectonism; the entire sequence is conformable, and tilts do not appear to decrease systematically upward within the section. However, fanglomerates in the upper part of the section locally contain clasts of lacustrine limestone and volcanic rocks, suggesting that adjacent parts of the basin were uplifted and eroding at the time. Conglomerate correlative to the upper part of the section at Sacramento Pass has been traced eastward as far as the Confusion Range, where it is overlain by a 29-Ma tuff presumed to be part of the Needles Range Formation. The simplest interpretation of all the available structural and geochronological data is that the earliest normal faults in the Snake Range region began to move in the early to mid-Oligocene, were active between 35 and 29 Ma during deposition of the Sacramento Pass section, and that the youngest generation of east-dipping normal faults began to move at some time after 29 Ma.

Northernmost Snake Range. The postvolcanic sedimentary sequences between the Kern Mountains and the Snake Range appear to postdate an earlier episode of normal faulting but are imbricated by the youngest east-dipping normal faults (Gans et al., in preparation). Relations exposed at the north end of the Snake Range suggest that both sets of faults bottomed into the northern Snake Range décollement. The westward tilts within the younger sedimentary sequences decrease markedly upsection, from 40° to 15°, suggesting that, like the North Creek Formation in Duck Creek Valley, they represent the syntectonic basin fill that accumulated in half grabens during movement on the youngest faults. They contain clasts that record the unroofing of plutonic and metamorphic rocks in the Kern Mountains and rocks as old as Middle Cambrian from the northern Snake Range. A 24-Ma vitric tuff interstratified within the younger sedimentary sequence places an upper age limit on the older episode of normal faulting and suggests that the youngest faults continued to move after the earliest Miocene.

Tectonic-stratigraphic summary

The eruption of the older andesites and rhyolites heralded the onset of volcanism in east-central Nevada. They were erupted intermittently over the 5-m.y. interval prior to eruption of the more voluminous Kalamazoo volcanic rocks, and may represent premonitory eruptions recording the coalescence of a batholith-sized magma chamber at shallow levels in the crust (e.g., Steven and Lipman, 1976). These older sequences are poorly preserved but were apparently derived from small centers scattered throughout the study area. None of the individual units appears to be very extensive, but the total volume of erupted material is almost certainly greater than 100 km^3. Their compositions are somewhat bimodal; rhyolite (commonly high-silica rhyolite) and andesite or low-silica dacite predominate (Fig. 4). The most mafic volcanic rocks were erupted from centers that presently lie peripheral to the main exposures of Kalamazoo volcanic rocks, suggesting that a higher proportion of low-density silicic melts accumulated in the central part of the study area and behaved as a density filter, impeding the ascent of more mafic magmas. The onset of extensional tectonism in east-central Nevada is inferred to have coincided with the eruption of the early andesites and rhyolites because: (1) intercalated conglomerates locally contain debris that records the denudation of deep structural levels in adjacent areas, and (2) feeders for some of these volcanic rocks locally cut the earliest extensional faults.

The Kalamazoo volcanic rocks compose the bulk of the erupted material, with an estimated original volume of approximately 1,000 km^3. All three members were erupted in less than 1 m.y. at about 35 Ma. Their source area is inferred to be either in the northern Schell Creek Range or buried beneath the northern part of Spring Valley. The Kalamazoo Tuff has a volume of approximately 300 km^3 and is zoned upward from a crystal-poor rhyolite base to a crystal-rich hornblende dacite top. The similar composition and mineralogy of the last-erupted part of the Kalamazoo Tuff and the overlying 500+ km^3 of hornblende dacite lavas suggest that the former may represent a compositionally zoned cap and the latter a sampling of the dominant volume of a dacitic magma body of batholithic dimensions. The age and distribution of the younger and smaller tuff of North Creek resemble those of the older two members, but it is more alkalic in bulk composition and contains abundant pyroxene rather than hornblende. Evidence that extensional faulting was contemporaneous with eruption of the Kalamazoo volcanic rocks includes the following. (1) The Kalamazoo Tuff appears to overlap a greater amount of structural relief than do the older volcanic sequences. (2) Angular unconformities are locally developed between the hornblende dacite lavas and the tuff of North Creek. (3) A comagmatic hornblende dacite intrusion in the northernmost Snake Range appears to postdate some of the extensional faulting in that area.

Exposures of the younger sedimentary and volcanic sequences are widely separated but remarkably similar. Fanglomerate typically overlies and predominates over lacustrine deposits. Clast contents record the unroofing of some of the deepest exposed structural levels. Intercalated monolithologic slide masses suggest that steep topographic scarps existed. Dips typically decrease upward within the sequences, indicating syndepositional growth faulting. Sparse radiometric age data from thin intercalated silicic tuffs suggest that the lower parts of these sequences are mid- to latest Oligocene, but their upper age limit is unconstrained. They typically overlap the older generations of normal faults unconformably but are involved in the youngest faulting. On both the northern and southern flanks of the northern Snake Range, faults that imbricate these sequences appear to sole into the Snake Range décollement. We believe the younger sedimentary and volcanic sequences represent separate basins or half-grabens that first began to form during the middle to late Oligocene along the youngest generation of east-dipping normal faults currently exposed in the ranges. We have no upper age constraint on this episode of faulting and sedimentation and do not know whether it entirely preceded or was continuous with the formation of the present basins and ranges (see discussion in Gans et al., 1985).

In many parts of the Basin and Range province, voluminous intermediate to silicic volcanism was followed by much smaller eruptions of basalt (± rhyolite). The only evidence for late-stage bimodal volcanism in east-central Nevada are rare rhyolite tuffs (such as the 24-Ma tuff in the northernmost Snake Range) and rare 23-Ma ($^{40}Ar/^{39}Ar$ on hornblende) lamprophyre dikes in the eastern Kern Mountains (Gans et al., in preparation). In addition, Hose and Blake (1976) reported a few 21-Ma olivine basalt flows in western White Pine County.

We have purposefully highlighted those field relations which suggest that volcanism and extensional tectonism in east-central Nevada were synchronous. However, in most areas there are neither major angular unconformities within the volcanic sections nor between the volcanic rocks and the underlying upper Paleozoic basement, which suggests that much of the faulting and tilting postdated Oligocene volcanism. The lack of more evidence for syndepositional tectonism within the volcanic sequences reflects the relatively short time interval (~1 m.y.) during which most of the volcanic rocks were erupted (Fig. 4) and the fact that Tertiary rocks are generally best preserved in the less extended areas, having been largely eroded from the most highly extended and uplifted areas such as the Snake Range and the central part of the Schell Creek Range. Given the limited preservation of Tertiary rocks and the absence of dateable units within the upper parts of the Tertiary sequences, it is not possible to accurately assign amounts and rates of extension to various time intervals. From the available data, we can say with confidence only that extensional faulting in east-central Nevada began at least 36 m.y. ago during some of the earliest volcanism, was ongoing at the time of the major outpourings of volcanic rocks at 35 Ma, and continued into the early Miocene for an unknown amount of time during deposition of the younger sedimentary and volcanic sequences. Locally, there are Quaternary scarps on some of the major range-front faults. On the basis of the structural and stratigraphic relations outlined above and cooling histories of the deeper structural levels (e.g., Lee et al., 1980; Lee and Sutter, 1987; Gans et al., 1988), we estimate that no more than 50 percent of the total extension across east-central Nevada occurred in the Oligocene; the remainder occurred during the Miocene to present.

GEOCHEMISTRY OF SYNEXTENSIONAL VOLCANIC ROCKS IN EAST-CENTRAL NEVADA

The Tertiary volcanic rocks in east-central Nevada provide an instructive test of some generally accepted petrotectonic associations. They were erupted at a time of subduction beneath the west coast of North America and closely resemble suites from the central Andes (e.g., Francis et al., 1984), yet it is difficult to call them "subduction-related," given their occurrence within a narrow, east-west–trending belt that extended up to 1000 km inboard of the continental margin (Fig. 1). Their local tectonic setting is better established; they were erupted through continental crust that had been previously thickened by Mesozoic thrust faulting and that was undergoing rapid large-magnitude extension. This synextensional volcanism resembles neither the bimodal basalt-rhyolite volcanism associated with later stages of Basin and Range extension (e.g., Christiansen and Lipman, 1972; Suneson and Luchitta, 1983) nor the alkalic, silica-undersaturated suites common in continental rifts (e.g., Gass, 1970; Neumann and Ramberg, 1978).

Major- and trace-element compositions

Fresh volcanic rocks range from basaltic andesite, with 54 percent SiO_2, to high-silica rhyolite, with 77 percent SiO_2 (Table 2). Care was taken to analyze only the freshest rocks; there is nonetheless a great deal of scatter in the alkali contents (Fig. 12). Vitrophyric samples are ubiquitously hydrated and have apparently lost sodium (e.g., Lipman, 1965; Noble, 1970), whereas devitrified rocks are commonly oxidized due to vapor-phase alteration. We did not find significant potassium metasomatism (e.g., Chapin and Glazner, 1983) because we did not analyze obviously altered rocks, but metasomatism may be rare in east-central Nevada because the pre-Tertiary basement consists largely of alkali-poor carbonates.

Despite the mobility of alkalies, it is clear from the major- and trace-element chemistry and the presence of biotite and sanidine phenocrysts that the suite as a whole is high-K and calc-alkalic. All samples are enriched in light rare earth elements (LREE) (Fig. 13), and ratios of incompatible elements (e.g., La/Ba = 0.03–0.05; La/Nb = 2.5–3) lie within the fields for high-K orogenic suites (Gill, 1981).

Volcanism in east-central Nevada exhibits some striking time-composition-volume trends. Early, small-volume eruptions were compositionally diverse and produced both the most mafic and most silicic rock units. Compositions are predominantly andesite to low-silica dacite and rhyolite to high-silica rhyolite; compositions in the range 66 to 71 percent SiO_2 are rare. In contrast, the subsequent, more voluminous eruptions of Kalamazoo volcanic rocks span a narrower range of compositions (65 to 74 percent SiO_2, mostly 67 to 69 percent) that effectively fills the earlier compositional gap. Of the total volume of volcanic rocks exposed, we estimate that approximately 20 percent is pyroxene andesite and dacite ($\leqslant$65 percent SiO_2), 65 percent is hornblende-biotite dacite (66 to 70 percent SiO_2), and 15 percent is biotite rhyolite ($\geqslant$71 percent SiO_2).

Early andesites and rhyolites. Because of the discontinuous nature and small volume of individual eruptive units within the older andesites and rhyolites, much more sampling will be required to fully characterize this complex suite. Locally, high-silica rhyolite ash-flow tuffs alternate with approximately equal thicknesses of andesitic lavas (e.g., section A in Fig. 3), but rhyolite is more typically subordinate or absent, and the older sections consist of monotonous andesite to dacite lavas (section G in

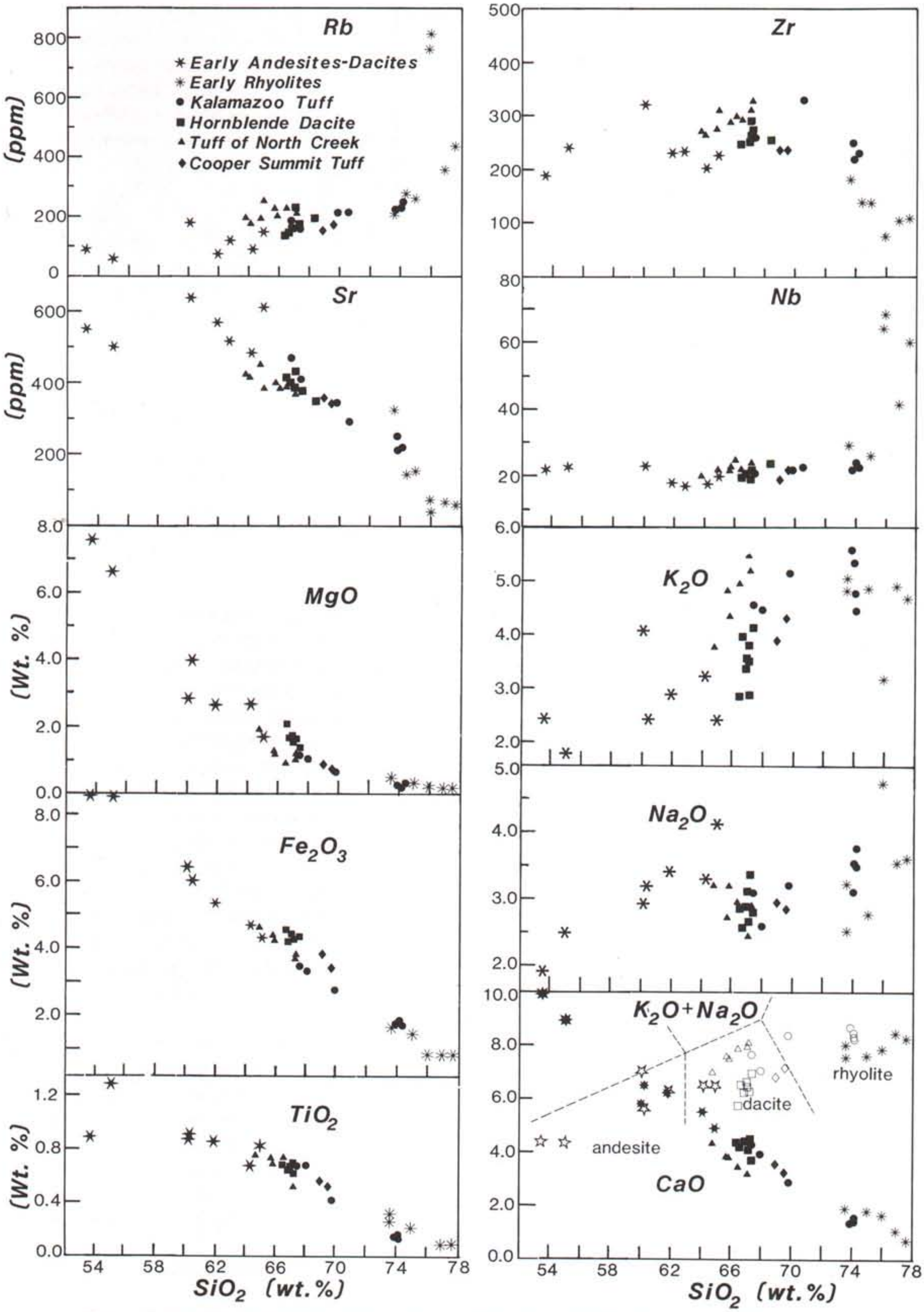


Figure 12. Variation diagrams for major and trace elements and combined alkalies (filled symbols) and CaO (open symbols) against SiO_2 in volcanic rocks from east-central Nevada.

