PALEOGEOGRAPHIC AND PLATE TECTONIC EVOLUTION OF THE EARLY MESOZOIC MARINE PROVINCE OF THE WESTERN GREAT BASIN

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ABSTRACT

A marine province existed in the northwestern Great Basin in which sedimentary and volcanic rocks accumulated from Early Triassic to late Early Jurassic time. Strata of the province comprise three paleogeographic terranes: shelf, basinal, and volcanic arc. They overlie late Paleozoic rocks which are thought to have chiefly constituted a magmatic arc that collided in Early Triassic time with the margin of the North American continent. The early Mesozoic marine province originated as a successor basin to the accreted late Paleozoic arc. Deposition in the marine province was extinguished by major mid-Jurassic deformation during which quartz arenite, evaporite, and volcanogenic rocks were deposited in an orogenic terrane.

The early Mesozoic volcanic arc terrane includes siliceous igneous rocks of Middle (?) and Late Triassic age which were probably comagmatic with the earliest Sierran plutonism and with a postulated belt of subaerial volcanism that extended far southeast of the marine province. Transition of the volcanic arc terrane from mainly igneous to sedimentary deposition within the Triassic suggests the Triassic magmatic event was fairly shortlived. The early Mesozoic shelf terrane occupies a narrow belt that is generally coincident with the relict Paleozoic continental margin. The basinal terrane represents a more subsident, probably generally deep-water region that lay offshore of the shelf terrane in northwestern Nevada. The enormous volume of mud that accumulated in the basinal terrane may have been fluvially transported to the marine province from the subaerial southeasterly prolongation of the Triassic volcanic arc.

The lateral and vertical distribution of strata of the early Mesozoic marine province of the western Great Basin records the transition of the western edge of the continent from its Paleozoic locus within the Great Basin to a Jurassic position as a continental arc in the Sierra Nevada. Plate models suggest that the orientation of convergent motion may have rotated from northwesterly at the beginning of the Mesozoic through westerly to south-southwesterly by mid-Jurassic time.

INTRODUCTION

Marine deposition occurred widely during the early Mesozoic in both the western and eastern Great Basin according to the record of preserved strata. The western marine province, the subject of this paper, includes an extensive region that underwent pronounced subsidence in the Triassic relative to areas east of 117°W and south of 38°N. The eastern and southern hinge lines of the subsident region are approximately coincident with the Paleozoic margin of the North American continent (Speed, 1977a). Rocks that accumulated in the western marine province comprise three regional terranes which are named shelf, basinal, and volcanic arc, according to their principal paleogeographic settings. The evolution of these terranes and the western marine province as a whole provide a record of the reorganization of the continental margin from its Paleozoic locus within the northern Great Basin to a Middle Jurassic position entirely west of Great Basin. The early Mesozoic shift of the margin to the west of the Great Basin is equivalent to the continental accretion of Rogers and others (1974), although the processes involved are different from what they envisioned.

The present paper summarizes the character, history, and origin of the three terranes that accumulated within the western marine province. It also considers two other lithic groups that are closely associated with the province: 1) the Koipato rhyolites which were apparently extruded in a restricted area at about the onset of subsidence and, 2) rocks here grouped as an orogenic terrane whose deposition was generally synchronous with the mid-Jurassic deformation that eliminated the marine province. Table 1 is a menu of the various Mesozoic and pre-Mesozoic terranes discussed herein. Descriptive sections are followed by models of the paleogeographic and plate-boundary tectonic evolutions of the western Great Basin and adjacent parts of the Sierra Nevada. This study has benefited greatly from the 15 years of work by many geologists in the western Great Basin since the first regional synthesis was presented by Silberling and Roberts (1962). It will show, however, that much still remains to be learned before models graduate from the infantile stage.

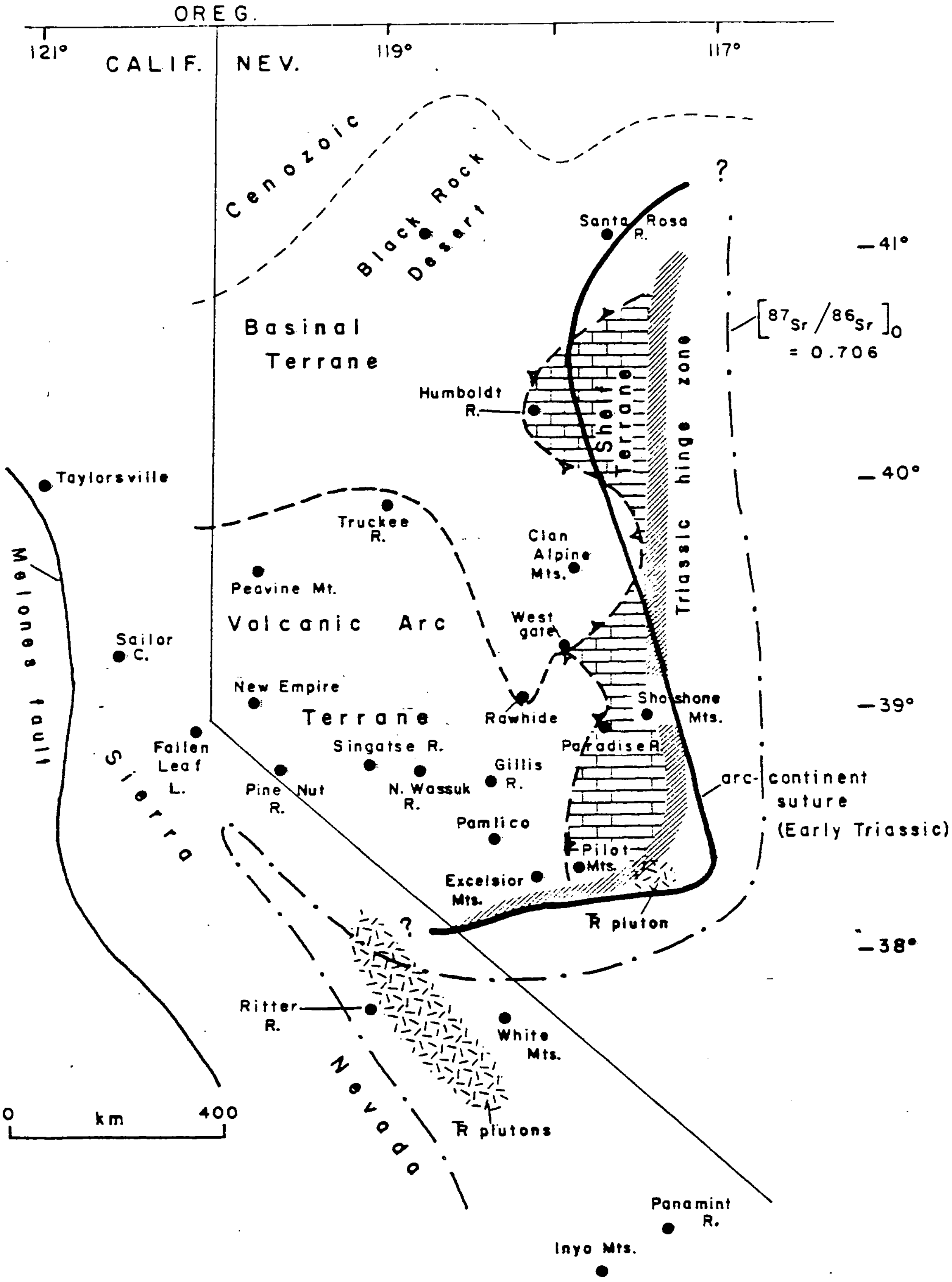

Figure 1: Map showing paleogeographic terranes of early Mesozoic marine province of the western Great Basin and other features referred to in text.

Table 1: Sequence of terranes in the western Great Basin discussed in text.

Age	Terrane			
late Early and Middle Jurassic	orogenic terrane			
late Late Triassic to late Early Jurassic	terranes of the early Mesozoic western marine province			
	volcanic arc terrane	basinal terrane	shelf terrane	
			southern	northern
				Koipato rhyolite (Early Triassic)
late Paleozoic	late Paleozoic volcanic arc terrane			late Paleozoic ocean floor terrane (Havallah sequence)

WESTERN MARINE PROVINCE

Lateral stratigraphic variations of marine Mesozoic strata of the Great Basin indicate two main depositional provinces existed in Triassic time. The western province (Fig. 1) was the site of variable but pronounced subsidence adjacent to and offshore from the general locus of the late Paleozoic continental margin of North America. Exposed strata of the western province range in age from late Early Triassic to late Early Jurassic. The eastern province occupied an intracontinental region in eastern and southern Nevada and western Utah; its marine contents are chiefly Early Triassic, and succeeding Upper Triassic and Jurassic deposits are variably of subaerial and marine (?) origin (Stewart, 1969; Stanley and others, 1971; Bissell, 1972; Stewart and others, 1972; Stewart, written comm. 1978).

The region of the central Great Basin between the two depositional provinces is devoid of early Mesozoic strata and was certainly less subsident if not an upland during much of the Triassic. Eastward onlap of the central zone from the western province is indicated by remnants of Middle and Upper Triassic beds in contact with Paleozoic rocks within 50 km east of the hinge zone (Fig. 1) (Nichols, 1971; Stewart and McKee, 1978). Moreover, rocks of both basinal and shelf terranes of the western province indicate that a region to the east of the hinge was at least partly subaerial during Late Triassic time. The basinal terrane includes deep water conglomerate containing probable Paleozoic pebbles from a nearby easterly source (Speed, this vol.) and the shelf terrane contains at least one major tongue of deposits (Grass Valley Formation) of a fluvial system (Silberling and Wallace 1969). Both contain woody fragments.

In the depositional province of the eastern Great Basin, there is a westward onlap of Lower Triassic beds (Collinson, 1976), and such strata contain conglomerates of probable westerly provenance (Koch, 1971; Stewart, written commun., 1978). The existence of 300 m or more of Chinle-like beds in the eastern province (Clark, 1957; Stewart and others, 1972) implies a subaerial environment in Late Triassic time. Thus, sediment transfer from the eastern to the western province conceivably occurred at that time.

