Structural Analysis of Rock Canyon near Provo, Utah

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ABSTRACT

A detailed structural study of Rock Canyon (near Provo, Utah) provides insight into Wasatch Range tectonics and fold-thrust belt kinematics. Excellent exposures along the E-W trending canyon allow the use of digital photography in conjunction with traditional field methods for a thorough analysis of Rock Canyon's structural features. Detailed photomontages and geometric and kinematic analyses of some structural features help to pinpoint deformation mechanisms active during the canyon's tectonic history. Largescale images and these structural data are synthesized in a balanced cross section, which is used to reconstruct the structural evolution of this portion of the range. Projection of surficial features into the subsurface produces geometrical relationships that correlate well with a fault-bend fold model involving one or more subsurface imbrications. Kinematic data (e.g. slickenlines, fractures, fold axes) indicate that the maximum stress direction during formation of the fault-bend fold trended at approximately 120°.

Following initial thrusting, uplift and development of a thrust splay produced by duplexing may have caused a shift in local stresses in the forelimb of the Rock Canyon anticline leading to late-stage normal faulting during Sevier compression. These normal faults may have activated deformed zones previously caused by Sevier folding, and reactivated early-stage decollements found in the folded weak shale units and shaley limestones. Movement on most of these normal faults roughly parallels stress directions found during initial thrusting indicating that these extensional features may be coeval with thrusting. Other zones of extension and brittle failure produced by lower ramp geometry appear to have been activated during Tertiary Basin and Range extension along the Wasatch Fault Zone. Slickenline data on these later normal faults suggest a transport direction of nearly E-W distinguishing it from earlier events.

INTRODUCTION

Most geologic settings around the globe have complex stratigraphic and tectonic histories. Each past depositional and deformational event provides an inhomogeneous medium upon which subsequent tectonic stresses may be expressed. This produces many variations in stress patterns not predicted by well-controlled laboratory experiments. Field studies provide needed insight into such complex stress variations produced in an inhomogeneous medium and grant a more comprehensive view of the evolution of an area involving superimposed tectonic regimes. The Wasatch Range in central Utah provides an ideal location to examine the complex interplay between earlier-formed structures, regional stratigraphy, and later tectonic events. E-W trending canyons throughout the range provide crosssectional views of the structures produced by the Sevier Orogeny and Basin and Range extension. This study examines the significance of preexisting conditions on later tectonic events by interpreting the structural history of Rock Canyon in the Wasatch Range near Provo, Utah.

Previous structural studies have shown that stratigraphic and structural features inherited from earlier episodes of deposition and deformation have a significant influence on subsequent deformation. Many authors site preexisting geologic features as controls for the localization of structures formed during later tectonic events (e.g. Bruhn and Beck, 1981; Zoback, 1992; Engelder and Peacock, 2001; Horne and Culshaw, 2001; Johnston and Yin, 2001; Martínez Catalán et al., 2003). The most frequently reactivated features are low-strength stratigraphic units and areas of intense fracturing, both of which are common in the Wasatch Range.

The presence of low-strength, fine-grained layers and their location within a system can have a profound influence on the styles of deformation expressed in an area. Rock units, such as shale, slate, and phyllite, provide zones of weakness along which bedding-parallel faults can propagate and ductile deformation can occur. The incompetence of these units can thereby alter the fold and fault mechanics and geometries by means of flexural flow, flexural slip, interlayer shearing, and fault localization processes (Boyer, 1986; van der Pluijm and Marshak, 2003; Engelder and Peacock, 2001; Horne and Culshaw, 2001; Ormand and Hudleston, 2003). Additionally, low-strength units generate variations in local stresses within surrounding bedding layers that may sharply contrast with the regional stresses of the tectonic regime (Engelder and Peacock, 2001; Martínez Catalán et al. 2003).

Pre-existing deformation can also produce zones of weakness and sharp rheological contrasts that serve to localize stresses and release energy along structural boundaries (Marshak, 2006). Fault reactivation is a common occurrence in various tectonic environments (e.g. Armstrong, 1972; Dewey, 1988) and has been attributed to the low energy required for reactivation and the more intense stresses that are produced along preexisting fault boundaries (Dewey, 1988).

