COLLIDED PALEOZOIC MICROPLATE IN THE WESTERN UNITED STATES[1]

R. C. SPEED
Department of Geological Sciences, Northwestern University, Evanston, Illinois 60201

ABSTRACT

A region of the Cordillera is underlain by a Paleozoic microplate, Sonomia, that accreted to the passive margin of sialic North America in Triassic time. Sonomia consists chiefly of sequential Paleozoic island arc terranes and is coupled in part to a deeper structure. Sonomia migrated in the Permian with left-oblique convergence above a consuming boundary toward the continent and propelled before it an accretionary wedge of ocean floor strata. Undersliding of the wedge by the continental slope and outer shelf created the Golconda allochthon, followed by an arrested subduction below Sonomia. Pre-collision motions on Sonomia's outboard margin may have been kinematically related to the truncation of the sialic continent south of the Sonomia suture. Sonomia may be related to other Paleozoic arc fragments that accreted at various times in the Pacific Northwest.

INTRODUCTION

Proposition: Parts of Nevada, California, and perhaps, Oregon, are underlain by a Paleozoic microplate, Sonomia (fig. 1), that migrated above a consuming boundary from a relatively distant site and collided with sialic North America early in the Triassic; post-collision fragmentation and dispersal may have left a small but unknown fraction of accreted Sonomia in place.

If correct, Sonomia is among the oldest of the plethora of terranes accreted in the Mesozoic to western North America (Jones et al. 1977, 1978; Muller 1977; Monger 1977; Churkin and Eberlein 1977; Davis et al. 1978). Its encroachment was apparently the last convergent event in the southern cordillera in which the subduction zone dipped away from a passive continental margin. Accretion of Sonomia added significant local girth to part of early Mesozoic North America and caused the major westward shift in the continental margin recognized by Burchfiel and Davis (1972). Part of the precollision outboard boundary of Sonomia may have been inherited as a later Triassic margin of modified North America. The collision of Sonomia provides a reasonable physical explanation for tectonic features of the so-called Sonoma orogeny in Nevada. The idea that a magmatic arc played a role in the Sonoma orogeny has long been popular (Moores 1970; Silberling 1973; Burchfiel and Davis 1972; Speed 1971, 1977; Churkin 1974; Dickinson 1977; and Stevens 1977). Most of these treatments are somewhat hypothetical, due largely to inadequate data on the geology of western Nevada. Recent work, however, implies that late Paleozoic arc rocks widely underlie the Mesozoic-Cenozoic cover of the western Great Basin and that such arc rocks have probable correlatives in the northern Sierra Nevada (Speed 1977, 1978*a* and references therein; Speed and Kistler 1977). Interpretations of these and other new data lead to proposals on the existence, constitution, and kinematic history of Sonomia, given below.

PALEOZOIC CONTINENTAL MARGIN AND OROGENY IN NEVADA

The eastern and southern boundaries of Sonomia in Nevada (fig. 1) circumscribe the continentward limit of outcrops of Paleozoic (and possibly Early and Middle Triassic) rocks of magmatic arc derivation. The boundary is thought to be a suture with the edge of sialic North America which existed in Paleozoic Nevada as a passive margin created by rifting in the Precambrian (Stewart 1972) or possibly later (Kistler 1978). Many authors have estimated the Paleozoic continental margin to exist in western or central Nevada, near or west of the westernmost outcrops of continental shelf

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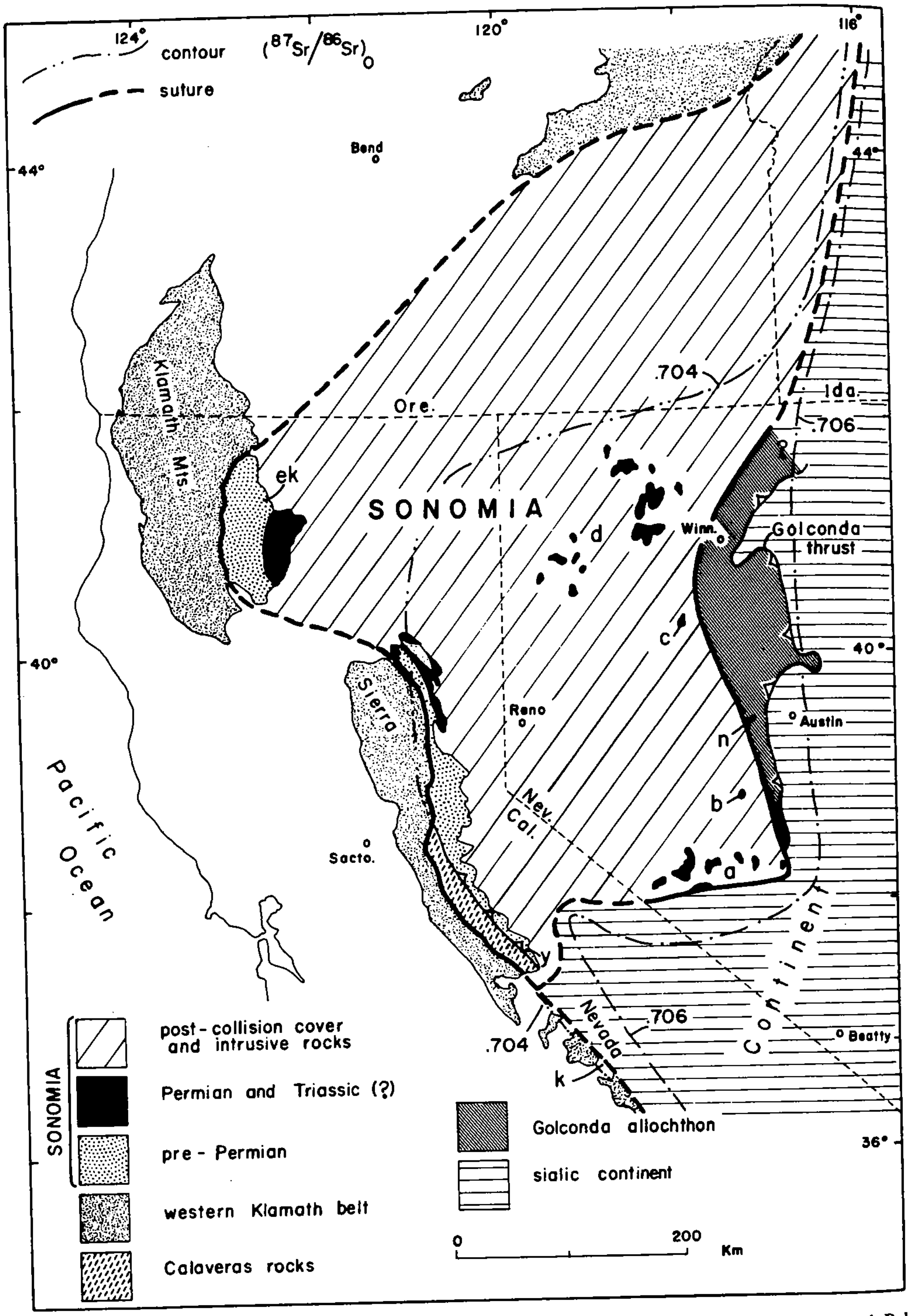