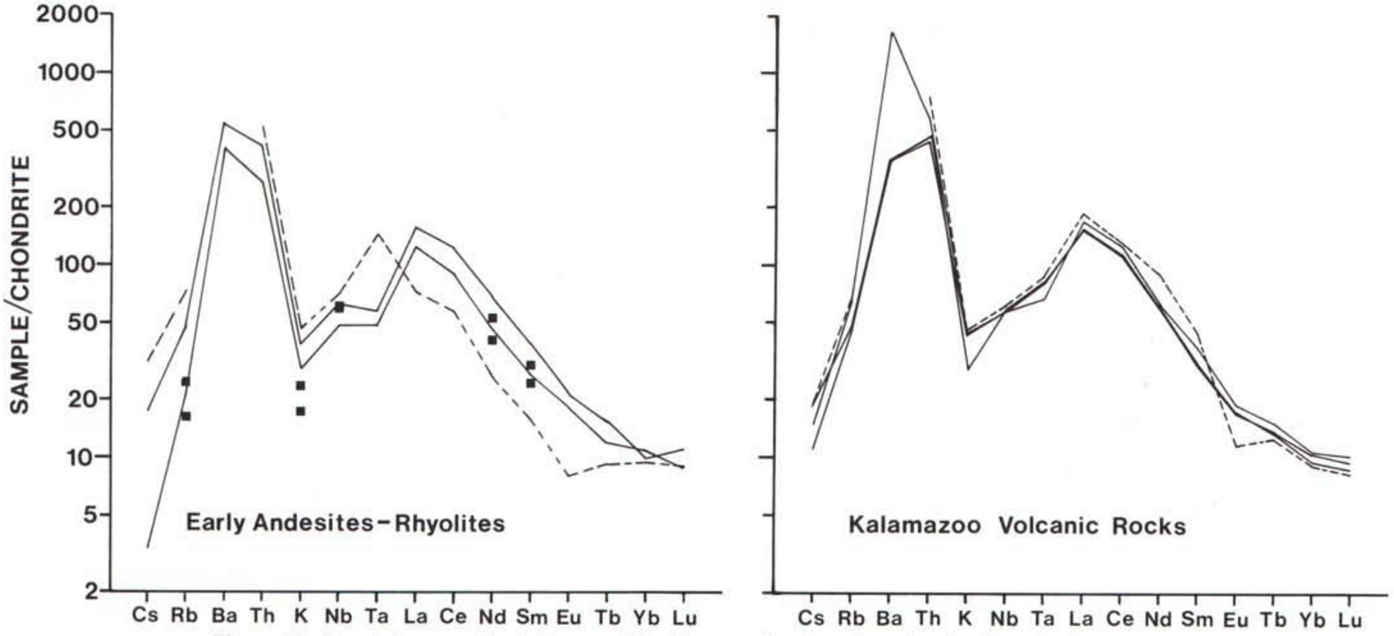


Figure 13. Chondrite-normalized incompatible element plots for selected volcanic rocks from east-central Nevada. Chondrite values from Taylor and McLennan (1985). Dashed lines are rhyolites; solid lines are andesites and dacites; squares are basaltic andesites.

Fig. 3). Thick intervals of apparently comagmatic lavas in the northernmost Schell Creek Range and southwestern Deep Creek Range appear to have systematic compositional trends, from more mafic and pyroxene-rich at the base to more silicic and plagioclase-rich upward (e.g., samples HR-2 vs. HR-4 in Table 2).

Kalamazoo volcanic rocks. The Kalamazoo Tuff is zoned from crystal-poor rhyolite with 74 percent SiO_2 at its base to crystal-rich dacite with 67 percent SiO_2 at its top, a zonation typical of many large ignimbrite sheets (Lipman et al., 1966; Hildreth, 1981). Modal analyses and major- and trace-element compositions of fiamme from the base of unit B and of pumice bombs from the top of unit D (Fig. 4; Table 2) represent compositions close to the end members of the range. Much of the tuff that intervenes between these samples is too vapor-phase altered or contains fiamme too small for reliable modal and chemical analyses; thus, it has not been demonstrated whether the tuff records a continuous zonation or whether compositional gaps exist. Microprobe analyses of glass from selected stratigraphic horizons within the tuff indicate that the basal part of the tuff is uniform in glass composition, whereas progressively higher levels within the tuff are marked by the appearance and increasing abundance of progressively more mafic pumice.

Samples of the overlying hornblende dacite lavas from a variety of stratigraphic levels and from widely separated localities have major-element contents that are remarkably consistent (i.e., 67 to 68 percent SiO_2, 4.0 to 4.5 percent CaO, ~0.65 percent TiO_2). Pumice bombs in the last-erupted part of the Kalamazoo Tuff are similar in chemical and isotopic composition to the overlying hornblende dacite lavas (Table 2, Figs. 12–15), suggesting that the lava represents a large sampling of the "dominant volume" of a magma chamber in which the Kalamazoo Tuff developed as a differentiated cap (cf. Smith, 1979). It is unusual for an ash-flow eruption to be followed by even larger eruptions of cogenetic lavas, and it seems to require a special set of circumstances. Perhaps active normal faulting in the roof of the Kalamazoo magma chamber during and after the tuff eruption decompressed and devolatilized the magma and allowed a large proportion of its contents to escape as lava flows.

Because it was not generally possible to extract fiamme from the tuff of North Creek, most analyses were made of bulk tuff samples. Fresh lavas that directly overlie the tuff have similar compositions and phenocryst content (e.g., sample 4SW-9A, Table 2), suggesting that the bulk-tuff analyses are fairly close to magmatic compositions, despite potential elutriation of ash. A suite of samples collected from different cooling units in a single vertical transect revealed no obvious compositional zonation within the tuff, in agreement with its relatively constant mineral modes, although more sections would need to be studied to determine if the tuff is unzoned (cf. Hildreth and Mahood, 1985). Although the tuff of North Creek is closely related spatially and temporally to the other two members of the Kalamazoo volcanic rocks, it is compositionally distinct. At equivalent silica content, it is richer in Al, K, Ba, and Rb and poorer in Ca than the underlying hornblende dacites (Table 2, Figs. 12 and 13).

Sr and Nd isotopic compositions

Samples spanning the range of compositions and ages of volcanic rocks were selected for Sr and Nd isotopic analyses

(Table 2) in order to place constraints on magma sources and the proportions of crustal and mantle melts in rocks of various compositions. Previous isotopic studies on Mesozoic and Cenozoic plutonic rocks in this region (Farmer and DePaolo, 1983, 1984) identified high $^{87}Sr/^{86}Sr_0$ and low $^{143}Nd/^{144}Nd_0$, which were interpreted to reflect sources entirely within the continental crust. Our results show $^{87}Sr/^{86}Sr_0$ spanning a broad range from 0.7084 to 0.7147; values of $^{143}Nd/^{144}Nd_0$ range from 0.51173 to 0.51223 ($\epsilon_{Nd} = -16.6$ to -7.4) (Figs. 14 and 15). Although these ratios indicate that all the analyzed samples contain a sizable crustal component, in contrast to Farmer and DePaolo (1983, 1984), we interpret the systematic variations of the ratios with bulk composition as reflecting a significant mantle contribution (Figs. 14 and 15).

Discussion

Chemical evidence for the sources of crustal melts. Most of the analyzed samples and all of the most voluminous units are depleted in Cs and Rb with respect to Ba, Th, and LREE (Fig. 13). This is a characteristic of old lower crust, which is depleted in the most incompatible elements due to loss of partial melts. Together with the results of the isotopic modeling (discussed below), this suggests that the melts assimilated into east-central Nevada magmas were largely derived from the deep crust. Some of the early rhyolites, however, have unusual mineral phases (e.g., Fe-Mn garnet, muscovite, green biotite, and albite) and the high concentrations of Rb and Nd and low concentrations of Fe and Zr (ThT and H-6 in Table 2) that are characteristic of low-temperature partial melts of enriched crustal rocks. In contrast to the volumetrically dominant dacites of the system, these early rhyolites may contain a significant proportion of enriched crustal material, either from the upper crust or from localized undepleted areas of the deep crust. Early intermediate lavas appear to span a range of alkalinity (cf. samples H-2 and HR-2), perhaps reflecting variations in either the amount or nature of crustal contamination.

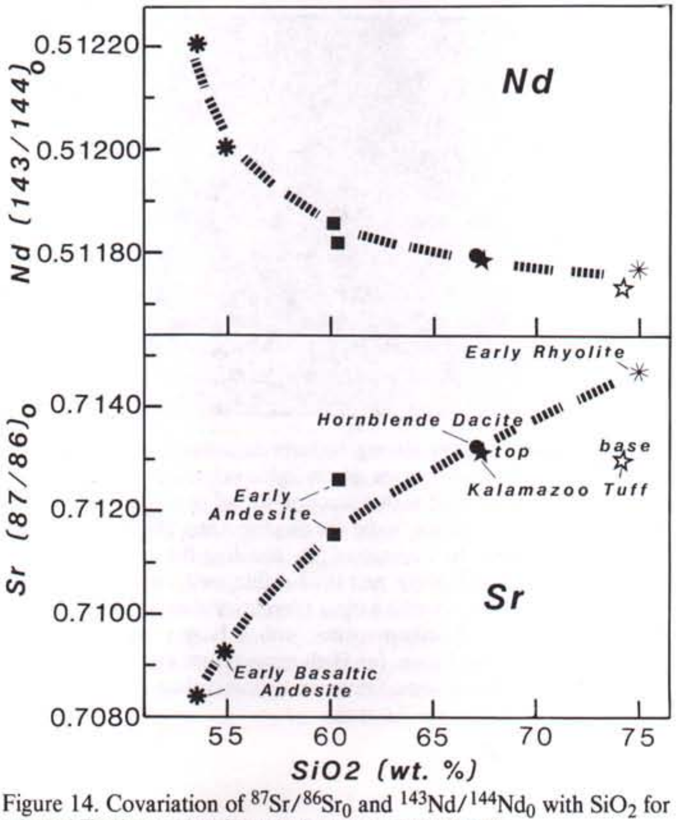


Figure 14. Covariation of $^{87}Sr/^{86}Sr_0$ and $^{143}Nd/^{144}Nd_0$ with SiO_2 for selected Tertiary volcanic rocks in east-central Nevada.

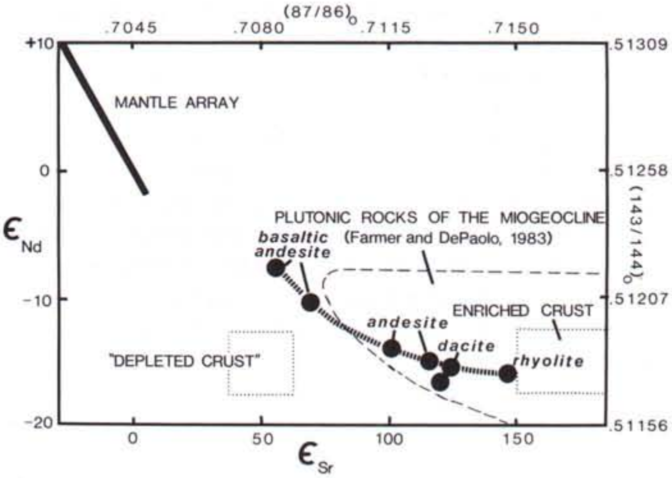


Figure 15. ϵ_{Sr} vs. ϵ_{Nd} for selected volcanic rocks from east-central Nevada. Mantle array, typical 2-Ga enriched and depleted crust, and the isotopic field for Mesozoic and Tertiary plutonic rocks in the miogeocline of the eastern Great Basin are from Farmer and DePaolo (1983).

The higher concentrations of Al, K, Ba, and Rb and lower concentrations of Ca in the tuff of North Creek and associated lavas—compared to the rest of the Kalamazoo volcanic rocks—suggest that the magma that was erupted as the tuff of North Creek contained a larger proportion of melts from alkali-feldspar–rich crustal rocks. Replacement of magma erupted as the Kalamazoo Tuff and the hornblende dacite lavas by hotter, more mafic magma may have caused melting of the already heated chamber walls; hybrids produced on mixing of these melts into the mafic magmas could have subsequently differentiated to magmas erupted as the tuff of North Creek and related lavas (cf. Novak and Mahood, 1986). Isotopic data, now lacking for the North Creek rocks, would test this idea.

