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PERMO-TRIASSIC TECTONISM IN VOLCANIC ARC SEQUENCES OF THE WESTERN U.S. CORDILLERA AND IMPLICATIONS FOR THE SONOMA OROGENY

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Abstract. The Permo-Triassic Sonoma orogeny, western U.S. Cordillera, involved tight folding and imbricate thrust faulting of basinal strata of the Golconda allochthon. This event is generally interpreted in terms of accretion of upper Paleozoic volcanic arc rocks of the western U.S. Cordillera ("McCloud arc") to the North American continent, either via back arc basin closure or arc-continent collision. The structural history of the McCloud arc during the Sonoma orogeny is poorly understood, however, as are the implications of this history for tectonic models. This paper presents a synthesis of the Permian to Triassic stratigraphic and structural evolution of the McCloud arc, incorporating new data from the Pine Forest Range, northwest Nevada. The synthesis indicates that, on a regional scale, the arc was affected by widespread uplift but only local tilting, folding and faulting in the Late Permian to Early Triassic. The timing of Permo-Triassic tectonic activity in the McCloud arc is thus similar to the middle Permian to Early Triassic age of deformation in the Golconda allochthon but the structures produced in the two groups of rocks differ markedly. The significance of this contrasting structural response to Sonoma age tectonism can be evaluated by comparison with other better understood examples of arc-continent accretion (back arc basin closure in the southern Andes, "compressional" arc-continent collision in New Guinea and "extensional" arc-continent collision in the Mediterranean). This comparison indicates that the contrasting structural history of the McCloud arc and Golconda allochthon is entirely compatible with an arc-continent accretion model for the Sonoma orogeny and cannot be used as a basis for concluding that the McCloud arc was not involved in the orogenic event. The comparison further indicates that either back arc basin closure or "compressional" arc-continent collision are the most likely settings for the Sonoma orogeny. In contrast, an "extensional" Mediterranean-style arc-continent collision, as has been recently proposed for the earlier (middle Paleozoic) Antler orogeny, is probably not an appropriate analogue for the Sonoma orogeny. The weak structural response of the McCloud arc during Sonoman compression also provides new constraints on the specific processes involved in arc accretion, either via arc-continent collision or back arc basin closure. These constraints suggest that there may be few fundamental differences between the two models during the final stages of arc accretion. Regardless of tectonic setting, Permo-Triassic uplift and associated deformation in the McCloud arc should be considered as much a response to the Sonoma orogeny as is tight folding and imbricate faulting in the Golconda allochthon.

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INTRODUCTION

The Sonoma orogeny in the western U.S. Cordillera is defined as the Permo-Triassic deformational event that resulted in tight folding and closely spaced thrust faulting of the upper Paleozoic Havallah sequence, now contained within the Golconda allochthon (Figure 1) [Silberling and Roberts, 1962]. Two principal tectonic models have been proposed to explain the Sonoma orogeny, both of which consider upper Paleozoic volcanic and related strata of Washington, Oregon, California, and Nevada (Figure 1) to represent a volcanic arc that was involved in the orogenic event. One model suggests that the Havallah sequence and related rocks were deposited in a back arc basin behind a west facing arc; deformation of back arc basin strata occurred as a result of collapse and closure of this basin in Permo-Triassic time, perhaps as a result of changes in plate motions [Burchfiel and Davis, 1972, 1975; Silberling, 1973; Miller et al., 1984, 1991; Tomlinson and Wardlaw, 1988; Tomlinson, 1990; Whiteford, 1990]. A second model interprets the arc to have been east facing, and suggests that the Havallah sequence and related rocks were deformed as they were offscraped from the subducting edge of the North American plate and incorporated into a growing accretionary prism east of the arc [Speed, 1979; Snyder and Brueckner, 1983; Brueckner and Snyder, 1985]. According to this model, final emplacement of the accretionary prism (Golconda allochthon) was thus caused by arc-continent collision.

An important but unresolved aspect of the history of this part of the Cordillera concerns the Permo-Triassic development of the upper Paleozoic arc itself and the significance of this history to tectonic reconstructions of the Sonoma orogeny. This subject has been difficult to address in part because the Permo-Triassic structural history of the arc appears to have varied from area to area. For example, a locally angular unconformity, representing a hiatus from Late Permian to Late Triassic or Early Jurassic time, has long been recognized in the northern Sierra Nevada and cited as evidence of tectonism associated with the Sonoma orogeny [Clark et al., 1962; McMath, 1966; Harwood, 1983, 1988]. In contrast, there is no clear evidence for any Permo-Triassic tectonism in the Bilk Creek Mountains of the Black Rock Desert (Figure 1), where no structural discordance, and possibly no gap in time, exists between Permian and Triassic rocks [Ketner and Wardlaw, 1981; Jones, 1990]. In addition, where recorded at all, Permo-Triassic tectonism in the arc is primarily manifested by the occurrence of disconformities or gently angular unconformities, in striking contrast to the tight folds and imbricate thrust faults displayed by rocks of the Golconda allochthon. The significance of this contrast in deformational style was first explored by Silberling [1973], who suggested that it may be an expected consequence of back arc basin closure during the Sonoma orogeny. Later studies by Silberling and Jones [1982], Jones et al. [1988], Charvet et al. [1990], and Jones [1990], however, argue that the minimal record of Permo-Triassic tectonism in the arc may indicate that the arc was not involved in the Sonoma orogeny. This suggests that the upper Paleozoic arc was far removed from the North American continental margin in Permo-Triassic time and therefore not related to continental margin tectonism, a conclusion that contradicts both tectonic models described earlier.

This paper focuses on establishing the nature of Permo-Triassic deformation affecting the arc, and interpreting this deformation in the context of the tectonic setting of the Sonoma orogeny. The first topic is addressed through a regional analysis of the Permian to Triassic stratigraphic and structural history of volcanic arc sequences of the western U.S. Cordillera. The second topic is addressed through a comparison between the Permo-Triassic structural history of the western

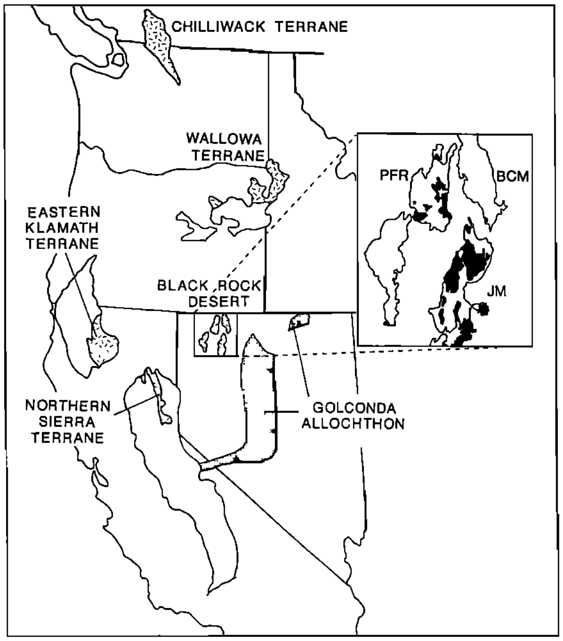

Fig. 1. Index map of the western United States showing areas of exposure of upper Paleozoic rocks. Dash pattern: volcanic arc and related rocks. Dot pattern: the Golconda allochthon. Inset of Black Rock Desert region with solid areas representing Paleozoic and Mesozoic rocks. PFR: Pine Forest Range. BCM: Bilk Creek Mountains. JM: Jackson Mountains.

