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THE WASATCH MONOCLINE, CENTRAL UTAH—A PRE-BASIN AND RANGE EXTENSIONAL STRUCTURE

Shelley A. Judge, David H. Elliot, Terry J. Wilson, and Kenneth A. Foland

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Cover

View to the northeast of the Wasatch monocline as expressed along Manti Canyon near Manti, Utah. Significant east-west drainage transects are perpendicular to the monocline axial trace, exposing strata folded into the limb of the monocline. In Manti Canyon, the variegated beds of the Cretaceous-Paleocene North Horn Formation are capped by cliff-forming strata of the Paleocene Flagstaff Formation. Monocline flexure is punctuated by east-dipping antithetic normal faulting that displaces strata by tens to hundreds of meters.

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The Wasatch Monocline, Central Utah—A Pre-Basin and Range Extensional Structure

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ABSTRACT

The Wasatch monocline is a major structure in the transition zone between the Basin and Range and Colorado Plateau physiographic provinces. The timing of formation of the monocline and its tectonic significance has been the subject of debate because it is an anomalous structural style for central Utah. Constraining the age for flexure and outlining the tectonic regime responsible for Wasatch monocline formation are principal objectives of this research. Field mapping near the southern end of the monocline revealed an unconformity between the older, middle Eocene Crazy Hollow Formation, included in monocline folding, and the younger, middle Eocene (Bartonian) formation of Aurora deposited against the monocline. We report an incremental step-heating and direct single-grain laser fusion age of 38.0 ± 0.2 Ma for biotite from an ash-flow tuff within the formation of Aurora, which constrains monocline formation to no younger than the mid-Eocene. Structural data from the Wasatch monocline, in the context of regional structural and tectonic analysis, indicate the monocline formed in an extensional regime as a forced fold or a rollover fold of the east-facing Sanpete half-graben, formed during pre-Basin and Range extension, also recorded in the Paleogene-Neogene basins of Utah Valley and Salt Lake Valley regions.

INTRODUCTION

Importance of Study

Most monoclines within the Colorado Plateau are prominent Laramide structures, formed as drag folds above reactivated, high-angle, reverse faults due to contractional tectonics (e.g., Kelley and Clinton, 1960; Davis, 1978, 1999; Anderson and Barnhard, 1986; Erslev and Rogers, 1993; Bump, 2003). Central Utah is the physiographic transition zone along the boundary between the Colorado Plateau province to the east and the Basin and Range province to the west. The Wasatch monocline is a broad and open fold with the form of typical regional monoclines; it extends for about 110 km (68 mi) through central Utah and is the structural backbone of the transition zone (Figure 1). The west-facing monocline also forms the western front of the Wasatch Plateau, a notable geomorphic feature of the region (Figure 2). The Wasatch monocline is in an area that has been subject to both contractional and extensional tectonics since the Early Cretaceous. The development of the monocline by either tectonic regime is of specific interest, because it is an anomalous structural style for central Utah. No indisputable Laramide-style deformation has been documented in the Wasatch Plateau region of central Utah, and this research confirms that the Wasatch monocline is not a Laramide-style feature, characterized by monocline flexure due to high-angle,

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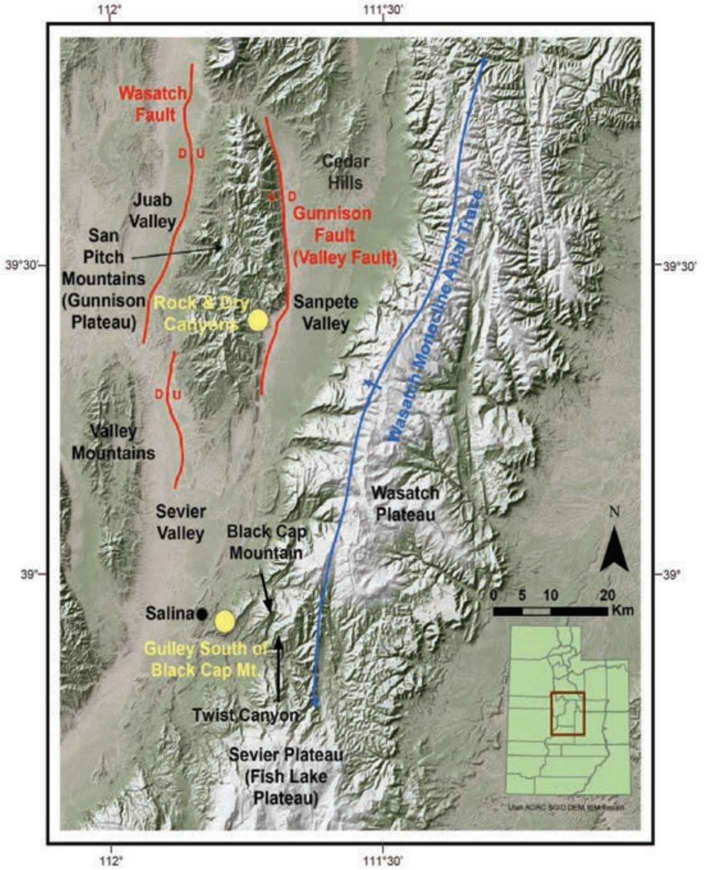


Figure 1. Regional DEM map of central Utah displaying the topographic highs and adjacent valleys. Important geographic or geologic localities from the text are mapped for reference, including: the Wasatch Plateau, San Pitch Mountains, Cedar Hills, and Valley Mountains (black), Sanpete, Sevier, and Juab Valleys (black), the axial trace of the Wasatch monocline (blue), and the Wasatch and Gunnison faults (red). The locations of Rock and Dry Canyons and gulley south of Black Cap Mountain (yellow) are also mapped.

reverse dip-slip motion of basement blocks (Davis, 1978). New information on the Wasatch monocline is invaluable for improving knowledge on the timing and extent of contraction or extension in the region, including correlating the timing of tectonic regimes to known events to the north and west.

Although workers have reported on Wasatch monocline development for over 140 years (e.g., Dutton, 1880; Spieker, 1946; Erb, 1971; Willis, 1986; Anderson et al., 2001; Schelling et al., 2007), the timing and formation of the Wasatch monocline has remained uncertain and controversial. Previous workers have suggested a wide range of possible ages for monocline formation from the Middle Eocene through the Early Miocene (ca. 40 to 20 Ma; e.g., Spieker, 1949; Erb, 1971; Willis, 1986; Witkind, 1994; Anderson et al., 2001). Spieker (1949) and his students generally accepted the monocline as late Eocene to Miocene in age using only stratigraphic and structural relationships. More recent age constraints have been based on radiometric age dates from several different formations (Willis, 1986), but these radiometric dates have not extended the inferred age range significantly. The exceptions are Anderson et al. (2001) and Frank Royse, Jr. (Chevron, written communication, 2020) who proposed that the monocline is Miocene or younger, essentially making it a Basin and Range structure.

Purpose of Research

Here we report new data to constrain the timing of monocline flexure and its relationship to contractional and/or extensional tectonics. New field-based information obtained to determine the timing of flexure includes studies on stress regimes, paleocurrents, stratigraphic field relationships, and ^{40}Ar/^{39}Ar dating. Focused mapping near the southern end of the structure reveals an angular unconformity between older strata included in monocline folding and younger strata deposited unconformably against the monocline. These stratigraphic data bracket the timing of flexure by providing maximum and minimum ages of monocline formation. Wasatch monocline age constraints can be combined with established tectonic information to provide a more comprehensive picture of changing stress regimes in a regional context.

