Geothermal Resources Council, SPECIAL REPORT NO. 13, May 1983

PRECENOZOIC TECTONIC EVOLUTION OF NORTHEASTERN NEVADA

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ABSTRACT

Nevada has undergone three major sequential tectonic regimes since late in Precambrian time: development of a passive continental margin formation in late Proterozoic and Early Cambrian time, maintenance of a passive continental margin together with collisions of displaced terranes through mid-Triassic time, and active margin phenomena ever since. The record of pre-Jurassic continental margin tectonics is well preserved in Nevada but is fragmentary elsewhere in western North America due to widespread tectonic erosion of the sialic margin. The edge of sialic Precambrian North America lies in Nevada. It formed mainly in the late Proterozoic west of an unusually wide zone of attenuated sialic crust. The sialic edge may have persisted in Nevada as the general ocean-continent transition until early in the Triassic. In that duration, collisions of the edge with migrating arc terranes (Sonomia, Antleria) caused the obduction of the oceanic Golconda and Roberts Mountains allochthons above the slope and outer shelf in Triassic and Mississippian times, respectively. After each collision, an oceanic configuration was regained at the sialic edge, perhaps due to thermal contraction of the arc lithosphere. Mesozoic active margin features in Nevada relate to subduction near the western margin of the Sierra Nevada in California. They include an extensive continental arc that persisted in western Nevada from late in the Triassic to the Late Cretaceous and a deforming foreland that spanned the rest of the state. The foreland tectonics include heterogeneous zones of thin-skinned contraction among cover rocks and heating and ductile deformation of deep seated rocks. Contraction of the foreland may have occurred across Nevada throughout Jurassic and Cretaceous times. Certain ancient structures in Nevada have been important in controlling the position and form of younger structures.

Introduction

The Phanerozoic* evolution of the North American continent and adjacent oceans in what is now Nevada was governed by three sequential tectonic regimes. The first, beginning late in Proterozoic time and continuing to Middle Cambrian time, created a passive margin to western sialic North America (Stewart, 1976). It caused the rifting and drifting away of a part of the continent of unknown size and the growth of oceanic lithosphere against the new sialic edge. The second regime maintained a passive continental margin of western North America from Middle Cambrian to Middle or Late Triassic time but permitted collisions of outboard terranes with the sialic margin in Mississippian and Early Triassic times (Speed, 1983). Since late in Triassic time, western North America has existed in a regime of active margin tectonics (Hamilton, 1969). This third and currently active regime has included diverse phenomena that have varied with time and position: subduction of oceanic lithosphere below the continent, phases of highly oblique convergence and suture-zone or intra-arc spreading, ridge-trench collision, growth of a continental arc, major foreland contraction and extension, and the accretion of displaced terranes to the sialic edge.

Although similarly eventful histories probably occurred along the entire western margin of North America, a record of pre-Jurassic events is best preserved in Nevada, and in fact, many elements of the record are known only in Nevada. The pre-Jurassic margin of North America in Nevada evidently escaped strong tectonic erosion which elsewhere removed and rafted away sizeable fragments of the sialic continent and early accreted terranes (Speed, 1983). Thus, Nevada provides an almost unique glimpse into the past of marginal western North America.

Pretertiary Tectonostratigraphy of Northwestern Nevada

Figure 1 shows the tectonic affiliations of Pretertiary rocks of northwestern Nevada and vicinity except in regions of nearly continuous Cenozoic cover (unit 1). Unit 7 is Precambrian sialic North America and its Paleozoic and Mesozoic cover. The unit has probably maintained near-coherency in Phanerozoic time but has undergone Mesozoic contraction and Cenozoic extension. The western 150 km or so of sialic North America (unit 7) are overlain by major allochthons of greatly displaced Paleozoic oceanic rocks. Such rocks compose unit 6a and include the Roberts Mountains allochthon which was obducted across the

*began at about 700 mybp.

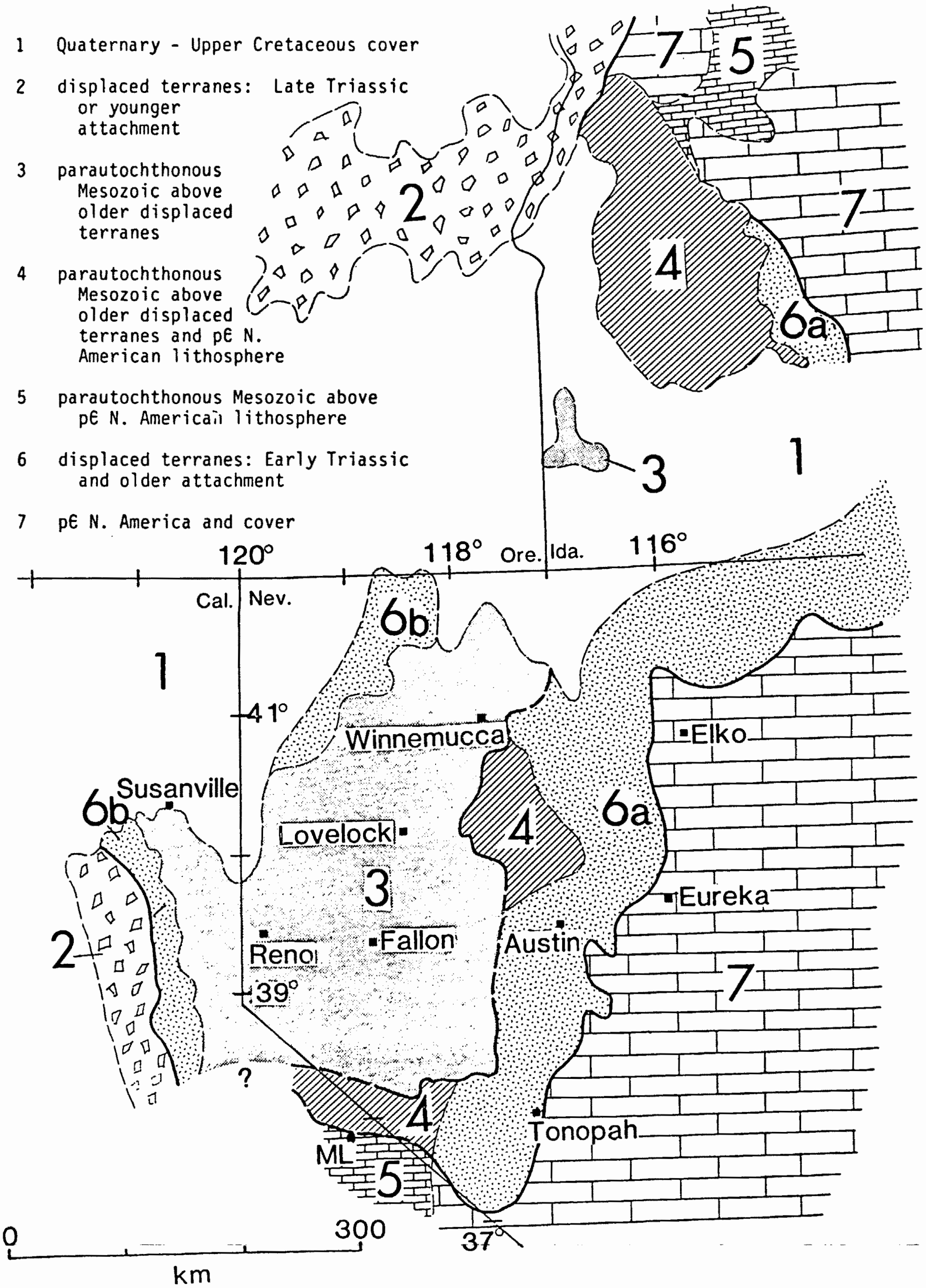

Figure 1. Map of northwestern Nevada and vicinity showing tectonic affiliations of principal outcrop units, emphasizing Pretertiary rocks where possible and excluding basin-range structure. Heavy lines are tectonic boundries with moderate to major displacement. ML is Mono Lake.

slope and outer shelf of North America in Mississippian time and the Golconda allochthon, which was emplaced early in Triassic time.