It is difficult to prove whether the central Great Basin was a positive region in the Jurassic. The similarity of the distribution of preserved Jurassic sedimentary rocks in the Great Basin with that of Triassic implies that the two Triassic depositional provinces continued as relatively subsident regions into the Jurassic. The intervening region may or may not have been submerged. Stanley and others (1971) inferred on meager evidence that a sea crossed the Early Jurassic Great Basin. The open marine character of beds and absence of evident strandline deposits of Early Jurassic age in the western province may be the best testimony for marine continuity.

The eastern boundary of the western marine province (Fig. 1) is drawn east of the outcrop belt of the shelf terrane which includes strata over 2 km thick deposited at a subsiding margin and west of the region that contains only scattered outcrops of thin Triassic rocks judged to have been stable platform accumulations. Thus, the boundary approximates the hinge zone between regions of significatly different rates of subsidence. Owing to the absence of an exposed complete platform to basin transition, it is impossible to locate an inflection of the shelf-platform margin any closer than about 50 km. Further, because the basinal and volcanic terranes are thrust over the shelf terrane, the width of the subsiding shelf is uncertain.

The hinge zone appears to be approximately coincident with regional geologic features (Fig. 1) that are believed to mark the long-standing Paleozoic continental margin (Speed, 1977a). One is a proposed suture of Early Triassic age between a late Paleozoic magmatic arc and the continent. Another is the 0.706 initial strontium isotope contour (Kistler and Peterman, 1973). Both features are located with imprecision at least as great as that of the hinge zone of the early Mesozoic western marine province.

A southern boundary of the western marine province can be defined on some of the same criteria as the eastern boundary: circumscription of early Mesozoic marine outcrops and essential coincidence with the continental margin, Early Triassic suture, and 0.706 Sr contour (Speed, 1977a). Southernmost autochthonous Lower Mesozoic rocks in this region (Gold Range Formation of Speed, 1977b) are partly subaerial accumulations of ignimbrite and volcanic sedimentary rocks; their nature provides no evidence that deposition was confined to the regions of preserved rocks. In fact, it is possible that isolated tracts of volcanogenic rocks of probable Triassic age in Inyo County (Fig. 1 White Mountains, Inyo Mountains, Panamint Range) are remnants of an originally extensive subaerial belt that was contiguous with the volcanic terrane of the marine province.

An original western boundary of the western marine province cannot be defined. Layered rocks of demonstrable Middle and Late Triassic age apparently do not occur in the Sierra Nevada (east of the Melones fault) in the region south of Taylorsville (Fig. 1) (Clark and others, 1962; Kistler, this vol. and oral commun., 1978). On the other hand, Triassic successions of the marine province in westernmost Nevada do not contain strong westerly facies gradients. Thus, the apparent absence of such rocks in the high Sierra implies erosional and(or) tectonic removal. In the same region of the Sierra, however, Lower and Middle Jurassic deposits are apparently thick and widespread, and evidence presented later indicates they may have been partly contiguous with Jurassic rocks of the western Great Basin (see also Noble, 1962; Stanley and others, 1971). Thus, it may be inferred that this region of the Sierra was active tectonically during the early Mesozoic.

The northern Sierra Nevada near Taylorsville and the Shasta region, however, contain marine Triassic rocks that were conceivably contiguous with those of the western Great Basin (Sanborn, 1960; Albers and Robertson, 1961; McMath, 1966; D'Allura and others, 1977). The thick Jurassic strata of this region are probably correlatives in part with successions of the Ritter pendant, Sailor Canyon Formation, and westernmost Great Basin, as discussed later.

It should be noted that the present shape of the western marine province (Fig. 1) is not necessarily the original one. Deformation is particularly severe in the southern half of the province (Oldow, 1977; Wetterauer, 1977; Speed, this vol.). Moreover, it has been proposed (Albers, 1967) that extensive territory including the southern half of the province has been thrown into sigmoidal Mesozoic bends of crustal dimensions about vertical axes called oroflexes. Although the oroflex concept is kinematically dubious, there is clearly evidence for deformation on a gross scale in that region.

Early Mesozoic rocks of the western marine province are widely underlain by mafic and intermediate volcanic rocks that are known or suspected to be Permian (Speed, 1977a). Several lines of evidence suggest that such volcanic rocks are the basement to all but the easternmost beds of the marine province which lie above an early Triassic allochthon of late Paleozoic ocean floor strata, also known as the Havallah sequence. It has been proposed that the Permian volcanic rocks are the upper layers of a late Paleozoic island arc that migrated east or southeast toward the North American continent and propelled before it an accretionary arc of late Paleozoic ocean floor sediments. The volcanic arc collided with the continental slope at about the beginning of the Mesozoic or at least, before late Early Triassic. The accretionary arc was underthrust by the continental slope and perhaps, partly extruded east across the shelf-slope break. Following its collision, the late Paleozoic arc terrane was welded to the continent, and relative motion of the continent was taken up on a new boundary somewhere west of the Great Basin (Speed, 1977a).

Koipato rhyolite

The Koipato Group (Wallace and others, 1969; Silberling; 1973) was named for a succession of volcanic rocks whose outcrops are coextensive with succeeding strata of the lobate northern tract of the early Mesozoic shelf terrane (Fig. 1). Rhyolitic magmatism of the Koipato Group seems to have retarded basin subsidence in the Koipato outcrop area. It is uncertain, however, whether the Koipato widely underlies strata of the western marine province or is restricted to the area of existing outcrop. I tentatively interpret that it is restricted by arguments given below.

The Koipato Group comprises the Limerick Greenstone and succeeding rhyolitic units according to Wallace and others (1969). A different interpretation indicates that the Limerick Greenstone in its type area of the Humboldt Range belongs to the late Paleozoic arc terrane and that the rhyolitic formations are younger and separated by unconformity from the greenstone (Speed, 1977a). The rhyolitic units constitute about 2 km of remarkably siliceous and alkali-rich ash flow tuff and volcanogenic sedimentary rocks. Associated intrusive and protrusive masses indicate that rhyolite sources existed in the Humboldt and Tobin Ranges (Wallace and others, 1969; Burke, 1973). A faunal age near the top the rhyolite succession in mid-Spathian, only slightly older than the succeeding and nearly conformable beds of the Star Peak Group, according to Silberling (1973). Rb-Sr data from samples throughout the rhyolite units suggest that the approximate age of extrusion is 235-240 my and that partial chemical homogenization occurred later in the Mesozoic (R. W. Kistler and R. C. Speed, in prep.). The initial strontium isotopic composition suggests the rhyolitic magmas were not generated in continental lithoshpere.

The Koipato ash-flow tuffs lap east over deformed beds of the late Paleozoic Havallah sequence, indicating that eruptions probably did not occur before collision of the late Paleozoic arc and the North American continent. The environment of deposition of at least the upper rhyolite succession was variably subaerial and shallow marine. Block faulting occurred during and (or) shortly after accumulation of Koipato rhyolite in the Tobin and New Pass Ranges (Burke, 1973; MacMillan, 1972). Although such faults may have been volcanotectonic, their probable existence in the pre-Koipato basement beyond the area of thick rhyolite accumulation suggests the faults were more likely products of crustal extension.

Siliceous volcanic rocks of approximately similar age to the Koipato rhyolites in Nevada and California are known only in the Ritter pendant of the Sierra Nevada (Koip sequence of Kistler, 1966; this vol.), but those rhyolites are chemically dissimilar to the Koipato rocks. The Bully Hill rhyolite of the Klamath province (Albers and Robertson, 1961) could be contemporaneous with the Koipato but could also be as young as Late Triassic. The base of strata deposited in early Mesozoic basin is exposed at four places (Fig. 1) beside the area of Koipato outcrop: central Humboldt County (Willden, 1964), New Pass Range (MacMillan, 1972; Willden and Speed, 1974), Union district (Silberling, 1959), and Excelsior Mountains (Speed, 1977c). In none of these areas does rhyolite lie between the early Mesozoic sedimentary rocks and the subjacent terrane considered to the the basement of the basin. In the Union district however, volcanic rocks here called basement are poorly dated, and it cannot be demonstrated that such rocks are not underlain by a hidden succession of Middle and Lower Triassic strata. Similarly, undated rhyolites occur in the Gold Range Formation (Table 1) of the Excelsior Mountains above basal clastic strata and could conceivably be Koipato equivalents.

To conclude, there seem to be no evident equivalents of the Koipato rhyolites in the southern cordillera except for the Koip sequence. The rhyolitic magmas emerged chiefly through the late Paleozoic volcanic arc lithospere. Such rocks must represent local magmatism, and in a later section, this inference is used to explain the form and existence of the wide northern shelf of the early Mesozoic basin.

Shelf Terrane

Strata included in the shelf terrane are mainly carbonate and less abundant silicaclastic rocks that were deposited on generally (but not uniformly) shallow subsiding shelves at the east flank of the western marine province. Carbonate platform or bank accumulations also occur at places in the other two early Mesozoic terranes, but they are dominant only in the shelf terrane. This terrane consists of two main regions, a northern one which is lobate to the west and in probable thrust contact with the basinal terrane (Speed, this vol.) and a southern one which occupies a narrow belt and which is in thrust contact with the volcanic arc terrane.

The northern region includes the Star Peak Group, a carbonate platform complex about 1 km thick of late Early Triassic (mid-Spathian) to middle Late Triassic (Karnian) age (Silberling and Wallace, 1969; Nichols, 1972; MacMillan, 1972; Burke, 1973; Nichols and Silberling, 1977). The Star Peak is overlain by Upper Triassic silicaclastic and carbonate rocks about 1 km thick of the Grass Valley, Dun Glen, and Winnemucca Formations* (Silberling and Wallace, 1969; Burke and Silberling, 1973).

