# Widespread effects of middle Mississippian deformation in the Great Basin of western North America

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## ABSTRACT

**Stratigraphic analyses in central and eastern Nevada reveal the importance of a deformation event in middle Mississippian time that caused widespread deformation, uplift, and erosion. It occurred between middle Osagean and late Meramecian time and resulted in deposition of both synorogenic and postorogenic sediments. The deformation resulted in east-west shortening, expressed as east-vergent folding and east-directed thrusting; it involved sedimentary rocks of the Antler foredeep as well as strata associated with the Roberts Mountains allochthon. A latest Meramecian to early Chesterian unconformity, with correlative conformable lithofacies changes, postdates this deformation and occurs throughout Nevada. A tectonic highland—created in the middle Mississippian and lasting into the Pennsylvanian and centered in the area west and southwest of Carlin, Nevada—shed sediments eastward across the Antler foreland, burying the unconformity. Postorogenic strata are late Meramecian to early Chesterian at the base and are widespread throughout the Great Basin. The tectonism therefore occurred 20 to 30 m.y. after inception of the Late Devonian Antler orogeny, significantly extending the time span of this orogeny or representing a generally unrecognized orogenic event in the Paleozoic evolution of western North America.**

**We propose a revised stratigraphic nomenclature for Mississippian strata in Nevada, based on detailed age control and the recognition of unconformities. This approach resolves the ambiguity of some stratigraphic names and emphasizes genetic relationships within the upper Paleozoic section. We take advantage of better stratigraphic understanding to propose two new stratigraphic units for southern and eastern Nevada: the middle Mississippian Gap Wash and Late Mississippian Captain Jack Formations.**

**Keywords: Paleozoic, tectonics, stratigraphy, Antler, foreland, lithostratigraphy.**

## INTRODUCTION

The conventional tectonic interpretation for the evolution of western North America is that there were two major orogenies in Paleozoic time; however, this interpretation does not explain the numerous local and regional-scale tectonic events recorded in upper Paleozoic rocks. The Late Devonian Antler orogeny and the Permian–Triassic Sonoma orogeny are both characterized as the eastward emplacement of oceanic-facies sedimentary and minor volcanic rocks over continental-margin sedimentary rocks (Roberts, 1951; Roberts et al., 1958; Silberling and Roberts, 1962). Many syntheses (e.g., Burchfiel and Davis, 1972, 1975; Speed and Sleep, 1982) have proposed that a long-lived subduction zone oriented down-to-the-northwest, possibly accompanied by slab rollback to the east (e.g., Dickinson, 2000), was responsible for the east-directed Antler and Sonoma orogenies, and all activity in between. However, this model is not robust in predicting the angular unconformities, disconformities, and deformation observed in upper Paleozoic rocks (e.g., Johnson and Visconti, 1992; Schwarz et al., 1994; Snyder et al., 1997; Silberling et al., 1997; Ketner, 1998; Schiappa et al., 1999; Trexler and Giles, 2000).

In this study, we have revised stratigraphic nomenclature on the basis of our recognition of widespread unconformities in the upper Paleozoic record; in many cases, these unconformities occur within existing formations. Each unconformity is, by definition, a boundary of at least formation rank and requires stratigraphic revision where it breaks a previously defined formation. Some of the unconformities can be mapped laterally into areas where the underlying rocks are deformed; these we have identified as key stratigraphic

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markers with tectonic significance. Some unconformities can also be traced laterally into areas where they are conformable surfaces with minor or no hiatus. Even in these cases, a tectonostratigraphic signal may exist in the form of a facies change forced by the same tectonic disruption. Correlation of the unconformities and their correlative conformable surfaces is made possible by detailed biostratigraphy.

Our biostratigraphic and stratigraphic studies and mapping reveal a widespread tectonic event in middle Mississippian time. The stratigraphic evidence for this tectonism is different in different places and ranges from an angular unconformity, to a disconformity, to a change in provenance, to tectonically forced sea-level changes recorded in distal carbonate strata. For example, there is an angular unconformity within the Mississippian section in the Diamond Mountains (Trexler and Nitchman, 1990; Trexler and Cashman, 1991), in the southern Adobe Range at Carlin Canyon (Snyder et al., 1997; Trexler et al., 1999), and throughout the Piñon Range (Silberling et al., 1997). The deformed rocks are everywhere overlain by post-tectonic strata that are early Chesterian in age. In contrast, in Mississippian rocks in the Eleana Range of southern Nevada, there is an abrupt change in provenance in early Chesterian time (Trexler et al., 1996). In Utah, there is evidence for tectonically forced sea-level change in middle Mississippian time and for creation of a restricted, shallow basin (Silberling et al., 1997; Jewell et al., 2000). In order to determine the nature and cause of these related stratigraphic changes, we have examined other sections throughout Nevada, focusing on the Kinderhookian–Chesterian time interval. Our database includes many measured sections with detailed biostratigraphy, as well as mapping and structural data.

In this paper, we show how tectonostratigraphic analysis of upper Paleozoic rocks can be based on the regional unconformities in the section, and we propose a revised stratigraphic terminology that both honors these unconformities and is consistent with our improved age control. We then focus on the middle Mississippian deformation, presenting first the stratigraphic evidence for its extent and then the structural evidence for the style, intensity, and location of the deformation. Finally, we discuss the significance of tectonic activity in the Mississippian, long after the Antler orogeny began, and its implications for tectonic evolution of the Cordillera. We separately explain our revised stratigraphic terminology for Mississippian rocks of the Antler foreland.[1] The new terminology (1) abandons or redefines names where units contain regionally significant unconformities and (2) selects formation names for units that are restrictive enough in thickness and extent that they also have relatively narrow age ranges. Our revision provides the stratigraphic detail necessary to interpret the tectonic evolution.

## MISSISSIPPIAN STRATIGRAPHY IN NEVADA—BACKGROUND

Mississippian stratigraphy in central Nevada has been interpreted as representing a foreland basin that filled progradationally in response to the Antler orogeny (e.g., Poole, 1974). This orogeny is usually characterized as the eastward emplacement of the Roberts Mountains allochthon onto a west-facing continental margin in Late Devonian time (Roberts, 1951; Roberts et al., 1958). The resulting peripheral foredeep formed because of loading and isostatic flexure and filled as the Antler highlands eroded during the Mississippian (e.g., Speed and Sleep, 1982; Giles and Dickinson, 1995). Generally, lithofacies in the Mississippian foreland stratigraphy fit this model. The section is almost entirely marine and mostly siliciclastic; it ranges in age from Famennian (latest Devonian) upward through the Mississippian. Conglomerates are coarser and more common to the west, near the allochthon, and overall the Mississippian section coarsens upward. Petrology and paleocurrent data generally support a western source for sediments (e.g., Poole [1974], Trexler and Cashman [1991], and references cited therein). The Chesterian (Upper Mississippian) section comprises shallow-marine siliciclastic and carbonate rocks and nonmarine siliciclastic strata (see footnote 1) (Poole and Sandberg, 1977; Trexler and Cashman, 1991; Perry, 1994, 1995; Trexler et al., 1995; Crosbie, 1997). This facies change in Late Mississippian time was originally interpreted as a shift from ''flysch'' to ''molasse'' sedimentation in the foreland (Poole, 1974).