FIG. 1.—Outcrop regions of Sonomia and related terranes and of rocks included in Western Klamath Belt; post-collision rocks in younger accreted terranes are unpatterned; letters denote localities referred to in text, dashed sutures imply uncertain or inferred locations.

facies. Two newer measures help to locate the margin and support the interpretation that it represents the edge of the sialic crust. 1) Models fitting gravity and local seismic network data that span the east-trending leg of the margin near loc. a (fig. 1) indicate a rapid southward thickening of crustal layers starting about 25 km north of a (Cogbill 1979). Geophysical data permit but are inadequate to resolve a similarly abrupt eastward crustal thickening below the northerly-trending margin in Nevada. 2) Initial strontium isotopic compositions seem to relate systematically to tectonostratigraphic terranes below which the magmas were generated; in particular, $(^{87}Sr/^{86}Sr)_0 \gtrsim 0.706$ exists in igneous rocks that emerged through terranes known or suspected to be underlain by Precambrian crystalline rocks (Kistler and Peterman 1973; Armstrong et al. 1977). Figure 1 shows the evident correlation between the 0.706 contour and the proposed sutured Paleozoic margin, albeit both lines are imprecise.

In eastern California, the Paleozoic continental margin (dashed line, fig. 1) is delineated by the northernmost outcrops of Paleozoic strata of probable continental affinities (Speed and Kistler 1977) and the nearly coincident 0.706 Sr contour. In the western Sierra Nevada, the boundary is taken to follow the 0.706 contour to a point near Yosemite (y, fig. 1) where it intersects a NW-trending younger contact, discussed below. South of the dashed line in the western Sierra layered rocks dated paleontologically are all Mesozoic (Saleeby et al. 1978). Certain undated rocks there, however, are believed to be Paleozoic on structural grounds (Kistler and Bateman 1966), and if true, their quartzite-carbonate lithology supports the existence of a continental terrane in the Paleozoic of the southern Sierra.

The subsurface westward edge of the sialic continent can be tracked from Nevada into Idaho by the 0.706 contour. Just north of the area of figure 1, exposures confirm the juxtaposition of the Precambrian and the noncontinental terranes that were accreted in Late Triassic or later times (Hamilton 1976; Brooks and Vallier 1978). Thus, it is not clear whether the edge of the sialic crust in southern Idaho represents a Paleozoic passive margin sutured to Sonomia or a younger truncation surface.

Within Nevada, the outer Paleozoic continental shelf is widely overlain by two partly superposed tracts of displaced Paleozoic ocean floor rocks. The lower is the Devonian-Mississippian Roberts Mountains allochthon (not shown on fig. 1), and the upper, the Golconda allochthon, whose emplacement was early in the Triassic (fig. 1). The Golconda overlies the subjacent allochthon and late Paleozoic shelf strata with present overlap of 60–80 km. It is an assembly of thrust nappes of turbidite of continental provenance, mafic volcanic rocks, and hemipelagic and pelagic deposits, whose benthonic fauna is of both North American and Klamath types (Stewart et al. 1977; Speed 1977; D. L. Jones and J. H. Stewart, oral commun. 1978). Fossils from such rocks are largely Pennsylvanian and Permian, but ongoing studies indicate that Mississippian-Devonian rocks may also be included in the Golconda allochthon (D. L. Jones, oral commun. 1978). Igneous arc-derived debris, depositional melange, and blueschist are not recognized in the Golconda allochthon. Structural geometries are relatively uniform in some nappes, variable in others; the following types are most common: 1) homoclines of upright or inverted beds; 2) sequences of tightly folded beds and coaxially folded tectonic S-surfaces about constant sub-horizontal axes; 3) generally homoclinal S-surfaces containing girdled fold axes, at places with downdip maxima. The girdled axes were probably products of rotation of originally horizontal axes or contemporaneous folding by stretching during thrusting (Sanderson 1973; Escher and Watterson 1974).

