A magnetostratigraphic age constraint for the proximal synorogenic conglomerates of the Late Cretaceous Cordilleran foreland basin, northeast Utah, USA

Ziaul Haque1,†, John W. Geissman1,2,§, Peter G. DeCelles3, and Barbara Carrapa3
1Department of Geosciences, the University of Texas at Dallas, Richardson, Texas 75080, USA
2Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, USA
3Department of Geosciences, University of Arizona, Tucson, Arizona 85721, USA

ABSTRACT

Reliable ages of proximal conglomerates in the Cordilleran foreland basin that are associated with emplacement and erosion of major thrust sheets are essential for reconstructing the kinematic history of the Sevier fold-thrust belt. Although these conglomerates have been dated by palynology, their absolute ages have been difficult to determine because of their coarse-grained texture and a lack of marine interbeds and tuffaceous deposits. We collected sets of oriented samples from outcrops in northeastern Utah, USA, to construct an overall magnetic polarity stratigraphy that can be correlated to the geomagnetic polarity time scale (GPTS). We sampled fine-grained, hematitic interbeds in the Upper Cretaceous Echo Canyon Conglomerate and Weber Canyon Conglomerate. Common paleomagnetic and rock magnetic analyses were conducted, and several rock magnetic results indicated that the dominant magnetic carriers in these weakly magnetized rocks are hematite and very subordinate magnetite/titanomagnetite/maghemite and goethite. Demagnetization results show that hematitic, fine-grained sandstone to siltstone intervals carry a geologically stable magnetization with directions and polarity consistent with the Late Cretaceous geomagnetic field. A small percentage of samples carry a laboratory unblocking temperature secondary overprint residing primarily in goethite. Magnetic polarity results indicate that the Echo Canyon Conglomerate is exclusively of normal polarity and that the younger Weber Canyon Conglomerate is of normal polarity in its lowermost part, reverse polarity in the middle, and normal polarity in the upper part of the sequence. The new data indicate that these coarse-grained strata were most likely deposited over the time span of the magnetic polarity Chron (C) 34n to C33r interval and the younger C33r to C33n interval; the former interval includes the Santonian-Campanian stage boundary (ca. 83.4 Ma/83.1 Ma). Palynological data suggest that these rocks span Coniacian-Santonian time (ca. 89–84 Ma); thus, the most parsimonious correlation of the normal polarity magnetozone of the Echo Canyon Conglomerate is with the youngest part of C34n Superchron, which is of ca. 30 Ma duration (ca. 115 Ma to 83.4 Ma/83.1 Ma). The normal polarity magnetozone of the lower part of the younger Weber Canyon Conglomerate likely correlates to the youngest part of C34n, whereas the reverse and normal magnetozone from the middle and upper parts of the Weber Canyon Conglomerate likely correlate to C33r and C33n, respectively. We infer that the Santonian-Campanian boundary resides in the lower Weber Canyon Conglomerate, which implies that deposition of the unit started prior to the C34n/C33r boundary age (ca. 83.4 Ma/83.1 Ma) and continued through the C33r and C33n chron. Sediment provenance data and growth structures tie the Echo Canyon and Weber Canyon Conglomerates to emplacement of the Crawford thrust sheet. Based on the magnetic polarity data, as constrained by the biostratigraphic age estimates from these synorogenic deposits, we hypothesize that the principal displacement along the Crawford thrust started during the Coniacian (>C34n/C33r boundary age) and continued into the middle Campanian (<C33r/C33n boundary age), from ca. 90–75 Ma, which is nearly 10 Ma longer than previously thought. The new age constraints demonstrate complete temporal overlap between proximal and distal coarse-grained deposits in this part of the Cordilleran foreland basin, coeval with active thrust displacement and rapid hinterland exhumation.

INTRODUCTION

Foreland basins preserve a record of orogenic processes that includes the timing of fault slip and exhumation of thrust sheets. Several models have been introduced to explain genetic relations between fold-thrust belt tectonics and foreland basin deposits. A long-standing concept in sedimentary geology asserts that foreland basin conglomerate deposits reflect transport over comparatively short distances along relatively steep slopes from a topographically high source terrain uplifted by tectonic processes. Therefore, the depositional age of the conglomeratic deposits is considered to be contemporaneous with hinterland deformation (often associated with topographic growth) and exhumation, providing a linkage between the stratigraphic record and tectonic processes (Armstrong and Oriel, 1965; Wilson, 1970; Ryder and Scholten, 1973; Royse et al., 1975; Heward, 1978; Wiltschko and Dorr, 1983; Graham et al., 1986; Burbank et al., 1988; Liu et al., 2005; Allen and Heller, 2012; Painter et al., 2014; Haque and Uddin, 2017). However, an alternative view—the “two-phase tectonostratigraphy” model—has been proposed by several authors to explain foreland basin stratigraphy (e.g., Beck et al., 1988; Heller et al., 1988; Blair and Bilodeau, 1988; Heller and Paola, 1992). In this model,
coarse-grained syntectonic deposits are trapped by rapid subsidence in the proximal foreland region while distal regions receive only finer-grained sediment. During periods of thrust belt inactivity, erosion and isostatic rebound in tandem with reduced flexural subsidence in the proximal part of the basin promote reworking of proximal coarse-grained sediment into the distal region. In essence, the two-phase model asserts that coarse-grained lithofacies in the distal foreland are “anti-tectonic,” recording periods during which the thrust belt is inactive (Fig. 1) and implying that coarse-grained proximal facies and distal finer-grained facies are asynchronous. This model is conceptually attractive because it links active thrust loading, flexural subsidence, and proximal to distal deposition of coarse-grained facies. Although the two-phase model has been often invoked to explain foreland basin stratigraphy, it has been difficult to rigorously test because coarse-grained proximal foreland lithofacies are difficult to date and correlate with distal coarse-grained lithofacies (for notable exceptions, see Burbank et al., 1988, and Horton et al., 2004). A reliable age model and temporal correlations of the proximal sedimentary deposits with more distal sedimentary sequences are keys to assessing the applicability of the two-phase model and to addressing questions regarding tectonic versus eustatic controls on foreland basin sequence stratigraphy (Horton et al., 2004).

The Utah-Wyoming sector of the North American Cordilleran foreland basin (Fig. 2) provides an excellent opportunity to test questions related to foreland basin evolution, including the wholesale application of the two-phase tectonostratigraphic model. Indeed, this sector of the foreland basin was the inspiration for the two-phase model (Beck et al., 1988; Heller et al., 1988). During Early Cretaceous to Eocene time (ca. 120–50 Ma), eastward propagation of regionally extensive thrust sheets at this latitude provided sediment to the eastward adjacent Cordilleran foreland basin (e.g., Armstrong and Oriel, 1965; Royse et al., 1975; Lamerson, 1982; Lawton, 1983; DeCelles, 1994, 2004; Gentry et al., 2018). In proximal areas alluvial fan and fan-delta conglomerates accumulated, whereas fluvial and shoreface sandstones along with marine mudrocks accumulated in more distal regions (e.g., Ryer, 1977; Lawton, 1982, 1985, 1986; Wiltschko and Dorr, 1983; DeCelles, 1994; Schwans, 1988; Pivnik, 1990; Lawton and Trexler, 1991; Devlin et al., 1993; Dyman et al., 1994; Painter et al., 2013; Leary et al., 2014). In the proximal region adjacent to and within the fold-thrust belt, provenance studies and growth structures suggest that deposition of thick conglomerates in the Kelvin and Frontier Formations was related to slip on the Willard-Meade thrust system, and deposition of the Henefer Formation, Echo Canyon Conglomerate, and Weber Canyon Conglomerate was related to displacement along the Crawford thrust (Royse et al., 1975; DeCelles, 1988, 1994; DeCelles et al., 1993; Royse, 1993; Gentry et al., 2018).

