Antler orogeny and foreland basin: A model

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ABSTRACT

The Antler orogeny occurred in Mississippian time at a passive margin of the sialic North American continent in Nevada and probably in Idaho. Its principal events were the emplacement of an extensive allochthon of oceanic rocks on the continental shelf, subsidence of an elongate foreland basin, and maintenance of highlands in the interior region of the allochthon during and after subsidence of the foreland basin. The orogeny was apparently not accompanied by thermal phenomena or large crustal shortening.

We follow earlier models by assuming that the orogeny was initiated by collision of an arc system with North America. Our proposal holds that a large accretionary prism of the probably far-traveled arc system was underthrust by the continental slope and outer shelf and became the Roberts Mountains allochthon. The Antler magmatic arc, now unexposed, thermally contracted after collision and was largely or entirely subducted in a later (Triassic) arc-continent collision. The Antler foreland basin was created by vertical loading and downflexing of the continental shelf by the allochthon, and sediment from subaerial regions of the allochthon ultimately filled and broadened the foreland basin. Quantitative models using the theory of a loaded thin elastic plate above a dense fluid provide reasonable agreement between calculated widths, depths, and asymmetry of plate deflections and the Antler foreland basin. Models predict that a flexural bulge of low amplitude migrated continentward ahead of the foreland basin during arc-continent closure. Certain stratigraphic phenomena in pre-foreland basin strata of central Nevada may record the passage of the bulge.

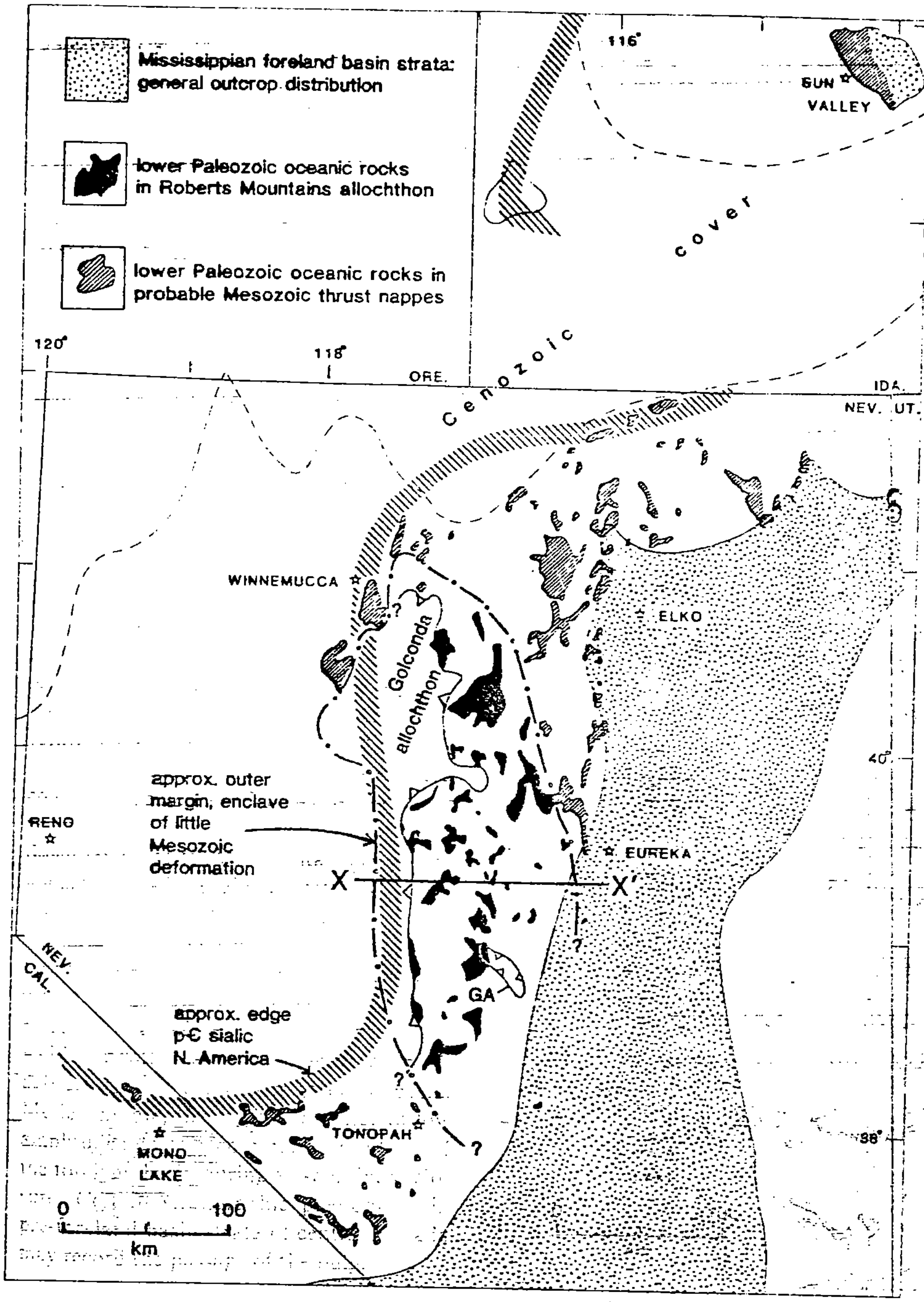

Figure 1. Map showing outcrop region of rocks related to the Antler orogeny: lower Paleozoic oceanic rocks that are now (black) or were originally (lined) in the Roberts Mountains allochthon and strata deposited in the Antler foreland basin. XX' is trace of section in Figure 2. Edge of Precambrian sialic North America taken from contour of initial $^{87}Sr/^{86}Sr = 0.706$.

INTRODUCTION

The Antler orogeny (Roberts, 1951) occurred in Mississippian time at a passive margin of the sialic North American conti-

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nent in Nevada and probably in Idaho (Fig. 1). Principal events of the orogeny were (1) displacement of oceanic strata in the Roberts Mountains allochthon as much as about 140 km continentward of the margin above the early Paleozoic shelf (Roberts and others, 1958; Stewart and Poole, 1974; Smith and Ketner, 1977); (2) subsidence of an elongate foreland basin (foredeep, exogeosyncline) during Mississippian time on the continental shelf at the toe of the allochthon (Poole, 1974); and (3) maintenance of highlands in the interior region of the allochthon during and after foreland basin subsidence. The orogeny was apparently not accompanied by magmatism, penetrative regional deformation or metamorphism of the autochthon, or significant crustal shortening.

The Antler may represent a class of orogenies in which allochthonous oceanic or at least deep basinal strata are emplaced above the sialic shelf without associated thermal phenomena inboard of the margin. Other examples may be the Ordovician Taconic orogeny (Rodgers, 1970; Williams, 1978) and the Pennsylvanian Ouachita orogeny (King, 1975; Viele, 1979). Like the Antler, both these events generated foreland basins on the continental shelf (Stevens, 1970; McIver, 1970; Galley, 1971; Nicolas and Rozendal, 1975). Similarly, oceanic strata were emplaced in the Golconda allochthon in Early Triassic time above the Nevada continental margin and the earlier Roberts Mountains allochthon (Speed, 1977) in the so-called Sonoma orogeny, indicating that such tectonic processes may recur at the same site. The Sonoma event differs, however, in that it generated either no foreland basin or a basin so inconspicuous as to be unrecognized. Antler-type orogenies are distinguished from the thrust belt–foreland basin associations exemplified by the Canadian Rockies (Bally and others, 1966; Price and Mountjoy, 1970) because the latter are intracontinental and are apparently related to thermal phenomena within the sialic continent.

The basic problems of the Antler orogeny and others of its kind are (1) the tectonics that initiated it, (2) the mechanisms that permitted oceanic strata to be thrust up some 4 km and laterally many tens of kilometres in the light of limits on nappe length imposed by rock strength (Hubbert and Rubey, 1959), and (3) the cause of foreland basin subsidence and apparently coupled uplift of a hinterland to the west.

Our objective is to present a general model, quantified where feasible, of the Antler orogeny that gives geologically and mechanically acceptable solutions to the problems above. The basic ingredients of the model (Speed and Sleep, 1980) are as follows: the Antler orogeny was initiated by a local collision of the passive margin with an arc system as first proposed by Moores (1970). The arc was probably migrating with large obliquity with respect to North America. The Roberts Mountains allochthon was derived from a thick accretionary prism of the forearc that was underrun by the slope and outer shelf of North America before convergence ceased due to the buoyancy of partially subducted continental lithosphere. The beached accretionary prism provided a Mississippian mountain belt along the continental outboard and created a parallel trough some 200 km wide along its continentward edge by vertically loading and downflexing the outer shelf.