The influence of preexisting structures on later events seems especially prevalent within fold-thrust belts. Fold-thrust belts are intensely-deformed crustal provinces that often localize and superimpose several stages of deformation in the same area (Allmendinger and Jordan, 1981; Allmendinger et al.,1983; Smith and Bruhn, 1984; Schirmer, 1985; Dewey, 1988; Yonkee, 1997). Various fold geometries and the mechanics involved in thrusting produce fault and fracture zones, which then provide pathways to localize strain produced by subsequent tectonic events (Ramsay and Huber, 1987).

This study discusses the effects of such superimposed structures and fault reactivation within the Wasatch Range by examining the structural relationships in Rock Canyon near Provo, Utah (Fig. 1). A structural analysis of the exposures in the E-W trending canyon allows interpretation of the kinematic evolution in this portion of the range and its relation to regional tectonics. Of particular interest are the interactions between preexisting stratigraphic contrasts, earlier deformational features, and how they have affected Sevier fold and thrust mechanics and subsequent faulting on the Wasatch Fault Zone (WFZ). These interactions have greatly influenced fold and fault mechanics and geometries along the canyon section and have produced normal faults of unknown age on the forelimb of the Rock Canyon anticline. The kinematic model developed from this study may provide insight into mechanisms found in other Wasatch regions, and in fold-thrust belts around the globe.

GEOLOGIC SETTING

The Wasatch Range of north-central Utah records many key deformational events, which have produced the complex structural relationships exposed in the range today. The western flank of the range is bounded by the seismically-active WFZ. This fault zone marks the easternmost boundary of the Tertiary Basin and Range province overprinted on the fold-thrust belt structural features of the Cretaceous Sevier Orogeny (Armstrong, 1968; Paulsen and Marshak, 1999). The degree of influence of older structures on the nature of later tectonic events in the Wasatch region has been previously discussed (e.g. Armstrong, 1972; Zoback, 1983; Paulsen and Marshak, 1999). A Precambrian rift zone present in north-central Utah has been speculated by some as a possible explanation for the location and geometry of the Sevier fold-thrust belt as well as some Laramide uplifts (Zoback, 1983; Schirmer, 1985; Yonkee et al., 1997; Johnston and Yin, 2001). The rift margin would have created a significant change in lithology and produce accompanying normal faults within the basement rocks. These stratigraphic and structural variations may have localized horizontal compressive stresses during the Sevier Orogeny to produce basement-cored anticlines and control the geometry of the fold-thrust belt (Armstrong, 1972; Stokes, 1976; Wiltschko and Eastman, 1983; Schirmer, 1985).

Passive margin and basin sediments of variable thickness overlie Precambrian basement (Hintze and Kowallis, 2009). Of these, the Pennsylvanian-Permian Oquirrh Basin produced an incredibly thick sequence of basin sediments whose margin appears to correspond closely to the line of the WFZ (Hintze and Kowallis, 2009). Paulsen and Marshak (1999) and Bruhn et al. (1983) have correlated the shape and thicknesses of these sedimentary basins with the overall geometry of the Sevier fold-thrust belt. Paulsen and Marshak's



Figure 1. Index map of study area. (a) Regional location and context of Rock Canyon among major structures. (b) Geologic map and stratigraphic column of the Rock Canyon area. The location of the balanced cross section (Fig. 3) is shown. Map modified from Baker (1964, 1972) and Robeck (2002) and column modified from Hintze (1978, 1993) and data compilations of Lyman (2001).

(1999) study shows that the locations of the thickest sections of these Paleozoic sequences correspond directly with the points of maximum curvature (foldthrust belt pushed farthest to the east) of both the Provo and Wyoming salients. Riess (1985) and Lyman (2001) have observed a similar correlation between basin sediment thickness contrasts and thrust localization in the northern and southern segments of the Charleston-Nebo thrust sheet, respectively. In addition, Kwon and Mitra (2004) have attributed lateral variations in deformational styles to the geometry of the pre-existing basin.