Nichols and Silberling (1977) have shown that the Star Peak Group is a carbonate platform complex that prograded generally west from Middle to early Late Triassic (late Anisian to late Karnian) time. Mafic volcanic rocks occur widely at Ladinian horizons of the Star Peak. The succeeding silicaclastic accumulations of the Grass Valley Formation grade west (Silberling and Wallace, 1969) across the shelf terrane from quartz arenite and carbonate rocks with increasing proportions of mudstone and channel-filling subarenite. The formation constitutes a substantially thicker mudstone-rich accumulation in the Humboldt Range (Fig. 1) at the westernmost exposure of the shelf terrane. Silberling and Wallace (1969) interpreted the Grass Valley as a westerly-prograding fluvial-deltaic complex. Their paleocurrent data from outcrops of Grass Valley that are structurally continuous with Star Peak beds indicate generally westerly sediment transport. The succeeding Dun Glen Formation represents a return of carbonate bank deposits on the shelf, and the Winnemucca, a general recursion of muddy silicaclastic debris. Rocks younger than Middle Norian are unrecognized in the northern tract of the shelf terrane.

Strata of the northern shelf terrane indicate generally continuing subsidence for much of Triassic, but facies and unconformities within the succession (Nichols and Silberling, 1977) indicate the rate was nonsteady and that the terrane was variably emergent during its deposition. Moreover, they believe there is evidence for upwarping during the Middle Triassic. The rate of subsidence of the northern shelf terrane appears to have increased generally west and perhaps south. Silicaclastic sediments (Tobin and Dixie Valley Formations) accumulated at the base of the terrane near the basin margin whereas carbonates constitute almost the entire section in the more offshore zone of the shelf that was underlain by thick Koipato rhyolite. The existence of mafic volcanic rocks in the Star Peak Group may suggest that crustal extension accompanied subsidence as does the interpretation of Nichols and Silberling (1977) that local relative uplifts during Star Peak deposition were products of tensional differential subsidence.

The Grass Valley Formation records an abrupt change of lithology and transport mode from the carbonate platform deposits (Silberling and Wallace, 1969). Their interpretation indicates that at the beginning of Norian time, alien mud and sand prograded west across the basin margin and carbonate platform as a deltaic complex. It implies further that a shelf to deep basin transition probably lay just west of the Humboldt Range at the beginning of the Norian and that the transport system of the Grass Valley Formation was one conduit of pelitic debris to the basinal terrane (Speed, this vol.).

The southern region of the shelf terrane consists predominantly of carbonate rocks 2-3 km thick. It includes the Luning, Gabbs, and Sunrise Formations of the Pilot Mountains, Paradise Range, Shoshone Mountian, Gabbs Valley Range, and scattered outcrops east of the latter range, as mapped by Ferguson and Muller (1949). It also includes the late Middle Triassic (Ladinian) Grantsville Formation (Silberling, 1959) of the Shoshone Mountians which is seemingly the oldest among those assigned. The actual maximum age of rocks of the southern shelf is uncertain. The Grantsville lies on poorly dated mafic volcanic rocks that may belong to the late Paleozoic basement of the western marine province or may simply be Triassic eruptives in a shelf sequence that extends to depth (Speed, 1977a). Elsewhere the shelf succession is either allochthonous (Oldow, 1977), or it has a buried base. Unlike the northern region of the shelf, the southern terrane includes rocks of late Late Triassic and Early Jurassic age.

Much of the southern shelf terrane is cut by thrusts, and it is possible that the whole southern terrane is allochthonous. Oldow (1977) found in the Pilot Mountains (Fig. 1), the southernmost outcrop area of the shelf terrane, that strata of the shelf terrane are piled up in a series of 13 thrust nappes; by structural and facies analyses, he interpreted the principal direction of motion of nappes to have been southeast and the magnitude of telescoping to

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*Auld Lang Syne was assigned as a group name by Burke and Silberling (1973) for formations above the Star Peak Group and for thick terrigeneous successions with unexposed base north of the Star Peak exposure region. Though the euphony of the group name is appealing, I have not used that terminology because rocks north of the Star Peak outcrop area are included in the basinal terrane (Speed, this vol.).

have been perhaps as great as 100 km. Further, the general north-south boundary between the volcanic and southern shelf terranes (Fig. 1) is probably tectonic along its entire length. In the Paradise Range, the volcanic terrane is thrust over the shelf terrane, but in the Pilot Mountains, the shelf terrane is overthrust. In the Garfield Hills and northern Gabbs Valley Range, it is not clear which terrane is structurally higher at the tectonic boundary. It is reasonable to conclude from preceding paragraphs that the original configuration of the southern shelf terrane and the age range of its strata are in some doubt. It seems likely, however, that as in the northern, rocks of the southern shelf terrane accumulated in proximity to the relict Paleozoic continental margin.

Triassic rocks of the southern shelf terrane are largely shallow marine carbonate together with coarse terrigenous clastic rocks whose debris was probably derived from short distances east of the basin margin. The middle member of the Luning Formation of Norian age (N. J. Silberling, oral commun., 1972) is particularly interesting because it contains abundant pelite together with coarser rocks interpreted by Oldow (1977) as a deltaic complex. In the Pilot Mountain, the upper half of the 1 km thick middle member contains feldspathic siliceous tuff and copious euhedral feldspar sand of evident volcanic origin (Nielsen, 1963; Oldow, 1977). Moreover, the middle member locally contains chert-boulder conglomerate, implying accumulation within several kilometers of basement prominences.

The upper member of the Luning Formation is a conspicuous massive Norian carbonate unit of about 700 m thickness that occurs with remarkable lithologic consistency throughout the southern shelf terrane (Silberling and Roberts, 1962). It is succeeded by several hundred meters of marine limy mudstone and thin bedded limestone of late Norian and Early Jurassic age. The upper member of the Luning and higher units suggest lateral continuity of depositional environments as compared to the heterogeneous middle member of the Luning Formation.

Basinal Terrane

Exposed rocks of the basinal terrane are chiefly Triassic pelites and interstratified quartz sandstone of known or suspected deep water origin. Thick successions of such rocks occupy an arcuate belt that circumscribes the western margin of the lobate northern shelf terrane (Fig. 1). Within this belt, the pelite-sandstone successions are of late Late Triassic (Norian) age, but their depositional base is not exposed. Moreover, outcrops of older strata are absent in the area of the belt so that the total thickness and age range of hidden successions of the basinal terrane are unknown. In the southern half of the belt, strata of the basinal terrane grade up to more calcareous rocks of latest Triassic and Early Jurassic age. In contrast, rocks of known Jurassic age are absent from the northern half of the belt, and Triassic pelites may be the last marine deposits of that area. West of the arcuate belt of abundant exposure of the basinal terrane, outcrops of similar rocks are scattered throughout northwestern Nevada (Fig. 1)

Specific map units of northwestern Nevada included in the basinal terrane are listed in Speed (this vol.). Early Mesozoic pelitic rocks of the northern Sierra Nevada and Shasta regions are perhaps correlative with the basinal terrane. The upper Arlington ("Cedar") and Swearingen Formation (D'Allura and others, 1977) and the Pit Formation and succeeding Triassic units (Sanborn, 1960) may have been originally contiguous.

The arcuate boundary between the basinal and shelf terranes (Fig.1) is a variably certain or probable thrust zone on which the basinal terrane is allochthonous (Speed, 1976; this vol.). The zone of dislocation is interpreted to lie close to the Triassic declevity that separated the shelf and basinal despositional realms. The magnitude of displacement of rocks of the basinal terrane near the thrust zone is probably small (few km ?). The strong deformation and general shelfward vergence of folds of strata within the basinal terrane, however, imply that lateral shortening of the terrane during shelfward thrusting was probably large. The time of thrusting and first tectonic deformation of the basinal terrane was approximately mid-Jurassic. Conceptually, the mid-Jurassic orogeny seems to have caused the basinal terrane to flatten against and squeeze out over the shelf edge.

The boundary between basinal and volcanic arc terrane is depositional at Rawhide Summit (Fig. 1), the only place the contact is exposed. There, distal turbidites of the basinal terrane are succeeded by proximal volcanogenic turbidite and Upper (?) Triassic carbonate rocks and at higher levels, by volcanic and carbonate rocks typical of the volcanic arc terrane. This one locality indicates northward progradation of rocks of the volcanic terrane over those apparently allied with the basinal terrane and ultimate shoaling of the depositional site. The pelitic rocks could, of course, be a tongue in an otherwise continuous succession of volcanogenic rock.

The Clan Alpine Mountains (Fig. 1) probably provide the greatest depth of exposure of strata within the southern part of the basinal terrane (Speed, this vol.). The Clan Alpine succession is about 5.8 km thick and spans Norian time; the upper 400 m could be Jurassic. The lower 4 km are predominantly distal turbidite and hemipelagite of which the mud fraction is composed of quartz, illite, chlorite, and plagioclase. The directions of currents that deposited the distal turbidites are unknown. Interstratified with the muddy rocks are deep water quartz arenite, chert-quartzite-limestone pebble conglomerate, and carbonate-particle deposits whose debris moved generally down and accumulated at the base of a northwesterly-facing slope (in modern geography). The sources of such particles were littoral regimes which included exposures of older rocks, biogenic and inorganic carbonate particle accumulations, and quartz sand beaches or bars.

The upper 1.5 km of the sequence in the Clan Alpine Mountains contains only fine silicate sediment of hemipelagic (?) origin and upward increasing proportions of carbonate rock, culminating in about 600 m of massive platform carbonate at the top of the section. The upper part of the section records either by-passing or elimination of sources of the coarse debris that occurs in the lower strata. Moreover, it indicates ultimate shoaling of the former deep basin floor.

West of the Clan Alpine Mountains, the basinal terrane includes Lower Jurassic beds as thick as 1 km (Speed, 1974) which are generally organic limy pelites. Such rocks were evidently deposited under open marine conditions, perhaps below wavebase.

Their carbonate debris was conceivably derived from the carbonate platform that forms of the upper strata of the basinal terrane in the Clan Alpine Mountains. Given that the Early Jurassic and Late Triassic subperiods were equally long, the mean rate of accumulation of sediment was more than 5x greater in the Late Triassic in the southern region of the basinal terrane.