FEATURES OF THE ANTLER OROGENY

Regional Relationships

The cryptic modern perimeter of the sialic Precambrian basement of the North American continent (Fig. 1) may be approximated by the contour of initial $^{87}Sr/^{86}Sr \sim 0.706$ for Mesozoic and Cenozoic magmatic rocks (Kistler and Peterman, 1978; Armstrong and others, 1978; R. W. Kistler, 1979, written commun.). The contour follows a belt in which seismic and gravity data indicate or suggest a general eastward thickening of the crust (Prohdehl, 1978; Cogbill, 1979). The near coincidence of the 0.706 contour and the westernmost outcrops of autochthonous Paleozoic rocks of outer-shelf facies (Kay and Crawford, 1964; Matti and McKee, 1977; Rowell and others, 1979) indicates that the sialic boundary in central Nevada is probably an ancient passive margin, not a later continental truncation such as probably exist in Idaho (Hamilton, 1976) and California (Hamilton and Myers, 1966). The passive margin is thought to have formed during late Precambrian rifting (Stewart, 1972).

Figure 1 indicates the distribution of rocks related to the Antler orogeny: lower Paleozoic oceanic rocks that occur in or are correlated with those of the Roberts Mountains allochthon and Mississippian foreland basin strata. In general, the present and Mississippian distributions and extents of Antler-related rocks probably differ substantially because of post-Antler tectonism. One region in central Nevada, however, has apparently been little affected by such deformation (Fig. 1), and outcrops of lower Paleozoic oceanic rocks within it (black, Fig. 1) may be the only remnants of the Roberts Mountains allochthon in its approximately original configuration.

Post-Antler tectonism occurred in at least four episodes, as follows.

1. Late Paleozoic deformation, uplift, and removal of the Roberts Mountains allochthon occurred locally north of a line between Winnemucca and Elko (Fig. 1) (Ketner, 1977). Such events may have been related to right slip in an east-striking displacement zone that caused a major deflection of tectonic units and facies in northern Nevada. Moreover, a klippe of rocks correlated with the Golconda allochthon that is well east of the main allochthon about 100 km northeast of Tonopah (Kleinhampl and Ziony, 1972; Laule and others, 1981) lies in part directly on the autochthon to the Roberts Mountains thrust. If the klippe is based by the Golconda thrust, this suggests that late Paleozoic erosion or tectonism may have stripped the Roberts Mountains allochthon in that area before Early Triassic time.

2. The Golconda allochthon was emplaced above the Roberts Mountains allochthon (Figs. 1, 2) and its partial cover of late Paleozoic shallow marine strata in Early Triassic time. Such thrusting was accompanied by little or no deformation of sub-Golconda rocks.

3. Jurassic and Cretaceous deformation of the Cordilleran thrust and fold belt apparently spanned much of Nevada (Speed, 1982) and caused tectonic intercalation of Antler-related rocks with lower Paleozoic shelf strata and with post-Antler cover as young as Triassic (Kerr, 1962; Silberling and Roberts, 1962; Larson and Riva, 1963; Hotz and Willden, 1965; Gilluly and Gates, 1965; Gilluly, 1967; Winterer, 1968; Riva, 1970; Coats and Gordon, 1972; Silberling, 1973; Nolan and others, 1974; Ketner and Smith, 1974; Skipp and Sandberg, 1975; Sandberg and others, 1975; Smith and Ketner, 1977, 1978; Whitebread, 1978; Speed, 1978; Dover, 1979; Evans, 1980). In the region of Jurassic and Cretaceous thrusting, a regional autochthon is unexposed, and only a few of the myriad thrusts that cut Paleozoic rocks are demonstrably of pre-Jurassic age. Dover (1979) contended that

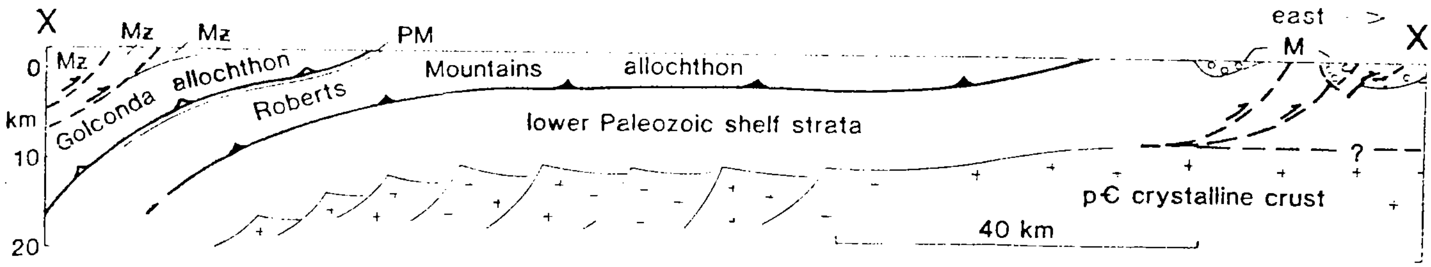

Figure 2. Diagrammatic section of pre-Tertiary structural relationships along XX' of Figure 1; Mz = Mesozoic, PM = Permian to Mississippian strata that overlap the Roberts Mountains allochthon, M = Mississippian foreland basin deposits.

Antler-related rocks in Idaho (Fig. 1) may have been translated east as much as 100 km in the Mesozoic. In contrast, a tectonic enclave in central Nevada from the ancient passive margin east for some 150 km was relatively undeformed in Mesozoic time (Fig. 1), as indicated by the existence of nearly flat-lying autochthonous late Paleozoic and Triassic strata (Ferguson and others, 1951a, 1951b, 1952; Muller and others, 1951; Roberts, 1964; MacMillan, 1972; Nichols, 1973; Burke, 1973; Stewart and McKee, 1976). Where exposed in this region, the contact between lower Paleozoic oceanic and shelf strata seems to be a single, laterally continuous tectonic surface that is the Roberts Mountains thrust (Stewart and McKee, 1976; McKee, 1976). Thus, although the Roberts Mountains allochthon most likely retains its original configuration in the central Nevada enclave, the enclave itself may have been translated as a giant nappe, probably cratonward, within the Mesozoic intracontinental thrust belt.

Furthermore, it has been postulated that during the late Mesozoic, a fragment of sialic North America and terranes accreted to its outer edge may have been rafted away from southeastern Oregon, western Idaho, and perhaps northernmost northwestern Nevada (Hamilton, 1976; Speed, 1982). The fragment may have included the bulk of any Antler-related rocks that originally existed at those latitudes.

4. Cenozoic Basin-Range tectonism caused extension of probably 10% to 20% in a west or northwest direction in central Nevada. Thus, the width of the Roberts Mountains allochthon in the central Nevada enclave (Fig. 1) was initially 15 to 30 km less.

To conclude, the main disturbance of Antler orogenic features was by Mesozoic foreland thrusting throughout the central cordillera except in the tectonic enclave in central Nevada (Fig. 1). Thus, the enclave is the regional focus of our analysis, and we assume that within the enclave (1) Antler-related rocks are in or insignificantly changed from their Mississippian positions relative to the subjacent Paleozoic shelf rocks, (2) the eastern limit of lower Paleozoic oceanic rocks is the approximate trace of the Roberts Mountains thrust, and (3) if a regional Mesozoic décollement extends from eastern to western Nevada, it lies deeply within or below the lower Paleozoic shelf succession (Speed, 1982). In particular, Ketner and Smith's (1981) suggestion that the Roberts Mountains allochthon was emplaced in the Mesozoic is considered unlikely for reasons given later. Outside central Nevada (Fig. 1), the locus and extent of the original Antler orogeny are uncertain.

Roberts Mountains Allochthon

A generalized section of the Roberts Mountains allochthon is shown in Figure 2, modified from Speed and Moores (1981). The allochthon is exposed over a distance of about 100 km and probably extends west below the Golconda allochthon another 30 to 50 km. It comprises pelite, radiolarian and other chert, tholeiite, quartz sandstone, and turbidite of Cambrian through Devonian age. If such rocks accumulated in broadly related environments, an oceanic realm seems most apt, probably including varied depositional sites such as fan, interfan, and basin plain. Limited structural data suggest that allochthon strata occur at least partly in nappes that juxtapose successions of various age ranges (Gilluly and Gates, 1965; McKee, 1976; Smith and Ketner, 1977; Stanley and others, 1977). Although early studies (Roberts and others, 1958) attempted to synthesize a comprehensive stratigraphy among rocks of the allochthon, the paucity of dating and the more recent recognition of tectonic stacking within the allochthon make correlations and resultant thicknesses highly suspect. Nonetheless, almost all workers agree that lithotypes of the allochthon accumulated in a basinal environment, probably on the ocean floor fronting Paleozoic North America. Arguments for a North American source of the terrigenous sediment in the allochthon are sound (Palmer, 1971), but there is no compelling reason to assume accumulation only near the continental margin in Paleozoic Nevada. Deformation of beds in the allochthon is generally large (Gilluly and Gates, 1965; Smith and Ketner, 1977; Evans and Theodore, 1978), but the complexity apparently varies from place to place and perhaps from nappe to nappe.