GEOLOGIC SETTING

Regional Tectonic Setting

The Wasatch monocline resides in a key location in the complex Mesozoic-Cenozoic tectonic framework of central Utah. The monocline lies in the transition zone, which separates the western margin of the Colorado Plateau Province and the eastern margin of the Basin and Range Province. It also lies along the late Precambrian to Paleozoic Cordilleran sedimentary hingeline of central Utah and with the eastern limit of the

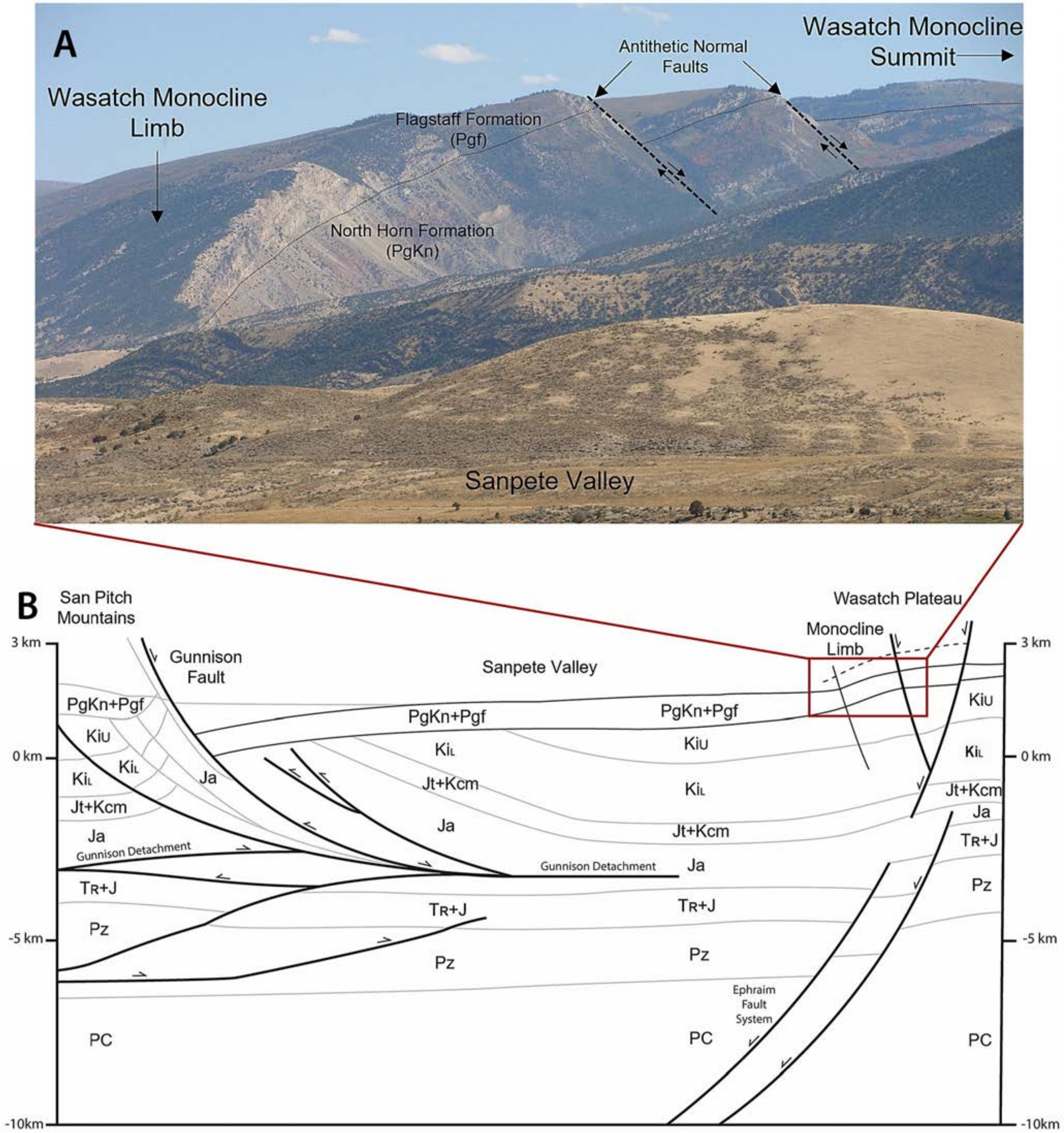


Figure 2. (A) Photograph of the Wasatch monocline in profile, as seen in Manti Canyon on the Wasatch Plateau. Manti Canyon is within the central part of the fold, signifying its highest structural relief. A series of east-dipping antithetic normal faults displace strata of the Flagstaff Formation and the North Horn Formation along the monocline limb, which dips west toward Sanpete Valley. View to the northeast. (B) Schematic cross section across Sanpete Valley. Modified from Schelling et al. (2007). The red box indicates the placement of the photograph along the cross-section profile. The locations of the Gunnison fault and Ephraim faults bound Sanpete Valley to the west and east, respectively. Ja = Jurassic Arapien Formation; Jt+Kcm = Jurassic Twist Gulch Formation and Cretaceous Cedar Mountain Formation; KiL = Cretaceous Indianola Group, lower; KiU = Cretaceous Indianola Group, upper; PC = Precambrian strata; PgKn+Pgf = Cretaceous-Paleogene North Horn Formation and Paleogene Flagstaff Formation; Pz = Paleozoic strata; TR+J = Triassic and Jurassic strata.

Cretaceous Sevier fold-thrust belt. The Utah hingeline, which geographically is oriented approximately north-south along the center of the state, has long been recognized as a zone of crustal weakness and tectonic activity during many periods of Utah's geologic history (Baer, 1976; Ritzma, 1981; Stokes, 1988; Hintze and Kowallis, 2021).

Central Utah has undergone changes from one stress regime to another through time. Structural overprinting shows both contractional features associated with Sevier orogenesis and extensional features associated with Oligocene-Miocene and then Basin and Range extension. Several studies have outlined the regional tectonic evolution. DeCelles and Coogan (2006) proposed a regional thrusting chronology associated with the Sevier fold-and-thrust belt of central Utah (c.a. 145 to 65 Ma; latest Jurassic-Early Cretaceous to Early Paleocene). Their chronology rewrote the previous tectonic interpretation for synorogenic deposits (see Villien and Kligfield, 1986). Constenius (1996) and Constenius et al. (2003) were instrumental in outlining the timing of pre-Basin and Range extension (ca. 49 to 20 Ma; Middle Eocene to Early Miocene) throughout the western U.S. Cordillera. They noted that the change from compressional to tensional stress regime was not synchronous everywhere, with northern segments of the Sevier fold-and-thrust belt showing extensional overprinting earlier in time.

Other studies conducted near the southern and northern extent of the monocline have focused on issues of structural overprinting. Toward the southern end, Cline and Bartley (2007) tested five competing hypotheses on observed relationships of the Cenozoic-Jurassic geology of Sevier Valley. They determined that the principal process responsible for a unique contact in Sevier Valley was regional extension and called the fault the Salina detachment. Anderson et al. (2001) noted many Neogene extensional features in the region near the town of Salina, and therefore suggested a Miocene or younger age for the Wasatch monocline. They based their results on structural concordance and the absence of deposition against paleotopography of the monocline. North of the monocline, in the Charleston-Nebo segment of the Sevier thrust belt, Constenius et al. (2003) provided evidence for crustal extension (ca. late Eocene to middle Miocene) evidenced by reactivation of thrust structures to form half grabens.

Monocline Expression

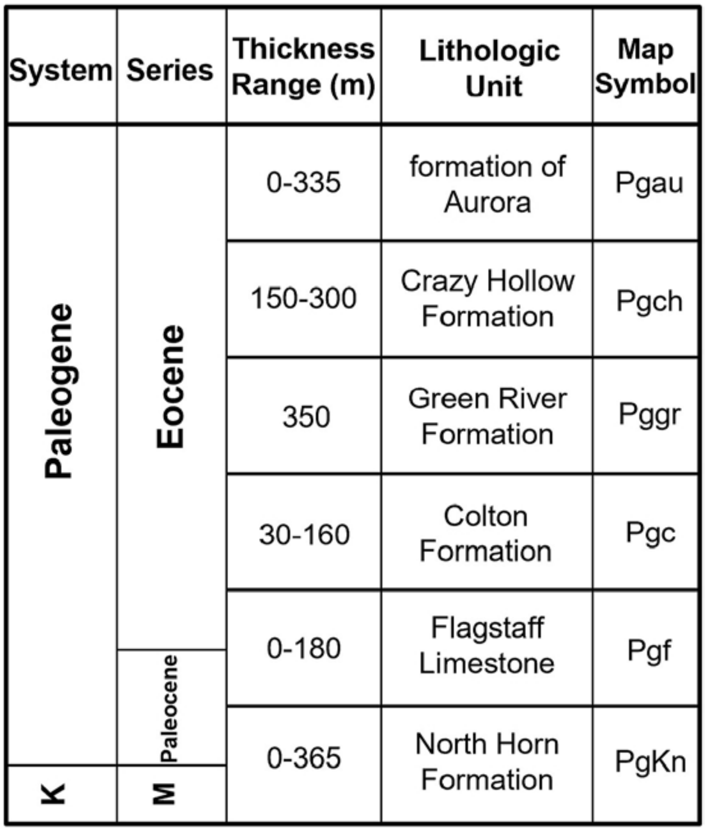
The Wasatch monocline is a north-northeast-trending, west-verging monocline in Sanpete-Sevier Valleys of central Utah exposed between Millburn and Salina Canyon for approximately 110 km (68 mi) (Figure 1; Willis, 1986). Its northern segment trends 020° to 030°; however, there is a noticeable change in the anticlinal axial trace to 000° to 005° near its southern end. The Wasatch monocline, a major geomorphic feature, is a doubly plunging fold, with its highest topographic expression and structural relief (1710 m; 5600 ft) in the central part of the fold (Figure 2). Topographic relief in the northern and southern ends is approximately 850 m (2790 ft) and 700 m (2297 ft), respectively. McGookey (1958) attributed this reduced relief at the southern end to less displacement, to less resistant strata exposed at the surface, and to the overlap of folded units by younger strata.