Several anomalous aspects of this foreland stratigraphy include (1) a relatively thin (2 km) stratigraphic section in the presumed foreland keel near Eureka, Nevada (Trexler and Cashman, 1991), and (2) a coarse, clastic section that records a very long period of tectonic activity for a postcollisional foreland. The thin stratigraphic section of the foreland keel suggests that the tectonic load may have been either well to the west, or not large; however, strata far to the east were affected. (Note: Published tectonic modeling of flexure assumes that the Antler allochthon was roughly in the position it occupies now, not significantly farther west—see Giles and Dickinson, 1995). Successful tectonic models must explain these observations. This tectonic activity occurred sporadically throughout most of Mississippian time, ~30 m.y. (discussed subsequently; also, see Silberling et al. [1997] and references therein). Clues to understanding these anomalies lie in the details of the foreland stratigraphy.

The stratigraphic nomenclature currently in use for Antler foreland-basin strata is complicated and sometimes misleading (Fig. 1). This is largely because most of the stratigraphic names were defined prior to both (1) acceptance of the plate-tectonics paradigm and (2) modern understanding of submarine-fan and delta systems that fill marine foredeep areas. Miscorrelation is easy because submarine-fan facies are, by their nature, laterally discontinuous, and because facies are so similar. Compounding the problem, the section is poor in fossils, especially between upper Kinderhookian and lower Chesterian age strata.

An angular unconformity within the Mississippian section was first recognized by Trexler and Nitchman (1990) in the Diamond Mountains (places mentioned in the text are located in Fig. 2). There, rocks below the unconformity are Kinderhookian through Meramecian, and the overlying strata are lower Chesterian and younger. These authors suggested that this unconformity was a sequence boundary. It has also been interpreted as a parasequence boundary (W.R. Dickinson, ca. 1992, written commun.). However, our more recent work shows that this unconformity correlates with others—and is thus regional in extent—and locally truncates tectonically deformed rocks. These characteristics preclude both the sequence boundary and parasequence boundary interpretations.

More recently, Silberling et al. (1997) documented middle Mississippian deformation in central Nevada and related it to continuing Antler tectonism. In addition, they showed how Mississippian stratigraphy of Nevada and western Utah could be organized into three genetic units they termed ''sequences.'' They named these for pioneering geologists in the Great Basin—in ascending order, the Morris sequence, the Sadlick sequence, and the Maughan sequence. This was an important step in revising stratigraphic organization, be-

[1]GSA Data Repository item 2003139, detailed regional discussion of stratigraphy in Nevada, is available on the Web at http://www.geosociety.org/pubs/ft2003.htm. Requests may also be sent to editing@geosociety.org.

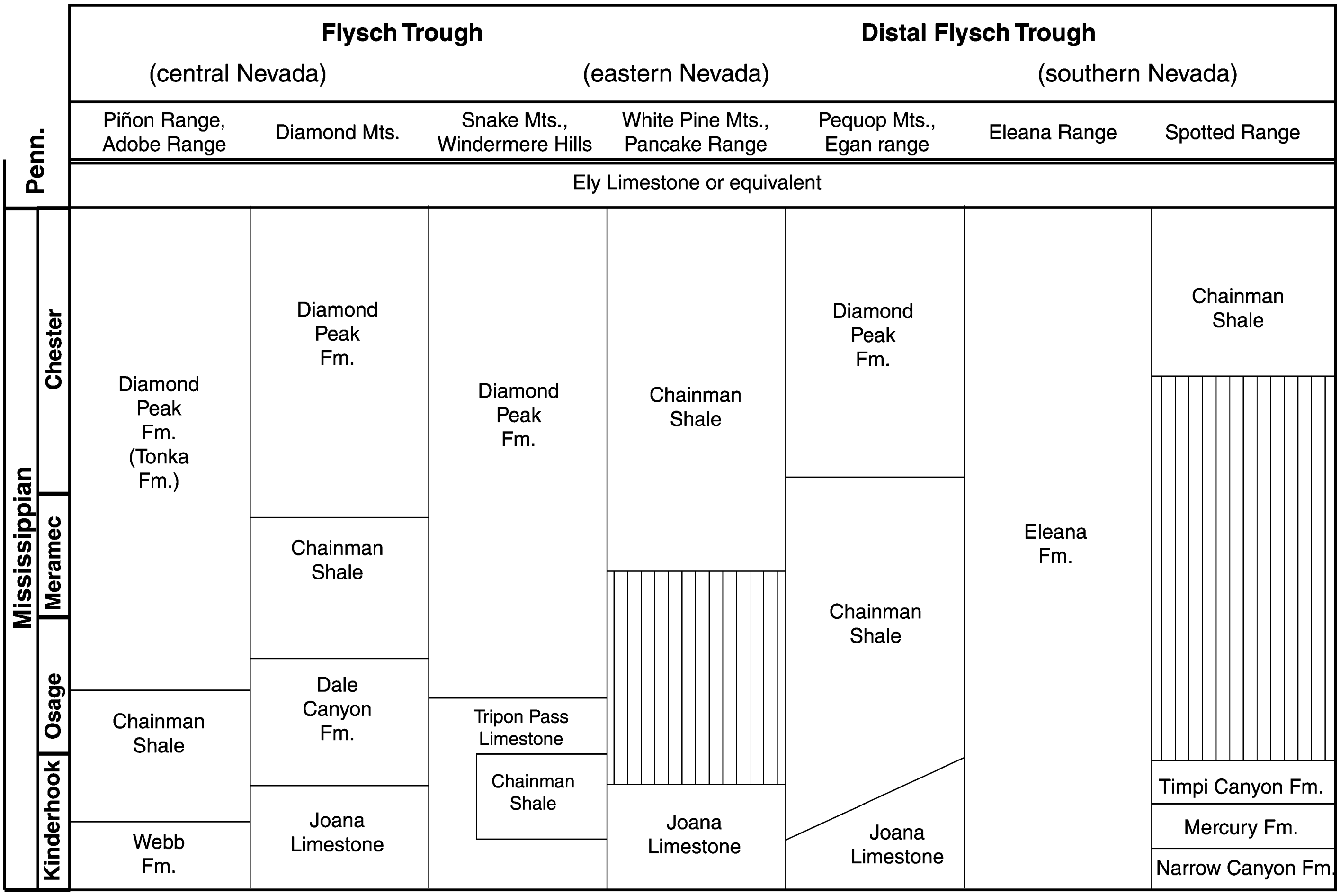



**Figure 1. Stratigraphy of Mississippian rocks of Nevada and western Utah, as synthesized by Poole and Sandberg (1977). Sections from localities corresponding to those in Figure 4 have been extracted for this figure from the original, more extensive compilation. Note the highly variable ages and age ranges for units identified as Chainman Shale and Diamond Peak Formation.**

cause it directly related the rocks both to their genetic origins and to their relationships with correlative rocks. There are two drawbacks, however: (1) The nomenclature is made more complex by giving all strata two names—a formation name (e.g., Dale Canyon Formation) as well as the name that denotes the sequence (e.g., Sadlick sequence). (2) These are not ''sequences'' in the seismic stratigraphy sense or scale. (Seismic-stratigraphic sequences result from eustatic sea-level control of sedimentation on ~100,000 yr, third-order cycles.)

