EARLY EASTWARD TRANSLATION OF SHORTENING IN THE SEVIER THRUST BELT, NORTHEAST UTAH AND SOUTHWEST WYOMING, U.S.A.

S. Lynn Peyton1,2, Kurt N. Constenius2, and Peter G. DeCelles1

ABSTRACT

Cross section restorations across the Sevier fold-thrust belt in northeast Utah and southwest Wyoming show bed length discrepancies within the hanging wall of the Absaroka thrust, suggesting that shortening above the Jurassic Preuss salt detachment was 8 to 14 km greater than shortening below the detachment. Interpretation of newly reprocessed, two-dimensional seismic reflection lines over the hanging wall of the Crawford thrust shows that the thrust is not offset across the salt detachment, indicating that: (1) the additional shortening within the Absaroka hanging wall was transferred east before main movement on the Crawford thrust; and (2) the magnitude of Paleocene and early Eocene shortening on the Medicine Butte thrust was essentially equal to subsequent extension on the middle Eocene to late Oligocene Almy-Acocks normal-fault system. Although early displacement on the Crawford thrust could be responsible for the extra shortening above the Preuss salt detachment, surface and subsurface geology suggest shortening from the western thrust system (Willard and Lost Creek thrusts) was transferred ~70 to 90 km east along the Preuss salt detachment between ~102 and 90 Ma, to the future location of the Absaroka hanging wall. From south of the Little Muddy Creek area in southwest Wyoming, to its southernmost outcrop in northeast Utah, the old Absaroka thrust is interpreted to be a frontal imbriccate of this pre-Crawford-thrust shortening.

INTRODUCTION

The Sevier fold-thrust belt in the western U.S.A. is one of the world’s best-documented thin-skinned retro-arc fold-thrust belts (e.g., DeCelles, 2004, and references therein), and the Utah-Wyoming-Idaho salient is one of the most studied parts of this thrust belt. Synorogenic sedimentary rocks, along with subsurface well and seismic data from petroleum exploration, closely constrain the timing and evolution of the thrust belt in this region. Thrusting in the Utah-Wyoming-Idaho salient progressed overall from west to east, with episodic out-of-sequence displacement on existing thrusts (Royse and others, 1975; Lamerson, 1982; Coogan, 1992; DeCelles, 1994). Coogan (1992) recognized two thrust systems with different basal decollements: an older (~140 to 90 Ma) western system consisting of the Willard, Meade, and Laketown thrusts in northeast Utah and southeast Idaho; and a younger (~90 to 50 Ma) eastern system consisting of the Crawford, Medicine Butte, Absaroka, and Hogback thrusts in northeast Utah and southwest Wyoming (figure 1). Both thrust systems climb up-section to the east, with frontal detachments in the salt-rich lower part of the Jurassic Preuss Red beds (figure 2). Total shortening from cross section restoration in this part of the Sevier thrust belt may be >150 km (Dixon, 1982; Lamerson, 1982; Coogan, 1992; Yonkee, 2005), or ~50% (Royse and others, 1975). A significant component of deformation (up to ~25%) was also locally accommodated by internal strain (Mitra, 1994). Yonkee and Weil (2010) calculated that layer-parallel shortening may vary from 5 to 30% in this area, which typically is not included in estimates of shortening from cross sections.

Balanced cross section restoration of the Absaroka thrust sheet of the eastern thrust system shows greater shortening in Jurassic and Cretaceous beds above the Jurassic Preuss salt detachment than in the underlying Mesozoic and Paleozoic sedimentary units (figure 3) (Lamerson, 1982; West and Lewis, 1982; Coogan and Constenius, 2003). Coogan and Constenius (2003) attributed this extra bed length to slip on the Preuss salt detachment during Willard, Crawford, and Medicine Butte thrusting. In this paper we investigate the amount and timing of this “extra” shortening by integrating reprocessed reflection seismic data interpretations with shortening estimates from cross sections. We show that a significant amount of this shortening can be attributed to the western thrust system, either on the Willard or Lost Creek thrusts (figure 1), although earliest movement on the Crawford thrust of the eastern thrust system cannot completely be ruled out. This shortening cannot be due to late- or post-Crawford

1Department of Geosciences, University of Arizona, Tucson, AZ 85721
Email: spoyton@coalcreekresources.com
2Snowslip Corp., Tucson, AZ 85704
3Present address: Coal Creek Resources, Inc., Lakewood, CO 80228

slip. We conclude that shortening of the western thrust system propagated as far east as the location of the hanging wall of the future Absaroka thrust, a distance of ~70 to 90 km, and that this distance was probably controlled by the eastern limit of deposition of the Jurassic Preuss salt.