The only other succession of the basinal terrane where a stratigraphy has been worked out is in the Santa Rosa Mountains (Fig. 1). There, Compton (1960) found a succession over 6 km thick of pelite, quartzose sandstone, and minor carbonate rocks of Norian and Norian (?) age. Unfortunately, data leading to interpretation of depositional environments of the basinal terrane are unavailable outside the Clan Alpine Mountains. The uniformity of mineral composition of the Triassic pelites and their widespread association with quartz sandstone, however, suggests that the entire basinal terrane had the same general sediment source.

Contemporaneous deposition of nearly identical sediment occurred in the northern shelf and basinal terranes in early and Middle Norian time. Comparison of thicknesses of approximately coeval intervals in the Clan Alpine sequence (Byers Canyon, Dyer Canyon, and lower half of Bernice Formations) with that of the Grass Valley, Dun Glen, and Winnemucca Formations of the central part of the northern shelf terrane (Silberling and Wallace, 1969) indicates the basinal succession accumulated about 3x more rapidly. A similar comparison with the Santa Rosa succession cannot be made because age equivalence is unknown. The differences in Norian accumulation rates between shelf and basinal terranes and the evidence for deep water deposition in at least the southern region of the basinal terrane indicate large differential subsidence between areas of the two terranes. The differential subsidence could have been either pre- or syn-Norian; if the latter case is true, the rate of basinal subsidence exceeded the impressive rate of sediment accumulation of roughly 10^2cm/10^3yr for about 5 m y. Later evidence will suggest that pre-Norian differential subsidence is more likely.

Interpretations of the direction of sediment transport in the Grass Valley Formation (Silberling and Wallace, 1969) and in lower formations of the Clan Alpine sequence (Speed, this vol.) imply easterly sources, surely for sand and coarser debris and at least part for the silicate mud. The eastern quartz sandrich part of the Grass Valley ("Osobb Formation") may be a preserved deposit of the same beach zone that supplied clean quartz sand to the deep water deposits in the Clan Alpine sequence.

To ascertain the histories of differential subsidence and accumulation of silicate mud of the basinal terrane, the character and age of the concealed rocks of the terrane must be inferred from exposures of the base of the terrane and subjacent rocks in the Black Rock Desert of northwestern Nevada (Fig. 1). Based largely on Willden's (1964) reconnaissence, the sequence in the Black Rock Desert is interpreted as follows (Speed, 1977a; this vol.): late Paleozoic volcanic arc and related sedimentary rocks are overlain by about 500 m of carbonaceous limestone and interbedded black mudstone and chert of early Mesozoic age; these beds are conformably succeeded by pelite and quartz sandstone that are typical of Triassic rocks of the basinal terrane. The best estimate of the age of the lowest horizons of the pelitic succession is late Middle Triassic (Ladinian), as diagnosed by N. J. Silberling (in Willden, 1964) for the Quinn River Formation.

The depositional environment of the Triassic rocks below the pelitic succession is uncertain. However, their content of chert and dark mudstone may imply that the region was basinal for an unknown duration before the onset of major influx of silicate mud and sand, probably in late Middle Triassic (Ladinian) time. It follows that if the earliest mud of the thick pelites of the basinal terrane was dumped into a preexisting deep water basin, the basal accumulations of the pelites are probably isochronous and everywhere Ladinian. Thus, it appears that the pelitic sediment entered the deeper marine region for a significantly longer duration than the early and middle Norian times during which it also spread over the northern shelf (to form the Grass Valley and Winnemucca Formations). A further implication is that a copious supply of mud and sand suddenly became available near the end of Middle Triassic time.

The volume of exposed rocks of the basinal terrane is estimated to be 10^5km^3, close to the value given by Burke and Silberling (1973). Of this, probably 70 percent is mudstone. It is reasonable to assume that concealed deposits might double the figure.

The pelitic rocks are seemingly homogeneous according to x-ray studies and density measurements and Compton's (1960) petrographic, chemical, and density data. They contain abundant quartz and lesser white mica and plagioclase as silt and perhaps finer particles. K-feldspar is apparently absent. Illite and chlorite compose the clay fraction. Compton's chemical analyses indicate the clay fraction is somewhat ferrugenous, and calculations with his data indicate about 10 percent total iron oxide as Fe_2O_3 in the clays. This value is somewhat higher than the 5-7 percent given for modern terrigenous clays by Garrels and Mackenzie (1973). Volcanogenic particles are not evident in the Clan Alpine sequence nor in the Santa Rosa succession, but in the latter, some detrital mica is biotite in various stages of alteration to white mica (Compton, 1960). Beyond the implication of an igneous source for biotite in the Santa Rosa sequence, the lithology of the mud fraction provides no direct indication of its origin. Later regional considerations suggest, however, that a volcanogenic origin of the pelitic debris was perhaps likely.

Volcanic Arc Terrane

The volcanic arc terrane contains intermediate and siliceous extrusive and related sedimentary rocks, interstratified carbonate rocks, and higher beds of generally less volcanogenic sedimentary rocks. The environment of volcanism and sedimentation was generally marine. The volcanic terrane of the marine province and its probable original subaerial prolongation to the south are arc-related because they form a belt that is parallel and adjacent to a Triassic tectonic boundary, as discussed later.

Table 2 summarizes stratigraphic relationships at major localities in this terrane. The data show how meager the age control is. The lower contact of most of these successions is buried or faulted. The only locality where a depositional base above regional basement is exposed is in the Excelsior Mountains; there, the early Mesozoic strata (Gold Range Formation) lie unconformably over 250-260 my old mafic rocks of the late Paleozoic arc at a position just north of the Paleozoic continental margin. (Speed, 1977b). Unfortunately, the lower part of the Gold Range Formation is undated. The depositional base of the early Mesozoic arc terrane at Rawhide Summit cannot be regarded as a regional contact because the subjacent mudstone may be only a tongue in a volcanic section that continues to depth.

Triassic and Jurassic strata of the volcanic arc terrane are widely overlain by quartz sandstone and volcanogenic rocks of the Dunlap Formation (Muller and Ferguson, 1939) and related units. In this paper, these suprajacent units are grouped in an orogenic terrane (Table 1) and discussed separately in a later secton.

The oldest dated rock in the early Mesozoic volcanic arc terrane appears to be andesite at the base of the exposed section in the Singatse Range (Table 2). The dated rocks give a Rb-Sr age of 215 m y (Einaudi, 1977), and they lie some distance below beds that contain faunas at the Karnian-Norian transition (J. C. Proffett, oral commun., 1976; fossils identified by N. J. Silberling). Assuming that Permian rocks are a ubiquitous basement to the early Mesozoic volcanic terrane, the onset of early Mesozoic volcanism was between 250 and 215 mybp. I infer below that igneous rocks of the early Mesozoic volcanic arc terrane were products of the earliest epoch of plutonism of the Sierra batholith. Intrusions generated in that epoch (Fig. 1) have an apparent age range of 215-200 mybp (Evernden and Kistler, 1970; Kistler, this vol.). Thus, andesite of the Singatse Range was among the first eruptions of the Mesozoic volcanic terrane.

The thickness of the volcanic arc terrane is poorly known except in the Singatse and Pine Nut Ranges where exposed sections are about 3 km (Einaudi, 1977) and 2 km thick (Noble, 1962), respectively. Most of the localities, however, give the impression of substantial thickness.

There seems to be a general concentration of volcanic rocks in lower parts of the successions where a stratigraphy can be recognized. At most places, increasing proportions of carbonate rocks occur upsection, commonly culminating in a thick massive carbonate unit of known or presumed Norian age. The massive carbonate rocks are succeeded by thin-bedded limy pelitic rocks that are latest Norian and Early Jurassic. Except for the region from the Singatse Range west, rocks of known Early Jurassic (and pre-Dunlap) age have little or no volcanogenic material. Moreover, Lower Jurassic rocks in the Singatse and Pine Nut Range are less volcanogenic than the Triassic parts of the section.

Lateral variations in the volcanic terrane are less evident and have been complicated by thrusting within the terrane and between the volcanic and southern shelf terranes. A significant difference, however, seems to exist between the early Mesozoic volcanic terrane of the Excelsior Mountains and that in areas farther north. The Gold Range Formation of the Excelsior Mountains contains high proportions of ash-flow tuff and fluvial terrigenous and volcanogenic sedimentary rocks, suggesting a prevailingly subaerial environment. In contrast, the volcanic terrane in the Gillis Range contains much massive flow foliated rhyolite and breccia that is irregularly associated with thin bedded volcanic sedimentary rocks and, at places, with marine carbonate rocks. The Gillis volcanic rocks and those of the Pamlico district (Oldow, this vol., are perhaps more generally marine than those of the Gold Range. The volcanic terrane near Rawhide Summit seems to have an even higher proportion of marine volcanic and carbonate sedimentary rocks. Thus, the southern strandline of the marine province may have lain generally north of the Excelsior Mountains in the Triassic. The existence of volcanic conglomerate in the Gillis and Sand Springs successions, however, implies that volcanic shoals existed within the marine region.

The widespread occurrence of massive carbonate rocks in the region of early Mesozoic volcanic rocks has been observed by many geologists and first documented by Muller and Ferguson (1939). They correlated almost all the carbonate rocks in the Hawthorne and Tonopah (1:125,000) quadrangle with the Luning Formation which is here restricted to the shelf terrane. In order to maintain the integrity of the Luning Formation, they were forced to envision that thrust faults separate volcanic and carbonate units which are in fact interbedded. It may be correct that the upper member of the Luning Formation and massive carbonate strata of the volcanic terrane were at least partly contiguous. Muller and Ferguson (1939) also correlated Lower Jurassic rocks that lie above Triassic volcanic sections with the Sunrise Formation that lies above the nonvolcanogenic Luning Formation. The lateral homogeneity of the beds of known and presumed Early Jurassic age makes Sunrise an applicable name.

Chemical analyses of Triassic volcanic rocks of the volcanic terrane are presented in great number by Rogers and others (1974), and a few more are in Ross (1961) and Speed (1977c). The data indicate that the rocks are calc-alkaline and range widely in composition. They include mafic as well as strongly siliceous (SiO_2 > 75 percent) types; alkali contents are markedly variable and occasionally as great as 10 percent. There is no evident spatial trend of the chemical data. As noted by Rogers and others (1974), the Triassic volcanic rocks are significantly more siliceous than the subjacent late Paleozoic rocks (their Excelsior Formation).

