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POSSIBLE TECTONIC CONTROLS ON LATE TRIASSIC SEDIMENTATION IN THE CHINLE BASIN, COLORADO PLATEAU

LAWRENCE H. TANNER
Department of Geography and Geosciences, Bloomsburg University, Bloomsburg PA 17815

Abstract.—Patterns of deposition of the Chinle Group formations record the influence of arc magmatism and the organization of a mobile foreland basin system during Late Triassic time. Accumulation of basal Chinle strata was controlled by paleorelief on the Tr-3 unconformity surface. Subsequent deposition of the Petrified Forest Formation may have been influenced by arc-related thermo-tectonic uplift, resulting in the Tr-4 unconformity. Depositional trends of the Owl Rock and Rock Point formations record the organization of elements of the Cordilleran foreland basin during Norian and Rhaetian time. Thinner packages of sediment were deposited over the crest of the forebulge and thicker sections were deposited in the backbulge axial basin. Migration of the forebulge, accompanied by regional uplift, caused incision of the Owl Rock depositional surface and formed an unconformity (the Tr-5) that cuts down to the west of the Four Corners area. Rock Point strata onlap the forebulge flank from east to west and are vertically gradational with overlying Wingate/Moenave strata. There is no evidence of a separate J-0 unconformity.

INTRODUCTION

Foreland basins are among the most dynamic tectono-sedimentary systems. They comprise mobile wedge-top, foredeep, forebulge, and backbulge depozones in which accommodation is controlled by crustal flexure, typically a consequence of subduction-related fold-thrust belt formation (DeCelles and Giles, 1996). This tectonic control on sedimentation permits the interpretation of the timing of formation and migration of individual components of the foreland basin system from sedimentary sequences and intervening unconformities (White et al., 2002). Several previous studies have attempted to fix the timing and position of elements of the Cordilleran foreland basin system using sediment accumulation curves. For example, DeCelles and Currie (1996) modeled progradation of a foreland basin system in northern Utah beginning in the Middle to Late Jurassic. These authors projected the location of the forebulge crest in central Utah at this time. Allen et al. (2000) rejected the timing of DeCelles and Currie (1996), and suggested instead movement and retro-foreland basin subsidence as early as Early Jurassic time. From subsidence rates, Allen at al. (2000) placed the crest of the Early Jurassic forebulge in easternmost Utah. This paper interprets the rise and migration of this forebulge and accompanying backbulge during the Late Triassic from patterns of sediment accumulation in the formations of the Chinle Group.

GEOLOGIC SETTING

Initial growth of the Cordilleran magmatic arc during the early Mesozoic (Dickinson, 1981) resulted in the formation of a retro-arc basin on the western edge of the North American craton. The Chinle basin, the continental portion of this basin, extended from southwestern Texas to northern Wyoming and was the site of terrestrial sedimentation from the Late Triassic through the Early Jurassic (Lucas, 1993, 1999; Lucas et al., 1997). Late Carnian to Rhaetian strata of the Chinle Group are now well-exposed in the Four Corners region (Fig. 1), which was situated within the basin at near-equatorial latitudes (less than 10° N) at this time (Scotese, 1994; Molina-Garza et al., 1995; Kent and Olsen, 1997). Deposition of the Chinle Group was controlled primarily by streams flowing northwest across a broad alluvial plain. The source areas for these sediments included the Mogollon highlands, located approximately 500 km to the south and southwest, the Uncompaghre highlands located 200 to 300 km to the east and northeast, and upland areas of Texas, including the Amarillo-Wichita and Ouachita-Marathon uplifts (Blakey and Gubitosa, 1983; McGowan et al., 1983; Marzolf, 1994; Riggs et al., 1996). Basal Chinle strata were deposited unconformably on an incised topographic surface developed on older Triassic strata of the Moenkopi Group or pre-Triassic rocks (the Tr-3 unconformity).