**GEOLOGIC BACKGROUND**

The western thrust system of the Sevier fold-thrust belt in northeast Utah has a basal decollement within Neoproterozoic miogeoclinal metasedimentary rocks, whereas the eastern system has a basal decollement in Cambrian shelf sedimentary rocks that ramps down to the west into Precambrian crystalline basement (Schirmer, 1988; Coogan, 1992; Yonkee, 1992). The major thrust of the western system, the Willard thrust (figure 1), was emplaced from ~140 to 90 Ma (Yonkee and others, 1997) and was not active after ~90 Ma (DeCelles, 1994). Yonkee (2005) estimated that Neoproterozoic to Mesozoic miogeoclinal sedimentary rocks in the hanging wall of the Willard thrust were displaced at least ~60 km to the east. Other thrusts include the Ogden and Lost Creek thrusts (figure 1), and to the north of the study area the Paris, Meade, and Lake-town thrusts. The eastern thrust system in northern Utah consists of three major thrusts, the Crawford, Absaroka, and Hogsback thrusts (figure 1), which were active from ~90 to 50 Ma (DeCelles, 1994). These thrusts carried Precambrian crystalline basement with overlying Paleozoic and Mesozoic shelf rocks eastward along a decollement in Cambrian shale (figure 2). Maximum displacements of ~30 km, ~40 km, and ~20 km have been documented for the Crawford, Absaroka, and Hogsback thrusts, respectively (Dixon, 1982; Lamerson, 1982; Coogan, 1992). The Medicine Butte thrust crops out between the Crawford and Absaroka thrusts (M’Gonigle and Dover, 1992; Dover and McGonigle, 1993) (figure 1), and soles into the Preuss
salt detachment. Displacement on the Medicine Butte thrust was ~3 to 4 km, an order of magnitude less than on the Crawford, Absaroka, and Hogsback thrusts (Constenius, 1996).

The major detachment horizons for the eastern thrust system in the study area include the Cambrian Gros Ventre Formation, Triassic Woodside and Dinwoody Formations, Jurassic Twin Creek Limestone, Jurassic Preuss Redbeds, and Cretaceous Frontier Formation (Royse and others, 1975; Lamerson, 1982). This paper focuses on the Jurassic Preuss Redbeds, which are composed of siltstone, shale, and sandstone beds, with salt (generally halite) in the lower part of the unit (Coogan and Yonkee, 1985). Halite in the Preuss Redbeds has been penetrated by many petroleum wells in the region, and is easily identified by its characteristic signature on well logs. Preuss salt thickness varies across the study area due to varying depositional thickness, thrust repetition, and salt flowage (Lamerson, 1982). Greatest variation in salt thickness occurs in the proximity of the Medicine Butte thrust, where Lamerson (1982) documents thicknesses between ~0 and 1400 m.

Proximal Cretaceous and Tertiary synorogenic sedimentary rocks are widely exposed and well studied in northeast Utah and southwest Wyoming, and have been used to constrain the timing of individual thrusts (Armstrong and Oriel, 1965; Royse and others, 1975; Lamerson, 1982; DeCelles, 1994). The poorly dated (Neocomian?)

**Figure 2.** Stratigraphic column of rocks carried on thrusts east of the Willard thrust. Modified from Royse and others (1975), Lamerson (1982), Coogan (1992), and DeCelles (1994).
Figure 3. Cross sections and restored sections through the hanging wall of the Absaroka thrust from: (A) Coogan and Constenius (2003) showing 12.9 km of extra bed length above the Preuss salt detachment; (B) West and Lewis (1982) showing 7.4 km of extra bed length; and (C) this study (east end of plate 1; modified from Lamerson, 1982) showing 8.4 km of extra bed length. LPz—Lower Paleozoic rocks; UPz—Upper Paleozoic rocks; TR—Triassic rocks; J—Jurassic rocks; Jsp—Jurassic Preuss and Stump Formations; K—Cretaceous rocks; KT—Cretaceous-Tertiary or Tertiary rocks. Pink layer indicates salt.
Ephraim Conglomerate was deposited during movement on the western thrust system, and is laterally equivalent to the lower part of the Lower Cretaceous Gannett Group (figure 2) (Royse and others, 1975). The Aptian Bechler Conglomerate (also part of the Gannett Group) is tied to slip on the Meade thrust by provenance and growth structure relationships (DeCelles and others, 1993). Overlying strata of the Cretaceous Bear River Formation, Aspen Shale, and Frontier Formation may record continued uplift and erosion of the western system. The Cretaceous Henefer Formation, Echo Canyon, and Weber Canyon Conglomerates were deposited ~89 to 84 Ma during movement on the Crawford thrust (DeCelles, 1994). The Hams Fork Conglomerate of the Evanston Formation was deposited ~75 to 68 Ma, corresponding to Absaroka thrusting (Lamerson, 1982). The main body of the Evanston Formation is late Paleocene (~62 to 58 Ma), corresponding to Hogsback thrusting (DeCelles, 1994). The youngest synorogenic sedimentary rocks are found in the Tertiary Wasatch and Green River Formations, which were deposited ~57 to 51 Ma (Constenius, 1996, and references therein).

The Medicine Butte thrust has been interpreted as a frontal imbricate of the Crawford thrust (Lamerson, 1982; Coogan, 1992), based on the fact that it roots into salt of the Jurassic Preuss Redbeds, eventually joining the Crawford thrust (figure 3). Lamerson (1982) concluded that thrust movement on the Medicine Butte thrust was episodic, with movement during Paleocene time, and youngest displacement after early Eocene time, based on synorogenic sedimentary rocks. Lamerson (1982) also proposed that the last phase of compressional movement on the Crawford thrust was taken up by displacement in the weak Preuss salt detachment, terminating in a series of frontal splays to the east, and that movement on the Absaroka thrust then folded the Medicine Butte thrust and resulted in further imbrication. Similarly, Royse (1993) identified an extensive decollement in the Preuss salt that linked westward to the Crawford thrust and was deformed by the Absaroka thrust. Constenius (1996) noted that the Medicine Butte thrust truncated and displaced units as young as late Paleocene (~63 to 59 Ma), and concluded that timing was coeval with movement on the Hogsback thrust. After regional tectonic shortening ceased, the Preuss salt detachment accommodated extension from early middle Eocene to late Oligocene time, ~49 to 27 Ma (Constenius, 1996). Approximately 3 km of extensional slip on the Almy-Acocks listric normal-fault system (figure 1) reactivated the Medicine Butte thrust and Preuss salt detachment.