Deformed Paleozoic rocks also exist in the Black Rock Desert region and northern Sierra Nevada (unit 6b, Fig. 1). These are also thought to be greatly displaced with respect to their sites of attachment to North America. However, they are probably structurally discrete from the obducted allochthons of unit 6a and probably occupy the lower structural levels of the Sonomia microplate (Speed, 1979) that collided with the passive margin of North America in Triassic time.

Units 3-5 (Fig. 1) are composed of Mesozoic sedimentary and igneous rocks that were deposited or intruded at or near (<300 km) their present sites after the collision of Sonomia and the onset of active margin tectonism. The threefold division of Mesozoic rocks in Figure 1 is based on the different tectonostratigraphy of their basements. Unit 3 includes mainly basinal strata continental arc rocks that were deposited on and intruded into the Sonomia microplate (Speed, 1978). Sonomia's cryptic suture is approximately coincident with the eastern boundary of unit 3. Unit 4 consists mainly of shelfal and carbonate platform deposits that overlie the Roberts Mountains and Golconda allochthon of unit 6b. Unit 5 is constituted by scarce remnants of Mesozoic rocks that appear to be depositional on or intrusive into ensialic North America. Unit 2 consists of displaced and suture-related terranes (Saleeby and Sharp, 1980; Schweickert, 1981) that attached to the edge of North America and early accretants during active margin tectonism in Late Triassic to Late Cretaceous time.

Figure 8 provides a sectional view of the tectonostratigraphic stacking of units 3-7 from the Jackson to the Shoshone Mountains in northwestern Nevada.

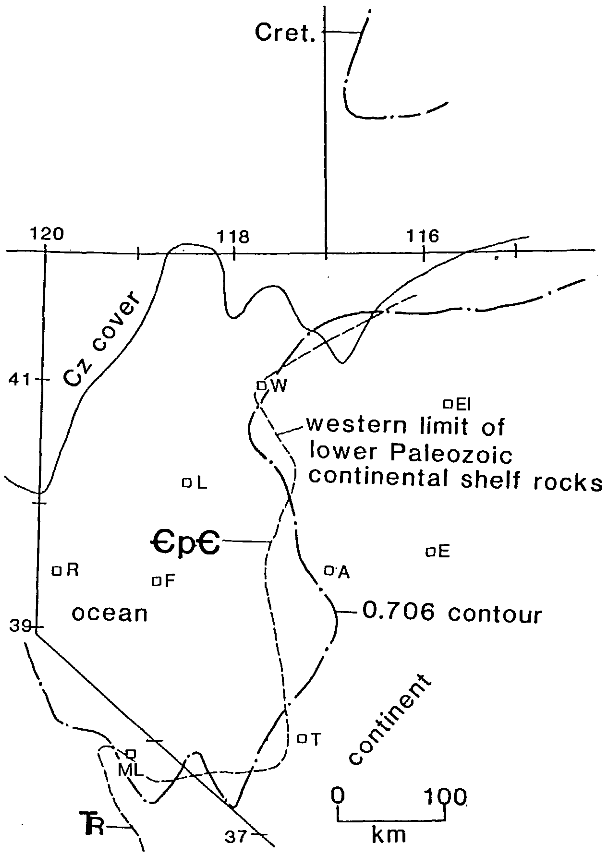

Figure 2. Approximate position of present edge of Precambrian sialic continental North America defined by 1) initial Sr isotopic ratio in Mesozoic igneous rocks with value of 0.706 and 2) present limit if lower Paleozoic shelf strata. Age coding gives time of formation of sialic edge. Letters abbreviate town names as given in Figure 1.

Edge of Sialic North America

Lines that approximate the present edge of contiguous sialic Precambrian North America in Nevada, Idaho, and California and probable ages at which segments of the margin were generated are shown in Figure 2. The sialic edge is a basement feature and is generally cryptic due to burial by younger rocks and nappes or obscuration by magmatism and metamorphism. The margin's surface trace is estimated by outermost outcrops of autochthonous continental platform or shelf facies (Roberts and others, 1958; Kay and Crawford, 1964; Matti and McKee, 1977), by ratios of initial Sr and Pb isotopes and mineralogy of autochthonous Phanerozoic magmatic rocks (Kistler and Peterman, 1973; Doe, 1973; Armstrong and others, 1977; Zartman, 1974; Miller and Bradfish, 1980), and locally (south of 41°N), by maxima in gravity gradients that indicate rapid lateral changes in crustal thickness and/or composition (Speed, 1983).

The present edge of Precambrian sialic crust evolved from a late Proterozoic passive margin that developed along entire western North America. This ancient sialic edge probably existed at varied distances outboard of the present edge. The present north-trending edge of sialic crust in Nevada (Fig. 2) may be the only preserved segment of the passive margin, its absence elsewhere due to tectonic removal during Mesozoic and Cenozoic active margin tectonics (Speed, 1983).

The existence of an ancient passive margin along the Pacific reach of North America was interpreted from autochthonous and parautochthonous upper Precambrian and lower Paleozoic shelf strata that crop out between the platform-shelf hinge and the present sialic edge (Fig. 2) by Stewart (1972, 1976) and Stewart and Suczek (1977). Lower strata of this sequence compose a terrigenous marginward-thickening clastic prism that reflects arching, rifting, and early drifting phases of passive margin development between about 550 and 700 myBP. Such strata lie above crystalline rocks and older Precambrian beds with highly discordant structural trends suggesting major reconfiguration of the continental margin in late Precambrian time. The clastic prism is succeeded by rocks of shallow marine subsiding shelf environments (Kay and Crawford, 1964; Matti and McKee, 1977).

The sialic crust in the region affected by passive margin tectonics (west of the platform-shelf hinge in central Utah) is between 30 and 35 km thick except where the Mesozoic continental arc (Fig. 6) is superposed on it, there producing crustal thicknesses as great as 50 km. The prevalent thicknesses are less than those in the craton of central Utah (Smith, 1978) east of the Paleozoic subsiding shelf. The region of thinner sialic crust possibly reflects an unusually broad zone of rifting and attenuation created during passive margin formation. Although the existence of upper Precambrian diamictite and mafic igneous rocks in the clastic wedge section just west of the shelf-craton hingeline in Utah support the idea of a broad zone of rifting, the magnitude of attenuation cannot be calculated because of probable strong Mesozoic thickening and Cenozoic thinning of the sialic crust west of the hingeline (Armstrong, 1972).

