DAVID BLOOM

TECTONIC EVOLUTION OF THE GOLCONDA ALLOCHTHON, NEVADA: PROBLEMS AND PERSPECTIVES

Walter S. Snyder
Research and Development,
Phillips Petroleum Company
Bartlesville, Oklahoma 74004

Hannes K. Brueckner
Department of Earth and Environmental Sciences
Queens College of CUNY, 65-30 Kissena Blvd.
Flushing, New York 11367
and
Lamont-Doherty
Geological Observatory
Palisades, New York 10964

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ABSTRACT

The upper Paleozoic Golconda allochthon of central and northern Nevada is an oceanic terrane that was thrust over continental North America sometime between the latest Permian and Late Jurassic. The rocks of the allochthon (the Havallah sequence) include: (1) ridge-type, tholeiitic pillow lava, (2) ridge-type massive sulfide and siliceous Fe and Mn deposits, (3) pelagic and hemipelagic, radiolarian chert and argillite, and (4) siliciclastic, calcareous and volcaniclastic turbidites. Structurally, the Havallah sequence is an imbricate stack of thrust plates bounded at the base by the Golconda thrust. Many of the internal thrust plates (lithotectonic units) have undergone complex, polyphase deformation involving at least four structural phases. The event resulting in emplacement of the allochthon eastward onto North America has been commonly termed the Sonoma orogeny.

Despite recent studies by several workers, some important questions remain unresolved. These include: (1) the paleogeographic setting of the Havallah depositional basin, (2) the mechanism, timing, and duration of internal deformation, and (3) the mechanism and timing of overthrusting onto continental North America.

We feel, based on existing structural, lithologic, and paleontologic data, that the best responses to these questions are as follows: first, that the Havallah basin was largely floored by oceanic crust, part of which was actively spreading throughout most of the upper Paleozoic, and thus represents a back-arc basin sequence, or, more likely, was part of a large ocean basin (Paleopacific); second, that the Golconda allochthon was tectonically stacked and internally deformed in an accretionary prism during a large portion of the upper Paleozoic prior to being thrust (obducted) eastward onto the North American continent; and third, that although the timing of this obduction is not yet well constrained, it probably occurred sometime during the late Early to Middle Triassic. Regardless of the timing, we emphasize that the tectonic overthrusting of the Golconda allochthon onto North America was only the culmination of a protracted structural evolution within an accretionary prism.

INTRODUCTION

The upper Paleozoic Golconda allochthon of central and northern Nevada (Fig. 1) is a component of the collage of terranes that have been accreted to western North America. We still lack a basic understanding of the paleogeography of these terranes, the timing and mechanisms of accretion, and the type and magnitude of post-emplacement deformation (Coney, 1972; Monger, 1977; Davis and others, 1978; Hamilton, 1978; and Jones and others, 1982). Although general overviews are valuable, the solutions to these problems will only come from continued detailed studies of each terrane. The Golconda allochthon is of further interest because of its easterly position in the collage, which requires that models for its emplacement form the basis for or strongly influence models for the subsequent accretion of outboard terranes.

The Golconda allochthon is an oceanic chert-turbidite-greenstone terrane that was thrust onto continental North America sometime between the latest Permian and Late Jurassic. The rocks of the allochthon include: (1) ridge-type, tholeiitic pillow lava (greenstone), (2) ridge-type massive sulfide and siliceous Fe and Mn deposits, (3) pelagic and hemipelagic radiolarian chert and argillite, and (4) siliciclastic, calcareous, and volcaniclastic turbidites. Tectonostratigraphic units within the allochthon (Fig. 1) include the: Schoonover complex (Miller and others, 1982b, and in press), Willow Canyon Formation (Laule and others, 1981), Pablo Formation (Speed, 1977b), and several unnamed chert-shale units. The Havallah sequence (Silberling and Roberts, 1962) comprises the bulk of the Goldconda allochthon and will be the general term used to refer to all these tectonostratigraphic units. Fossils (foraminifera, radiolaria, and conodonts) suggest an age range of Late Devonian to early Late Permian for the Havallah sequence.

Structurally, the Havallah sequence is dominated by internal thrusts and shear zones, and is bounded at the base by a single or multiple sole thrust, the Golconda thrust. Beneath the Golconda thrust are the upper Paleozoic rocks of the Overlap sequence and the erosional remnants of the Roberts Mountains allochthon (Silberling and Roberts, 1962). The original extent of the Golconda allochthon is shown on Figure 1 as a more or less continuous structural entity. This assumption may be incorrect. For example, the Willow Canyon Formation and its neighbor to the southeast may be gravity driven klippe detached from the main body of the allochthon. Conversely, some exposures of presumed lower Paleozoic chert sequences in the Antler Orogenic Belt east of the presently known Golconda allochthon may, with additional paleontolgic data, turn out to be

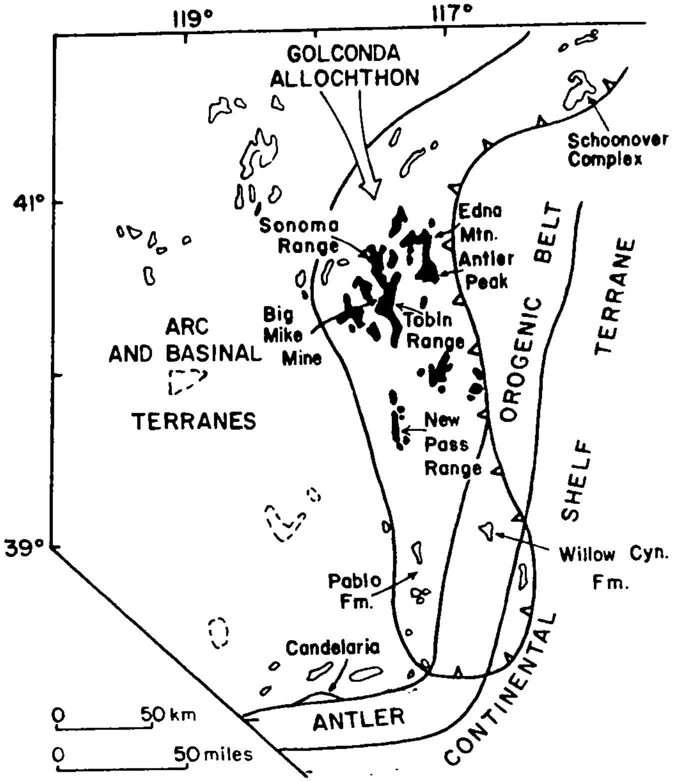

Figure 1. Upper Paleozoic paleogeography of Nevada showing outcrops of the Havallah sequence, modified from Speed (1977a) and Stewart and others (1977). Outcrops originally assigned to the Havallah sequence are shown in black. Thrust on eastern boundary of the Golconda allochthon is conceptual, assumes an original sheet-like form to the Golconda allochthon, and would be equivalent to the Golconda thrust.

pieces of the Havallah sequence (Laule and others, 1981 and in press). Finally, the present position of the Schoonover complex in northeastern Nevada may partly be the result of Mesozoic thrusting, and thus not reflect the original location of the Golconda allochthon in that region.

Despite recent studies by several workers, (e.g., Silberling, 1975; Miller and others, 1982a, b; Stewart and others, 1977; MacMillan, 1972; Laule and others, 1981; and Dickinson and others, in press) some important questions remain unanswered. The paleogeographic setting of the Havallah depositional basin is unresolved. Was the Havallah a relatively small back-arc basin adjacent to North America at the paleolatitude of northern Nevada, or does the Golconda allochthon contain structural scraps of a much larger ocean basin (paleo-Pacific)? How was the Havallah basin opened and closed; what were the mechanisms and duration of these events and when did they occur? Finally, the mechanism and timing of the emplacement of the allochthon onto North America is still a topic for discussion.

Our goal in this paper is to discuss some logical alternatives for the tectonic evolution of the Golconda allochthon. Although we have developed what we feel is the best working hypothesis for the evolution, we acknowledge that it is a provisional model and thus, this paper should be viewed as a progress report.

A final, somewhat sobering thought seems appropriate, to wit, Dickinson's (1977) uncertainty principal for orogenic belts: "It may be impossible to know simultaneously the relative ages and the relative positions through time of all crustal elements encountered in the field."

PETROTECTONIC ASSOCIATIONS

The petrotectonic associations within the Havallah sequence are the key indicators of the type of crust that formed the basement of the Havallah basin, the depositional environment of the sedimentary rocks, and the source of the clastic debris. Detailed descriptions of the rock types within the Havallah have been presented elsewhere (Fagan, 1962; Roberts, 1964; MacMillan, 1972; Snyder, 1977, 1978, in preparation; Stewart and others, 1977; Miller and others, 1982a, b, in press; and Dickinson and others, in press). Only a brief summary will be given here.

Greenstone

The greenstones are mostly nonschistose metabasalts, although meta-andesite (?) has been reported (Miller and others, 1982b). The greenstones contain albite, chlorite, epidote, leucoxene, + relic pyroxene, + calcite, +quartz, and clay, and can be divided into three basic lithologic types: (1) pillow lava, (2) massive flows, and (3) hyaloclastites and pillow breccias. The bulk of the greenstone is either pillow lava or massive flows. Hyaloclastites are composed of fragmental basaltic glass, now altered to chlorite-rich material, which resulted from the shattering of the glassy outer surfaces of subaqueous lava flows (Rittman, 1962; Silvestri, 1963). Pillow breccias are composed of broken and whole pillows floating in a hyaloclastite matrix. All gradations exist from pillow breccia with tightly packed pillow fragments to rather homegenous "aquagene tuff" (Carlisle, 1963) which contains few, if any, large clasts of pillow lava.

Major oxide analyses of the greenstones broadly confirm their basaltic character, and suggest they are tholeiites (Snyder, 1977, in preparation; Rogers and others, 1974). However, possible chemical changes due to the ubiquitous, low grade alteration limits the usefulness of the major oxide data. The relatively refractory elements Ti, Zr, and Y provide a means to better classify the general petrotectonic affinity of these altered basalts. Most analyses plot in the ocean floor basalt fields (Fig. 2) of the discrimination diagrams of Pearce and Cann (1973). The data on Figure 2 thus support the interpretation of the major oxide data and further suggest that the bulk of the pillow lavas were tholeiites extruded at an oceanic spreading center(s).