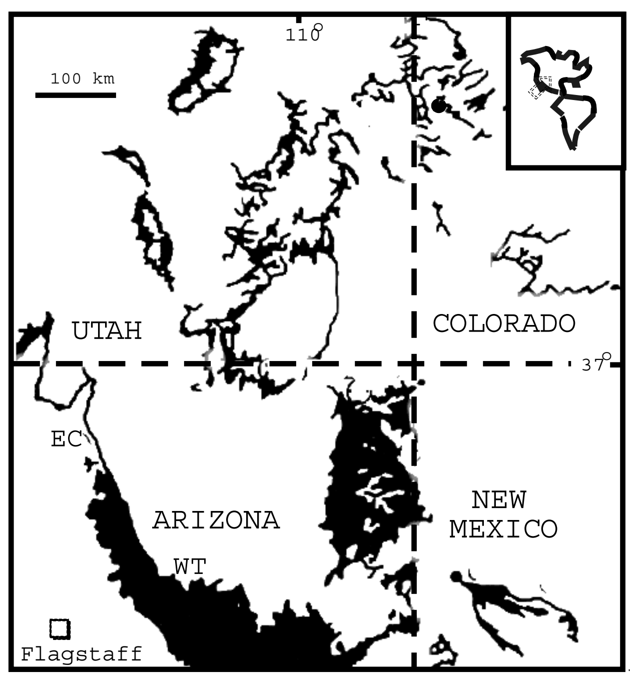

FIGURE 1. Outcrop of Chinle Group strata in the Four Corners area (adapted from Lucas et al., 1997). Locations mentioned in text: EC = Echo Cliffs, WT = Ward Terrace.

STRATIGRAPHY

The stratigraphic hierarchy used by some previous workers for the Chinle Group strata contains numerous redundancies and archaic names for correlative strata. Therefore, this study adheres to the simplified hierarchical scheme established by Lucas (1993) and Lucas et al. (1997).

The informally named "mottled strata" were described by Stewart et al. (1972) in reference to alluvial sediments (mudstones, sandstones, and conglomerates) at the base of the Chinle Group that exhibit strong pedogenic mottling (gleying) and attain a maximum thickness of about 30 m. These strata, for which the name Zuni Mountains Formation is proposed (Heckert and Lucas, 2003), underlie or are laterally equivalent to the basal strata of the Shinarump Formation (Lucas et al., 1997). The Shinarump Formation consists of up to 80 m of crossbedded conglomerates and quartz-arenite sandstones of late Carnian age. The mottled strata and Shinarump Formation were deposited in paleovalleys incised into the underlying Triassic or pre-Triassic strata (Stewart et al., 1972; Blakey and Gubitosa, 1983; Demko et al., 1998).

Upper Carnian strata immediately above the Shinarump Formation are named regionally the Cameron, Bluewater Creek, and Monitor Butte formations. Lucas (1993) and Lucas et al. (1997) demonstrated the stratigraphic equivalence of these formations, which consist of a maximum of 84 m of gray bentonitic to red mudstones, and laminated to cross-bedded fine-grained sandstones. The lowermost strata of the Petrified Forest Formation in the Four Corners region are designated the Blue Mesa Member (Lucas, 1993; Lucas et al., 1997). These strata, also of late Carnian age, overlie the Cameron/Bluewater Creek/Monitor Butte formations and consist of up to 100 m of bentonitic mudstones with variegated hues of blue, gray, purple, and red, and thin interbedded sandstones (Lucas, 1993; Lucas et al., 1997). The Blue Mesa Member and the underlying Cameron/Bluewater Creek/Monitor Butte formations were mapped collectively as the "lower bentonitic part" of the Chinle Formation by Stewart et al. (1972). Thickness of the combined formations varies from less than 30 m in southeastern Utah to over 450 m in northwestern New Mexico.