Access to monocline exposures is excellent not only along the trend of the monocline, but also across the monocline flexure due to several cross-strike structural transects formed by large drainage basins. In profile, nearly flat-lying Paleogene sedimentary strata that dip less than 10° west form the plateau summit; these strata are displaced by several northeast-southwest-striking en echelon grabens. The plateau grabens are large-scale features that dominate the landscape of the summit. Smaller shoulder grabens and east-dipping antithetic normal faults break the continuity of the folded strata within the anticlinal hinge zone of the Wasatch monocline. Along the limb of the monocline, strata dip 15° to 40° west—steepest within the central part of the monocline limb—and are cut by a series of antithetic normal faults that divide the limb into distinct structural domains (Figure 2). In each structural domain, smaller-scale mesoscopic normal faults, joints, and veins are prominent. Eventually, limb strata plunge beneath the adjacent Sanpete Valley; a broad, synclinal hinge has been interpreted at depth in several balanced structural cross sections of the region (Schelling et al., 2007).

Regional Stratigraphy

Geologic units are well exposed along the length and width of the Wasatch monocline due to the several east-west-drainage transects. Units exposed in the central part of the monocline include the Cretaceous to Paleogene North Horn Formation and the Paleogene Flagstaff, Colton, Green River, and Crazy Hollow Formations (Figure 3). The North Horn Formation represents shallowing of the foredeep during Gunnison thrust emplacement during the Sevier orogeny (DeCelles and Coogan, 2006). Flagstaff through Crazy Hollow strata were deposited during times of Laramide uplift, which produced areas of high topographic relief separated by numerous basins (Dickinson et al., 1988). In central Utah, intermontane ponded basins dominated, and the Flagstaff and Green River Formations represent lacustrine intervals that interfingered with siliciclastic-rich Colton and Crazy Hollow fluvial units (Stanley and Collinson, 1979; Weiss and Warner, 2001; Davis et al., 2009; Dickinson et al., 2012).

Additional units with significant volcanic/volcaniclastic components are exposed along the monocline at its extreme northern and southern ends. At the northern end, the Moroni Formation laps onto the Green River Formation in several places, and in all probability, also laps onto the Crazy Hollow Formation along the eastern flanks of the Cedar Hills (Fograscher, 1956; Albrecht, 2001; Weiss and Warner, 2001). Moroni K/Ar dating from Cedar Hills samples, conducted by Albrecht (2001), provided a 34.3 ± 0.3 Ma age for the formation. At the southern end, beds assigned to the formation of Aurora by Willis (1986) lap onto the monocline; we show here that Aurora strata figure significantly in the geologic history of monocline flexure. The formation of Aurora was proposed by Willis (1986; replaced Bald Knoll Formation) but not formally defined. Willis (1986) described it as a sequence of "interbedded mudstone, bentonitic shale, limestone and sandstone." He further mentions that the formation becomes increasingly volcanic toward the south (away from Salina) and includes rhyolitic ash-flow tuff. For purposes of this research, we follow the stratigraphic definition of the formation of Aurora set by Willis (1986) but acknowledge that Aurora Formation was used in a stratigraphic column by Hintze and Kowallis (2021).



System	Series	Thickness Range (m)	Lithologic Unit	Map Symbol
Paleogene	Eocene	0-335	formation of Aurora	Pgau
		150-300	Crazy Hollow Formation	Pgch
		350	Green River Formation	Pggr
		30-160	Colton Formation	Pgc
	Paleocene	0-180	Flagstaff Limestone	Pgf
K	M	0-365	North Horn Formation	PgKn

Figure 3. Generalized stratigraphic column of principal units affected by flexure of the Wasatch monocline in the southern portion of the study area. Thickness data taken from the mouth of Salina Canyon. Modified from Hintze and Kowallis, 2021). K = Cretaceous; M = Maastrichtian.

COMPETING HYPOTHESES FOR MONOCLINE DEVELOPMENT

There are several competing hypotheses to explain the origin and timing of Wasatch monocline development: (1) contractional folding associated with the final stages of the Sevier orogeny (e.g., Spieker, 1946; Standlee 1982; Lawton, 1985; Villien and Kligfield, 1986); (2) differential subsidence due to salt tectonics (e.g., Witkind, 1992, 1994); (3) Laramide-style contractional deformation above a reactivated, high-angle reverse fault, modeling many other monoclines in the Colorado Plateau (for research on verified Laramide monocline examples, see Davis, 1978; Reches and Johnson, 1978; Yin, 1994; Davis and Bump, 2009; Keating et al., 2012); and

(4) extensional deformation associated with a younger tensional regime (Anderson et al., 2001; Schelling et al., 2007; Frank Royse, Jr., Chevron, written communication, 2020). These several competing hypotheses coincide with three different orogenic events affecting the region (i.e., Sevier, Laramide, and Basin and Range tectonism) and with the wide range of proposed ages for development of the monocline (Middle Eocene through the Early Miocene or even younger; e.g., Spieker, 1949; Erb, 1971; Willis, 1986; Witkind, 1994; Anderson et al., 2001; Frank Royse, Jr., Chevron, written communication, 2020).

METHODS

This research tests the hypotheses for monocline origin through an integrated, primarily field-based study of the development and timing of flexure. We obtained a series of data sets (i.e., field mapping, stereonet analysis on stratal bedding, and ash-flow tuff geochronology) and combined data about the geologic structures of the region and the age, lateral extent, and sedimentary characteristics of regional formations.

Field Mapping

The most important locality with respect to monocline timing is in a gulley southwest of the summit of Black Cap Mountain and west of Twist Canyon (UTM 12 S. 0423792 E., 4310373 N.; Figures 4 and 5). Here, Aurora beds are in contact with the Crazy Hollow Formation, and the nature of this contact has been uncertain for decades in the literature. Willis (1986) indicated the importance of finding a depositional relationship between the two units in this region; however, it was Erb (1971) who first provided clues as to where this depositional relationship might be located, even though he did not definitively identify the Crazy Hollow Formation. In his thesis, Erb (1971) stated, “Unless some future worker can determine, without doubt, the identity of the Crazy Hollow(?) wedge, this particular angular unconformity will be of little use in determining the validity of…flexing of the Wasatch Monocline.” The suggestion of an angular unconformity in this area provided incentive to include Black Cap Mountain as a