The Little Muddy Creek area in southwest Wyoming has been the focus of much study due to the outcrop of two thrusts in the Absaroka system (figure 1) (Royse and others, 1975; Vietti, 1977). Royse and others (1975) and Lamerson (1982) demonstrated that a major lateral ramp is exposed in the hanging wall of the western fault in the Absaroka system (the old Absaroka thrust (OAT)) in this area, as the thrust climbs southward from Devonian through Jurassic strata in its hanging wall. These rocks, and the OAT, were together deformed during slip on the more eastward "young Absaroka thrust" (YAT). A thick syntectonic conglomerate (the Little Muddy Creek Conglomerate) was produced by slip on the OAT, and was subsequently strongly deformed during slip on the YAT (Vietti, 1977; Lamerson, 1982; Pivnik, 1990). South of the Little Muddy Creek area, the oldest rocks found in surface outcrops on the hanging wall of the OAT are Jurassic Preuss Redbeds, with Cretaceous rocks in the footwall (i.e., the hanging wall of the YAT) (Lamerson, 1982). Royse and others (1975) interpreted that the OAT in the Little Muddy Creek area was active during the mid-Santonian, whereas the YAT moved during latest Cretaceous time.

Shortening discrepancies have been recognized within the hanging wall of the Absaroka thrust; the section above the Preuss salt detachment has been shortened significantly more than the section below. Coogan and Constenius (2003) identified ~13 km of excess bed length above the Preuss salt relative to Jurassic Twin Creek Limestone and older strata in the hanging wall of the Absaroka thrust at Anschutz Ranch field (figure 3A). Similarly, cross sections by West and Lewis (1982) and Lamerson (1982) show excess bed lengths of 7.4 km and 8.4 km, respectively, above the Preuss salt detachment (figures 3B and 3C).

**AMOUNT AND TIMING OF SHORTENING**

**Shortening Estimates**

We constructed a balanced cross section that extends from the Wasatch Range on the west, into Uinta County, Wyoming, on the east (figure 1, plate 1). The western part of the cross section, consisting of the footwall and hanging wall of the Willard thrust, and the Wasatch culmination, was based on surface mapping by Coogan and King (2001) and Coogan (2004a, 2004b). Seismic-reflection data, well-log data, and surface geologic maps were the basis of our interpretation of the central part of the cross section in the proximity of the hanging wall of the Crawford thrust (Coogan, 2004a, 2004b, 2004c). We reinterpreted data presented in Lamerson's (1982) plate 4 to construct the eastern part of the cross section across the Painter Reservoir oil field in the hanging wall of the Absaroka thrust (figure 3C). Shortening estimates calculated from this cross section are 28 km, 24 km, and 28 km for the Lost Creek, Crawford, and Absaroka thrusts, respectively. We did not restore the Willard thrust, which is estimated to have ~60 km of displacement (Yonkee, 2005), or the Hogsback thrust, estimated to have ~15 to 20 km of displacement (Dixon, 1982).

To investigate the timing of shortening above the Preuss salt detachment, we first reconstructed bed lengths above and below the detachment. Differences in bed length between formations above and below the Preuss salt are apparent from restored cross sections (figure 3). We used cross sections published by other authors (Lamerson, 1982; West and Lewis, 1982; Constenius, 1996; Coogan and Constenius, 2003), along with our own cross section (plate 1) to estimate: (1) the amount of extension on the Almy-Acocks listric normal-fault system; (2) the amount of shortening across the Medicine Butte thrust; and (3) the difference in bed length between the top of the Jurassic Nugget Sandstone and the Jurassic Stump Formation, using a pin in the down-dip part of the hanging wall and a pin in the footwall of the Absaroka thrust. For a true estimate of shortening, early middle Eocene to late Oligocene extension (Constenius, 1996) should be restored before measuring bed lengths. In practice, the total amount of ad-
ditional shortening above the Preuss salt was calculated by adding the amount of extension to the bed length difference. Table 1 shows that in the hanging wall of the Absaroka thrust in northeast Utah and southwest Wyoming there is a discrepancy of ∼8 to 14 km between shortening above and below the Preuss salt detachment. Internal strain, or layer-parallel shortening was not included in our calculations or cross section, although it may be important in estimates of total shortening (Mitra, 1994; Yonkee and Weil, 2010). We assumed that layer-parallel shortening was similar above and below the Preuss salt detachment.

### Timing of Shortening

Relations along the cross sections in figure 3 and plate 1 between the surface traces of the Crawford and Absaroka thrusts constrain timing of movement on the Preuss salt detachment. (1) Folding above and below the Preuss salt detachment is decoupled as fold hinges are not aligned and fold amplitudes are different. (2) The Preuss salt detachment is folded by hanging wall anticlines on the Absaroka thrust. (3) The long thrust flat in the Preuss salt in the hanging wall of the Absaroka thrust does not have a corresponding flat in the footwall. Instead, the Absaroka thrust forms a continuous footwall ramp through the Preuss salt (figure 3A, plate 1). (4) Thrusts in the eastern part of the Absaroka hanging wall that sole into the Preuss salt, along with the Preuss isoclinal fold above Anschutz Ranch East field, are beveled by the basal Evanston unconformity, whereas to the west the same unconformity is folded and cut by the Medicine Butte thrust (figures 3A and 3C). These observations suggest that thrusts above the Preuss salt detachment to the east of the Medicine Butte thrust are older than the youngest phase of slip on the Medicine Butte thrust, and predate Absaroka thrust deformation.