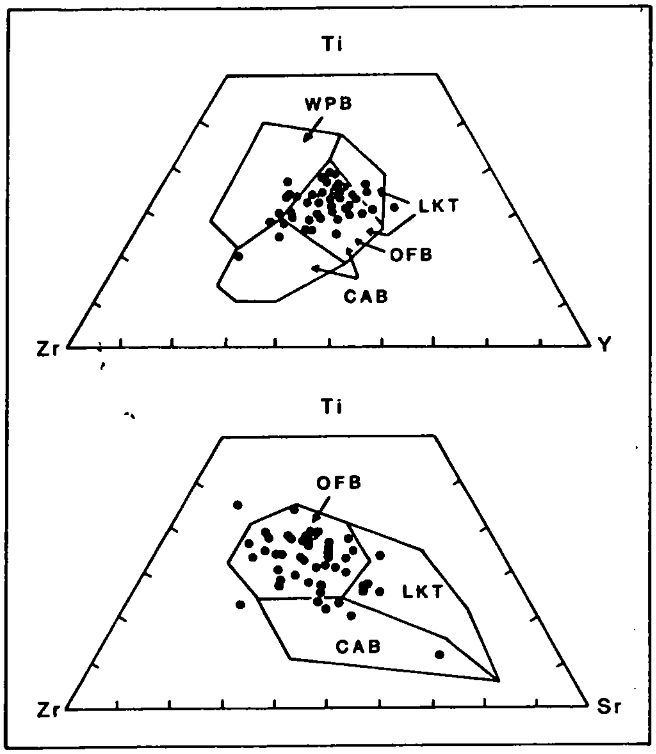

Figure 2. Plots of Ti, Zr, Y, and Ti, Zr, Sr for Havallah pillow lavas. Graphical technique from Pearce and Cann (1973). All samples (50) are from the center of pillows or from massive flow units. LKT = low potassium tholeiite of island arcs; OFB = ocean floor basalt; WPB = within plate basalts; CAB = calcalkaline basalts of island arcs.

Chert-argillite

The siliceous sedimentary rocks of the chert-argillite assemblage comprise over 50 percent of the Havallah sequence. There is a textural and compositional gradation between pure, bedded (or ribbon) chert, siliceous argillite, argillite, and siliceous shale or mudstone and these lithologies are characteristically interbedded. The dark, commonly nodular chert which replaces limestone is not discussed here. Bedding thickness ranges from a few millimeters up to 25 cm. Bedded chert is composed primarily of cryptocrystalline to microcrystalline quartz with significant, but variable, amounts of chalcedony, mainly along veins. Terrigenous detritus includes clay (largely illite and chlorite), quartz silt, and variable amounts of dolomite, calcite, and feldspar. Authigenic phases include locally abundant pyrite and perhaps some of the dolomite. Volcaniclastic chert-turbidites are locally associated with lithic sandstones (Fig. 3). The chert is commonly cut by veins of megaquartz and chalcedony. Most of these veins are the product of diagenesis and sediment loading, although some may be related to a combination of diagenesis and tectonism.

Abundant radiolaria within the bedded chert suggest that these quartzose rocks are the final diagenetic product of original biogenic siliceous

Figure 3. Volcaniclastic, chert turbidite, Willow Creek, Battle Mountain. Volcaniclastic debris concentrated at base of bed. Possible water escape feature extends out of the sand horizon.

Figure 4. Ribbon chert and siliceous argillite.

Figure 5. Lenticular bedded chert. Note the preferred orientation of the long axes of the lenticles and their possible clockwise rotation.

ooze (Snyder, 1972, 1977; Fagan, 1962). There is no unambiguous evidence that any significant amount of the chert was derived from the alteration of silicic tuff. With increasing proportions of hemipelagic clay detritus, biogenic radiolarian ooze grades into siliceous mudstone (argillite). Coarser detritus reflects the composition of interbedded turbidite deposits. Graded chert, defined by radiolaria concentrations in the lower portions of beds, can be attributed to current reworking of siliceous ooze (Fagan, 1962; Nisbet and Price, 1974).

Dark colored, medium to thick bedded, silty cherts appear to be silicified limestone turbidites (Miller and others, 1982a; Laule and others, in press). The silt fraction represents preserved detritus of the original limestone turbidite. These "cherts" contain the Nereites trace fossils which are characteristic of unaltered Havallah limestones. Silica released during the solution-reprecipitation diagenesis of interbedded radiolarian chert was the probably source of the silica.

The chert-argillite assemblage represents pelagic and hemipelagic sediments deposited in a starved basin. Water depths cannot be inferred from the presence of these siliceous rocks. Calcareous nannofossils are not known from the Paleozoic (Garrison and Ficher, 1969). Therefore, during the Paleozoic, radiolarian-rich sediments could have been deposited in relatively shallow water above the calcium carbonate compensation depth, and yet not be masked by a rain of carbonate debris.

The often cited pinch and swell and lenticular profiles of bedded chert in the Havallah and other chert sequences generally are not primary features. These lenticular bedding features invariably have long axes parallel to bedding, aligned in preferred orientations. They are thus tectonic features (compare Figs. 4 and 5). Bedding-parallel microstylolites suggest that significant silica dissolution accompanied the formation of these structures. This pressure solution resulted from the tectonic deformation of siliceous rocks that were in intermediate (opal-A or opal-CT) diagenetic stages (see Structure section; Brueckner and Snyder, in press). However, mound-like features (Monroe structures), which also have lenticular or elliptical profiles, are strictly diagenetic features (see Fagan, 1962). Monroe structures form conspicuous knobs on bedding surfaces that are circular in form. Compressed laminations suggest differential compaction in the rock surrounding the Monroe structures. During the early phases of tectonism, these structures acted as points for stress concentration and therefore pressure solution in adjacent beds. Monroe structures are therefore early diagenetic features.

Sandstones

The compositions, ages, and distributions of Havallah sandstones provide important information for understanding the evolution of the Havallah basin (Dickinson, 1977; Dickinson and others, in press; Miller and others, 1982b, 1983; Snyder and Girty, 1979). There are four basic sandstone types within the Havallah sequence: (1) silty and sandy limestones, (2) quartz arenites, (3) lithic sandstones, and (4) volcaniclastics.

The limestones include calcirudites, limestone turbidites, and silty micritic limestones. The calcirudites are composed of intraclasts of foraminifera, chert, and quartz in a microspar matrix. Grain size of the terrigenous components varies from about 2 to 5 mm. The calcirudites generally crop out as massive beds (about 1 m thick). The abraded foraminifera within these debris flows are apparently indigeneous to the Permian miogeocline of the western Cordillera (Stevens, in Stewart and others, 1977). A western source terrane for some of these limestones is suggested by one sample which yielded a Permian fusulinid assemblage typical of that found in the eastern Klamath Mountains of northern California (Stewart and others, 1977). The upper Paleozoic rocks of the eastern Klamath Mountains comprise an arc terrane (Dickinson, 1977; Speed, 1977; Schweickert and Snyder, 1981). Efforts to recollect this sample have failed, and therefore a non-North American source for some of the limestones has not been conclusively identified (C. H. Stevens, oral communication, 1982).

Typical exposures of limestone turbidites in the Havallah sequence show a base-missing (i.e., A and B Bouma intervals are missing) distal turbidite sequence (e.g. Stewart and others, 1977). The petrographic examples studied are characterized by a micrite to microspar matrix which makes up as much as 75 percent of the rock. Terrigenous, sand to silt sized, subangular to subrounded, framework components include lithic clasts, chert fragments, feldspar, quartz, intraclastic spar, and fossil debris. Lithic clasts are composed of monocrystalline quartz set in a crypto- to microcrystalline quartz matrix. Fossil debris includes abraded foraminifera and bryozoan fragments. Quartz grains are polycrystalline and monocrystalline. Some monocrystalline quartz fragments are composed of rounded to subrounded central grains with secondary overgrowths of optically and crystallographically continuous quartz. Rare pebble sized carbonate intraclasts are composites of sand or silt sized quartz or chert grains in a sparry matrix. Feldspar is highly altered to sericite, but polysynthetic twins can still be recognized.

The micritic limestones are composed of about 37 percent monocrystalline quartz silt and 63 percent micrite. A vague lamination in hand samples is due to small changes in grain size. The micritic limestones probably represent very distal turbidites.

The quartz arenites contain as much as 100 percent quartz. These mature quartzose sands however are interbedded with units that contain as much as 12 percent chert lithics. The amount of matrix ranges from 8-17 percent, and grain shapes are subangular with generally poor sorting. The dominant terrigeneous component is monocrystalline quartz which exhibits undulatory extinction and deformation lamellae and bands. Polycrystalline or composite quartz fragments also are present in varying proportions. The mechanism of transport of these sands probably was by some form of fluidized or grain flow process.

The matrix of the lithic sandstones ranges from 11-33 percent and is composed of intergrowths of sericite, chlorite, cryptocrystalline quartz, and red, iron-stained clay. Grain shapes are subrounded to subangular. The framework grains generally range from 0.01 to 5mm. Terrigenous framework grains are variable in composition and include monocrystalline quartz, polycrystalline or composite quartz, chert, potassium feldspar (optically determined), plagioclase (An_{11} to An_{13}), metamorphic rock fragments, and lithic fragments. In one sample, volcanic fragments form 20 percent of the rock. The protolith of the lithic fragments probably is siltstone. The mineralogy of the samples studied suggests that the source terrane contained andesitic, plutonic, chert and hemipelagic lithologies, and metamorphosed rocks.

The volcaniclastics are generally gradational in composition with the lithic sandstones. The volcaniclastics are marked by a greater abundance of feldspar and volcanic lithics in addition to the framework grains listed for the lithic sandstones. Some are best termed feldspathic sandstones. Locally some quartz-feldspar porphyry and possible rhyolite clasts have been noted in breccias and coarse sandstones (e.g., at Willow Creek, Battle Mountain and the southern Shoshone Range). Volcanic conglomerates or breccias also occur at Clear Creek, in the Sonoma Range, and in the Independence Mountains. Some of the clasts are up to 50cm in size. Examination of a few samples of the so-called tuffs from the Schoonover complex (Miller and others, 1982b) suggests that they are better termed feldspathic sandstones because they are composed primarily of feldspar but also contain variable amounts of metamorphic, chert, volcanic, and sedimentary lithics.

Most of the volcaniclastics were derived from a magmatic source terrane. The Antler Orogenic Belt (Fig. 1) has been identified as the probable source for the lithic sandstones (Miller and others, 1982a, in press; Dickinson and others, in press). However, the apparent compositional gradation between the volcaniclastic and lithic sandstones suggests that both types of clastics may have been derived from a combined magmatic-recycled orogen source. This latter possibility bears directly on the tectonic interpretations for the evolution of the Golconda allochthon.

STRATABOUND-STRATIFORM MINERALIZATION

The chert-greenstone units of the Havallah sequence contain massive jasperoid, siliceous manganese and massive sulfide deposits. These lithologies and mineralization denote a oceanic paleoenvironment, and most probably represent products of the magmatic, sedimentary, and hydrothermal processes that operate at oceanic spreading centers (Snyder, 1977, 1978).

The Big Mike mine in the northern Tobin Range, is a massive sulfide deposit of the classic volcanogenic-type (Fig. 1). The Fe-Cu-Zn sulfide mineralization consists of stratiform pyrite in carbonaceous shale, a massive stratabound lens, and zones of cross-cutting stringer veins, veinlets, and disseminations. The massive ore occurs within a carbonaceous chert-shale unit between underlying and overlying units of pillow lava. The details of the geology, ore petrology, and the trace element and isotopic geochemistry of this deposit are reported elsewhere (Snyder, 1977; Rye and others, in press).