Evidence that the late Precambrian - Early Cambrian passive margin may be preserved in Nevada (Fig. 2) comes from differences among autochthonous and parautochthonous lower Paleozoic strata that can be interpreted as inner and outer shelf facies (Kay, 1960; Rowell and others, 1979; Matti and McKee, 1977). Moreover, shoalwater carbonate rocks that locally form outermost outcrops of the Paleozoic shelf succession are considered deposits on a ridged outer shelf edge. The tectonic removal of an outer zone of continental rock including the Precambrian sialic edge at other sites in western North America (Idaho and central California in Figure 2) is inferred from the absence of the pre-Jurassic tectonostratigraphic units that are sutured against or obducted on the sialic continent in Nevada (Speed, 1983) and the truncation of the Paleozoic craton-shelf hingeline and projected Paleozoic structures by the present sialic edge (Hamilton and Myers, 1966).

Passive Margin Accretionary Tectonics

The Foothills suture in the Sierra Nevada (contact of units 2 and 6a, Fig. 1) is a major accretionary surface that separates terranes that attached to the passive margin of North America before Middle Triassic time from those that arrived during the later active margin phase (Saleeby and Sharp, 1980; Schweickert, 1981; Saleeby, 1982).

East of the Foothills suture, three accretionary terranes are exposed, the Roberts Mountains and Golconda allochthons and Sonomia (Figs. 3 and 4). A cryptic fourth terrane, Antleria, is postulated. The Roberts Mountains allochthon consists of a tectonic assemblage of pelagic, hemipelagic, turbiditic, and volcanic rocks of early Paleozoic age and probable oceanic derivation. It laps over lower Paleozoic strata of the North American continental shelf at least 130 km from the sialic edge and was almost certainly emplaced from the west early in Mississippian time (Roberts

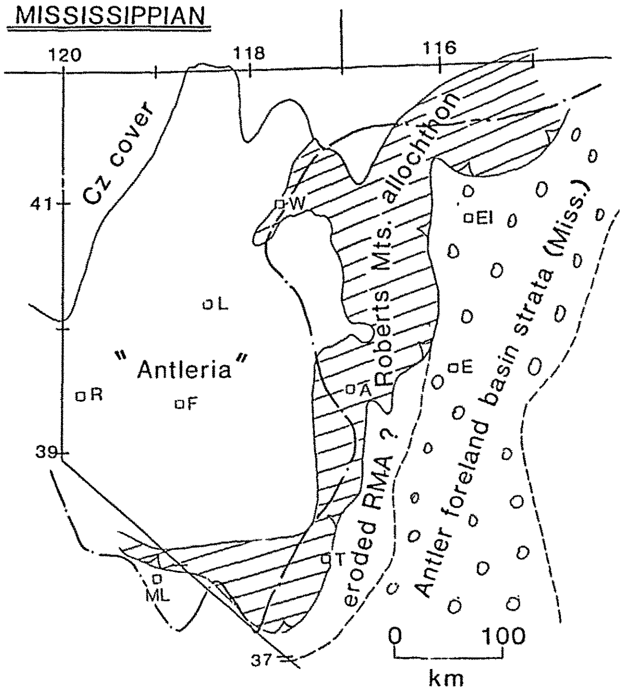

Figure 3. Major tectonic features resulting from arc-passive margin collision in Mississippian time. Dash-dot line is isotopic 0.706 line.

and others, 1958; Smith and Ketner, 1968; Stewart and Poole, 1974; Poole, 1974; Speed and Sleep, 1982; Dickinson and others, 1983). The Golconda allochthon possesses similar rocks and architecture to the Roberts Mountains except that the rocks are of Mississippian to Permian age (Silberling, 1973; Stewart and others, 1977; Speed, 1977, 1979; Miller and others, 1981, 1983; Snyder and Brueckner, 1983). It was emplaced in Early Triassic time at least 100 km inboard of the sialic edge and above the earlier Roberts Mountains allochthon and the late Paleozoic and Early Triassic cover to the Roberts (Speed, 1979).

Sonomia (Fig. 4) is thought to be a lithospheric fragment of Paleozoic arc-related tectonostratigraphic units, surmounted by a Permian magmatic arc (Speed, 1979). It collided with the edge of sialic North America early in the Triassic. Its main exposures are at the microplate margins where late Mesozoic deformation has transported Sonomia's rocks to the surface, either by imbricate thrusting as in Nevada or by rotation and flattening as in the northern Sierra Nevada. The central regions of Sonomia are deeply buried below thick Triassic flysch and continental arc volcanics that succeeded Sonomia (Speed, 1978). Sonomia is the earliest of exposed displaced lithospheric terranes to have attached to western North America. It is a question whether Sonomia was a contiguous mass upon initial collision or whether it includes sequentially accreted fragments. Paleomagnetic data show no anomalies in the area of Sonomia with respect to North America