An unconformity (Tr-4) separates the Blue Mesa Member from the overlying sandstone-dominated Sonsela Member of the Petrified Forest Formation, which attains a maximum thickness of 50 m, and the equivalent Moss Back Formation (Heckert and Lucas, 1996, 2002; Lucas et al., 1997). The Painted Desert Member, of early to middle Norian age, overlies the Sonsela/Moss Back strata and consists of as much as 150 m of grayish red and reddish brown mudstones and thin interbedded sandstones (Lucas et al., 1997). As mapped by Stewart et al. (plate 4; 1972), the thickness of the entire Petrified Forest Formation ranges from just over 30 m at its northeastern limit in eastern Utah, increasing southward to over 400 m at its southeastern extent in northwestern New Mexico. The overlying Owl Rock Formation comprises up to 150 m of interbedded mudstones, sandstones, and limestones of approximately middle Norian age. These strata crop out in northern Arizona, northwestern New Mexico, and southern Utah (Stewart et al. 1972; Lucas and Huber, 1994).

Across the Four Corners area, the late Norian to Rhaetian Rock Point Formation is recognized as the youngest member of the Chinle Group (Lucas, 1993; Lucas et al., 1997). The Rock Point Formation, termed the Rock Point Member of the Wingate Sandstone by Stewart et al. (1972), includes strata formerly assigned to the Church Rock Member of the Chinle Formation (Stewart et al., 1972; Dubiel, 1989; Lucas et al., 1997). Strata of this formation consist of up to 300 m mainly of interbedded brown to red, nonbentonitic mudstones and laminated to rippled sandstones (Stewart et al., 1972; Dubiel, 1989; Lucas et al., 1997). The contact between the Rock Point and underlying Owl Rock formations is unconformable (the Tr-5 unconformity), except where the Owl Rock is absent. In the Four Corners region, the Rock Point Formation grades vertically to the eolian-dominated Wingate Formation of Rhaetian to Hettangian age.

TECTONIC SYNTHESIS

Initial accumulation of Chinle sediment was limited to paleovalley systems that were tens of kilometers to over 100 km wide and incised into the (Moenkopi and older) Tr-3 surface (Stewart et al., 1972; Blakey and Gubitosa, 1983). These paleovalleys and associated tributaries had paleorelief of as much as 80 m, so deposition of the mottled strata, Shinarump Formation, and the lowermost strata of the Cameron/Monitor Butte/Bluewater Creek formations was limited to these topographic lows, and thin to absent between them (Stewart et al., 1972, plate 4; Blakey and Gubitosa, 1983; Demko et al., 1998). Subsequent accumulations of younger Chinle strata show no such limitation, however, indicating that the incised topography had been infilled by the end of Carnian time. Isopach trends for the "lower bentonitic part" of the Chinle (Stewart et al., 1972), i.e., the Cameron/Bluewater Creek/Monitor Butte formations and the Blue Mesa Member of the Petrified Forest Formation, display a consistent increase in thickness from north to south, indicating faster basin subsidence to the south of the Four Corners (see Stewart et al., 1972, plate 4). The shape of this basin was defined by the location of the Mogollon highlands to the south-southwest and the Ancestral Rockies to the northeast, resulting in a basin axis oriented approximately ESE-WSW (Fig. 2A).

Kraus and Middleton (1987) suggested that base-level changes during deposition of lower Chinle strata resulted in part from episodes of thermo-tectonically controlled uplift and subsidence in the Mogollon highlands. The presence of volcanic detritus in the lower Chinle provides compelling evidence for the initiation of arc-related magmatism at this time. Thus, the Tr-4 unconformity defined between the Blue Mesa and Sonsela/Moss Back strata (Lucas et al., 1997; Heckert and Lucas, 2002) may have resulted from regional uplift and an increase in the local depositional gradient associated with early Cordilleran magmatism.