Other lithologic properties of the region have had a significant influence on the styles of faulting and associated folding. Shale and shaly limestone layers have consistently been found to house the major detachment horizons of Sevier-age thrusts throughout the range (Allmendinger and Jordan, 1981; Schirmer, 1985; Schirmer, 1988; DeCelles and Mitra, 1995; Yonkee, 1997; Constenius, 1998). Major bedding-parallel detachments are most often found in the Cambrian Ophir Shale, the Maxfield Limestone, and the Mississippian Manning Canyon Shale (Allmendinger and Jordan, 1981; Schirmer, 1985; Yonkee, 1997; Constenius, 1998). These incompetent layers have also influenced the mechanisms by which the mountain belt was folded by contributing components of layer flowage and bedding-parallel slip to the system (e.g. Schirmer, 1985). Several studies have observed major variations in bedding thicknesses within the shale layers seen throughout the Wasatch mountain belt (Schirmer, 1988; Yonkee, 1997, Constenius, 1998). This thickening and thinning of the weaker units has been attributed to ductile flow between competent units and thrust slices within incompetent units causing layer repetition (Schirmer, 1985; Schirmer, 1988; Yonkee, 1997).

Normal faults of the WFZ typically form along the western backlimbs of the Sevier fold and thrust anticlines that compose the Wasatch Range (e.g. Smith and Bruhn, 1984). Normal to the fold axes of these anticlines, many canyons cut through the range exposing portions of the non-eroded fold geometry. A generalized folding mechanism may not be applicable to the entire range; however, a similar mechanism for folding would be expected in regions with comparable structural and stratigraphic properties. Riess (1985) interpreted the structures found through the Charleston thrust sheet to be the result of fault-propagation folding based on the magnitude and geometry of the anticline. Farther north in the range, Schirmer (1985) uses a fault-bend fold model to describe the structural properties and geometrical relationships exhibited in eight cross sections that cut through the Willard, Ogden, Weber, and Taylor thrust sheets. Additional studies in various sections of the Willard/Ogden thrust sheets by Yonkee et al. (1997), Royse et al. (1975), Schirmer (1988), Paulsen and Marshak (1999), and DeCelles and Mitra (1995) match the observed anticlinal and fault geometries to a fault-bend fold model with duplexing and imbrication.

The Charleston-Nebo thrust sheet has also been interpreted to correspond to a fault-bend fold model with duplex structures by Constenius (1998). DeCelles and Mitra (1995) observed further that duplexing in the Wasatch Range was directly related to areas where basement highs interacted with the basal decollement. This idea is consistent with a study by Mitra (1986), who stated that one way duplexes can form is by an increase in frictional resistance on the major thrust. The contrast in rheology at a basement high could produce the frictional resistance needed to induce propagation of new thrusts from the basal decollement.

Just as Paleozoic structures influenced Sevier orogenic deformation, so also have these had a profound affect on WFZ processes. Many seismic and structural studies have suggested that the WFZ has a listric geometry that soles into the regional Sevier-age detachments found within the incompetent strata of the belt (Allmendinger and Jordan, 1981; Smith and Bruhn, 1984; Yonkee, 1997; Constenius, 1998; Lyman 2001). However, some still view the WFZ as planar in nature and largely unaffected by Sevier deformation (Riess, 1985; Zoback, 1992).

Smith and Bruhn (1984) and Allmendinger et al. (1983) speculated on a combination of the two hypotheses by noting that some normal faults in the WFZ used preexisting structures while others appeared to propagate on their own. A regional study by Zoback (1992) dismissed Sevier influence on the WFZ, but instead attributed Wasatch fault localization to the much earlier Proterozoic normal faulting. Geologic maps, cross sections, and field observations of the range show remarkable patterns in a relationship between the position of the WFZ and the Sevier fold-thrust belt (Baker, 1964, 1972, 1973; Schirmer, 1985; Constenius, 1998). The WFZ tends to form along the backlimbs of the anticlines close to the anticlinal cores leaving behind the forelimb features of the fold-thrust belt. Schirmer (1985, 1988) and Bruhn et al. (1983) suggest that localization of the WFZ occurred by normal motion reactivation of the Sevier footwall ramps. Schirmer (1985) also observed that the curvature of the WFZ corresponds with lateral and oblique ramps produced during Sevier folding and thrusting.