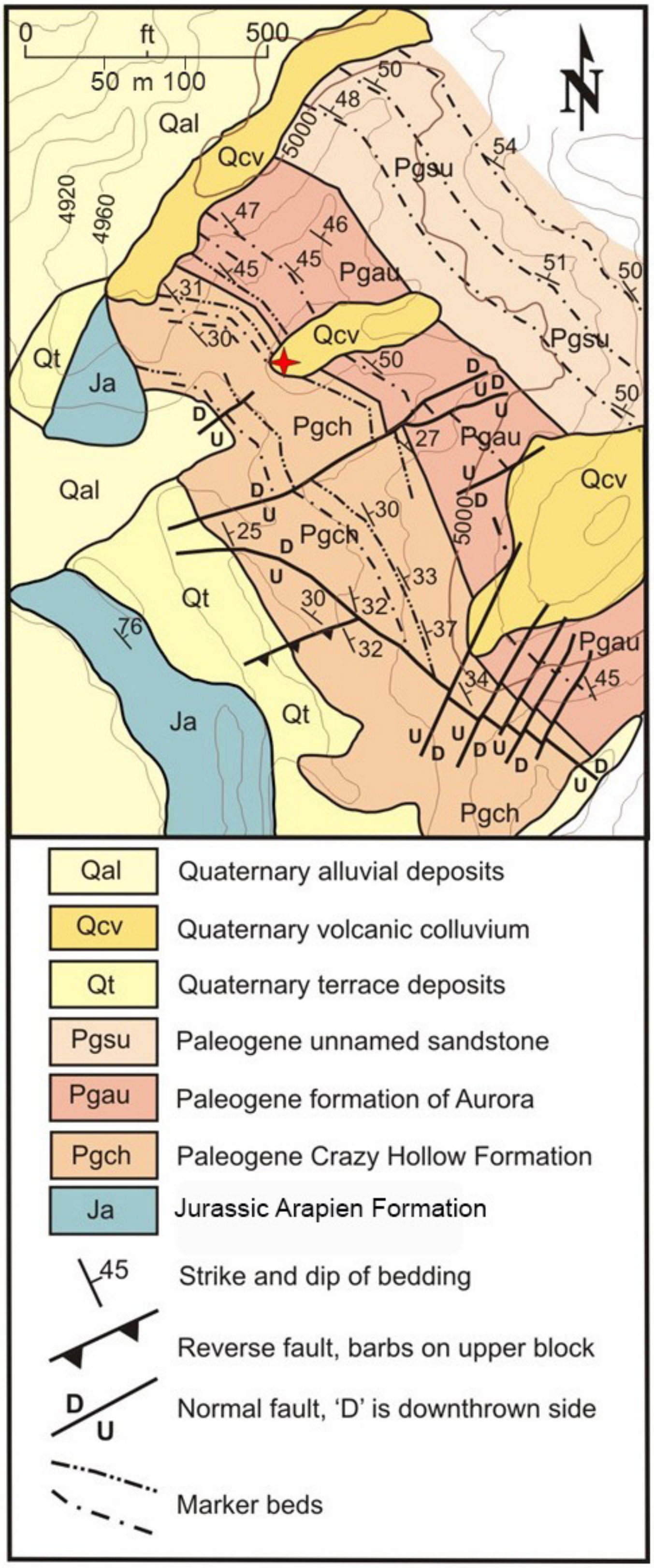


Figure 4. Geologic map of the area south of Black Cap Mountain. The red star in the center of the map marks the viewpoint for Figure 5 (photograph of the gulley transect).

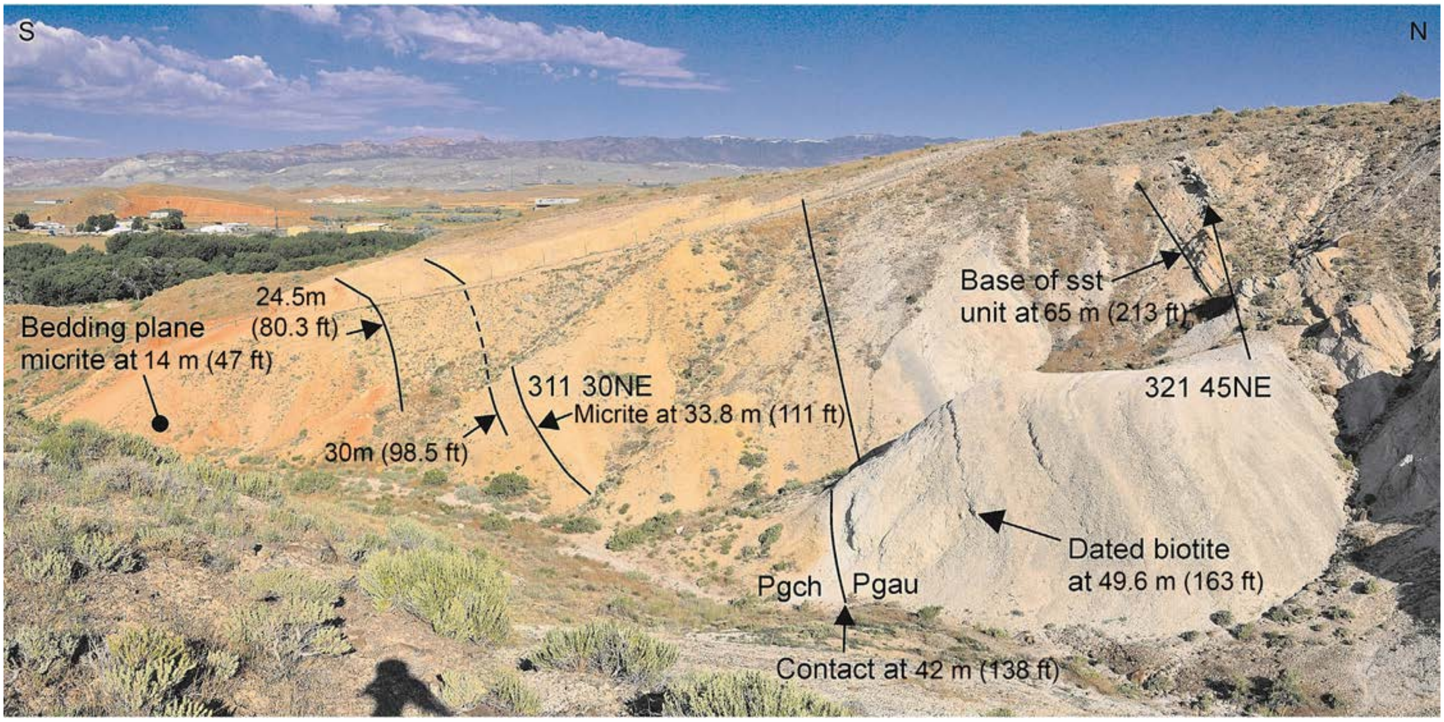


Figure 5. Photograph of the gulley south of Black Cap Mountain that shows the spatial relationships between the Crazy Hollow Formation (Pgch) and the overlying and onlapping formation of Aurora (Pgau). The ash-flow tuff is apparent in the bottom right of the photograph, and an arrow designates where samples were collected for $^{40}Ar/^{39}Ar$ age dating. The thickness associated with each resistant bed correlate to the stratigraphic placement within the graphic column in Figure 6.

field mapping site in this study.

This research clarifies the nature of the spatial relationships and the contact between the Crazy Hollow Formation and the formation of Aurora. The goal of field mapping near Black Cap Mountain was (1) to identify definitively each unit in the field, and (2) to locate and to interpret either a conformable or unconformable contact between the two units (Figure 4). Although we had scoured the trend of the monocline for exposures that provided concrete spatial relationships, only the southern end of the monocline was suitable for detailed mapping. Using unit descriptions for Crazy Hollow and for Aurora strata (Willis, 1986; Weiss and Warner, 2001), we identified both units. A northeast-southwest transect through one gulley was used to measure and to document the numerous bedding attitudes of both units near the contact (Crazy Hollow, n = 22; Aurora, n = 38) (Figure 5). We constructed a detailed stratigraphic column (Figure 6) that starts above the characteristic red beds of the Crazy Hollow Formation but includes its typical 'salt-and-pepper' sandstone and terminates at the unconformably overlying ash-flow tuff within Aurora strata. Careful field mapping in the area documented bedding patterns, small-scale faulting, and contacts between exposed units (Figure 4). Finally, we gathered stratigraphic thickness data between two selected beds—one bed in the Crazy Hollow and the other in the Aurora—to test for stratigraphic consistency along three separate transects, each progressively closer to the monocline fold axial trace. This was done to discount any other structural explanation responsible for bedding attitude disparities.