U.S. Cordillera and the structural history of other better understood examples of arc-continent accretion.

PERMIAN TO TRIASSIC HISTORY OF THE VOLCANIC ARC

Upper Paleozoic volcanic and sedimentary sequences occur in the Chilliwack, Wallowa, eastern Klamath, and northern Sierra terranes of Washington, Oregon and California, and in the Black Rock Desert region of Nevada (Figure 1) and are interpreted to represent related remnants of a volcanic arc that lay some distance offshore of the continental margin of North America [Burchfiel and Davis, 1972, 1975; Miller, 1987; Miller et al., 1991]. Correlations between the upper Paleozoic rocks in these areas have been reviewed and discussed by Miller [1987], Wyld [1990], and Miller et al. [1991]. Following Miller [1987] these upper Paleozoic sequences will be referred to as parts of the McCloud volcanic arc. Within most of these areas the Permo-Triassic boundary has been recognized and described previously. The Permo-Triassic boundary in the Pine Forest Range, in contrast, has only recently been recognized [Wyld, 1990]. Because this portion of the boundary provides important new information on the structural history of the McCloud arc during Permo-Triassic time, the history of the Pine Forest Range in Permian to Triassic time will be described in detail below, followed by a regional synthesis of the Permian to Triassic history of the McCloud arc.

Pine Forest Range

The Pine Forest Range, northwest Nevada (Figure 1), contains a structurally intact section of lower (?) and middle Paleozoic through uppermost Triassic rocks [Wyld, 1990]. Permian and Permian (?) strata in the range unconformably overlie Upper Mississippian rocks and comprise a relatively thin sequence that includes probable Permian-age limestone and clastic rocks overlain conformably by well dated lower Guadalupian (lowermost Upper Permian) limestone (Figures 2 and 3 and Table 1). These strata are entirely shallow marine and are overlain variably by a thin and discontinuous sequence of interbedded chert and shale or by a regionally continuous sequence of limestone dated at Ladinian or Carnian (late Middle or early Late Triassic) near the base (Figure 2). Broad folding of the Mississippian and Permian rocks, as well as truncation of over 600 m of these strata along the boundary with the chert and limestone is obvious as shown in Figure 2. Considering only the well-constrained ages of the Triassic limestone and the Permian and older limestones and clastic rocks, these relations document a period of tectonism in the Pine Forest Range involving weak folding, uplift and erosion sometime between the early Late Permian and the late Middle or early Late Triassic. More precise determination of the timing of tectonism and the general history of this area from Permian into Triassic time depends critically on the age and significance of the chert/shale sequence.

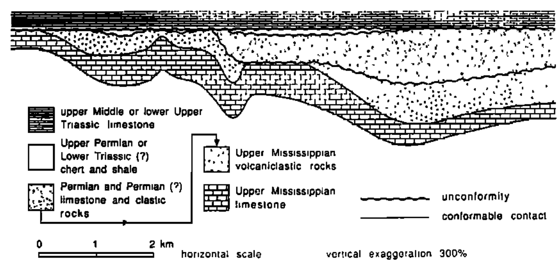

Fig. 2. Approximate downdip view showing unconformities and stratigraphic relations between upper Mississippian through Middle or Upper Triassic units in the east central Pine Forest Range [Wyld, 1990]. Figure was constructed by holding the base of the upper Middle or lower Upper Triassic limestone horizontal. Note 300% vertical exaggeration. Upper Mississippian limestone and Upper Mississippian volcaniclastic rocks were previously interpreted to be middle Carboniferous and early Pennsylvanian (?), respectively, based on preliminary U/Pb zircon data from tuffs in the volcaniclastic unit [Wyld, 1990]. These revised age assignments are based on a new concordant U/Pb zircon date of 327 Ma from the tuff (J. E. Wright, personal communication, 1991).

As shown in Figure 2, the chert/shale sequence is discontinuous but its outcrop distribution broadly parallels the base of the Triassic limestone. Bedding in the chert/shale sequence is also generally parallel to bedding in the overlying limestone. In contrast, the chert/shale sequence demonstrably overlies the Permian and older strata along a discordant contact (Figure 2). Collectively, these relations indicate tectonism prior to deposition of the chert/shale sequence but little evident deformation between deposition of the chert/shale sequence and the Triassic limestone. Conodonts extracted from the cherts are poorly preserved but have been dated by M. R. Orchard as probably Permian [Wyld, 1990]. An Early Triassic age is also possible but Middle or Late Triassic ages are considered unlikely (M. R. Orchard, personal communication, 1989). On the basis of this data, uplift and deformation associated with the unconformity beneath the chert and limestone occurred during the Late Permian and/or the Early Triassic and was succeeded by subsidence to depths sufficient for the accumulation of pelagic/hemipelagic sediments. The age data also indicate the presence of a hiatus between the chert/shale sequence and the