Proportions of mantle and crustal components. Petrologic calculations of the proportion of crust- and mantle-derived material in the felsic volcanic rocks place important constraints on possible tectonomagmatic models. If the felsic rocks are entirely crustal in origin, then models that invoke previous crustal thickening as the cause of both extension and melting are favored. If, on the other hand, the felsic rocks contain a significant proportion of mantle-derived material, then models in which both extension and crustal melting are triggered by asthenospheric upwelling are more likely. The values of the isotopic ratios of the rocks do not, by themselves, require that the east-central Nevada rocks contain a mantle component, because even the most mafic samples have negative ϵ_{Nd} values, and the most evolved rocks have ratios appropriate for Middle Proterozoic basement (e.g., Farmer and DePaolo, 1984). The strong correlation between isotopic ratios and silica content (Fig. 14), however, would not be expected if all the melts were crustally derived, but it *is* consistent with the spectrum of compositions being formed by interaction of mantle-derived basaltic magmas with felsic crustal melts. This complements abundant petrographic evidence for mixing: (1) virtually all of the more mafic units contain highly embayed quartz xenocrysts rimmed by pyroxene (Fig. 16); (2) embayed, high-temperature, Ca-poor, diopsidic augite occurs together with low-temperature ferrohypersthene in some andesitic lavas; and (3) some rhyolites contain multiple populations of plagioclase ranging from An_{75} to An_{30}. Simple mechanical mixing is unlikely to produce magmas more felsic than silicic andesite, however, because large proportions of crustal end member lead to thermal "quenching" of the basaltic magma as it approaches the equilibrium temperature of the mixture (Frost and Mahood, 1987). For more felsic magmas, a model involving simultaneous assimilation of crustal melts and fractional crystallization of hybrid magma (Taylor, 1980; DePaolo, 1981) is more realistic.

Simultaneous assimilation and fractional crystallization are also suggested by the shapes of the isotopic data arrays (Fig. 17). One of the characteristics of bulk mixing is that on rectilinear plots involving an isotopic ratio, the data define curves that begin and end at the mantle and crustal end members. It is clear from Figure 17 that no choice of end members could generate a mixing curve to accommodate all the Nd and Sr isotopic data for the east-central Nevada rocks. Assimilation–fractional-crystallization processes, however, produce data arrays that typically do *not* end at the composition of the crustal component (De Paolo, 1981).

Assimilation–fractional-crystallization modeling of isotopic data. In order to calculate the proportion of crustal material in the magmas, one must estimate the concentrations and isotopic ratios of Sr and Nd for the mantle-derived basalt and crustal assimilant(s). Neither the mafic nor silicic end members are well constrained. Interaction of asthenospheric basalt with subcontinental lithosphere may impart a range of isotopic signatures to mafic magmas, and the isotopic composition of the Precambrian basement and the miogeocline are poorly known; the few existing data (e.g., Farmer and DePaolo, 1984) span a wide range of ϵ_{Nd} and ϵ_{Sr}. Sediments of the late Precambrian McCoy Creek Group, a dominant portion of the sedimentary sequence exposed in eastern Nevada, have an average ϵ_{Nd} of −18 in the Schell Creek Range (Farmer, 1985). For the basement, we have generally used isotopic compositions and trace-element abundances similar to those of Farmer and DePaolo (1983) in their study of Great Basin granitoids. Young basalts of the southern Basin and Range (Hedge and Noble, 1971; Leeman, 1982; Semken, 1984), which are thought to be uncontaminated by continental crust and derived from melting of an enriched subcontinental lithosphere, have high $^{87}Sr/^{86}Sr$ and Sr concentrations ranging from 300 to

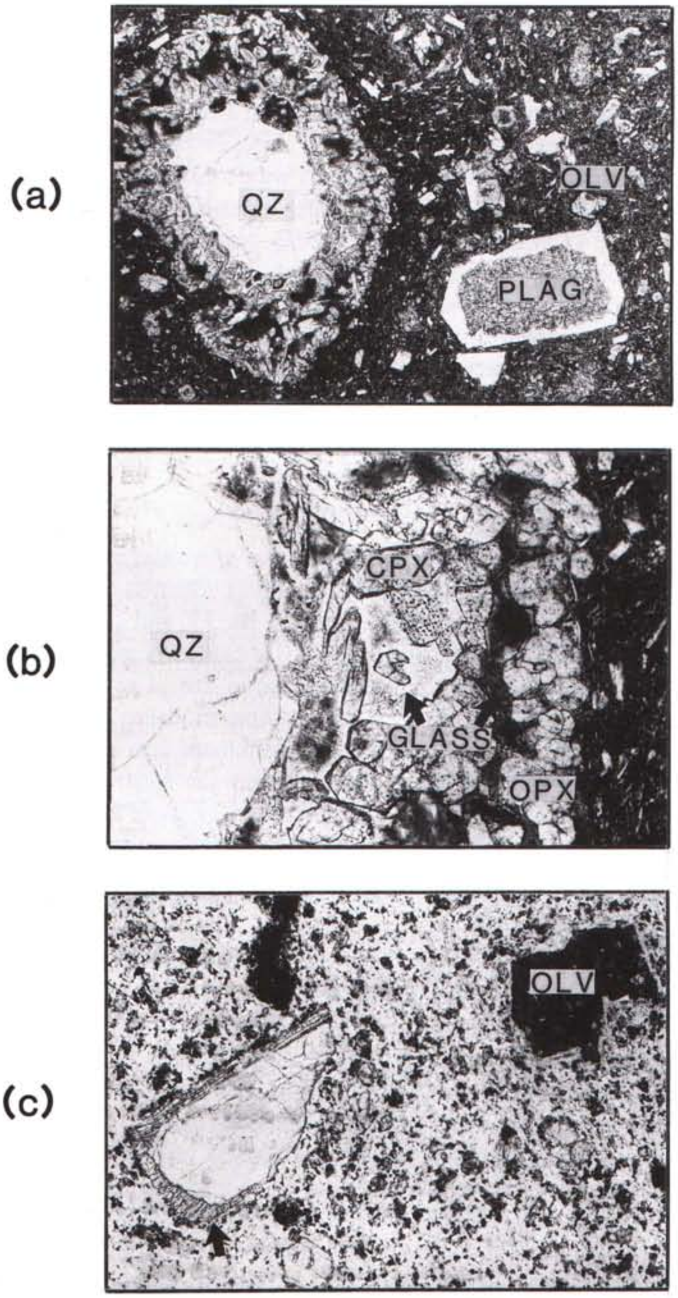


Figure 16. Some typical mixing textures in andesite lavas from the eastern Great Basin viewed in plane light. (a) Large polycrystalline quartz xenocryst armored with a reaction rim of pyroxene. Note sieve-textured calcic core and clear sodic rim on plagioclase phenocryst. Width of photo = 7.2 mm. (b) Closeup of (a), detailing the reaction relation between the quartz xenocryst and the basaltic melt. Inner part of rind consists of clinopyroxene with a clear (rhyolitic) glass in the interstices. Outer rind consists of orthopyroxene with a brown interstitial glass. Width of photo = 1.44 mm. (c) High-temperature augite rimmed by low-temperature hypersthene. Olivine pseudomorphed by iddingsite in upper right. Field of view = 3.6 mm.

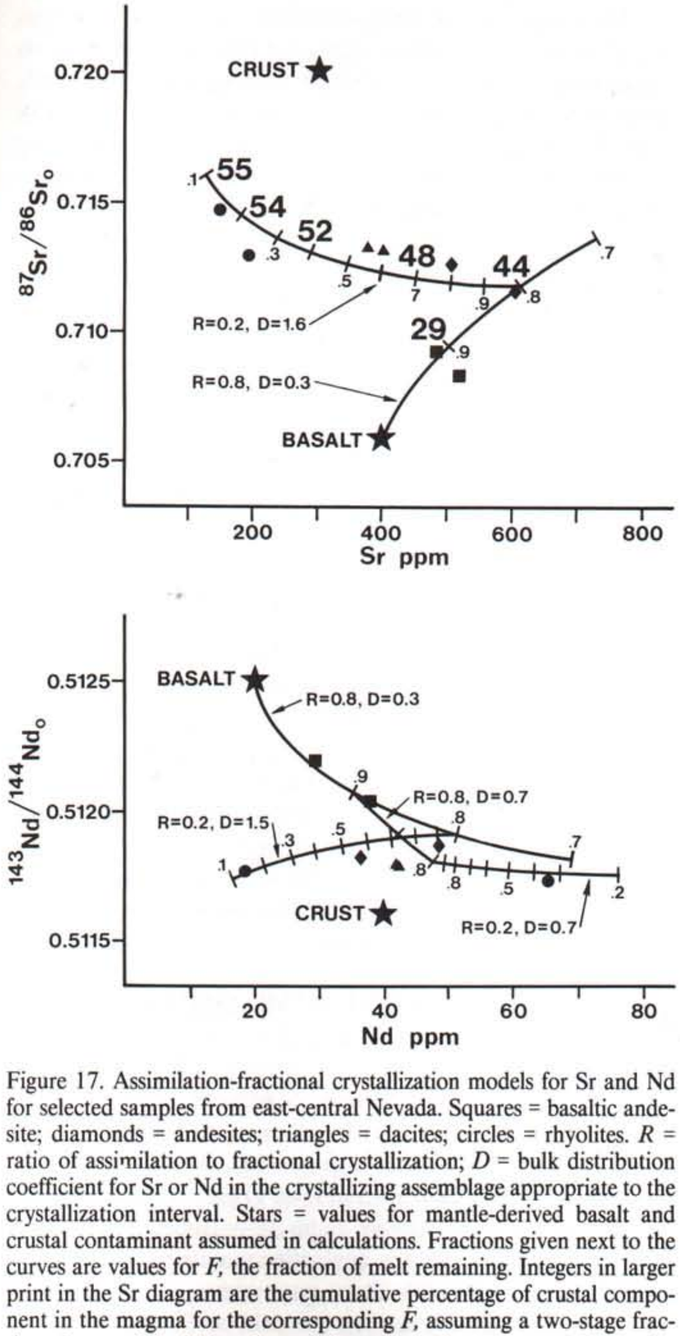


Figure 17. Assimilation-fractional crystallization models for Sr and Nd for selected samples from east-central Nevada. Squares = basaltic andesite; diamonds = andesites; triangles = dacites; circles = rhyolites. R = ratio of assimilation to fractional crystallization; D = bulk distribution coefficient for Sr or Nd in the crystallizing assemblage appropriate to the crystallization interval. Stars = values for mantle-derived basalt and crustal contaminant assumed in calculations. Fractions given next to the curves are values for F, the fraction of melt remaining. Integers in larger print in the Sr diagram are the cumulative percentage of crustal component in the magma for the corresponding F, assuming a two-stage fractionation model. Although models such as these are nonunique, the shapes of the arrays strongly suggest that most of the elevation of Sr and depression of Nd isotopic ratios from mantle values is a result of assimilation early in the crystallization history and occurs in the deep crust where temperatures are high (resulting in large values of R). Fractionation from andesite to rhyolite is generally accompanied by a much smaller rate of assimilation (lower R), which is consistent with fractionation in the upper crust, where wall rocks are much further from their solidus temperatures.

1100 ppm. The shapes of the data arrays place additional constraints on the possible concentrations and isotopic compositions of Sr and Nd in the parental basalt and in the assimilant.

In addition to the compositions of the end members, the ratio of assimilation to fractional crystallization (r) and the bulk distribution coefficients for Sr and Nd in the fractionating assemblages (D) must be estimated (DePaolo, 1981). The bulk distribution coefficients can be calculated from the known partition coefficients for the observed phenocryst phases. The value for r is generally not known independently. The depletion of Rb and Cs relative to other incompatible elements in east-central Nevada rocks argues for the lower crust being a source of much of the assimilant, in which case values of r should be relatively large. For a given amount of fractionation, larger amounts of assimilation are possible where wall rocks are near their solidi; thus, as a mafic magma moves from the lower crust to the cooler upper crust, r would be expected to decrease. As fractionation and assimilation proceed, the liquid becomes more silicic, resulting in larger D for both Sr and Nd. As for the chemical and isotopic compositions of the end members, the values of r are constrained somewhat by the shapes of the data arrays.

A variety of models using basalts derived from "normal" and "enriched" mantle, differing abundances of Nd and Sr in the crustal and mafic end members, and varying values for r and D were tested. Because there are essentially six independent variables, these solutions are not unique. Many combinations of end members, r, and D can be eliminated, however, because they do not fit the data even qualitatively. Figure 17 presents the most successful model; i.e., the model in which both the Nd and Sr isotopic arrays are closely approximated using the same value of r; various compositions represent about the same amount of fractionation in models based on Sr and on Nd; and the calculated amounts of fractional crystallization for given silica contents are reasonable. The crustal end member used in the model has $^{87}Sr/^{86}Sr = 0.720$, Sr = 300 ppm, $^{143}Nd/^{144}Nd = 0.5116$ ($\epsilon_{Nd} = -19$), and Nd = 40 ppm, and the mantle-derived end member is a slightly enriched basalt with $^{87}Sr/^{86}Sr = 0.706$, Sr = 400 ppm, $^{143}Nd/^{144}Nd = 0.5125$, and Nd = 20 ppm. The Sr array can be modeled just as successfully using a "normal" mantle end member, but a correspondingly high value for $^{143}Nd/^{144}Nd$ cannot be easily accommodated by the data.

The Sr and Nd data arrays require at least a two-stage assimilation–fractional-crystallization history. In Figure 17, the passage of basalt through the crust is modeled in two stages in which r decreases and D increases in the second stage. More realistic models involving changing r, D, and the composition of the assimilant during the evolution of the magma are not justified in light of the sparse data for both the volcanic rocks and the potential assimilants, but are unlikely to produce relative amounts of mantle and crustal components that differ drastically from those calculated here. Using a "normal" mantle end member ($^{87}Sr/^{86}Sr = 0.704$) results in a larger calculated proportion of crustal melt in all the rocks, but the main conclusions that arise from the modeling are unchanged.