Uncertainty in ages of rocks exists at many places in the volcanic arc terrane, but it seems that volcanism generally waned within late Triassic time. The region of Triassic volcanism, which contained sites of carbonate production and accumulation during magmatism, was then covered pervasively by a shallow marine carbonate regime within the Norian. Subsidence of the region continued and could even have increased during widespread carbonate accumulation relative to that of the earlier volcanic stage.

East of the Singatse Range, the Lower Jurassic deposits (Sunrise) record a generally offshore, plane-floored marine environment, considered by Stanley (1971) to be generally subtidal. Like the probably contiguous Lower Jurassic rocks of the basinal terrane, these rocks suggest that the rate of subsidence in the Early Jurassic marine province exceeded the rate of carbonate production such that deepening of the province increased with time. The only Sunrise facies indicating nonmarine conditions or nearby terrigenous sources are the Jurassic red beds of the Gold Range Formation (Table 2).

From the Singatse Range west, the Lower Jurassic deposits (Gardnerville Fm.) indicate probably a west-

Table 2: Lithic Successions Within the Volcanic Arc Terrane

Location (Fig. 1)	Lithic Succession (older to younger)	References
Excelsior and Pilot Mountains	Gold Range Fm.: unconformable on Permian arc rocks; includes >3 km(?) of coarse terrigenous and volcanic rocks interlayered with siliceous ash-flow tuff and breccia (undated) and upper 100 m of Lower Jurassic red beds and marine carbonate rocks	Speed (1977b)
Garfield Hills	Pamlico Fm.: allochthonous; Triassic intermediate and siliceous lava, breccia, and sediment interlayered with carbonate rocks; increasing proportions of carbonate upward; conformably overlain by Lower Jurassic limy pelite of Sunrise Fm.	Oldow, this vol.
Gillis Range	thick succession of intermediate and siliceous lava, breccia, protrusions, and volcanic sediment, probably chiefly marine; thin carbonate interbeds with Late Triassic fossils (N. J. Silberling, written commun., 1972); succeeded by massive (>300 m?) carbonate unit and higher, by dark shaly limestone and mudstone of Norian age	Ferguson and Muller (1949) Ross (1961) Speed (1977b and unpubl. data)
Paradise Range	undated laterally variable intermediate massive volcanic rocks, volcanic sediments, and carbonate rocks, all probably allochthonous; assemblage of quartz porphyry, Kfeldspar porphyry, quartz sandstone, and dolomite of the orogenic terrane is locally associated	Vitaliano and Callaghan (1963) Speed (1977c)
Westgate	undated andesite, volcanic conglomerate, quartz porphyry; allochthonous	Corvalán (1962) Willden and Speed (1974)
Rawhide Summit	Late Triassic volcanic sediments overlying mudstone (of basinal terrane) and interbedded with carbonate rocks; increasing proportions of andesite, welded tuff, and carbonate rocks; (probably Late Triassic) upsection, massive carbonate unit (>500 m, locally conglomeratic) at top	Ross (1961) Willden and Speed (1974)
Truckee Range	undated andesite and siliceous rocks	Willden and Speed (1974)
Peavine Mtn.	intermediate breccia and tuff, volcanic sediments; Late Triassic(?)	Bonham (1969)
Singatse Range	thick succession of Karnian(?) andesite and rhyolite, upper Karnian-lower Norian carbonate and silicaclastic strata, massive limestone, Lower Jurassic limy pelitic rocks (tuffaceous)	John C. Proffett (oral commun., 1976) Einaudi (1977)
Pine Nut Range	Norian intermediate and siliceous volcanic breccia, lava, tuff, and ash-flow tuff interstratified with marine limestone (1000 m) of the Oreana Peak Fm.; Norian and Lower Jurassic mudstone, volcanogenic sediments, and limestone as young as late Toarcian (1000 m) of the Gardnerville Fm.; succeeded by rocks of orogenic terrane	Noble (1962)
northern Wassuk Range	andesite and siliceous volcanic rocks overlain by massive Triassic(?) limestone; siliceous argillite and siltstone, at least partly of Early Jurassic age, with limestone interbeds in upper horizons	E. C. Bingler (written commun., 1978)
New Empire quadrangle	andesite overlain by dacite flows and ash-flow tuff; interbedded Upper Triassic limestone and marine pyroclastic rocks correlated with Oreana Peak Fm.; calcareous and tuffaceous pelitic rocks correlated with Gardnerville Fm.; succeeded by siliceous volcanic rocks of probable affiliation with orogenic terrane	E. C. Bingler (written commun., 1978)
Fallen Leaf Lake	over 2 km of graded thin-bedded calcareous turbidites of at least partly Early Jurassic age; overlain by thick conglomerate and andesite of probable affiliation with orogenic terrane	Loomis (1961)

erly increasing rate of subsidence, influx of more silicate and volcanogenic debris than in the Sunrise rocks, and at least occasional turbidity current transport (Noble, 1962; E. C. Bingler, written comm., 1977; R. C. Speed, unpubl.). As first proposed by Noble (1962), the Gardnerville strata (here extended east to the Singatse Range) seem to be transitional between contemporaneous subsiding shelf deposits of the Sunrise and largely volcanogenic trough accumulations of the Sailor Canyon (Milton) Formation in the central Sierra Nevada (Fig. 1). In fact, the Sailor Canyon trough probably included the Early Jurassic rocks of the Ritter pendant (Kistler, 1966; Stanley and others, 1971; Kistler, this vol.) and the Mt. Jura section of the northern Sierra (McMath, 1966).

Although the correlation of sections containing massive Norian carbonate rocks and "Sunrise" beds between the volcanic and southern shelf terranes seems reasonable, there is little basis for alliance of lower parts of the two successions. The existence of volcanogenic material in the middle member of the Luning Formation of one of the thrust nappes of the Pilot Mountains is the only evidence for intergradation (Nielsen, 1963) between volcanic and shelf terranes. Thus, one must appeal either to an abrupt transition (for example, volcanism restricted to the west of a shelf edge) or to a broader zone of intergradation that is overthrust by rocks of the volcanic terrane.

Contact relationships among the three early Mesozoic terranes suggest that the basinal terrane and the volcanic arc terrane (except for the Gold Range Formation, Table 2) could be companions in a giant allochthon that moved continentward over the shelf terrane. It is noteworthy that if a continuous thrust zone actually underlies the basinal and volcanic arc terranes, the surface trace of thrust would roughly parallel and be coextensive with the Permo-Triassic Golconda thrust as drawn by Speed (1977a).

Facies provide no certain indication that the southernmost outcrops (the Gold Range Formation, Table 2) of the volcanic terrane represent the southern limit of its deposition. The bulk of the Gold Range was probably deposited subaerially, and lithic equivalents may have extended untold distances to the south. In fact, scattered tracts of poorly dated volcanogenic rocks that are possibly correlative with the volcanic arc terrane of the western marine province occur to the south of the Gold Range Formation (Fig. 2) in the Inyo, White, and Panamint Ranges of Inyo County, California (Johnson, 1957; Merriam, 1963; Ross, 1967; Abbott, 1972; Crowder and Ross, 1973; Stevens and Olson, 1972). Successions in each tract may be Late Triassic (age brackets vary from as close as Middle Triassic-Early Jurassic to as open as pre-Cretaceous), and Abbott's (1972) study indicates that those of the Inyo and Panamint Ranges are compositionally like the Triassic volcanic rocks of the Gillis Range (Rogers and others, 1974). The depositonal environment of Inyo County volcanic rocks is not certain, but there is no evidence for marine environments. Thus, I propose that the realm of deposition of Triassic volcanic rocks extended southward of the marine province in western Nevada on emergent ground as far as Death Valley, and perhaps, beyond.

The paucity of outcrop of Triassic volcanic rocks south of the marine province is due partly to massive erosion because the well known southeastward increase in average age of rocks exposed between the Excelsior Mountains and Death Valley implies progressively greater post-Triassic uplift to the south. The volcanic rocks may also have undergone tectonic covering by thrust sheets of Lower Paleozoic rocks, as inferred in the White Mountains by Stevens and Olson, 1972.

Intrusions of the Lee Vining epoch, the earliest phase of the Sierra Nevada batholith, crop out just south of the western marine province (Fig. 1) (Evernden and Kistler, 1970). Such plutons have an apparent age range of 215-200 mybp (Kistler, this vol.; oral commun., 1978) according to concordant hornblende (K-Ar), zircon, and Rb-Sr dates. A small pluton with a hornblende age of 210 my occurs within the southern volcanic arc terrane (Fig. 1) (Speed and Armstrong, 1971), and other scattered bodies with ages in the same range seem to occur in a belt that trends southeast at least 500 km from the area of Triassic plutons in Figure 1 (Burchfiel and Davis, 1972). The probable overlap in age of Triassic volcanic rocks of the marine province and the Triassic plutons of the Sierra batholith strongly implies the two suites of igneous rocks were comagmatic. Moreover, the postulated southeasterly subaerial prolongation of the early Mesozoic volcanic terrane and generally coextensive Triassic plutons provide a glimpse of the locus of an elongate magmatic belt that was the first Phanerozoic arc developed on the continent in the southern cordillera (Hamilton, 1969).

OROGENIC TERRANE AND DESTRUCTION OF THE MARINE PROVINCE

The early Mesozoic marine province of the western Great Basin underwent major deformation and final effacement as a site of marine deposition in late Early Jurassic and Middle Jurassic time (late Toarcian and Bajocian). During this interval, sediments of the orogenic terrane accumulated at local sites within the region of the marine province south of about 40°N. Most sites were created by tectonic subsidence (Ferguson and Muller, 1949; Speed and Jones, 1969; Wetterauer, 1977) but a few seem to be relics of the earlier open marine environment.