Similar arguments tie the Little Muddy Creek Conglomerate in southwestern Wyoming to an early phase of displacement on the Absaroka thrust system and the Hams Fork Conglomerate to a second episode of Absaroka thrusting (Royse et al., 1975; Lamerson, 1982; DeCelles, 1994; Pivnik, 1990) (Fig. 3A). The combined stratigraphic information has been interpreted to suggest that the Willard-Meade thrust system was active from the Aptian to Turonian (ca. 120–90 Ma), the Crawford thrust system was active from the Coniacian to the end of the Santonian (ca. 89–84 Ma), and the early and late phases of displacement on the Absaroka thrust system were active during the Late Santonian to early Campanian (ca. 84–78.5 Ma) and the Maastrichtian to early Paleocene (ca. 69–62 Ma) (Fig. 3B) (Royse et al., 1975; Lamerson, 1982; DeCelles, 1994; Liu et al., 2005).

The weakest link in this reconstruction is the ages of the conglomerates that are used to constrain the timing of thrusting. These proximal deposits are difficult to date because of their coarse-grained texture, nonmarine depositional environment, and the absence of tuffaceous deposits for radiometric age dating. Most age assignments are based on palynology (Nichols and Warner, 1978; Nichols et al., 1982; Jacobson and Nichols, 1982; Nichols and Bryant, 1986) and have not been independently calibrated to the geologic time scale. The unambiguous nature of the magnetic polarity reversal pattern defining the global geomagnetic polarity time scale (GPTS) during the time interval between the mid- to Late Cretaceous and early Cenozoic, however, facilitates an alternative means through magnetic polarity stratigraphy (Opydyke and Channell, 1996) for estimating the depositional age of these synorogenic sedimentary deposits with some degree of certainty (Fig. 3B). Given the Coniacian-Maastrichtian age approximations for these sedimentary deposits based on palynologic studies, reliable magnetic polarity data should identify at least one reverse polarity magnetozone, the oldest of which would correlate with the ca. 4-Ma-long chron C33r, which postdates the ca. 30-Ma-long C34n (the Cretaceous long normal polarity chron). Any younger reverse polarity magnetozones would correlate with the C32/C31 chron. The age-proximity of these conglomerates to the end of the Cretaceous Superchron C34n (ca. 83.4 Ma [He et al., 2012] to ca. 83.07 Ma [Wang et al., 2016]) offers a straightforward test of their ages and has the potential to improve the chronology of sedimentation and thrusting as well as interpretations of regional subsidence history and geodynamics of the foreland basin system and the validity
TECTONIC SETTING

During the Late Jurassic, subduction of Pacific Ocean lithospheric plates beneath the North American continent initiated development of the Cordilleran orogen (Monger and Price, 1979; Burchfiel et al., 1992; Saleeby, 1992; DeCelles, 2004; Yonkee and Weil, 2015). The United States part of the Cordilleran orogenic fold-thrust belt extends from the latitude of Las Vegas, Nevada, to the Montana/Canada border and is referred to as the Sevier thrust belt (Armstrong, 1968). The best-preserved part of the Sevier thrust belt lies in Utah, southern Nevada, and western Wyoming (Armstrong, 1968; Royse et al., 1975; Coogan, 1992; Friedrich and Bartley, 2003; Constienius et al., 2003; DeCelles and Coogan, 2006; Yonkee and Weil, 2015). The northeast Utah and southwest Wyoming part of the Sevier belt includes the Willard, Crawford, Absaroka, and Hogsback thrusts in addition to several comparatively minor thrusts (e.g., the Lost Creek, Medicine Butte, Tunp, and Coalville thrusts; Fig. 2) (Royse et al., 1975; Lamerson, 1982; Coogan, 1992; Peyton et al., 2011). Thrusting followed an overall eastward progression from Early Cretaceous through middle Eocene time (Lamerson, 1982; Wiltschko and Dorr, 1983; DeCelles, 2004; Peyton et al., 2011; Gentry et al., 2018) and generated coarse-grained detritus deposited into the adjacent Cordilleran foreland basin. Total shortening in the northeastern Utah-Wyoming sector of the Sevier belt is estimated to be greater than 200 km (Coogan, 1992; DeCelles, 1994; Yonkee et al., 2019). Previous work suggests that the Crawford, Absaroka, and Hogsback thrusts accommodated ~100 km of shortening in three episodes at ca. 89–84 Ma, ca. 84–62 Ma, and ca. 56–50 Ma, respectively (DeCelles, 1994; Gentry et al., 2018). These periods of crustal shortening are based on provenance data and cross-cutting and growth-structure relationships in the Henefer Formation, Echo Canyon Conglomerate, Weber Canyon Conglomerate, and the Evanston and Wasatch Formations. These deposits accumulated in alluvial fans and fan deltas along the topographic front of the thrust belt, forming a greater than 1000-m-thick megasequence of synorogenic conglomerate that tapers and fines eastward into distal sandy-gravelly fluvial and upper shoreface deposits that are interbedded with offshore shale of the Hilliard Formation (Devlin et al., 1993). Provenance data and detrital zircon ages suggest that the Henefer Formation, Echo Canyon Conglomerate, and Weber Canyon Conglomerate were derived mostly from rocks in the hanging wall of the Crawford thrust (DeCelles, 1994). The Little Muddy Creek Conglomerate and the Hams Fork Conglomerate of the Evanston Formation are linked to the Absaroka thrust (Lamerson, 1982; DeCelles, 1994). The Henefer Formation rests conformably upon the Cenomanian-Turonian Frontier Formation, and the Echo Canyon Conglomerate lies conformably on the Henefer Formation. These units are exposed in the limbs of the gently northeastward-plunging Stevenson Canyon syncline (Fig. 4A). The Weber Canyon Conglomerate crops out only along the trace of the East Canyon backthrust and farther northeastward along the footwall of the buried Crawford thrust tip line as far north as Lost Creek Reservoir (DeCelles, 1994; DeCelles and Cavazza, 1999) (Fig. 4A).

FIELD SAMPLING

As outlined above, the primary purpose of this study is to obtain robust magnetic polarity information for all suitable rock types preserved in coarse-grained proximal sedimentary deposits...
exposed in northeastern Utah. The Echo Canyon area, around the junction of Interstate Highways 80 and 84, has excellent outcrops of all of the main conglomerate units, including the Echo Canyon Conglomerate, Weber Canyon Conglomerate, and the Hams Fork Conglomerate of the Evanston Formation. Fine-grained hematitic sandstones, siltstones, and silty-shales intercalated within the Echo Canyon and Weber Canyon conglomerates are the targets for sampling to obtain magnetic polarity information in this study.