The early part of the fractionation history from mantle-derived basalt to andesite can only be modeled successfully if the value for *r* (i.e., the rate of assimilation to crystallization) is very large (0.8 in the best-fit model of Fig. 17). This requires that the melting wall rocks be very near their solidi so that only a small input of heat is required to melt them. High wall-rock temperatures are most likely to be found in the lower crust. This conclusion, that fractionation from mantle-derived basalt to andesite took place largely in the lower crust, is consistent with the Cs- and Rb-depleted nature of most east-central Nevada volcanic rocks. The fairly low value of the bulk distribution coefficient for Sr ($D = 0.3$ in the model calculation) is additional support for lower-crustal fractionation and assimilation. It suggests that some of the fractionation took place in the lowermost crust, at a depth too deep for plagioclase to be stable. This is consistent with the observation that plagioclase is a rare phenocrystic phase in the basaltic andesites and even in many of the andesites. Thus many of the andesites may have formed by assimilation of lower crustal melts by plagioclase-free or plagioclase-poor basaltic magmas. The Nd data is modeled most successfully when the Nd content of the contaminant is moderately high. This also suggests that upper crustal rocks are not involved at this stage, because enriched upper crustal rocks commonly have Nd contents equal to or lower than basalts and andesites because of fractional crystallization of LREE–enriched phases such as apatite, allanite, monazite, or chevkinite.

Because the values for *r* are high during initial stages of crystallization, most of the assimilation and acquisition of the crustal component occurs in the lower crust, and most of the elevation of $^{87}Sr/^{86}Sr$ and lowering of $^{143}Nd/^{144}Nd$ takes place very early in the fractionation history. In the model calculation, by the time the remaining proportion of magma is 80 percent of the original magma volume ($F = 0.8$ in Fig. 17), the magma is about half crustal component. Using our slightly enriched basalt as a starting point yields about 45 percent crustal component in the andesites. If one uses a more "normal" basalt (with $^{87}Sr/^{86}Sr = 0.704$ rather than 0.706), the andesites are formed when the fraction of magma remaining is about 50 percent and the crustal component is correspondingly higher, about 65 percent. Note, however, that *smaller* amounts of crustal contamination would be calculated if greater Sr contents or larger $^{87}Sr/^{86}Sr$ were assigned to the crustal end member.

Isotopic compositions of Sr and Nd change less between andesite and rhyolite than they do between basalt and andesite. This small change with fractionation requires that values of *r* be smaller than from basalt to andesite and *D* be larger. The data are fit with a value for *r* of 0.2, a low value that would be expected when fractionation took place in relatively cool wall rocks at upper crustal depths (DePaolo, 1981). As a result of this low rate of assimilation, dacites contain about 50 percent mantle material (30 percent if a "normal" mantle end member is used), and even after the cumulative melt fraction drops to less than 20 percent for the rhyolites, the proportion of crustal component rises only an additional 5 percent (Fig. 17).

Summary

The greater mineralogical, chemical, and isotopic heterogeneity of early eruptive units suggests that they were derived from isolated magma bodies that underwent varying degrees of hybridization with crustal partial melts. For some of the compositionally more extreme early rhyolites, for which we do not have isotopic data, the melts may be almost entirely crustal. The entire compositional range of the Kalamazoo Tuff and associated dacite lavas is similar in initial Sr and Nd isotopic composition, suggesting that once the early basalt-crust hybrids coalesced into a large upper crustal magma chamber, there was little further interaction with wall rocks. Within the Kalamazoo chamber, magmas may have convectively mixed to form a dominant volume of dacite, and fractional crystallization produced the compositional zonation reflected in the Kalamazoo Tuff.

Most of the assimilation takes place in the lower crust during fractionation from basalt to andesite. Depending on end members chosen, the crustal component in andesites can exceed 50 percent. Subsequent fractionation at higher levels of the crust is accompanied by relatively little assimilation. As a result, dacites and rhyolites contain only a slightly higher proportion of crustal component than andesites. The most significant result of the petrologic modeling for tectonic models is that the hornblende dacites, which are estimated to make up 65 percent of the erupted volume, contain approximately 30 to 50 percent mantle component. An even larger volume of magma was presumably intruded and not erupted; therefore, a significant amount of new mantle material was added to the crust during Oligocene synextensional magmatism. This suggests that models for extension in the Great Basin should have a role for asthenospheric upwelling and resulting mantle-derived basaltic liquids.

ERUPTIVE HISTORIES OF SOME OTHER HIGHLY EXTENDED REGIONS

The following section draws some comparisons of the extensional and magmatic history of east-central Nevada with some other parts of the Basin and Range province. Brief summaries of six other highly extended domains (Fig. 1) are presented, emphasizing the absolute and relative timing of volcanism and faulting and, where possible, offering qualitative assessments of eruptive and extensional strain rates. These areas were selected to provide reasonable geographic (i.e., north to south) coverage and because they were perceived to have some of the best published structural, stratigraphic, and geochronologic constraints. Only areas that have experienced large-magnitude extensional strains are included because only these have accumulated sufficient finite strain to permit estimation of incremental strain rates over time intervals of a few million years. Less extended areas may not record the same relation between extension and magmatism that we describe below (e.g., Taylor et al., 1987). Our biased sampling may be justified, however, given that much of the upper crustal extension across the Basin and Range province at any given latitude is concentrated within these highly extended domains. These localized upper crustal strains were apparently accommodated by lateral flow and stretching of much broader areas in the lower crust (Gans, 1987), so any systematic temporal and/or genetic relations between magmatism and extension within these domains may be relevant to coeval volcanism in adjacent areas that lack significant normal faulting at the surface.

Yerington district, west-central Nevada

The classic study by Proffett (1972, 1977) of the Yerington district in west-central Nevada was one of the earliest to demonstrate that parts of the Basin and Range province had been stretched by more than a factor of two. The detailed map and cross sections of the Singatse Range (Proffett and Dilles, 1984a) illustrate the characteristic structural style of highly extended terranes: older, gently dipping normal faults repeat steeply tilted sections of Tertiary volcanic rocks and their pre-Tertiary basement and are cut by successively steeper sets of normal faults, the youngest of which bound the present basins and ranges. As emphasized by Proffett (1977), the only reasonable kinematic interpretation of these geometric relations is that the older subhorizontal faults were once at higher angles (60°) and penetrated deeply as gently curved or planar normal faults. These faults then rotated to lower angles during progressive extension. Once faults had rotated 30° to 40°, the resolved shear stress was insufficient to maintain movement, and a new generation of high-angle normal faults were developed, as explained by the theoretical model of Morton and Black (1975). Multiple generations of normal faults and associated steep tilts of Tertiary strata are also characteristic of the adjoining Wassuk, Buckskin, and Pine Nut ranges in west-central Nevada (Bingler, 1978; Hudson and Oriel, 1979; J. Dilles, 1984, personal communication) and define a 100-km-wide domain of large-magnitude extension. Detailed stratigraphic and geochronologic studies of Tertiary sections within this region (e.g., Gilbert and Reynolds, 1973; Proffett and Proffett, 1976) provide important constraints on the timing of volcanism and extensional faulting.

The oldest Tertiary rocks in the Yerington district include discontinuous intervals of conglomerate and rare mafic lava flows. These are overlain by as much as 1.5 km of regionally extensive rhyolitic to dacitic ash-flow tuffs (e.g., the Mickey Pass and Singatse Tuffs) that range in age from 28 to 24 Ma. After a hiatus of approximately 5 m.y., volcanism renewed with the eruption of large volumes of hornblende andesite to dacite lavas and breccias. In the Singatse Range these are largely 19 to 17 m.y. old, but apparently become younger toward the west (Silberman et al., 1975). The andesites are commonly overlain by, and interfinger with, thick sections of fanglomerate, tuffaceous sandstone and siltstone, and rare tuff. The Tertiary sections are locally capped by 8- to 11-Ma basalt lavas.

The onset of extensional faulting in the Yerington district coincided with the eruption of the 19- to 17-Ma hornblende andesite. Feeder dikes for these lava flows cut some of the oldest normal faults, yet the basal flows appear to be fully involved in the faulting and tilting (Proffett, 1977). Westward dips within the Tertiary succession decrease systematically upward, from an average of 60° in preextensional ash-flow tuff and basal hornblende andesite to only 10° to 15° in 8- to 11-Ma capping basalts. The average of 45°–50° of rotation implies stretching factors (β) of 2.1 to 2.9, using the equations of Thompson (1960) and assuming that new generations of faults initiate after 30° to 40° of rotation. This is equivalent to an average extensional strain rate of approximately $3\text{–}4 \times 10^{-15}$/s during this 8-m.y. interval. Proffett and Dilles (1984b) concluded that, in the northern Wassuk Range, as much as 40° of the rotation may have occurred prior to 14 Ma, suggesting even higher strain rates ($5\text{–}8 \times 10^{-15}$/s) in the first few million years of the extensional history. The minor tilting (10°–15°) in the last 10 m.y. implies a much slower average extensional strain rate of approximately 5×10^{-16}/s.

Death Valley, southeastern California

The Death Valley region in eastern California represents one of the youngest and most impressive domains of large-magnitude extension within the Basin and Range province. Bounded on the northwest by the relatively unextended Coso Range–Darwin Plateau and on the southeast by the Spring Mountains block, the domain is approximately 140 km wide and includes the Panamint Range, Black Mountains, Greenwater Range, Funeral Mountains, Resting Spring Range, and Nopah Range. Complex mosaics of normal and strike-slip faults together with thick sections of variably deformed late Cenozoic volcanic and sedimentary rocks record an intense history of extension and magmatism that began in the Miocene and continues today. Details of the local geology and of conflicting tectonic interpretations are provided by Noble (1941), Drewes (1963), Hunt and Mabey (1966), Burchfiel and Stewart (1966), Stewart (1983), McAllister (1970, 1976), Hall (1971), Wright and Troxel (1973, 1984), Wright (1976), and Wernicke et al. (1986, 1988).

Cenozoic faults in the Death Valley region strike either north to northeast (normal faults) or northwest (right-lateral strike-slip faults). Both apparently reflect west-northwest–east-southeast extension, and the strike-slip faults commonly separate areas of differential extension. Throughout the region, upper Precambrian and Paleozoic miogeoclinal strata typically dip 40°–60° to the east or southeast. Because the oldest Tertiary volcanic and sedimentary units are also steeply tilted, resting with little angular discordance on Paleozoic strata, most of the westward tilting must be a consequence of Cenozoic extensional faulting. Multiple generations of normal faults with a broad range of present-day dips are exposed throughout the Death Valley region. Typically, older, gently dipping normal faults within the ranges (e.g., the Amargosa "thrust," the Tucki Wash fault) are cut by progressively steeper faults, such as those that bound the present ranges. Where the older, gently dipping faults repeat steeply dipping stratigraphic successions, it seems likely that they represent rotated high-angle normal faults akin to the older faults at Yerington. In other areas, the structurally deepest faults cut Precambrian crystalline basement or highly deformed metasedimentary rocks such that the amount of footwall rotation and offset on the faults is unclear.

Several lines of evidence suggest that the transect from the Spring Mountains to the Darwin Plateau has been extended approximately 200 percent (90 to 100 km). Published cross sections of individual ranges (e.g., Hunt and Mabey, 1966) suggest stretching factors on the order of 2.5 to 3.5. Similarly, the average eastward tilts of 50° imply a stretching factor of 2.9, if one assumes domino-style rotations on 60°-dipping normal faults, with new generations initiating after 40° of rotation (e.g., Gans and Miller, 1983). Wernicke et al. (1988) estimated even a higher magnitude of extension (~150 km) across this region on the basis of a correlation and reconstruction of early Mesozoic thrust faults. In any case, the structural style and average amount of tilting within the Death Valley extensional domain are strikingly similar to areas such as east-central Nevada and the Yerington district.

Tertiary rocks in the Death Valley region can be divided into three broad groups. The oldest is exposed mainly in the Funeral Mountains (Bat Mountain Formation) and comprises up to 1300 m of fanglomerate, lacustrine deposits, and rare interstratified tuff that have yielded ages of 25 to 20 Ma (Cemin et al., 1985). Middle to upper Miocene rocks, exposed widely throughout Death Valley, include both predominantly sedimentary sequences (e.g., Artist Drive Formation) and thick (⩾1 km) sections of volcanic rocks (e.g., the "Older Volcanic Rocks" of Drewes [1963], Shoshone Volcanics of Haefner [1976], and Rhodes Tuff and Sheephead Andesite of Wright and Troxel [1984]). These volcanic rocks are largely andesite to rhyolite and have yielded ages of 14 to 6 Ma, with peak eruptive activity at 10 to 7 Ma (Fleck, 1970; Wright and Troxel, 1984; Cemin et al., 1985). The Black Mountains and Greenwater Range appear to be major eruptive centers where large, possibly comagmatic intrusions of granite and granodiorite are exposed (Drewes, 1963). The youngest group includes thick (up to several kilometers) sections of fanglomerate and lacustrine deposits with abundant interstratified basaltic lavas and silicic tuffs (e.g., the Furnace Creek, Funeral, Copper Canyon, and Nova Formations and the Greenwater Volcanics). Existing geochronology suggests that these younger sequences range in age from 6 Ma to younger than 3 Ma (Fleck, 1970; Hall, 1971; Cemin et al., 1985).