This terrane contains the following rock units: Boyer Ranch Formation (Speed and Jones, 1969); Lovelock Formation (Speed, 1974); Muttlebury Formation (Speed, 1975); Humboldt lopolith (Speed, 1976); Middle Jurassic rocks at Westgate (Corvalán, 1962; Willden and Speed, 1974); association of quartz porphyry-quartz arenite-limestone conglomerate in the southern Stillwater Range (Willden and Speed, 1974), Paradise Range, and Quartz Mountain (R. C. Speed, unpubl.); Dunlap Formation (Ferguson and Muller, 1949; Nielsen, 1963; Stanley, 1971; Wetterauer, 1977); gypsum, quartz sandstone, contiguous volcanogenic strata at Ludvig, Singatse Range in the western Excelsior Mountains, and in the Pine Grove Hills (R. C. Speed, unpubl.), and the Preachers, Veta Grande, and Gold Bug Formations of Noble (1962).

Rocks of the orogenic terrane lie variably with conformity or unconformity above strata of the three Mesozoic terranes and in the Pilot Mountains, above pre-Mesozoic rocks. Basal strata of the orogenic terrane are almost uniformly quartz sandstone which may be interstratified with carbonate-evaporite rocks or include quantities of coarse terrigenous sediment. These rocks are commonly overlain by volcanogenic sedimentary rocks and minor volumes of andesite and siliceous volcanic rocks. Major exceptions to this theme occur at two places. Marine carbonate rocks that are late Early Jurassic and interstratified with quartz sandstone at Westgate (Fig. 1) are continuous with early Middle Jurassic limestone (Corvalán, 1962). In the Pine Nut Range (Noble, 1962) and nearby areas, quartz sandstone is overlain by several kilometers of volcanogenic rocks of which welded tuff is the predominant constituent.

Dating of the quartz sandstone of the orogenic terrane is meager but permissive of isochronous deposition in late Early Jurassic (late Toarcian) time. Some overlap in times of depostion of Sunrise rocks and the orogenic terrane is conceivable, but Stanley's (1971) contention they are facies is totally unsupported. Deposition of volcanogenic debris of the orogenic terrane is dated at one place in the Dunlap Formation, there also probably late Early Jurassic. Evidence from the Humboldt lopolith indicates quartz sandstone was accumulating (or perhaps, reaccumulating) at about 165 mybp.

Deformation of the Mesozoic strata of the marine province occurred by the creation of folds and thrust nappes at the free surface (Ferguson and Muller, 1949, Speed and Jones, 1969; Speed, 1975; Oldow, 1977). These surface phenomena were probably synchronous with deep-seated movements that culminated in the major thrust faults between terranes. The thrusts are apparently of great trace length, but their magnitude and direction of displacement are poorly known in a regional sense. For example, the southeastern part of the basinal terrane (Clan Alpine sequence) probably moved northeast relative to the northern shelf terrane (Speed, this vol.) whereas rocks of the southern shelf terrane in the Pilot Mountains moved southeast relative to an autochthon of the volcanic arc terrane (Oldow, 1977). If a uniform displacement originally occurred on the major thrusts of the province, progressive deformation during the mid-Jurassic orogeny and rotation by subsequent tectonic events have made it hard to decipher.

At the onset of regional deformation in the Jurassic, the marine province south of 40°N was an open marine region with probably greatly diminished subsidence relative to its average Triassic rate except near the western boundary. The eastern shoreline may have been within the western Great Basin (Speed and Jones, 1969), or the sea may have extended east into Utah (Stanley and others, 1971). Deformation caused mountains along what is now the southern margin of the marine province (Ferguson and Muller, 1949; Wetterauer, 1977) and warps of free surface at other places. Quartz sand from the same sources that fed the Jurassic Nugget-Navajo-Aztec sand accumulations in the eastern Great Basin migrated into the tectonic lows that developed in the western marine province (Speed and Jones, 1969; Stanley, 1971). The thicknesses of quartz sand trapped in these lows varies from a few tens of meters to nearly 2 km. Evaporites were deposited with or without quartz sandstone in those basins with restricted circulation. Quartz sand that entered basins near the mountainous regions was comingled with deluges of coarse terrigenous debris. Quartz sand in units of possible Early Jurassic age in the southern Sierra Nevada (Jones and Moore, 1973; Schweikert and others, 1977) may have been derived from the same sources.

Cessation of deposition of quartz sand north of about 39°N was apparently caused by increased uplift and deformation (Speed and Jones, 1969), although marine deposition occurred as late as Bajocian time at Westgate (Corvalán, 1962). South of 39°N, the source of debris in the volcanogenic rocks which abruptly succeed the quartz sandstone is inferential. The thick succession of volcanic rocks above the quartz sandstone in the Pine Nut Range (Noble, 1962), however, indicates that volcanic sources existed in what is now a westerly direction. There is also a general southward thickening of the volcanic sedimentary rocks (in the Dunlap Formation), but this probably reflects the direction of increased subsidence of a tectonic trough. Minor magmatism occurred within the areas of the marine province during accumulation of the orogenic terrane, but such igneous activity seems not to have been a major sediment contributor.

Conditions in the western Great Basin before and after the onset of orogeny at the end of Early Jurassic time indicate change from general quiesence to tectonic disruption and encroachment of a major quantities of volcanic sediment toward the southern region of the province. The absence of marine beds younger than Bajocian in the western Great Basin suggests that the western Great Basin has remained high and dry ever since the mid-Jurassic orogeny.

ORIGIN OF SUBSIDENCE OF THE WESTERN MARINE PROVINCE

The remarkable proximity of the continentward margin of the subsident region of the early Mesozoic marine province and the proposed Early Triassic collisional boundary between a late Paleozoic volcanic arc and the North American continent (Speed, 1977a) provides a ready explanation for the subsidence of the marine province. The marine province represents a successor basin to the collided late Paleozoic arc, and its subsidence was caused by thermal contraction of the late Paleozoic arc lithosphere.

After collison, the convergent boundary jumped west to an unknown, perhaps distant, location. Near its continental suture, at least, the lithosphere of the late Paleozoic arc cooled and contracted because pre-collison subduction-related heating was eliminated.

The rate of contraction, hence subsidence, was not evidently uniform throughout the successor basin. The basinal terrane presumably records the zone of maximum subsidence rate. The subsiding shelves sank apparently less rapidly even though parts of the shelf terrane lie above the late Paleozoic volcanic arc. The lower rate of subsidence close to the suture may be explained by the flexural rigidity of the volcanic arc and its weld at the suture. This effect does not, however, account for the wide and lobate form of the northern shelf terrane and the seemingly coextensive Early Triassic Koipato magmatism. A relatively simple hypothesis holds that local melting of subducted sediment added volume and water to the arc lithosphere at about the time of collision. Such events perhaps locally cooled and thickened the arc lithosphere and created a region of lower subsidence rate. Preliminary strontium isotopic studies (R. W. Kistler and R. C. Speed, in prep.), however, suggest the Koipato rhyolite was not a product of melting of continental or continentally-derived material. Perhaps upleaking of subduction-related water alone into a part of the colliding lithosphere could have provided the same results.

Subsidence of the part of the marine province in which the early Mesozoic volcanic arc terrane accumulated was evidently affected by heating that caused Triassic magmatism. If the hypothesis is correct that Triassic volcanism started at about 215 mybp, reheating in the lithosphere below the volcanic terrane presumably started sometime earlier, perhaps at 220 mybp. If collison of the late Paleozoic lithosphere was complete at about 235 mybp (approximate time of Koipato rhyolitic volcanism), a gap of some 15 m y intervened between the onset of cooling and reheating. Thus, the general hypothesis predicts that early subsidence occurred in the region of the volcanic arc terrane and that the later Triassic volcanism either filled the basin or accompanied uplift that caused regionally shallow marine conditions. The later Triassic magmatic event was fairly short-lived as here inferred from stratigraphic successions and more general, as interpreted by Kistler (1974) from chronologic studies of plutonic rocks of the Sierra batholith. Cessation of Late Triassic igneous activity in the volcanic terrane thus allowed resumption of lithospheric contraction, subsidence of the surface, and the development of a regional carbonate bank. It may be inferred that carbonate production could not keep pace with subsidence and that by latest Triassic time, the region became a more continuous offshore marine regime that accumulated the fines of the Sunrise type.

ORIGIN OF SILICATE MUD IN THE BASINAL TERRANE

An important factor in paleogeographic models of the Late Triassic of the cordillera is the origin of the copious silicate mud that accumulated in the basinal terrane and to a lesser degree, in the shelf terrane. As discussed earlier, the pelitic constituents of these terranes have no characteristics that evince their provenance. It would appear that some at least of the mud was transported by fluvial means west across the continental margin into the marine province starting approximately in late Middle Triassic and waning in late Late Triassic times. With these constraints, two source regions can be envisioned: 1) the subaerial region of the Triassic continental magmatic arc that extended southeast of the western marine province, and 2) a continental region east of the northern Colorado Plateau, as suggested by Silberling and Wallace (1969).

Although the existence of a major source east of the northern Colorado Plateau cannot be discounted, the arc source seems likely to have been a major contributor. The timing of onset and cessation of Triassic volcanism may be harmonious with that of mud influx to the marine province (within the uncertainty of absolute and relative time scales in the Triassic). The spottiness of thick remnants of volcanic successions of postulated Late Triassic age in Inyo County argues that an original belt of such rocks was severely eroded. The abundance of detrital mica that may have originally been biotite in rocks of the basinal terrane supports a volcanic source. Finally, sediment patterns in the subaerial Upper Triassic rocks of the southern Colorado Plateau support the idea that a volcanic source existed in southeastern California and Arizona and that fluvial transport was northerly to northwesterly (Stewart, 1969; Stewart and others, 1972). Thus, the marine province of northwestern Nevada and subaerial realms further east may have shared this sediment supply (J. H. Stewart, oral commun., 1978). The absence of evident volcanic particles in the basinal terrane and in Upper Triassic rocks of the northern plateau requires that such material was comminuted during long (300 km) transport and(or) alterated during diagenesis.