Stereonet Analysis

We undertook data analysis of bedding attitudes in both the Crazy Hollow Formation and the formation of Aurora (Figure 7). Because of the impact of multiple deformation events in the area and small-scale faulting east of the gulley, only measurements from the northeast-southwest-gulley transect were used for final analysis to prevent any chance of comparing attitudes from

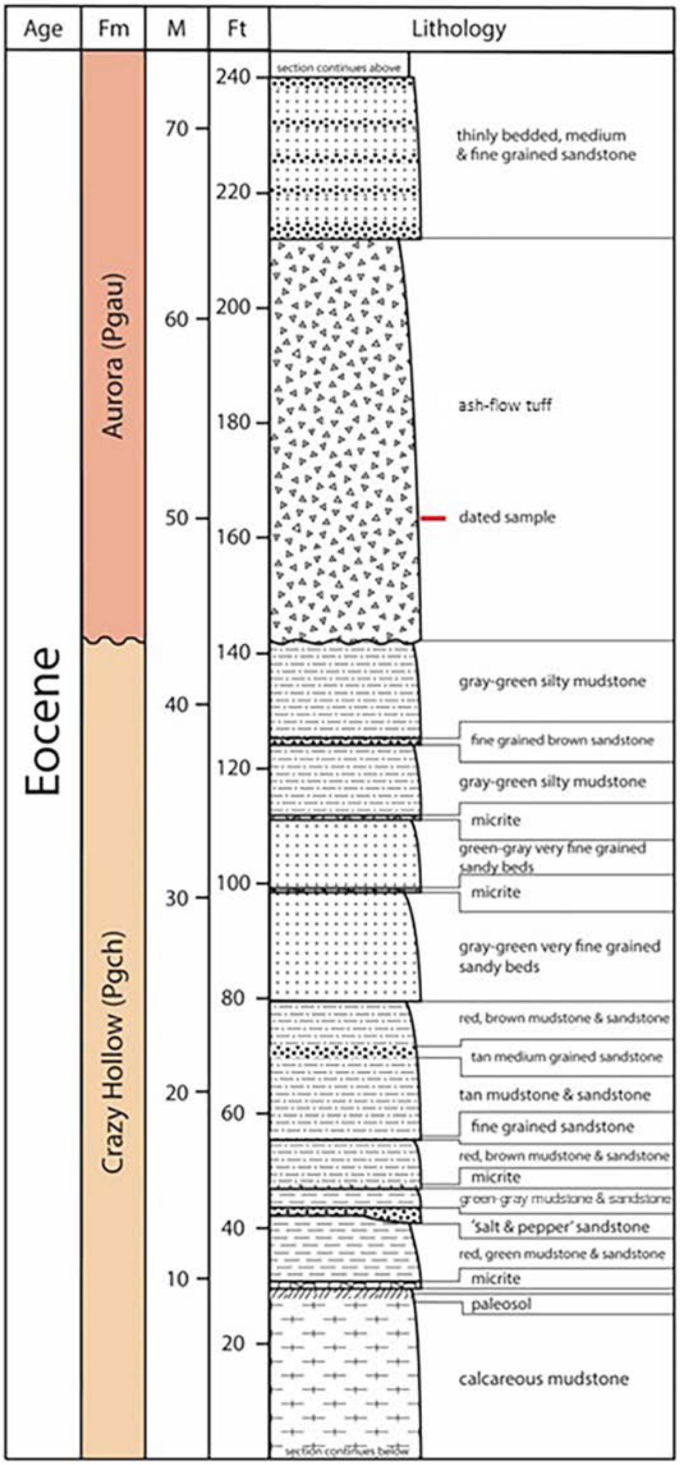


Figure 6. Stratigraphic column of part of the Crazy Hollow Formation and the formation of Aurora. The column was measured in a prominent gulley south of Black Cap Mountain and shown in Figure 5.

different fault blocks. Bedding measurements from a single formation within a single fault block were plotted, and the average bedding orientation was determined from the contoured maxima of poles to bedding planes. Both the Crazy Hollow and Aurora average bedding planes were rotated to restore bedding in Aurora strata back to horizontal to simulate its attitude at the time of its deposition. The resultant stereonet shows the attitude of the Crazy Hollow Formation at the time of deposition of Aurora strata (Figure 7), documenting their angular discordance.

Ash-Flow Tuff Exposures

Field observations at Black Cap Mountain focused on white to gray ash-flow tuff beds in the lower part of Aurora strata. For this study, samples for analysis were taken from the least weathered interval near the base of the ash-flow tuff and again at about 7.6 m (25 ft) above the base of the unit (Figure 7). Biotites within the ash-flow tuff were dated using two different $^{40}Ar/^{39}Ar$ techniques, incremental step-heating and direct, single-grain laser fusion, following the methods described in McDougall and Harrison (1988, 1999) and Foland et al. (1993). Our goal was to compare these $^{40}Ar/^{39}Ar$ dates to previous age dating of the Aurora. Willis (1986) described three K/Ar radiometric dates from nearby localities: 40.5 ± 1.7 Ma from the lower part of the unit in the southernmost Salina 7.5-minute quadrangle, about 5.5 km (3.4 mi) to the south-southeast, and 39.6 ± 1.5 Ma and 38.4 ± 1.5 Ma from near the top of the unit in the adjacent Aurora 7.5-minute quadrangle, about 9.3 km (5.8 mi) to the west.

FIELD RESULTS AND ANALYSIS

Angular Discordance Near Black Cap Mountain

Constraining the timing of Wasatch monocline flexure is a primary aim of this research. Black Cap Mountain is the only known place where a depositional contact between the beds involved in Wasatch monocline flexure and overlapping beds are exposed. Due to subsequent erosion and deformation along the trend of the monocline, no other localities provide this critical field relationship. At this locality, red beds assignable to the Crazy Hollow Formation are overlain by 43.3 m (142

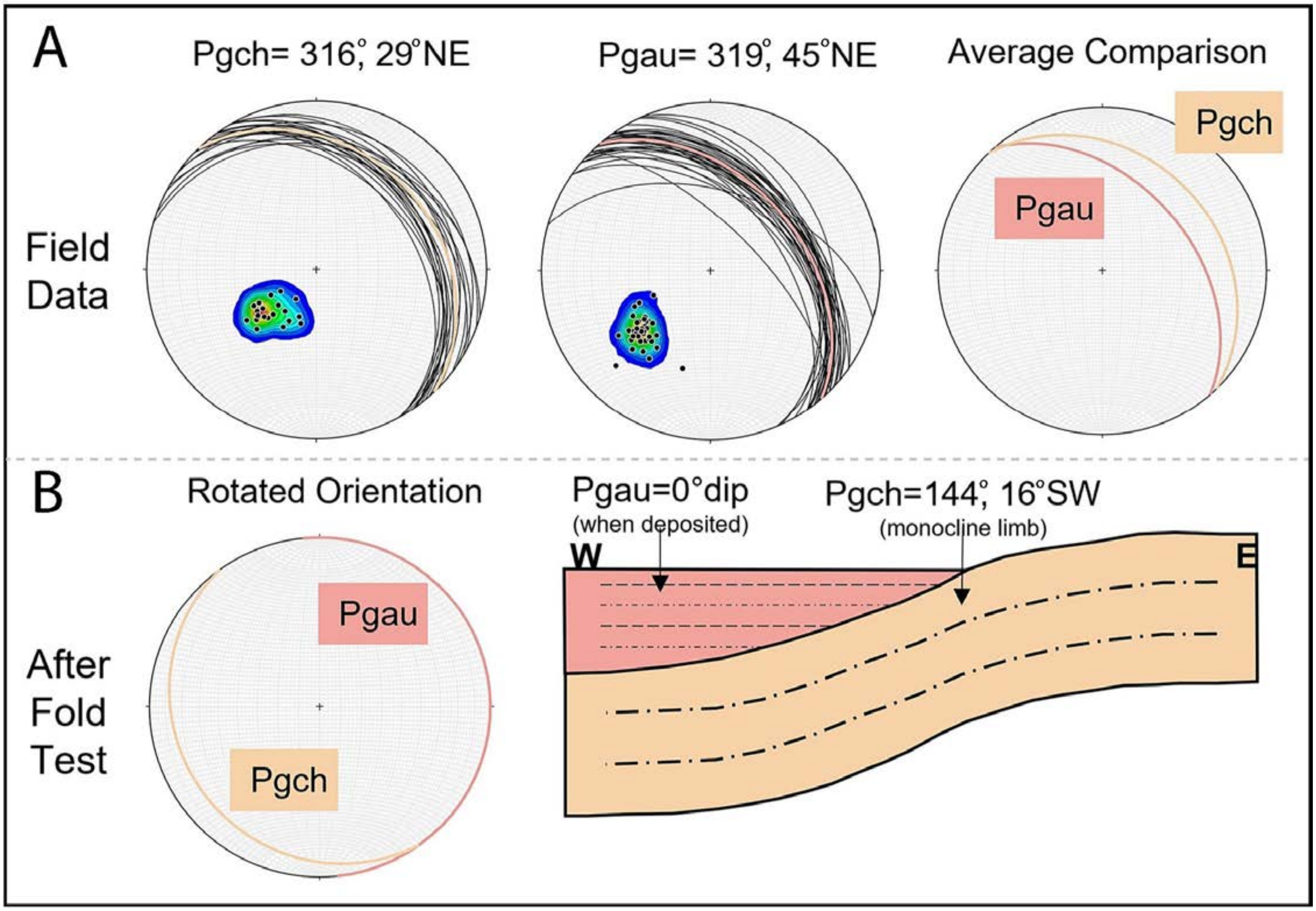


Figure 7. (A) Stereonet plots showing the average bedding attitude from measurements taken from the Crazy Hollow Formation and the formation of Aurora in the vicinity of the mapped area shown in Figures 4 and 5. Field data from the Crazy Hollow show an average orientation of 316°, dip 29° NE. (N. 44° W., dip 29° NE.), whereas field data from the Aurora show an average orientation of 319°, dip 45° NE. (N. 41° W., dip 45° NE.). (B) Raw field data of Aurora strata were rotated back to horizontal (a fold test) to determine the orientation of the Crazy Hollow Formation at the time the Aurora was being deposited. When the Aurora was horizontal (0° dip), the Crazy Hollow was oriented 144°, dip 16° SW. (S. 36 E., dip 16° SW.). An idealized cross section (without antithetic normal faults) shows the discordant relationship between Crazy Hollow and Aurora strata.