Autochthon

The autochthon of the Roberts Mountains thrust contains calcareous strata of Cambrian through Devonian age that crop out in windows and Cenozoic horsts across nearly the full width of the allochthon (Stewart, 1980, Fig. 22). Such rocks were deposited on the early Paleozoic shelf of North America (Roberts and others, 1958) and represent inner-shelf to shelf-edge facies (Kay and Crawford, 1964; Stewart and Poole, 1974; Matti and McKee, 1977). Antler-age deformation of rocks of the autochthon seems markedly less than that of the allochthon (Merriam, 1963; Gilluly and Gates, 1965; Nolan and others, 1974; McKee, 1976; Smith and Ketner, 1977). Tight folds of Antler age appear to be absent from the autochthon except locally in a thin zone immediately below the Roberts Mountains thrust. A possible exception to this relationship is a major recumbent fold in parautochthonous shelf-margin strata in the Toquima Range (just east of the passive margin at about 39.5°) figured by Kay and Crawford (1964). The lack of documentation of this structure, however, makes its existence questionable. Antler-age thrusting within the shelf sequence is established by the recognition of parautochthonous nappes of outer- over inner-shelf strata below the main allochthon in contact with the Roberts Mountains thrust (Roberts and others, 1958; Kay and Crawford, 1964; Gilluly and Gates, 1965; McKee, 1976; Smith and Ketner, 1977). In general, however, such redistribution within the autochthon was not accompanied by pervasive deformation, metamorphism, or transport of deep-seated rocks to shallow levels. To conclude, Antler-age deformation of the autochthon seems to have been due to shear transmitted by a surface thrust rather than to intracontinental orogeny.

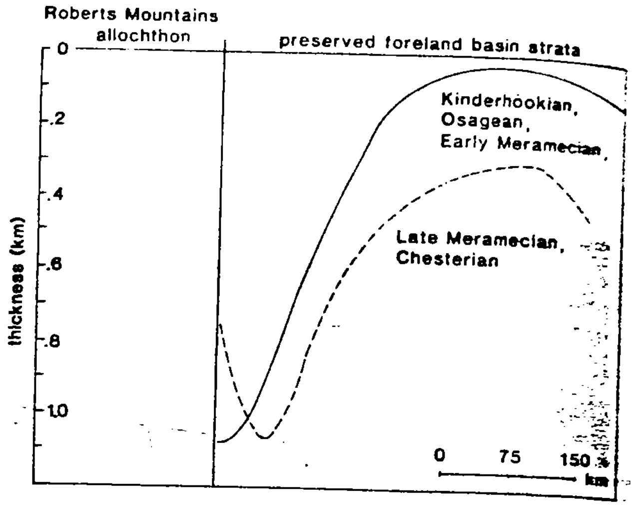

Figure 3. Thickness-distance curves for two time divisions of foreland basin strata at 40°N. Data from Poole and Sandberg (1977) and Stewart (1980).

Foreland Basin

The Antler foreland basin is an asymmetric structural trough defined principally by a thick clastic wedge of Mississippian sediment derived from the west, apparently from the Roberts Mountains allochthon (Poole, 1974; Poole and Sandberg, 1977; Harbaugh and Dickinson, 1981). Maximum preserved thicknesses of the clastic wedge are as great as 3.5 km and occur at or near their westernmost outcrops[1] (Fig. 3); the wedge thins eastward to less than a kilometre thickness at a distance of about 200 km (Poole and Sandberg, 1977; Stewart, 1980).

Preserved strata of the foreland basin occupy a belt some 200 km wide that generally borders the eastern margin of the outcrop region of Antler-related lower Paleozoic rocks (Fig. 1). Within the Mesozoic tectonic enclave (Fig. 1), there is a gap of 10 to 25 km between outcrops of the two terranes, probably due to post-Mississippian erosion. Northward, the two belts narrowly overlap, due at least partly to Mesozoic thrusting and perhaps also to deposition of foreland basin strata on the oceanic rocks (Ketner and Smith, 1977). Thus, initial contact relations of the two terranes are not definitively preserved. The present distribution implies, however, that the width of a Mississippian zone of gaps or overlaps was small, probably less than 25 km.

The foreland basin evolved on the continental shelf which had earlier accumulated shoal-water carbonate and siliciclastic sediments from Cambrian to Late Devonian times. The onset of foreland basin subsidence, taken as the maximum age of basinal strata in successions whose sediments are clearly of allochthon provenance, was in Early Mississippian time. The transition is marked by subtidal siliciclastic and calcareous beds, including turbidites (Webb, Dale Canyon, and lower Eleana Formations) that lie above and are westerly facies of carbonate bank deposits (Joana Limestone) of Kinderhookian to early Osagean age (Poole and Sandberg, 1977; Gutschick and others, 1980). Although resedimented faunas are recognized in some initial foreland basin deposits (Hose and others, 1979; C. A. Sandberg, 1981, oral commun.), the occurrence of numerous samples yielding isochronous faunas (C. A. Sandberg, 1981, oral commun.) suggests deposition may have started as early as Kinderhookian time. Succeeding Mississippian strata of the western trough record a flood of terrigenous debris from the allochthon, first as deep marine-fan deposits (Poole, 1974) and later as a fan delta (Harbaugh and Dickinson, 1981). The clastic wedge prograded continentward across the earlier starved eastern basin and onto bordering carbonate banks during the Mississippian (Poole and Sandberg, 1977; Sandberg and Gutschick, 1980). By Early Pennsylvanian time, the region of the basin was once again largely blanketed by shoal-water carbonates, but Lower Pennsylvanian thicknesses, including local coarse siliciclastic accumulations, indicate that subsidence of the western trough continued into Atokan time (Smith and Ketner, 1977; Stewart, 1980).

The timing of depositional events in the western trough of the foreland basin, important to time-series models of the Antler orogeny, is unfortunately not yet precisely established. Owing to the predominance of resedimented debris and the scarcity of fossils in Mississippian rocks in that region (C. A. Sandberg, 1980, oral commun.), it is difficult to track deposition and subsidence rates and water depths with time. Further, because maximum preserved thicknesses of foreland basin strata are generally at or near their westernmost exposures, it cannot be assumed that remnant strata include a basin axis. It turns out, however, that our quantitative model of the Antler foreland basin predicts maximum basin depth at the toe of the allochthon.

Figure 3 shows a twofold time division of thicknesses of foreland basin strata from Poole and Sandberg (1977) and Stewart (1980). Although the two curves are probably not very precise in the western trough, they suggest that the basin broadened with time and that subsidence rates increased westward. Again, because beds of the western trough are imperfectly perserved or dated, maximum subsidence rates cannot be determined.

Dating of Events

Emplacement of the Roberts Mountains allochthon has been widely accepted to have occurred between late Late Devonian and mid–Early Mississippian times on the basis of studies by Smith and Ketner (1968, 1977). They stated that initial foreland basin strata of Kinderhookian age lap unconformably over rocks in the Roberts Mountains allochthon as young as mid-Famennian age. Ketner and Smith (1981), however, have questioned the evidence for an unconformity and suggested that instead the contact could be a thrust. In the absence of a depositional overlap of Paleozoic rocks across the Roberts Mountains thrust, Ketner and Smith proposed that a Mesozoic age of emplacement of the allochthon is possible. We argue that although the earlier assertion of a depositional overlap may be faulty, present evidence supports the earlier view of mid-Paleozoic emplacement, as follows:

1. The Kinderhookian age of onset of subsidence of the Antler foreland basin and

[1] The isopachs for Mississippian rocks west of the locus of maximum preserved thickness shown by Poole (1974), Poole and Sandberg (1977), and Stewart (1980) are largely extrapolated.

provenance of the bulk of foreland basin sediments from a proximal western highland lithologically like the Roberts Mountains allochthon.

2. The wide area of overlap of the Roberts Mountains allochthon above lower Paleozoic shelf strata and the near coincidence of boundaries of present outcrop areas between the allochthon and Antler foreland basin rocks; two correlative points are: (a) our model for the origin of the foreland basin by vertical loading of the outer shelf by the allochthon predicts that thickest basin strata should occur at the toe of the allochthon, as observed (Fig. 1), and (b) there is no reason for the near coincidence of the allochthon toe and western margin of foreland basin strata if the allochthon were post-Mississippian and unrelated to the Antler foreland basin.

3. The existence of nearly undeformed Triassic and late Paleozoic strata in central Nevada above the Roberts Mountains allochthon; such rocks would seem more likely to be considerably deformed if they had been transported to their present sites on top of the allochthon.

If our argument for Early Mississippian emplacement of the allochthon is correct, latest Devonian and Early Mississippian sediment in its path was obducted onto the allochthon and either resedimented concomitantly or after emplacement. Moreover, foreland basin strata probably lapped west across the probably steep lower slope of the allochthon as inferred by Poole (1974).