The orientation of the Chinle depositional basin changed significantly during Owl Rock (middle Norian) deposition. The isopach trend for this formation (Stewart et al., 1972, plate 5) displays a SW-NE axial trend with a depocenter in southeastern Utah. Subsequent deposition of the Rock Point Formation followed a similar trend, except that the depocenter migrated eastward to southwesternmost Colorado during the Rhaetian (Stewart et al.,

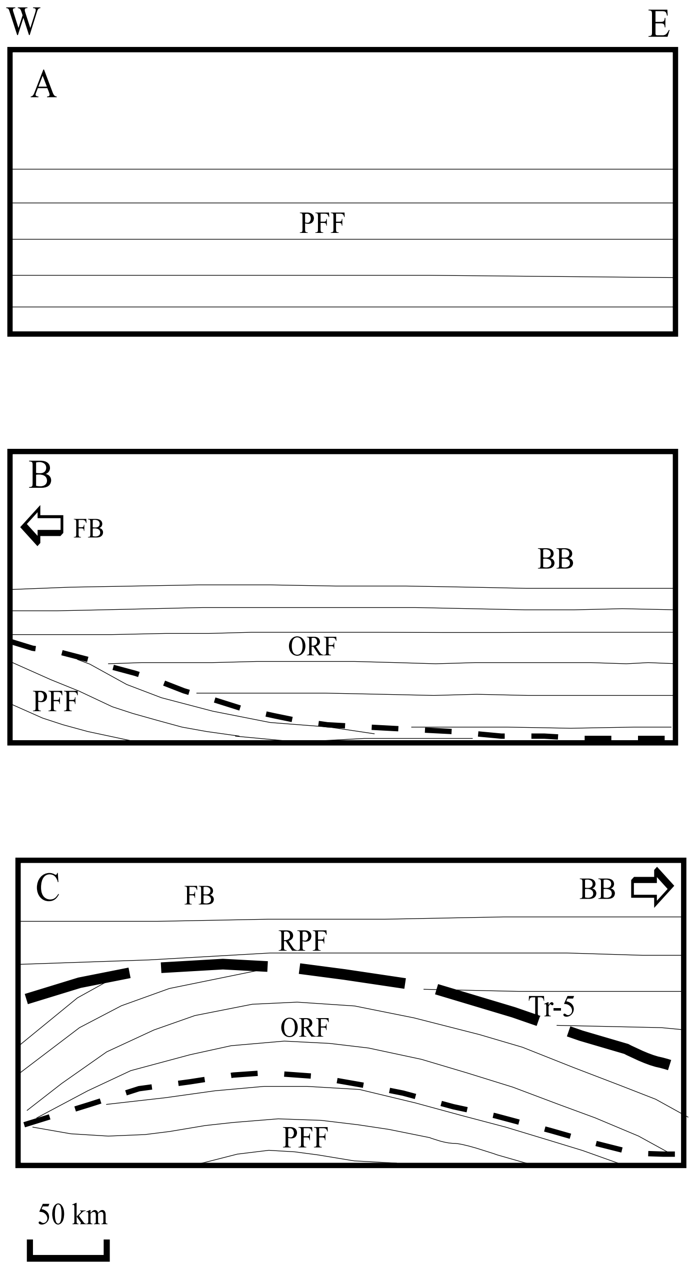

FIGURE 2. Sequence of idealized W-E cross-sections from western Arizona/Utah to the Four Corners (Fig. 1) depicting foreland basin controls on Chinle sedimentation. **A**, Early Norian deposition of Petrified Forest Formation (PFF) in (relatively) undisturbed Chinle basin. **B**, During middle Norian time, a rising forebulge (FB) was located west of the Four Corners region, causing uplift to the west and incision of the PFF and thickened deposition of the Owl Rock Formation (ORF) in the backbulge axial basin (BB) west of the Four Corners. **C**, During Rhaetian time, regional uplift and eastward migration of the forebulge crest caused incision of the Owl Rock depositional surface, creating the Tr-5 unconformity. The Rock Point Formation (RPF) onlapped this unconformity and was thickest in the backbulge basin axis to the east of the Four Corners.