The Medicine Butte thrust is located directly above a fault-bend fold in the hanging wall of the Absaroka thrust, suggesting that the fault-bend fold already existed and in-

### Table 1. Estimates of extension, bed length, and shortening.

| Cross section source | Field                      | Extension on AANF (km) | Shortening on MBT (km) | Difference (km) | Bed length difference across PSD (km) | Difference in shortening above and below PSD (km) | Difference in shortening excluding MBT (km) |
|----------------------|----------------------------|------------------------|------------------------|-----------------|---------------------------------------|--------------------------------------------------|____________________________________|
| This study (Plate 1) | Painter Reservoir & East Painter Reservoir | 2.6                    | 2.1                    | -0.5            | 8.4                                   | 11.0                                             | 8.9                                          |
| Lamerson (1982) Plate 4 | Painter Reservoir & East Painter Reservoir | 3.7                    | 1.7                    | -2              | 4                                     | 7.7                                              | 6.0                                          |
| Lamerson (1982) Plate 10 | Yellow Creek & Glasscock | 1.5                    | 2.1                    | 0.6             | 9                                     | 10.5                                             | 7.0                                          |
| Lamerson (1982) Plate 11 | Anschutz Ranch & Anschutz Ranch East | 0.9                    | 1.2                    | 0.3             | 7.3                                   | 8.2                                              | 7.0                                          |
| Coogan and Constenius (2003) | Anschutz Ranch & Anschutz Ranch East | 1.4                    | 1.4                    | 0               | 12.9                                  | 14.3                                             | 12.9                                         |
| Constenius (1996) | Anschutz Ranch & Anschutz Ranch East | 1.5                    | 2.5                    | 1               | 8                                     | 9.5                                              | 7.0                                          |
| West and Lewis (1982) | Anschutz Ranch & Anschutz Ranch East | 1.1                    | 0.5                    | -0.6            | 7.2                                   | 8.3                                              | 7.8                                          |

AANF—Almy-Acocks normal-fault system; MBT—Medicine Butte thrust; PSD—Preuss salt detachment.
fluenced the trajectory of the Medicine Butte thrust where it ramps to the surface from the Preuss salt detachment (Constenius, 1996). This also implies that shortening on the Medicine Butte thrust occurred after displacement on the Absaroka thrust. Progressively deformed synorogenic sedimentary rocks of the Maastrichtian-Paleocene Evanston and late Paleocene-early Eocene Wasatch Formations provide evidence of the timing of movement on the Medicine Butte thrust. Similarly, evidence of the collapse of the thrust belt and top-to-west motion on the salt detachment is seen where synextensional growth strata of the early middle Eocene Fowkes Formation and late Eocene-Oligocene Norwood Tuff have been downdropped and rotated along the Acocks listric normal fault and the extensionally reactivated part of the Medicine Butte thrust (Constenius, 1996). Shortening on the Medicine Butte thrust is similar in magnitude to the amount of extension on the Almy-Acoks normal-fault system (table 1).

In summary, our observations suggest that movement on the Medicine Butte thrust postdates displacement on the Absaroka thrust, whereas movement on the thrusts above the Preuss salt detachment to the east of the Medicine Butte thrust occurred before the Absaroka thrust was active.

Possible scenarios resulting in additional shortening above the Preuss salt in the hanging wall of the Absaroka thrust are: (A) late movement on the Crawford thrust (~86 to 84 Ma, before Absaroka thrusting) where slip was transferred to the Preuss salt instead of upward to the surface; (B) early movement on the Crawford thrust (~89 to 87 Ma); and (C) pre-Crawford movement on the western thrust system (Willard or Lost Creek thrusts, older than ~90 Ma; DeCelles, 1994).

Simple fault-bend fold and fault-propagation fold diagrams illustrate the geometry of the Crawford thrust predicted by these different scenarios (figure 4). If the additional shortening was the result of late movement on the Crawford thrust, with slip being transferred to the Preuss salt detachment instead of the surface, as suggested by Lamerson (1982), then the part of the Crawford thrust that ramped to the surface above the detachment would have been carried passively along the salt detachment. Thus, the Crawford thrust would have been offset eastward toward the foreland along the salt detachment, and the dip of the hanging wall strata would reflect the ramp-flat-ramp geometry of the offset Crawford thrust below (figure 4A). If the additional slip was transferred to the salt detachment during early movement on the Crawford, then a fault-bend fold anticline would have formed where the thrust changed from a ramp to a flat in the Preuss salt detachment. Depending upon the amount of displacement, the east-dipping limb of this anticline could be preserved either in the footwall or hanging wall of the Crawford thrust when it ramped to the surface (figure 4B). If the additional shortening was transferred east from the Willard or Lost Creek thrusts, pre-dating the Crawford thrust, then the Preuss salt detachment would be offset by later Crawford thrusting (figure 4C). In figure 4C we have shown the Crawford thrust forming as a fault-propagation fold to illustrate that the end result of this scenario may look similar to figure 4B, where dips in the hanging wall of the Crawford thrust roll to the east near to the thrust. An important distinction between the second and third scenarios is whether there has been displacement along the Preuss detachment in the hanging wall of the Crawford thrust. If the slip was transferred east during early Crawford movement, then there should be no displacement in the Preuss salt in the hanging wall of the Crawford thrust (figure 4B). If slip was associated with Lost Creek or Willard thrusting it would result in displacement along the Preuss detachment in the hanging wall of the Crawford thrust (figure 4C).