Constraints on the ages of the oldest extensional faults in the Death Valley region are sparse. Significant extension prior to the early Miocene is unlikely, because the oldest Tertiary strata typically rest with little or no angular discordance on Paleozoic rocks and appear to be fully involved in the faulting and tilting (e.g., Noble, 1941; Hunt and Mabey, 1966; McAllister, 1976). Early(?) to middle Miocene fanglomerate in the southern Funeral Mountains and the Furnace Creek Basin records local unroofing of relatively deep levels within the miogeoclinal succession (Cemin et al., 1985). However, it is not clear whether the differential uplift in that area records the onset of extensional faulting or unrelated tectonism (e.g., strike-slip faulting). In the northern Panamint Range, the 10- to 12-Ma Little Chief Granite cuts minor normal faults (Wernicke et al., 1986), and steeply tilted (40°–50°) Paleozoic strata are unconformably overlain by gently tilted (15°–25°) 8-Ma volcanic rocks (Hunt and Mabey, 1966; W. Hildreth, 1987, personal communication). In most localities, gently dipping latest Miocene and Pliocene (6 to 4 Ma) strata unconformably overlie highly faulted and tilted middle to late Miocene volcanic and sedimentary rocks (e.g., Drewes, 1963; McAllister, 1970; Cemin et al., 1985), suggesting intense deformation in the late Miocene. Elsewhere, thick sections of Pliocene (5 to 3 Ma) synorogenic deposits (e.g., the Copper Canyon and Nova Formations) are tilted up to 40° and are cut by the major range-bounding faults (Drewes, 1963; Hall, 1971). Taken together, these observations suggest a prolonged history of extension that began in the mid-Miocene, coincident with voluminous calc-alkaline volcanism, culminated in the late Miocene and early Pliocene as volcanism evolved to predominantly basaltic or bimodal, and continues today.

Socorro, New Mexico

Perhaps nowhere in the western U.S. is the record of mid-Tertiary extensional faulting and volcanism better documented than in the Socorro region of the Rio Grande rift. Detailed structural mapping and palinspastic reconstructions of the Lemitar Mountains by Chamberlin (1978, 1983) identified multiple generations of imbricate "domino-style" normal faults that repeat steeply dipping Tertiary sections and caused approximately 200 percent east-west extension. A sequence of distinctive and regionally extensive Oligocene to Pliocene volcanic and sedimentary units (e.g., Osburn and Chapin, 1983a, b) record in exceptional detail the history of progressive tilting and offset on rotational high-angle normal faults. High-precision $^{40}Ar/^{39}Ar$ dating of ash-flow tuffs within these synextensional sequences has resolved relative age differences of approximately 0.15 m.y. (McIntosh et al., 1986), thereby permitting highly accurate estimation of eruptive rates and extensional strain rates.

Tertiary rocks in the Socorro region consist of (1) an older (40 to 29 Ma) preextensional sequence of volcaniclastic rocks with intercalated silicic tuffs and intermediate lavas, (2) a sequence of 29- to 27-Ma rhyolite ash-flow tuffs and andesite lavas that were erupted during the early stages of extension, and (3) predominantly sedimentary sequences deposited during continued extension from 27 Ma to present. Chamberlin (1983) cited the upward decrease in tilts and the thickening of individual units toward the oldest normal faults as evidence that rapid, large-magnitude extension began during deposition of the middle sequence. For example, in the Lemitar Mountains, the 28.78-Ma La Jencia Tuff and 28.46-Ma Vick's Peak Tuff immediately predate the onset of extension, because they have the same average 60° dip as the older sedimentary and volcanic sequence. However, dips decrease systematically by an average of 10° within the overlying middle member of the La Jara Peak Basaltic Andesite and overlying 27.97-Ma Lemitar Tuff, and they decrease an additional 10° to 15° within the upper member of the La Jara Peak Basaltic Andesite and the overlying 27.36-Ma South Canyon Tuff. These relations are fairly unambiguous; extension began at 28.5 Ma, during the local peak of volcanism, and produced an average of 20° to 25° of westward rotation within 1.1 m.y., implying an initial extensional strain rate of approximately $1 \times 10^{-14}/s$.

Extensional strain rates in the Socorro region slowed considerably after 27 Ma; westward dips appear to decrease much more gradually, from 35° to 20° within the 27- to 12-Ma lower Popotosa Formation. A second, less dramatic episode of rapid extension (10°–15° of tilting in 5 m.y.) during deposition of the upper Popotasa Formation appears to coincide with a younger pulse of rhyolitic volcanism 12 to 7 m.y. ago (Chamberlin, 1978). The faults that block out the present basins and ranges in the Socorro Region began to move 7 to 4 m.y. ago and have produced less than 10° of rotation within syntectonic basin fills (Sierra Ladrones Formation).

Eldorado Mountains, southern Nevada

Anderson's (1971) classic study of imbricated, steeply tilted Tertiary sections in the Eldorado Mountains, Nevada, was one of the first to address the tectonic implications of this structural style and to point out the temporal and spatial coincidence of intense volcanism, plutonism, and extension in parts of the Basin and Range province. The Eldorado Mountains, together with the Eldorado River and Black Mountains and White Hills, lie within an 80- to 100-km-wide corridor of large-magnitude extension in southernmost Nevada and northwestern Arizona, bounded on the west by the McCullough Range and on the east by the Colorado Plateau (e.g., Spencer and Reynolds, 1986). Structural, stratigraphic, geochemical, and geochronological data discussed by Anderson (1971, 1977, 1978), Anderson et al. (1972), and Weber and Smith (1987) place important constraints on the magnitude and timing of extension and volcanism in this region.

Tertiary rocks in the Eldorado Mountains have an aggregate thickness of nearly 5 km. They were divided by Anderson (1971) into: (1) the voluminous, 20(?)- to 15-Ma Patsy Mine Volcanics, including lower and upper members consisting largely of andesite and a middle member of crystal-poor rhyolite; (2) the 15-Ma dacitic tuff of Bridge Spring; (3) the 15- to 12-Ma Mount Davis Volcanics, a heterogeneous assemblage of basalt to rhyolite (mostly andesite) lavas, tuffs, and intercalated clastics; and (4) 12-Ma and younger Fortification Basalt and clastic rocks of the Muddy Creek Formation. Large gabbroic to granitic intrusive masses are exposed throughout the region and yield K-Ar ages of 14 to 17 Ma, overlapping the time span of most of the volcanism.

The structure of the Eldorado Mountains is dominated by imbricate moderate- to low-angle, west-dipping normal faults that repeat or "shingle" east-dipping Tertiary sections. Anderson (1971) inferred that most of the exposed faults were synchronous, and he cited the range of present fault dips as evidence that they were strongly curved and flattened at very shallow crustal levels. However, a multistage faulting history involving relatively planar, high-angle faults (with many imbricate splays) seems equally plausible given the large rotations of both hanging walls and footwalls at all exposed structural levels. The total amount of extension across the extensional corridor is not well constrained, but given the steep tilts and profound imbrication of the lower parts of the Tertiary sections, it is probably on the order of 50 to 70 km, or in excess of 100 percent.

Anderson et al. (1972) cited prominent angular unconformities between flat-lying or gently dipping 13- to 14-Ma basalts and steeply dipping older Tertiary strata in the Black and Eldorado Mountains as evidence that most of the extensional deformation occurred over a short time interval during eruption of the Mount Davis Volcanics (15 to 13 Ma). Dips of the older Tertiary rocks in the Eldorado Mountains generally decrease upward, however, from an average of 90° in the lower part of the Patsy Mine Volcanics to an average 55° in the tuff of Bridge Spring, to 35°–45° in the lower part of the Mount Davis Volcanics. This suggests that extension began somewhat earlier (i.e., 16 Ma), synchronous with peak eruptive activity. The average of 70° to 90° of eastward tilting in less than 3 m.y. suggests stretching rates of $1–2 \times 10^{-14}/s$. Subsequent extension along the present range-bounding faults has been much slower and was accompanied by volumetrically minor eruptions of alkali olivine basalts.

Whipple Mountains and environs, southeastern California–western Arizona

Geologic mapping and structural studies by many different investigators suggest that much of the area on either side of the lower Colorado River in southeastern California and western Arizona was highly extended during the Cenozoic (e.g., articles in Frost and Martin, 1982). The structural evolution of the central part of this extensional corridor, including the Turtle, Mopah, Whipple, Chemehuevi, and Mojave Mountains, has been discussed by Carr et al. (1980), Dickey et al. (1980), Davis et al. (1980, 1982), Howard et al. (1982a, 1982b), Howard and John (1987), John (1987), and Davis (1988). The stratigraphy and geochronology of selected Tertiary volcanic and sedimentary successions within this transect were described by Nielson (1986), Nielson and Turner (1986), and Hazlett (1986).

The most striking structural element of the Whipple Mountains and environs is a system of gently dipping "detachment" faults, separating complexly faulted Tertiary and pre-Tertiary rocks above from relatively coherent crystalline rocks below. Although the amount of displacement, initiation angle, regional extent, and initial depth of individual detachment faults are controversial, there is general agreement that the faults formed as a consequence of large-magnitude, northeast-southwest–directed extension during the Miocene. Tertiary strata in the hanging wall(s) or upper plate(s) typically dip to the southwest and are imbricated by northeast-dipping normal faults. The amount of supracrustal extension across the 100-km-wide transect is not well constrained, but is probably at least 100 percent, or 50 km, based on the average 30° to 60° southwestward tilt of upper-plate fault blocks (e.g., Howard and John, 1987) and an inferred 40-km separation between a Miocene dike swarm in the Mojave Mountains block and the correlative(?) Chambers Well dike swarm in the western Whipple Mountains (Davis et al., 1982; Howard et al., 1982a).

Tertiary sections in the vicinity of the Whipple Mountains are typically 1 to 2 km thick and consist, in ascending order, of: (1) a heterogeneous assemblage of andesitic to rhyolitic lava and tuff that appears to be largely 22 to 19 m.y. old (e.g., Nielson, 1986; Nielson and Turner, 1986), although some ages as old as 25 to 32 Ma were reported by Davis et al. (1982), (2) the 18- to 19-Ma Peach Springs Tuff of Young and Brennan (1974), a regionally extensive silicic ash-flow tuff that serves as an important stratigraphic/structural marker unit (Glazner et al., 1986), (3) thick sections of fanglomerate and lacustrine deposits with rare interstratified tuff, and (4) a 10- to 15-Ma capping sequence of basalt, rhyolite, and conglomerate (e.g., Carr et al., 1980).

The onset of extensional deformation in the Whipple Mountains region is not well constrained. Mylonitic fabrics in the Whipple Mountains are, in part, bracketed between 26 ± 5 and 19 ± 1 Ma (Wright et al., 1986; DeWitt et al., 1986). Davis (1988) summarized a variety of thermochronologic, barometric, and geologic data from the Whipple Mountains that suggest these mylonitic rocks were rapidly uplifted and cooled between 20 and 18 Ma in response to movement on the Whipple detachment fault. Angular unconformities and decreasing tilts upward within "upper plate" Tertiary sections provide the most direct evidence on the timing of extensional deformation. In the Mohave Mountains, the older (22[?]- to 19-Ma) volcanic rocks have dips that decrease upward from near vertical to 40°–50° and are unconformably overlain by more gently dipping (15° to 25°) Peach Springs Tuff and time-equivalent units (Nielson, 1986). Elsewhere, much of the tilting appears to have occurred prior to or shortly after deposition of the Peach Springs Tuff (Davis, 1986). Flat-lying to very gently dipping 10- to 15-Ma basalts and rhyolites unconformably overlie steeply dipping, highly faulted older Tertiary strata in many localities and provide an upper age limit on most of the extensional faulting (e.g., Carr et al., 1980; Howard and John, 1987). Taken together, the available data suggest that: (1) the onset of extension coincided approximately with the onset of volcanism at approximately 22 Ma; (2) the early part of the extensional history (20 to 18 Ma) was characterized by extremely high strain rates ($\sim 10^{-14}/s$), and it coincided with eruption of hundreds to thousands of cubic kilometers of intermediate to silicic magma; (3) both extensional strain rates and eruptive rates decreased markedly shortly after 18 Ma; (4) the switch to predominantly basaltic or bimodal volcanism at approximately 15 Ma occurred during the slower, latter part of the extensional history; and (5) by about 10 Ma, both extension and volcanism had effectively ceased in the vicinity of the Whipple Mountains.

Chocolate Mountains area, southeastern California

Thick sections of Tertiary volcanic and sedimentary rocks are exposed in several of the ranges of southeastern California and adjacent Arizona (Fig. 1). Recent field studies in the Chocolate Mountains (Crowe, 1973, 1978; Frost et al., 1986), Midway Mountain (Berg et al., 1982), the Trigo Mountains (Garner et al., 1982) and the Castle Dome and Kofa Mountains (Sherrod et al., 1987) suggest that this region has been affected by large-magnitude extension in the Tertiary and represents the southern continuation of the Colorado River extensional corridor described above. Geochronologic and geochemical work by Olmstead et al. (1973), Crowe (1973), Crowe et al. (1979), Murray (1982a), Weaver (1982), and Sherrod et al. (1987) have helped define the space-time-composition patterns of volcanism in this region and place some constraints on the timing of extensional faulting.

Discontinuous intervals of prevolcanic fanglomerate occur at the base of many Tertiary sections, and were apparently shed off highs in the Precambrian to Mesozoic basement. They are overlain by up to several hundred meters of pyroxene-bearing andesite to dacite (55 to 65 percent SiO_2) lava, breccia, and subvolcanic intrusions that have yielded K-Ar ages ranging from 35 to 26 Ma. These are overlain by the voluminous 22 to 28 Ma (mostly 25 to 26 Ma) Silicic Volcanic Sequence of Crowe et al. (1979), which includes rhyolite to dacite domes, flows, and associated pyroclastic deposits, commonly followed by more regionally extensive ash-flow tuffs. The Capping Volcanic and Sedimentary Sequence consists of mafic and subordinate rhyolitic flows interstratified with fanglomerates; it apparently postdates much of the extensional faulting and tilting. This sequence may include lavas as old as 26 Ma, but eruption of true basalts apparently did not occur until 17 to 13 Ma, and migrated southeastward with time (Murray, 1982b).