Our work throughout Nevada has shown that (1) the middle Mississippian unconformity is one of a number of regional unconformities from middle Mississippian through Permian time and (2) they all represent genetically important breaks in the stratigraphic record (Fig. 3) (Snyder et al., 2000). These unconformities were tectonically generated and are nearly isochronous (to the resolution of upper Paleozoic biostratigraphic control, i.e., ±~1–5 m.y.). What is more important is that these unconformities can be correlated laterally to ''event horizons'' (e.g., lithofacies shifts) that have the same origin. This feature makes them useful far beyond the areas of actual uplift, deformation, and erosion. We have adopted a numbering scheme for these unconformities (Fig. 3), using a system much like that used for the Mesozoic section on the Colorado Plateau (Pipiringos and O'Sullivan, 1978; Peterson and Pipiringos, 1979). They are numbered sequentially from oldest to youngest within each time period; for the upper Paleozoic, we use C = Carboniferous, P = Permian (Snyder et al., 2000). Our reassessment of Mississippian stratigraphy in Nevada uses these unconformities and their correlative event horizons as natural breaks that separate packages of genetically related strata (see footnote 1).

## MISSISSIPPIAN STRATIGRAPHY AND THE C2 BOUNDARY

For purposes of tectonic interpretation, it is useful to organize Mississippian strata in Nevada genetically, i.e., as rocks that were deposited either above or below the regional C2 boundary. Strata *below* the boundary were deposited in the Antler foreland basin. The boundary unconformity itself represents erosion following tectonic disruption of the foreland, which we discuss subsequently. Strata *above* the boundary, uniformly dated as early Chesterian, overlap across the old, in places deformed, Antler foreland. To the east and southeast, the C2 boundary disappears into continuous sections not disrupted by middle Mississippian deformation. In some of these areas, the boundary can still be identified by lithostratigraphic or facies changes. A detailed discussion of the stratigraphic revisions ne-

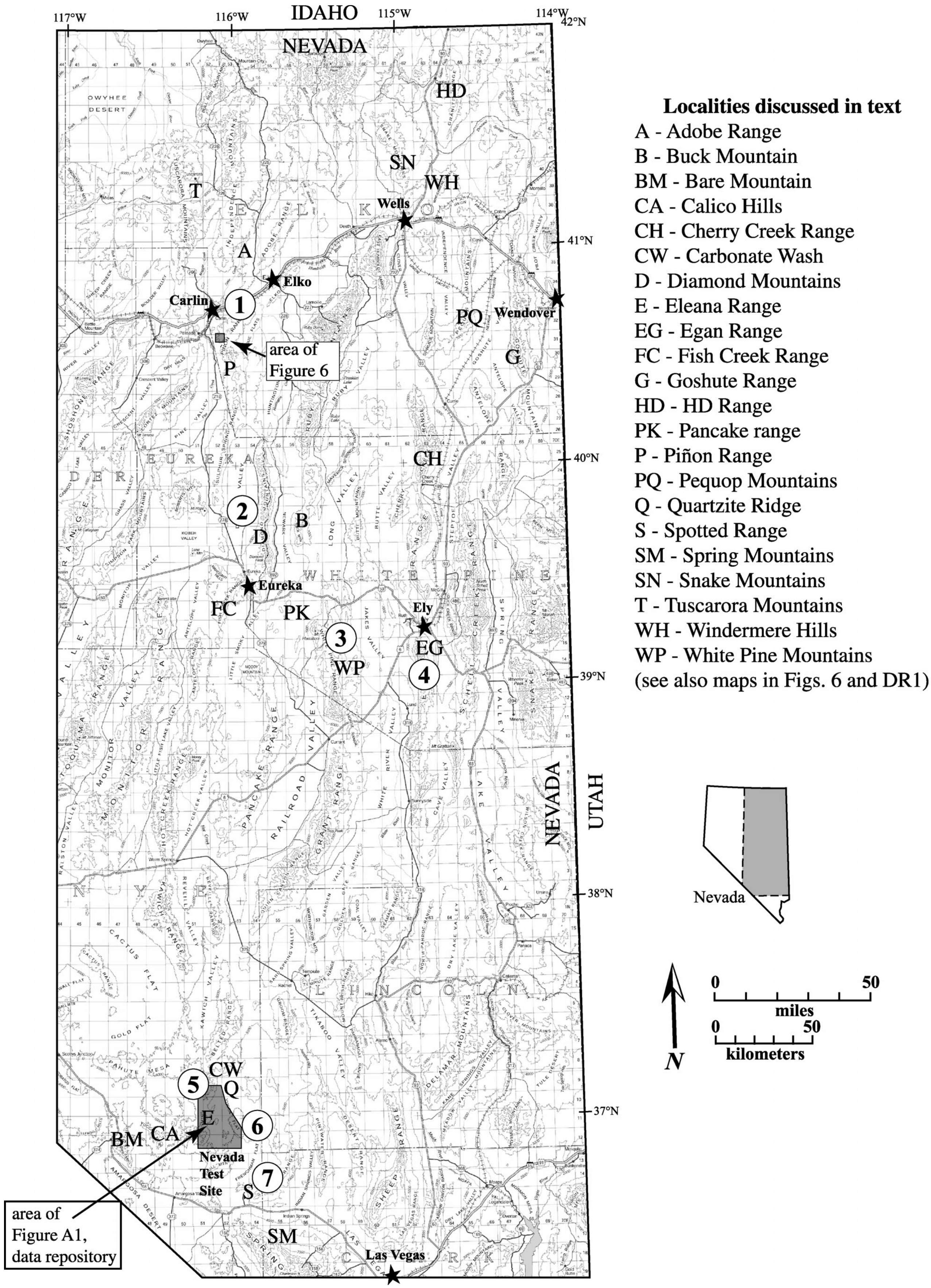



**Figure 2. Geographic map of the eastern part of Nevada. Numbers in circles are locations of stratigraphic columns in Figure 4.**