**SEISMIC DATA**

Predictions for the geometry of the Crawford thrust from the proposed scenarios were tested using seismic-reflection data. Five, two-dimensional (2D) seismic lines that cross the hanging wall and the surface trace of the Crawford thrust were reprocessed (figure 1). These lines were originally acquired by Exxon in 1982 and 1984. Modern processing techniques including pre-stack time migration resulted in dramatic improvement in data quality over the original processing. Two exploration wells provided ties between the 2D seismic data and subsurface geology. The Amoco Deseret well (section 2, T. 6 N., R. 5 E.), drilled in 1980, reached a total measured depth of 5318 m (17,448 ft) within Cambrian rocks in the hanging wall of the Crawford thrust. The Amoco Champlin No. 432C well (section 1, T. 6 N., R. 5 E.) reached a total measured depth of 4232 m (13,883 ft) within the Cretaceous rocks in the footwall of the Crawford thrust, after penetrating Cretaceous through Ordovician rocks of the hanging wall. We integrated surface mapping (Coogan and King, 2001; Coogan, 2004a, 2004c, 2006) with the well and seismic data to produce our interpretations. Figure 5 shows a pre-stack time migration of seismic line 82J19 both without (figure 5A) and with (figure 5B) our interpretation.

A depth section of line 82J19 was calculated by applying an interval-velocity model to the pre-stack time migration (figure 5C). A few key faults and formation tops are dashed to provide a reference frame for comparison to figure 5B. Notice that beds in the footwall of the Crawford thrust dip to the west in the depth section, in agreement with wells and surface geology. The time section displays significant velocity pull-up due to the higher velocities of the older rocks in the hanging wall of the Crawford thrust. Similarly, at the northwest end of the time section, the Crawford fault and the rocks in its hanging wall seem to flatten. This is due to high velocity rocks on the Willard thrust hanging wall causing velocity pull-up. On the depth section, the Crawford thrust dips uniformly west. Although our depth section is not perfect (there appear to be velocity problems beneath the Crawford thrust to the west of the Champlin well), it illustrates the dangers of interpreting only time sections in this structurally complex area.

Footwall cutoffs below the Crawford thrust are well imaged on the reprocessed seismic data, allowing us to confidently interpret the location of the Crawford thrust. Strong reflections are visible from the base of Jurassic Twin Creek Limestone and the Triassic Woodside-Dinwoody Formations in the hanging wall of the Crawford thrust. These reflections have a constant dip, and do not indicate...
A **Late movement on the Crawford thrust.** Crawford thrust (CT) cuts to surface. Later shortening transferred from ramp to flat in Jurassic Preuss salt detachment (PSD) to form structures to east, offsetting CT.

B **Early movement on the Crawford thrust.** Initial CT shortening transferred from ramp to flat in Jurassic salt (PSD) to form structures to east. Later CT cuts to surface.

C **Pre-Crawford movement on western thrust system.** Shortening from Willard or Lost Creek thrust (LCT) transferred to east along PSD to form structures to east. Later CT forms by fault propagation folding and cuts to surface.

![Schematic cross sections showing possible timing scenarios for transfer of displacement east on the Preuss salt detachment. CT—Crawford thrust; PSD—Preuss salt detachment; LCT—Lost Creek thrust; PCx—Precambrian crystalline rocks; LPz—Lower Paleozoic rocks; UPz—Upper Paleozoic rocks; Mz—Mesozoic rocks; K—Cretaceous rocks. Red lines are active thrusts, black dashed lines are future thrusts, and black solid lines are previously active thrusts.](image)

**Figure 4.**

any folding or dip changes that might be expected to result from post-Crawford shortening along the Preuss salt detachment. All five seismic lines show that the Crawford thrust has not been offset along the Preuss salt detachment. The Twin Creek Limestone is poorly imaged above the Nugget Sandstone in the hanging wall of the Crawford thrust due to its complex structure and near-vertical to overturned dip (plate 1).

**DISCUSSION**

**Timing**

Interpretation of the seismic data allows us to evaluate timing scenarios discussed earlier and outlined in figure 4. Key observations from the seismic data include: (1) the Crawford thrust, which is well delineated by footwall cutoffs and hanging wall stratigraphy, forms a continuous
Figure 5. (A) Uninterpreted pre-stack time migrated seismic reflection profile 82J19. (B) Interpreted pre-stack time migrated seismic reflection profile 82J19. Interpretation was based on synthetic seismograms from the Deseret and Champlin wells and surface geology (Coogan and King, 2001), and was used in the construction of the balanced cross section in plate 1. (C) Depth section calculated from pre-stack time migrated section using an interval velocity model. Dashed lines represent interpretation from B for comparison. Seismic data courtesy of ExxonMobil. PCx—Precambrian crystalline rocks; LPz—Lower Paleozoic rocks; UPz—Upper Paleozoic rocks; TRwd—Triassic Woodside and Dinwoody Formations; TRt—Triassic Thaynes Formation; TRa—Triassic Ankareh Formation; Jn—Jurassic Nugget Sandstone; Jtc—Jurassic Twin Creek Limestone; Jsp—Jurassic Preuss and Stump Formations; Kg—Cretaceous Gannett Group; Kbr—Cretaceous Bear River Formation; Ka—Cretaceous Aspen Shale; Kf—Cretaceous Frontier Formation.
fault and is not offset along the Preuss salt detachment (figure 5); and (2) the hanging wall stratigraphy of the Crawford thrust dips uniformly west indicating the fault has a simple footwall ramp geometry.