SUMMARY: MODEL OF PALEOGEOGRAPHIC EVOLUTION OF EARLY MESOZOIC WESTERN MARINE PROVINCE AND RELATED AREAS

The long standing Paleozoic continental margin in what is now central and western Nevada (Fig. 1) was the locus of collision with an easterly to southeasterly migrating late Paleozoic volcanic arc. The collision occurred in the Early Triassic perhaps at about 235 mybp but not necessarily everywhere at the same time. The late Paleozoic arc welded to the continental margin, and the convergent boundary that had previously dipped below the arc jumped far west to an unknown site (Speed, 1977a). Loss of subduction-related heating caused thermal contraction of the arc and created the subsident region of the early Mesozoic western marine provice of the Great Basin. A perturbation of unspecified nature, perhaps creating massive influx of subduction-related water may have caused local late stage Koipato magmatism in the collided (or colliding) edge of the arc lithosphere. Such magmatism was associated with processes that caused a lobate tract of the arc lithosphere to subside less rapidly than adjacent regions.

In the early phase of subsidence (235-215 mybp), the offshelf realm of the province was probably a deep water basin in which shelf-derived hemipelagic(?) carbonate and silicaclastic muds accumulated over the late Paleozoic basement (Fig. 2a).

Widespread magmatism began at about 215 mybp and caused volcanism in the southern half of the marine province (Fig. 2b) and probably in a contiguous belt of emergent territory at least as far south as Death Valley. Plutons of the Lee Vining intrusive epoch (Evernden and Kistler, 1970) in the Mono region and a Triassic intrusion in the southern marine province were comagmatic with the volcanic rocks. Together, these Triassic igneous rocks were the products of the construction of a new volcanic arc whose prolongation south of the marine province records the first Phanerozoic magmatism within the continental realm of the southern cordillera.

Magmatism in the southern part of the marine province filled the basin with volcanic rocks and (or) caused uplift of the seafloor so that shallow marine conditions existed there through most of the Norian. The volcanic terrane may have prograded north over the basinal terrane.

The subaerial Triassic volcanic pile which lay south of the marine province (Fig. 2b) was the source of the enormous volume of finegrained silicaclastic sediment that exists in the basinal terrane. Such sediment was apparently transported by fluvial systems 100 to 300 km north to the eastern margin of the subsident region. There, one or more fluvial-deltaic conduits, like that documented by Silberling and Wallace (1969) for the Grass Valley Formation, delivered sediment across the subsiding shelf to the upper slope break. From there, turbidity currents were the principal mode of transport of sediment to the basin floor, at least in the southern part of the deep basin. The subsiding shelf which occurred along the eastern margin of the deep basin was chiefly the site of carbonate regimes and of quartz sand beaches except where and when they were overrun by deltaic deposits (Grass Valley and Winnemucca Formations of Silberling and Wallace, 1969; facies

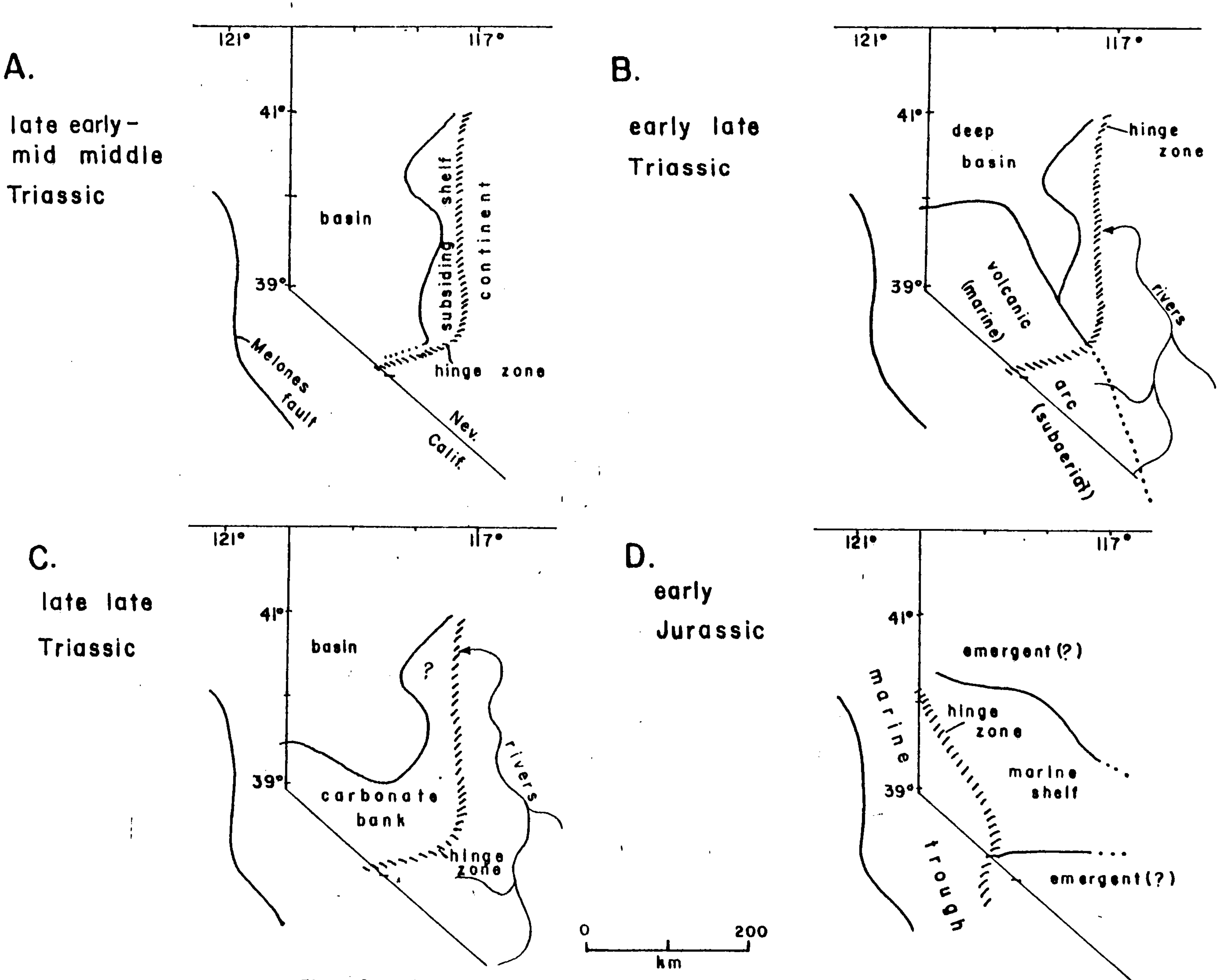
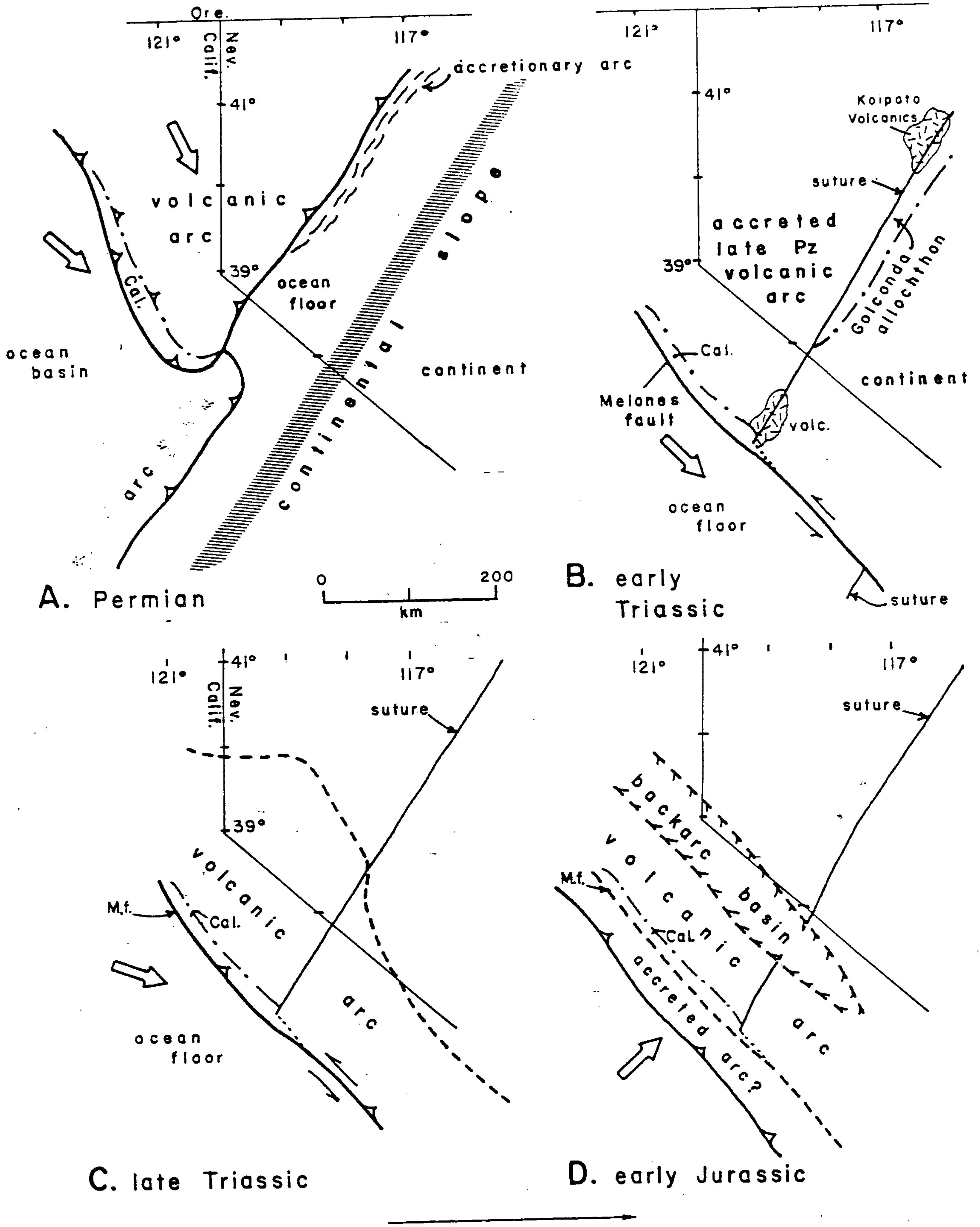


Figure 2: Paleogeographic evolution of the early Mesozoic western Marine province.