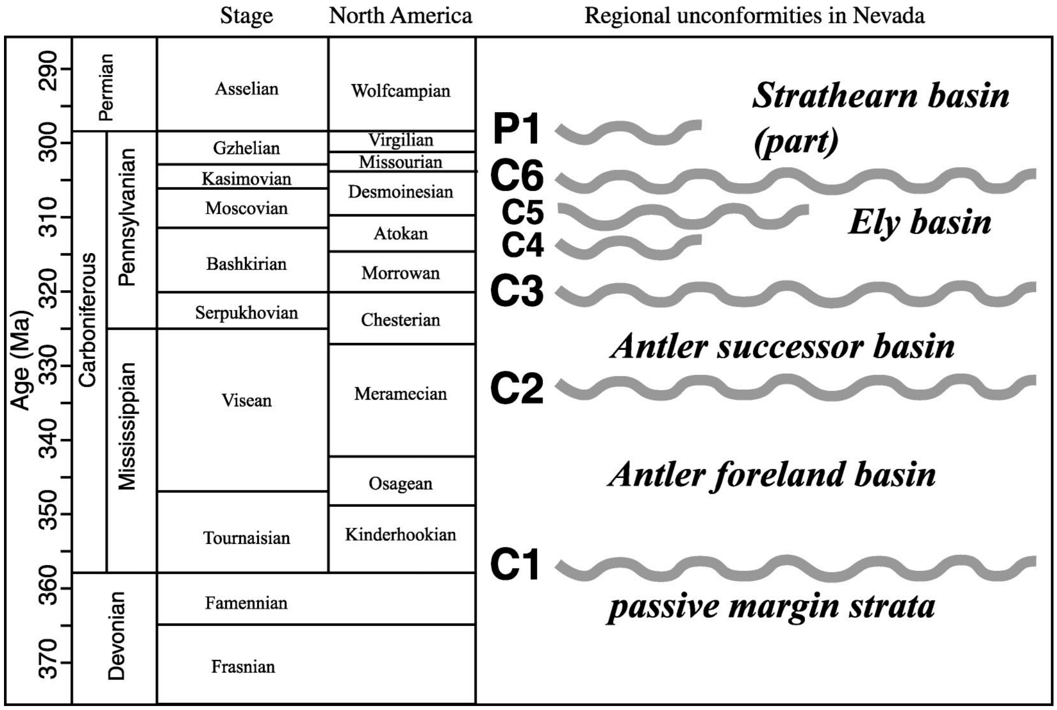



**Figure 3. Important, regional unconformities of the Carboniferous in the Great Basin, western North America (Snyder and Trexler, 2000; Snyder et al., 2000; Trexler et al., 2004). Time scale here and in Figure 4 is the current version adopted by the IUGS (International Union of Geological Sciences).**

cessitated by the recognition of the C2 boundary is available (see footnote 1).

## Sub-C2 Stratigraphy Summary

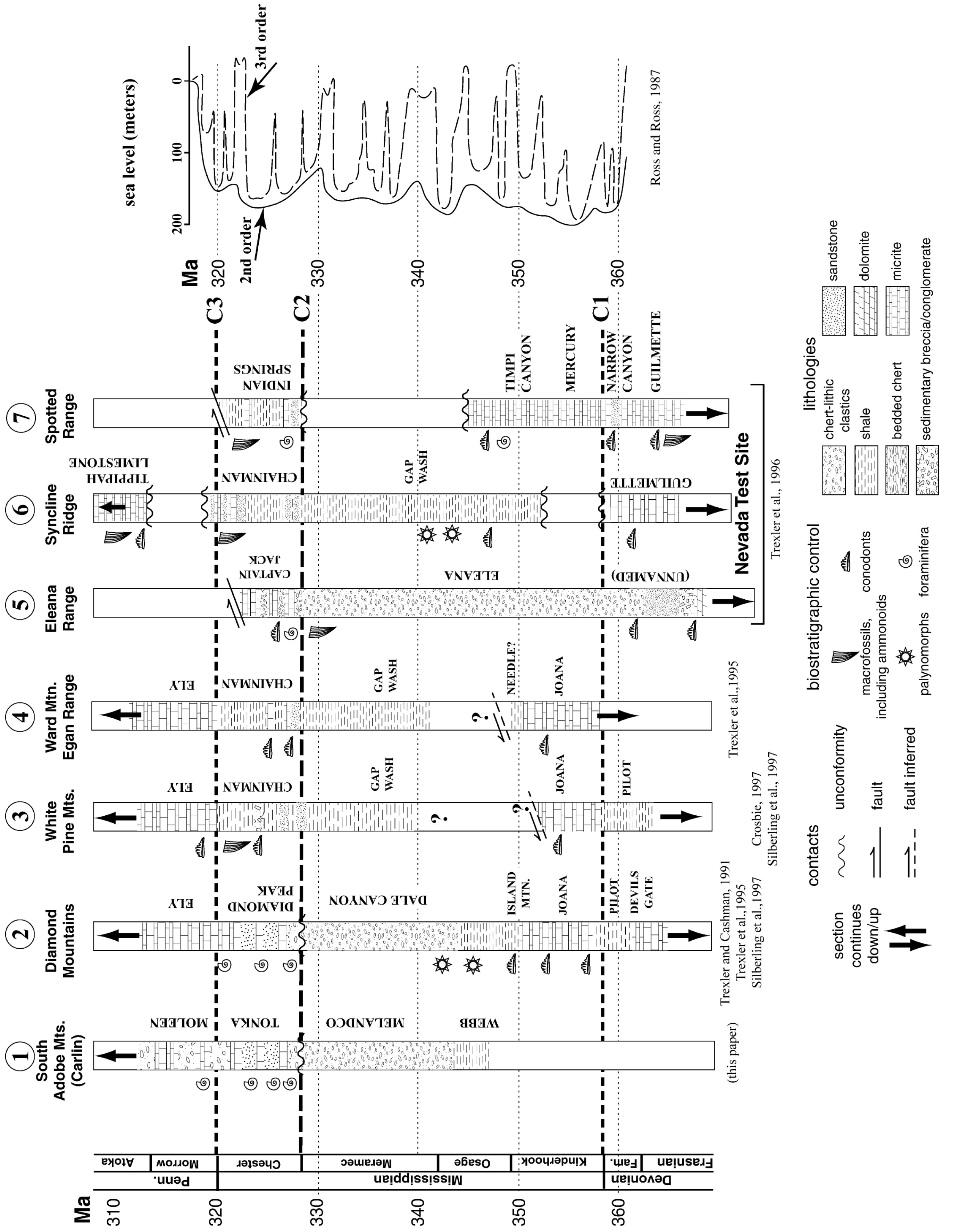
Kinderhookian through Meramecian age strata of north-central Nevada are siliciclastic sedimentary rocks whose deposition is attributable to the filling of the Antler foredeep and related basins. The thickest deposits form a narrow belt from northeast to south-central Nevada. Here, they comprise as much as 2 km of heterolithic conglomerate, litharenite, and shale or argillite. The section is undated in most areas because of poor fossil preservation. To the east, in central and eastern Nevada, the section is thinner and much finer grained.

Where good age control is available, it suggests that the bulk of the siliciclastic sediments did not start to arrive in the central Nevada foredeep until Osagean time. For example, the Island Mountain Formation lies at the base of the siliciclastic section in the Diamond Mountains and is interpreted to have formed during the initial subsidence of the foredeep (Nichols and Silberling, 1995). The youngest conodonts in the Island Mountain Formation are early Osagean (Nichols and Silberling, 1995; Silberling et al., 1997); therefore the bulk of the siliciclastic section in the Diamond Mountains was deposited after this time. In southern Nevada, chert-clast conglomerates that overlie Famennian deposits are interpreted to represent the initial Antler orogenic pulse of sediment (Carbonate Wash and Tarantula Canyon at Bare Mountain; see Trexler et al., 1996). However, siliciclastic sediment also overlies Osagean limestone beds at Bare Mountain (Trexler et al., 1996). The very thick siliciclastic section in the Eleana Range is undated, but is interbedded at the top of the section with Chesterian strata.