1972). These changes in depositional patterns appear to reflect basin reorganization beginning in the Norian, most probably as a consequence of incipient eastward-directed crustal flexure.

The precise timing of initial convergence-generated thrusting and deformation is unclear, but Late Triassic dates have been suggested from studies in the Mojave Desert (Burchfiel et al., 1970; Dunne, 1977; Burchfiel and Davis, 1981). This age is important because it marks the formation of the retro-arc foreland system, comprising foredeep, forebulge, and backbulge, that controlled subsequent patterns of Chinle sedimentation. The contact between the Owl Rock and underlying Petrified Forest formations in the Four Corners region is generally considered conformable (Stewart et al., 1972; Dubiel, 1989; Lucas et al., 1997), but the occurrence of intraformational conglomerate beds at the contact in the western Four Corners region (e.g., Echo Cliffs) suggests a correlative unconformity to the west related to differential uplift, possibly marking the preliminary rise of a forebulge in the vicinity of western Utah/Arizona during the middle Norian (Fig. 2B). Subsequent deposition of the Owl Rock Formation was largely confined to the backbulge axial area, centered just northwest of the Four Corners.

In the Four Corners region, late Norian to early Rhaetian uplift is documented by the Tr-5 unconformity, which separates the Owl Rock Formation from overlying strata (Fig. 2C). This surface correlates regionally with the so-called J-0 unconformity that is thought to separate Triassic Chinle strata from overlying Glen Canyon formations of Early Jurassic age (Pipiringos and O'Sullivan, 1978). Reynolds et al. (1989) described a regional angular unconformity that formed across western Arizona and southeastern California sometime before the Middle Jurassic, and Marzolf (1991) suggested that this unconformity correlates with the J-0 unconformity of the Colorado Plateau. Volcanic detritus in this conglomerate suggests that the unconformity, which cuts downward to the southwest, is contemporaneous with both regional uplift and foreland thrusting and arc magmatism (Marzolf, 1991).

Across most of the Four Corners region, the unit overlying the Tr-5 unconformity is the Rock Point Formation, which had a depocenter to the east of the Four Corners. In the western Four Corners region (e.g., in the Echo Cliffs and on Ward Terrace), lowermost Moenave Formation strata (Dinosaur Canyon Member), of latest Rhaetian to Hettangian age, overlie this unconformity, resulting in a greater stratigraphic gap with increasing distance to the west of the Four Corners. Regional uplift was accompanied by migration of the forebulge-backbulge system, as recorded by the eastward shift of the Rock Point depocenter by approximately 50 to 70 km. This uplift, however, enforced the depositional hiatus through the Rhaetian across the western part of the Four Corners region and western Utah and Nevada. Rock Point sediments onlapped the forebulge from east to west as an influx of erosional and arc-derived sediment filled the backbulge basin during the Rhaetian. Thus, the age of the basal sediments deposited on the unconformity increases from west to east. Forebulge migration and uplift of previously deposited sediments may have triggered fluvial incision of the Hite bed at the top of the Rock Point sequence. By Hettangian time, the crest of the forebulge was well established in eastern Utah-Arizona, and thickened Moenave strata were deposited on the arc and back-bulge facing flanks during the latest Rhaetian-earliest Hettangian (see Riggs and Blakey, 1993, fig. 4A).