The massive jasperoid and siliceous managnese deposits within the Havallah sequence are products of the same type of hydrothermal system that produced the Big Mike sulfide ore body (Snyder, 1978). The stratabound manganese deposits are spatially associated with pillow lava and consist of manganese oxides in a fine-grained quartz or chert gangue. These bodies were deposited by submarine hot springs near the exhalative vents. The hematite-rich massive jasperoids are conspicuous features in the chert-greenstone units. Radiolaria have been extracted from some of the sill-like jasperoids, indicating that these conformable bodies were deposited at or near the sediment-seawater interface. Dike-like bodies of jasperoid crosscut the bedding of the chert and were deposited along faults and fractures as indicated by the repeated brecciation and recementation within these jasperoid bodies. Jasperoid fragments also occur as clasts within hyaloclastite pillow breccias.

The metallogenetic setting of the Havallah sequence is closely analogous to the hydrothermal processes that operate at modern oceanic spreading centers (e.g., Rona, 1982; Normark and others, 1982; Koski and others, 1982). As in the modern counterpart, the generation of this mineralization can be modeled by a hydrothermal system where recirculated seawater rises along faults and fractures at or close to spreading centers. The magmatism provides the necessary heat to drive the hydrothermal system. The hydrothermal or hot spring waters precipitate minerals both at the sediment-water interface and at depth along the faults and fractures. Under favorable circumstances, these hot spring systems deposit large amounts of quartz, iron, manganese, copper, zinc and sulfur in the from of massive "mounds" on the seafloor or as fracture fillings and disseminations in the surrounding pillow lava and sediments.

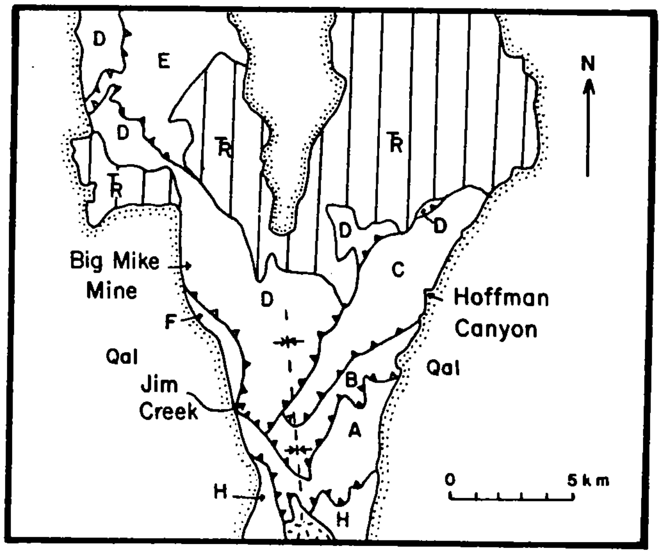

Figure 6. Lithotectonic map of a portion of the Tobin and Sonoma Ranges. Units A to H are part of the Havallah sequence; TR includes the Koipato and Star Peak Groups.

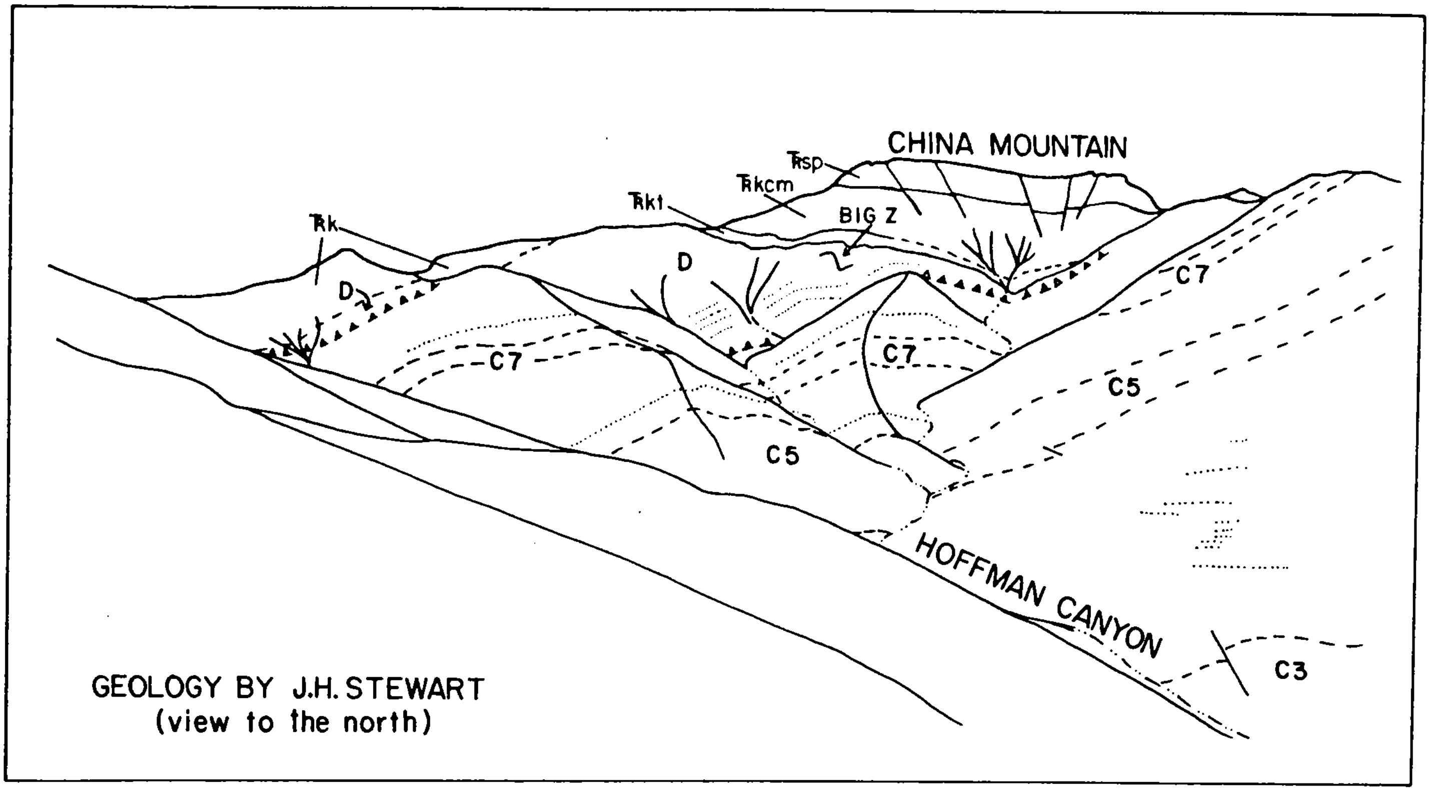

Figure 7. Sketch from photographs of the geology of units C and D, Figure 6. TR k: Koipato Group undivided; TR kt: Rochester tuff (Koipato); TR kcm: China Mountain Fm. (Koipato); TR sp: Star Peak Group. The C and D units correspond to those in Figure 6. Note, both here and in Figure 6, the marked angular unconformity between the Havallah and the Koipato, and the planar nature of this contact. Distance across skyline is approximately 3½ km, and distance from viewer to China Mountain is about 4 km.

LITHOTECTONIC STRATIGRAPHY

Lithotectonic units bounded by large displacement thrust faults define the tectonic stratigraphy of the Golconda allochthon. These map units are defined primarily by lithology and age and are generally structurally complex and do not represent simple stratigraphic units. Most contacts within the lithotectonic units are structural; a few may be depositional. The subunits bounded by these internal thrusts are called tectonic packets. Units A through H are lithotectonic units from the northern Tobin Range (Fig. 6). Units C and D represent the most obvious examples of lithotectonic units (Stewart and others, 1977; Fig. 7). Unit D is a chert-greenstone unit of Mississippian-Early Pennsylvanian age, whereas unit C consists of one-third Pennsylvanian bedded chert and two-thirds Permian limestone turbidites (J. H. Stewart, B. Murchey, D. Jones, B. Wardlaw, oral communication, 1982). These units are separated by the Hoffman Canyon thrust (Stewart and others, 1977). Lithotectonic units may be similar in age and lithology, but differ mainly in the degree of internal structural disruption (e.g., unit B is more "chaotic" than unit C (Fig. 6).

Unit C also provides good examples of tectonic packets (Units C1 through C7) separated by hillside-scale imbricate thrusting (Fig. 7). Even-numbered packets (i.e., C2, C4, etc.) are Permian limestone turbidites, odd-numbered units (i.e., C1, C3, etc.) are largely older chert-argillite (Stewart and others, 1977). Many, if not all the packets are structurally bounded. Parallel bedding attitudes between and within these subunits are not good evidence for depositional contacts because the thrust surfaces are generally subparallel to bedding. The tectonic packets locally contain internal shear zones and thrusts. The displacement along most of these structures is not yet known, although some are certainly small and merely sheared out fold hinges (MacMillan, in Stewart and others, 1977).

We mapped an approximately 500-meter section at a scale of about 1:1500 in Willow Creek, Battle Mountain (Fig. 8). Radiolarian ages indicate that this is apparently a single Lower Permian stratigraphic unit (Miller and others, 1982a; B. Murchey, personal communication, 1982). However, it has been structurally imbricated along thrusts of outcrop scale displacements (Fig. 8) and is hence a lithotectonic unit. The Golconda thrust forms the base of this unit. Folds that refold earlier folds and thrusts occur within the allochthon directly above the Golconda thrust. Those portions of the autochthonous Antler Peak Limestone that are in contact with the thrust also contain a few scattered folds. Structures demonstrably tied to the Golconda thrust can be delineated with certainty only within approximately 50 m of the thrust surface, as noted by MacMillan (1972) in the New Pass Range. The refolded structures as well as folds and faults that are not refolded higher in the structural

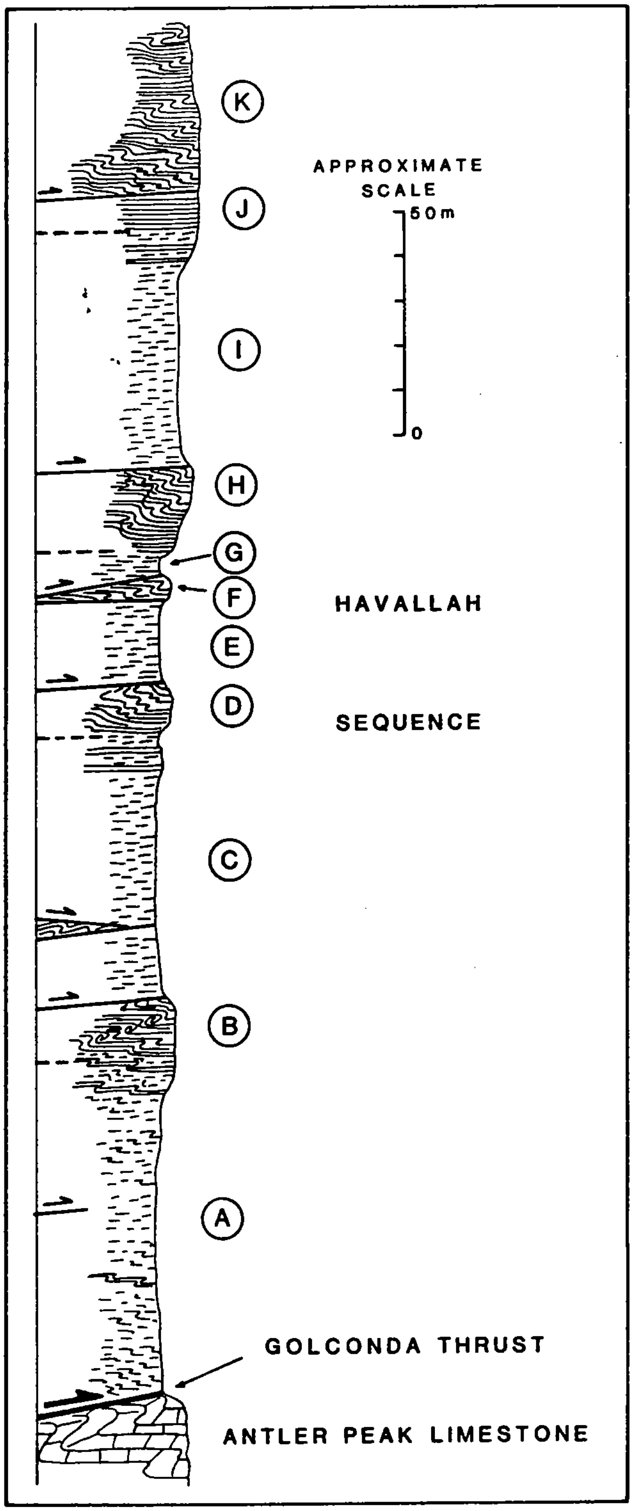

Figure 8. Schematic structural section of the Lower Permian chert-argillite sequence, Willow Creek, Battle Mountain. Note refolded folds in unit B. Any number of low displacement, cryptic thrusts could cut the argillite sections. Dashed lines denote argillite units (A,C,E,G,I) and solid lines, chert packets (B,D,F,J,K). Heavy dashed lines are depositional contacts. View is to the north.