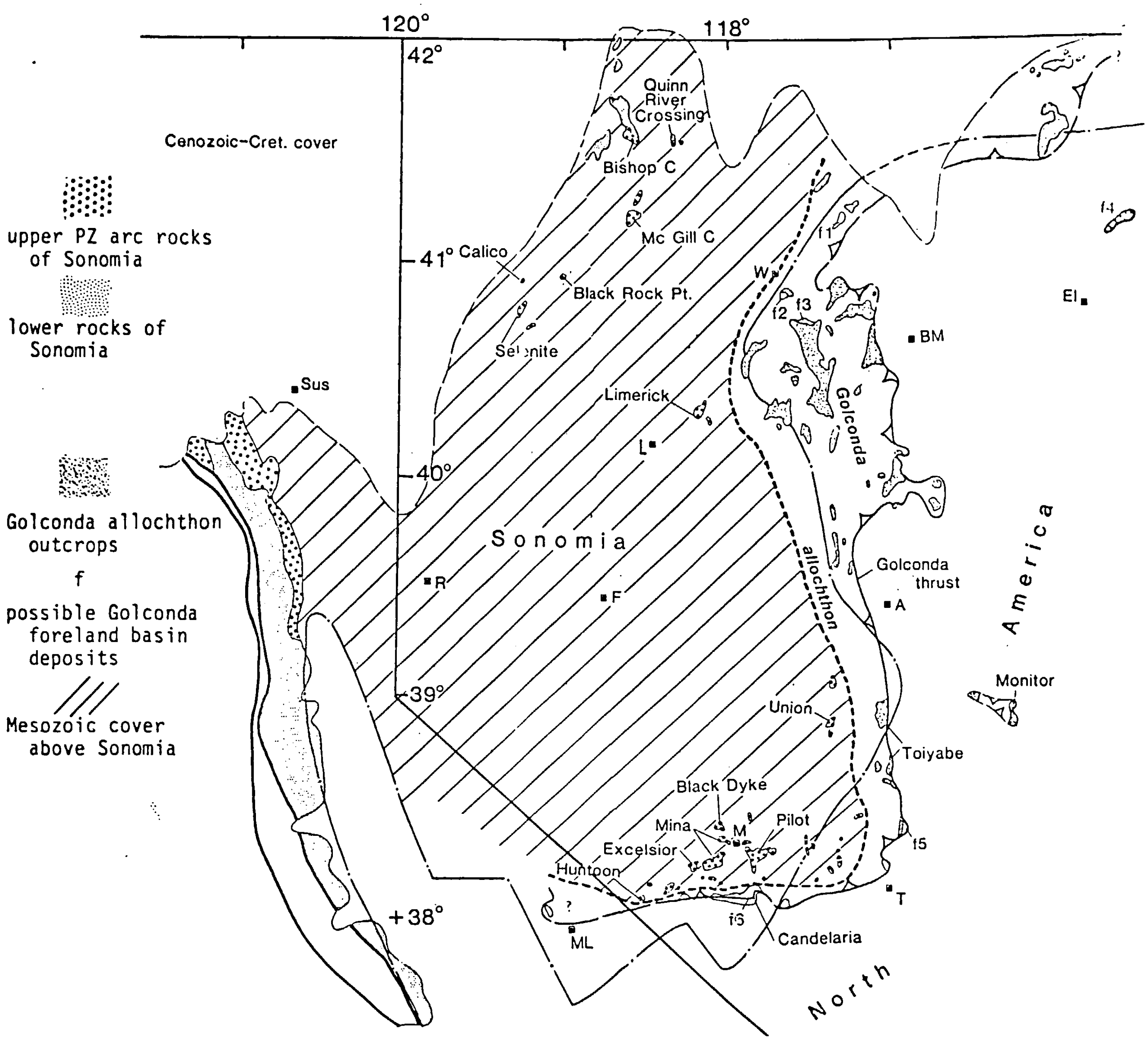

Figure 4. Major tectonic features resulting from arc-passive margin collision in Early Triassic time. Place names indicate outcrop areas of rocks of Sonomia. Heavy dash line is approximate locus of suture between Sonomia nad North America. Dash-dot line is isotopic 0.706 line.

in Cretaceous and possibly Late Jurassic times (Gromme and others, 1967, 1982; Hannah and Verosub, 1980; Russell and others, 1982; Frei and others, 1982), thus permitting western Sonomia to have been autochthonous since at least those times. Moreover, the absence of recognized major sutures within the perimeter of Sonomia suggests that it may have been initially coherent.

Because of the closeness in minimum ages of rocks in the Golconda allochthon and Sonomia, their long reach of probable contact, and the occurrence of copious Early Triassic magmatic arc-derived debris in a foreland basin of the Golconda allochthon at Candelaria (Fig. 4), the emplacement of the two terranes was probably paired and constituted the Sonoma orogeny of Silberling and Roberts (1962).

The emplacements of both the Golconda and Roberts Mountains allochthons had similar manifestations: transport from an oceanic region as a predeformed tectonic mass, absence of related magmatism and metamorphism within the continent, and lack of pervasive crustal shortening or mountain-building within the continental crust. Deformation within the overridden continental shelf strata consists only of local shear strain and(or) thrust duplexing in a thin zone below the obducted allochthon (Gilluly and Gates, 1965; Kay and Crawford, 1964).

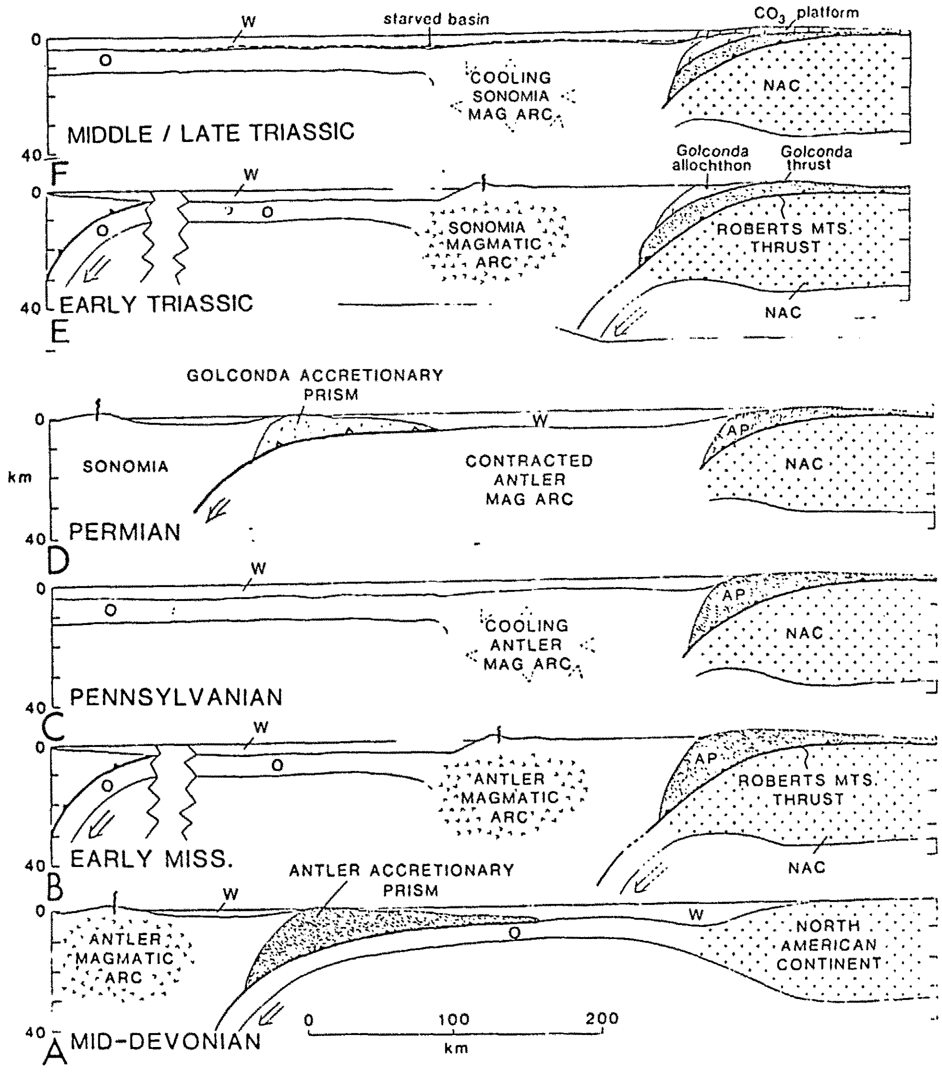

Figure 5. Model of Antler and Sonomia orogenies as collisions of arc systems with the passive margin of western North America, modified after Speed (1979) and Speed and Sleep (1982).