Distribution of foreland strata was influenced both by irregular paleogeography of the collision margin and by flexural effects of eastward-directed collapse of the continental borderland (Poole and Sandberg, 1977; Speed and Sleep, 1982; Snyder and Trexler, 2000). Irregularities along the complex collision zone resulted in a remnant basin in the south that filled axially, depositing sediments of the Eleana Formation (Trexler and Cashman, 1997). Topographic irregularities to the north also led to the formation of carbonate submarine fans (e.g., the Tripon Pass Formation; Frye, 1998) derived from the continental shelf (which was to the northeast). Some studies (e.g., Giles et al., 1999) suggest that sedimentary rocks of this age were deposited in a Late Devonian and Early Mississippian back-bulge basin created by obduction of the Antler allochthon. Other workers (Nichols and Silberling, 1990, 1993, 1995; Silberling et al., 1997) see no flexural effects in strata older than latest Kinderhookian. However, they have interpreted Osagean and Meramecian strata in eastern Nevada and Utah to have been influenced by topographic relief that was caused by tectonic loading and flexure. Notably, they attributed these tectonic effects to the events that deformed foreland-basin strata in Osagean and Meramecian time (Silberling et al., 1997), which we would argue produced the C2 angular unconformity in central Nevada.

The best names we determined to use for genetically linked, sub-C2, Mississippian units in the Great Basin are Melandco For-

**Figure 4. Revised correlation diagram for Mississippian rocks of eastern Nevada, with age control, for key localities discussed in text. Columns are identified and located by number in Figure 2. Uppercase formation names are shown as they are used in this paper. Time scale is that currently adopted by the IUGS (International Union of Geological Sciences). Sea-level curve of Ross and Ross (1987) has been adjusted to fit the most recent numerical age determination for stage boundaries.**



Ma
310
320
330
340
350
360
Penn.
Mississippian
Devonian
Atoka
Morrow
Chester
Meramec
Osage
Kinderhook
Fam.
Frasnian
1 South Adobe Mts. (Carlin)
MOLEEN
TONKA
MELANDCO
WEBB
(this paper)
2 Diamond Mountains
ELY
DIAMOND PEAK
DALE CANYON
ISLAND MTN.
JOANA
PILOT
DEVILS GATE
Trexler and Cashman, 1991
Trexler et al.,1995
Silberling et al.,1997
3 White Pine Mts.
ELY
CHAINMAN
GAP WASH
JOANA
PILOT
Crosbie, 1997
Silberling et al., 1997
4 Ward Mtn. Egan Range
ELY
CHAINMAN
GAP WASH
NEEDLE?
JOANA
Trexler et al.,1995
5 Eleana Range
CAPTAIN JACK
ELEANA
(UNNAMED)
6 Syncline Ridge
TIPPIPAH LIMESTONE
CHAINMAN
GAP WASH
GUILMETTE
Trexler et al., 1996
7 Spotted Range
INDIAN SPRINGS
TIMPI CANYON
MERCURY
NARROW CANYON
GUILMETTE
Nevada Test Site
C3
C2
C1
sea level (meters)
0
100
200
3rd order
2nd order
Ross and Ross, 1987
contacts
unconformity
fault
fault inferred
section continues down/up
biostratigraphic control
macrofossils, including ammonoids
conodonts
palynomorphs
foraminifera
lithologies
chert-lithic clastics
shale
bedded chert
sedimentary breccia/conglomerate
sandstone
dolomite
micrite

mation in northern Nevada, Dale Canyon Formation in central Nevada, and Eleana and Gap Wash Formations in southern Nevada (see footnote 1). In eastern Nevada, sub-C2 Osagean and Meramecian strata have not yet been differentiated from other Mississippian rocks. When they are, we suggest that the name Gap Wash be applied to these rocks as well. Farther east, in western Utah, established stratigraphic names for sub-C2 platform carbonate and siliciclastic rocks should be used (see Silberling et al., 1997). We have supplied a detailed discussion of reasons for selection of names and definitions of these and other correlative units (see footnote 1).

### Super-C2 Stratigraphy Summary

Strata that overlie the C2 boundary unconformity record systematic variations in depositional environment. These sedimentary rocks range from nonmarine, siliciclastic, deltaic rocks in the west, to shallow-marine carbonates, conglomerates, litharenites, and lagoonal shales in central Nevada, and to shelf and lagoonal carbonaceous shales and quartzites in eastern Nevada. The source of heterolithic siliciclastic sediments of this age appears to be recycled Antler foreland-basin strata (Trexler and Cashman, 1991, 1997; Perry, 1994, 1995). The detritus for the eastern and southeastern quartz arenite (Scotty Wash) beds was derived from the craton (Trexler and Cashman, 1991). Throughout the Great Basin, these strata are overlain by Pennsylvanian limestone.

In southern Nevada, the C2 boundary is a conformable contact between siliciclastic and carbonate-clast turbidites. The appearance of Chesterian carbonate turbidites (the Captain Jack Formation) on the Nevada Test Site and vicinity can be attributed to inundation of the eroded Antler foreland region to the north and enhanced carbonate productivity, possibly owing to postorogenic isostatic subsidence.

In eastern and southeastern Nevada, there is no stratigraphic signal directly related to middle Mississippian tectonism in central Nevada. Instead, eustatic control of sedimentation resulted in deposition of quartzite and carbonaceous shale intervals. We interpret these quartzite beds as lowstand shelf deposits that signal a progressive, westward return to eustatic control of sedimentation (see Ross and Ross [1987] sea-level curve in Fig. 4). Our age control shows that depending where on the shelf a given section was located, these lowstand sand sheets could have begun to appear as early as late Meramecian; they were common throughout the shelf by early Chesterian time. We infer that these quartz arenite beds signal the end of Antler tectonism and a return to a stable seaway that lasted until late Chesterian time (Trexler et al., 2004).

The names best used for genetically linked super-C2 Mississippian units in the Great Basin are Tonka Formation in northern Nevada, Diamond Peak Formation in central Nevada, Chainman Shale in eastern and southeastern Nevada, and Captain Jack Formation and Chainman Shale in southern Nevada. We have provided a detailed discussion of the derivation these names and definition of these and correlative units (see footnote 1).