stack are believed to be pre-Golconda thrust structures. This observation is stengthened by the fact that the Golconda thrust cuts several thrust-bounded lithotectonic units at Battle Mountain, including the one depicted in Figure 8.

The age and structural complications illustrated by the lithotectonic stratigraphy demonstrate that the old Havallah and Pumpernickel Formations (Roberts and others, 1958) are not valid stratigraphic units, as first noted by Silberling and Roberts (1962). These old terms can be used as general lithologic guides in areas where detailed remapping has not been done. Importantly, depositional contacts within the Havallah sequence should not be assumed, but must be documented. The present thrust plate geometry is not that of a simple older over younger imbricate stack. Rather, variable older over younger and younger over older structural juxtapositions are the rule. The difficulty of assuming depositional contacts and the complex structure make reconstruction of a vertical basin stratigraphy extremely hazardous.

STRUCTURE

The structural fabric of the Golconda allochthon provides critical data for: (1) unravelling the lithotectonic stratigraphy and hence the paleogeography of the Havallah basin; (2) evaluating models of basin closure, and (3) dating the time of the Sonoma orogeny. Detailed analysis of this fabric is presented elsewhere (Brueckner and Snyder, in press), so only a brief summary will be given here.

As noted above, the structure of the Havallah sequence is dominated by penetrative thrusts at all scales (Figs. 6, 7, and 8). These thrusts have cut the chert, argillite, and other lithologies into "packets" which may be centimeters to tens of meters thick and meters to hundreds of meters long. Most chert packets are bounded by thrusts and these thrusts ultimately shear off individual units along strike. Thus, there is no orderly stratigraphic succession perpendicular to strike and limited continuity parallel to strike. The pervasive shearing of the Havallah gives it a deceptively homoclinal appearance and obscures the complicated internal structures. These internal structures include veins, high-angle fractures, breccias, and more than one generation of folds. Different chert packets exhibit these structures to varying degrees: some have most, others a few, and still others almost none. A most striking feature of this extremely heterogeneous structural style is that virtually undeformed ribbon chert can be found in direct contact with highly deformed chert packets.

Structural Chronology

Table 1 provides a preliminary chronology of the deformational events that have affected parts of the Havallah sequence (see Brueckner and Snyder, in press, for a more complete discussion). We emphasize that no single packet contains all of these structural fabrics, although a few contain most of them. Even though the events are placed in chronological order, the structures in a packet of one age may have formed at a totally different time than similar looking structures in a packet of different age.

Depositional and Early Diagenetic Structures

Certain features within the Havallah sequence formed during deposition and early diagenesis. These include slump folds in the limestone turbidites. Quartz-filled fractures that generally occur at high angles to bedding, but otherwise show no obvious preferred orientation, are believed to have formed due to diagenetic volume changes and to sediment loading. Heterogeneously distributed, bedding-parallel microstylolites suggest many chert layers suffered dissolution during D_0, presumably also a result of sedimentary loading. The degree of development and spacing of the microstylolites varies, sometimes radically, from layer to layer, indicating variable solubilities during pressure solution. Finally, the nodules that give some chert layers a mound-like texture (Monroe structure) may have formed during this event.

First Phase Structures

Many of the processes that began during D_0 are believed to have continued during D_1 except that the structures developed in an anisotropic strain field. We believe that oriented lenticles with long axes parallel to bedding and elliptical profiles formed during this time (Fig. 5). Microstylolites wrap around these lenticles suggesting bedding-parallel solution continued during lenticulation. The slaty cleavage in argillite may have formed through a combination of pressure solution and perhaps flattening that resulted in the rotation and diagenetic recrystallization of clays. High-angle fractures cut chert layers and have dip slip displacements and strikes that parallel the long axes of lenticles. These fractures rarely affect more than one or a few layers. Vertical adjustments to differential bedding parallel solution during D_1 may have produced these fractures. Rare, rootless, isoclinal folds may have formed during D_1, but it is difficult to distinguish these possible F_1 folds from the more prevalent F_2 folds.

Second Phase Structures

Several generations of east-verging folds of variable geometry and shears characterize this event. Evidence for multiple generations include refolded folds, folds cut by shears, shears cut by younger shears, and shears that have been folded. Most fold axes parallel the lenticle lines formed during D_1, but those few localities where the fold axes are not parallel, show the lenticle lines to be folded. Thus, folding post-dated the lenticulation event suggesting that the folding is a separate and later structural event (F_2).

There are at least two east-verging fold subsets based on refolding relationships and their relationships to shear zones. Pre-shear structures and folds that have been refolded are classified as F_{2A} folds (Table 1). Shear zones that cut the F_{2A} folds reflect a later event (S_2) and are in places deformed by F_{2B} folds. Similarly, folds that refold earlier folds are labeled F_{2B}. Naturally, folds that are not associated with shears, or refold earlier folds, or show strong evidence of ductile deformation could fall into either subset and hence are simply called F_2 folds. Virtually all F_2 folds are overturned toward the east and suggest overthrusting to the east or underthrusting to the west.

There are at least two and probably more shear sets in the Havallah sequence, some of which may have post-dated D_2. Younger shears cut older shear zones at several localities. Two and even three sets of shallow-plunging slickensides can be observed at many outcrops.

Third Phase Structures

A later set of folds (F_3) appears to be restricted to chert beds near thrusts of large displacement. These folds are geometrically very similar to F_{2B} folds. They have parallel profiles, relatively open geometries, eastward vergence and a disharmonic folding style. However, they fold one and sometimes two sets of F_2 folds and some of the F_3 folds are very large, such as the fold just above the thrust contact of unit D with unit C in Hoffman Canyon, Tobin Range (Big Z in Fig. 7), which has an amplitude of approximately 30 meters. This fold deforms one or two previous set(s) of tight to isoclinal folds which we interpret to be F_2. Refolded folds near the Golconda thrust in Willow Creek, Battle Mountain, may have a similar origin (Fig. 8). However, these folds may be F_{2B} folds which refold F_{2A} folds. The large folds and the large-scale thrusts possibly are related to the eastward obduction of the Golconda allochthon onto the North American continent, an event which we believe to be distinct from the internal shearing and folding of the Havallah sequence during D_2.

Fourth Phase Structures

The last folding episode to affect the Havallah sequence was generally minor in nature in the areas we have studied. Small-scale, open, buckle folds of western vergence have been observed which refolded all previous folds (Fig. 9). Minor folds of westward vergence cut the shear fabric of the Golconda thrust at Edna Mountain, near Golconda Summit, and in the Toquima Range (Laule and others, in press). Finally, the area around Clearwater Canyon, Sonoma Range, contains large-scale thrusts which have been attributed to Mesozoic faulting (Gilluly, 1967; Silberling, 1975). These faults are associated with folds with strong axial surface cleavages, some of which display a westward vergence. These considerations justify classifying F_4 folds as belonging to a separate event and tentatively correlating this event with Mesozoic tectonics.

TABLE 1

STRUCTURAL EVENTS OF THE HAVALLAH SEQUENCE, NORTH-CENTRAL NEVADA

Event	Fabric Elements	Orientation	Comments
D_0	Qtz-filled and empty fractures, microstylolites (SC_0) Monroe structures.	Fractures-variable, high angles to beds. SC_0 parallel to layering.	Fractures the result of volume changes during diagenesis.
D_1	Slaty cleavage in argillite = microstylolite seams (SC_1), lenticles, step planes, isoclinal folds (F_1?).	SC_1 parallel to layering. Lenticle lines form girdle or N-plunging point maximum.	F_1 folds may be F_0 slump folds or unusually tight F_2 folds. Flattening event.
D_2	Asymmetric, concentric open to isoclinal folds (F_2). Vergence east. Some folds with axial surface cleavage. Pervasive shearing.	Folds parallel lenticle lines (girdle or point maximum). Shears low angle to bedding.	Fold lenticle lines, hence post-D_1. Shears juxtapose chert packets. Shearing in accretionary complex.
	Asymmetric tight to isoclinal folds that pre-date shears (F_2A).		Shears cut off folds and folded shear packets.
	Shear zones (S_2)	Low angle to bedding.	May be more than one generation.
	Asymmetric, open folds, post shear (F_2B). Solution cleavage (SC_2).	SC_2 normal to beds, parallel F_2B axial plane.	Folds deform shear zones and F_2A folds.
D_3	Large-scale thrusts within Havallah (S_3). Large asymmetric concentric folds. Vergence east.	Folds parallel lenticle lines. Major thrust at low angle to bedding in Havallah.	Shearing during obduction? Folds and thrusts deform F_2 fabric.
D_4	Asymmetric, gentle to open concentric folds (F_4). Vergence west.	Folds parallel lenticle lines.	Possibly related to Mesozoic events.
D_{4+}	Close-spaced fractures.		Relationships between these structures not certain.
	Rhomb fractures.		
	Joints.		
	Basin and Range faults		

Diagenesis and Deformation - A Model

The structures within the Havallah sequence suggest both ductile and brittle deformational processes. Ductile structures are puzzling because the lack of regional metamorphism implies that the deformation occurred at low pressures and temperatures. Lithified, quartzose chert might be assumed to be too rigid to deform in a ductile manner under these conditions. Most ductile folds are associated with brittle structures (thrusts, fractures) suggesting the folds post-dated lithification.

The ductile structures and the heterogeneous distribution of these structures can be explained if the chert was deformed while it was undergoing diagenesis. This model is developed in other papers (Snyder and others, in press; Brueckner and Snyder, in press) so only a brief summary is presented here.