Such phenomena indicate that the margin of North America remained passive during the two obductions. Because Sonomia was active as a magmatic island arc until at least Late Permian time, the Golconda allochthon can be regarded as an accretionary prism in Sonomia's forearc that was driven across the slope and outer shelf of North America during its collision with the arc system (Speed, 1977, 1979). Figures 5d to 5f illustrate a model of such events. In Figure 5d, Sonomia is shown as an island arc system migrating with closing and lateral components along coastal North America (Speed, 1977, 1979). The arc surmounted a subduction zone in which the downgoing slab was oceanic lithosphere attached to the passive margin of North America. Closure ceased when continental lithosphere started down below Sonomia by which time the forearc, the Golconda allochthon, was almost fully emplaced on the outer continental shelf. If the oceanic slab attached to Paleozoic North America broke off and sank upon cessation of closure, a finite but probably minor width of sialic continental edge may have been taken into the mantle with it. Upon welding to North America, a new ocean-facing convergent zone probably developed somewhere west of Sonomia, and Sonomia underwent thermal contraction and subsidence due to loss of subduction-related heating. The origi of the deepwater Triassic successor basin that is approximately coextensive with Sonomia is thus explained.

Because of the tectonic similarity of the emplacements of the Roberts Mountains and Golcond allochthons, a similar collisional process is envisioned for the Roberts. The Roberts is also regarded as an accretionary prism (Dickinson, 1977; Speed and Sleep, 1982) that was underrun by the continental shelf before final collision between the continent and a migrating island arc system (Figs. 5a-5c). The Antler magmatic arc, however, is a postulate because it is nowhere exposed. The Antler arc is assumed to have thermally contracted, like Sonomia, because upon collision, the subduction zone jumped west and the arc lost its heat source (Speed and Sleep, 1982). The contracted Antler arc may have been completely subducted below Sonomia.

There is no evidence for the direction or magnitude of transport of Sonomia and Antleria and their respective forearcs relative to their position of attachment in Nevada. Magnetizations in Sonomian rocks measured at sites in California (Hannah and Verosub, 1980) and in Nevada (Russell and others, 1982) were reset during late Mesozoic magmatism such that original latitude anomalies are unknown. The turbidites within fault packets in the Golconda and Roberts Mountains allochthons are certainly or probably of North American provenance (Speed, 1977; Miller and others, 1983) but the dimensions of the region over which they were swept up before obduction onto the shelf is unknown. The lack of correlation of beds in many adjacent packets and the tectonic intercalation of packets of mainly pelagic and of mainly turbiditic facies suggest a large lateral distance along the passive margin.

A major effect of the Mississippian collision was the generation of an asymmetric foreland basin (Fig. 3) with amplitude $\leq$3.5 km that rimmed the continentward edge of the Roberts Mountains allochthon (Poole, 1974). The basin probably reflects elastic or elasticoviscous downflexing of strong continental lithosphere during vertical loading by the allochthon and broadening during progressive sedimentation which widened the region of loading (Speed and Sleep, 1982). Certain stratigraphic features below the foreland basin fill suggest that an upbulge migrated eastward ahead of the downwarp, as predicted by the theory of flexure.

In contrast to the extensive foreland basin developed during the Mississippian continental margin event, foreland basin deposits associated with the Triassic Golconda allochthon are recognized only adjacent to the southern third of that allochthon (Fig. 4). This may be because the northern Golconda allochthon was too small to cause significant flexure, because it remained submarine and provided no orogenic sediment to such a basin, or because it was later thrust over related foreland basin strata.

The principal effects of the accretion of Sonomia to the passive sialic margin were the addition of large girth to the morphologic continent and the generation of a deepwater basin west of the Sonomian suture and the edge of sialic North America. The Triassic basin was successor to and approximately coextensive with Sonomia and accumulated early pelagic and hemipelagic sediments followed by great thicknesses of Late Triassic terrigenous turbidite (Speed, 1978). The subsidence of the successor basin is hypothesized to have been due to thermal contraction of the lithosphere of Sonomia (Speed, 1977, 1979).

Extensive Cenozoic rocks north of the Pretertiary outcrops of northwestern Nevada and California presumably cover one or more sutures between late Mesozoic displaced terranes (unit 2 of Fig. 1) and Sonomia and North America. Such terranes are partly represented in the Blue Mountains of Oregon and are there attached to Precambrian late Mesozoic sialic North America. This suture was created by rafting away from southeastern Oregon and western Idaho a fragment of sialic North America, terranes that were earlier accreted to the passive margin, and perhaps, other terranes attached early in the Mesozoic during the active margin phase (Speed, 1983).

Active Margin Tectonics

An active margin developed on western North America (Hamilton, 1969; Burchfiel and Davis, 1972) in Middle or Late Triassic time. The subduction trace between an east-dipping oceanic slab and the morphologic continent then existed at or west of the Foothills suture (Saleeby and Sharp, 1980; Schweickert, 1981) in the Sierra Nevada (Fig. 1) such that at least part of Sonomia and perhaps other early accreted terranes were incorporated into Triassic North America.

During the passive-to-active margin transition in the Triassic, the outer 100-200 km of Precambrian sialic North America and obducted allochthons subsided as carbonate-deltaic shelf (Silberling and Wallace, 1969; Nichols and Silberling, 1977; Speed, 1978). The present distribution of such strata (Fig. 6) probably is a good approximation of the original shelf configuration except for their southern outcrops which may be oroclinal (Albers, 1967), although this is disputed by Oldow (1983). The successor basin also accumulated basinal sediment during the Triassic (Fig. 6), but the distribution of such sediment has been more perturbed by Mesozoic deformation than that of shelfal strata. A set of thrust sheets of Mesozoic volcanic rocks partly overlies the basinal strata south of Lovelock (Fig. 6). The third major Mesozoic rock facies is Triassic to Cretaceous volcanic and intrusive rocks that made up a long-standing continental magmatic arc (Fig. 6).

Sections below discuss several of the main effects of active margin tectonism on Nevada and Idaho: the Mesozoic continental arc, thin-skinned foreland contraction of Jurassic-Paleogene age, and tectonic erosion.

Mesozoic Continental Arc: A continental magmatic arc (Hamilton, 1969) emerged in eastern California and western Nevada (Figs. 6 and 7) late in Triassic time, probably between 215 and 235 myBP according to oldest dates of silicic volcanic and plutonic rocks obtained so far (Kistler, 1966; Brook, 1980; R. W. Kistler, 1982, oral commun.; Wright and others, 1983). The arc crossed the suture between earlier accreted terranes and sialic North America at about 38^{O}N (Speed, 1978). Manifestations of the arc are silicic and intermediate volcanogenic (breccia, lava, sediments) and plutonic (granodiorite, quartz diorite, quartz monzonite) rocks that range as young as about 80 my. The arc region is defined by the existence of Mesozoic volcanic rocks and by a high proportion of plutonic rocks (at least half) among Preterti-

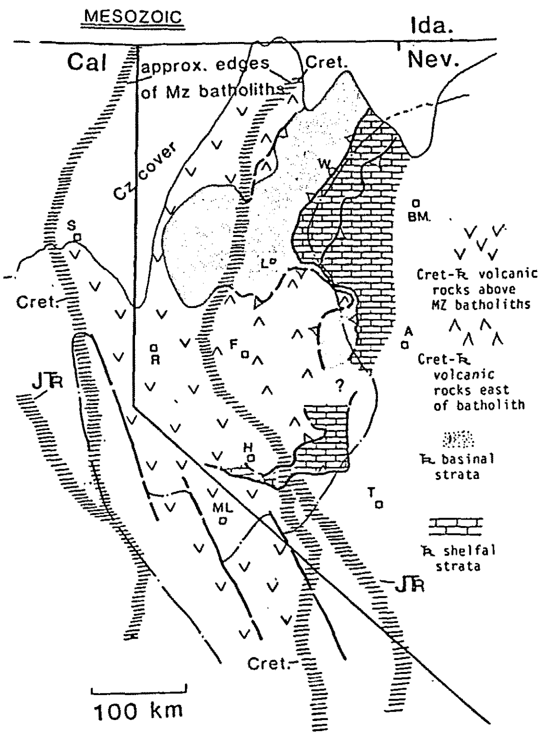

Figure 6. Map showing paleogeographic terranes of early Mesozoic marine and younger volcanic and intrusive rocks of the western Great Basin. Dash-dot line is isotopic 0.706 line.

ary exposures (Speed, 1983).