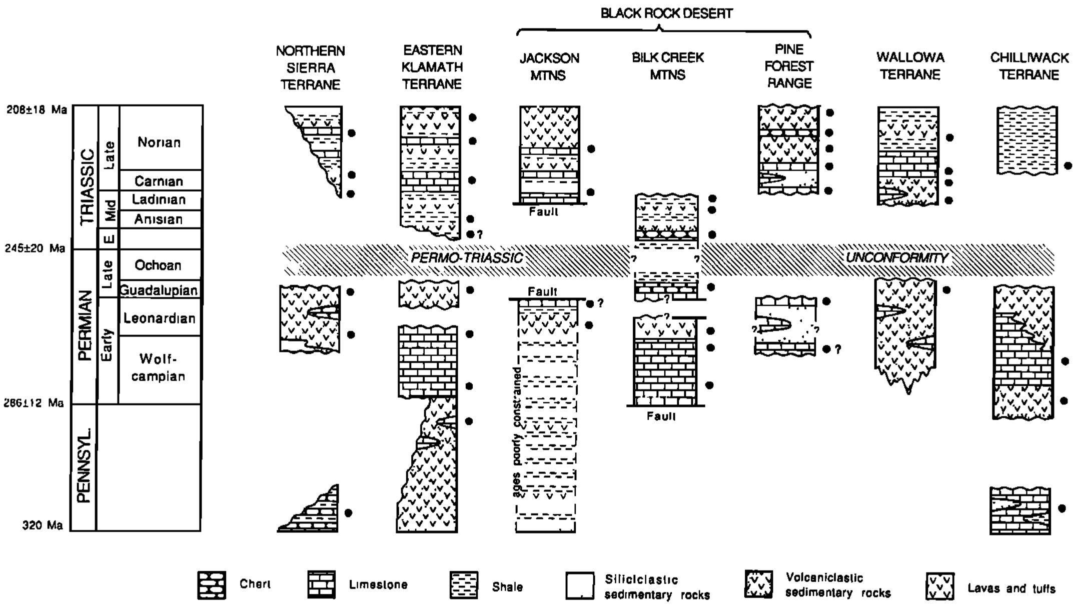

Fig. 3. Stratigraphic columns showing the relations between Permian and Triassic strata in arc sequences of the western U.S. Cordillera. Solid circle indicates fossil age control ("?" denotes uncertainty in age determination; see Table 1). An Upper Permian or Lower Triassic sequence of chert and shale is also present in the Pine Forest Range but is not depicted on this figure because of the fact that this sequence is discontinuous and very thin (generally less than 10 m) and is therefore not believed to represent a significant amount of time (see text). See Figure 1 for locations. Sources of data same as in Table 1. Time scale from Harland et al. [1982].

limestone that spans most or all of Middle Triassic time as well as possibly part or all of the Early Triassic, a period of as much as 15 m.y. according to the DNAG time scale. Although there is no significant evidence of deformation and only limited evidence of erosion between the chert/shale sequence and the limestone (Figure 2), this substantial hiatus indicates continued tectonic instability in the region during Early (?) and Middle Triassic time. Because the chert/shale sequence is discontinuous, thin (generally <10 m), and does not appear to represent a substantial amount of time, it is convenient to ignore it in the following discussions and instead view the Permo-Triassic history of the Pine Forest Range in terms of a period of Late Permian to Middle Triassic tectonic instability that resulted in a hiatus spanning most of that time period and demonstrably involved uplift and deformation during the Late Permian and/or Early Triassic.

Regional Synthesis

The Permian to Triassic stratigraphic and structural record of the McCloud arc in Washington, Oregon, Nevada, and California is summarized in Table 1 and Figure 3. Permian strata typically overlie older rocks across a middle Paleozoic unconformity and apparently reflect subsidence starting in the Late Pennsylvanian to Early Permian. These Permian strata generally consist of lava flows and volcaniclastic and sedimentary rocks, including the distinctive McCloud limestone and its correlatives [Skinner and Wilde, 1966; Miller, 1987]. By middle Permian (Leonardian and Guadalupian) time, subsidence was more pronounced, at least in the eastern Klamath and northern Sierra terranes where thick sequences of volcanic strata accumulated over short time intervals in locally extensional or transtensional marine basins [Harwood, 1988; Miller, 1989; Harwood and Murchey, 1990].

Middle Permian strata in the McCloud arc are typically overlain unconformably by younger strata (Figure 3 and Table 1). These relations have long been recognized in the Chilliwack, Wallowa, and northern Sierra terranes, but the nature of the Permo-Triassic boundary in the Black Rock Desert and eastern Klamath terrane has been less clear. In the latter area the absence of any obvious structural discordance or major hiatus between Permian and Triassic rocks has led some workers to conclude that the Permo-Triassic boundary is probably conformable [Albers and Robertson, 1961; Silberling and Jones, 1982; Miller, 1987; Renne and Scott, 1988]. When all available age data as well as variations in ages of units with area are considered, however, stratigraphic relations in the eastern Klamath terrane collectively indicate a hiatus from middle Permian to Anisian (early Middle Triassic) time in the southern part of the terrane and a probable hiatus from middle Permian to some part of the Early Triassic in the central and northern parts of the terrane (Table 1) [Coogan, 1960; Silberling and Jones, 1982; Curtis, 1983; Fraticelli et al., 1985; Miller, 1990; Miller and Harwood, 1990; Noble and Renne, 1990]. Similar arguments for a Permo-Triassic unconformity in the eastern Klamath Mountains have also been stressed by Miller [1990] and Miller and Harwood [1990].

A conformable Permo-Triassic boundary has also been suggested for the Black Rock Desert, based on relations in the Bilk Creek Mountains where Lower Triassic strata overlie lower Guadalupian (lowermost Upper Permian) rocks with no evident discordance (Table 1) [Ketner and Wardlaw, 1981; Jones et al., 1988; Jones, 1990]. As the Triassic rocks in this area are separated from the Permian rocks by only a thin sequence (30 m) of undated strata the apparently concordant stratigraphy could either reflect the presence of a condensed Upper Permian to Lower Triassic section or the presence of an Upper Permian to Lower Triassic disconformity [Ketner and Wardlaw, 1981;

Jones, 1990]. This latter alternative is now supported (but not required) by the documentation of an unconformity between Permian and Triassic rocks in the nearby Pine Forest Range as well as by the conspicuous absence of Permian rocks younger than middle Permian and Triassic rocks older than late Middle or early Late Triassic in the Jackson Mountains (Figure 3 and Table 1) [Russell, 1984; Maher, 1989]. These relations collectively suggest that a hiatus spanning the Late Permian to Middle Triassic is present throughout much of the Black Rock Desert region.