With increasing temperature (usually due to burial), siliceous sediments undergo a three stage mineralogic diagenesis from the initial biogenic opal-A to opal-CT (cristobalite) to quartz. These transformations take place by solution-reprecipitation reactions. Lithologies that correspond to these mineralogic states are: radiolarian ooze (or diatomite; porosities up to 70 percent); porcelanite (porosity up to 35 percent) and CT-chert (less that 10 percent porosity); and finally, nonporous quartz chert. Corresponding clay-rich sediments would begin as siliceous mudstones and terminate diagenesis as argillites. The presence of clay retards the diagenetic conversion rates. Thus, opal-A or opal-CT siliceous mudstone layers may be interbedded with opal-CT or quartz porcelanite layers at some point during diagenesis, a feature that is common in the Miocene Monterey Formation, California (Snyder and others, in press).

The basic thesis of the diagenetic strain model is that the rheology of the sediments progressively changes during diagenesis. Radiolarian sediment is expected to deform in a ductile manner as a result of its low rigidity and high porosity. Porcelanite, which is still quite porous yet, a hard rock, may deform in a ductile or brittle manner depending on strain rate, pore pressure, and other factors. CT-chert is a dense, nonporous rock that would be relatively rigid and hence tend to deform in a brittle manner. Quartz chert at low pressures and temperatures, should, to a first approximation, behave rigidly and fault rather than fold.

In addition to rigidity considerations, the mineralogically metastable opal-A and opal-CT rocks also readily deform through solution mechanisms. In general, opal-A is more soluble than opal-CT which is in turn more soluble than quartz. Hence, siliceous sedimentary rocks in lower diagenetic states are more likely to suffer pressure solution than are rocks in more advanced stages of diagenesis. Bedding parallel and high angle microstylolites and slaty cleavage (D_0 and D_1, Table 1) are believed to form in this manner. The typical chert-shale rhythmic bedding may have been enhanced when silica, dissolved from the intervening opal-A, clay-rich layers, migrated to the more silica-rich, opal-CT porcelanite layers. Lenticulites (D_1 and D_2?) are thought to result from solubility contrasts between layers in different diagenetic states. The pressure-solution mechanism also may allow an otherwise rigid or brittle CT-chert to fold (Groshong, 1975; Snyder and others, in press).

Part of the heterogeneity in the distribution and style of structures is thus explained by the timing of diagenesis relative to that of the deformational event. Variously interlayered radiolarian sediment, siliceous mudstone, porcelanite, or chert will deform differently under otherwise identical strain conditions. Thus folded, sheared, or essentially undeformed chert packets commonly are juxtaposed. Superimposed on this are possible changes in strain rate, tectonically controlled pore pressures, and the concentration of structures along or near shear zones; all of these further contribute to a structural heterogeneity.

The diagenetic strain model strongly influences our evaluation of models for basin closure. Depending on temperature, mineralogy, and sedimentation rates, the total time for diagenetic conversion to the quartz stage may be as long as 50 m.y., but is usually thought to be much less (von Rad and others, 1977; Hein and others, 1978). The oldest and the youngest chert in the Havallah display the same sequence of structures. However, the time span between the deposition of the oldest and youngest cherts is about 110 m.y., thus, the diagenetic strain model requires the older chert to have begun deformation before the youngest chert was even deposited. We feel these considerations strongly favor a prolonged subduction versus a short-lived back-arc thrusting as the mechanism for basin closure.

Conclusions

The Golconda allochthon is largely an imbricate thrust stack. However, it contains numerous heterogeneously distributed, internal structures that indicate ductile deformation and pressure-solution processes preceded and accompanied internal shearing. These structures are cut by thrusts and folds possibly related to the emplacement of the allochthon along the Golconda thrust onto North America, but this relationship cannot be conclusively established. Much of the pre-emplacement deformation occurred before the siliceous sediments were converted to quartzose rocks. The oldest chert packets display the same diagenetically controlled structural fabric as the youngest. We suggest that chert packets received their structural imprint successively as they were stacked into the toe of an accretionary prism. This accretionary prism may have been active for most of the upper Paleozoic. Thus, Mississippian sediments were intercalated into the prism while still diagenetically immature (i.e., within a few tens of millions of years after deposition).

The accretionary prism model allows prolonged deformation of the Havallah sequence as a whole, prior to the emplacement of the Golconda allochthon onto North America. We might add that individual chert packets may have acquired their pre-Golconda fabric during a relatively short interval of progressive strain as they were incorporated into the prism. But we emphasize that different packets may have been deformed at different times.

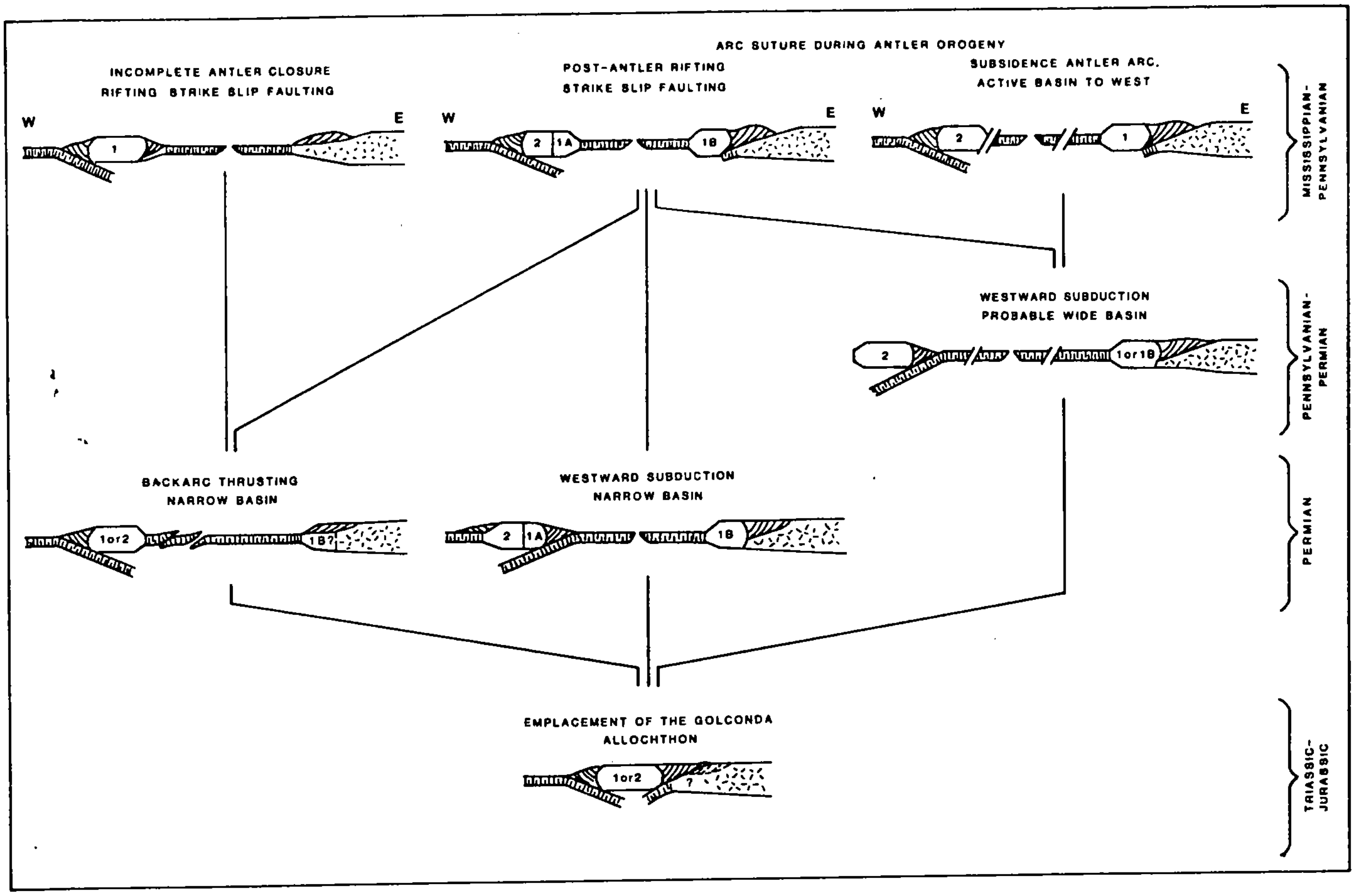

Figure 9. Schematic flow chart for various models of the tectonic evolution of the Havallah basin and Golconda allochthon. Arc terranes are numbered 1 and 2. Arc 1 was involved in the Antler orogeny and 1A and 1B denote rifted remnants of this arc. Arc 2 represents an arc terrane that was not involved in Antler tectonism. No scale is intended and breaks in sections denote unknown relative widths; see text for discussion.

TECTONIC MODELS

There are three general theories for the development of the Golconda allochthon: (1) the classical, non-plate tectonic interpretation (Roberts, 1964); (2) back-arc thrusting and obduction (Burchfiel and Davis, 1972, 1975; Miller and others, 1982a, in press), and (3) subduction and obduction (Burchfiel and Davis, 1972; Dickinson, 1977; Speed, 1977a, 1979; Snyder, 1977; Schweickert and Snyder, 1981). The last two models offer the most viable explanations for the tectonic evolution of the Havallah sequence, and both suggest that the basin was closed by an arc-continent collision.

Before the back-arc versus subduction models for basin closure can be assessed, the mechanism for basin initiation must be discussed. Figure 9 provides a schematic summary of the various possibilities for the tectonic evolution of the Havallah basin and the Golconda allochthon. Many subtle variations have not been included in this diagram. For example, orthogonal plate motions are not required in Figure 9, rather, any amount of oblique opening or closing can be envisioned. The reader is encouraged to refer to Figure 9 to help focus the following discussions and to possibly stimulate the development of viable alternatives to those shown.

Basin Initiation

One often cited model for the initiation of the Havallah basin is rifting following the Late Devonian-Early Mississippian Antler orogeny (Burchfiel and Davis, 1972, 1975; Silberling, 1973; Churkin, 1974a,b; Schweickert, 1976; Speed, 1977a; Dickinson, 1977; Schweickert and Snyder, 1981). The Antler orogeny is presumed to have been the result of an arc-continent or continent-continent collision. There are several problems with this model. First, there is no post-rift remnant arc (Dickinson, 1977). Second, there are few (Nelson Formation, Goughs Canyon Formation ?) if any rift-related magmatic rocks of appropriate composition or age. The voluminous volcaniclastics in the Schoonover complex may represent deposits from a near-by magmatic center during or shortly after rifting as suggested by Miller and others (1982b, in press). However, as noted earlier, these sandstones could have been derived from an arc in a remote part of the paleo-Pacific and thus not be related to a rifting episode.

A more important constraint is the Early Mississippian and possible Late Devonian ages for part of the allochthon. These data suggest that at least some of the rocks within the Golconda allochthon were part of a separate, long-lived basin that existed during and was unaffected by the Late Devonian Antler event, as anticipated by Speed (1977a, 1979). Additional paleontologic data are clearly needed to firmly establish the maximum age of the Havallah rocks.