A less-studied structural feature that is seen repeatedly in the Wasatch Range are east-dipping normal faults throughout the eastern part of the Sevier foldthrust belt. These normal faults are pervasive on geologic maps and cross sections, and are briefly discussed in some structural studies (Baker, 1964, 1973; Hintze, 1978; Schirmer, 1985; Schirmer, 1988; Yonkee, 1997; Yonkee et al., 1997; Constenius, 1998). Many of these faults are fairly local extensional structures that cut through the forelimbs of the Sevier anticlines often becoming obscured in incompetent layers. Several authors interpret or illustrate these normal faults to be rotated Sevier detachments that have or have not been reactivated to produce normal motion (Bruhn and Beck, 1981; Schirmer 1985; Schirmer, 1988; Yin and Kelty, 1991; Constenius, 1998). However, many of the east-dipping faults cut through multiple layers and do not remain bedding subparallel.

Typically normal faults in the Cordillera are thought to be related to the stresses brought about by the Basin and Range extensional regime (Armstrong, 1972; Wiltschko and Dorr, 1983; Zoback, 1983; Paulsen and Marshak, 1999). Most authors have not fully addressed the origin of these faults in their studies of the range despite their prevalence (Schirmer, 1985; Yonkee, 1997).

METHODS

Excellent exposures along the E-W trending Rock Canyon allow the use of digital photography in conjunction with traditional field methods for a thorough analysis of the canyon's structural features. Detailed photomontages and analysis of some structural features help to pinpoint mechanisms that were active at different times in the canyon's tectonic history. Larger-scale images and these structural data are synthesized in a balanced cross section, which was used to reconstruct the structural evolution of this portion of the range.

Digital photography

To construct a rough, but detailed cross section of the north side of Rock Canyon, digital photographs were taken along the length of the canyon at various size scales. For spatial referencing, an azimuth and location of origin was recorded for each photograph. Larger-scale photomontages were put together using Adobe Illustrator CS with separate layers for traced fractures and bedding.

Many of the larger-scale photos were taken from the ground at various elevations to provide alternate perspectives. Other photos were taken from the air to add further dimension and scale. However, the digital photographs from the airplane lack the spatial referencing data of those from the ground. The purposes of these larger-scale "photo sections" were to provide an overall view of the canyon structure and to identify the major canyon structures that would need more careful analyses.

In addition, outcrop- and small-scale photographs were taken to add detail to the overall structure of the larger section and to identify smaller-scale processes significant to interpreting the kinematic history of the canyon section. Through the use of digital photography, a detailed cross-sectional map of the exposed canyon wall and its structures was constructed. The kinematic evolution seen in this section was then correlated with the major structures projected into the balanced cross section created from field data.

The photomontages were also used to create a large-scale fracture trace map extending from the canyon mouth to the first left fork (\sim 2.4 km) for a qualitative fracture analysis to determine general fracture patterns and densities. The apparent dips of the fractures analyzed on the trace map are good approximations of their actual dips indicated by the fact that canyon fault data suggest that most of the poles to the fault planes are closely parallel to the exposed canyon wall. Therefore, carefully chosen photograph angles can produce a fairly accurate representation of actual structure orientations.