TABLE 1. Permian and Triassic Stratigraphy of Volcanic Arc Sequences of the Western U.S. Cordillera, and the Nature of Their Permian-Triassic Boundary

Location of Sequence*	Permian Stratigraphy	Triassic Stratigraphy	Permian-Triassic Boundary
Northern Sierra terrane	Shallow to deep marine facies mafic to intermediate lavas, volcaniclastic rocks, polymictic** clastic rocks, and chert (upper Wolfcampian (?) and Leonardian in lower part, lower Guadalupian in upper part).	Present only locally: shale, quartzose clastic rocks, tuffaceous rocks, and shallow marine limestone (Carnian, and locally Ladinian, to Norian).	Disconformity to highly angular unconformity. Hiatus mostly spanned late Guadalupian to Early Jurassic, but rocks above unconformity are locally Ladinian-Carnian. Substantial tilting, with minor faulting and folding but no penetrative deformation, locally associated with unconformity.
Eastern Klamath terrane	Platformal limestone (Wolfcampian to lower Leonardian); overlain, in most places disconformably, by basinal to shallow marine volcaniclastic rocks, mafic to silicic lavas, and minor limestone (Leonardian (?) to Guadalupian at base, lower Guadalupian at top).	Basinal to shelf facies shale, siltstone, and volcaniclastic rocks (Anisian at base in south, Lower Triassic (?) at base in north, Ladinian-Carnian at top); overlain by shallow marine limestone (Carnian), and volcaniclastic rocks, shale, siltstone, and limestone (Norian).	No angular discordance observed, but late Guadalupian to early Middle Triassic are missing in south and late Guadalupian and possibly part of Early Triassic are apparently missing in north. Some pre-Triassic penetrative deformation and folding may be present [Miller, 1990].
Bilk Creek Mountains	Shallow marine limestone (Wolfcampian to lower Leonardian); overlain by shale and turbidite facies volcaniclastic rocks (lower Leonardian at base); overlain unconformably or structurally by chert, carbonate, shale and volcaniclastic rocks (lower Guad-alupian); overlain, with no discordance, by 30 m of undated siltstone and shale.	Undated siltstone and shale; overlain, with no discordance, by chert, siltstone, shale, and minor volcaniclastic rocks (Lower Triassic at base, Middle Triassic at top).	May be conformable or disconformable. If disconformity is present, hiatus at most spanned late Guadalupian to Early Triassic time.
Jackson Mountains	Mostly slope and shelf facies volcaniclastic rocks, quartzose clastic rocks, andesitic lavas, limestone, chert, and shale (late Leonardian fossils present in lower part, possible late Early to middle Permian fossils near top).	Basinal to shelf facies shale, limestone, and polymictic clastic rocks (Ladinian or Carnian near base, Norian at top); overlain by basin to slope facies mafic to intermediate lavas and volcaniclastic rocks (upper Norian).	Generally not exposed due to faulting. May be exposed in one location where no angular discordance is observed and middle Permian (?) rocks are overlain by Triassic rocks that contain Ladinian or Carnian fossils 450 m above the contact. No evidence of pre-Triassic deformation of Permian rocks.
Pine Forest Range	Shallow marine limestone and polymictic clastic rocks (probably Permian at base, lower Guadalupian at top); overlain along weakly angular unconformity by chert and shale (Upper Permian or Lower Triassic (?)).	Chert and shale (Upper Permian or Lower Triassic (?)); overlain unconformably by deep marine limestone and polymictic clastic rocks (Ladinian or Carnian at base, Norian at top); overlain by deep marine mafic to intermediate lavas, volcaniclastic rocks, and minor chert (Norian).	Late Permian to Middle Triassic time largely missing across two unconformities. Tilting, minor folding and erosion occurred prior to deposition of chert. Some tilting and/or uplift and erosion occurred between deposition of chert and overlying limestone. No penetrative deformation associated with either unconformity.

TABLE 1 (continued)

Location of Sequence*	Permian Stratigraphy	Triassic Stratigraphy	Permian-Triassic Boundary
Wallowa terrane	Volcaniclastic rocks, and minor mafic to silicic lavas and limestone (undated in lower part, Leonardian or Guadalupian in upper part).	Mafic to intermediate lavas, limestone and volcaniclastic rocks (Ladinian-Carnian in lower part, upper Carnian in upper part); overlain by shallow marine limestone and deeper marine shale and volcaniclastic or polymictic clastic rocks (Upper Carnian to Norian).	Disconformable. Hiatus spanned some part of Leonardian or Guadalupian to Ladinian or Carnian time. No folding or penetrative deformation associated with disconformity.
Chilliwack terrane	Volcaniclastic rocks and polymictic clastic rocks (Pennsylvanian or Lower Permian); overlain by shallow marine limestone (Lower Permian); gradationally overlain by, and/or laterally gradational with, mafic to silicic lavas, volcaniclastic rocks, minor limestone and chert (inferred to be Permian).	Siltstone and shale (Upper Triassic).	Disconformable. Hiatus appears to have spanned some part of Permian through Late Triassic time. No folding or penetrative deformation associated with disconformity.

Sources of data: Chilliwack terrane [Danner, 1977; Monger, 1977; Monger and Berg, 1984]; Wallowa terrane [Vallier, 1977; Brooks and Vallier, 1978]; Pine Forest Range [Wyld, 1990]; Bilk Creek Mountains [Ketner and Wardlaw, 1981; Jones, 1990]; Jackson Mountains [Willden, 1964; Russell, 1984; Maher and Saleeby, 1988; Maher, 1989]; eastern Klamath terrane [Sanborn, 1960; Albers and Robertson, 1961; Silberling and Jones, 1982; Curtis, 1983; Watkins, 1985; Miller, 1987, 1989, 1990; Renne and Scott, 1988; Miller and Harwood, 1990; Noble and Renne, 1990]; northern Sierra terrane [D'Allura et al., 1977; Harwood, 1983, 1988; Hannah and Moores, 1986; Harwood and Murchey, 1990; Miller and Harwood, 1990].

* See Figure 1 for locations.

** "Polymictic" indicates that clastic rocks contain a mixed assemblage of volcanic and sedimentary clasts.

In many parts of the McCloud arc, the Permo-Triassic unconformity is a disconformity that is not associated with any clearly evident deformation (Table 1). In the Pine Forest Range, however, folding, tilting, uplift and erosion of strata underlying the unconformity are evident, as noted above. Similar relations are seen in the northern Sierra terrane where folding and faulting of pre-Triassic strata is locally evident as well as dramatic tilting of the pre-Triassic section (Table 1) [Harwood, 1983, 1988]. Some pre-Triassic folding and penetrative deformation of strata underlying the unconformity may also be present in the eastern Klamath terrane [Miller, 1990]. These relations are important as they document that the Permo-Triassic unconformity in the McCloud arc is associated with tectonism and cannot simply be a response to low global sea level during the Permian and Triassic [Vail et al., 1977; Haq et al., 1987]. Internal deformation of the arc was clearly limited, however, and the primary response to tectonism appears to have been uplift and erosion, resulting in common disconformities rather than angular unconformities.