The transport direction of the Golconda allochthon is best understood in the New Pass Range (loc. n, fig. 1, MacMillan 1972), where the geometric effects of younger deformations are clear. Folding of lower plate strata occurs only for about 50 m below the Golconda thrust, and within that interval, fold elements indicate ESE transport. A similar direction is indicated by structures within the allochthon, both by zones of colinear axes that trend NNE and by WNW-dipping girdles.

The folding and thrusting of strata of the Golconda allochthon are the basis for the classic Sonoma orogeny (Silberling and Roberts 1962). Orogeny is probably too dramatic a word for the Sonoma event because there was no evident mountain building, metamorphism, magmatism, or significant deformation of sub-allochthonous rocks. Indeed, it has long been a mechanical puzzle how rocks of the Golconda allochthon got from their oceanic site of deposition up and across the edge of the continental shelf. The model given later for the Golconda allochthon explains it as an outer arc (or accretionary wedge) which was underthrust by the continental slope during Triassic subduction.

The existence of the Golconda allochthon in northernmost Nevada and Idaho is uncertain. Correlations between strata of the allochthon and basinal late Paleozoic rocks of Idaho (Roberts and Thomasson 1964) have been challenged by Stevens (1977).

The shape of the Paleozoic margin of the sialic continent was modified significantly by younger tectonic events. One event was the removal of a continental fragment of unknown size from what is now the foothills of the southern Sierra Nevada (along or near line k, fig. 1), as first documented by Hamilton and Myers, 1966 (see also Burchfiel and Davis 1972; Schweikert 1976; Saleeby et al. 1978; Speed 1978*a*; and later discussion). The truncation probably occurred in the Triassic but conceivably somewhat earlier. The second event was the onset of right-oblique convergence which created bends and northward drag of the Sonomia-continent suture near the post-collision boundary and shortening in an ENE direction; in the Sierra Nevada, the right-oblique motion may have started by the beginning of the Jurassic (Saleeby et al. 1978) whereas structures due to such motion in Nevada are not apparently older than mid-Jurassic (Speed 1978*a*).

SONOMIA

Identification and delineation of Sonomia derive from 1) the widespread, perhaps laterally, continuous Permian and Permian(?) ? magmatic-arc rocks that constitute its upper layers, 2) its inboard join with the sialic continent, and 3) its outboard boundary with a younger complex of disrupted oceanic rocks and volcanic arc rocks (Davis et al. 1978; Jones et al. 1978; Saleeby et al. 1978) shown on figure 1 as the western Klamath belt, following and extending Irwin's (1977) usage. The age of the outboard boundary is known to be mid-Jurassic in the Klamath Mountains and as least as young as Late Triassic elsewhere (Irwin et al. 1978). In Nevada, each of the outcrop regions of Sonomia (fig. 1) is a window through the Mesozoic and Cenozoic cover that exposes volcanic rocks of either known Permian age or, where not directly dated, of pre-late Middle Triassic age. Such rocks, dominantly basaltic andesite and subordinate basalt and siliceous rocks, occur mostly as breccia but also as lava and intrusive masses. Initial Sr compositions in andestes are known (0.704–0.7055) in two of the four outcrop regions (R. W. Kistler and R. C. Speed, work in progress), but other ongoing chemical studies on the volcanic rocks are too preliminary for interpretation of spatial variability. Associated sedimentary rocks are largely volcanogenic conglomerate and turbidite, together with carbonate rocks, pelite, and chert which collectively represent varied marine platform and basinal environments of accumulation. Sediment of conceivable continental origin is absent from Sonomia of Nevada, except for minor quartz sandstone at loc. a (fig. 1) whose sediment may well have been derived from within Sonomia.

Dating of Sonomia in Nevada is as follows: loc. a of figure 1 (vicinity of Mina, Nev.), volcanic breccia and derivative turbidites have Permian hornblende ages, and intercalated strata have Late Permian radiolaria (D. L. Jones, oral commun. 1978) and mid-Permian fusilinids; loc. b, (Union district, Shoshone Mountains), the volcanic sequence contains fossils known elsewhere in late Paleozoic through early Middle Triassic beds and lies below late Middle Triassic strata (Silberling 1973); loc. c, (Humboldt Range), undated mafic rocks (Limerick Greenstone) lie unconformably below late Early Triassic Koipato rhyolite; loc. d (Black Rock Desert), Permian megafossils occur at two sites in volcanic-sedimentary sequences, and at another (Quinn River Crossing), Permian carbonate rocks lie above andesite, although the contact may be tectonic (Willden 1964). Recent work (B. J. Russell and R. C. Speed, unpubl.), however, implies that the basis for an earlier age designation of Permian or older for the main volcanic mass (Happy Creek) at loc. d (Willden 1964) is probably invalid, and such rocks are not directly dated. Nonetheless, it seems evident that andesitic volcanism at locality d occurred in the Permian and perhaps early in the Triassic, but not in significant volume during or after late Middle Triassic, the oldest known age of widespread Mesozoic cover rocks in that area.