The Cenozoic structure of southeastern California is poorly known. Most sections of Oligocene volcanic rocks presently dip moderately to steeply (35° to 60°) to the northeast or southwest and are repeated by gently to steeply dipping normal faults (e.g., Crowe, 1978). Many of the gently dipping contacts once thought to be depositional between the volcanic rocks and their basement have more recently been interpreted as "detachment faults" (Berg et al., 1982; Garner et al., 1982), although it seems likely that many are rotated early generations of high-angle normal faults. Indeed, the map pattern in the southeasternmost Chocolate Mountains closely resembles that of the Yerington district (Proffett, 1977), where older subhorizontal faults repeat steeply dipping volcanic sections and are subsequently cut by younger, steeper normal faults. Crowe (1978) argued that extensional faulting began prior to 32 Ma, on the basis of the distribution of pre-volcanic fanglomerate and inferred paleotopographic trends. However, dips within the older Tertiary rocks are fairly uniform and only diminish significantly near the top of the volcanic pile. In the southeastern Chocolate Mountains, imbricated sections of steeply dipping 32- to 27-Ma volcanic rocks are unconformably overlain by a more gently dipping sedimentary and volcanic sequence, including a 25.7-Ma andesite flow (Crowe, 1978); this suggests that rapid extensional faulting and tilting occurred approximately 26 Ma. Sherrod et al. (1987) concluded that the principal extensional deformation throughout this region began during the waning stages of voluminous silicic volcanism (24 to 22 Ma) and was largely over by the eruption of "capping" basalts at 20 to 13 Ma.

Summary

The examples described above highlight an important aspect of Cenozoic tectonics and magmatism in the Basin and Range province. Despite major regional variations in the absolute timing of volcanism and normal faulting, local eruptive and extensional histories are strikingly similar. Thus, the Oligocene magmatic and structural evolution of the Socorro region closely resembles the early Miocene history of the Whipple Mountains, which in turn, closely resembles the late Miocene and Pliocene history of Death Valley. It must be emphasized that these are not isolated examples. Cenozoic magmatism and extension appear to have evolved in a similar fashion in many other parts of the western United States, including (1) the Pioneer metamorphic core complex in southern Idaho (e.g., Silverberg, 1988), (2) parts of central Nevada (Smith, personal communication, 1988), (3) the Wickenberg Mountains area in central Arizona (Fryxell et al., 1987), and the Santa Catalina/Pinaleño metamorphic core complexes of southeastern Arizona (e.g., Davis and Hardy, 1981; Dickinson and Shafiqullah, 1989). These similar histories produce a characteristic structural style and synextensional stratigraphy, illustrated schematically in Figure 18. The following features are common to most of the more highly extended domains within the Basin and Range province.

(1) Multiple generations of normal faults that imbricate steeply dipping Tertiary sections document extensional strains within the upper crust of 100 to 200 percent (i.e., β of 2–3) across extensional corridors whose present width varies from a few tens of kilometers to 150 kilometers. The characteristic structural style consists of older, gently dipping (rotated) normal faults with associated imbricate splays, cut by progressively steeper sets of normal faults, the youngest of which bound the present basins and ranges. Some of the gently dipping faults in these domains have been called "detachment faults" (e.g., Davis et al., 1980), although their initiation angle, amount of horizontal translation, and tectonic significance remain matters of much debate (cf. Wernicke, 1981; Miller et al., 1983; Davis et al., 1986).

(2) The oldest volcanic rocks in any given area commonly compose a heterogeneous suite, ranging from basalt to rhyolite, with andesite and dacite dominating. In some places (e.g., eastern Nevada and southeastern California), small-volume precursor eruptions occurred over several million years prior to the major outpourings of volcanic rocks. There is commonly a broad compositional evolution within these older volcanic sequences, from largely intermediate compositions (andesites or basaltic/andesites) at the base to more silicic (dacite to rhyolite) compositions upward.

(3) Most of the volume of volcanic rocks within these highly extended terrains were erupted over an interval of a few million years or less, blanketing the landscape with an average of 1 km of lavas and tuffs at peak eruptive rates in excess of 1,000 $km^3/m.y.$

(4) Although the precise onset of extensional faulting is often poorly constrained, in most places it appears to be synchronous with, or immediately after, peak magmatic activity. Rapidly decreasing tilts upward within the lower parts of the Tertiary sections, and sedimentological evidence for rapid unroofing of adjacent areas, suggest that the initial extensional strain rates were extremely high ($>10^{-14}/s$).

(5) Volcanic activity often decreased markedly and locally ended altogether shortly after the onset of extension. The dominantly volcanic lower parts of Tertiary sections are typically overlain by thick sections (as much as 2 to 3 km) of fanglomerate, lacustrine deposits, monolithologic breccia, and only minor intercalated volcanic units. These sedimentary sequences have numerous internal angular unconformities with decreasing tilts upward, suggesting that they represent syntectonic basin fills or half-grabens in the hanging walls of rotational fault systems.

(6) In some areas, gently dipping, capping sequences of basalt (± rhyolite) interstratified with fanglomerates overlie steeply dipping older Tertiary rocks along profound angular unconformities and place an upper age bracket on most of the extensional deformation. The total time elapsed between the youngest of the steeply tilted volcanic rocks and the oldest capping basalts is commonly only a few million years. Capping sequences are generally cut and gently tilted by the youngest, range-bounding faults, demonstrating that extension continued during and after their deposition, albeit at greatly reduced strain rates.

DISCUSSION: EXTENSION AND MAGMATISM IN THE BASIN AND RANGE PROVINCE

Driving mechanisms

Two fundamentally different hypotheses have been put forward to explain the cause or driving mechanism for mid-Tertiary extension and magmatism in the Basin and Range province. One holds that Cenozoic tectonism and magmatism were controlled largely by plate interactions along the west coast of North America. For example, Coney and Reynolds (1977) and Coney (1979) suggested that the abrupt slowdown in convergence rates between the North American and Farallon plates at about 40 Ma was accompanied by steepening of the subducting slab, an east to west reverse sweep of calc-alkaline magmatism, and relaxation of compressive stresses in the overriding plate, causing extension in the arc or backarc. The other view attributes the extension to thermal relaxation and gravitational spreading of crust that was overthickened during previous (Mesozoic to early Tertiary) crustal shortening (e.g., Coney and Harms, 1984; Glazner and Bartley, 1985; Wernicke et al., 1987). Clearly, these processes are not mutually exclusive, and it seems likely that both played important facilitating roles; however, neither hypothesis adequately

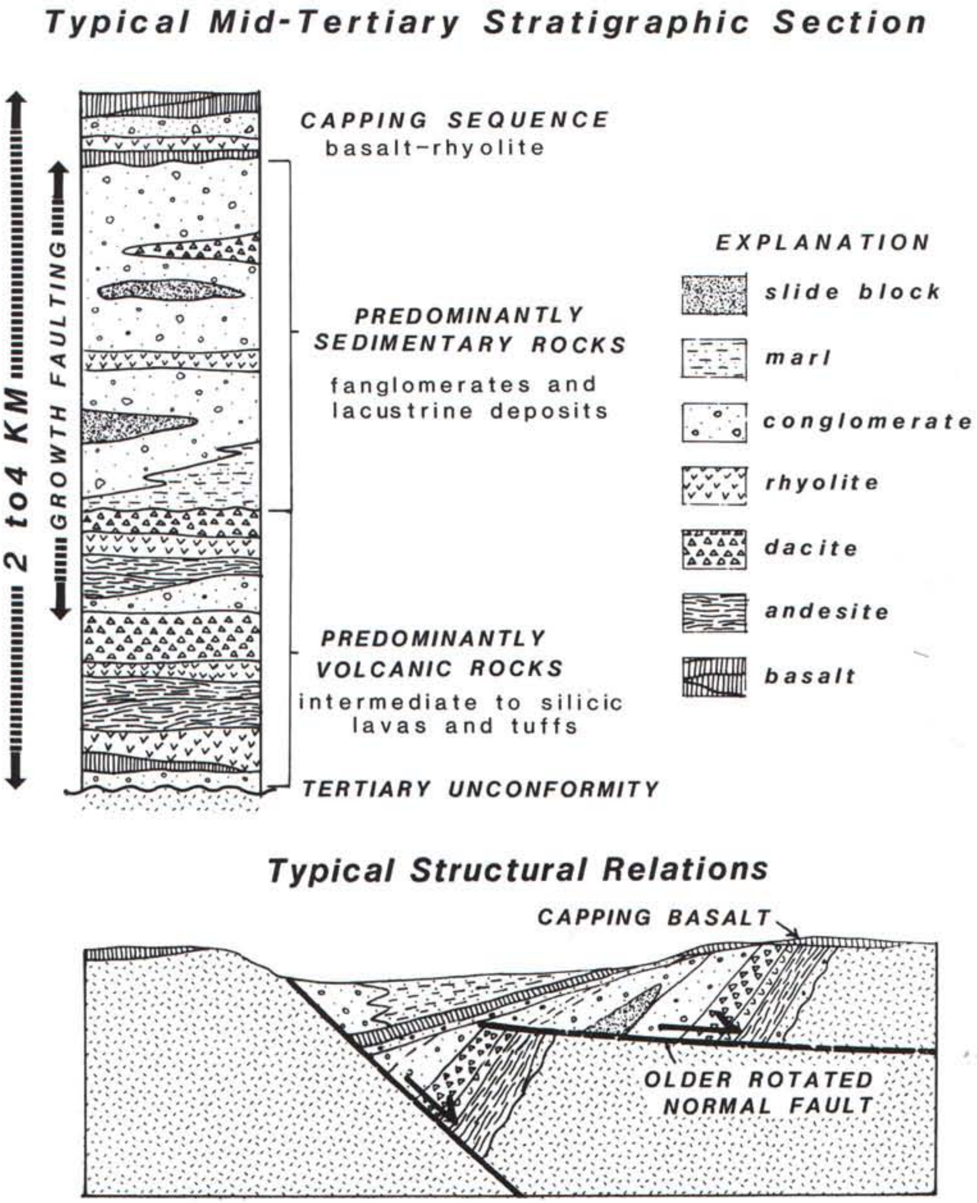


Figure 18. Typical Tertiary stratigraphic section and structural relations from highly extended areas within the Basin and Range province.

explains certain aspects of local eruptive and extensional histories or the highly diachronous nature of both volcanism and faulting within the province.

Space-time distributions of extension and volcanism

The eruptive and extensional histories of the highly extended domains discussed in the text are shown qualitatively in Figure 19, plotted as a function of their age and latitude. These domains represent only a small fraction of the total area affected by Cenozoic volcanism and extensional faulting, but are sufficient to illustrate some general spatial and temporal patterns. In the northern Basin and Range province, the onset of both Cenozoic magmatism and extension at any particular latitude migrated southward, from southern Oregon and northern Nevada in the Eocene, to central Nevada and Utah in the Oligocene, to southern Nevada in the Miocene (e.g., Armstrong, 1970; Lipman et al., 1972; Stewart and Carlson, 1976). This general southward migration is apparently mirrored by an opposing northward or northwestward migration in the southern Basin and Range province, particularly along the lower Colorado River extensional corridor (e.g., Glazner and Bartley, 1984). The onset of predominantly basaltic or bimodal volcanism is also diachronous and typically lags behind the onset of extension by 5 to 15 m.y. The onset of both volcanism and extension generally predate passage of the Mendocino triple junction, especially in the northern Basin and Range province (Fig. 19).