Aside from the evident tectonic relationship between the emplacement of the allochthon and Antler foreland basin, it has also been proposed that certain events preceding the Mississippian foreland basin on the continental shelf were caused by early pulses of the Antler orogeny (Poole, 1974; Poole and Sandberg, 1977; Sandberg and Poole, 1977; Sandberg and others, 1980; Gutschick and others, 1980; Sandberg and Gutschick, 1980). Such events include: (1) development of slopes leading to deposition of sediment gravity flows in the Pilot Shale beginning in early Late Devonian (late Frasnian) time, (2) uplift and development of an erosional unconformity in latest Devonian (late Famennian) time within the Pilot Shale, and (3) deposition of largely shallow-water deposits including carbonate banks (Joana Limestone) of Kinderhookian age above the Pilot Shale. The upper early Osagean part of the Joana Limestone was deposited in deeper water (Gutschick and others, 1980) and was in turn overlain by initial deposits of the foreland basin. Without convincing evidence that sediment of allochthon provenance was deposited in the Pilot Shale or Joana Limestone, it is difficult to be certain of an Antler affiliation of the aforementioned events. However, our model of the Antler orogeny, given later, predicts that a laterally propagating upwarp preceded the emplacement of the allochthon on the continental shelf. The upwarp could in fact account for the vertical motions recorded by the three events given above.

Strata of the foreland basin indicate that the Roberts Mountains allochthon was a subaerial sediment source from Early Mississippian to Early Pennsylvanian times. By the end of the Early Pennsylvanian, however, the differential motion of the foreland basin–western highland couple seems to have ceased. The succeeding Paleozoic behavior of central Nevada was one of regional uplift and erosion, local shallow-marine deposition on the former highland, and general easterly transport of terrigenous debris into carbonate basins farther shelfward (Ketner, 1977).

There seems to be no evidence for widespread regional shortening of the shelf of Paleozoic North America in central Nevada during or after the Antler orogeny, except for the questionable recumbent fold figured by Kay and Crawford (1964). Phenomena described above indicate heterogenous vertical motion. The only feature implying lateral tectonic transport is the Roberts Mountains allochthon, and its emplacement was not accompanied by significant horizontal strains in the rocks below it.

INITIATION OF THE ANTLER OROGENY

The initiation of the Antler orogeny was almost certainly related to some form of continental margin tectonism as indicated by the translation of an allochthon of oceanic deposits across the then passive continental margin. Among various conceptual processes for such tectonism reviewed by Nilsen and Stewart (1980), we consider a collision of the passive margin with an island-arc system (Moores, 1970; Dickinson, 1977) in a form presented by Speed (1977, 1979) as the best candidate. As discussed below, no other process satisfies as many of the observational conditions outlined above.

Our conceptual model of the collision of an Antler arc system and the western edge of sialic North America held fixed, and some succeeding Paleozoic events is illustrated in Figure 4. The intraoceanic arc system before collision (Fig. 4A) is assumed to have had a large forearc region (Seely, 1979) with dimensions like those of the southern Lesser Antilles forearc (Westbrook, 1975).

The Antler accretionary prism was a pile of fault slices chiefly of subwavebase deposits of pelagic and terrigenous origin scraped off the descending slab of oceanic litho-

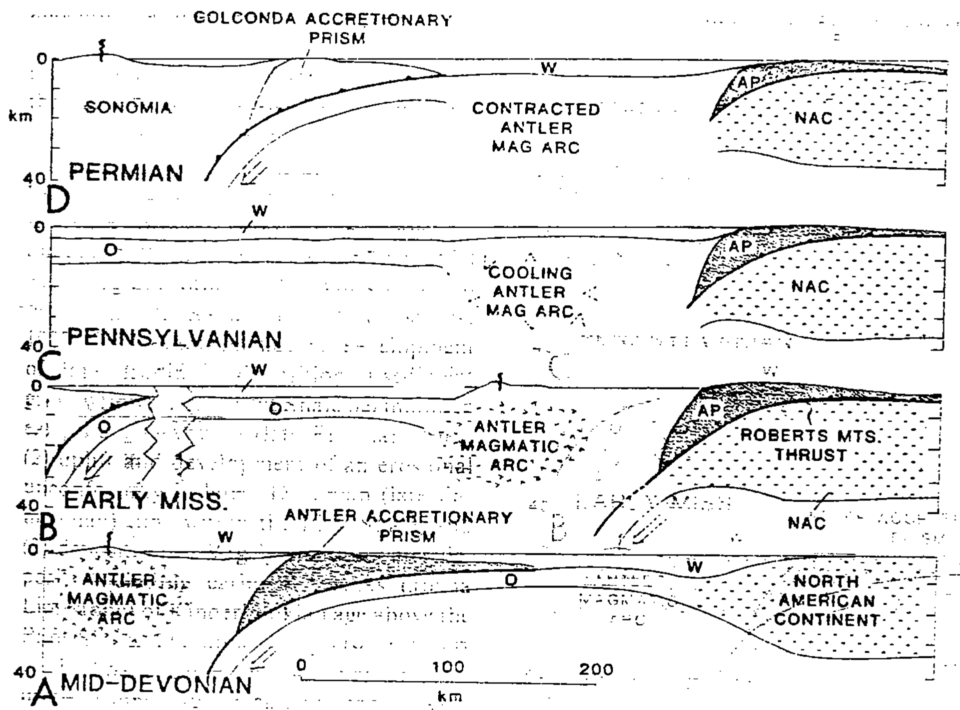

Figure 4. Time series of conceptual events that initiated the Antler orogeny (4A and 4B) and followed it (4C and 4D). W = water, O = oceanic crust, AP = accretionary prism; see text for discussion.

sphere of the Devonian North American plate. Like some modern accretionary prisms, the Antler prism may have been as thick as 20 km at its structural high. It may have extended with diminishing thickness 100 to 200 km to its oceanward toe, overriding the slab with aseismic décollement. As inferred below, the relative motion between the two plates was probably highly oblique to the continental margin.

As closure between arc and continent continued in the Devonian, the accretionary prism encountered the base of the continental slope and was subsequently underthrust by the continent. Plate closure continued until subduction of continental lithosphere below the Antler arc was arrested in Early Mississippian time by buoyancy or some other force (Fig. 4B). Thereupon, convergence was taken up at an unknown boundary oceanward of the Antler arc, the arc system became sutured to the continent, and the oceanic slab initially attached to North America may have broken off and sunk (Fig. 4B). If the prism was 180 km wide between structural high and toe at the time of suturing, continental underriding would have translated the prism complex at least 130 km across the continental shelf. In Figure 4B, the beached accretionary prism is the Roberts Mountains allochthon, and its basal décollement is the Roberts Mountains thrust.

If the Roberts Mountains allochthon is in fact a relict accretionary prism, it contains no recognized systematic changes of lithotypes with height in the tectonic stack of the type suggestive of normal convergence and parallelism of facies in ocean-floor strata and a continental margin. Thus, we postulate that the Antler arc migrated with large obliquity to the margin and that it accreted strata from a long stretch of ocean bordering western North America. Assuming the near-margin deposits consisted of laterally sporadic fan and channel build-ups of terrigenous sediment interspersed with zones rich in pelagic and hemipelagic lithotypes, the conceived process would have produced a lithologically heterogenous accretionary prism. If the idea of oblique convergence is correct, it follows that structurally higher strata were transported great distances from their sites of deposition. Unfortunately, dating in the allochthon is too sparse to allow comparison of age ranges of tectonic packets with position.

The arc-continent collision model shown in Figures 4A and 4B is virtuous in several ways:

1. It eliminates the classical mechanical problem (Hubbert and Rubey, 1959), with respect to the Roberts Mountains allochthon, of how to thrust a thin, layered succession of length many times that allowed by the strength of rocks. In the model, the allochthon is prepackaged as a tectonic pile of great thickness in dynamic equilibrium with a basal décollement before emplacement on the continental shelf. Although there may have been small adjustments to the prism configuration when it ramped up the continental slope, these were probably insignificant compared to the inherent structural complexity of the prism.

2. The model explains the strong contrast in deformation of the allochthon and autochthon and the apparent lack of shortening in the autochthon. The latter point stands to reason because the whole continental lithosphere was involved in the collision, not simply the Paleozoic shelf strata. If the thin zone of moderate deformation seen at the top of the autochthon in a few exposures is representative, it can be suggested that the prism was generally decoupled or that large strain occurred only within the allochthon during emplacement.

3. The postulated collision configuration eliminates need for magmatism and for thermal or deformation-related metamorphism in the continental part of the orogen.

4. The model of Figure 4A has a potential modern analog in that accretionary prisms with dimensions as great as those of the Roberts Mountains allochthon currently exist (Westbrook, 1975). If a continent were on the subducting plate below one of these prisms, it is easy to envision that the collision product would be like the Roberts Mountains allochthon.

The hypothesis of an arc-continent collision suffers only from the absence of a recognized Antler magmatic arc or relics of it. However, the lack of exposure of the Antler arc can be explained by its deep subsidence due to thermal contraction upon suturing to North America and isolation from subduction-related heating (Fig. 4B). The contracted arc lithosphere was then partially or totally consumed in a later arc-continent collision, as described below.