Interpretation that Sonomia pervades the subsurface of northwestern Nevada derives from: 1) the absence of any other pre-Mesozoic basement rocks in windows of that area; 2) the remarkably similar distributions of the region of outcrops of Sonomia and that of thick succeeding Mesozoic marine deposits (Speed 1978*a*, fig. 1) which suggests that Triassic-Jurassic subsidence was related to the behavior of a laterally coextensive sublayer (I have interpreted the subsidence as due to post-collision thermal contraction of arc lithosphere) and 3) initial Sr of younger igneous rocks that invade Sonomia is similar to that of Sonomian volcanic rocks in Nevada. To expand the latter point, two general hypotheses exist for the evolution of Sr isotopes in igneous rocks. One holds that the source region of melts, perhaps the base of the lithosphere, is coupled to the external shell and that the Sr isotopes of a melt reflect the age and chemistry of the source (Kistler and Peterman 1973). The second assumes that melts come from a ubiquitous ^{87}Sr-poor source and that they are variously enriched in ^{87}Sr relative to ^{86}Sr by contamination during upward passage (Armstrong et al. 1977). Although the two schemes are not equally likely, both lead to the same result here: continental lithosphere produces relatively radiogenic Sr ($\gtrsim 0.706$) whereas oceanic lithosphere (and/or crust) produces relatively primitive Sr ($\gtrsim 0.704$). The Sr of island arcs falls generally between these limits and depends on age of the arc, either by aging of a coupled lithosphere or by time-dependent thickening of an arc crust. The Sr of both Permian and younger igneous rocks in the Nevada region of Sonomia are appropriate for melts generated in or passed through an island arc lithosphere or thick crust of Paleozoic age (Speed 1977).

Like that of Nevada, the Permian (and possibly Late Pennsylvanian and Triassic) volcanic sequence of the northern Sierra Nevada (fig. 1) consists of andesite, basalt, siliceous lava, and sedimentary rocks that record varied depositional environments (McMath 1966; D'Allura et al. 1977). Moreover, initial Sr of northern Sierra and northwestern Nevada plutons are similar. Unlike Nevada, however, the Sierra exposes units that underlie the Permian volcanic rocks, thus providing a possible pre-Permian history of Sonomia and a glimpse at what may underlie northwestern Nevada. Depositionally below the Permian rocks is an arc-related Late Devonian-Mississippian sequence, and below that, the varied Shoofly terrane of probable early Paleozoic age (D'Allura et al. 1977). The Shoofly contains deep marine siliciclastic beds: pelite, minor chert, and quartzose turbidites of continental provenance. The Shoofly thus provided Sonomia with an internal source of quartzose sediment, although such debris occurs meagerly in younger strata. The western border of Sonomia in the northernmost Sierra is a fault of Late Triassic or Jurassic age which juxtaposes it with peridotite and other rocks of the western Klamath belt. Farther south, a fault-bounded terrane of Permian-Carboniferous(?) oceanic rocks which composes the Calaveras Formation east of the Melones fault (fig. 1) intervenes between the Shoofly and the western Klamath belt (L. Clark, written commun., 1971; Moores 1979).

The Paleozoic sequence of the eastern Klamath Mountains (ek, fig. 1), included here in Sonomia, has long been thought to be correlative with that of the northern Sierra Nevada (Davis 1969). Indeed, the existence of andesite and more siliceous volcanic rocks of Permian and Permian(?) age in the Klamath region implies arc-related volcanism contemporaneous with that elsewhere in Sonomia. Contrasts exist, however, between Sonomia of the Klamath and Sierra regions: first, in the histories of pre-Permian volcanism and second, discussed later, in post-collision structure and in the Sr isotopic composition of Mesozoic granitic rocks (fig. 1). Early Paleozoic rocks of Klamath Sonomia are partly arc or arc-derived and were apparently deposited on ophiolite, some of which at least is Ordovician (Potter et al. 1977; Irwin 1977). The early Paleozoic Shoofly of the Sierra is not generally volcanogenic, and whereas arc volcanism did not start in the Sierra until the Late Devonian, it seems to have peaked by mid-Devonian in the Klamaths (Potter et al. 1977). Finally, arc volcanism occurred throughout the late Paleozoic in the Klamaths (Watkins 1973) but seems to have been largely absent in the Pennsylvanian of the Sierra.

The question arises whether the different volcanic histories of Sonomia in the Klamath and Sierra regions resulted from varying tectonic settings within a contiguous terrane or whether they indicate that Sonomia was assembled from two or more terranes late in the Paleozoic. A clear-cut answer is surely left to future studies. Apparently similar Paleozoic faunal affinities (A. J. Boucot, referenced by Hamilton, 1978) and the content of sediment of continental provenance in early Paleozoic rocks of both the Klamaths and the Sierra, however, provisionally suggest older coherence of Sonomia.

The northern boundary of Sonomia is unexposed and its location uncertain. It may exist in the subsurface of the Mesozoic window of central Oregon (dashed line, fig. 1), sutured with an outboard terrane of disrupted oceanic rocks that is probably correlative with the western Klamath belt (Davis et al. 1978; Jones et al. 1978). Alternatively, it may lie below continuous Cenozoic cover somewhere south of the locus in Oregon shown in figure 1 and north of outcrops of Sonomia in Nevada and California. Arguments in favor of the locus on figure 1 are: 1) the exposed southern margin of the belt of disrupted oceanic rocks in the central Oregon window is a tectonic contact with Upper Triassic volcanic rocks that are thought to be autochthonous (Dickinson and Thayer 1978), and, like similar Triassic rocks in Nevada (region of locality a to Reno) and California, to lie above Sonomia; 2) broken Paleozoic formations that resemble parts of Sonomia of the Klamath region (Stevens 1977) crop out below the Upper Triassic volcanic rocks in one area of the central Oregon window (Dickinson and Thayer 1978). On the other hand, Brooks and Vallier (1978) have argued that all the pre-Tertiary rocks of the central Oregon window are allochthonous. If they are correct, Sonomia cannot exist in the subsurface of the window, and its northern boundary must lie farther south.