In terms of field sampling, oriented cores were collected from most of the suitable exposures using a portable water-cooled rock drill following standard paleomagnetic sampling methods (Butler, 2004). For those fine-grained horizons that were too friable to be drilled, small, oriented block samples were collected. Typically, six to 10 oriented samples were collected from every horizon sampled. Where possible, oriented samples were also collected from cobbles and boulders of hematitic siltstone and very fine-grained sandstone that were likely derived from Triassic strata in the source sections to conduct a conglomerate test for the determination of possible remagnetization of the entire section. A Pomeroy orientation device was used for core sample orientation, and bedding orientations were obtained from or near the sampling sites for structural correction of the in situ paleomagnetic data. The relative positions of each horizon sampled in the Echo Canyon and Weber Canyon conglomerates are shown in Figures 5A and 5B, and a detailed description of the lithology and depositional systems of each of these units can be found in DeCelles (1994).

Echo Canyon Conglomerate

The Echo Canyon Conglomerate has a maximum thickness of ∼630 m and crops out in both limbs of the Stevenson Canyon syncline, forming prominent red cliffs along the Interstate Highway 80 (Fig. 4A). The base of the Echo Canyon Conglomerate rests transitionally on top of the Henefer Formation, and the top is beveled by a 20–30° angular unconformity beneath the overlying Hams Fork Conglomerate of the Evanston Formation (Figs. 4B and 4C). The Echo Canyon Conglomerate consists of moderately to poorly sorted pebble to boulder conglomerate with interbedded red and gray sandstone, siltstone, and mudstone. Based on the principal rock types in the Echo Canyon Conglomerate, the unit is divided into two parts of subequal thicknesses; the lower part is characterized by a cobble- to boulder-size clast population of well-cemented sandstone, limestone, siltstone, and minor chert and quartzite whereas the upper part is dominated by quartzite clasts. The sandstone, siltstone,
and limestone/dolostone clasts were derived from Paleozoic and Mesozoic strata exposed in the hanging walls of the Crawford thrust, and the quartzite clasts were largely derived from the Proterozoic rocks in the hanging wall of the Willard thrust (DeCelles, 1994). We collected ∼70 samples of fine-grained sandstone and mudstone horizons from eight suitable sites from this unit.

**Weber Canyon Conglomerate**

The Weber Canyon Conglomerate contains massive, matrix- and clast-supported boulder conglomerate with minor sandstone, siltstone, and mudstone interbeds. This unit crops out extensively in the Lost Creek Reservoir area along both sides of the Weber River and Interstate Highway 84 near Croydon, Utah, near East Canyon Reservoir and along Utah State Highway 65 near Big Mountain Pass (Fig. 4A). Thickness of the unit varies along strike due to the changing exposure level but typically it is at least 500 m thick (DeCelles, 1994). Its base is an angular unconformity on top of Middle Jurassic strata, and its top is either a modern erosion surface or a disconformity at the base of the overlying Hams Fork Conglomerate (Figs. 4B and 4C). This unit consists primarily of sediment-gravity flow deposits that accumulated in the proximal parts of alluvial fans within 1–2 km of the trace of the Crawford thrust. Clasts in the conglomerate are predominantly of well-cemented sandstone, quartzite, and carbonate rocks derived from proximal Crawford thrust rocks as well as more distal Willard thrust rocks; generally, the clast contribution from the Willard thrust sheet increases northward. The distinguishing features of the Weber Canyon Conglomerate are growth structures that record progressive folding associated with eastward slip on the main Crawford thrust and westward backthrusting along the East Canyon backthrust, a passive roof thrust on the triangle zone that marks the southern part of the Crawford thrust (DeCelles, 1994).

We collected samples from 34 sites, unevenly spaced, in fine-grained, hematitic mudstone/sandstone horizons from four localities (continuous outcrop exposures) designated as the Toone Canyon, Weber Canyon, Big Mountain, and East Canyon Dam sections for magnetic polarity study (Fig. 4A). Of the four sections sampled, the Weber Canyon section represents the lowest part of the conglomerate succession, and 78 samples from five sites were collected. The Big Mountain and East Canyon Dam sections are located ~18 km and 30 km southwest along-strike, respectively, from the Weber Canyon section and stratigraphically could be coeval or younger in position. We obtained 80 samples from 12 sites at the Big Mountain Dam section and 65 samples from 10 sites at the East Canyon Dam section, respectively. Our youngest samples from the Weber Canyon Conglomerate were collected in the Toone Canyon section 5.2 km south of the Lost Creek Dam. About 90 samples were collected from seven horizons in nearly flat-lying strata near the top of a growth syncline along the Crawford thrust a few tens of meters below the Hams Fork Conglomerate.

**LABORATORY METHODS AND MATERIALS**

Specimens were prepared from the samples collected for paleomagnetic and rock magnetic analysis. Core samples were cut, using non-magnetic diamond blades, into standard ∼2.2-cm-
high × ~2.5-cm-diameter right cylinders; typically, one specimen of the ideal size/shape was obtained per independent sample. Block samples were cut into small (≈4–5 cc) cubic shapes, and these were glued into ceramic cubes that are 20 mm on a side (Beijing Eusci Technologies, Inc.) using non-magnetic alumina cement (Zircar).

Rock magnetic and paleomagnetic analyses were conducted on prepared specimens to identify their magnetic characteristics as well as to obtain magnetic polarity information. Isothermal remanence magnetization (IRM) acquisition curves were acquired by stepwise application of a direct current (DC) magnetic field with an ASC (IM-10-30) impulse magnetizer to a maximum field of 2.97 T; stepwise DC backfield demagnetization was applied to determine the coercivity of remanence. Isothermal remanent magnetization (IRM) unmix analysis was conducted to better define the magnetic coercivity components inferred from the IRM acquisition data following the approach by Maxbauer et al. (2016). To further investigate the magnetic mineralogy in these rocks, the three-component thermal demagnetization of the IRM method was used following Lowrie’s (1990) approach. The DC fields applied to each specimen investigated were 0.3 T (soft component), 1.2 T (medium component), and 2.97 T (hard component) in reverse order. To monitor potential mineralogic alteration during heating experiments, continuous heating versus cooling susceptibility measurements were obtained on selected powdered specimens using an AGICO MFKI-A susceptibility instrument interfaced with a CS4 high-temperature furnace. Anisotropy of magnetic susceptibility (AMS) measure-
ments were made using an AGICO MFKI-A susceptibility measurement system equipped with an automatic 3D rotator (Studýnka et al., 2014) to assess the preservation of an original depositional sedimentary fabric and to check for the presence of any secondary, deformation-related fabrics. The progressive thermal demagnetization technique was mostly used to isolate components of the natural remanent magnetization (NRM), and the remanence at all demagnetization steps was measured using either a 2G-Enterprises cryogenic magnetometer equipped with DC squids or an AGICO JR6A spinner magnetometer, both of which are housed in a magnetically shielded room.