Field data collection

Kinematic and structural data were collected in the field to produce a more accurate balanced cross section and to recognize structural trends throughout the canyon. Data were collected according to accessibility; therefore the majority of the data collected came from the lower sections of the canyon, fault and shale valleys, or along the ridge toward the mouth of the canyon. The availability of measurable structures also limited much of the data to smaller subsidiary structures and their conjugates. The types of data collected include bedding plane orientations, fault plane orientations, slickenlines, en echelon fracture sets, joint sets, cleavage orientations, and vein orientations. Particular attention was paid to the structures in close proximity to the major structures in the canyon. These data were correlated directly to the photo sections produced through digital photography, and then used to construct the balanced cross section and smaller sections. Various sets of data were plotted on lower hemisphere stereographic projections using FaultKinWin 1.2.2 and StereoWin 1.2 (Allmendinger, 2001).

Balanced cross section construction

Lower hemisphere stereographic projections of bedding and faults (Fig. 2) sampled along the entire length of the canyon indicate that most Sevier and Basin and Range structures combined strike roughly normal to a direction of 276°. This trendline differs from those WSW-ENE lines used in studies of the northern parts of the Sevier folded belt (Schirmer, 1985; Schirmer, 1988; Evans and Neves, 1992; DeCelles and Mitra, 1995), but is consistent with data collected south of the Uinta-Cottonwood arch. Average transport directions within the Provo salient trend along a WNW-ESE direction with angles off of E-W more pronounced to the south (Riess, 1985; Constenius, 1998; Lyman, 2001).

The line for the balanced cross section was chosen based on this overall average between Sevier and Basin and Range transport directions (Fig. 1). The line was positioned to include major structural features and to provide the most accuracy in projected faults and bedding.

Major structures were then projected onto the topographic profile to provide controls on the structural features of the canyon. Faults inferred to be associated with Wasatch Fault deformation were then undeformed to determine the pre-Basin and Range fold geometry of the Rock Canyon anticline. This fold geometry was then compared to several fault-bend and fault propagation fold models of Suppe (1983, 1985) to find the best-fit model. The section was then balanced using techniques outlined in Woodward et al. (1989).

RESULTS AND DISCUSSION

Sections produced from compilations of digital images and field data reveal major canyon structures key in the development of our structural evolution model. A portion of the balanced cross section along the length



Figure 2. Equal area lower hemisphere stereo-plots of: (a) poles to bedding with fold axial plane, and (b) poles to faults with overall orientation both sampled along can yon section

of Rock Canyon is shown with domain data in Fig. 3. More detail along this length is shown in Fig. 4, which is an unbalanced section put together by digital images of the exposed canyon wall. Several features seen in these sections require further discussion to support our interpretation of the structural evolution in this portion of the Wasatch Range. The following features will be addressed in this section: 1) Sevier versus Basin and Range deformation, 2) synorogenic and foreland extension, and 3) fold model and thrust geometry.

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Figure 3. Canyon-scale balanced cross section showing major structures from data taken along the exposed canyon wall. Fold dip domains are shown with their respective fault and bedding data. Data are plotted as poles to planes on equal area lower hemisphere stereographs. Fault plots show fault slip directions and P and T dihedra solutions determined by slickenline data.

Sevier vs. Basin and Range Deformation

Distinguishing between Basin and Range brittle structures and Sevier deformation is rather difficult due to the fact that they overprint one another and kinematic indicators are often missing, obscured, or inaccessible. However, by creating a photomosaic of the canyon fractures, and comparing deformation extents from other normal fault studies, we have the needed context to interpret the fault data.

Fracture analysis

The fracture trace map produced from digital images along the canyon length (Fig. 5) shows the following distinct patterns:

1) Fracture density is high at the mouth of the canyon and near dip domain boundaries of the Sevier anticline,

- 2) Approximately 400 m up the canyon from the mouth there is a fairly large section of rock with a much lower fracture density, and
- 3) This same distance up the canyon (400 m) marks a boundary between two slightly different styles of deformation seen along the canyon wall.