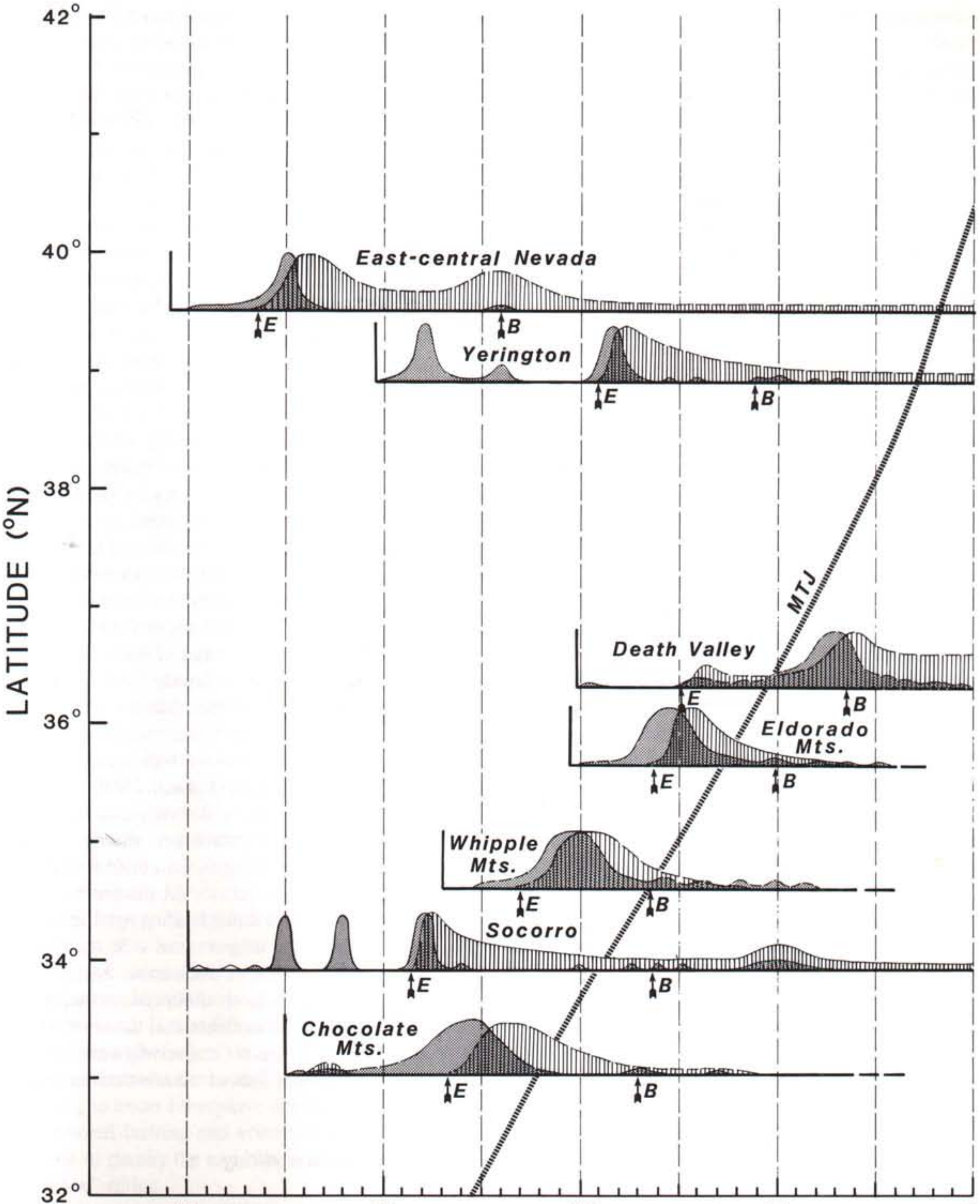


Figure 19. Eruptive rates (shaded) and extensional strain rates (vertical ruled pattern) of selected parts of the Basin and Range province, plotted as a function of age and latitude. These curves are highly generalized and are based on available geochronologic and structural data from each area. Vertical axes for each domain are probably logarithmic; maximum strain rates and eruptive rates are approximately 10^{-14}/s and 1,000 km^3/m.y., respectively. E marks onset of rapid, large-magnitude extension; B shows the approximate time of transition to predominantly basaltic or bimodal volcanism. The position of the Mendocino triple junction (MTJ) as a function of age was obtained from Engebretson et al. (1985). See text for sources of data.

There are some complexities to these spatial and temporal patterns that are not adequately represented in Figure 19. The timing of extension and magmatism appears to have varied significantly within individual domains and in different domains at the same latitude. For example, both extensional faulting and volcanism within the Yerington and Death Valley domains appear to young westward toward the relatively unextended Sierra Nevada batholith. This is mirrored by eastward younging of late Cenozoic faulting and volcanism toward the Colorado Plateau (Best and Brimhall, 1974). Similarly, peak extensional strain rates occurred from 30 to 35 Ma in east-central Nevada and from 12 to 19 Ma in Yerington, although both are situated approximately at lat 39° N (Fig. 19). An obvious bias is introduced by considering only domains of large-magnitude extension. Large volumes of volcanic rocks were erupted in areas such as the San Juan volcanic field (Steven and Lipman, 1976) and Marysvale, Utah (Steven et al., 1984), but were not directly associated with large supracrustal strains. Nevertheless, the overall pattern of Eocene to Miocene volcanism and extensional tectonism migrating parallel to the continental margin and occurring up to 1500 km inboard of that margin appears to be valid and is difficult to reconcile with a simple model of extension in an Andean arc or back-arc setting (e.g., Coney and Reynolds, 1977; Coney, 1979; Zoback et al., 1981).

Glazner and Bartley (1984) suggested that the northward migration of normal faulting and calc-alkaline volcanism in the southern Basin and Range province was linked to the northward migration of the Mendocino triple junction. In their model, the short-lived episodes of magmatism and extension effectively filled the "hole" created by an unstable triple-junction geometry (e.g., Ingersoll, 1982). Available data from the Colorado River area suggest that peak eruptive and strain rates predated the passage of the triple junction by approximately 5 m.y. (see Fig. 19), but this is probably within the errors of plate reconstructions (e.g., Stock and Molnar, 1983). Our principal objection to their model is that it addresses only a restricted part of the southern Basin and Range province and fails to explain similarly transgressive magmatic and extensional histories elsewhere in the province. The southward sweep in the northern Basin and Range province is especially hard to relate to relative plate motions because it occurred while there was a significant northward (oblique) component to subduction of the Farallon (or Kula) plates, and North America was moving southward in a fixed hot-spot reference frame (Engebretson et al., 1985).

Wernicke et al. (1987) and Sonders et al. (1987) attributed complexities in the spatial and temporal distribution of Cenozoic extension and magmatism to complexities in the earlier (Mesozoic and early Tertiary) shortening and plutonic histories. They concluded that extension was initially localized in areas of previous crustal thickening (e.g., Coney and Harms, 1984), but that its timing was controlled by the magnitude and timing of this thickening and by the initial thermal structure of the lithosphere. In their model, early intermediate to silicic volcanism was due to conductive heating and widespread partial melting of the previously thickened crust, and was closely followed by rapid extension as the thermally weakened lithosphere gravitationally spread under its own weight. The varying time intervals between the termination of thrust faulting and the onset of extension at different latitudes were thought to reflect differences in the thermal state of the lithosphere at the time of thrusting.

In detail, the spatial and temporal distributions of Cenozoic extension and magmatism bear as little relation to the Mesozoic shortening and magmatic history as they do to Cenozoic plate motions. Some highly extended domains are situated in the frontal part of the Sevier-Laramide thrust belt (e.g., the Virgin and Mormon Mountains in southern Nevada), whereas others lie far back in the hinterland (e.g., Yerington). Although there may be important along-strike variations in the timing and magnitude of shortening in the Sevier belt (e.g., Armstrong and Oriel, 1965; Burchfiel et al., 1970; Lawton, 1985), they do not adequately account for the systematic southward sweep of extension and magmatism in the northern Basin and Range province. Wernicke et al. (1987) suggested that the varying time lag between the termination of shortening and the onset of extension was controlled primarily by the thermal structure of the lithosphere at the time of shortening. Thus, Eocene extension in the Pacific Northwest was thought to have immediately followed shortening because this shortening occurred within the coeval magmatic arc, whereas the relatively recent onset of extension in southern Nevada was thought to reflect the largely "amagmatic" character of shortening in this region. However, there is widespread evidence for prograde amphibolite-facies metamorphism and plutonism at depth throughout nearly all of the region that was subsequently extended (e.g., Armstrong and Hansen, 1966; Haxel et al., 1984), and in many places, it can be demonstrated that these elevated thermal conditions were established *during* shortening (e.g., Miller et al., 1988). In Arizona, Laramide shortening occurred within the coeval magmatic arc, yet the onset of extension followed the termination of thrust faulting by at least 20 to 30 m.y. If elevated lower crustal temperatures were the sole requirement for gravitational spreading of thick crust, then extension should have everywhere immediately followed shortening. Finally, as discussed below, there is evidence that the onset of volcanism at any particular latitude was not exclusively a crustal melting event, but was triggered by a flux of mantle-derived basalts into the crust.

Active versus passive rifting

Sengor and Burke (1978) suggested that there are two kinds of continental rifting: "active" rifting in response to asthenospheric upwelling, and "passive" rifting in response to regional stress fields created by plate interactions and boundary conditions. This distinction is not easily applicable to most real situations but it brings into focus a basic question: Are the elevated isotherms and basaltic magmatism typical of most extensional provinces solely a consequence of thinning (and decompression) of the lithosphere, or did active upwelling of asthenosphere first thermally weaken the lithosphere and thereby allow it to extend? Most analyses of Basin and Range extension, including the two general models discussed above, have tacitly assumed a passive rifting model and emphasized the role of stresses within the lithosphere (created either by plate boundary conditions or by overthickening the crust). This emphasis obscures the important role that mantle-derived magmatism played in the earliest stages of the extensional history.

As discussed above and summarized in Figure 19, 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. In many places, precursor eruptions occurred for several million years before the first normal faults began to move. The fact that few basalts reached the surface during the early stages of volcanism led Wernicke et al. (1987) to suggest that this early calc-alkaline magmatism was primarily a crustal melting event, and not necessarily indicative of significant melting in the mantle. Four lines of evidence suggest that even the earliest (preextensional) magmatism was driven by a flux of mantle-derived basalt into the crust.

(1) The earliest eruptions in any given area are often also among the most mafic (i.e., basaltic andesites and andesites), whereas one would expect granite minimum melts (such as the Himalayan leucogranites) to form during anatexis of an overthickened crust.

(2) To produce the andesites that characterize the earliest stages of volcanism would require unrealistically large degrees of partial melting of crustal rocks and, in any case, would still require an external source of heat to sufficiently raise crustal temperatures.

(3) Isotopic, mineralogic, and petrographic data from these suites provide evidence for mixing between a more primitive (basaltic) component and a highly radiogenic crustal component (e.g., Glazner and Turner, 1984; Putirka and Weigand, 1987; Naumann and Smith, 1987; this study).

(4) The most voluminous rocks, the hornblende dacites, are modeled as containing a significant proportion (30 to 50 percent) of young mantle material. These relations suggest that the onset of extension closely followed a large(?) flux of mantle-derived basalt into the crust. To the extent that asthenospheric upwelling and partial melting in the lower lithosphere apparently provided the trigger for extensional faulting and volcanism at the surface, it seems appropriate to classify the early stages of Basin and Range extension as "active" rifting.

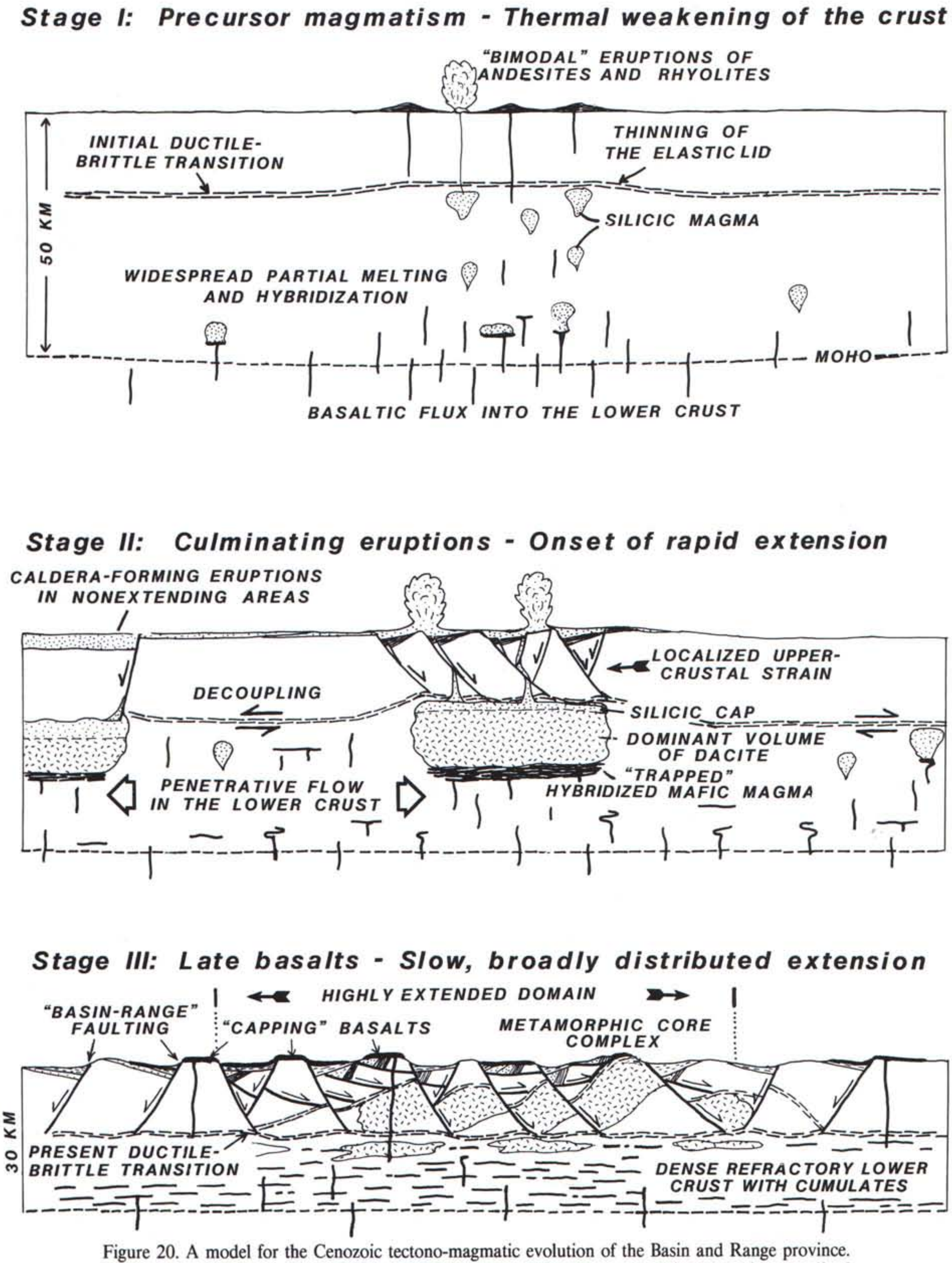
Model for Basin and Range extension and magmatism

The ultimate cause of extension and magmatism in the Basin and Range province remains largely a matter of conjecture. Both a reduced confining stress caused by the change in plate motions at approximately 40 Ma and the gravitational instability caused by previous thickening enhanced the ability of the crust to extend. The onset of rapid, large-magnitude extension in any particular area, however, was apparently triggered by a pulse of basaltic magmatism. We focus our attention on how extensional tectonism and magmatism interacted to produce the stratigraphic and structural relations observed at the surface. Exactly what initiated melting in the mantle and caused the thermal anomaly to migrate roughly parallel to the continental margin is beyond the scope of this work. England and Houseman (1988) have suggested that the recent uplift and onset of extensional tectonism on the Tibetan Plateau were caused by the convective loss of the lower part of the lithosphere and the consequent increase in potential energy of the remaining lithospheric column. This process, wherein the thermal boundary layer drops off and is replaced by hot asthenosphere, might also cause widespread partial melting in the upper mantle and result in a close temporal and spatial association of "fundamentally basaltic" magmatism and the onset of extensional tectonism. Perhaps a similar process was operative in the Basin and Range province during the middle Tertiary and migrated erratically to produce the complex space-time distribution of volcanism and extensional faulting.