| Specimen name                  | Components | Bh     | Bh.sd  | DP     | DP.sd  | P      | P.sd  | Magnetic minerals       |
|-------------------------------|------------|--------|--------|--------|--------|--------|--------|-------------------------|
| Echo Canyon Conglomerate      | EC62Gb     | 3.32   | 0.89   | 1.04   | 0.36   | 0.39   | 0.15   | Goethite/Hematite        |
|                              | EC63L      | 3.02   | 0.09   | 0.84   | 0.07   | 0.57   | 0.03   | Goethite/Hematite        |
|                              |            | 2.72   | 0.00   | 0.24   | 0.02   | 0.44   | 0.03   | Hematite                 |
| Weber Canyon Conglomerate     | WC4a       | 2.9    | 0.00   | 0.42   | 0.00   | 0.89   | 0.00   | Goethite/Hematite        |
|                              | BM11b      | 1.62   | 0.00   | 0.39   | 0.00   | 0.83   | 0.02   | Goethite/Hematite        |
|                              | ECD1Gb     | 1.52   | 0.003  | 0.33   | 0.004  | 0.32   | 0.003  | Goethite/Hematite        |
|                              | ECD8Ga     | 3.06   | 0.005  | 0.36   | 0.006  | 0.99   | 0.003  | Goethite/Hematite        |
|                              | 2TC1Ma     | 2.28   | 0.002  | 0.45   | 0.003  | 0.96   | 0.003  | Goethite/Hematite        |
|                              | 3TC1Gb     | 2.37   | 0.001  | 0.58   | 0.002  | 0.97   | 0.007  | Goethite/Hematite        |

Notes: Bh—the mean coercivity values; DP—dispersion; P—relative proportion; sd—standard deviation.

Figure 6. Anisotropy of magnetic susceptibility (AMS) data, in lower hemisphere projection, of specimens from the Weber Canyon Conglomerate unit is shown. (A) In situ and (B) tilt-corrected projection of the minimum ($K_{\text{min}}$), intermediate ($K_{\text{int}}$), and maximum ($K_{\text{max}}$) susceptibility axes of the specimens from Weber Canyon (WC), Big Mountain (BM), and East Canyon Dam (ECD) sections. (C) In situ projection (sub-horizontal strata) of the specimens from the Toone Canyon (TC) section. (D) Shape parameter versus degree of anisotropy. (E) Magnetic foliation versus magnetic lineation plot.
Orthogonal vector demagnetization (Zijderveld, 1967) diagrams were used to plot the remanence directions at each demagnetization step. The principal component analysis approach by Kirschvink (1980) was followed using the Remasoft (AGICO, Inc.) data reduction program to construct best-fit lines and incorporating 7–12 demagnetization steps, typically with anchoring to origin, used to assess the characteristic remanence magnetization (ChRM) directions. Specimens that had a substantial fraction of the remanence unblocked in the laboratory above 400 °C were used for polarity interpretation, and results from individual specimens were accepted if maximum angular deviation (MAD) values of a best-fit line were below 20°, a typical MAD value for the low NRM-intensity rocks (see the Supplemental Material1, Table 1). All of the analyses were conducted at the University of Texas at Dallas Paleomagnetic and Rock Magnetic Laboratory in the Department of Geosciences.

RESULTS

Rock Magnetism Results

Representative specimens were selected for rock magnetic analyses to determine the dominant magnetic carriers and to monitor any mineralogic alteration at elevated temperatures during demagnetization. Anisotropy of magnetic susceptibility (AMS) data were obtained on all specimens of appropriate size/shape from the Weber Canyon Conglomerate to decipher the depositional and, if any, post-depositional deformation fabrics. Specimens from fine-grained interbeds in the Weber Canyon Conglomerate have bulk magnetic susceptibilities ranging from ~0.7–166 (×10−6 SI volume units). AMS results from the Weber Canyon Conglomerate at sampling localities Weber Canyon, Big Mountain, and East Canyon Dam show a typical fabric associated with a relatively turbulent flow depositional environment where the minimum susceptibility axes at the site level are dispersed and sub-vertical (Figs. 6A and 6B). At the Toone Canyon locality, on the other hand, AMS results show a well-defined, fine-grained detrital sedimentary fabric where the minimum susceptibility axes at the site level are essentially vertical and well-grouped relative to the paleohorizontal (Fig. 6C). The degree of anisotropy (P) versus shape parameter (T) and magnetic foliation \( F = K_{max}/K_{ave} \) versus magnetic lineation \( L = K_{ave}/K_{min} \) plots show the presence of mixed grain fabrics (oblate to triaxial to prolate) in the lower and middle parts of the Weber Canyon Conglomerate, whereas the specimens from the uppermost part (Toone Canyon section) dominantly consisted of oblate grain fabrics (Figs. 6D and 6E). The preferred NNE-SSW orientation of the \( K_{max} \) directions is likely related to the regional ESE-directed layer parallel shortening (LPS) fabric consistent with the other structural and AMS data in the area (e.g., Weil and Yonkee, 2009).

IRM acquisition and DC backfield demagnetization results show that saturation is barely reached in a field of ~3 T and that coercivity of remanence values exceed 0.5 T for Echo Canyon Conglomerate and specimens from the lower and middle part of the Weber Canyon Conglomerate (Fig. 7). The behavior is consistent with the presence of both hematite and goethite in these rocks. However, the steeper slope of both curves

---

1Supplemental Material. Table S1: Paleomagnetic results from the samples collected at different stratigraphic levels of Echo Canyon Conglomerate and Weber Canyon Conglomerate from the Echo Canyon area of northeast Utah, USA; Table S2: Paleomagnetic results from the samples collected from the red siltstone, likely Triassic age, intraclasts (cobbles and boulders) from the Echo Canyon and Weber Canyon Conglomerates in the Echo Canyon area of northeast Utah, USA. Please visit https://doi.org/10.1130/GSAB.S.12990755 to access the supplemental material, and contact editing@geosociety.org with any questions.
component thermal demagnetization of IRM different magnetic mineral phases. In the three-component analysis, unblocking of hard (2.97 T), medium (1.2 T), and soft (0.3 T) components at ~680 °C suggests that hematite is present in both conglomerate units. The relative intensity of the hard and medium components in the specimens from the Echo Canyon and Weber Canyon Conglomerates suggests dominance of hematite, whereas the relative intensity of the soft component in the Weber Canyon Conglomerate specimens from the Toone Canyon section suggests an abundance of magnetite/titanomagnetite grains (Fig. 9). In some specimens, primarily from the East Canyon Dam and Big Mountain sections, a significant decrease in intensity of the hard component at ~100 °C indicates the presence of goethite. Some specimens show a drop in the soft and medium components at ~500 °C to 600 °C, which indicates the presence of a cubic phase that is likely magnetite/titanomagnetite (Fig. 9).

Paleomagnetic Results

Echo Canyon Conglomerate

The Echo Canyon Conglomerate contains interbedded, laterally confined wedges of red to tan sandstone, laterally continuous red and gray siltstone, and mudstone lenses. Many samples collected from the siltstone and mudstone intervals yield high quality and interpretable paleomagnetic results. NRM intensity values for specimens from this unit range from 0.5 mA/m to 2 mA/m, and the laboratory
unblocking temperatures are distributed with a range of 400 °C to ~682 °C (Fig. 11A). About 60% of the specimens prepared from this unit produced interpretable magnetic polarity results in demagnetization with a MAD value of less than 20°. Characteristic remanent magnetization (ChRM) directions of specimens that yield interpretable results from this unit are exclusively of normal polarity with an overall specimen mean direction, after correcting for tilt of the strata, of Declination (Dec) = 349°, Inclination (Inc) = + 41.6°, estimated precision parameter (k) = 11.7, and α95 = 6.4° (N (sites) = 7, n (samples) = 47) (Fig. 12A). A relatively low number of ChRM directions (n = 4) obtained from well-indurated hematitic cobbles and boulders (likely of Triassic age) in this unit suggest, but do not conclusively support, a positive conglomerate test and that the magnetization carried by these rocks is most likely primary (Fig. 12C).