The youngest strata below the Permo-Triassic unconformity in all arc sequences containing the unconformity are either known or believed to be middle or Late Permian, but the ages of oldest strata above the unconformity are more variable (Figure 3 and Table 1). In the eastern Klamath terrane, for example, postunconformity strata are Early Triassic (?) to early Middle Triassic in age. Some Lower Triassic strata may also be present in the Pine Forest Range, but, in general, Paleozoic rocks in the Pine Forest Range are overlain by upper Middle or lower Upper Triassic strata. Similarly, strata overlying the unconformity in the Chilliwack and Wallowa terranes and parts of the northern Sierra terrane are all late Middle or Late Triassic in age, while much of the northern Sierra terrane records a gap in time continuing into the Early Jurassic. In all areas, strata above the unconformity are marine and commonly reflect basinal conditions of deposition (Table 1), suggesting that Permo-Triassic uplift was succeeded by Triassic subsidence. The variable ages of the oldest postunconformity strata suggest that subsidence may initially have only been a locally developed phenomenon that did not become widespread until Late Triassic time.

Summary

The data discussed above indicate that the various exposed remnants of the McCloud arc experienced a generally similar history during Permian to Triassic time. Subsidence and at least local extension occurred in the Early to middle Permian and was succeeded in Late Permian through some part of Triassic time by a period of widespread uplift associated with minor tilting, folding and faulting. Because this period of time is largely represented by unconformities, it is difficult to determine precisely when uplift occurred; however, the ubiquitous absence of any dated strata of latest Permian (late Guadalupian or Ochoan) age and the general absence of any Lower Triassic strata (Figure 3 and Table 1) suggests that active uplift was ongoing in the latest Permian and much of the Early Triassic. One area within the arc (the Bilk Creek Mountains) may record continuous deposition across the Permo-Triassic boundary and may indicate that there were local areas in the arc that either subsided or were not subjected to as much uplift during this period of time; alternatively, this area simply records a short period of uplift lasting only from Late Permian (late Guadalupian) to some part of Early Triassic time. Highstanding conditions continued in many areas of the arc until the late Middle and Late Triassic, but the presence of lower Middle Triassic marine deposits in some areas suggests that active uplift had ceased by early Middle Triassic time.

COMPARISON WITH THE GOLCONDA ALLOCHTHON

The Golconda allochthon (Figure 1) consists of uppermost Devonian to lower Upper Permian (Guadalupian) strata (Havallah sequence and related rocks), deposited in the "Havallah" basin and deformed and thrust eastward onto the continental margin in Permo-Triassic time [Silberling and Roberts, 1962; Silberling, 1973; Miller et al., 1982, 1984, 1991; Snyder and Brueckner, 1983; Brueckner and Snyder, 1985; Murchey, 1990; Tomlinson, 1988, 1990]. Dominant structures in the allochthon are imbricate thrust faults and tight folds, with tectonic transport towards the east; these structures were largely formed prior to emplacement of the allochthon onto the continental margin. Deformation occurred under low-pressure and low-temperature conditions, and penetrative fabrics are uncommon. Structures within the allochthon have been interpreted to reflect long-lived polyphase deformation in a growing accretionary prism [Brueckner and Snyder, 1985], but this interpretation has been disputed by Miller et al. [1984, 1991], Tomlinson et al. [1987] and Tomlinson [1990], who demonstrate that shortening in many parts of the allochthon entirely postdated deposition of the youngest strata.

Age constraints for the timing of deformation within, and thrust emplacement of, the allochthon have been reviewed by Miller et al. [1991]. As emphasized by these authors, available data argue for completion of deformation and thrust emplacement in Early Triassic time. The time at which deformation began is less certain, however, as any interpretation of this subject depends critically upon whether deformation can be shown to postdate deposition of youngest strata in the basin [e.g., Miller et al., 1984, 1991; Tomlinson et al., 1987; Tomlinson, 1990] or to have occurred synchronously with deposition throughout the history of the basin [e.g., Brueckner and Snyder, 1985]. Although this subject remains incompletely resolved, available data do demonstrate that shortening postdated deposition of middle Permian strata within most areas of the allochthon [Miller et al., 1984, 1991; Murchey, 1990; Tomlinson et al., 1987; Tomlinson, 1990], thus indicating that at least much of the deformation in the allochthon occurred during middle Permian to Early Triassic time. This timing of deformation is very similar to the timing of uplift and tectonism in the McCloud arc as documented above. Although the style of deformation differs markedly between the two groups of rocks, the similarity in timing of deformation is consistent with an interpretation that the same underlying tectonic controls were responsible for structural activity in both sequences, as discussed below.

COMPARISON WITH OTHER EXAMPLES OF ARC-CONTINENT ACCRETION

In attempting to reconstruct the tectonic setting of the Sonoma orogeny the Permo-Triassic structural history of the McCloud arc and Golconda allochthon must be evaluated. In particular, it is critical to establish whether the contrasting structural development of the two groups of rocks is compatible with an arc accretion model for the Sonoma orogeny or whether it alternatively indicates that the arc was not involved in the orogenic event [c.f., Silberling and Jones, 1982; Jones et al., 1988; Charvet et al., 1990; Jones, 1990].

As has been well documented by numerous authors, deformation within convergent margin settings can be complex and can vary both spatially and temporally. Studies of modern convergent margins indicate that changing boundary conditions, such as the absolute velocity of the converging plates or the angle of subduction, strongly influence whether a regime of crustal shortening or extension prevails in the upper plate [e.g., Uyeda and Kanamori, 1979; Dewey, 1980; Cross and Pilger, 1982; Bott et al., 1989; Wdowinski et al., 1989]. Similar studies further indicate that the actual stress field within the upper plate can vary spatially as well as temporally, with compression affecting one region of the crust while extension affects another [Nakamura and Uyeda, 1980; Bott et al., 1989; Wdowinski et al., 1989]. These complexities are compounded in studies of ancient convergent margins because the character and degree of development of observed structures will depend not only on the deformational history but also on the composition of the deforming crust, paleo-heat flow, the total amounts of shortening/extension and crustal thickening/ thinning, and the current levels of exposure. All of these factors make it difficult to generalize about the expected structural development of convergent margins during events such as arc-continent collision or back arc basin closure.

Perhaps the best evidence that back arc basin closure or arc-continent collision can result in significant shortening of basinal strata trapped between the arc and continent but only minimal shortening of strata in the arc comes from studies of other convergent margin systems where the tectonic setting of arc-continent accretion is well established. Three end-member types of arc-continent accretion are known to occur, and examples of each are considered: (1) arc-continent accretion accomplished via back arc basin closure above a continent-directed subduction zone, (2) arc-continent collision, above an arc-directed subduction zone, in which trench retreat [e.g., Dewey, 1980] and intra-arc extension and subsidence are not important ("compressional" collision), and (3) arc-continent collision in which trench retreat promotes widespread intra-arc extension and subsidence during collision ("extensional" collision).