The locus of Mesozoic continental arc magmatism varied within eastern California and western Nevada (Fig. 6), although its track is imprecisely known because crystallization ages of both volcanic and plutonic rocks older than Late Cretaceous age are not sufficiently well known. However, the arc may have existed nearly in place between 38° and 39° with only minor east-west migration and with almost continuous magmatism (Evernden and Kistler, 1970; Stern and others, 1981; Chen and Moore, 1982). An exception is a possible magmatic lull in Early Cretaceous time. North of that latitude band, the existence of an autochthonous Cretaceous plutonic arc is well established, but the existence of Triassic and Jurassic precursors can be inferred only from scattered volcanic remnants (Speed, 1983; Russell, 1983). South of 38°N, the locus of Cretaceous magmatism seems to diverge from the belt of earlier Mesozoic plutonic and volcanic rocks (Fig. 6). Cretaceous and possibly latest Jurassic mag- ~~netization directions in the region of the con-~~ tinental arc show no significant anomalies with respect to North America (Gromme and others, 1967; Hannah and Verosub, 1980; Russell and others, 1982; Frei and others, 1982; Geissman and others, 1984).

The main effects of arc development on the continent were crustal thickening and intra-arc deformation. Where continental arc rocks invade the sialic continent (Fig. 6), crustal thickness is 5-15 km greater than that of normal craton, such as the presumably undeformed crust of the Colorado Plateau (Eaton, 1963; Johnson, 1968; Pakiser and Jones, 1975; Prohdehl, 1979; Smith, 1979). Moreover the crust below Sonomia thickens substantially below the Mesozoic continental arc (Eaton, 1963; Prohdehl, 1979; Stauber, 1980). Chemical and isotopic studies imply that major magma additions to the crust were mantle-derived but reflective of the different lithospheres in which they were generated and/or contaminated (Hamilton, 1969; Kistler and Peterman, 1973, 1978 Miller and Bradfish, 1980).

Deformation related to the continental arc consists of protracted shortening normal to the arc, arc-parallel shear, and at least local arc-vergent thrusting at its backside. Progressive ENE-coaxial shortening of Jurassic and mid-Cretaceous age in arc-related strata, maximum at about 80% in older rocks, was demonstrated by Tobisch and others (1982). Their arc-parallel flattening plane parallels the most pervasive Mesozoic axial planar fabric orientations of the arc region between 37° and 40°N (Kistler and Bateman, 1966; Schweickert, 1981; Saleeby and Sharp, 1980; Speed, 1978; Nokelberg and Kistler, 1982). Shear on mainly discrete NNW-striking planes led to Mesozoic right-lateral displacements of decreasing magnitude east toward the arc-foreland boundary (Speed, 1978, 1983; Kistler and others, 1971, 1980). Such motions may be the primary cause of the clockwise Mina deflection of Pretertiary features in western Nevada (Albers, 1967; Stewart and others, 1968) and of the northerly salient of sialic continental crust within the central Sierra Nevada (Kistler and Peterman, 1978 R. W. Kistler, 1982, written commun.). The partitioning of shear and normal displacements among discrete structures evidently occurred in this ancient arc as in some modern arcs during convergence with moderate obliquity (Fitch, 1972; Walcott, 1978; Beck, 1983). Arcward thrusting of Cretaceous age at the backside of the continental arc has been recognized in northwestern Nevada (Russell, 1983) and could be widespread to the south.

Magmatism and metamorphism at deep crustal levels also occurred during Mesozoic time within the continental foreland from the arc nearby as far east as the Paleozoic craton-shelf hingeline. The timing of such phenomena is not precisely known but seems to have spanned 70 to 165 myBP with possible peaks of plutonism at 155-165 and 70-80 myBP (Armstrong and Suppe, 1973; Allmendinger and Jordan, 1981; Lee and others, 1983). Thermal phenomena of the foreland differ from those of the arc by 1) the restriction to relatively deep levels and absence of evident volcanism (except for one site, the Late Jurassic Pony Trail Group, Muffler, 1964), 2) the smallness and discreteness of individual plutons, and 3) the compositions of foreland plutons indicating cru-