**Weber Canyon Conglomerate**

Samples of the Weber Canyon Conglomerate were collected from four well-exposed sections (Toone Canyon, Weber Canyon, Big Mountain, and East Canyon Dam) to attempt to cover the entire sequence. The NRM intensity of specimens from this unit in the Toone Canyon section is the highest we measured and ranges from 1.5 to 7 mA/m, which is largely consistent with the deeper red color of the siltstones and fine-grained sandstones in this section. The laboratory unblocking temperature spectra of the NRM from well-indurated hematitic siltstone clasts range from ~345 °C to ~680 °C (Fig. 11B), and ~90% of the samples pass the magnetic polarity determination criteria. The ChRM directions of interpreted specimens are well-defined with MAD values mostly less than 10°, and these directions are exclusively of normal polarity with a specimen mean direction of Dec = 3.6°, Inc = +51.4°, k = 12, and α95 = 5.3° (N = 7, n = 65) (Fig. 12A). The NRM intensity of specimens from the Weber Canyon section ranges from 0.15 mA/m to 2.5 mA/m, and the laboratory unblocking temperature mostly ranges from ~490 °C to ~680 °C. Of the specimens collected from the Weber Canyon section, ~70% yielded interpretable ChRM directions with a maximum angular deviation of best fit anchored line less than 15°. The directional results are entirely of normal polarity with an overall specimen mean direction, after strata tilt correction, of Dec = 9°, Inc = +47.5°, k = 7.1, α95 = 8.7° (N = 5, n = 44) (Fig. 12A). ChRM directions (n = 19) obtained from well-indurated, hematitic siltstone clasts (again likely of Triassic age) from this unit demonstrate a positive conglomerate test (Fig. 12C). A randomness test on the directions obtained from the Triassic age cobbles and boulders conducted at 99% confidence level following the Watson (1956) method and a smaller resultant vector length (R = 5.22) than a calculated parameter (R0 = 7.26) suggest that the directions obtained from the conglomerate test are random, which implies a primary magnetization.
Overall NRM intensities for rocks from the Big Mountain and East Canyon Dam sections are relatively low, with values ranging from ~0.1 mA/m to 2 mA/m, and demagnetization results from these sections are comparatively less well-defined than those from the other sections. Specimens from the Big Mountain and East Canyon Dam sections show laboratory unblocking temperature ranges from <200 °C to ~680 °C with those specimens that demagnetize at low temperature, mostly below 250 °C, showing a secondary magnetization that primarily resides in goethite. About 40% of the specimens from the Big Mountain section and 42% from the East Canyon Dam section pass demagnetization response criteria for polarity interpretation, and the relatively low percentage of accepted results from these sections could be due to the remagnetization effects, which overprint the primary signal, as well as the relatively low NRM intensities of these rocks. After the stratal tilt correction, the ChRM directions from the Big Mountain section yielded comparatively less well-defined results of normal polarity with a mean direction of Dec = 326.5°, Inc = +28°, k = 4.3, and α95 = 16° (N = 5, n = 25) at stratigraphic levels from the base of the section to ~60 m in height, and also what we tentatively interpret as a reverse polarity with Dec = 149.5°, Inc = −42.3°, k = 10.8, and α95 = 14.6° (N = 1, n = 11) at the stratigraphic level of 130 m. After correcting for bedding tilt, specimens from the East Canyon Dam section that exhibit laboratory unblocking temperatures above ~400 °C yield a ChRM direction that is entirely of reverse polarity and largely well-defined, with a specimen mean direction of Dec = 190.4°, Inc = −56°, k = 6.8, and α95 = 11.8° (N = 8, n = 26) (Fig. 12A). The well-defined low-temperature overprint from this section, with unblocking temperatures of less than 250 °C, yields a specimen mean direction of Dec = 5.8°, Inc = 62°, k = 43.4, and α95 = 4° (n = 45) in geographic coordinates (Fig. 12D).

COMPOSITE MAGNETOSTRATIGRAPHY

Fine-grained sandstones and mudstones interbedded within coarse-grained conglomerate-dominated lithofacies in the Echo Canyon section yield interpretable magnetizations of dual polarity that are overall similar in direction to that of the mid-Cretaceous geomagnetic field for the area. Admittedly, at the horizon level, the directional dispersion of results is relatively high, as presented above, and we interpret this as being at least in part a function of the relatively low NRM intensities of these rocks. The estimated mean characteristic remanent magnetization (ChRM) directions from all the samples that provide acceptable, interpretable results, and corrected for observed stratal tilt at each section, are separated into normal and reverse polarity estimates. The combined specimen mean direction for normal polarity results is Dec = 355°, Inc = +48°, α95 = 4° (n = 175), and that of the reverse polarity results, from the middle to upper part of the Weber Canyon Conglomerate, is Dec = 177°, Inc = −52°, α95 = 10° (n = 38) (Fig. 12B; Table 2). The calculated expected field directions from paleomagnetic pole compilations for North America (e.g., Diehl, 1991; Kent and Irving, 2010) in the study area for rocks of ca. 83 Ma to 76 Ma ranges in declination from ~337° to ~353.3° and inclination from ~63.5° to ~64.8°. The differences in inclination value of our observed results and the expected values may be in part due to inclination shallowing related to sediment compaction and related diagenetic processes. If, for example, we utilize a flattening factor (f) of 0.70, where the factor f can range from one (no flattening) to zero (completely flattened), to
correct our results, we obtain inclination values of +58° (normal polarity) and –61.5° (reverse polarity). Such a flattening factor has been demonstrated to be realistic for the types of rocks we have sampled (Kodama, 2012). In addition, the elongation-inclination (E-I) method (Tauxe and Kent, 2004) for correcting inclination shallowing in sedimentary rocks yields a corrected inclination value of +62° (Fig. 13) for the entire ensemble of normal and reverse (inverted) polarity results, which is also similar to expected calculated field inclinations. The calculated Fisher cone of confidence (A95 = 9.4°) for virtual geomagnetic poles (VGP) along with the paleosecular variation minimum and maximum (A95 min = 1.5° and A95 max = 3°) from the ensemble of accepted samples following the approach of Deenen et al. (2011) suggests that these rocks sufficiently recorded paleosecular variation (PSV). However, an additional source of dispersion, which is challenging to account for, could include differential vertical axis rotation among our sampling localities as related to thrust fault displacement. We note that some of
the section site mean directions are discordant in a clockwise sense from expected mid-Cretaceous field directions, which is consistent with the patterns in the southern part of the Wyoming salient (Weil et al., 2010), but our overall grand mean direction reported above is similar to the expected field direction of the mid-Cretaceous field for the study area. The combined foldtest on results from all of the specimens from the Echo Canyon, Weber Canyon, Big Mountain, and East Canyon Dam sections shows that the maximum eigenvalue ($\tau_1$) is highest at about fifty percent unfolding, and both the in situ and tilt-corrected coordinate systems are excluded within the 95% confidence interval [19%–51%], which suggests a complex magnetization with a potential syn-folding remanence acquisition, a common phenomenon in synorogenic sediments (Fig. 14A). The relatively flat nature of the $\tau_1$ may be due to the complex structural regime of the area associated with the minor faulting and folding along the east canyon backthrust as well as the fact that the differences in the structural corrections that are applied to these data are relatively small. A reversal test conducted to determine whether the normal and reverse polarity populations from the Echo Canyon and Weber Canyon conglomerates are statistically antipodal, as defined by McFadden and McElhinny (1990), yields a smaller observed angle ($\gamma_o = 3^\circ$) than the calculated critical angle ($\gamma_c = 9.5^\circ$) and indicates a positive reversal test with class B status (Fig. 14B). The cumulative distributions of Cartesian components of the bootstrapped means (500 pseudo samples) for the normal and reverse polarity data sets overlap at the 95% confidence intervals (method explained in Tauxe, 2010), which also suggests that the results pass the reversal test (Fig. 14C).