Well-studied examples of the first two include the Mesozoic back arc basin closure recorded in the southern Andes and South Georgia Island regions ("southern Andes region") [Suarez and Pettigrew, 1976; Bruhn and Dalziel, 1977; Thomson et al., 1977; Bruhn, 1979; Dalziel and Palmer, 1979; Suarez, 1979; Tanner and Rex, 1979; Tanner et al., 1981; Tanner, 1982] and the Tertiary "compressional" arc-continent collision of New Guinea [Jaques and Robinson, 1977, 1980; Hamilton, 1979; Johnson, 1979; Norvick and Hutchison, 1980; Milsom, 1973; Cullen and Pigott, 1989]. In both of these areas, volcanic arc strata are separated from an adjacent continental block by a belt of coeval deep marine deposits that were strongly deformed during arc-continent accretion (Figure 4). These basinal strata are affected by thrust faulting, pervasive continent-vergent folding, and variable degrees of penetrative deformation, in much the same way that basinal strata of the Golconda allochthon were deformed during the Sonoma orogeny. In contrast, arc strata in both areas were affected only by uplift, weak tilting, minor faulting, and some gentle, long-wavelength folding during arc accretion (Figure 4). This structural record is, correspondingly, very similar to the Permo-Triassic deformational record of the McCloud arc. Significantly, data from both New Guinea and the southern Andes region clearly demonstrate that deformation of arc and basinal strata, although of contrasting styles, occurred during arc-continent accretion.

The best examples of "extensional" arc-continent collision occur in the Mediterranean region [Malinverno and Ryan, 1986; Royden and Burchfiel, 1989] and include the Cenozoic collision between the Africa-Adriatic continental plate and a volcanic arc constructed on the continental crust of Corsica and Sardinia (Figure 4) [Malinverno and Ryan, 1986 and references therein]. In this system, arc-continent collision resulted in uplift and widespread continent-directed thrust faulting and folding of continental margin strata, now contained within the Apennine mountain chain (Figure 4). Compression near the suture zone was associated, however, with contemporaneous extensional