Current appreciation of Sonomia indicates that its maximum conceivable modern extent is that shown in figure 1. It contains rocks as old as Ordovician and as young as Permian, possibly Triassic. Assuming the Klamath terrane has always been part of Sonomia, arc volcanism occurred in each of the systems it contains. The history of Sonomia was probably complex as judged by the existence of rocks and structures due to early Paleozoic tectonism in both the Sierra and the Klamath regions (D'Allura et al. 1977; Potter et al. 1977) and by differences between rocks of those regions. It is possible to suggest, however, that early Paleozoic rocks of the two provinces formed a magmatic (Klamath)-outer (Sierra) arc couple. Sr isotopic data imply that Sonomia of Nevada and the Sierra is underlain by a long coupled deeper structure (lithosphere or crust) of island arc type that either gave birth to or profoundly influenced the Sr composition of pre- and post-collision igneous rocks of that region. The existence of a distinctive deeper structure below a major part of Sonomia seemingly qualifies Sonomia as a microplate. The large area of apparently concomitant volcanic activity in Permian Sonomia suggests that Sonomia was then more complex than a simple linear magmatic arc. In fact, Sonomia was conceivably undergoing subduction on two sides in the Permian.

COLLISION OF SONOMIA

Sonomia migrated over oceanic terrane toward the passive continental margin in late Paleozoic time and ultimately collided with and stuck to the margin. Such events are indicated by 1) broadly noncontinental lithic character of Permian Sonomia, 2) the great length (> 500 km) of inferred direct contact between Sonomia and continent, 3) the fact that the contact is tectonic and syncollisional at its only exposed reach (loc. a, fig. 1; Speed 1977), and 4) the approximate contemporaneity and geographic correspondence of the Golconda allochthon and the Sonomia-continent contact. From the last relationship, it seems evident that Sonomia traveled across the ocean basin in which the late Paleozoic Golconda sediments were deposited

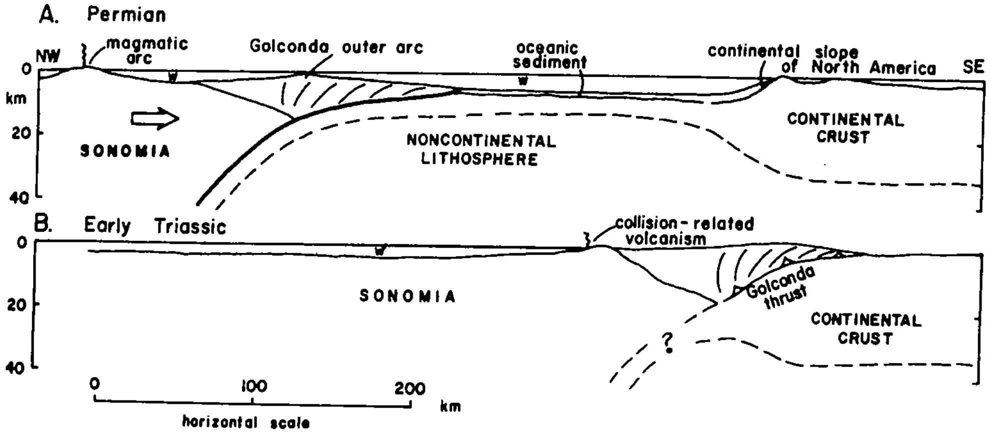

FIG. 2.—Sections depicting collision of Sonomia at about 40°N; w = water

and caused part of them at least to be removed from the seafloor and displaced across the flank of the continent. The only model of convergence between Sonomia and Permo-Triassic North America that satisfies these constraints and the earlier recounted characteristics of the Sonoma "orogeny" is shown in figure 2. Permian Sonomia (fig. 2A) migrated with a continentward component above subducting ocean floor. Rocks of the Golconda allochthon were mechanically accumulated in thrust packets on an outer arc (or accretionary wedge) that was propelled by migrating Sonoma. Ultimately, the continental slope and outer shelf underrode the outer arc and attempted a soon-to-be-arrested penetration below Sonomia (fig. 2B). When closure ceased, convergence jumped to a distant but unrecognized outboard locus, and with the loss of subduction-related heating, continentward Sonomia began to cool and contract. The proposed off-continent dipping subduction of figure 2 is reversed from that advocated by Burchfiel and Davis (1972), Silberling (1973), and Churkin (1974), all of whom assumed a marginal basin was somehow maintained between the Permian arc of the northern Sierra and the Golconda allochthon. Burchfiel and Davis (1972), however, did acknowledge but disfavored the possibility (p. 102) that Permo-Triassic subduction dipped away from the North American continent and that rocks included here in Sonomia (their Klamath-Sierra arc) were exotic to the Nevada-California region.

The Golconda thrust can be regarded as the detachment surface between the southeastward prograding accretionary wedge and the undersliding plate. Folds and thrusts within the allochthon formed mainly during growth of the outer arc, and most of the structures attributed to the Sonoma "orogeny" were transported from afar. Thus, the meager orogenic involvement of terranes below the Golconda allochthon is explained. Moreover, the ancient problem of how to thrust a thin succession of sea floor sediments for 50–100 km does not apply here—for at the time of final underthrusting the Golconda outer arc was probably a very thick mound of deformed rocks backed by Sonomia. In support of this origin, structures of the Golconda allochthon, mentioned earlier, are similar in many respects to those of the exposed part of the Barbados outer arc (Speed 1978*b*). The wedge of deformed sedimentary rocks of the Barbados arc is as thick as 20 km and overlies oceanic crust with aseismic décollement for some 200 km east of the subduction trace between the American plate and the Antillean magmatic arc (Westbrook 1975).