Burchfield and Davis (1972, 1975) and Miller and others (in press) have suggested that the lower Paleozoic ocean basin may not have been completely closed during the Antler orogeny - that is, the arc did not suture with North America. The Havallah basin presumably would have been initiated by subsidence of the non-obducted portion of the Roberts Mountains allochthon followed by the initiation of oceanic spreading centers. Although this scenario mitigates the remnant arc problem, some of the other complications for the rifting model still hold. Specifically, the Late Devonian and Mississippian chert-greenstone-jasperoid units indicate that the Havallah basin was actively spreading during the Antler orogeny. Further, the mechanics of the flake tectonics required by this model present their own set of problems (Dickinson, 1977).

Another way to overcome the remnant arc problem is to postulate that an Antler arc did accrete to North America but subsequently thermally contracted and subsided from view (Speed, in Nilsen and Stewart, 1980; Speed and Sleep, 1982). This model requires that an east-facing arc and accretionary wedge complex collided with and overrode the North American continental margin until arrested by buoyancy in the Early Mississippian. According to the model, rapid subsidence of the new continental margin occurred during the Mississippian and continued through the Pennsylvanian into the Permian.

The arc subsidence model (Fig. 9) is attractive in that it accounts in a semiquantitative way for obduction and for the timing and size of the Antler Orogenic Belt and related foreland basin. It also allows the continued production of Havallah oceanic crust during the Antler orogeny as spreading continued in an oceanic basin behind (i.e., to the west) of the Antler arc. The Late Devonian-Mississippian volcaniclastic rocks are thus viewed as debris shed from the subsiding arc.

The obvious difficulty with the subsidence model is that it cannot be tested because the arc has conveniently disappeared beneath Mesozoic and Cenozoic rocks. It could also be applied ad hoc to the rifting scenario, with the remnant arc similarly subsiding from view, thus obviating some of the arguments against this model.

Basin Growth

A major constraint for reconstructing the evolution of the Havallah basin is provided by the widespread chert-greenstone-jasperoid associations. This association implies that deposition occurred locally on newly formed oceanic crust. If so, the Havallah basin was an actively spreading ocean basin at least from the Late Devonian-Early Mississippian through the early Late Permian (late Leonardian-Guadalupian).

The greenstones are altered, and cannot be dated radiometrically. However, the associated cherts contain radiolaria and conodonts and hence provide reliable ages if it is assumed the cherts were deposited more or less synchronously with or shortly after basaltic volcanism. In most cases this assumption is verified by chert that was mineralized by mid-ocean ridge-type hydrothermal systems (i.e., jasperoid dikes, manganese and sulfide ores, etc.). Chert-greenstone-jasperoid associations contain Late Devonian-Mississippian radiolaria and conodonts in the Schoonover complex in the Independence Mountains (Miller and others, 1982b) and in the Havallah sequence at Edna Mountain and in the northern Tobin and southern Sonoma Ranges (W. S. Snyder, B. Murchey, and D. L. Jones, unpublished data). The clearest example of this association is at the Big Mike mine, where radiolaria from jasperoids give Mississippian ages. Permian (Leonardian-Guadalupian) fauna have been extracted from bedded jaspers associated with pillow basalts in the Toquima Range (Laule and others, 1981, in press). Thus the oldest and youngest known rocks of the Havallah sequence give evidence of active spreading. All chert-greenstone-jasperoid associations have not been dated and we cannot yet document that active spreading continued throughout the entire life of the Havallah basin. For example, the association has not been described from Pennsylvanian rocks.

The entire age range of the Havallah sequence may not yet have been dated. We may never know if the oldest and youngest portions of the sequence were structurally incorporated into the Golconda allochthon, nor can we demonstrate that ocean crust of every age was incorporated into the exposed portions of the allochthon. Another problem arises with previous mapping, where chert-argillite units of Devonian or older age were assigned to the lower Paleozoic Roberts Mountains allochthon. Thus, some exposures of the Devonian Slaven Chert and Silurian Elder Sandstone may be part of the Golconda allochthon and possible pieces of the Havallah basin. For example, units previously considered to be lower Paleozoic and part of the Roberts Mountains allochthon (Willow Canyon Formation, Toquima Range) are actually young portions of the Golconda allochthon (Laule and others, 1981, in press). Thus, the Golconda allochthon may be more extensive, older, and perhaps younger than previously thought.

A general estimate of the width of the Havallah basin can be calculated, assuming that the basin was active for a minimum of 110 m.y. (e.g., Dickinson, 1977). At half spreading rates of 5 to 0.5 cm/year, the half basin width would be 5,500 to 550 km. If subduction did not occur or was significantly slower than spreading, then the total basin width would be up to twice these values. The larger figure would represent a major ocean basin, whereas the lower estimate is in the range of marginal ocean basins. However, we cannot say for certain that active spreading occurred during the entire life of the Havallah basin. Lower estimates are required if active spreading did not occur continuously during the upper Paleozoic or if active subduction consumed large portions of the newly created oceanic crust. These estimates are thus crude at best, but suggest rather strongly that the Havallah basin had sufficient time to evolve into a large ocean.

There are three main groups of sandstones in the Havallah sequence: (1) limestone and siliciclastic turbidites, (2) recycled orogenic, lithic sandstones, and (3) volcaniclastics. The latter two are not always distinct and their compositions seem to merge. Previous studies have tied the first two to North American sources, and the more recently recognized volcaniclastics to a western magmatic arc provenance (e.g. Dickinson and others, in press; Miller and others, 1982b; Snyder and Girty, 1979). A western source for the volcaniclastics seems unavoidable because no magmatic source was available on the North American continent during the upper Paleozoic. However, the North American source for the limestones and lithic sands can be questioned, and thus some logical alternative must be kept in mind.

The composition of the lithic sandstones clearly indicates that they are recycled orogenic sands. The provenance for these rocks included large volumes of chert, some quartzsite and mafic volcanics. One possible, and seemingly the simpliest choice for the source is the lower Paleozoic Roberts Mountains allochthon which is comprised of chert, greenstone and quartz sandstones (Dickinson and others, in press; Miller and others, 1982b, in press). However, at least locally, these lithic sandstones can also contain appreciable feldspar, some pyroxene and more silicic volcanic lithics, plutonic quartz, and metamorphic rock fragments. Thus, the compositions of the lithic sandstones merge toward that of the volcaniclastics. The point argued here is that <u>any</u> chert-greenstone-sandstone orogenic welt could have supplied the debris for these lithic sandstones. A likely alternative is a subduction complex - active or inactive. For example, the lower Paleozoic sediments that form the substrate for the northern Sierra and Klamath arc complexes are possible source terrances (Schweickert and Snyder, 1981). A combined magmatic arc-accretionary wedge complex provenance would conveniently account for the apparent compositional gradation between the volcaniclastic and lithic sandstones. Again, the northern Sierra or Klamath arc complexes are possible combined source terranes. Such a combined source would also mitigate the presence of metamorphic rock fragments in these sands, for which there is no known source in the Roberts Mountains allochthon.

The simpliest source for most of the limestone turbidites and associated quartz arenites appears to be the Pennsylvanian-Permian of the North American shelf. The Antler Orogenic Belt had subsided by this time, and carbonate and quartz sandstone deposition (the Overlap sequence) had been re-established across the Antler foreland basin and the orogenic belt. The fusulinids of probable North American affinites within some of these Havallah sands (Stevens, in Stewart and others, 1977) indicate a cratonic source. However, not all these sandstones contain identifiable fossils. Some units could represent forearc deposits that eventually became structurally interleaved in the subduction complex. A modern analogue is Nias Island, Sunda arc (Moore and Karig, 1980). The unconfirmed limestone samples that yielded fusulinids of Klamath Mountains affinities (Stewart and others, 1977) are intriguing candidates for such forearc deposits. Further, these Havallah sandstones generally are only mildly deformed compared to the structurally interlayered chert packets (e.g., Hoffman Canyon, Tobin Range). In a forearc setting, sandstones could be deposited on deformed chert-argillite of the accretionary prism and then structurally interleaved with the chert packets during later deformation in the accretionary wedge and during the emplacement of the Golconda allochthon onto North America. Further detailed studies of the composition, paleontology, and structure of these sandstones are required. It is possible that the limestone turbidites were derived from two sources. In any case, these sediments do not constrain the size of the Havallah basin because even a wide ocean basin will receive proximal sediments along the part that borders North America.

These considerations and the regional structure suggest to us that a single vertical stratigraphic sequence for the Havallah basin cannot be reconstructed by simply a one-dimensional stacking of sedimentary rocks from one lithotectonic unit on top of the other, even within a single mountain range (e.g. Miller and others, in press). Distal and proximal sediments from even a wide ocean basin can be tectonically interleaved, particularly in a long-lived accretionary prism (e.g., the Franciscan Formation, California). The existence of long-lived, active spreading centers requires a three-dimensional reconstruction. Existing data simply does not allow this to be done with any accuracy.

An example for the Lower Permian Havallah sequence will suffice to demonstrate the point. Lower Permian lithologies include: (1) voluminous limestone turbidites (e.g., Independence Mountains; Hoffman Canyon, Tobin Range), (2) chert-argillite and volcaniclastic sandstone and breccia (e.g. Willow Creek, Battle Mountain), and (3) chert-greenstone-jasperoid units (e.g., Toquima Range) (Figure 10). The carbonate assemblage represents deposition close to a source of limestone and quartz sand with only minor chert debris; quite possibly this source was the North American shelf but also possibly an accretionary prism. The second assemblage represents a dominantly hemipelagic environment near a magmatic arc. The volcaniclastics contain dacite, rhyolite (?), chert, and jasperoid clasts. The jasperoid clasts must have been derived from previously uplifted portions of the Havallah sequence because, though there are numerous Cenozoic-age jasperoids in the Great Basin, no Paleozoic jasperoid has been reported from this region of the North American continent including the Roberts Mountains allochthon. Importantly, some volcaniclastic strata were, in places, injected into the bedded chert as clastic dikes and sills during D_2 folding and thrusting, indicating high fluid pressures and deformation shortly after deposition (Brueckner and Snyder, in press). Thus, the Willow Creek section (assemblage 3) appears to represent sediments deposited on the western margin of the basin, next to a magmatic arc, and in front of a growing imbricate thrust stack. Finally, the Toquima Range section, in the lower part at least, clearly represents an active spreading ridge environment distant enough from both the North American margin and the magmatic arc to be free of clastic debris from either source (Fig. 10).