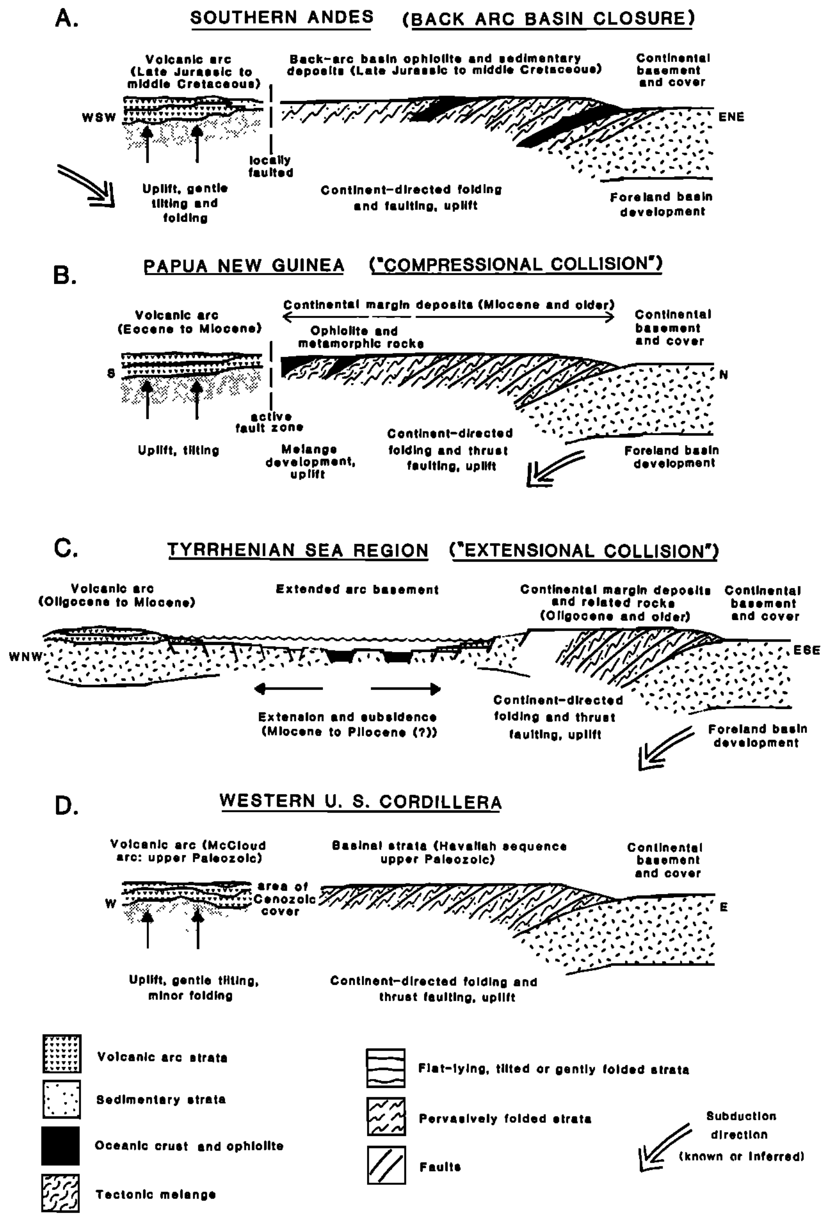

Fig. 4. Generalized, schematic cross sections of arc-continent accretion. For clarity, structures, intrusions, and strata younger than the age of arc accretion are omitted in all sections. (a) A collapsed Mesozoic back arc basin in the southernmost Andes region showing structural relations between volcanic arc strata, back arc basin strata, and the South American continent (relations summarized from Suarez and Pettigrew [1976], Bruhn and Dalziel [1977], Thomson et al. [1977], Bruhn [1979], Dalziel and Palmer [1979], Suarez [1979], Tanner and Rex [1979], Tanner et al. [1981], and Tanner [1982]). Arc accretion occurred during middle Cretaceous time. (b) "Compressional" Tertiary arc-continent collision in Papua New Guinea showing structural relations between the Australian continental basement and continental margin strata, a subduction complex, and the collided volcanic arc (relations summarized from Jaques and Robinson [1977, 1980], Hamilton [1979], Johnson [1979], Norvick and Hutchison [1980], Milsom [1973], and Cullen and Pigott [1989]). Collision occurred during early through late Miocene time. (c) Cenozoic "extensional" arc-continent collision that involved trench retreat and intra-arc extension in the central Mediterranean region showing structural relations between the Adriatic continental plate, continental margin and related strata (now part of the Apennine mountain chain), and the collided volcanic arc and its extended basement (Corsica-Sardinia and Tyrrhenian sea region) (relations summarized from Heezen et al. [1971], Alvarez et al. [1974], Carmignani et al. [1978], Savelli et al. [1979], Pescatore and Slaczka [1984], Malinverno and Ryan [1986], and Anderson and Jackson [1987]). The Apennine fold and thrust belt developed from Oligocene and Miocene to Plio-Pleistocene time and is inferred to have formed as an east-southeasterly growing accretionary prism. The Tyrrhenian sea opened as the trench retreated to the east-southeast during collision. The locus of arc volcanism migrated with the trench, although active volcanism ceased during the main phase of intra-arc extension. (d) The McCloud volcanic arc and deformed basinal strata of the Havallah sequence (the latter now contained within the Golconda allochthon) of the western U.S. Cordillera.

faulting and subsidence in the arc; over 300% intra-arc extension has occurred, sundering the basement of the volcanic arc and forming the Tyrrhenian sea basin, which is now over 3000 m deep (Figure 4) [Heezen et al., 1971; Malinverno and Ryan, 1986; Anderson and Jackson, 1987]. This intra-arc tectonic history is interpreted to result from collision-driven trench retreat and subsequent upper plate extension [Malinverno and Ryan, 1986]. Although the structural history of this arc differs from the Permo-Triassic structural history of the McCloud arc (see discussion below), this example nonetheless also serves to demonstrate that the structural response of an arc to arc-continent accretion may be very different from that of basinal strata trapped between the arc and continent.

These three examples provide clear evidence that arcs can experience a minimal amount of crustal shortening during arc-continent accretion, at least at high crustal levels, compared to that experienced by basinal strata trapped between the arc and the continent, a conclusion that applies to both arc-continent collision and back arc basin closure. It is beyond the scope of this paper to discuss specific factors causing this variation in structural response, and it is not implied that limited shortening deformation within arc strata is a necessary consequence of arc-continent accretion, as it may not always be. However, these examples do serve to demonstrate that the Permo-Triassic deformational history of the McCloud arc and Golconda allochthon is entirely consistent with an arc accretion model for the Sonoma orogeny and cannot be used as an argument that the arc was not involved in the orogenic event. This conclusion is further supported by a wide variety of new data indicating stratigraphic, sedimentalogic and paleogeographic ties between the McCloud arc, Havallah basin and North American continent [Tomlinson and Wright, 1986; Harwood and Murchey, 1990; Tomlinson, 1990; Whiteford, 1990; Harwood et al., 1991; Miller and Saleeby, 1991].

COMPARISON BETWEEN THE ANTLER AND SONOMA OROGENIES

The structural record in the McCloud arc and Golconda allochthon is remarkably similar to that in the closed back arc basin system of the southern Andes and the "compressional" arc-continent collision of New Guinea (Figure 4). Either of these models are therefore viable analogues for the Sonoma orogeny, a conclusion that is in accord with most previous interpretations of the tectonic setting of the orogeny. The record of regional uplift in the McCloud arc during the Sonoma orogeny, however, does not appear to be consistent with a Mediterranean-style "extensional" arc-continent collision model in that trench retreat in these collisions should result in widespread intra-arc extension and subsidence (Figure 4) [Malinverno and Ryan, 1986; Royden and Burchfiel, 1989]. This conclusion is relevant in light of the interpretation by Burchfiel and Royden [1991] that a short-lived period of Mediterranean-style "extensional" arc-continent collision was responsible for the Early Mississippian Antler orogeny in the western U.S. Cordillera, an orogenic event whose similarities to the Sonoma orogeny have long been noted.

The interpretation of Burchfiel and Royden [1991] concerning the tectonic setting of the Antler orogeny is based in part on a record of compression and uplift in continental margin strata during this earlier event, contemporaneous with subsidence and extension between the compressional belt and the accreted lower-middle Paleozoic arc (now exposed largely in the Sierra Nevada and Klamath Mountains). In addition they note the long-puzzling lack of volcanic arc material in the Antler orogenic belt, a feature difficult to reconcile with classic "compressional" arc-continent accretion models in which arc uplift and erosion are expected. This lack of volcanic input can instead be related to a history of extension, subsidence and associated deep marine conditions of deposition in at least parts of the accreted arc during the time of the Antler orogeny [Watkins, 1986; Harwood and Murchey, 1990].

None of these relations appear to characterize the Sonoma orogeny. There is no record of extension or subsidence immediately behind the Golconda allochthon during the time of the Sonoma orogeny and, although intra-arc extension and subsidence appears to have affected the McCloud arc during the very earliest stages of the orogeny (middle Permian), this history was replaced by uplift and some compression during the main phase of the orogeny (Late Permian to Early Triassic). In addition, volcanic arc detritus formed a significant input to parts of the Havallah basin during the earliest stages of the Sonoma orogeny [Tomlinson and Wright, 1986; Tomlinson, 1988, 1990]. Whether arc input continued during the main phase of the Sonoma orogeny cannot be determined because of the lack of strata of this age preserved in the Golconda allochthon and environs. Middle Permian arc input, however, does require proximity if not local uplift and erosion of the McCloud arc during at least part of the Sonoma orogeny.

Collectively, these features point out significant differences between the Antler and Sonoma orogenies that have not previously been explored and suggest that it may be inappropriate to seek identical tectonic models to explain both orogenic events. As noted below, however, the tectonic setting of the Sonoma orogeny may have been similar in certain respects to the tectonic setting proposed by Burchfiel and Royden [1991] for the Antler orogeny.