ft) of strata comprising mudstone, siltstone, sandstone, and thin micrite beds (Figures 5 and 6). This sequence includes thin sandstones with black chert grains characteristic of the Crazy Hollow Formation, but otherwise it is atypical of that formation and somewhat similar to Aurora strata as described by Willis (1986, 1988). This 43.3 m-thick (142 ft) interval is overlain by a white ash-flow tuff, which itself is overlain by a sequence of volcaniclastic sandstones and tuffaceous beds that share similarities with both Aurora strata and the "unnamed sandstone, mudstone and conglomerate beds" of Willis (1986).

Field mapping supports a difference in the attitudes between the Crazy Hollow Formation and Aurora strata (Figure 4). Bedding analysis along our northeast-southwest transect demonstrates an angular discordance of about 15° between the Aurora ash-flow tuff and the underlying beds (Figure 7). The average bedding attitude for the Crazy Hollow beds beneath the unconformity is 316°, dip 29° NE. (N. 44° W., dip 29° NE.), whereas that for the Aurora ash-flow tuff and overlying strata is 319°, dip 45° NE. (N 41° W., dip 45° NE.). When the ash-flow tuff is rotated back to horizontal during the fold test, the underlying fine-grained strata and the definitive Crazy Hollow beds assume an average attitude of 144°, dip 16° SW. (S 36° E., dip 16° SW.) (Figure 7). Thus, at the time of deposition of the ash-flow tuff, the underlying eroded and truncated beds were dipping about 15° southwest and therefore were part of the west-dipping limb of the Wasatch monocline. These transect bedding results replicated in all bedding data produced from field mapping of both units in the area.

Our stratigraphic column (Figure 6) starts above the characteristic red beds of the Crazy Hollow Formation, includes its typical salt-and-pepper sandstone, and terminates at the unconformably overlying the ash-flow tuff. Thin micrite beds in that interval are a key to demonstrating the angular discordance. Thickness transects of stratigraphic intervals between selected Crazy Hollow micrite marker beds and the ash-flow tuff demonstrate increasing thickness between the markers from east to west up the gulley wall. These differences in stratigraphic thickness show that the ash-flow tuff unit is progressively thinning to the east toward the mapped axial trace of the Wasatch monocline. These data demonstrate the presence of a westward-thickening wedge that onlaps the monocline limb and can be dated to give an upper age limit for monocline flexure.

The angular relationship just described raises several stratigraphic issues. If the 43.3-m (142 ft) section of beds above the typical red Crazy Hollow strata and below the unconformity are assigned to the Crazy Hollow Formation, then it represents a depositional environment unlike any other in that formation. If they should be assigned to the formation of Aurora, then the ash-flow tuff above the unconformity could be assigned to the "unnamed sandstone, mudstone and conglomerate beds" of Willis (1986). Alternatively, if the 43.3-m (142 ft) section and the overlying ash-flow tuff belong to Aurora strata, the angular relations could be evidence for a progressive unconformity developed by temporal coincidence of monocline deformation and deposition of Aurora strata. For the purposes of this discussion, the ash-flow tuff is assigned to the Aurora.

Geochronology

Dating the ash-flow tuff is critical to this study because of its relationship to older Crazy Hollow beds near Black Cap Mountain. The ash-flow tuff is easily identified in the field. The white to pale-gray tuff is rhyolitic in composition and contains abundant pumice fragments and hexagonal to pseudo-hexagonal biotite. The two different $^{40}Ar/^{39}Ar$ techniques of incremental step-heating and direct, single-grain laser fusion yielded consistent radiometric dates for the biotites (Figure 8). Two step-heating runs gave well-defined plateaus with remarkably similar plateau ages (t_p) of 37.9 ± 0.2 Ma and 38.0 ± 0.2 Ma. For each run, the isotope correlation ages (t_{ic}) are identical to the plateau ages. One run by the single-grain laser fusion technique on 24 grains was conducted. Several grains had large uncertainties, and these were rejected, leaving 17 grains in the final estimated date of 38.2 ± 0.2 Ma (weighted by age uncertainties), which does not differ from the date derived from all 24 grains. The date obtained from weighting each analysis by the amount of ^{39}Ar released is 38.5 ± 0.3 Ma. The isotope correlation age for the single grain analyses (n = 17) is 38.1 ± 0.2 Ma, although it is not a particularly well-constrained correlation.

Dates obtained in this study range from 37.9 ± 0.2 Ma to 38.5 ± 0.3 Ma. Most dates cluster around 38.0 Ma. Therefore, a best estimate age of 38.0 ± 0.2 Ma is accepted for the Aurora ash-flow tuff. Because initiation of flexure is older than the base of the ash-flow tuff that onlaps the limb of the Wasatch monocline, the accepted $^{40}Ar/^{39}Ar$ date provides a minimum age for flexure of the monocline: namely, pre-late Eocene (pre-Priabonian).

DISCUSSION

Critical Age Relationships

The Wasatch monocline did not have significant topographic relief during Eocene Crazy Hollow deposition. Paleocurrent directions, collected from the Crazy Hollow in the Sanpete-Sevier Valley, indicate a general flow pattern from south-southeast to north-northwest through the area where the Wasatch monocline presently stands (Judge, 2007). These patterns suggest that the Wasatch monocline did not affect paleoflow during