Figures 4C and 4D show conceptually the post-collision behavior of the sutured Antler arc. By mid-Pennsylvanian time (Fig. 4C), about 50 m.y. after collision, the lithosphere below the Antler arc had cooled significantly and contracted to the extent of reinstituting a deep ocean basin immediately west of North America. The new basin invited westward flow of sediment from the continental borderland and its cap of rocks of the Roberts Mountains allochthon. The consequent erosion of the borderland caused isostatic uplift which may b[e] recorded in the Pennsylvanian and Permia[n] unconformities and lithotypes of the regio[n] of the Antler orogenic belt, as discusse[d] above. By Permian time (Fig. 4D), coolin[g] of the Antler arc was probably nearly complete, and the increased density of the ar[c] lithosphere probably permitted it to be largely if not completely subductible. Sonomia (Speed, 1979), an alien microplate fronted by an active arc system, migrated toward North America in the Permian, consuming first the oceanic lithosphere and/or back-arc basin that lay outboard of the contracted Antler arc, and then the arc lithosphere itself. The ultimate collision of Sonomia emplaced the Golconda accretionary prism over the outer reaches of the Early Triassic continental shelf and Roberts Mountains allochthon. If Sonomia stopped short of completely consuming the Antler arc lithosphere, the deep structure of west-central Nevada may include lower Paleozoic igneous rocks.

A maximum rate of subsidence from thermal contraction of the lithosphere beneath the Antler magmatic arc can be obtained from depth-age relationships of ocean ridges (Parsons and Sclater, 1976, equations 11 and 21). The subsidence history of the top surface of the arc lithosphere may be approximated by cooling of a half-space for which subsidence is proportional to the square root of cooling time:

$$d(t) = \frac{\rho_a}{\rho_a - \rho_f} A\, t^{1/2} \qquad (1)$$

where d is the depth to basement relative to the initial elevation, t is the time after the heating event, ρ_a is the density of the asthenosphere, ρ_f is the density of the fill above the contracting lithosphere, and A is a constant which depends on thermal and geometric parameters. Analysis of North Pacific and North Atlantic data by Parsons and Sclater (1976) indicates that A is 244 (m.y.)^1 for times less than 70 m.y. In the present case, the actual subsidence rate, especially for small times, was somewhat less than this, because the upper regions of the lithosphere of an arc are not as hot as those of a mid-ocean ridge. The principal uncertainties are the initial thermal state of the arc and the effect of unknown amounts of radioactive heating on the final thermal state of the arc.

To estimate subsidence history, we assume that contraction started at the end of the Kinderhookian (340 m.y. B.P.), that ρ_a was 3,300 kg/m^3, and that the basin was filled with water (ρ_f = 1,000 kg/m^3). From

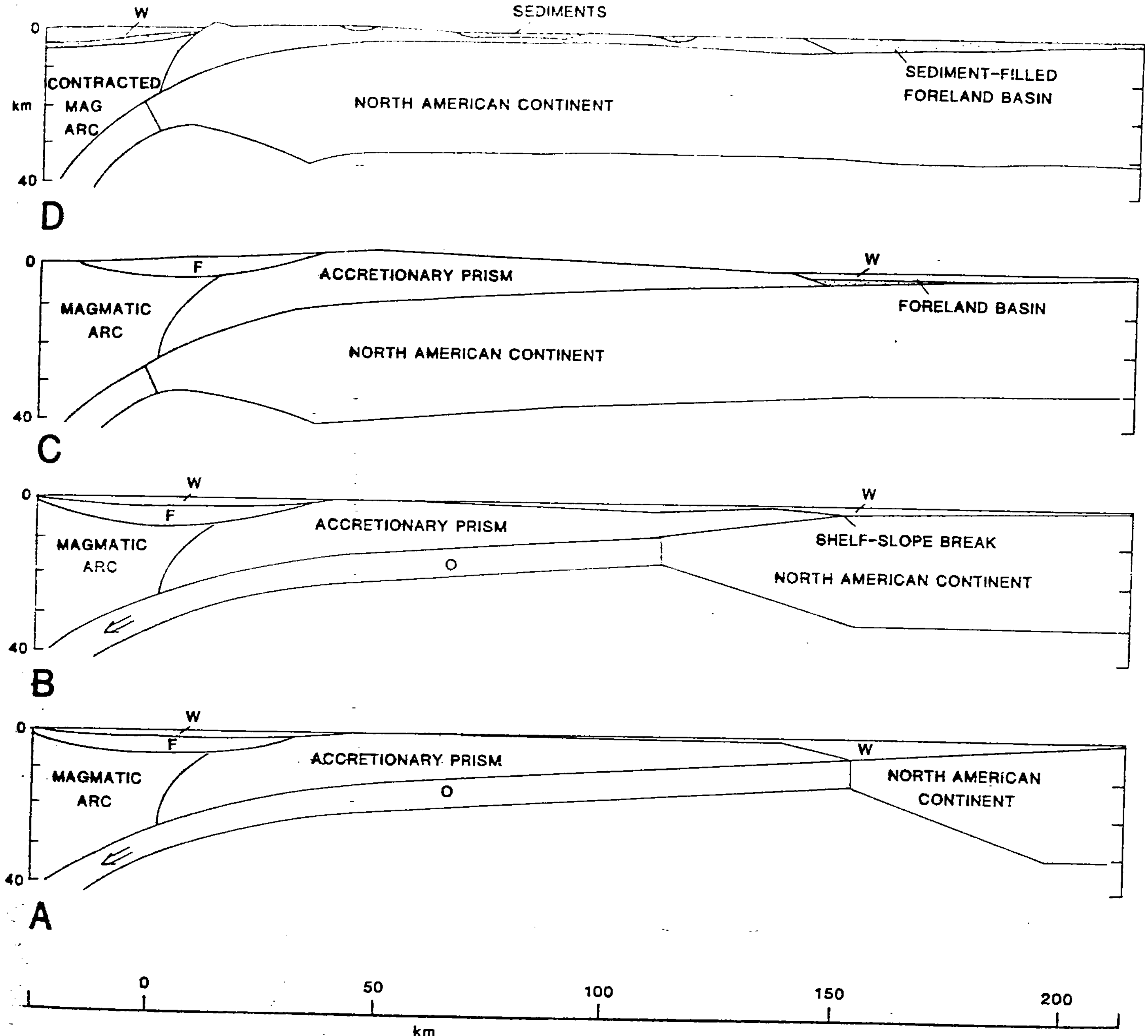

Figure 5. Time series of conceptual events in the evolution of the Antler foreland basin; magmatic arc arbitrarily held fixed; W = water; F = forearc basin; see text for discussion.

equation 1 the arc subsided 1.5 km by the end of Mississippian time (320 m.y. B.P.), 2.2 km by mid-Pennsylvanian time (300 m.y. B.P.), and 2.9 km by mid-Permian time (270 m.y. B.P.). If the basin above the Antler arc was covered by sediment (ρ_f = 2,300 kg/m^3) rather than water, the subsidence would be a factor of 2.3 greater than we computed, or 5 km by mid-Pennsylvanian time and 6.7 km in mid-Permian time.

The actual amount of subsidence was probably intermediate between these estimates. On one hand, the paleogeographic position of the Antler arc precluded a starved basin (Fig. 4C). On the other, upper Paleozoic strata of the Triassic Golconda allochthon (Fig. 2), which are presumably derived in part from the region above the subsided Antler arc, are subwavebase deposits.

ANTLER FORELAND BASIN AND HIGHLANDS

Following the emplacement of the Roberts Mountains allochthon, the Antler orogeny continued through Mississippian time with subsidence of the Antler foreland basin and generation of the Antler highlands outboard of the basin in the region of the allochthon. As noted above, the basin-highland phase of the orogeny seems not to have been associated with regional shortening or extension, magmatism, or metamorphism. We infer, therefore, that basin-highland evolution was not a product of plate boundary tectonics but was simply a consequence of loading of the continental shelf by the Roberts Mountains allochthon. Our concept of the process is illustrated in Figure 5, and Figures 6 and 7 present quantitative models of the foreland basin and related continentward arch in time series.

The story begins (Fig. 5A) with the encroachment of the Antler accretionary prism on the base of the slope of the North American continent. The prism is assumed to be about 130 km wide and to thicken arcward, rapidly at first, then more gradually to a thickness of 15 to 20 km at the outer rise. Choice of prism shape is by modern analog, as discussed later.

The prism-arc system loads the lithosphere that underrides it. An elastic response of the lithosphere would yield a regional downwarp (equations 2–4) of maximum displacement equal to that created by isostasy well under the prism. The downward displacement of the lithosphere would be equal to or somewhat less than one-half the isostatic value at the toe of the prism and would diminish to zero at a point 100 to 200 km continentward of the toe. A low-amplitude elastic arch of some 200-km width would occur continentward of the downwarp. The actual dimensions of the elastic deflection depend, of course, on the characteristics of the prism and the lithosphere, as discussed below.