The timing of the collision is constrained as follows: 1) continental margin overrun by Sonomia at Candelaria (loc. a, fig. 1): early Early Triassic or later; 2) emplacement of Golconda allochthon: youngest rocks overrun, early Early

Triassic; oldest cover strata correlated across Golconda thrust, late Middle Triassic; 3) deposition of cover strata straddling the Sonomia-allochthon boundary: late Early Triassic. Assuming it was approximately synchronous all along the suture, the collision thus occurred in the time range, early Early Triassic—late Middle Triassic. If it was late Early Triassic or older, Mesozoic strata that cover Sonomia are entirely post-collision accumulations. If the collision was later, however, some or all of such strata would be fore-arc basin deposits that were transported in with Sonomia. In favor of the earlier age: the Koipato rhyolites, which locally base the cover strata, are early Early Triassic ash flow tuffs of markedly alkalic and siliceous composition that apparently represent late local magma generation in continentward Sonomia. The tuffs were deposited on block faulted terrain. Both magma generation and depositional sites of the rhyolite can be interpreted as caused by post-collision extension. Further, succeeding marine strata, which are essentially conformable with the rhyolite, contain little sediment indicative of a nearby active magmatic arc. In favor of the younger age: local andesitic magmatism of meager volume continued throughout the Middle Triassic along a probable shelf-basin transition (vicinity of loc. c, fig. 1; Nichols and Silberling 1977) within the cover strata, and certain undated andesitic turbidites at loc. d (fig. 1) could be of mid-Triassic age: both might suggest Sonomia was an active migrating arc as late as mid-Triassic. Moreover, Nichols and Silberling (1977) have identified an extensive erosional unconformity in late Middle Triassic cover strata which they interpret as a product of regional uplift. It is conceivable that the uplift reflects the underthrusting of the Golconda outer arc by the continental slope (fig. 2). To conclude, decisive evidence for an Early or (and?) Middle Triassic collision is yet to be acquired. I think a mid-Early Triassic collision is more probable and in accord with a thermally subsiding, post accretion basin in which the cover strata accumulated (Speed 1978*a*). There is a certain attraction, however, in a late mid-Triassic collision which might correlate with time of formation of ±220 m.y. blueschists (Hotz et al. 1977) that occur in tectonic blocks near Sonomia's probable outboard margin. The blueschists could conceivably have been created within or west of Triassic Sonomia at a new boundary which took up the convergence that had previously occurred between Sonomia and the continent before their collision.

It is of course unlikely that Sonomia hit the continent everywhere simultaneously. Sonomia itself provides no evidence of sequential ages of collision. However, the orientation of structures in the Golconda allochthon and subjacent rocks (loc. n, fig. 1) relative to the local trend of the suture suggests left-oblique convergence. This result supports Silberling's (1973) inference that the Golconda thrust was earlier in its northern reaches.

WESTERN BOUNDARY OF SONOMIA

Did the present western boundary delimit pre-collision Sonomia in California, or did Sonomia once extend far to the west? In the Sierra Nevada, the present boundary seems closely related to the western edge of Sonomia at least as far back as the Triassic, and the Sonomia-Calaveras fault might in fact be a segment of the pre-collision margin of Sonomia. In the Klamath Mountains, however, there is no evident relic of an original boundary.

A new magmatic arc was built on Sonomia and the sialic continent (Burchfiel and Davis 1972) after their mutual collision along a locus that is 100–200 km inboard from and generally parallel to their existing western boundary in the Sierra (fig. 3C). Dated volcanic rocks of this arc, including those of the Klamath Mountains, are mainly Late Triassic and no older than late Middle Triassic (Silberling and Tozer 1968, p. 43; Speed 1978*a*; compare Davis et al. 1978, p. 6). Thus, the new magmatic belt implies the onset of east-dipping subduction in later Triassic time along a zone that broadly corresponds to the present boundary in the Sierra, as recognized by Schweikert (1976). Further, the western boundary of Sonomia and the truncated continental edge in the southern Sierra were evidently a continuous convergent margin by then.

If the Calaveras unit (fig. 1) was attached tectonically to Sonomia before collision with the sialic continent, the Calaveras probably represents a wedge of oceanic sediments accreted to Sonomia's Permian western margin. If, on the other hand, the Calaveras-Sonomia fault is post-collision, an unknown expanse of Sonomia west of the current margin could have been removed during the Triassic. The fault is intruded by diorite that was dated by $^{238}U/^{206}Pb$ in zircon at 259 m.y. by Morgan and Stern (1977), implying the fault was the pre-collision margin of Sonomia (Speed 1978*a*). New zircon analyses from the same pluton, however, indicate Jurassic ages (Sharp and Saleeby 1979) which are concordant with K–Ar ages of hornblendes (Evernden and Kistler 1970). Thus, tectonic juxtaposition of the Calaveras unit to Sonomia is currently dated no closer than Permian-Jurassic. Nonetheless, early deformation features of the Calaveras (pre-granite foliations that strike generally parallel to the unit trend, dip easterly, and contain steep stretching lineations; Schweikert 1976; W. Nokleberg and R. W. Kistler, written commun., 1978; Sharp and Saleeby 1979) permit the interpretation that the Calaveras accreted against and below the western edge of Permian Sonomia. If such timing is correct, it would appear that continental truncation was kinematically related to plate motions at the western margin of Sonomia at the time of collision.