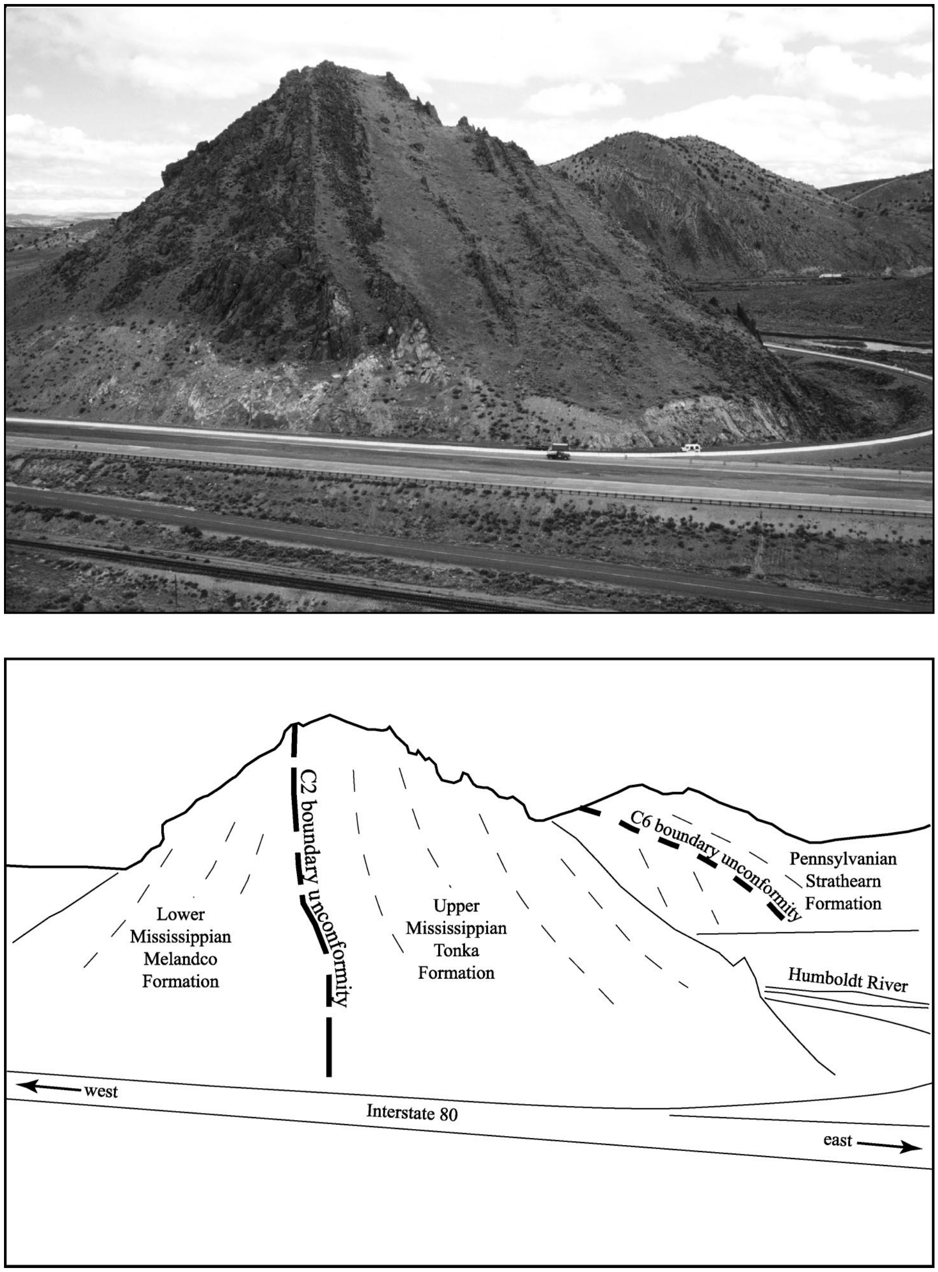



**Figure 5. The C2 and C6 unconformities exposed in the south-facing canyon walls at the west end of Carlin Canyon. Boundaries C3, C4, and C5 have been removed by erosion under the C6 unconformity. See Figure 2 for Carlin location.**

## A MIDDLE MISSISSIPPIAN DEFORMATION EVENT

The C2 boundary is preserved throughout central Nevada; its expression varies systematically with geographic position. It is an an-

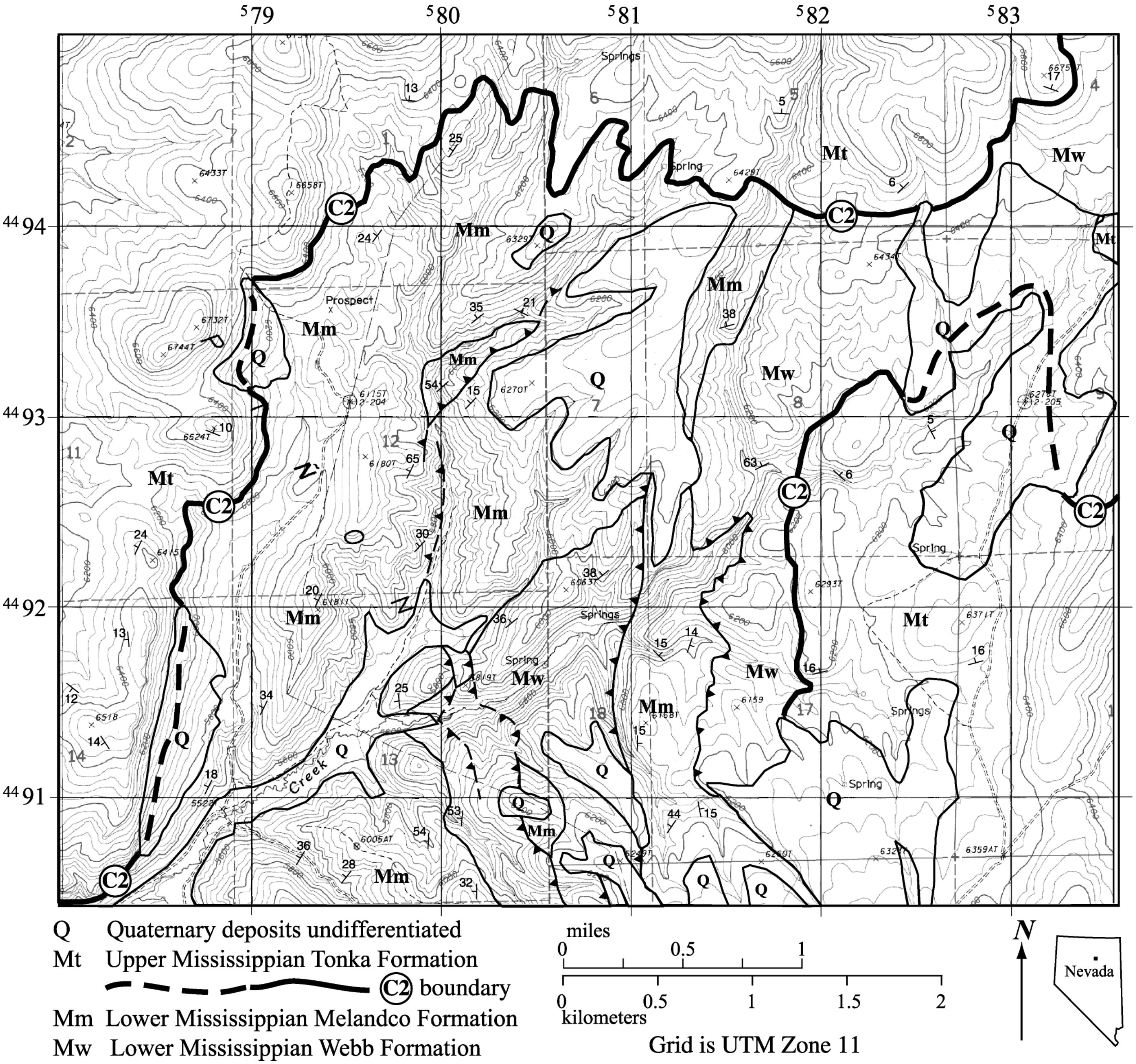



**Figure 6. Geologic map of part of the Ferdelford Creek headwaters (from Tosdal, unpublished mapping). The topographic base is part of the Raven's Nest 7.5′ quadrangle. Thrust faults duplicating the Webb-Melandco contact are overlain by the Tonka; this deformation therefore occurred in middle Mississippian time. The C2 boundary unconformity is coincident with the base of the Tonka Formation.**