Although the Crawford thrust does not appear to be offset along the Preuss salt detachment, synorogenic sedimentary rocks and structural relationships indicate that the Medicine Butte thrust was active after Crawford and Absaroka thrusting (Lamerson, 1982; Constenius, 1996). Comparison of estimated shortening and later extension on the Medicine Butte thrust (table 1) shows that net offset of the Crawford thrust along the Preuss salt detachment by post-Absaroka shortening and extension would have been small (probably < 1 km) and may not be detectable with seismic data. Thus, the lack of offset of the Crawford thrust along the salt detachment, along with the simple footwall ramp geometry, imply that late movement on the Crawford thrust (but pre-Absaroka) cannot explain the additional ~6 to 13 km of bed length above the Preuss salt in the hanging wall of the Absaroka thrust (table 1).

Early movement on the Crawford thrust, with displacement transferred east along the Preuss salt detachment rather than to the surface, could have produced geometries very similar to our observations, provided the east-dipping limb of the hanging wall anticline ultimately remained in the Crawford hanging wall (figure 4B). A Triassic-cored anticline mapped in the Lost Creek area directly above the Crawford thrust (Coogan, 1992, 2004a, 2004b), is consistent with this scenario. However, similar geometries are also generated by eastward propagation of shortening from the western thrust system, followed by later Crawford thrusting with folding produced by fault-propagation folding rather than fault-bend folding (figure 4C).

Surface geology provides evidence that shortening from the western thrust system was responsible for the excess bed length in rocks above the Preuss salt detachment in the Absaroka thrust sheet. In the hanging wall of the Crawford thrust, imbricates of the Lost Creek thrust caused tight folding of the Twin Creek Limestone (plate 1). The Lost Creek thrust climbs up-section from west to east, from a detachment in the Gypsum Spring Member of the Twin Creek Limestone just east of the surface trace of the Willard thrust, to the Preuss salt detachment just west of the surface trace of the Crawford thrust near Lost Creek reservoir (Coogan and Constenius, 2003). Recognition of the Lost Creek thrust at the level of the Preuss salt detachment in the hanging wall near the trace of the Crawford thrust, strongly suggests that the Lost Creek thrust is continuous with the Preuss salt detachment in the footwall of the Crawford thrust, and was offset by Crawford slip, similar to relations in figure 4C.

If shortening occurred in the area of the future Absaroka thrust during Willard or Lost Creek thrusting, then synorogenic sediment derived from the western thrust system (Gannett Group, and Bear River, Aspen, or Frontier Formations, figure 2) should vary in thickness over the structures, with possible underlying erosional truncation of formations (i.e., Jurassic Stump Formation). The Lower Cretaceous Gannett Group, and Bear River and Aspen Formations were folded by this shortening (plate 1), indicating that some slip and folding along the Preuss detachment occurred after Aspen deposition (after ~102 Ma). We studied well logs from Painter Reservoir and East Painter Reservoir fields (figure 1) along with logs from several kilometers to the east and west. However, complex structure, regional thinning, and deviated well paths, made it difficult to recognize presence of stratigraphic thinning in the Gannett Group, Bear River Formation, or Aspen Shale, or erosional truncation of the Stump Formation, that could record slip prior to 102 Ma. Major shortening on the Crawford thrust occurred from ~89 to 84 Ma (DeCelles, 1994) and, as discussed above, likely postdated shortening along the detachment. Therefore, the preferred interpretation is that shortening along the salt detachment occurred during deposition of the Cenomanian-Turonian Frontier Formation (~102 to 90 Ma). Unfortunately, the Frontier has been eroded from the hanging wall of the Absaroka thrust in this region.

Implications

Figure 6 shows a sequential restoration of plate 1, with slip transferred eastward along the Preuss salt detachment (Lost Creek thrust) during deposition of the Cenomanian-Turonian Frontier Formation (~102 to 90 Ma). Frontal structures of the detachment are located ~70 to 90 km east of the Willard thrust front, causing a widening of the thrust belt and the wedge-top depozone (DeCelles and Giles, 1996) by the same amount. The location of these structures was likely controlled by the eastern limit of deposition of the Preuss salt, which is found as far east as the hanging wall of the Absaroka thrust, but is not present in its footwall (J. Coogan, Western State College [currently Petro Matad], personal communication, 2009).

Mechanical modeling of thrust belts has shown that when the basal detachment is within a very weak horizon, such as salt, the thrust belt has: (1) a larger width (up to 500 km) than when the detachment is within a stronger horizon; (2) a very low-angle taper; and (3) frontal thrust structures that verge in opposite directions (Davis and Engelder, 1985). While we do not observe any evidence for symmetrical vergence of thrusts above the Preuss salt detachment on the hanging wall of the Absaroka thrust, the occurrence of salt can explain the large distance from the Willard thrust to the frontal structures of the Preuss detachment, the corresponding low taper angle of the thrust wedge (figure 6B), and the location of the frontal thrusts at the eastern edge of the Preuss salt. The significant decrease in yield strength of the detachment achieved when the Lost Creek thrust reached the Preuss salt resulted in the wedge taper angle becoming supercritical. Thus, the thrust belt widened by propagating ~70 to 90 km east, with little or no thrusting between the frontal structures and the previous wedge. This is a minimum estimate of widening because our sequential restoration does not include layer-parallel shortening. The load of the wedge likely induced flow of the salt eastward along the detachment, resulting in salt thickening in the frontal thrusts, now the hanging walls of the Medicine Butte and Absaroka thrusts (Lamerson, 1982). Subsequent slip on the Lost Creek and Crawford thrusts served to build taper internally within the thrust wedge (figures 6C and 6D).
A. Post-Willard, pre-Lost Creek (~105 Ma)