The configuration of the western boundary underwent local changes in Jurassic and later times. In the Klamath Mountains, Sonomia (and underlying Paleozoic metamorphic rocks) is a shallowly east-dipping, nearly homoclinal sheet (Davis 1969) of at least 100 km width above the Jurassic underplate of the western Klamath belt (Irwin 1977, fig. 5; Irwin et al. 1978; Davis et al. 1978, fig. 6). In the Sierra, the same sequence is vertical and was evidently folded and shortened toward the ENE in the later Jurassic (McMath 1966; Moores 1976) and perhaps later times. Thus, Klamath Sonomia seems to have been detached from its lithosphere (assuming it had one like Nevada-Sierra Sonomia) and behaved as a decoupled passive or even west-moving nappe relative to underthrust terranes. In contrast, Sonomia in the Sierra and Nevada evidently maintained its vertical and lateral integrity and deformed in response to compression; as a result, the western boundary of Sonomia and the continent in the Sierra probably migrated ENE from its original position and from that in Klamath Sonomia.

Davis et al. (1978) argued that Late Jurassic and Early Cretaceous plutons, which intrude Sonomia and the western Klamath belt in the Klamath Mountains, were products of in-place arc magmatism. If true, such melts were derived from oceanic or juvenile arc-type lithosphere that then lay below the detached Klamath Sonomia. Thus, the primitive Sr in plutons of the Klamath Mountains is explained. Both structural and isotopic contrasts between Sonomias of the Klamath and Sierran provinces imply that Klamath Sonomia had become a nappe by Late Jurassic time. This casts doubt on Hamilton's (1969) idea that the Klamath salient was created by Cenozoic basin-range extension.

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If Sonomia extends to central Oregon and if Upper Triassic volcanic rocks there are not exotic, it would seem that the Late Triassic magmatic arc of Nevada and California (fig. 3C) extends into Oregon. There, however, the Triassic volcanic belt trends east, and together with outboard accreted terranes, it is juxtaposed discordantly with the Precambrian continent (Hamilton 1978). One might conceive that the central Oregon belts rotated clockwise from an original northerly trend on line with the Klamaths to close an embayment from which fragments of Sonomia and perhaps, sialic continent and other terranes, had been rafted away to the north.

PLATE MODEL

Figure 3 depicts a simplistic model of the collision of Sonomia and some succeeding events, modified from Speed (1978*a*) and assuming coincidence of present and pre-collision western boundaries. The Paleozoic continental margin is assumed to have been linear and NNE-trending, as suggested by its mean trend through the late Mesozoic bends. Figure 3A depicts Sonomia encroaching on the continent in the Permian with the Golconda outer arc at its underthrust southeast margin. Its southwest margin is another convergent zone where oceanic plate X is shown moving below and

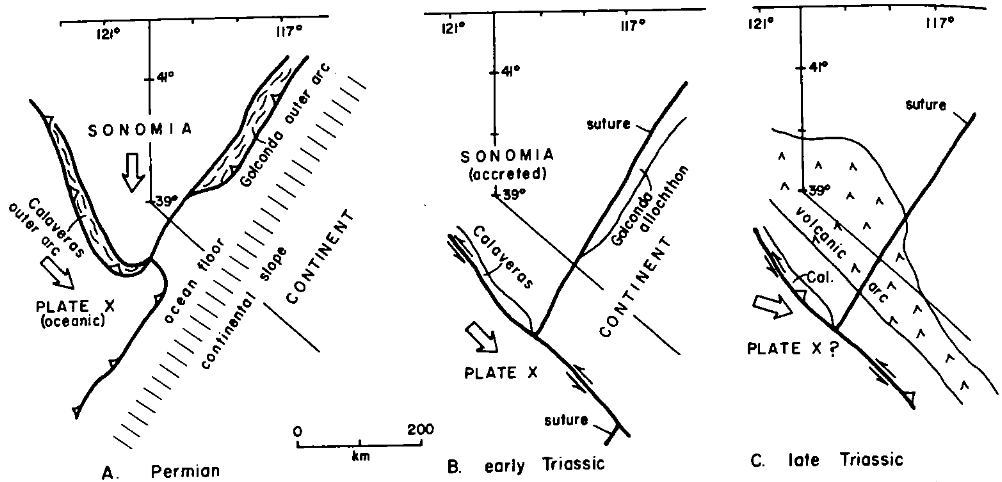

FIG. 3.—Plate schema depicting collision of Sonomia and some succeeding events; large arrows indicate direction of motion of outboard plates relative to fixed continent; teeth on upper plate at consuming margin and small arrows show relative lateral motion; pattern in C shows region of known and probable magmatism of Late Triassic age in Nevada and central eastern California; discussion of scenes A, B, and C in text.

accreting the Calaveras sediments (partly derived from Sonomia) below and against Sonomia. The dual subductions of Sonomia may account for its apparently broad realm of concurrent Permian volcanism. The migration direction of plate X is chosen parallel to the continental truncation trace at the Kings-Kaweah suture (loc. k, fig. 1; Saleeby et al. 1978) and to the 0.706 initial Sr contour in the southern Sierra (Kistler 1978). The Sonomia-Plate X boundary is also approximately on line (after adjustment for Cenozoic distortions) with a SE-trending zone in southeastern California and Arizona identified by Silver and Anderson (1974) along which some 500 km of left lateral offset of Precambrian terranes occurred in the Mesozoic. On collision of Sonomia with the continent, convergence was taken up at an unidentified locus northwest of existing Sonomia.