The interpreted magnetic polarity results indicate that: (1) the Echo Canyon Conglomerate is exclusively of normal polarity; (2) the Weber Canyon Conglomerate yields normal polarity in the entire Weber Canyon section and the lower part of the Big Mountain section but reverse polarity in the entire East Canyon Dam section and uppermost part of the Big Mountain section; and (3) the sampled part of the Weber Canyon Conglomerate in the Toone Canyon section is exclusively of normal polarity. The magnetic polarity correlation between the Weber Canyon and Big Mountain sections suggests that they could be stratigraphically coeval, whereas the reverse polarity magnetozone from the upper part of the Big Mountain section is correlated to the East Canyon Dam section. The Toone Canyon section results could be interpreted to represent a part of the Weber Canyon Conglomerate that is roughly equal in age to that in the Weber Canyon and Big Mountain sections, or these results could be recording a younger normal polarity chron. We tentatively favor the latter interpretation (Fig. 15) because the sampled part of the Toone Canyon section lies close to the top of the Weber Canyon Conglomerate and is just a few tens of meters below the unconformably overlying Hams Fork Conglomerate of the Evanston Formation.

**DISCUSSION**

Magnetic polarity stratigraphic information, in the absence of independent chronologic control, generally cannot provide accurate age information for the development of chronostratigraphic records. However, paleontologic
Magnetostratigraphy of the Upper Cretaceous Cordilleran foreland basin strata

Geological Society of America Bulletin

(mainly palynologic) age estimates have been reported from the Echo Canyon, Weber Canyon, and Hams Fork Conglomerates, as well as the Henefer Formation (Nichols and Warner, 1978; Nichols et al., 1982; Lamerson, 1982; Nichols and Bryant, 1986, 1990). The Echo Canyon Conglomerate has yielded numerous palynologic age estimates (e.g., Proteacidities retusus interval zone), with the general conclusion being that it is Coniacian-Santonian (ca. 89–85 Ma) in age. Detrital apatite fission-track (AFT) data from this unit yield a maximum possible depositional age estimate that is of low precision (90.5 ± 14.0 Ma) (Painter et al., 2014) but consistent with the palynologically determined age. A Coniacian-Santonian age of the Echo Canyon Conglomerate would place this unit entirely within but near the termination of the Cretaceous normal polarity Superchron (C34n) (Fig. 15).

Because of its extremely coarse-grained texture, the Weber Canyon Conglomerate has been historically difficult to date; however, it has produced a single palynologic age of early to middle Campanian (Yonkee et al., 1997). This age, slightly younger than that of the Echo Canyon Conglomerate, is also consistent with the fact that the Weber Canyon Conglomerate contains growth structures related to folding directly below the East Canyon backthrust, whereas the Echo Canyon Conglomerate does not contain growth geometry and is simply folded in the hanging wall of the backthrust (Figs. 4B and 4C; DeCelles, 1994). An early to middle Campanian age for the Weber Canyon Conglomerate is also consistent with abundant age-diagnostic palynomorphs of Late Campanian-Maastrichtian age recovered from the overlying Hams Fork Conglomerate (Lamerson, 1982; Nichols and Bryant, 1990; DeCelles, 1994). Thus, we would predict that the magnetic polarity data should identify at least one reverse polarity magnetozone (which would likely correlate with C33r) in the Weber Canyon Conglomerate. Combining an estimated mid-Campanian palynologic age for the Weber Canyon Conglomerate with the magnetic polarity stratigraphy documented here suggests that the lower part of the unit is within the Cretaceous normal polarity Superchron (C34n), the middle part of the unit preserves a record of deposition during C33r, and the upper part of the unit contains C33n. Together the data suggest that the Weber Canyon Conglomerate is of latest Santonian through middle Campanian age (ca. 85–76 Ma), a much longer time duration of deposition than was previously inferred (DeCelles, 1994; Yonkee et al., 1997).

Provenance studies suggest that deposition of the Henefer Formation (Coniacian), Echo Can-
TABLE 2. SITE MEAN PALEOMAGNETIC RESULTS

| Unit    | Site  | Lat(‘N) | Lon(‘W) | Dec(°) | Inc(°) | n  | k   | α95 | Bedding attitude(d/dd) |
|---------|-------|---------|---------|--------|--------|----|-----|-----|------------------------|
| ECC     | EC61  | 40.96393| 111.41674| 2.2    | 45.8   | 7  | 18  | 14.5 | 19/298                 |
| ECC     | EC60  | 40.96412| 111.4164 | 8     | 41.6   | 2  | 16  | 67   | 19/298                 |
| ECC     | EC67  | 40.96319| 111.41213| 30.2   | 58.6   | 2  | 18  | 29.5 | 22/298                 |
| ECC     | EC66  | 40.96519| 111.41237| 338.6  | 33.9   | 13 | 10  | 13.6 | 22/298                 |
| ECC     | EC65  | 41.01028| 111.37793| 330   | 44.4   | 8  | 17  | 11.7 | 22/298                 |
| ECC     | EC63  | 41.01028| 111.37793| 332   | 41.1   | 10 | 23  | 10.5 | 34/300                 |
| ECC     | EC64  | 41.01028| 111.37793| 0.4    | 30.8   | 4  | 30  | 17   | 34/300                 |