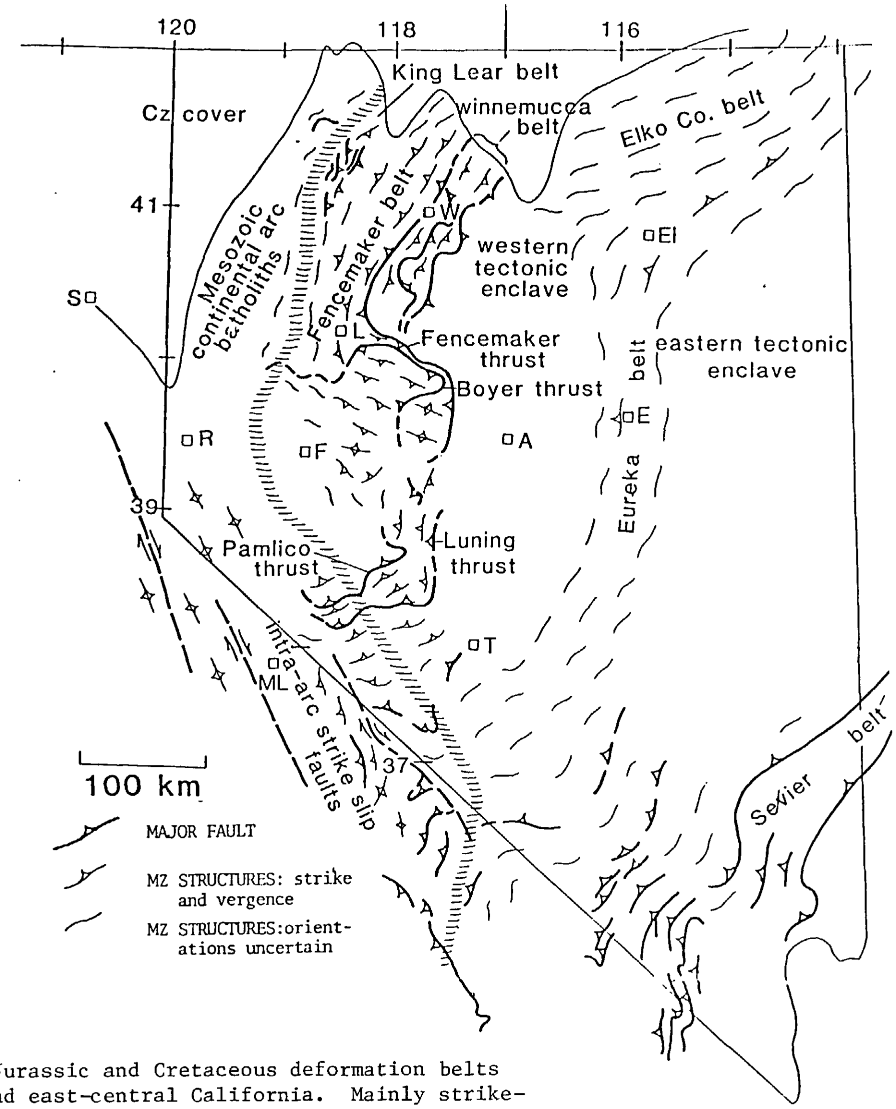

Figure 7. Jurassic and Cretaceous deformation belts in Nevada and east-central California. Mainly strike-slip faults and(or) shear zones within continental arc and thin-skinned thrust and fold belts in foreland to east.

stal or sedimentary precursors (mainly S-type vs. I-type of arc). Mesozoic metamorphism and deformation of Precambrian and lower Paleozoic strata occurred deep within the continental shelf succession but such effects are apparently absent in the upper few kilometers of Paleozoic strata (Howard, 1971, 1979; Snoke, 1979). Such relationships are recognized in Cenozoic uplifts (core complexes). Mesozoic magma generation and metamorphism in the foreland are likely to have been related processes. Metamorphic minerals indicate depths as great as about 15 km, far deeper than the undisturbed, expected stratigraphic depth of the metamorphosed strata. Thus, either metamorphism occurred in strata of anomalous depositional thickness or where strata were thickened tectonically. In the latter case, thickening may reflect contraction at deep levels of foreland during the Mesozoic (Armstrong, 1972).

It is a fundamental question whether the elevation of the geotherms at depth in the Mesozoic foreland was directly related to subduction or whether it was a product of motions within the continental lithosphere and(or) subjacent asthenosphere. An appeal to foreland heating by the same slab that caused magmatism in the continental arc would require the unlikely condition that melting occurred across a zone about 600 km wide. Present dating indicates that foreland plutons are not contemporaneous with the possible Early Cretaceous lull in continental arc magmatism, a time when a shallowly-dipping slab could have existed. Thus, Armstrong's (1972) hypothesis of heating due to crustal thickening seems to account best for the broad reach of foreland thermal phenomena and their restriction to deeper crustal levels in the Mesozoic.

Thin-Skinned Foreland Deformation: The region between the continental arc and the Paleozoic platform-shelf hinge in the western Colorado Plateau was the foreland of North America (Fig. 7) that underwent mainly contractile deformation from Jurassic to Paleocene times. Post-Early Triassic Mesozoic structures within this region are almost entirely within Mesozoic and Paleozoic cover rocks. The structures record nonthermal, thin-skinned tectonics with little evident involvement of the crystalline basement (Armstrong, 1968; Burchfiel and others, 1980; Royce and others, 1975; Speed, 1978, 1983; Dunne and others, 1978; Oldow, 1981, 1982; Allmendinger and Jordan, 1981). Thin-skinned contractile displacements are heterogeneous and are concentrated in several belts (Fig. 7), some of which splay about two regional enclaves in which there was apparently little Mesozoic shortening of cover rocks (Armstrong, 1972; Speed, 1983). The enclaves do contain low angle faults with younger-on-older juxtaposition which may indicate extensional deformation. It is not generally clear, however, whether such faults are Mesozoic or Cenozoic.

The foreland thrust and fold belts (Fig. 7) are mainly north-striking and underwent east-west contraction between 39° and 41°N. The deflection of the Luning belt (Fig. 7) (Oldow, 1981, 1982) is probably related to motions in the intra-arc shear zone (Speed, 1978). The origin of the northeasterly trend of the thrust belt of northeastern Nevada is unclear. Vergence varies among the thrust and fold belts, indicating both easterly and westerly overriding between 39° and 41°N. Local vergence can be related to facing of ramps at deep structural levels (Speed, 1983).

Figure 8 illustrates possible structural relationships among three thrust belts in northwestern Nevada. The Jackson Mountains at the northwestern end are underlain by Mesozoic volcanic and plutonic rocks of the continental arc, including the Lower Cretaceous intra-arc basin deposits of the King Lear Formation (Willden, 1958; Russell, 1983). West-vergent thrust slices of Triassic arc and basinal facies (Russell, 1983) are piled against the arc edifice. The Triassic successor basin fill between the Jackson Mountains and Sonoma Range is greatly thickened by deformation and has ridden ESE at its eastern margin over the Triassic basin-shelf margin in the Fencemaker belt. Below the east-verging Fencemaker allochthon lies a series of west-verging thrust slices of the Jurassic Winnemucca thrust belt (Speed, 1983). The Winnemucca belt cuts mainly Triassic shelfal strata, subjacent Golconda and Roberts allochthons, and beds of the Paleozoic continental shelf. East of the Winnemucca belt is the western tectonic enclave (Fig. 7) with nearly undisturbed Triassic beds. The vergence of the belts is thought to be due to the facing of proximal basement ramps, except in the case of the Fencemaker belt for which the earlier Winnemucca belt provided a west-facing ramp.

The timing of displacements in the Sevier belt (Fig. 8), dated by a nearly continuous series of foreland basin deposits, is Late Jurassic to Paleocene (Royce and others, 1975; Jordan, 1981) at least near the Utah-Wyoming border. Motions i the western belts are more difficult to date but indicate as a whole that deformational events occurred from Early Jurassic to Late Cretaceous times (Speed, 1978, 1984; Speed and Kistler, 1980 Oldow, 1981). The data are suggestive of either continuous or periodically reactivated movements at each site, but not a systematically east-migrating wave of deformation. Shortening is estimated at 50% in the Sevier belt at the easter margin of the foreland (Armstrong, 1968; Royce an others, 1975) and greater than 50% in the Fencemaker belt (Wiens and others, 1982). Assuming similar values for each belt, the foreland contracted EW at least 300 km or 33% relative to ini tial width.

The question arises whether the displacement within the cover were continuous vertically down into the foreland basement, or on the other hand, were taken up at a detachment within the cover or at greater depth. The first case predicts hetero geneous crustal thickening with maxima below the thrust belts and is supported by the approximate coincidence of the western edge of Paleozoic shel strata and sialic basement. The second alternative implies the existence of a detachment fault that spanned the entire foreland (Speed, 1983) to a presumed point of arrested propagation on the continentward side. Assuming rigid media, the total displacement by thrusting within the foreland cover would equal the offset across the detachment at its western limit. In this case, there would be little or no expression of forelan deformation in basement thicknesses, nor in isostatic responses; the absence of both phenomen are suggested by the lack of related effects in gravity, mountain building, and orogenic sedimentation.