B. Early Lost Creek - shortening propagates eastward along Preuss salt (~102 to 90 Ma)
Deposition of Frontier Formation

C. Late Lost Creek - fault propagation folding and thrusts cut to surface (~102 to 90 Ma)
Deposition of Frontier Formation

Figure 6. A. Sequential restoration of cross section from plate 1 from the Willard thrust on the west to the Absaroka thrust on the east. Location of plate 1 is shown on figure 1. (A) Stratigraphic configuration at ~105 Ma after shortening along the Willard thrust. (B) During early Lost Creek thrusting, displacement was transferred east along the Preuss salt detachment. The Frontier Formation thins across the eastern thrusts. (C) Later Lost Creek thrusting resulted in fault propagation folding and the Lost Creek thrust cutting to surface.
D. Post-Crawford (~84 Ma)

E. Post-Absaroka (~70 Ma)

F. Post-Medicine Butte (~55 Ma)

**Figure 6.** (D) Geometry at ~84 Ma after the Crawford thrust cuts to surface. (E) Shortening on the Absaroka thrust folded the Preuss salt detachment. (F) Between ~70 and 55 Ma shortening was accommodated on the Medicine Butte thrust, Hogsback thrust, and Young Absaroka thrust. pCx—Precambrian crystalline rocks; Zs—Proterozoic sedimentary rocks (note that Neoproterozoic to Cambrian Geertsen Canyon Quartzite is included with Lower Paleozoic rocks on the hanging wall of the Willard thrust); LPz—Lower Paleozoic rocks; UPz—Upper Paleozoic rocks; TR-J—Triassic and Jurassic rocks; Jsp—Jurassic Preuss and Stump Formations; K—Cretaceous rocks; WT—Willard thrust; LCT—Lost Creek thrust; PSD—Preuss salt detachment; CT—Crawford thrust; OAT—Old Absaroka thrust; YAT—Young Absaroka thrust; MBT—Medicine Butte thrust; HT—Hogsback thrust; Al—Almy normal fault; Ac—Acocks normal fault. Long-dashed line shows estimated erosion surface.
Comparison with Other Areas and Thrust Belts

Approximately 20 km south of Lost Creek Reservoir, the Crawford thrust has been interpreted as a blind thrust that did not ramp up through the Cretaceous section to the surface (Coogan and Constenius, 2003). Instead, it formed a triangle zone with the East Canyon backthrust (figure 1). Shortening from the Crawford thrust was transferred westward along the backthrust in the Preuss salt detachment, and possibly also eastward onto the Medicine Butte thrust (DeCelles, 1994; Coogan and Constenius, 2003). This along-strike change in geometry of the Crawford thrust, along with backthrusting at the Preuss level, is also consistent with a low taper wedge, and suggests that the backthrust in the Preuss detachment may have formed before movement on the Crawford thrust. Coogan and Constenius (2003) interpreted a duplex, which formed during late movement on the Crawford thrust, with the Preuss salt detachment forming the roof thrust. Without cross-cutting relationships between the Crawford thrust and the Preuss salt detachment, we cannot determine whether the excess bed length in the Absaroka hanging wall in the vicinity of Anschutz Ranch field is due to Lost Creek, Willard, or Crawford thrusting; however, our results to the north suggest that displacement from the western thrust system was transferred east along the Preuss salt detachment, forming both the East Canyon backthrust and the structures now in the hanging wall of the Absaroka thrust, with later Crawford thrusting reactivating the East Canyon backthrust (figure 1).

North of our study area, along the southeastern Idaho-Wyoming border, Coogan and Youngke (1985) documented that the Meade thrust, which is part of the western thrust system, has a thrust flat for 30 km along the Preuss salt detachment, supporting our idea that displacement from the western thrust system was transferred many tens of kilometers along the salt detachment. South of the Uinta-Cottonwood arch, the Charleston and Nebo thrusts have a prominent thrust flat in evaporites of the Jurassic Arapian Shale. Here, displacement was transferred ~35 km to the east during the first phase of motion, between ~100 and 80 Ma (Constenius and others, 2003).

Davis and Engelder (1985) discussed examples of fold-thrust belts with salt detachments around the world which have a taper of <1°, including the Appalachian Plateau, the Franklin Mountains of northwest Canada, and the Zagros Mountains of Iran. The Jura Mountains, where Mesozoic sedimentary rocks have been folded above a detachment in Triassic evaporites, are a 70-km-wide fold belt. The Simply Folded belt of the Zagros Mountains is wider than 200 km in places. The Potwar Plateau of northern Pakistan, part of the Himalayan fold-thrust belt, has a width of 100 to 150 km and a taper of 0.8° ± 0.1° (Jaume and Lillie, 1988). Thus, regions underlain by a salt detachment have wide thrust belts, low taper angles, and salt-cored anticlines, similar to patterns along the Preuss detachment.