Ore.
121°
Calif.
Nev.
117°
accretionary arc
41°
volcanic arc
39°
Cal.
ocean floor
ocean basin
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A. Permian
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Koipato Volcanics
suture
accreted late Pz volcanic arc
39°
Golconda allochthon
Cal.
continent
Melones fault
volc.
ocean floor
suture
B. early Triassic
121°
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Calif.
Nev.
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volcanic
M.f.
Cal.
ocean floor
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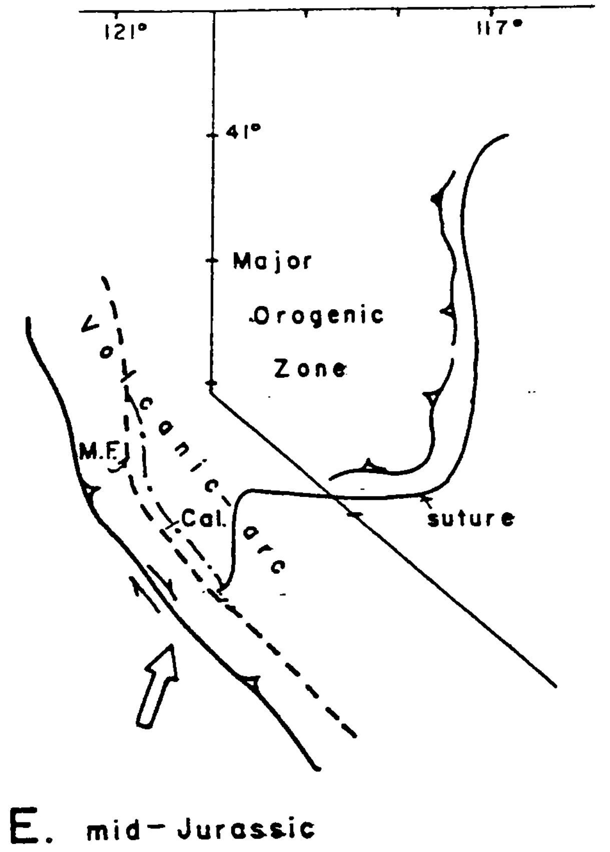

Figure 3: Diagrams showing model plate evolution in Permian to mid-Jurassic time; large arrows indicate direction of relative velocity of impinging plates, continent fixed; Cal. is Calaveras assemblage east of Melones fault and of the Merced River type.

of the middle member of the Luning Formation Oldow, 1977).

By late Norian time (200 mybp?), major changes had occurred in the marine province (Fig. 2c). Volcanism waned and may in fact have ceased. The southern region of the province was then covered partly if not continuously by carbonate banks. The basinal terrane received only meager influxes of silicaclastic debris relative to those of earlier time. Moreover, subsidence of the deeper basin waned, and the southeastern reaches of the basinal terrane shoaled as a carbonate bank near the end of Norian time. The entire marine province north of 40° may have emerged at about this time.

At about the beginning of the Jurassic, regions of the southern basinal terrane and the volcanic arc terrane were the remaining subsea realms of the marine province (Fig. 2d). The early Jurassic sea was probably of moderately uniform depth throughout, and it may have extended farther east than did Triassic seas of the province. The apparent prolongation of subsidence in the southern half of the province compared to that of the northern half may have been due to longer cooling time of its lithosphere because it was affected by a pulse of Late Triassic magmatism that was absent in the northern half.

The southwestern portion of the marine province in the Early Jurassic was transitional to a subsiding trough or basin that lay farther west and accumulated large volumes of volcanogenic material. Indeed, the evolution of the early Mesozoic marine province provides a record of the sudden creation of a basin marginal to the continent, its transformation through lithospheric cooling to a continental shelf-like regime, and the generation of a new marginal trough west of the accreted lithosphere.

Mid-Jurassic orogeny severely massaged the earlier marine province but probably had little to do with the inherent origin and evolution of the province. Rather, the orogeny seems more likely to have been related to reorganization of convergence at the new continental margin.

PLATE TECTONIC MODELS

Figure 3 illustrates a plate kinematic model which accounts for much of the evolution of the western marine province of the Great Basin and for certain other continental margin features. The kinematic constraints employed in the model are:
1) relative motion between late Paleozoic volcanic arc and continental margin at the time of collision was near-normal to the trend of the margin in central Nevada (Speed, 1977a); the suture has probably been rotated since collision, and the initial straightness and orientation are compliant parameters; northwesterly relative velocity is reasonable if the suture was initially straight, but more westerly if the suture has been little deformed.
2) the large width and lateral extent of the Jurassic phase of the Sierra batholith (Kistler, 1974) implies that Jurassic convergence was nearly normal to the trend of the plutonic mass (N25W) in California and parts south.
3) a component of right slip existed together with a large closing component during mid-Jurassic convergence at a boundary in or near the western Sierra Nevada; strong compression of Lower and Middle (?) Jurassic rocks in the Ritter pendant (Kistler, this vol.) was ascertained by Tobisch and Fiske (1977), and flattening of Jurassic strata in a N70°E direction exists in the southern region of the marine province; right slip is suggested by the configuration of the Early Triassic suture and continental margin as defined by the 0.706 strontium isotopic contour in the southern part of the marine province, assuming these trend lines were initially straighter as first argued by Albers (1967) and Stewart and others (1968); mid-Jurassic right slip may also be indicated by geometric analyses of deformed Mesozoic rocks in the western Sierra (Wetzel and Nokelberg, 1976) and by the possible north-westerly trend of the spreading center that created the mid-Jurassic Coast Range ophiolite (Hopson and others, 1974).

The models of Figure 3 assume a smooth transition in relative velocity from a north-westerly Permian direction to a north-northeast one in Middle Jurassic times.

Figure 3a shows a Late Paleozoic volcanic arc migrating southeast in the Permian and overriding ocean floor. The late Paleozoic volcanic rocks lie above earlier arc-related volcanic rocks and the lower Paleozoic Shoo-Fly Formation that are now exposed in the northern Sierra Nevada (D'Allura and others, 1977). Southwest of the volcanic arc was a plate boundary with slight convergence which had caused accretion of trench accumulations (the Calaveras Formation east of the Melones Fault;

Schweikert and others, 1977) against and under the arc pedestal. Migration of subduction zone below the Calaveras allowed Permian (259 my, Morgan and Stern, 1977) plutonism of the volcanic arc to affect the Calaveras as well as rocks of the arc pedestal. The plate southwest of the volcanic arc was presumably of chiefly oceanic character.

Figure 3b shows an assumedly straight Early Triassic collision boundary between volcanic arc and continent east of what is now the Melones fault. The accretionary arc of late Paleozoic ocean floor sediment propelled by the migrating volcanic arc lies on and was probably extruded over the continental shelf edge. A new convergent boundary developed about this time northwest of the area of Fig. 3 and the newly-defunct volcanic arc became welded to the continental margin, subsided, and created a successor Early Mesozoic marine province.

I speculate that the plate southwest of the late Paleozoic volcanic arc found means of detaching a fragment of the North American continent while maintaining essentially constant relative velocity. The new boundary is shown to be a transform fault with convergent motion taken up at an unknown location far to the southeast. This contrived boundary accounts for the oblique truncation of the continent first documented by Hamilton and Myers (1966); it accords with one of the truncation models of Burchfiel and Davis (1972), parallels the locus in the crestal Sierra Nevada of the 0.706 strontium isotopic line of Kistler (1974), and provides one means of explaining the major left lateral offset in Precambrian terranes of the Mojave region (Silver and Anderson, 1974). I agree with Schweikert (1976) (see also Kistler, this vol.) that the present Melones fault is the best candidate for the truncation surface.

By about 220-215 mybp (Ladinian-Karnian), relative velocity of the continent (and its accreted late Paleozoic arc in northwestern Nevada) rotated enough that the previous strike slip boundary had enough convergence to cause major magmatism (Fig. 3c). Zones of largely marine and largely subaerial volcanism were separated approximately at the Paleozoic continental margin because the substrata of those two zones had such disparate thermal, hence subsidence, histories in earlier Triassic time. The Late (and Middle?) Triassic volcanism shown in Figure 3c was the product of the first continental arc developed in the southern cordillera.

To account for the waning of Late Triassic volcanism and the apparent accumulation of thick volcanogenic strata in a subsiding trough in Early and Middle Jurassic time, I postulate (Fig. 3d) that the convergent boundary migrated west relative of its early Late Triassic position. The migration may have been caused by the further rotation of the relative velocity between continent and subducting plate to an orientation nearly normal to the earlier boundary and by accretion of various Jurassic arcs (Schweikert and Cowan, 1975). Thus, the Melones fault may have been abandoned at this time. A subsiding trough developed in back of the Early Jurassic arc, and caused deposition of rocks of the Ritter pendant, Sailor Canyon Formation, part of the Mt. Jura sequence, and the westernmost beds of western marine province of the Great Basin. The rest of the province was either emergent or a marine platform.

Figure 3e shows continuing rotation of the relative velocity to a north-northeasterly orientation and a sense of right-oblique convergence relative to the plate boundary. Figure 3e indicates major closure of the back-arc trough and right lateral drag together with major shortening of features in the Great Basin in a direction normal to the convergent component. Discrete right slip offset may have occurred on many faults in a zone which lies within the present Sierra Nevada. Thrusts in the Great Basin allowed rocks of the basinal and volcanic terranes to squeeze out over the shelf of the marine province to accommodate the shortening. Albers' (1967) sigmoidal bends were created by such tectonics. The Sierra foothills belt east of the Melones fault contains rocks that were originally contiguous with the substratum of the marine province of the Great Basin. Such rocks moved north relative to their Triassic position during Jurassic plutonism by virtue of the postulated right slip component of relative motion in Middle Jurassic and probably later times. The foothills belt may also have moved relatively west due to insertion of the plutonic belt.

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