**Mean ChRM from EC section**

|        | -439 | 41.4671 | 111.52675| 10.5  | 25.9  | 10  | 7.4  | 19/090 |

**Mean ChRM from WC section**

|        | -9   | 47.5    | 44       | 7.1   | 8.7   | 47/316|

**Mean ChRM from BM section**

|        | -326.5 | 28.1    | 25       | 4.3   | 15.9  | -    |

**Mean ChRM from EC section**

|        | -190.4 | -56     | 26       | 6.8   | 11.8  | -    |

**Mean ChRM from WC section**

|        | -12   | 45.3    | 11       | 7.62  | 17.8  | -    |

**Mean ChRM from BM section**

|        | 328   | 42.8    | 4        | 9.71  | 31.1  | -    |

**Mean ChRM from EC section**

|        | 11.2  | 64.6    | 10       | 53.72 | 6.7   | -    |

**Mean ChRM from WC section**

|        | 11.4  | 59.1    | 11       | 64.15 | 5.8   | -    |

**Mean ChRM from BM section**

|        | 39.9  | 64.9    | 3        | 18.75 | 29.3  | -    |

**Mean ChRM from EC section**

|        | 350.1 | 55.7    | 11       | 64.15 | 5.8   | -    |

**Mean ChRM from WC section**

|        | 3.6   | 51.4    | 65       | 12.5  | 5.3   | -    |

**Mean ChRM from BM section**

|        | 355.3 | 47.8    | 175      | 7.7   | 4.1   | -    |

**Mean ChRM from TC section**

|        | 176.9 | -52.3   | 38       | 6.2   | 10.2  | -    |

**Notes:** Lat, Lon—site latitude, longitude; Dec—declination; Inc—inclination; n—number of samples; k, α95—Fisher precision parameter and radius of 95% confidence; Bedding attitude—dip (d) and dip direction (dd); ChRM—characteristic remanent magnetization; ECC—Echo Canyon Conglomerate; WCC—Weber Canyon Conglomerate; EC—Echo Canyon; WC—Weber Canyon; BM—Big Mountain; ECD—East Canyon Dam; TC—Toone Canyon.

Figure 13. Inclination shallowing correction following the approach by Tauxe and Kent (2004). (A) Plot of elongation versus inclination for the data (heavy red line) and for the TK03.GAD model (green line) along with the bootstrapped confidence bound of 52° to 75° (blue dashed line) with an elongation parameter of 1.38 and a flattening factor of 0.62. (B) The cumulative distribution of 5000 bootstrapped crossing points (red line) from the data shown in Figure 12B produced a corrected inclination of ~62° (green line) and the bootstrapped confidence bound of 52° to 75° (blue dashed line) with an elongation parameter of 1.38 and a flattening factor of 0.62.
ern Wyoming. Of particular interest are the fine-grained Hilliard Shale and Baxter Shale (both are Coniacian-Santonian and contain prominent sandstone intervals) and the medium- to coarse-grained and conglomeratic sandstones of the Blair, Adaville, Rock Springs, and Ericson Formations, which have been dated by ammonites, palynology, detrital zircon U-Pb ages, and U-Pb ages on tuffaceous layers in the same time interval represented by the Henefer Formation and the Echo Canyon, Weber Canyon, and Hams Fork Conglomerates (Smith, 1965; Cobban, 1969; Devlin et al., 1993; Finn and Johnson, 2005; Kirschbaum and Roberts, 2005; Leary et al., 2014; Lynds and Slattery, 2017; see summary and numerous references in Painter et al., 2014). Insofar as the new data indicate that the Crawford thrust remained active throughout the time interval represented by these units (ca. 90–75 Ma), it is now evident that the two-phase model for foreland basin stratigraphy is not straightforwardly applicable to this part of the Cordilleran foreland basin. Instead, the combination of new and previously reported data suggests that the Crawford thrust system remained active, and coarse-grained sediment continued to be produced and transported from proximal to distal parts of the foreland continuously during the 90–75 Ma time interval. This interpretation is consistent with rapid hinterland exhumation recorded by detrital thermochronology and short lag times of foreland basin deposits (Painter et al., 2014).

CONCLUSIONS

Magnetic polarity investigation of samples from numerous hematitic fine-grained inter-

Figure 14. (A) Bootstrapped foldtest result of the Echo Canyon (EC), Weber Canyon (WC), East Canyon Dam (ECD), and Big Mountain (BM) sections. The unfolded data are represented by the red line, and light blue lines indicate the first 25 bootstraps. The maximum eigenvalue ($\tau_1$) at a particular untilting percentage is shown as a cumulative distribution function (CDF) with 95% confidence interval limits for 1000 bootstraps. Highest $\tau_1$ between [19%–51%] of unfolding suggests a complex magnetization with potentially a syn-folding remanence acquisition. (B) Calculated geomagnetic field directions for Late Cretaceous time for the study area and the projection of the normal polarity direction and the transposed reverse polarity direction determined in this study. (C) Cumulative distributions of Cartesian components of the bootstrapped means (500 pseudo samples) from the data shown in Figure 12B. Reverse polarity data have been flipped to their antipode. Overlapping normal (blue line) and the antipode of the reverse (red line) polarities at the 95% confidence interval indicate passage of the bootstrap reversal test.
beds in thick successions of Upper Cretaceous synorogenic conglomerate in northeastern Utah shows that these rocks usually carry geologically stable magnetizations that we interpret to be primary and of Late Cretaceous age. These magnetizations allow a composite magnetic polarity stratigraphy to be established for the synorogenic sequence consisting of the Echo Canyon Conglomerate and Weber Canyon Conglomerate with additional implications for the age of the unconformity that separates these units from the overlying Hams Fork Conglomerate of the Evanston Formation. Of the samples analyzed, some are characterized by a well-defined low laboratory unblocking temperature normal polarity overprint in a few sections that we attribute to relatively recent, post deformation chemical weathering and the production of goethite. A higher laboratory unblocking temperature magnetization, largely carried in hematite, is isolated in many samples, and demagnetization behavior can be confidently interpreted for polarity information. We demonstrate that the Echo Canyon Conglomerate and the lower part of the Weber Canyon Conglomerate are of normal polarity and can be correlated to the C34n long normal polarity Superchron, the termination of which is at ca. 83.4 Ma or 83.1 Ma. The well-defined reverse polarity magnetozone from the medial part of the Weber Canyon Conglomerate is correlated to the C33r chron, the age of the termination of which is estimated to be between 79.9 Ma and 78.91 Ma. If our interpretation of the Toone Canyon section, with its exclusively normal polarity, as the uppermost part of the Weber Canyon Conglomerate holds true, then the correlation of this section with chron C33n suggests that the entire unit has a depositional age range of ca. 85 Ma to 76 Ma. Because the Weber Canyon Conglomerate contains Crawford thrust-related growth structures, the time-span of Crawford thrusting is extended to include all of Coniacian to Late Campanian time, roughly 90 Ma to 75 Ma. Regional age-stratigraphic correlation of the proximal conglomerates with distal facies in the Cordilleran foreland basin demonstrates transport of coarse-grained sediment into the distal foreland throughout active Crawford thrusting that is in apparent conflict with predictions of the two-phase foreland basin stratigraphic model but in agreement with short thermochronological lag times recorded in foreland basin deposits. Additional magnetic polarity studies of the upper part of the Little Muddy Creek Conglomerate, the Hams Fork Conglomerate, and the main (upper) part of the Evanston Formation may provide better age resolution by locating younger polarity reversal boundaries in those sequences. Such studies may improve interpretations of regional subsidence history and geodynamics of the Cordilleran foreland basin system in the Late Cretaceous into the early Paleogene.

Figure 15. Composite magnetic polarity stratigraphy of the proximal Cordilleran foreland basin deposits from northeast Utah and correlation with the Late Cretaceous part of the geomagnetic polarity time scale (GPTS) by Ogg et al. (2012) with revised C34n/C33r and C33r/C33n boundaries (He et al., 2012; Albright and Titus, 2016; Wang et al., 2016). EC—Echo Canyon; WC—Weber Canyon; BM—Big Mountain; ECD—East Canyon Dam; TC—Toone Canyon sections; VGP—virtual geomagnetic poles.