Figure 3B portrays the idea that plate X continued its earlier motion after collision with the continent via a transform fault (see also Davis et al. 1978) through the continent to a new convergent zone far to the southeast. If the transform operated for even half of Triassic time, a left-lateral migration of the continental fragment of 500 km is easy to conceive. Figure 3A implies that plate X hit the continent before Sonomia in which case continental truncation preceded Sonomia's collision. Plate X, however, might have collided at about the same time as Sonomia such that truncation of the continent was concomitant and a geometric consequence of an unstable triple junction. Sonomia could not have collided much before plate X, assuming that the Calaveras unit records convergence of Sonomia relative to X.

The model of figure 3 implies further that later in the Triassic the motion of plate X relative to the continent-Sonomia pair (fig. 3C) had become sufficiently convergent to produce an inboard magmatic arc. By Jurassic time (Speed 1978*a*, fig. 3) the motion of outboard terranes relative to the same approximate boundary had rotated, perhaps abruptly, to right-oblique convergence. This event was apparently related to the onset of major deformation and drag of Sonomia and the continent in the Sierra and parts east.

Alternative plate models would consider, among other parameters, that the western boundary of Sonomia and the sialic continent is are a product of post-collision truncation and that a fragment of Sonomia plus continent was rafted away in the Triassic.

ORIGIN OF SONOMIA

Three general source regions can be imagined for Sonomia: a distant transoceanic site, an offshore region laterally along western North America, and a local site offshore from the collision locus. Benthonic fossils of early and late Paleozoic rocks of Sonomia (Stevens 1977) have distinctive aspects, but are apparently more like North American than alien equivalents. Thus, the transoceanic source seems doubtful. The idea of a local site (Burchfiel and Davis 1972; Silberling 1973; Churkin 1974) holds that rocks now included in Sonomia represent a fringing arc that developed in the Devonian and either collided or partially closed to emplace the Roberts Mountain allochthon. Then, in the late Paleozoic, the arc either moved seaward or, in the case of incomplete original closure, remained fixed to provide a marginal basin for sediments of the Golconda allochthon. Final closing movements of the arc were synchronous with the Sonoma orogeny. Such schemes seem unlikely because a fringing arc-marginal basin couple should have yielded at least some comingling of arc- and continent-derived sediment in the basin (Dickenson 1977). Arc-derived sediment is unrecognized in rocks of the Golconda allochthon.

Kistler (1978) conceived a quasi-local origin of Sonomia but with different orchestration. He proposed that the Sonomia-continent suture was originally a Paleozoic intercontinental rift from which a continental fragment (now represented in part by the Salinian block) rafted west; the magmatic arc and Golconda allochthon were created when the continental fragment briefly reversed course and headed back to its birth site in the Permian.

I believe an origin of Sonomia elsewhere along coastal western North America is perhaps most feasible; it accommodates the objections to the other hypotheses, fits the interpretation of left-oblique convergence in the emplacement of the Golconda allochthon, and offers explanations for major regional structural features. The existence of in place and accreted magmatic arc terranes of late Paleozoic age in British Columbia (Monger 1977) shows that a northerly source of Sonomia is feasible.

The mid-Paleozoic (Antler) Roberts Mountains allochthon, like the Golconda, is probably a beached accretionary wedge and a product of arc-continent collision. The Antler magmatic arc, however, is not observed at the scene of collision, and there is no evident correlation through timing of volcanic events in Klamath Sonomia (Potter et al. 1977) with an Antler collision. The Late Devonian onset of volcanism in the Sierra, however, is suggestive that the Antler arc might lie within Sonomia. If it does, it probably traveled far between mid-Paleozoic and Triassic collisions. Alternatively, if one inverts the well-worn notion that the Sonoma orogeny obeyed similar tectonics to the Antler, the following story emerges: the Antler magmatic arc welded to the continent after mid-Paleozoic collision and then thermally contracted to form at least the continentward rim of the Golconda ocean basin. In Permo-Triassic time, the subsided Antler arc subducted below Sonomia (Speed and Moores 1978). If thrust slices of Devonian-Early Mississippian rocks of magmatic arc affinities are found in the Golconda allochthon, this idea would gain support.

Sonomia might be related to other late Paleozoic magmatic arc terranes that accreted in the Pacific northwest in the late Mesozoic, for example, the Wrangellia and Stikine terranes (Jones et al. 1977; Monger 1977). Perhaps such terranes are pieces of an extensive arc complex that was fragmented in the Permian and which escaped capture by the continent until much later. They could, alternatively, be fragments of northern Sonomia, perhaps including chunks of continent and accretionary wedges, that after collision were dislodged and swept north from Oregon and possibly from as far south as the Nevada-Oregon border.

To conclude, I suggest that continental margin tectonics of western North America involved significant lateral motions in the Early Mesozoic (and probably in the Paleozoic) as they have in later times. Thus, older outboard terranes like Sonomia may have occupied various geographic positions, probably with rotation and several reversals of direction of lateral motion. Under such circumstances, a specific, short lived structure such as the Sonoma orogeny in Nevada depends on local factors and would be unlikely to be correlated temporally or kinematically with distant tectonic features elsewhere along the Pacific margin.

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