Tectonic Erosion of the Sialic Edge During Oblique Convergence: Local truncation of the oute sialic continent and rafting away of continental fragments occurred at various times and places during and possibly associated with the onset of active margin tectonism.

A probably large raft of sialic North Americ and early accreted terranes (Sonomia and possibly others) is thought to have been extracted from tł region of southeastern Oregon, southwestern Idahc and possibly northern Nevada and California (Hamilton, 1976; Speed, 1983). Evidence is that 1) the probably preserved late Precambrian sialic edge, pre-Jurassic accreted terranes, and parautc chthonous Mesozoic stratal units of central and western Nevada, all mainly north-striking, are apparently missing from the region to the north, 2) the sialic edge in Idaho intersects the Paleozoic craton-shelf hinge, an unlikely primary arrangement, and 3) displaced terranes with larg late-Mesozoic rotations (Hillhouse and others, 1982), which are absent from rocks of Nevada, sutured in the Cretaceous against the sialic edg in Idaho. The withdrawal of a continental raft : Oregon and Idaho may have resulted from the propa gation of a rift-transform system inboard of the

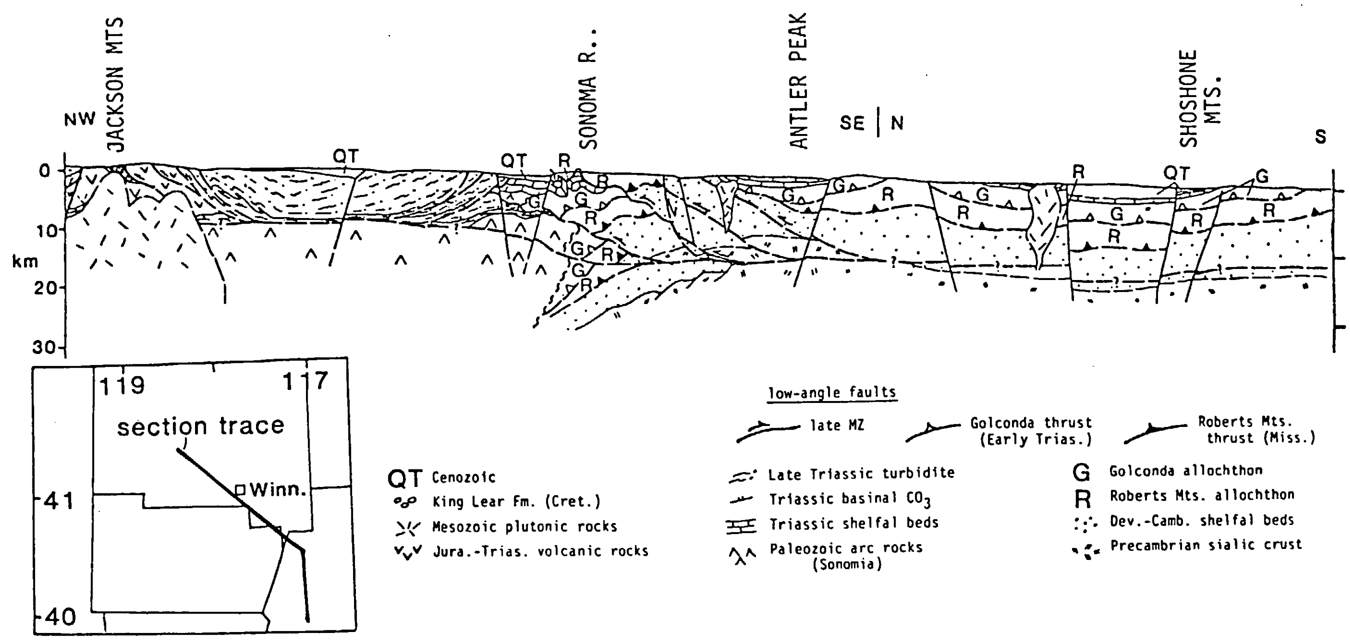

Figure 8. Cross section illustrating Mesozoic thrust fold belts and tectonostratigraphy of northwestern Nevada.

sialic margin during highly oblique convergence in mid-Mesozoic time. The formation of the modern Gulf of California and north-westward rafting of continental Baja California may be an analog. The fragment removed from Oregon and Idaho was presumably replaced by oceanic lithosphere whose spreading centers migrated north with respect to a southern boundary.

Structural Inheritance

East of the Sierra Nevada, there is abundant evidence for the influence of older features on the form and position of younger structures, but reactivation of sutures as new major displacement zones or continental boundaries seems not to have occurred.

The ancient sialic edge of possible Precambrian age in Nevada (Fig. 2) has been maintained through Phanerozoic time as a distinct but covered boundary. It influenced later ocean-continent configurations by forming a buttress to which island arcs sutured in Mississippian and Early Triassic times. It approximately underlies a major Triassic transition between a carbonate shelf to the east and deepwater successor basin to the west. This transition is thought to reflect large differences in temperature gradients and degree of subsequent thermal contraction across the suture between the sialic continent and the arc terrane of Sonomia which became inactive upon collision. The ancient sialic edge also controls zones of surface breakthrough of displacements during Jurassic and Cretaceous foreland contraction. The imbrication may reflect a ramp on the basement surface across the sutured edge of the continent (Speed, 1983).

Other evident influences of older on younger structures occur in the foreland deformation belts (Figs. 7, 8). The Sevier belt is coincident over 1000 km with the hingeline between craton and subsiding shelf. The hingeline thus defines a west-facing ramp on the top of the crystalline basement and also in horizons in suprajacent layered rocks. Another ramp effect is the localization of the Eureka thrust belt (Fig. 7) at the eastern edge of the Roberts Mountains allochthon, a locus of maximum rate of change of downbuckling of horizons in the autochthon due to loading by the allochthon (Speed and Sleep, 1982).

The zonation of Neogene faulting in the Basin and Range province between a westernmost belt (Walker Lane) containing strike-slip together with dipslip faults and the classic mainly dipslip faults to the east may be influenced by older structure. The westernmost belt includes at least part of the region in which intra-arc strike-slip faulting occurred in Mesozoic time. The most conspicuous set of Neogene strike-slip faults parallels the Mesozoic faults and may represent reactivations of the older faults. It is not clear whether the NNW-trending right slip faults of the western Basin-Range take up some of Pacific-North American relative plate motion or whether they are simply faults of a conjugate set that take up pure shear with east-west extension. If the first hypothesis is correct, the very wide zone of Neogene plate boundary deformation may be attributable to inherited structures of appropriate orientation.

Finally, there is an evident spatial correspondence in the extent of deformation in western sialic North America during three discrete pulses that represent greatly different tectonic settings: 1) region of attenuated, presumably rifted sialic crust in late Precambrian passive margin formation, 2) region of thin-skinned contraction during late Mesozoic foreland deformations, and 3) region of late Cenozoic extensional basin-range faulting. The cause of repetitive deformation over such a broad zone is not clear but could be related to pre-late Precambrian lithospheric structure.

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