gular unconformity in northern Nevada, from the Carlin area in the Adobe Range 150 km south to outcrops in the Diamond Mountains near Eureka (Fig. 2). Within this belt, in the northern Piñon Range south of Carlin, the unconformity erosionally truncates strata as old as Late Devonian (Figs. 6A and 16 in Silberling et al., 1997; R.M. Tosdal's unpublished mapping). In southern Nevada at the Nevada Test Site, the boundary is present in several thrust sheets from Quartzite Ridge to Bare Mountain, an along-strike distance of 80 km. It is marked by an abrupt lithologic change, always conformable, with no missing strata. Rocks of this age are known but rarely exposed between Eureka and the Nevada Test Site and have not been studied in detail. Direct evidence for the deformation event represented by the unconformity is limited to the ~150-km-long belt of outcrops from the southern Diamond Mountains north to the Adobe Range.

At Carlin Canyon, the C2 boundary is an ~25° angular unconformity between rocks of the Melandco Formation (below) and the Tonka Formation (above) (Fig. 5). In addition to the angular relationship, there is a change from Melandco submarine-fan conglomerate and litharenite below the unconformity to Tonka shallow-marine conglomerate, litharenite, and carbonate above it. The Melandco is undated here, but biostratigraphic control is very good in the overlying Tonka (Fig. 4). This angular unconformity may have been overlooked in the past because it is subvertical, owing to subsequent deformation, and because coarse conglomerates crop out both above and below it. The subsequent deformation here includes both Pennsylvanian folding and thrusting (Snyder et al., 1997; Trexler et al., 1999, 2004) and later folding that has been correlated with Mesozoic deformation farther north in the Adobe Range (Smith and Ketner, 1977). The Melandco dips steeply eastward below the more gently east-dipping Tonka in Carlin Canyon. However, the unconformity is not exposed over a wide enough area here to reveal more about the geometry of the sub-C2 deformation.

Several workers have independently recognized and documented folding and thrust faulting of sub-C2 rocks in the Ferdelford Creek drainage in the northern Piñon Range. This area was initially mapped by Jansma (1988), who interpreted the structure as a window of Webb and Woodruff Formations under a thrust sheet of Mississippian clastic rocks (her ''Chainman Shale''; our Tonka Formation) (Jansma, 1988; Jansma and Speed, 1990, 1993). Silberling et al. (1997) re-examined the Ferdelford Creek area, documenting east-southeast–vergent folds and thrust imbricates involving Woodruff, Webb, and ''Dale Canyon'' (our Melandco) Formations (Figs. 12 and 13 in Silberling et al., 1997). They reinterpreted Jansma's ''thrust'' contact as an unconformity, depositionally overlain by the Upper Mississippian Tonka Formation. Independently, one of us (Tosdal) mapped the Raven's Nest 7.5′ quadrangle (Fig. 6); his structural interpretation of the Ferdelford Creek area agrees with that of Silberling et al. (1997)—east-verging folds and east-directed thrust faults in Devonian and Mississippian strata are depositionally overlain (along the C2 unconformity) by subhorizontal Upper Mississippian rocks (Fig. 7A). Although opinions differ as to whether to call this deformation a distinct event or a late stage of ''Roberts Mountains'' (Jansma, 1988) or ''Antler'' (Silberling et al., 1997) thrusting, all workers agree that the deformation is middle Mississippian.

C2 deformation has also been recognized at several localities south of Ferdelford Canyon in the Piñon Range. Folding with local subvertical bedding is present within the Melandco Formation in the southeast corner of the Raven's Nest quadrangle (R.M. Tosdal's unpublished mapping). Axes of these folds plunge gently north-northwest (Fig. 7B). These folded rocks are unconformably overlain by gently dipping Tonka Formation. North-striking, east-directed thrust faults and associated overturned folds in Ordovician through Mississippian (pre-Tonka) units also crop out along strike farther south at the southern border of the Raven's Nest quadrangle (R.M. Tosdal's unpublished mapping). The present contact with the Tonka Formation in this area is faulted, so the age of the thrust deformation cannot be constrained on the basis of field relationships. North-trending folding and thrusting along strike still farther to the south, in the drainages of Willow Creek and Trout Creek, are also unconformably overlain by gently dipping Tonka Formation (N.J. Silberling and K.M. Nichols, 2001, personal commun.). In Papoose Canyon, also in the Piñon Range, Silberling and Nichols mapped several east-directed thrust sheets involving Ordovician, Devonian, and Mississippian (Dale Canyon) rocks. These are depositionally overlain by Upper Mississippian rocks (our ''Tonka'') (see map, Fig. 16, and description, p. 188, in Silberling et al., 1997).

In the Diamond Mountains north of Eureka, the C2 boundary unconformity can be mapped along the length of the range (Trexler and Cashman, 1991). The angular discordance there is between 20° and 30°, and the Dale Canyon Formation dips eastward below the unconformably overlying the Diamond Peak Formation. As in the Adobe and Piñon Ranges, a later tectonic overprint obscures this unconformable relationship.

At the Nevada Test Site in southern Nevada, evidence of tectonism is indirect but compelling. In rocks of early Chesterian age, there is a significant shift in dominant clast composition from siliciclastic to carbonate. These data document creation of a productive car-

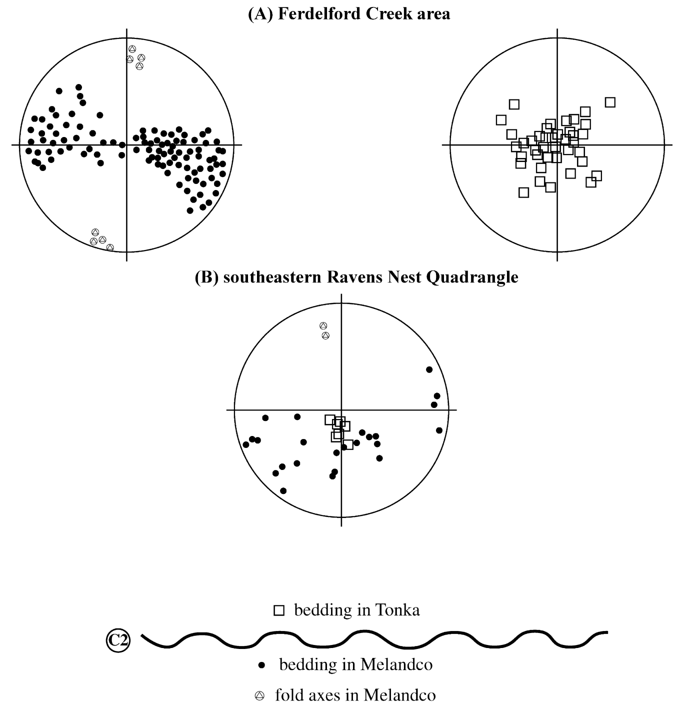



**Figure 7. (A) Stereogram of fold axes and poles to bedding above and below the C2 unconformity (Tonka and Melandco Formations, respectively) in Ferdelford Creek headwaters, Raven's Nest 7.5′; quadrangle. The Melandco Formation is folded around north-northeast–trending axes, and the Tonka Formation is not. The deformation of the Melandco therefore occurred in middle Mississippian time; see text for discussion of age control. Data as plotted by Silberling et al. (1997); data for pre-C2 rocks are from Jansma (1988), and bedding attitudes for the unconformably overlying Tonka Formation are from Smith and Ketner (1977). (B) Stereogram of fold axes and poles to bedding above and below the C2 unconformity (Tonka and Melandco Formations, respectively) in the southeast part of the Raven's Nest 7.5′ quadrangle. The Melandco Formation is folded around north-northwest–trending axes, and the Tonka Formation is not. The deformation of the Melandco therefore occurred in middle Mississippian time; see text for discussion of age control. Data are from unpublished mapping by R.M. Tosdal.**