DISCUSSION

Allen et al. (2000) depicted retro-foreland (foredeep) subsidence across central Utah during the Early Jurassic, by which time a forebulge was already established in easternmost Utah (east of Capitol Reef). This model is based on the convex shape of subsidence curves for strata deposited during the Early Jurassic (e.g., the Navajo Sandstone) and on the assumption that initial thrust-loading of the craton is recorded by the Luning-Fencemaker thrust belt of western Nevada. Importantly, however, the stratigraphy on which they base the timing of this model is faulty, so that their timing and rate of forebulge migration may be somewhat in error. In their figure 1 (p. 160), strata of the Glen Canyon Group are depicted as resting on a flat unconformity, the J-0, and the oldest Glen Canyon Group formations, the laterally equivalent Moenave and Wingate formations, are shown with a maximum age of uppermost Hettangian. This is clearly not the case, as basal Wingate strata contain an Upper Triassic fauna (Lucas et al., 1997) and paleomagnetic data now indicate the position of the Triassic-Jurassic boundary within the Moenave and Wingate formations (Molina-Garza et al., in press). Furthermore, in the Four Corners region, Wingate strata rest conformably on strata of the Upper Triassic (Rhaetian) Rock Point Formation. Therefore, no J-0 unconformity exists in this region, and forebulge rise and migration were earlier than projected by Allen et al. (2000).

Nevertheless, the interpretation of the Early Jurassic forebulge position of Allen et al. (2000) accords well with depositional patterns of the uppermost Chinle formations. However, isopach trends of the Owl Rock and Rock Point formations suggest a Late Triassic forebulge position 50 km or more west of the Jurassic position suggested by Allen et al. (2000). The chronologic ages of the stages of the Late Triassic are not firmly established, but a Triassic-Jurassic boundary age of 201-202 Ma is now widely accepted (Pálfy et al., 2002), setting the Carnian-Norian boundary at approximately 215-217 Ma. If 10 million years is estimated as the interval from the middle Norian to late Rhaetian, the resulting rate of foreland basin migration rate is approximately 5 mm yr^{-1}. This figure matches that projected by DeCelles and Currie (1996), but is faster than the rate of 4 mm yr^{-1}modeled by Allen et al. (2000). Regardless of rate, a Late Triassic age of forebulge rise and migration is clearly indicated by the patterns of deposition of the Owl Rock and Rock Point formations.

CONCLUSION

Sediment accumulation patterns in the Chinle Group formations record an increasing tectonic influence on sedimentation near the end of the Triassic Period. Deposition of basal Chinle strata was controlled by the relief incised into the Tr-3 unconformity surface. Early Cordilleran arc magmatism may have caused uplift-related incision at the Tr-4 unconformity during deposition of the Petrified Forest Formation. Isopach patterns of the Owl Rock and Rock Point formations indicate organization of the Cordilleran foreland basin as early as mid-Norian. Sedimentary sequences for both formations were thinner over the rising forebulge and thickened in the backbulge axial basin. Regional uplift and forebulge migration caused incision of Norian sediments, forming the Tr-5 unconformity. Rock Point sediments, which were thickest in the backbulge axial basin, onlap the forebulge from east to west. Thus, the magnitude of the stratigraphic gap encompassed by the Tr-5 unconformity increases from east to west and there is no separate J-0 unconformity.

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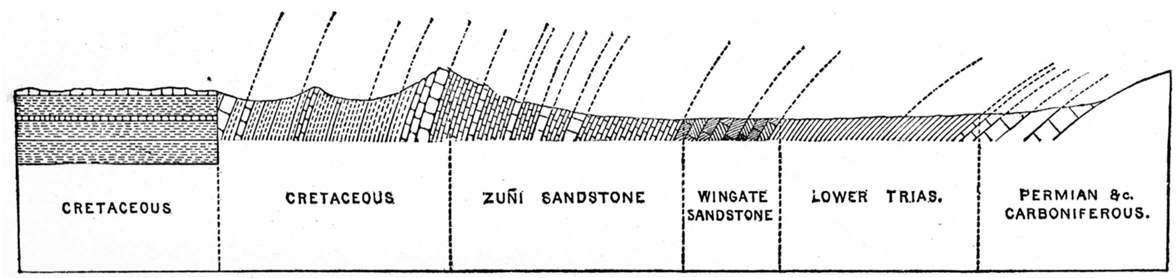

Dutton's (1885, fig. 5) cross section through the Nutria monocline.