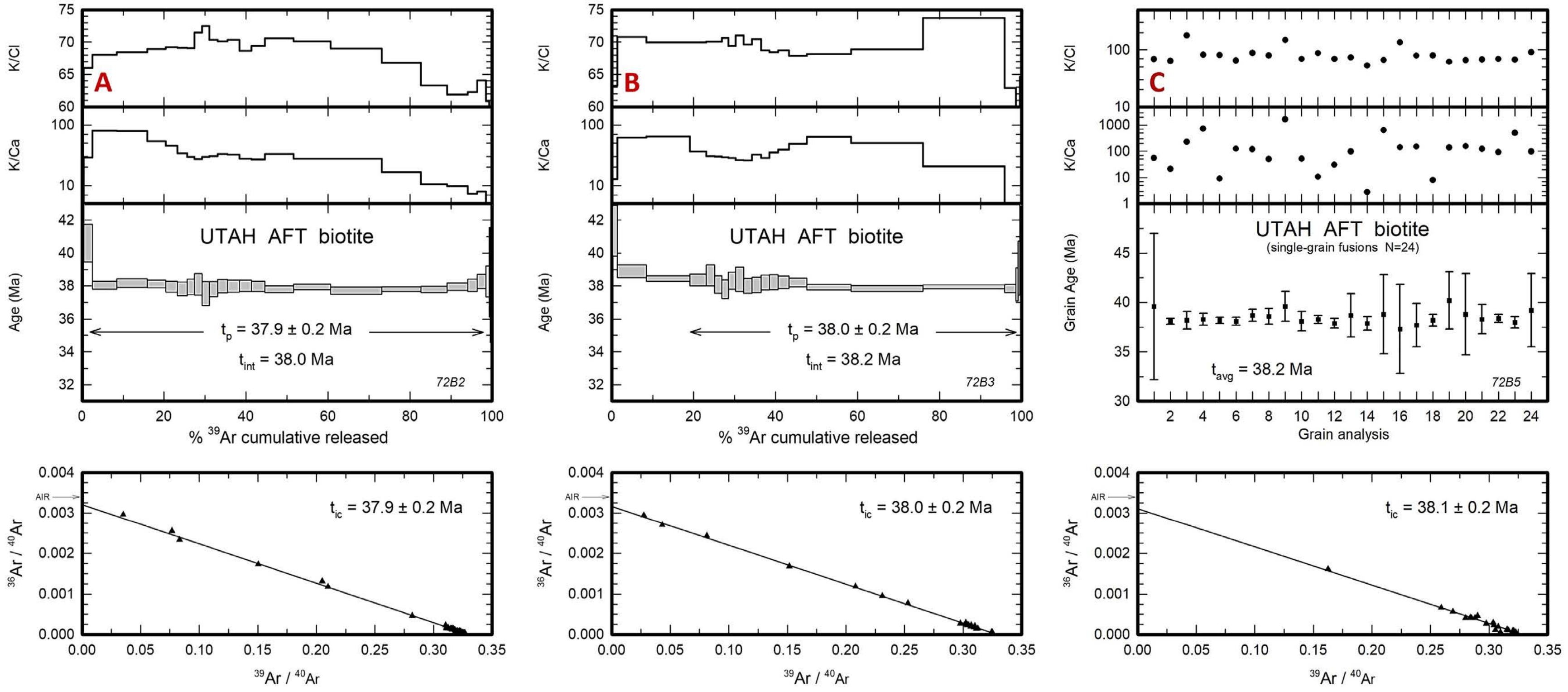


Figure 8. Age dating results from the ash-flow tuff in the formation of Aurora. (A and B) ^{40}Ar/^{39}Ar incremental-heating release pattern for biotite; t_{int} = integrated age; t_p = plateau age. The accepted age for the airfall tuff near the base of the formation of Aurora is 38.0 ± 0.2 Ma. (C) ^{40}Ar/^{39}Ar single grain fusion pattern for biotite; t_{avg} = average age; t_{ic} = isotope-correlation age. Single grain fusion ages compare favorably with the incremental step-heating results.

deposition of the unit. Unfortunately, the age of the Crazy Hollow Formation is poorly constrained. Previous age dating includes three stratigraphically disparate air-fall tuffs from the underlying Green River Formation in Sanpete Valley that yielded biotite ages of about 46.4 to 43.1 Ma by ^{40}Ar/^{39}Ar analysis (Sheliga, 1980). The Aurora ash-flow tuff gives a minimum age for monocline flexure of 38.0 ± 0.2 Ma (Figure 8), with fold initiation preceding ash-flow deposition.

This Aurora ash-flow tuff age is slightly older than ages for the volcanic/volcaniclastic Moroni Formation of the Cedar Hills and south of Thistle farther to the north, both near the northern end of the Wasatch monocline. K/Ar ages between 30.6 ± 1.1 Ma to 37.8 ± 2.2 Ma on biotite, plagioclase, and hornblende separates, were obtained by Witkind and Marvin (1989), whereas ^{40}Ar/^{39}Ar dates of 34.3 ± 0.3 Ma on biotite from an ash-flow tuff and 37.5 ± 0.1 Ma on amphibole from a sandstone were obtained by Albrecht (2001). The hornblende analyzed by Witkind and Marvin (1989) came from an ash-flow tuff south of Thistle, but its stratigraphic position is not recorded. The detrital amphibole (Albrecht, 2001) only gives a maximum age of deposition of the Moroni Formation. Constenius et al. (2003) reported two sanidine dates from pumice clasts at the base of the Moroni Formation south of Thistle. These are 34.4 ± 0.1 Ma and 34.6 ± 0.1 Ma and are similar to the biotite date obtained by Albrecht (2001) for an ash-flow tuff.

End of Sevier Contraction

Sevier orogenesis impacted the Sanpete Valley region, from the San Pitch Mountains in the west to the Wasatch Plateau in the east. Contractional events, in the form of a north-northeast-trending, west-vergent monocline (the Rock and Dry monocline) and several thrust faults, are exposed along the eastern margin of the San Pitch Mountains (Kilmer, 1988; Judge et al., 2011). Many previous workers attributed formation of the Rock and Dry monocline to contractional events associated with the final stages of the Sevier orogeny (e.g., Spieker, 1946; Standlee, 1982; Lawton, 1985; Villien and Kligfield, 1986; Kilmer, 1988). Lawton and Weiss (1999) and Weiss and Sprinkel (2002) mapped the area in 7.5-minute quadrangles and suggested that the Rock and Dry monocline was a fault-propagation fold that formed during the Late Eocene to Oligocene or post-Early Eocene, respectively. Two authors herein (Judge et al., 2011) undertook a modern structural analysis of the Rock and Dry monocline, following initial work done by Kilmer (1988).

Structural work on the Rock and Dry monocline focused on the near-continuous exposures of units involved in monocline flexure, with a focus on dip domain stations along cross-strike transects in the Paleogene Flagstaff Limestone (Figure 3). Kinematic data and analyses of these mesoscopic structural features (stylolites and teeth, calcite veins, and thrust faults) of the Rock and Dry monocline indicated that an east-west compression (trend 278° to 098° [N. 82° W. to S. 82° E.]) preceded flexure and continued as the monocline developed. This maximum compression direction is sub-perpendicular to the trend of the monocline. West-vergent thrust faults with an average orientation of 020°, dip 42° SE. (N. 20° E., dip 42° SE.) along east-dipping bedding planes in the Jurassic Twist Gulch Formation place the Twist Gulch over the Campanian-Paleocene North Horn Formation. The back thrusts caused localized flexure and uplift of Paleogene strata in the area into a fault-propagation fold. These thrust-fold spatial associations and the evidence for layer-parallel compression clearly link Rock and Dry monocline formation with forced-folding associated with west-vergent thrusting and regional compression of the Sevier thrust belt. The Rock and Dry monocline, therefore, was developed in the latest stage of back thrusting associated with the Gunnison thrust system in the easternmost Sevier thrust belt (Kilmer, 1988; Judge et al., 2011).

The timing of the Rock and Dry monocline has regional tectonic implications. Because the Paleocene to Lower Eocene Colton Formation (Figure 3) is the youngest unit visibly affected by Rock and Dry monocline folding, flexure and amplification of the monocline occurred after deposition of at least the lower approximate 60 m (197 ft) of the Colton. If the overlying Green River Formation, exposed only to the west of the Rock and Dry monocline at higher elevations, is also involved in that flexure, then the Green River ash beds dated at about 46 to 43 Ma (Sheliga, 1980) provide a maximum age of post-Early Eocene for the contractional Rock and Dry monocline. Considering a younger age limit for the Green River Formation of about 42 Ma, then this back thrusting likely occurred prior to about 41 Ma. It was the youngest phase of Sevier orogenesis in this region.

Pre-Monocline Extension

The limb of the Wasatch monocline is dominated by normal faults, both large-scale antithetic faults and hundreds of small-scale mesoscopic faults (Judge, 2007). These faults, some of which are accommodation features resulting from flexure, document multiple slip events and divide the limb into several distinctive north-south-trending structural domains. Although strike-slip faults occur locally, normal faults are by far the most abundant and pervasive structures. Reverse or thrust faults are nearly absent along the monocline summit and limb, as are tectonic stylolites (Judge, 2007).

In addition to the abundant normal faults, each structural domain exposes prominent smaller-scale, mesoscopic joints and calcite veins within Paleogene units. Data from the systematic joints and veins (i.e., attitude, spacing, density, morphologic, and mineralogic characteristics) were collected along several cross-strike transects for a kinematic analysis across the monocline. Simple fold test analyses of the joints and veins show that these fractures formed prior to the limb rotation of the Wasatch monocline (Judge, 2007). Therefore, a tensional stress regime in the Sanpete Valley region pre-dated monocline flexure. This tensional regime suggests that the Wasatch monocline formed in a different and younger tectonic regime than the Sevier-influenced Rock and Dry monocline, just west across the valley (Judge, 2007). Based on the dated unconformable relations discussed previously, the change to a tensional regime occurred in the Eocene prior to monocline flexure.