The eruptive and extensional histories of different parts of the Basin and Range province are so similar as to suggest a basic genetic relationship. Figure 20 illustrates a three-stage evolutionary model for crustal stretching and magmatism that can explain these similarities. The key elements of the model follow.

1. A flux of mantle-derived basalt into the crust is the first event to affect any particular area. Because the earlier magmatism predates the onset of extension by up to several million years, it cannot be the consequence of lithospheric stretching (and decompression), but rather, is generated by "active" upwelling of asthenosphere. For example, calculations by McKenzie and Bickle (1988) suggest that a "normal" lithosphere would have to be stretched by a factor of 2 or more before any appreciable melting occurs in the upper mantle due to decompression. The input of mantle-derived basalts causes widespread partial melting in the lower crust. Small increments of basalt are capable of producing large volumes of partial melt because temperatures in the lower crust were already close to the granite solidus (e.g., Sonders et al., 1987). Extensive fractionation, assimilation, and mixing of contaminated basaltic magmas with crustal melts produces the spectrum of intermediate to silicic compositions erupted at the surface. Underthrusting of upper crustal lithologies to deeper levels during the Mesozoic might explain the extreme trace-element enrichments and highly radiogenic character of some of the early crustal melts (rhyolites). The small volumes and the geochemical heterogeneity of individual eruptions during the early stages of volcanism suggest that they were fed from relatively small, isolated magma reservoirs. No uncontaminated basalts reach the surface at this time because the crust is too thick and hot and is permeated with low-density silicic melts.

2. In some areas, sufficient quantities of these hybrid melts coalesce to form mid-crustal magma chambers. These chambers grow by intercepting ascending contaminated basaltic and andesitic liquids, and fractionation of these mixed and hydridized magmas produces large volumes of relatively homogeneous dacitic magma. Some of the chambers develop compositionally



Stage I: Precursor magmatism - Thermal weakening of the crust

Stage II: Culminating eruptions - Onset of rapid extension

Stage III: Late basalts - Slow, broadly distributed extension

Figure 20. A model for the Cenozoic tectono-magmatic evolution of the Basin and Range province. Although the absolute timing of both extension and magmatism varied regionally, this generalized three-stage evolution is applicable to the most highly extended areas of the province. See text for discussion.

zoned caps that erupt as zoned ash-flow tuffs (e.g., the Kalamazoo and Peach Springs Tuffs).

3. The onset of rapid, large-magnitude extension during, or immediately following, peak volcanism is a consequence of thermal weakening of the lithosphere. Lithospheric strength in areas of relatively low geothermal gradients is thought to be concentrated in two layers: one in the uppermost mantle that is controlled by the rheology of olivine, and one in the middle crust that is controlled by quartz rheology (e.g., Molnar and Chen, 1983; Smith and Bruhn, 1984). The initial thermal event that caused melting in the mantle and a flux of basalt into the lower crust presumably heated and weakened the upper mantle sufficiently that, immediately prior to the onset of extension, only the upper, brittle crust remained strong. As basaltic magmas continued to inject the lower crust, hybridize, and ascend to shallow crustal levels, this elastic lid was thinned and weakened until it failed catastrophically by imbricate normal faulting. The upper crust presumably failed where it had been thermally eroded the most; i.e., above the largest accumulations of magma. Note that the initial (pre-extensional) widths of the highly extended areas discussed in the text were on the order of a few tens of kilometers, dimensions similar to that of a magma chamber that could feed the volumes of volcanic rocks observed at the surface. The observation that peak eruptive rates generally coincided with the onset of normal faulting suggests that the two processes reinforced each other. The accumulation of magma in shallow reservoirs localized initial failure, and brittle failure along faults frequently may have been the decompression event that triggered catastrophic explosive eruptions (cf. Hildreth and Mahood, 1986).

4. The earliest normal faults had geometries similar to those that bound the present basins and ranges; at least some of them were demonstrably steeply dipping planar faults that penetrated to depths of 7 to 15 km (e.g., Proffett, 1977; Howard et al., 1982a, b; Gans and Miller, 1983). Thick sections of mid-Tertiary fanglomerate and lacustrine deposits demonstrate the existence of extensional basins or half-grabens with dimensions and bounding faults comparable to the modern basins in the Basin and Range province.

5. Initial upper crustal strain rates were extremely high, on the order of 10^{-14}/s, but this strain was localized within narrow corridors. Multiple generations of imbricate normal faults within these corridors indicate that the upper crust was weakest and continued to fail at the site of initial failure. Geophysical and geological evidence reviewed by Gans (1987) suggests that the localized strains in the upper crust were accommodated by more broadly distributed, penetrative(?) stretching and flow at lower crustal levels.

6. The loss of gravitational potential due to crustal thinning caused strain rates to decrease exponentially until the present relatively stable crustal thickness of 25 to 30 km was achieved. Normal faulting became more widely distributed once the regional thermal structure and the thickness of the brittle layer became more uniform. Present-day faulting is concentrated along the margins of the Basin and Range province, expanding into the thicker, gravitationally unstable crust of the Sierra Nevada and Colorado Plateau (e.g., Best and Brimhall, 1974).

7. "Primitive" basalts were erupted only late in the extensional/magmatic histories for several reasons. Thinning of the crust reduced the likelihood of contamination en route to the surface. As the crust thinned, the proportion of "cold" crust deforming by brittle fracture increased, even though the actual thickness of the brittle layer may have stayed approximately the same. The changing composition of the lower crust with time also reduced the likelihood of contamination. The earlier, voluminous intermediate to silicic magmatism probably depleted the lower and middle crust of most of its readily meltable components, leaving behind a network of young gabbroic bodies (or their metamorphic equivalents) representing stalled basalt magma bodies, mafic to ultramafic cumulates derived from these magmas and their hybrids, and a denser, refractory residue of older crust. Such a lower crust is in accord with recent seismic refraction evidence for a thin, relatively high-velocity, lower crustal layer beneath parts of the Basin and Range province (Thompson et al., 1986).

Implications and unresolved problems

The model outlined above provides a general framework for interpreting the extensional and magmatic history of the Basin and Range province, particularly of its more highly extended segments. Additional studies integrating the structure, stratigraphy, petrology, and geochronology of volcanic rocks elsewhere in the province are needed to test whether the eruptive and extensional histories are as consistent and interrelated as indicated above. The scenario depicted in Figure 20 has important implications for thermomechanical models of extension, the petrogenesis of Cenozoic volcanic rocks, and the structure and evolution of the crust in the Basin and Range province.

The temporal and spatial coincidence of large-magnitude supracrustal extension with major eruptions of intermediate to silicic volcanic rocks in areas such as east-central Nevada suggests that the upper crust failed in response to intrusion and ductile flow in the *underlying* lower crust. This argues strongly against "rooting" these upper crustal strains along gently dipping "detachment faults" to zones of lower crustal accommodation many tens to hundreds of kilometers away (e.g., Wernicke, 1981). The model advocated here revives the old, currently unfashionable idea that supracrustal extensional faulting in the Basin and Range province was largely a response to deep-seated intrusion (e.g., Thompson, 1960; Anderson, 1971; Wright and Troxel, 1973; Lachenbruch and Sass, 1978). We emphasize the role that the inferred mid-crustal batholiths played in thermally weakening the overlying elastic lid, thereby localizing failure and concentrating subsequent upper crustal strains, and do not necessarily imply that intrusions accommodated or caused a significant percentage of the strain by dilating the lower crust.

By restricting our analysis to the more highly extended parts of the Basin and Range province, we ignored large, mid-Tertiary eruptive centers that were not obviously associated with significant supracrustal extension, such as the San Juan volcanic field in Colorado (Steven and Lipman, 1976), parts of the Mogollon-Datil volcanic field in New Mexico (Elston, 1976), and much of the Oligocene to Miocene ignimbrite province in the central Great Basin (e.g., Steven et al., 1984; Boden, 1986). Why did these areas not extend, and was there anything fundamentally different about the magmatism? The model in Figure 20 attempts to explain only what localized the earliest extensional faulting, not what controlled the distribution of all major eruptive centers. Within any broadly synchronous magmatic belt, we suggest that the crust failed only where it was first weakened, whereas volcanism was widespread because the input of basaltic magma into the crust was more widespread. Although partial melting, hybridization, and the development of shallow silicic magma chambers occurred nearly simultaneously across broad segments of the Basin and Range province, strain may have continued to be localized within the narrow corridors of initial failure, apparently because these areas continued to be the weakest. The model implies that, at any particular latitude, initial failure was coincident with the locus of the earliest magmatic activity. Existing geochronological data are not sufficient to test this hypothesis, although it is noteworthy that the earliest (39 to 40 Ma) eruptions within the highly extended corridor in east-central Nevada are the oldest known at this latitude. Other factors that may have played important roles in dictating where supracrustal strains were localized include preexisting structural weaknesses and variations in the pre-extensional crustal thickness.

The localization of upper crustal strain might produce systematic differences between the character of volcanism inside and out of the extensional corridors. Rapid extensional faulting and thinning of the upper crust would tend to continuously decompress magma chambers within the extensional corridors and favor frequent, smaller volume eruptions of less-evolved magma. In contrast, the structurally more coherent roofs of magma chambers in adjacent areas would allow melts to coalesce and differentiate into large silicic magma bodies, favoring infrequent eruptions of voluminous silicic pyroclastic material. Thus, we predict that volcanic sections within the highly extended domains should have a higher proportion of andesite to dacite lava flows, whereas eruptive centers in less-extended areas should produce a higher proportion of voluminous silicic ash-flow tuffs.

Compositional, petrographic, isotopic, and thermal considerations suggest that all Cenozoic magmatism in the Basin and Range province should be viewed as "fundamentally basaltic" (e.g., Christiansen and Lipman, 1972; Hildreth, 1981). The transition from calc-alkaline intermediate to silicic volcanism to predominantly basaltic volcanism may simply reflect a decreasing amount of hybridization due to crustal thinning and depletion of the lower crust by removal of partial melts. It is not clear whether there has been a continuous flux of mantle-derived basalt into the crust throughout the extensional/magmatic history, or whether there were two distinct pulses: an early one associated with the passage of the thermal anomaly that triggered the onset of extension and magmatism, and a later one caused by lithospheric thinning and decompression (e.g., McKenzie and Bickle, 1988). A comparison of the chemical and isotopic compositions of mafic lavas occurring near the base of and capping syntectonic Tertiary sections may yield important clues about the source regions of the initial mantle melts and whether the nature of basaltic magmatism has changed with time.

The volume of Tertiary volcanic rocks in the Basin and Range province suggests that a significant amount of mantle-derived material was added to the crustal column. East-central Nevada was blanketed by an average thickness of 1 km of volcanic rocks. Assuming that ten times this amount crystallized in the crust (Smith and Shaw, 1978), which was subsequently extended 100 percent, perhaps 5 km of the crustal section consists of Oligocene plutons. Our modeling of Sr and Nd isotopic data suggests that the most voluminous units contain about 30 to 55 percent mantle material. Thus, about 2 to 3 km of the crustal section can be attributed to new mantle material added by Oligocene magmatism. Although crude, these estimates are compatible with mass-balance calculations by Gans (1987), which suggest that an average of 5 km of the present 30-km crustal thickness in the eastern Great Basin was added to the crust during the Cenozoic. It is not clear whether these magmatic additions are uniformly distributed throughout the lower crust or are concentrated in more restricted areas of underplating.

The uniform crustal thickness of the Basin and Range province was interpreted by Gans (1987) to reflect decoupling of a heterogeneously extended upper crust from a more uniformly stretched lower crust. It was argued that the lower crust apparently had a sufficiently low viscosity that it was capable of flowing outward from beneath less-extended segments of the upper crust, thereby preventing the creation of any topography on the Moho. The Cenozoic magmatic history of the Basin and Range province provides additional support for this model. Large crustal contributions to synextensional volcanic rocks imply that a significant portion of the lower and middle crust was partially molten at the time of extension, so there is little doubt that viscosity of the lower crust was low.

The foremost conclusion to be drawn from existing data on the Basin and Range province is that Cenozoic volcanism and extensional tectonism were intimately related and that both were triggered by an active flux of basaltic magma into the crust. Pervasive injections of mantle-derived basalt into the crust, widespread partial melting, and penetrative flow have extensively reworked the lower and middle crust and may have shaped most of its modern petrologic and geophysical characteristics. The complicated extensional fault systems that give the province its distinctive physiographic character may only be a passive, surficial response to a thermal-magmatic collapse of the entire lithosphere.

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