bonate platform to the east and northeast that shed sediment to the west and southwest, across the foreland (Trexler and Cashman, 1997; Trexler et al., 1996).

## DISCUSSION

Timing of the Antler orogeny has always been based on the age of synorogenic strata. No known Antler (latest Devonian to earliest Mississippian) structural relationships are bracketed directly by good biostratigraphic age control. The principal signature of this event is in strata that record subsidence in a synorogenic basin, the Antler foreland (Poole, 1974). This tectonic signal has been detected as far east as western Utah (Giles et al., 1999). The earliest tectonically induced sedimentation is represented by the Upper Devonian Woodruff Formation and Pilot Shale. Murphy et al. (1984) utilized map relationships and lithostratigraphic correlation to date thrusting in the Roberts Mountains as latest Devonian and earliest Mississippian. On the basis of these arguments, the Antler orogeny is inferred to have begun in Famennian (latest Devonian) and/or Kinderhookian (earliest Mississippian) time (e.g., Giles and Dickinson [1995] and references cited therein). Although east-directed emplacement of the Roberts Mountains allochthon along the Roberts Mountains thrust was originally attributed to the Antler orogeny (Roberts, 1951; Roberts et al., 1958), the thrust has commonly been reactivated and can nowhere be shown to be unequivocally Late Devonian–Early Mississippian in age. There is currently no known sedimentary overlap of an ''Antler'' thrust that is dated as older than Pennsylvanian.

Two well-known formations have traditionally been interpreted to be syntectonic Antler-age deposits, the Chainman Shale and Diamond Peak Formation. These formations were assigned to shale (Chainman) and conglomerate (Diamond Peak) in the Antler foreland, although their names were applied loosely (Fig. 1). We now understand that both of these units contain the regional C2 boundary. We thus redefine the sub-C2 parts of these units as the Melandco and Dale Canyon Formations (see footnote 1), representing the Antler foreland-basin fill. Above the C2 boundary, Antler-foreland overlap units include the restricted Diamond Peak, Tonka, and Chainman Formations. The traditional usage that combined these foreland and overlap stratigraphies into one syntectonic sequence has long obscured the details of Mississippian tectonics.

The age of the C2 boundary is well constrained between late Osagean and earliest Chesterian time, which means that the tectonism that deformed strata below the C2 boundary occurred at least 20 m.y. (and possible as long as 30 m.y.) after the inception of the Antler orogeny. There is limited evidence suggesting that thrusting could have occurred in Osagean time (Johnson and Pendergast, 1981). Others have noted that Antler foreland strata (Melandco and Dale Canyon Formations) can be found under the ''Roberts Mountains thrust'' (e.g., Lisenbee, 2001), although the thrust fault in these areas may have been reactivated much more recently. As already discussed, many workers have shown that deformation must have occurred in Meramecian time on the basis of the age of deformed sediments in the Piñon Range and Diamond Mountains.

Knowledge of the deformation style of the initial Antler orogeny is limited mainly to the kinematics of deformation in the Roberts Mountains allochthon (and this deformation, as noted, has only been conclusively dated as older than Pennsylvanian). Antler deformation style has also been inferred from regional relationships attributed to crustal-loading flexure patterns (Giles and Dickinson, 1995). In contrast, the style of Meramecian deformation is *directly* recorded in folded and thrust-faulted Antler foredeep sedimentary rocks that are overlapped in many areas by Chesterian strata. Although both events appear to have resulted in east-directed contraction, it is difficult to compare their kinematics because (1) their shortening is roughly coaxial and (2) all Devonian and Mississippian deformation in the region is extensively overprinted by late Paleozoic and Mesozoic deformation. However, Meramecian deformation is recorded in folded and faulted sedimentary rocks of the foredeep axial zone, east of the Antler allochthon. Stratigraphic evidence of lower and middle Mississippian tectonism extends eastward into Utah (e.g., Nichols and Silberling, 1993; Silberling et al., 1997; Jewell et al., 2000).

The coincidence of the C2 boundary overlap strata with a significant, third-order eustatic transgression suggests that Mississippian tectonism was truly ended by earliest Chesterian time. The transgression (Fig. 4) dominated the distribution of clastic sediments across the shelf through the Late Mississippian and may have controlled cycles of clastic and carbonate sedimentation in central Nevada. Continued erosion of a remnant highland nearby to the west during the Late Mississippian resulted in thick sections of fluvial and deltaic conglomerate in north-central Nevada. Sections generally have interbedded shallow-marine and lagoonal carbonate deposits demonstrating that sedimentation locally kept pace with subsidence and sea-level rise until the end of the Mississippian in most areas.

In summary, there is evidence throughout Nevada and western Utah for widespread middle Mississippian tectonism. We emphasize that this tectonism occurred at least 20 m.y., and possibly as much as 30 m.y., after the inception of the Antler orogeny; during this later tectonism, the rocks of the Antler foreland basin were deformed. We therefore interpret this later tectonism to be either a distinct late phase of the Antler orogeny or a separate orogenic event. Biostratigraphic age control indicates that the tectonism had ended by early Chesterian time (ca. 327 Ma). The strongest preserved middle Mississippian deformation—east-directed thrusting and folding—occurs in the northern Piñon Range of north-central Nevada. Uplift and erosion were widespread both to the north and south of the Piñon Range, where the middle Mississippian deformation is expressed as an angular unconformity. In all known examples, the rocks underlying the unconformity dip moderately to the east (after restoration of the latter to horizontal), suggesting that the main tectonic highland was farther west. In southern Nevada, deposition of the Eleana and Captain Jack Formations was continuous across the Meramecian–Chesterian boundary, but a significant change in clast composition marks the formation boundary and signals a new carbonate-rich source area to the north. The Gap Wash and Chainman Formations of eastern Nevada were far enough east of the foreland to have been deposited as a continuous section, but they recorded tectonically driven Late Devonian subsidence, followed by a return to eustatic control in Late Mississippian time. Farther east, in western Utah, uplift and restricted-marine conditions occurred in late Osagean and Meramecian time, as local sea level dropped in response to tectonism. Further work, with good biostratigraphic age control, may uncover additional evidence of middle Mississippian tectonism in the western United States, in the form of synorogenic erosion and sedimentation in Osagean–Meramecian time.

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