Evidence of Pre-Basin and Range Extension

In central Utah, there is no evidence of Laramide-style, basement-cored uplifts distinct to other regions influenced by contractional tectonics. The long-lived compressional Sevier stress regime that produced localized Rock and Dry monocline back thrusting was replaced by a tensional stress regime in the Eocene. Cordilleran pre-Middle Miocene extension is well documented, with some evidence for extension as early as the Eocene (e.g., Burchfiel et al., 1992; Axen et al., 1993; Murphy et al., 1998; Rowley et al., 1998). There is ample evidence of mid-Cenozoic extension in Utah. To the north of our study area, Constenius (1996) and Constenius et al. (2003) have documented extension in the Uinta arch region and northward along the Wyoming border. This period of extension has been attributed to gravitational collapse following cessation of Sevier contractional tectonism (Constenius, 1996; Vogel et al., 2001; Constenius et al., 2003). To the west and south of our study area, geologic contacts in Sevier Valley show evidence for regional tectonic extension (Cline and Bartley, 2007). On a broader scale, Constenius et al. (2003) pointed out that this mid-Cenozoic extension is recorded regionally by the metamorphic core complexes in northeastern Nevada and adjacent Idaho. In particular, the Snake Range detachment has been dated as no older than ca. 35 Ma, the age of the regionally extensive Kalamazoo ash-flow tuff deposited on a subdued landscape (e.g., Gans et al., 1989; Miller et al., 1999).

During the mid-Cenozoic, there was extensive volcanism in Utah, linked with the transition from regional contraction to extension (e.g., Constenius 1996; Constenius et al., 2003). The volcaniclastic Aurora strata and our new age at Black Cap Mountain likely reflect this regional framework. We establish a 38 Ma age for the Aurora ash-flow tuff. This age is slightly older than the ages of 33.5 to 36.6 Ma given for emplacement of the Keetley Volcanics, which are a part of the Wasatch intrusive belt and located in the central Wasatch Range, east-southeast from Salt Lake City (Vogel et al., 2001; Constenius et al., 2003). The age for the Aurora ash-flow tuff also is slightly older than the age assigned to tephras in the Tibble half graben on the south flank of the Uinta arch (Constenius et al., 2003). The oldest tephra from basin-fill in the Tibble half graben has been dated at 36.4 ± 0.2 Ma using a biotite $^{40}Ar/^{39}Ar$ plateau age (Vogel et al., 2001). Finally, the Marysvale volcanic field lies 65 km (40 mi) to the south-southwest of our study area; however, there is no indication that its initial volcanism, which is accepted at 32 Ma (Steven et al., 1978; Cunningham et al., 2007), was active at the time of Aurora ash-flow tuff deposition.

For central Utah, Constenius (1996) and Constenius et al. (2003) proposed that, south of 40° N. latitude, extension began at about 39 Ma; they bracketed extension regionally based on the relationships between the ages of the youngest foreland basin deposits, Paleogene volcanic/volcaniclastic deposits, and synextensional basin-fill. Constenius et al. (2003) showed a series half grabens bounded by normal faults in their work on the Charleston-Nebo salient of the Utah thrust belt to the north of this study. In these half grabens, pre-extension strata have rollover fold geometries and underlie basin deposits characterized by symmetrical stratal growth.

One of the obvious extensional structural features of Sanpete Valley is the Gunnison fault (also called the Valley fault and the Wales fault; see Fong, 1995; Lawton and Weiss, 1999; Weiss and Sprinkel, 2002; Main, 2015), which forms the structural boundary between Sanpete Valley and the San Pitch Mountains (Figure 1). The fault is an east-dipping normal fault with several thousand meters of offset. From well data, Sprinkel (1994) shows Paleogene units with 945 m (3100 ft) of stratigraphic offset between the San Pitch Mountains and the underlying Sanpete Valley. The Gunnison fault's 60° east dip at the surface becomes listric at depth below Sanpete Valley and is responsible for the formation of a half graben beneath the valley; the San Pitch Mountains are its horst block to the west (e.g., Fong, 1995; Lawton and Weiss, 1999; Schelling et al., 2007; Main, 2015). Weiss and Sprinkel (2002) suggested that early movement along the fault might have occurred during the Miocene. Here we suggest that the formation of the Sanpete half graben, a result of movement along the Gunnison fault, could have been initiated at the same time (ca. 39 Ma) as proposed by Constenius et al. (2003) for the region immediately to the north. The Gunnison fault remains in a tensional stress regime, as recent alluvium north of the Rock and Dry monocline is cut by the fault, and fault scarps are evident in outcrop (e.g., Fong, 1995; Lawton and Weiss, 1999; Weiss and Sprinkel, 2002).

Formation of the Wasatch Monocline During Extension

We document a narrow time window between contractional deformation and extensional deformation between about 41 to 38 Ma, which agrees with the proposed timing of early extension for central Utah (Constenius, 1996; Constenius et al., 2003). Therefore, we argue that the Wasatch monocline formed in an extensional setting.

There is a spatial proximity between the Wasatch monocline and the subsurface west-dipping Ephraim fault interpreted from seismic data (Moulton, 1976; Schelling et al., 2007). The Ephraim fault has typically been interpreted as a normal fault that formed as part of the eastern boundary of the Middle Jurassic Sanpete-Sevier rift. Some recent interpretations, however, suggest post-Jurassic reactivation of the Ephraim fault during Neogene Basin and Range extension (e.g., Schelling et al., 2007; Frank Royse, Jr., Chevron, written communication, 2020). This suggests a model of the monocline as a forced fold above a west-dipping subsurface normal fault, analogous to folds modeled by Withjack et al. (1995). The age data reported here, however, indicates monocline formation in the Eocene, associated with pre-Basin and Range extension.

An alternative model is development of the monocline as a rollover fold associated with a half graben bound to the west by the listric, east-dipping Gunnison fault that forms the Sanpete half graben (Schelling et al., 2007). Analogous rollover folds in extensional settings (see models of Groshong, 1989; Schlische, 1995; Poblet and Bulnes, 2005; Withjack and Schlische, 2006; Uzkeda et al., 2014) have many of the same general features as those of the Wasatch monocline: (1) a lower limb that is either horizontal or dips slightly toward the major fault; (2) synthetic and antithetic faults displacing the fold limb; and (3) the presence of a shoulder graben near the anticlinal hinge of the monocline (Withjack et al., 1995). Rollover folds exhibit axial traces parallel to subparallel to the strike of major listric normal faults (Schlische, 1995). In the case of the Wasatch monocline, its axial trace (020° to 030° in the northern segment, 000° to 005° in the southern segment) is subparallel to the trace of the Gunnison fault, which is segmented and varies from 005° to 030°.

We prefer the rollover model given the newly documented timing of monocline development during the regional development of extensional half grabens during

Sevier orogenic collapse, as documented by Constenius et al. (2003). Future modeling work is planned to test compatibility of these extensional folding mechanisms with the architecture of the Wasatch monocline.

CONCLUSIONS

The purpose of this research is to better constrain the age of Wasatch monocline flexure and to improve our understanding of the geologic history of central Utah regarding the change from the Sevier compressional stress regime to the pre-Basin and Range tensional stress regime. Three lines of evidence provide information about the timing and affiliated stress regime of monocline flexure: (1) the transition from contraction in the Rock and Dry monocline to extension and development of the Wasatch monocline in a short time window in the Eocene, (2) paleoflow patterns of Paleogene fluvial systems that crossed central Utah without deflection by topography at the site of the monocline, and (3) the age of a volcaniclastic unit in the formation of Aurora deposited as a wedge onlapping the Wasatch monocline during flexure.

Biotite from an ash-flow tuff at the base of the onlapping formation of Aurora at the southern end of the Wasatch monocline yielded a best estimate $^{40}Ar/^{39}Ar$ age of 38.0 ± 0.2 Ma. Thus, the Wasatch monocline flexure was initiated after the middle Eocene (using Sanpete Valley Green River Formation biotite dates) but before the upper Eocene ash-flow tuff at the base of the Aurora.

In contrast to both Sevier deformation and classical Laramide monocline formation, the Wasatch monocline is interpreted here to have most likely formed as a rollover fold associated with a half graben in an extensional setting. Because the Wasatch monocline documents early extensional tectonics in the region, the development of the monocline must post-date Sevier orogenesis. This interpretation of the Wasatch monocline supports Weiss and Sprinkel (2002) and more recent work in Sanpete and Sevier Valleys by Cline and Bartley (2007), Schelling et al. (2007), and Main (2015). If Wasatch monocline development occurred during this tensional stress regime, then it is one of the first documented occurrences of pre-Basin and Range extension affecting Sanpete-Sevier Valley and extends the region of extension related to gravitational collapse of the Sevier thrust belt defined by Constenius (1996) and Constenius et al. (2003) in northern Utah.

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