As North America and the arc system closed, the elastic deflection propagated inboard, as suggested in Figures 5A to 5C (where the arc is held fixed). If cessation of closure occurred at first contact between continental and arc lithospheres (Fig. 5C) and if the average rate of underthrusting of the prism was about 1.0 cm/yr, the stage represented by Figure 5A was about 13 m.y. earlier. However, if the continental lithosphere had subducted more, the part outboard of that shown in Figure 5C presumably broke off and sank with the slab, and there would have been a greater time differential between stages A and C of Figure 5.

In stage A (Fig. 5A), the accretionary prism was almost entirely submerged, and a deep starved basin existed between the structural high of the prism and the shelf-slope break. As the continental slope underthrust the prism (Fig. 5B), the basin shallowed, and carbonate may have accumulated on the prism flank and outer continental shelf at this time. Between stages B and C (Figs. 5B and 5C), the accretionary prism emerged above sea level and became widely subaerial by the time of final closure (Fig. 5C). Transport of debris from the exposed outer part of the prism to the submerged toe and beyond to the continental shelf presumably began before closure stopped. The sediment and possibly some thickness of subjacent layered rock on the shelf either accreted to the encroaching prism or was obducted above it and then resedimented.

The emergent Antler accretionary prism of stage C (Fig. 5C) formed the Antler highlands. Assuming pointwise isostatic balance, the elevation of the highlands would have been about one-quarter of the local thickness of the prism, thus 3 to 5 km at the outer rise. In fact, the distributed elastic deflection of the subjacent lithosphere would cause the western 50 km or so of the prism to be at least a factor of 2 higher than the value given by isostasy (see discussion of equations 3 below).

The basin that fronted the beached accretionary prism at the time of closure (Fig. 5C) was the Antler foreland basin. Its westward-facing slope was created by the elastic deflection of the continental lithosphere, and its eastward facing slope was formed by the flank of the prism. At the outset (Fig. 5C), the basin would have been deepest at the toe of the prism. Assuming passage of sediment was blocked from continent to basin, terrigenous debris from the highlands would have prograded continentward in a clastic wedge across earlier pelagic and hemipelagic deposits on the submerged prism toe and the foreland basin floor.

During the Mississippian, sedimentation probably caused significant changes in highland-foreland basin geography. Early in the period, sediment from the Antler highlands was presumably transported east to the foreland basin and west to a postulated trough, a relict forearc basin (Seely, 1979), that lay between the highlands and the magmatic arc. By mid-Mississippian time and thereafter, however, contraction of the magmatic arc was sufficient to have allowed deposition of highland sediment on the arc surface and far to the west on the deep-ocean floor (Figs. 4C and 5D). The isostatic response to the sediment transfer was to uplift the highlands and depress further the foreland basin and the inactive magmatic arc. A second response was the continentward elastic broadening of the foreland basin because sedimentation effectively caused the prism load to migrate eastward. As the highlands continued to rise during the Mississippian, early foreland basin deposits that lapped on the lower prism slope were uplifted and resedimented eastward toward the foreland basin axis.

By the end of Mississippian time, the highlands were much reduced and the mechanical load initially supplied to the outer continental shelf by the prism decreased by transport of sediment west to the oceanic basin (Fig. 4C). The load reduction would have resulted in regional uplift of both highland and foreland basin and caused the basin to become shallow water or subaerial if sediment had not already filled it (Fig. 5D). At this stage, concentration of sediment in the foreland basin progressively diminished, and the region soon regained a more shelf-like configuration.

To quantify the above ideas, we used the theory of flexure and an elastic lithosphere floating on a dense substratum, the asthenosphere. This formulation is sufficient to illustrate the general features of the process. More complex calculations are not warranted because the geometry of the accretionary prism and the Antler foreland basin is too poorly known. Our purpose is not to determine the detailed mechanical properties of the Carboniferous lithosphere but rather to use modern analogs to appraise our proposed mechanism for the Antler foreland basin.

The deflection of a thin elastic plate is described by

$$N \frac{d^4w}{dx^4} + kw = p(x) \qquad (2)$$

where N is the flexural rigidity of the plate, w is the vertical displacement, x is horizontal distance, $k = (\rho_a - \rho_f)g$ is the difference in specific weight between the asthenosphere (of density ρ_a) and the material that fills the basin (of density ρ_f), g is gravity, and p(x) is the driving load per unit area. Analytic solutions which follow (equations 3–5) have been obtained for three models of the accretionary prism which probably span the range of physically relevant configurations. The first solution is for the load of a semi-infinite sheet between $x = -\infty$ and $x = 0$:

$$w(x) = \frac{p}{2k} \cos(x/\alpha) \exp(-x/\alpha); \; x > 0 \qquad (3a)$$

or

$$w(x) = \frac{p}{k} [1 - \tfrac{1}{2} \cos(x/\alpha) \exp(x/\alpha)]; \; x \leq 0 \qquad (3b)$$

where the flexural parameter $\alpha = (4N/k)^{1/4}$ has dimensions of length. From (3a) the deflection of the lithosphere is a depression of width $\pi\alpha/2$ between the toe of the accretionary prism and a more continentward elastic upbulge of slight amplitude. At the toe of the prism (x = 0), w = 0.5 p/k and one-half the deflection given by pointwise isostasy. Equation 3b gives the deflection below the prism and shows that the full elastic deflection is first attained at $x = -\pi\alpha/2$.

The second solution for a very narrow accretionary prism of some width λ along x is obtained by adding a negative sheet between $x = -\lambda$ and $x = -\infty$ to the solution in equation 3a. If $\lambda \geq \pi\alpha/4$, this solution differs little from that of a semi-infinite sheet (equation 3). It is thus not necessary to know the details of the prism farther than that from the toe. For a prism significantly narrower than $\pi\alpha/4$, a line load centered at $x = 0$ is appropriate. The solution is:

$$w(x) = \frac{\lambda p}{\sqrt{2}\,k} \exp(-x/\alpha) \cos(x/\alpha - \pi/4); \quad x \geq 0 \tag{4}$$

Here the width of the depression is $3\pi\alpha/4$.

A third solution (equation 5) is for a wedge-shaped prism which thickens at a constant rate and consequently exerts a steadily increasing load (constant dp/dx) between $x = 0$ and $x = -\lambda$ and is of constant thickness at $x < -\lambda$. At $x \geq 0$, this solution is:

$$w(x) = \frac{\alpha}{4\rho g}\frac{dp}{dx}\Big\{(\exp(-\frac{x}{\alpha})[\cos\frac{x}{\alpha} - \sin\frac{x}{\alpha}] - \exp -(\frac{x+\lambda}{\alpha})[\cos\frac{x+\lambda}{\alpha} - \sin\frac{x+\lambda}{\alpha})]\Big\} \tag{5}$$

If λ is small, equation 5 is identical to that for a semi-infinite sheet (equation 3a). If, on the other hand, the wedge extends far from the prism toe (x large), the depression continentward of the toe will have a width of $\pi\alpha/4$.

To conclude, the width of the depression in front of the accretionary prism is probably within the limits ($\pi\alpha/4$ and $3\pi\alpha/4$) and depends on the profile shape of the prism. A concentrated or line load gives the maximum width, and a load that increases gradually from the toe, the minimum. Local variations in load distribution near the prism toe ($x = 0$) and gross variations at large distances from the toe ($x < -\pi\alpha/2$) have little effect on the width of the depression.

Formation of a significantly wide depression requires the lithosphere to be relatively cold and, hence, stiff. Relevant estimates of the flexural rigidity (N) are 10^{23} nt-m for the Atlantic coast of the United States (Steckler and Watts, 1978) and 10^{24} nt–m for older oceanic lithosphere seaward of trenches (Chapple and Forsyth, 1979). For water-filled basin, the specific weight contrast (k) is 23×10^3 nt/m^3, giving flexural parameter estimates of 65 km and 115 km when combined with the above values of N. For a sediment-filled basin, the specific weight contrast is 7×10^3 nt/m^3, and the flexural parameter is correspondingly greater by a factor of $(2.3/0.7)^{1/4}$ or 1.35. Table 1 presents calculated width of depressions for various combinations of prism shape and flexural parameter.

TABLE 1. CALCULATED FORELAND BASIN WIDTHS

k ($kg \cdot m^{-3}$)	N (nt·m)	α (km)	Accretionary prism shape ($n\pi\alpha/4$) wedge (n = 1)	sheet (n = 2)	line (n = 3)
2,300	10^{23}	65	51	102	153
2,300	10^{24}	115	90	180	270
700	10^{23}	87	69	136	207
700	10^{24}	154	122	242	365

Note: widths are in kilometres. Quantities are defined in the text.

The initial profile shape of the Roberts Mountains allochthon is unknown because it has been much eroded. Our conceptual model (Fig. 5) implies that the load was extensive rather than concentrated oceanward of the basin edge. Modern accretionary prisms (Karig and Sharman, 1975; Westbrook, 1975) thicken from the toe with a convex-up profile or have a comparatively steep outer face of width less than $\pi\alpha/2$ and a gentle inner face. Therefore, the most likely shape of the Antler prism was between a wedge and a sheet, implying a value of n between 1 and 2 in Table 1.