Old or Early Absaroka thrust

From Painter Reservoir field in the north to Anschutz Ranch East field to the south, the western imbricate of the Absaroka thrust, which we refer to as the old Absaroka thrust (Lamerson, 1982; Early Absaroka fault of Royse and others, 1975; OAT of figure 6) can be interpreted from cross sections to be the frontal thrust of the Preuss salt detachment (plate 1, figure 3). In outcrops east of Evanston, Wyoming, the Jurassic Preuss Redbeds are the oldest formation observed in the hanging wall of the OAT, forming a hanging wall flat that can be traced for over 10 km (Dover and McGonigle, 1993). Lamerson (1982) observed that between the outcrops east of Evanston and Rockport Reservoir (figure 1), wells that penetrated the Absaroka thrust east of the hanging wall cutoff of the Jurassic Nugget Sandstone encountered Preuss Redbeds in the hanging wall of the OAT. Thus, the Preuss Redbeds in the hanging wall of the OAT are carried on a thrust flat throughout much of the study area. This hanging wall thrust flat does not have a corresponding flat in the footwall of the Absaroka thrust, suggesting that it formed before the OAT and was part of the Lost Creek thrust system. However, rocks in the footwall of the OAT imply a different timing. Cretaceous rocks in the footwall of the OAT (hanging wall of the YAT) include the Frontier and Hilliard Formations (Lamerson, 1982). If, as we suggest, the OAT was a frontal imbricate of the Lost Creek thrust and was active during Frontier deposition (~102 to 90 Ma), then it would be impossible for the Hilliard Shale, which is younger than the Frontier, to be present in the footwall. We therefore propose that there were two episodes of shortening on the OAT. The first episode involved shortening on the Preuss salt detachment during the time of Frontier deposition and Lost Creek thrusting. This formed the hanging wall thrust flat with Preuss Redbeds over Frontier Formation in the footwall. Later movement during mid-Santonian time coincided with Hilliard deposition (Lamerson, 1982), with the OAT ramping up from the Cambrian, merging with the existing thrust plane at the Preuss salt detachment for several kilometers, and incorporating Hilliard Shale into the footwall (figures 6D and 6E). In the Little Muddy Creek area, overturned Paleozoic, Jurassic, and Lower Cretaceous rocks crop out in the hanging wall of the OAT. Evidence of older Lost Creek thrusting on the Preuss salt detachment is not apparent in this area. North of Little Muddy Creek, early shortening along the Preuss detachment has not been documented in the hanging wall of the Absaroka thrust. However, Coogan and Youngke (1985) recognized different styles of shortening above and below the Preuss salt detachment along parts of the Meade thrust (western thrust system) and Crawford thrust (eastern thrust system) in southeast Idaho and adjacent parts of Wyoming.

CONCLUSIONS

We have shown using seismic data and cross sections that: (1) Paleocene to early Eocene shortening on the Medicine Butte thrust was essentially offset by middle Eocene to Oligocene extension of a similar magnitude on the Almy-Acocks normal-fault system; and (2) excess shortening in the hanging wall of the Absaroka thrust is likely the easternmost deformation of the Lost Creek or Willard thrust, and is therefore related to the earliest phase of thrusting in this part of the Sevier belt. Key facts supporting this
last conclusion are: (1) the Crawford thrust is not offset along the Preuss salt detachment, indicating that shortening was transferred east before main movement of the Crawford thrust, and (2) the presence of the Lost Creek thrust at the Preuss salt level in the hanging wall of the Crawford thrust, suggesting that the Lost Creek thrust is offset across the Crawford thrust. Timing constraints from synorogenic sedimentary rocks and folded Lower Cretaceous strata indicate that this shortening was probably transferred east ~102 to 90 Ma, during deposition of the Frontier Formation. This is in contrast to previous interpretations that the Jurassic Preuss salt detachment to the east of the Crawford thrust is a footwall imbricate of the Crawford (e.g., Lamerson, 1982). Sequential restorations show that this displacement was likely transferred ~70 to 90 km east, to the location of the future hanging wall of the Absaroka thrust. The eastern extent of this deformation was controlled by the depositional limit of Preuss salt. Another possible, but we think less likely, interpretation is that this shortening is related to earliest movement on the Crawford thrust.

The old Absaroka thrust south of the Little Muddy Creek area experienced two episodes of shortening. The first episode was during Lost Creek thrusting and Frontier deposition, and resulted in the formation of the frontal imbricate of the Lost Creek thrust, placing Jurassic Preuss Redbeds over Frontier Formation beneath the Preuss salt detachment. The second episode of thrusting occurred during deposition of the Hilliard Shale and resulted in the old Absaroka thrust ramping up from the Cambrian and merging with the Preuss salt detachment and Lost Creek thrust for several kilometers.

ACKNOWLEDGMENTS

Funding was provided by Williams Production RMT Company, Chevron, and ExxonMobil. We thank Steve Natali and Mary Sue Purcell for facilitating the Williams donation, and Jerry Kendall for his efforts to provide the ExxonMobil data. Rick Bogehold and Mark Vogel at Excel Geophysical Corporation reprocessed the seismic data and allowed use of their facilities. IHS provided well data and Petra software. Divesto donated WinPICS seismic interpretation software. TGS Nopec donated digital well logs. P2 Energy Solutions donated a land grid. Velocity Data Bank provided check-shot surveys at a much-reduced rate. GeoLogic Systems LLC donated Lithotect structural analysis software and Bob Ratliff assisted with its use. We thank Jim Coogan for many useful discussions, ideas, and data throughout the project. Rick Sorenson and Rich Bottjer at Cirque Resources in Denver helped with well log interpretation. Interesting discussions with Facundo Fuentes and Gary Gray improved our interpretation. We thank Adolph Yonkee and Doug Sprinkel for their constructive reviews.

REFERENCES


Plate 1. (A) Balanced cross section and (B) restored sections across the Absaroka thrust, and (C) the Crawford and Willard thrusts. See figure 1 for location. (click for larger view)