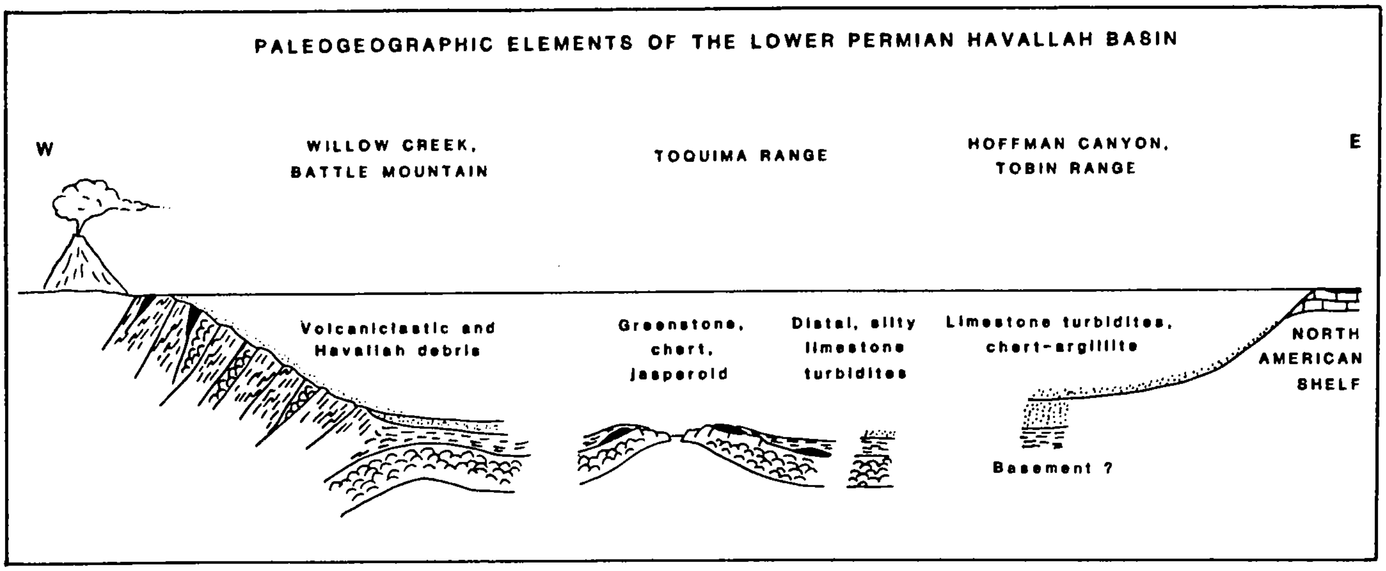

Figure 10. Paleogeographic elements of the Lower Permian Havallah basin. No scale intended; breaks in schematic cross-section denote unknown distances.

Basin Closure

There are two possible scenarios for the closing of the Havallah basin: (1) back-arc thrusting of a narrow marginal basin, or (2) subduction of a narrow or wide oceanic basin (Fig. 9).

The gross structural fabric of the allochthon is compatible with both models because each predicts the development of an imbricate thrust stack and associated asymmetric buckle folds. We have suggested that a strain model which involves the deformation of siliceous sediments in varying stages of diagenesis best accounts for the observed details of the structural fabric. Since the diagenesis is time dependent, and all cherts display the same general fabric, we have argued that the deformation of some of the oldest parts of the allochthon must have started some tens of millions of years before that of the youngest (Brueckner and Snyder, in press).

The question becomes; is the narrow basin and timing of deformation required by the back-arc model compatible with the diagenetic strain model? We feel the answer to this question is no. The existence of an early Late Permian spreading center in the Havallah basin (Laule and others, in press) constrains back arc compression to have begun no earlier than the Late Permian. By this time, the Mississippian cherts would almost certainly have converted to quartzose rocks, which under the low pressures and temperatures of deformation, would behave in a brittle fashion. These sedimentary rocks display pervasive ductile as well as brittle structures. Thus, we argue that these rocks were intially strained much earlier, probably as early as the Pennsylvanian, and possibly as early as the Mississippian.

In contrast, the subduction model can accommodate the existence of active spreading centers during deformation in an accretionary wedge. Further, if the subduction zone was initiated early (Pennsylvanian?), then partly lithified sediments can be deformed ductily. The initial size of the Havallah basin necessary to allow for such prolonged subduction depends on the spreading rates and the relative motion of the arc and ocean basin. These motions are indeterminate at this time, but absolute plate motion studies such as those of O'Hare and others (1982) may eventually shed some light on this problem. A narrow ocean basin can be maintained if subduction keeps pace with spreading. Thus, the subduction model accounts for the timing of deformation and allows the Havallah basin either to remain a relatively narrow back-arc basin or to evolve into a large ocean basin.

The Golconda allochthon is not a simple thrust stack, as we have illustrated earlier. Lithotectonic units of the same age, yet of markedly different paleogeographic positions, are now complexly interleaved in the allochthon. If subduction of the Havallah basin was highly oblique, then it is possible to envision the tectonic interleaving of deposits of continental margin, forearc, and open ocean environments (Fig. 10). Although oblique convergence can also be claimed for the back-arc model, it seems less likely that units of disparate lithologies and paleoenvironments and yet of similar ages would be juxtaposed.

Miller (1982) and Miller and others (1982b, in press) have stated that the Havallah clastics are compositionally tied to a North American source with only some early (Late Devonian-Early Mississippian) arc — derived detritus. This interpretation has been used to substantiate the hypothesis that all the Havallah sediments were deposited in a relatively narrow basin marginal to North America. The narrow basin constraint is then used to argue that the Havallah was a back-arc basin, ultimately closed by back-arc thrusting. However, the compositions of the clastics cannot be conclusively tied to solely North American sources. While we do not argue against a North American source for some of the clastics, particularly the limestone turbidites, we do suggest that the clastics could have been derived from alternate localities. We have pointed out, for example, that Permian rocks within the allochthon reflect marginal North American, forearc, and detrital-free spreading center depositional environments. The latter two could have been at any, unknown distance from the North American shelf. Thus, the sandstone compositions do not provide conclusive evidence for back-arc closure of a narrow Havallah basin.

Summary

In summary, the Havallah basin was largely floored by oceanic crust with active spreading centers characterizing one of the yet youngest dated units. Whereas the most voluminous sandstone debris may have a North American provenance, other sediments, particularly the volcaniclastics and lithic sandstones, could have been derived from outboard, arc-accretionary wedge complexes. The accretionary wedge source terranes could have been inactive (i.e., the northern Sierra, Schweickert and Snyder, 1981) or active (the Havallah accretionary wedge). These relationships suggest that the Havallah basin may have been part of a wide ocean basin. This then favors a subduction model for closure over that for back-arc thrusting. The diagenetic strain model for the structural fabric of the allochthon also favors the subduction model in that deformation must have started significantly earlier than the Late Permian. Finally, the Havallah sequence contains Late Devonian-Early Mississippian chert-greenstone-jasperoid lithotectonic units. This implies that active spreading occurred in the Havallah basin during the Antler orogeny and that the Havallah sequence was not deposited in a post-Antler, back-arc basin.

SONOMA OROGENY

The timing of the emplacement of the Golconda allochthon onto North America is a controversial subject (Gabrielse and others, in press). The maximum age for this event is post-early Late Permian (Guadalupian) since rocks of this age occur in the allochthon and the autochthon (Edna Mountain Formation). The minimum age is not well constrained. The Sonoma orogeny is commonly viewed as the event during which the allochthon was emplaced onto North America. More strictly however, Sonoma tectonism has been typified in the northern Tobin Range (Hoffman Canyon) by the relatively undeformed Lower and Middle Triassic Koipato and Star Peak rocks that unconformably overlie the highly deformed Havallah sequence (Fig. 7) (Silberling and Roberts, 1962; Stewart and others, 1977; Stewart, 1980). The timing of the orogeny was thus placed as pre-Koipato. However, the Koipato-Star Peak strata do not overlap the Golconda thrust. This raises the possibility that the Koipato and perhaps the Star Peak rocks rode in on top of the allochthon, and thus do not date the age of emplacement (Dickinson, 1977).

Equating the emplacement of the Golconda allochthon with the Sonoma orogeny can be questioned (J. H. Stewart, personal communication, 1983; Gabrielse and others, in press). Ferguson and others (1952) noted that the Havallah sequence (then the Pumpernickel and Havallah formations) was "... strongly folded and thrust faulted before the overlying ... Koipato formation ... was deposited," and thus assigned a Permian age to this "orogeny" but a later Mesozoic age to the Golconda thrust. Silberling and Roberts (1962) applied the term "Sonoma orogeny" to the deformation dated by the relationships in Hoffman Canyon (Fig. 7). They then discussed whether the Golconda thrust was related to Jurassic and Cretaceous orogeny or to the Sonoma orogeny, and concluded that although available data did not allow a clear choice, neither did it preclude relating the Golconda thrust to the Sonoma orogeny (Silberling and Roberts, 1962). Speed (1971) first applied the term "Golconda allochthon" to the entire structural package above the Golconda thrust. Most recent authors have correlated the Golconda thrust with the Sonoma orogeny (Roberts, 1964; Hotz and Willden, 1964; Silberling, 1973, 1975; Burchfiel and Davis, 1972, 1975; Dickinson, 1977; Stewart and McKee, 1977; Nichols and Silberling, 1977; Speed, 1979; Stewart, 1980; Schweickert and Snyder, 1981; Miller and others, in press). These authors view the emplacement of the Golconda allochthon as the culmination of the Sonoma orogeny.

We agree with this usage and note that the emplacement of the allochthon is a regional structural event that marked a major reorganization of the tectonic configuration of western North America (Gabrielse and others, in press). The deformation seen in Hoffman Canyon is indeed part of the Sonoma orogeny, and there it is pre-Koipato in age. However, where the allochthon is not directly overlain by the Koipato Group, there is no proof that deformation preceded Koipato deposition, despite the fact that the structural style is identical to that in the Hoffman Canyon area. The internal structural fabric of the allochthon is here viewed as a product of the deformation associated with the Sonoma orogeny, and the Golconda thrust is regarded as the last structure formed by this tectonism. The critical question is the age of the end of the Sonoma orogeny, that is, the age the Golconda allochthon was emplaced onto the North American continental margin.

Structure

The dominant structural fabric of the Golconda allochthon, (i.e., the D_2 imbricate thrusts and associated folds) was developed prior to the emplacement of the allochthon onto North America. This is suggested by the protracted strain history of the Havallah rocks which must have begun during the early stages of diagenesis of even the oldest rocks in the allochthon. Folds related to the development of the Golconda thrust can be seen in both the autochthon and allochthon within 50 to 100m of the thrust. However, we do not have any evidence which conclusively dates any other internal structures as synchronous with Golconda thrusting. We suspect that there are late emplacement structures within the allochthon, and we have speculated that the F_3 folds may represent this deformation. For example, in Hoffman Canyon, F_3 folds are associated with the thrust that separates large-scale lithotectonic units (units C and D, "Big Z" fold, Fig. 7). If this is true, the age of emplacement is indeed pre-Koipato since here, the Koipato unconformably overlies these structures (Fig. 7; Brueckner and Snyder, in press). MacMillan (1972) has similarly hypothesized that the pre-Koipato internal fabric of the allochthon in the New Pass Range indicates a pre-Koipato age for emplacement. Although most internal thrusts are subparallel to the Golconda thrust, the Golconda thrust cuts the major fault-bounded lithotectonic units at several localities (Toquima Range, Battle Mountain, and Edna Mountain). Therefore, the internal structural fabric of the allochthon is at least locally truncated by the Golconda thrust.

It now seems that the pervasive structural fabric of the allochthon was developed within the Havallah basin via either the subduction or back-arc thrusting. Strain associated with emplacement of the allochthon may have been mostly or totally concentrated along the Golconda and subsidiary thrusts. Except within a few tens of meters of the Golconda thrust, subsidiary structures associated with emplacement cannot be clearly identified. Thus at present, the structural fabric cannot be used to conclusively date the timing of emplacement of the allochthon.