The early Antler foreland-basin deposits are subwavebase and perhaps deep-water, implying that the early basin was chiefly water-filled. Accordingly, the range of minimum predicted widths for a water-filled early basin is 51 to 180 km (Table 1). Later basin deposits indicate that the sedimentation rate exceeded the subsidence rate and that the basin ultimately became sediment-filled. The corresponding range of predicted widths for the later basin is 69 to 242 km (Table 1). From Figure 3, the approximate widths of the actual Antler foreland basin between the allochthon toe and eastern basin margin (point of zero slope on thickness curves) are 150 km at the end of early Meramecian time and 200 km at the end of Chesterian time. The increase in actual basin width with time evidently reflects the increased proportion of sediment in the fill with time. The agreement between observed and predicted values in magnitude and time trend indicates the proposed loading mechanism is credible and that the Antler accretionary prism was more sheet-like than wedge-like.

Computed models of the effects of the propagation of an accretionary prism over a passive margin are illustrated in Figures 6 and 7. The density of the prism is assumed to be 2,500 kg/m^3, as determined for the Lesser Antilles accretionary prism by Westbrook (1975). For convenience, the same density is used for the sediment fill of the foreland basin. The prism is assumed to thicken by 0.1 km/km from the toe where under water. The rate of increase in load, dp/dx, is doubled where the prism is over the continental slope (−50 to 0 km on the horizontal axis of Fig. 6) to give a smooth upper surface. The rate of elevation increase of the prism above water is reduced by a factor of 0.6 relative to its submarine profile to give a constant dp/dx and to provide a slope at a realistic angle of repose. Horizontal distances are referenced to an origin at the shelf-slope break (Figs. 6 and 7).

At stage A (Fig. 6A), the prism toe has arrived at the base of the continental slope. The continental outboard is downflexed between distances of −50 and 80 km with an amplitude of about 1 km at the shelf-slope break. Between 80 and 420 km, the continent is upwarped with a maximum elevation of 250 m (Fig. 7, curve A).

At stage B (Fig. 6B), the prism toe has arrived at the shelf-slope break and thickened somewhat during transit of the continental slope. The foreland basin is 3 km deep at the toe of the prism and extends 140 km continentward of the toe. The upwarp (Fig. 7, curve B) lies between 140 and 500 km and is over 300 m high at a distance of 230 km from the prism toe.

At stage C (Fig. 6C), the prism has ceased migration after traversing 80 km of continental shelf and attaining a total continental overlap of 130 km. The foreland basin is 2.6 km deep at the prism toe and extends 110 km continentward of the toe. The upwarp has a maximum elevation of about 350 m at 290 km and extends to 560 km (Fig. 7, curve C).

Stage D (Fig. 6D) represents a later time, when the beached prism has been reduced to sea level by erosion and its foreland basin

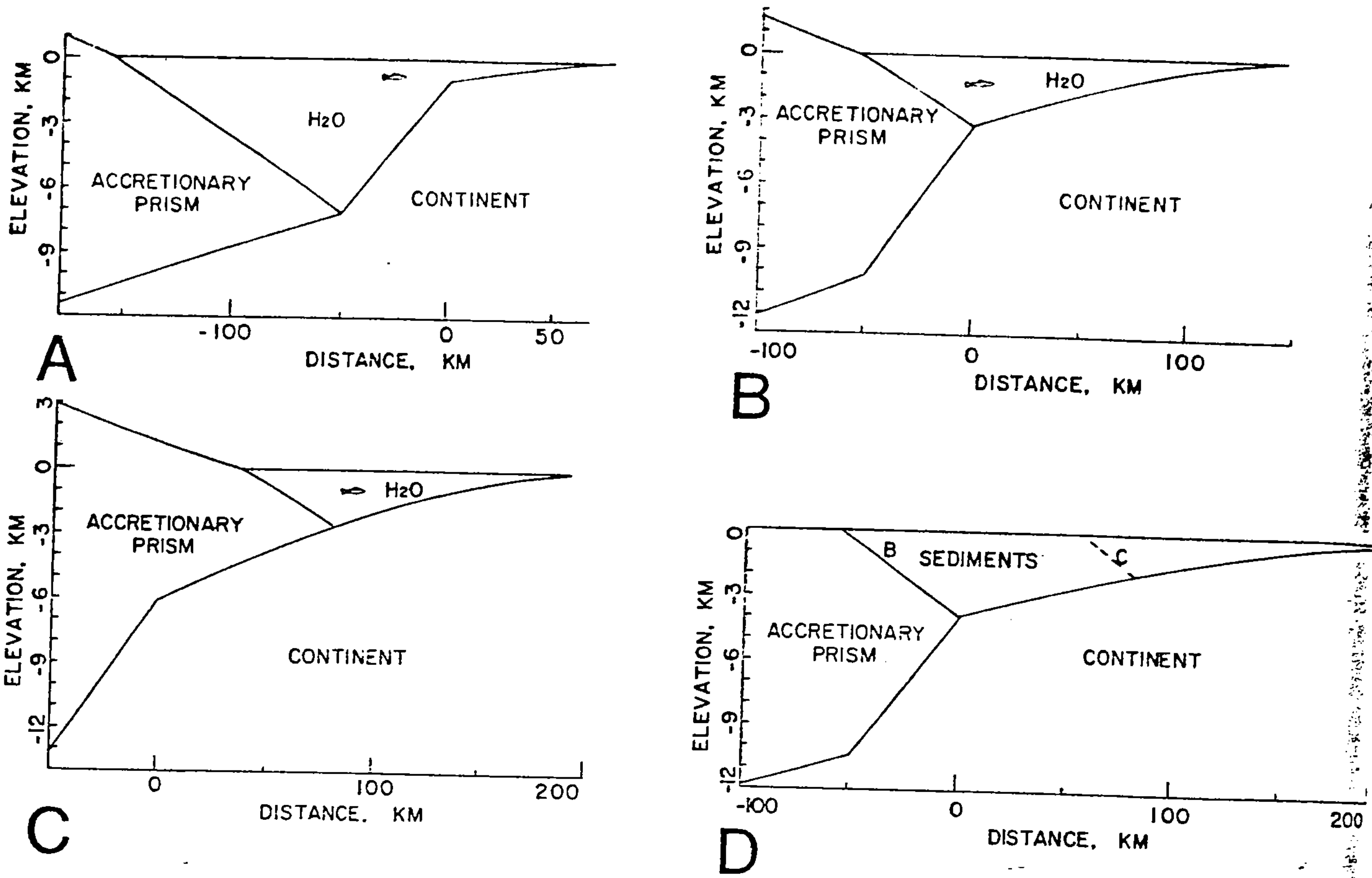

Figure 6. Calculated flexure of the lithosphere from a simplified thrust sheet is plotted for various times. The initial water depth inland from the shelf break (0) is assumed to be sea level. The initial water depth seaward of 50 km is 5 km. The thrust sheet has constant thickness to the left of the drawing at times A, B, and C. At time D the entire region is eroded and sedimented to sea level. The position of the thrust edge is indicated assuming the thrust stopped at time B. The position had the thrust stopped at time C is the dashed line. See text.

has been completely filled with sediment. Line C shows the prism-sediment boundary for a prism that migrated as far as stage C, whereas line B shows the same boundary for a prism that stopped migration at stage B. The curves of Figure 6D illustrate the principle that the farther inboard the prism propagates, the smaller the volume of foreland basin sediments that would be ultimately preserved.

To conclude, our highland-basin model yields basin widths, depths, and asymmetry that generally agree with those of the Antler foreland basin. Three particular points concerning sediment onlap on the allochthon, time-dependent effects, and the flexural bulge migration are discussed below.

The basin model of Figure 6 predicts that maximum thickness of sediment in the foreland basin occurs at the toe of the accretionary prism. It also indicates that for the shape of the prism, the width of the belt of marine sediment that lapped west onto the Roberts Mountains allochthon was narrow, perhaps 30 to 50 km (Fig. 6C). The width of the sediment overlap would have been even narrower if the lower slope of the allochthon had been steeper than that assumed. Thus, given a very steep allochthon front, the model provides a primary origin for the apparent meager width of overlap between the Roberts Mountains allochthon and Antler foreland basin deposits. The existence of a steep allochthon face is not unreasonable because (1) debris flow and other plastic bodies typically have bulbous toes (Johnson, 1970, p. 450) and thus have more slablike than wedgelike profiles, and (2) the broad width of the Antler foreland basin also suggests the allochthon had a steeply rather than shallowly inclined front, as discussed above.