Geological Society of America Bulletin
Lawton, T.F., 1983. Late Cretaceous fluvial systems and the age of foreland uplifts in central Utah, in Lowell, J.D., ed., Rocky Mountain Foreland Basins and Uplifts—Denver, Colorado, Rocky Mountain Association of Geologists, p. 181–199.

Lawton, T.F., 1985. Style and timing of frontal structures, thrust belt, central Utah: Bulletin of the American Association of Petroleum Geologists, v. 69, p. 1145–1159.

Lawton, T.F., 1986. Compositional trends within a clastic wedge adjacent to a forebulge: Inland Group, central Utah, U.S.A., in Allen, P.A., and Homewood, P., eds., Foreland Basins: International Association of Sedimentologists Special Publication 8, p. 411–423, https://doi.org/10.1130/0091-7613(1991)019<0369:FOTFAD>2.3.CO;2.

Lawton, T.F. and Trexler, J.H., Jr., 1991. Piggyback basin in the Sevier orogenic belt, Utah: Implications for development of the thrust wedge: Geology, v. 19, no. 8, p. 689–692, https://doi.org/10.1130/0091-7613(1991)019<0689:IPBAITO>2.3.CO;2.

Leary, R., DeCelles, P.G., Gehrels, G.E., and Morris, M., 2014. Fluvial deformation during the transition from flexural to dynamic subsidance in the Cordilleran foreland: Basin Research, v. 27, p. 1–22, https://doi.org/10.1111/br.12085.

Liu, S.-F., Nummedal, D., Yin, P.-G., and Luo, H.-J., 1980. The Late Cretaceous and lower Tertiary rocks in the Salt Lake City 30′ quadrangle, Utah: U.S. Geological Survey Open File Report 2017-3.

Lynds, R.M., and Slattery, J.S., 2017. Correlation of the Wanship Formation and their geochronologic constraints on the Late Cretaceous terrestrial cyclostatigraphy and ge magnetic polarity from the Songliao Basin, Northeast China: Earth and Planetary Science Letters, v. 468, p. 37–44, https://doi.org/10.1016/j.epsl.2016.04.007.

Lawton, T.F., 1983. Late Cretaceous fluvial systems and the age of foreland uplifts in central Utah, in Lowell, J.D., ed., Rocky Mountain Foreland Basins and Uplifts—Denver, Colorado, Rocky Mountain Association of Geologists, p. 181–199.

Nichols, D.J., and Bryant, B., 1986, Palynologic data from the upper Cretaceous–Lower Tertiary Sea of Cortez deposits: Geological Society of America Bulletin, v. 126, no. 11–12, p. 1439–1464, https://doi.org/10.1130/B3099.1.

Peyton, S.L., Costensius, K.N., and DeCelles, P.G., 2011. Early eastward translation of shortening in the Sevier thrust belt, northeast Utah and southwest Wyoming, U.S.A., in Sprinkel, D.A., Yonkee, W.A., and Chidsey, T.C., Jr., eds., Sevier Thrust Belt: Northern and Central Utah, Geological Society Special Publication 40, p. 57–72.

Pivnik, D.A., 1990, Thrust-generated fan-delta deposition: Little Muddy Creek Conglomerate, SW Wyoming: Journal of Sedimentary Research, v. 60, no. 4, p. 489–503.

Royer, F., Jr., 1993, An overview of the geologic structure of the thrust belt in Wyoming, northern Utah, and eastern Idaho, in Stowe, A.W., Steidtmann, J.R., and Roberts, S.M. Geology of Wyoming, Memoir No. 5: Laramie, Wyoming, The Geological Survey of Wyoming, p. 273–311.

Rody, F. Jr., Kriner, M.A., and Reese, D.L., 1975. Thrust belt structural geometry and related stratigraphic problems Wyoming-Idaho-northern Utah, in Bylouard, D.W., ed., Deep Drilling Frontiers of the Central Rocky Mountain, Rocky Mountain Association of Geologists, p. 41–54.

Ryer, T.A., 1977, Patterns of Cretaceous shallow-marine sedimentation, Coalville and Rockport areas, Utah: Geologic Survey Open File Report 22-57, 50 p.

Sandefer, W., 1990, A Summary of Stratigraphy and Geology: University of California Press, Berkeley, University of California Press, Berkeley, p. 217–230.

Smith, J.H., 1965, A test for randomness of directions: Geophysical Journal of the Royal Astronomical Society, v. 1, no. 4, p. 725–729.

Smit, J.H., 1965, A Summary of Stratigraphy and Geology: University of California Press, Berkeley, University of California Press, Berkeley, p. 217–230.

Smit, J.H., 1965, A Summary of Stratigraphy and Geology: University of California Press, Berkeley, University of California Press, Berkeley, p. 217–230.

Watson, G.S., 1956, A test for randomness of directions: Geophysical Journal of the Royal Astronomical Society, v. 1, no. 4, p. 725–729.

Wang, T., Ramezani, J., Wang, C., Wu, H., He, H., and Browning, S.A., 2016, High-precision U-Pb geochronologic constraints on the Late Cretaceous terrestrial cyclostatigraphy and ge magnetic polarity from the Songliao Basin, Northeast China: Earth and Planetary Science Letters, v. 468, p. 37–44, https://doi.org/10.1016/j.epsl.2016.04.007.

Weil, A.B., and Yonkee, A., 2009, Anisotropy of magnetic susceptibility in weakly deformed red beds from the Wyoming salient, Sevier thrust belt: Relations to layer-parallel shortening and orogenic curvature: Lithosphere, v. 1, no. 4, p. 235–256, https://doi.org/10.1130/L42.1.

Weil, A.B., Yonkee, A., and Sussman, A., 2010, Reconstructing the kinematic evolution of curved mountain belts: A paleomagnetic study of Triassic red beds from the Wyoming salient, Sevier thrust belt, USA: Geological Society of America Bulletin, v. 122, no. 1, p. 3–23, https://doi.org/10.1130/0016-7606(2010)122<3:REMOSA>2.3.CO;2.

Wilson, M.D., 1970, Upper Cretaceous-Paleocene synorogenic conglomerates of southwestern Montana: American Association of Petroleum Geologists Bulletin, v. 54, no. 10, p. 1843–1867.

Yonkee, W.A., DeCelles, P.G., and Coogan, J., 1997, Thrust-generated fan-delta deposition: Little Muddy Creek Conglomerate, SW Wyoming: Journal of Sedimentary Research, v. 67, no. 4, p. 683–692, https://doi.org/10.1306/2015.08.001.

Zijderveld, J.D.A., 1967, A demagnetization of rocks: Measurements of results. Dalam, R.K., ed., Sedimentation of Late Cretaceous and Tertiary Rocks in the Sevier Seismic Belt—Utah: Relations to wedge exhumation history of the Willard thrust sheet, northern Utah: Geology Studies, v. 42, no. 1, p. 73–80.

Allen, P.A., and Homewood, M., 1983. Cretaceous and lower Tertiary rocks in the Salt Lake City 30′ quadrangle, Utah: U.S. Geological Survey Open File Report 2017-3.