Early Triassic Emplacement

Speed (1977a) described relationships in the Candelaria area (Fig. 1) that suggest emplacement of the allochthon in the Early Triassic. There, the Candelaria Formation was deposited on remnants of the Antler Orogenic Belt during the Early Triassic. The clastics of the early Early Triassic lower member of the Candelaria Formation were derived locally from continental sources (Speed, 1977a). The clastics of the conformable upper member of the Candelaria Formation (of inferred early Early Triassic age) contain debris derived from a magmatic arc. There is no evidence for a Late Paleozoic arc on continental North America. Thus the upper member marks the approach of an arc terrane and the overlap of arc-derived debris onto autochthonous North America. If these relationships are correct, they imply that at least in west-central Nevada, the Golconda allochthon was emplaced in the Early Triassic.

Early Late Triassic Emplacement

Silberling (in Stewart and others, in press) suggests that the pelitic and coarse clastic rocks of the Late Triassic Auld Lang Syne Group (Burke and Silberling 1973) put a cap on the age of emplacement. The age and compositional similarities of the Auld Lang Syne Group and Chinle Formation imply a common source for these units. A series of rivers is envisioned that extended from the site of the fluvial Chinle deposition on the Colorado Plateau to the site of the Auld Lang Syne deposition on top and west of the Golconda allochthon and Star Peak Group rocks. Some Triassic rocks in northeastern Nevada may represent erosional remnants of the fluvial system that fed the Auld Lang Syne basin. The Auld Lang Syne Group then, represents deposition of Chinle sands as deltaic complexes and as basinal turbidites far to the west of their clastic sources.

A mid-Karnian disconformity with associated greenstone separates the Auld Lang Syne Group from the underlying late Early to early Middle Triassic Star Peak Group carbonates. Local unconformities within the Star Peak rocks suggest extensive vertical tectonism within the subjacent Havallah rocks. Late Ladinian Star Peak units locally rest directly on the deformed Havallah rocks. These pre-Late Triassic events would, in this scheme, reflect pre-emplacement tectonism. Thus, Silberling has developed an intriguing possibility that the Golconda allochthon could have been emplaced as late as the early Late Triassic.

Laule and others (1981, in press) have described a new extension to the Golconda allochthon, the Willow Canyon Formation in the Toquima Range (Fig. 1). The Willow Canyon Formation includes late Leonardian to Guadalupian radiolarian chert, greenstone, and jasperoid. Siliciclastic debris occurs in overlying silicified limestone turbidites (cherts). Thus as suggested by the presence of greenstone and jasperoid, in the early Late Permian, the Havallah basin contained an active spreading center that was removed from a source of continental or arc debris. The appearance of the siliciclastic debris marks a slightly later infux of fine grained continental detritus.

We originally argued that the Willow Canyon Formation puts time constraints on an Early Triassic timing for the emplacement of the Golonda allochthon (Laule and others, 1981). We suggested that between the Guadalupian and the Spathian (Koipato), an interval of about 10 m.y., a relatively large ocean basin would have to be closed - a basin large enough that the active spreading center was far removed from sources of either arc or continental clastic material. Since only a small amount of closure could be expected in 10 m.y., we felt that a pre-Koipato age for emplacement of the allochthon would not allow enough time to close a large ocean basin. This line of reasoning must be revised in light of the absolute plate motion studies by O'Hare and others (1982). Their studies indicate a period of rapid movement of North America, generally to the northwest, during the Late Permian and most of the Triassic. Depending on the configuration of subduction zones and the absolute motion of the Paleopacific, an ocean basin as wide as 800 km could conceivably be closed during a time interval of 10 m.y. Plate motion studies during the Paleozoic and early Mesozoic are clearly difficult. These studies do suggest, however, that an Early Triassic age of emplacement for the Golconda allochthon is possible even with the existence of the early Late Permian chert-greenstone-jasperoid units in the Toquima Range.

Recent, preliminary paleomagnetic data from the eastern Klamath Mountains (Mankinen and others, 1982) imply that these Permian through Jurassic arc rocks were at their present latitude relative to North America by the Late Triassic. The Klamath arc terrane is presently outboard of the Golconda allochthon and has been often cited as part of the arc terrane that collided with North America during the Sonoma orogeny (e.g., Burchfiel and Davis, 1972; Silberling, 1973; Dickinson, 1977; Speed, 1977; Schweickert and Snyder, 1981). Assuming little or no north or south translation within the error limits of the paleomagmetic data, this geometry implies a pre-Late Triassic timing for the emplacement of the Golconda allochthon.

SUMMARY AND DISCUSSION

The Havallah sequence contains chert-greenstone-jasperoid units of Mississippian to Permian ages. Pelagic and hemipelagic chert and argillite of Late Devonian to Permian age comprise the vast majority of Havallah sediments. These lithologies imply that the Havallah basin was dominantly an open ocean, floored by oceanic crust, and that active spreading likely characterized the basin throughout its existence.

Dated chert-greenstone-jasperoid units indicate that the Havallah basin contained an active spreading center during the Late Devonian-Early Mississippian Antler orogeny. Thus, the Havallah basin was a separate ocean basin, unaffected by the compressional tectonics of the Antler event. This clearly rules out the initiation of the Havallah basin via post-Antler rifting. It indirectly supports, but does not prove, the arc-subsidence model for the Antler arc and Roberts Mountains allochthon proposed by Speed and Sleep (1980, 1982) and adopted by Dickinson and others (in press). This conclusion relies critically on available paleontologic data. More paleontologic data is obviously needed before post-Antler rifting for initiation of the Havallah basin can be conclusively ruled out.

Rifting is suggested by the possible lithologic and tectonic ties between the lower Paleozoic rocks of the Klamath-northern Sierra terrane and Roberts Mountains allochthon (Schweickert and Snyder, 1981). Although not proven, this correlation is a viable hypothesis. The Golconda allochthon is structurally above the Roberts Mountains allochthon, and east of the Klamath-northern Sierra arc terrane. This paleogeography and structure imply that the upper Paleozoic Havallah basin was developed between the arc terrane to the west and the edge of the North America shelf (the Roberts Mountains allochthon) to the east. In other words, the possibly correlative rocks in the Klamath-northern Sierra and the Roberts Mountains allochthon were separated by the rifting event that produced the Havallah basin. The rifting may have been initiated during the Antler orogeny, but this possibility needs further evaluation. Reworked fossil debris may account for the dated Late Devonian and Early Mississippian conodonts and radiolaria, and therefore the rifting event could be entirely post-Antler in age.

Most other information about the initiation and growth of the Havallah basin is equivocal (e.g., the lack of post-rift remnant arc or rift related volcanism). Paleomagnetic studies may eventually provide critical constraints on this problem, but only if such data indicate that the Golconda allochthon contains rocks that originated at significantly high or low paleolatitudes relative to the craton of northern Nevada.

The Havallah sequence is not, as a whole, sedimentologically tied to North America. The limestone turbidites are largely composed of debris shed from the North American shelf. However, some of the limestones may represent forearc deposits similar to those of Nias Island, Sunda arc. The volcaniclastic sandstones were derived from a magmatic arc. Lithic sandstones are composed of recycled orogenic debris shed from either or both the Roberts Mountains allochthon (Antler Orogenic Belt) or an accretionary prism. The gradational compositions between the volcaniclastic and lithic sandstones suggest that some, if not most, of these sandstones represent debris derived from a combined arc-accretionary prism complex. The Paleozoic Klamath and northern Sierra arc-accretionary wedge complexes and an actively growing Havallah subduction complex could have supplied the clastic debris for the volcaniclastic and lithic sandstones.

There is enough time (approximately 110 m.y.) recorded in the Havallah rocks to accommodate the growth and collapse of a large ocean basin - how large is indeterminate. Therefore, the units that are structurally preserved in the Golconda allochthon could simply represent tectonically stacked distal and proximal components of a basin that could have been very large. The presence of proximal sediments derived from North America does not constrain the size of the Havallah basin. However, the presence of distal components (arc debris, chert-greenstone-jasperoid assemblages of oceanic spreading center affinities) suggests that the basin may have been large.

Our structural interpretation (Brueckner and Snyder, in press) suggests that the Golconda allochthon was a prepackaged imbricate thrust stack before it was thrust eastward onto North America. Two problems stem from this suggestion: (1) how was the imbricate thrust stack formed (i.e., what was the mode of basin closure), and (2) what was the timing of the emplacement of the allochthon?

We favor prolonged subduction versus back-arc thrusting as the mechanism for closing the Havallah basin. The heterogeneous distribution of solution features and ductile folds implies that the oldest sediments in the Golconda allochthon were strained well before the youngest rocks. This suggests that basin "closure" may have begun as early as Late Mississippian or Early Pennsylvanian. Further, the youngest sediments contain the same structural fabric as the oldest rocks which implies that the tectonic regime did not change during the protracted deformation. Subduction which progressively deforms first the older and then the younger sediments satisfies these constraints. In contrast to this, basin-wide compression required by back-arc thrusting could not have been initiated until the Late Permian as suggested by the early Late Permian chert-greenstone-jasperoid units which indicate that active spreading continued through this time. If the initial deformation began in the Late Permian, then the oldest rocks should not exhibit the same structural fabric as the youngest - this is not the case for the Havallah. The back-arc thrusting model requires that the Havallah basin was a relatively narrow basin because such thrusting in a wide basin would evolve into subduction. Thus, the back-arc scenario requires some special mechanism to keep the basin narrow because the widespread chert-greenstone-jasperoid units imply that active oceanic spreading characterized the basin throughout the upper Paleozoic. However, subduction is a viable mechanism to maintain a narrow basin that contains an active spreading center. Thus, we feel that subduction provides the most satisfactory model for closure of the Havallah basin.

The emplacement of the Golconda allochthon onto North America then, is logically viewed as the culmination of a protracted structural evolution that began within an accretionary wedge and ended, presumably, with an arc-continent collison and obduction of the subduction complex. The Klamath-northern Sierra terranes are the best candidates for this arc. Most structures within the allochthon were formed prior to the emplacement onto North America. Thus, the term "Sonoma orogeny", strictly speaking, should be restricted to the actual emplacement of the allochthon. However, as we earlier outlined, due to the widespread usage of the term "Sonoma orogeny" to encompass all the deformation, we do not advocate this as a general redefinition of the term.

Speed and Sleep (1982) have pointed out that the Antler and Sonoma events did not develop the classic signatures of "orogenies" - i.e. prominent mountain belts, magmatism, metamorphism, or marked shortening of the autochthonous basement. We agree with this objection, but feel that because of widespread usage in the literature, these tectonic events will continue to be referred to as orogenies. The above qualifications are necessary for discussion of emplacement mechanisms for the respective allochthons, as Speed (1982) has done, but should not become a major topic of debate.

The timing of the emplacement of the Golconda allochthon has been tightly constrained only in the Candelaria area (Speed, 1977a; Fig. 1). If the Candelaria relationships are correct, then the allochthon was emplaced during the late Early Triassic in that area, and perhaps slightly earlier or later elsewhere. The pre-Koipato, D_3, structures within the Havallah sequence may be related to obduction of the allochthon and are compatible with an Early Triassic emplacement. It is conceivable that compressional tectonics may have continued through the Middle Triassic until subsidence created a basin for deposition of the clastic and pelitic sediments of the Late Triassic Auld Lang Syne Group.

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