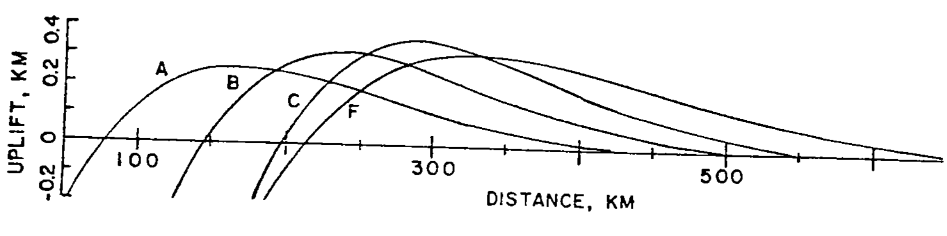

Figure 7. The uplift in front of the thrust sheet is shown for the times in Figure 6. At times A, B, and C no erosion is assumed to occur. At time D a region originally at sea level is assumed to have been uplifted by flexure and then eroded back to sea level. The broad uplift may produce an observable unconformity which is time transgressive.

The evolution of the foreland basin after complete emplacement of the accretionary prism would depend on sedimentation and on mechanical properties of the lithosphere

Sediments derived from the prism but far from its toe would provide new loads in the basin and would increase subsidence and width of the basin. Carbonate banks and far-traveled cratonic sediment would have the same effect on the foreland basin. However, sedimentation from the toe of the allochthon to the nearby basin floor would produce only a minor shift of load and cause little uplift or subsidence. Once the basin is filled, any subsequent removal of mass from the highlands or basin would produce uplift of the system. If the loaded lithosphere could maintain elastic strain over the erosion history of the allochthon, the flexture would broaden and diminish in amplitude as the load was spread out by erosion and sedimentation. If, on the other hand, creep could relax the strains related to flexure, the allochthon would subside more and the basin would rebound and narrow with time. The geometric effects of creep are likely to be obscured by the broadening of the basin by sediment filling.

The model also predicts that a broad flexural bulge of height as great as 350 m should have propagated across the continental shelf landward of the foreland basin during closure between the accretionary prism and the North American continent (Fig. 7). Late Devonian and Early Mississippian stratigraphic features that preceded the subsidence of the Antler foreland basin, as recounted above, may be related to the migration of a flexural bulge. Late Frasnian and Famennian turbidite in the Pilot Shale may have been derived from the leading edge of the bulge, and the intra-Famennian lacuna within the Pilot Shale below the western trough may represent erosion on passage of the bulge. The overlying deposits including the Joana Limestone may have accumulated in shallow water on the trailing edge of the bulge, and the deepening of the Joana may track the easterly migration of the bulge. Strata above the Joana Limestone indicate increasingly basinal conditions and are interpreted to record the encroachment of the Antler foreland basin. Unfortunately, the dating available to us of key horizons is insufficiently precise to determine a closure velocity.

EARLIER MODELS

With respect to initiation of the Antler orogeny, Moores (1970) was first to invoke the collision of an arc with North America. Most subsequent models, including ours, employ some form of collision, although Roberts (1972) and Ketner (1977) sought explanations that involve no plate-boundary tectonics. Moores (1970) proposed that the orogeny was caused by one of a series of collisions between passive western North America and arcs that crossed or were generated in the proto–Pacific Ocean. Our collision configuration differs from Moores' in two respects: (1) the rocks that became the Roberts Mountains allochthon were brought to the continental slope by the arc as a prepackaged tectonic edifice, not as a complex created by collision with the continent, (2) the arc system may have migrated obliquely along western North America, and (3) no subcontinental subduction was involved. Moreover, our model holds that the Antler magmatic arc was removed from view by thermal contraction, whereas Moores (1970) provided no explanation for the lack of exposure of the postulated arc. Burchfiel and Davis (1972), Silberling (1973), Churkin (1974), and Poole (1974) concluded that the Roberts Mountains allochthon emerged from a backarc basin that lay between the continental slope and a local magmatic arc, now located in the Sierra Nevada and the Klamath Mountains, that surmounted a subcontinental subduction zone. The orogeny was thought to be caused by a collapse of the backarc basin, but the mechanisms of obduction of the basin sediments in these treatments are vague. The paucity of arc-derived rocks in the Roberts Mountains allochthon argues against a backarc basin origin of allochthon sediment. Moreover, there is little correspondence between early Paleozoic volcanic histories of the Sierra and the Klamath Mountains and between the latter and timing of Antler events. Whereas the early Paleozoic rocks of the Klamath and Sierra provinces may have been long-term local residents, they may also represent fragments of arcs of other terranes that were generated at distant sites along the western margin of North America (Speed, 1979). Dickinson (1977) considered underthrusting of the continental edge beneath oceanic rocks as a more likely origin of the Roberts Mountains allochthon than other mechanisms he surveyed. We agree.

Three alternative schemes for generation of the Antler highland-foreland basin couple are (1) sustained lateral loading of the continental margin by Mississippian subduction with a subcontinental slab (Poole, 1974), (2) lateral heat conduction from the cooling Antler magmatic arc into and consequent expansion of the peripheral continental lithosphere, and (3) cooling at the base of the lithosphere along a locus that was to become the forearc basin.

The first idea is mechanically infeasible if conceived as an elastic buckle because the half-wavelength of the first buckle of a lithosphere over a viscous substrate should be many times that of the Antler foreland basin and because the stress needed to buckle the lithosphere is excessive.

We have investigated the second mechanism and found that the heat gained by the continental lithosphere by lateral conduction from the cooling Antler magmatic under optimum transfer conductions (vertical contact) would expand the continental outboard by no more than 100 m. Such relief seems inadequate to have initiated an adjacent foreland basin by sedimentary loading.

The third scheme assumes that hot material is created or emplaced at the base of the continental lithosphere inboard of the Paleozoic passive margin, either by rifting or by convection following detachment and sinking of the slab upon collision of North America and the Antler arc (Fig. 4B). In analogy with subsidence of mid-ocean ridges, thermal contraction of the lithosphere above the hot region may have created the Antler foreland basin, in the way inferred for Atlantic continental margins and interior basins by Sleep (1971). The thickness (S) of sediments in the basin versus time, assuming sedimentation keeps pace with subsidence, is:

$$S = S_0(x)\,[1 - \exp(-t/50\ \text{m.y.})] \qquad (6)$$

for a thermal contraction origin, where $S_0(x)$ is a slowly varying function of horizontal position and t is time. Depth-time curves for sediment thickness of the Antler foreland basin, interpolated from Figure 3, can be reasonably fit by equation 6. The correspondence suggests that thermal contraction is a feasible origin of the foreland basin.

The sedimentation rate, however, is a poor indication of subsidence rate in a basin that was chiefly water-filled in its early history but sediment-filled later. The declining rates of sedimentation are more likely due to filling of the depression and denudation of the source terrain than to thermal contraction of the lithosphere.

To conclude, the alternative mechanisms for generation of the Antler foreland basin are either inadequate or unduly complex.

We contend that flexure of the continental shelf by vertical loading due to the Roberts Mountains allochthon, as given above, is the only tractable hypothesis yet proposed.

OTHER FORELAND BASINS

If our model of the Antler orogeny has general applicability to a class of orogenies discussed above, it should account for the seeming variability of foreland basin development among examples presented. Assuming that the lack of association of foreland basin deposits with the Golconda allochthon is not due to erosion, lack of recognition, or overriding by reactivation of the allochthon, the main variables are the characters of the accretionary prism and of the continental margin at time of collision.

If the accretionary prism were small, an orogeny resulting from arc-continent collision might differ significantly from that discussed above. The width and thickness of the prism might be small enough that the toe would not migrate beyond the shelf-slope break and the prism might not break the water surface. Further, the elastic depression of the continental shelf would be proportionally less. As a result, no highlands would emerge to provide coarse detritus; the basin would undergo less sediment loading; and the basinal deposits would be pelagic, hemipelagic, or carbonate turbidite types, which might be difficult to recognize as foreland-basin deposits. If the continental slope were broad relative to the typical 50-km modern value, the chances increase that a small collided prism would not have evolved into a highland.

CONCLUSIONS

Our model of the Antler orogeny holds that initiation of activity was by an arc-continent collision and that succeeding motions of a highland-foreland basin couple were due simply to vertical loading of the continental shelf by a beached accretionary prism. The model accounts well for regional geologic characteristics of the orogeny, answers the mechanical problem of how to emplace oceanic strata tens of kilometres across the shelf-slope break, and explains the absence of associated magmatism, metamorphism, and regional shortening. It predicts that an Antler magmatic arc subsided deeply after collision by thermal contraction, that the initial Antler highlands were the subaerial part of the accretionary prism, and that the deepest part of the foreland basin was at the toe of the prism. Moreover, it suggests that there would have been meager overlap of Antler foreland basin deposits on the Roberts Mountains allochthon if the toe of the allochthon had a relatively steep slope during emplacement. Analytic models of elastic deflections of the continental slope and shelf give widths, depths, and asymmetry that accord well with values of the Antler foreland basin. Models predict that a flexural bulge as high as 350 m preceded the migrating foreland basin. Certain Late Devonian and Early Mississippian features that underlie Antler foreland basin deposits may record the passage of the bulge.

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