TECTONICS OF THE SONOMA OROGENY

Although the data presented here do not distinguish between "compressional" arc-continent collision and back arc basin closure for the Sonoma orogeny, they do yield new insights into the specific processes involved in either arc accretion scenario. Of particular importance is the very limited record of crustal shortening in the arc region during Sonoma age compression, a record differing substantially from the pronounced penetrative deformation characterizing the Cordilleran arc region during later periods of compression (e.g. Jurassic [Schweickert et al., 1984; Wright and Fahan, 1988]). Only two situations appear capable of explaining this record. (1) Crustal shortening, accomodated at high crustal levels in the Havallah basin, was accomodated at depth in the arc region, leaving the upper levels of the arc as a relatively undeformed, coherent block. (2) Crustal shortening initiated in strata of the Havallah basin but was short-lived and ceased prior to any substantial deformation of the arc. In the context of an arc-continent collision model, this would imply that convergence between the arc and continent ceased shortly after collision. As the underlying tectonic forces drawing the two plates together are unlikely to have ceased due to collision, however, it is probable that continued convergence would have been accomodated after collision by initiation of continent-directed subduction beneath the accreted arc. Such flips in subduction polarity are both a predicted and observed response to arc-continent collision [McKenzie, 1969; Dewey and Bird, 1970; Cooper and Taylor, 1987].

In the context of back arc basin closure, it is unlikely that shortening would have been localized entirely in the back arc basin as compressional stresses at convergent margins increase towards the trench [Nakamura and Uyeda, 1980; Bott et al., 1989; Wdowinski et al., 1989] and shortening in the back arc should therefore have been accompanied by simultaneous shortening in the arc. The lack of substantial deformation in the upper part of the McCloud arc therefore argues for shortening at depth beneath the arc. An obvious interpretation incorporating this conclusion is one in which the back arc basin closed via short-lived subduction of the back arc crust beneath the arc, in the process of which strata deposited in the basin were offscraped into an accretionary prism on the continent side of the arc and ultimately thrust onto the continental margin. Subduction of the floor of the Havallah basin has been suggested by previous workers and is supported by the virtual absence of any ophiolitic rocks in the Golconda allochthon despite evidence that the Havallah basin was floored by oceanic crust [Burchfiel and Davis, 1972, 1975; Snyder and Brueckner, 1983; Brueckner and Snyder, 1985; Tomlinson, 1990]. Subduction of the back arc crust beneath the arc is also consistent with the continent-directed vergence of structures in the Golconda allochthon. If this model is correct, then back arc subduction may have ceased relatively quickly due to interference between the two oppositely-directed subducting slabs beneath the arc, leaving the arc as a largely undeformed, coherent block. Interestingly, this model is very similar to the model proposed by Burchfiel and Royden [1991] for the Antler orogeny except that in this model the arc experiences uplift and compression rather than extension and subsidence during accretion.

An important corollary of these interpretations is that during the final stages of arc accretion, back arc basin closure and arc-continent collision may be structurally identical for all practical purposes. Distinguishing between the two tectonic settings based purely on structural grounds would thus be very difficult. This conclusion has also been stressed by Miller et al. [1982, 1984, 1991] and is supported by the observation that structures formed during back arc basin closure in the southern Andes are very similar to structures formed during arc-continent collision in New Guinea (Figure 4). This structural ambiguity underscores the importance of using other lines of evidence, such as stratigraphic, paleogeographic, and/or regional relations, in interpreting the Permo-Triassic development of the western U.S. Cordillera [e.g., Miller et al., 1984, 1991; Tomlinson and Wright, 1986; Miller, 1987; Miller and Wright, 1987; Tomlinson, 1988, 1990; Harwood and Murchey, 1990; Stevens et al., 1990; Whiteford, 1990; Harwood et al., 1991; Miller and Saleeby, 1991]; at the present time, these latter relations collectively favor a model in which the McCloud arc was west facing and the Havallah basin was a back arc basin.

CONCLUSIONS

In evaluating the tectonic setting of orogenesis, the structural history of all parts of an orogenic belt must be taken into consideration. The Permo-Triassic history of the McCloud arc has often been ignored in structural and tectonic interpretations of the Sonoma orogeny, however, leading to controversy over whether the structural history of this arc is actually compatable with the arc-continent accretion models typically proposed for the orogenic event. In this paper, the Permian through Triassic history of the McCloud arc is examined on a regional scale and it is concluded that an important period of tectonism, primarily manifested by uplift but also associated with limited compressive deformation, affected the arc during the time of the Sonoma orogeny. The Permo-Triassic structural history of the arc is very different, however, from the record of tightly spaced folding and imbricate thrust faulting developed in basinal strata trapped between the arc and the continent (now contained in the Golconda allochthon), a difference that must be evaluated before tectonic models can be accurately constructed. Because the state of stress in convergent margin settings is dependent on a wide variety of factors whose influence can vary both spatially and temporally, it is not possible to define any single model that is universally appropriate for the expected structural development of rocks formed in these settings. The history of the McCloud arc and Golconda allochthon is thus more profitably evaluated through a comparison with other areas where arc accretion has occurred but the tectonics of arc accretion are better understood (back arc basin closure in the southern Andes, "compressional" arc-continent collision in New Guinea, and "extensional" arc-continent collision in the Mediterranean). This comparison indicates that the contrasting structural history of the McCloud arc and Golconda allochthon is perfectly compatable with an arc accretion model for the Sonoma orogeny and cannot be used as a basis for concluding that the McCloud arc was not involved in the orogenic event. Further implications of this comparison are: (1) both back arc basin closure and "compressional" arc-continent collision are consistent with the Sonoma age structural history of the McCloud arc and Golconda allochthon and (2) a Mediterranean-style arc-continent collision involving trench retreat and associated intra-arc extension and subsidence, as appears applicable to the middle Paleozoic Antler orogeny in the western U.S. Cordillera [Burchfiel and Royden, 1991], is not consistent with the record of regional Sonoma age uplift in the McCloud arc. The contrasting amounts of deformation recorded in the McCloud arc and Golconda allochthon further imply that crustal shortening during the Sonoma orogeny was either accomodated at depth in the arc or that shortening inititated in the basin and ceased before the arc was significantly deformed. If arc-continent collision is the appropriate model, these relations suggest that collision was short lived and may have been followed by a flip in subduction polarity. If back arc basin closure is the appropriate model, the structural relations suggest that closure took place via short-lived subduction of the back arc crust beneath the arc. An important implication of these conclusions is that, during final arc accretion, the process of back arc basin closure may be very similar to the process of arc-continent collision, thus lending further emphasis to the view that the two tectonic settings cannot be readily distinguished on structural grounds alone. Other lines of evidence, including stratigraphic, paleogeographic, and regional relations, are therefore critical to establishing the tectonic setting of the Sonoma orogeny.

Finally, the record of Late Permian to Early Triassic uplift with local folding, tilting and faulting in the McCloud arc is concluded to be as much an expression of the Sonoma orogeny as is the tight folding and closely spaced thrust faulting of the Golconda allochthon. The structural consequences of the Sonoma orogeny should thus be expanded to include Sonoma age uplift and associated tectonism in the McCloud arc.

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