To the west of this region, the major faults are primarily west-dipping normal faults mostly at low angles $(40^{\circ}-60^{\circ} \text{ apparent dip})$. There are few vertical-subvertical fractures and only a minor component of very low angle fractures (<40° apparent dip). These very low angle fractures are bedding-parallel faults found just at the mouth of the canyon. However, to the east of the boundary, there is a large increase in the number of verticalsubvertical joints as well as high-angle (>60° ap-

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Figure 4. Detailed cross-sectional map of exposed north canyon wall structures (top) created from several different scales of photomontages. Section extends from the canyon mouth to the First Left Fork. Unit descriptions are shown in Fig. 1. Aerial photo (bottom) of the canyon is given for general reference. (a), (b), and (c) marked sections are shown in more detail in Figs. 10, 11, and 12 respectively.

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Figure 5. Fracture trace map (top) derived from the geologic cross-sectional map of the north wall of Rock Canyon (Fig. 4). Fractures grouped into four apparent angle ranges are color-coded to indicate changes in fracture patterns throughout the canyon. The 400 meter boundary is also shown for reference. Geologic units (bottom) in the canyon range from the Precambrian Mineral Fork Tillite (pCmf) to the Mississippian Humbug Formation (Mh) at the top of Squaw Peak.

parent dip) east- and west-dipping normal faults. This region also has several very low angle faults, some of which are beddingparallel but others which appear to have formed across bedding to accommodate rotation of the hanging wall.

Farther east on the crest of the anticline, verticalsubvertical fractures are still pervasive, however, many of the major faults in this section are at lower angles (<40° apparent dip) and tend to cross-cut bedding at higher elevations and become bedding-parallel toward the canyon floor. This style of deformation is seen along the rest of the canyon wall although it becomes much less concentrated eastward up the canyon.

We interpret these two differing deformational styles to be related to the two different tectonic regimes that helped form the range. The fracture deformation east of the 400 m boundary is mostly related to late Sevier tectonic processes and the structures to the west mostly correspond with Basin and Range normal faulting.

Normal fault footwall deformation

To help determine the age of the deformation seen in the WFZ footwall, we review previous research that discusses the type and extent of deformation seen in the footwalls of similar normal faults. Observations made in the fracture analysis are fairly consistent with literature on normal fault footwall deformation (Evans and Neves, 1992).

Most studies on normal fault deformation discuss mainly the structures found in the hanging wall and the footwall is often largely disregarded (e.g. Imber et al., 2003). However, regardless of the major focus of the study, deformation patterns on normal faults are difficult to fit into a definitive model (Shipton and Cowie, 2003; Berg and Skar, 2005). This is due to the large number of factors that can influence the width of the damage zone on either side of the fault. Major influencing factors include: rheology of lithologic units, stress system, number of slip events, types of subsidiary structures, and preexisting deformational features (Caine et al., 1996; Knott et al., 1996; Kim et al., 2004).

Several authors have attempted to resolve these issues by showing that there is a direct proportionality between fault throw and damage zone widths (Mc-Grath and Davison, 1995; Knott et al., 1996; Shipton and Cowie, 2001, 2003; Kim et al., 2004). Shipton and Cowie (2001, 2003) determined that the average width of a fault damage zone is approximately 2.6 times the throw in high-porosity sandstone. This correlation does seem to apply generally to small (4-5 km in length) normal faults in sandstones of low clay content and was observed by Shipton and Cowie (2001, 2003) on the Blueberry and Big Hole faults in central Utah. Antonellini and Aydin (1995) showed a similar relationship by measuring deformation band zone widths in rocks of various lithologies.

In their study, individual sandstone units with low clay content (<5%) had widths closely matching Shipton and Cowie's (2001, 2003) approximation whereas sandstones with high clay content (>5%) had considerably smaller deformation zones. Although these results appear to correlate with Shipton and Cowie's (2001, 2003) conclusion, there are numerous examples of faults in rocks of similar lithology to which this relationship does not apply (e.g. the Moab fault in Utah and the Ninety Fathom fault in NE England; Berg and Skar, 2005; Harris et al., 2003, respectively).

One explanation for such variants was offered by Shipton and Cowie (2003) who indicated that faults of larger size and faults that had undergone multiple episodes of deformation did not fit into their model. These ideas support the fact that preexisting structural and lithological weaknesses in rocks can have a large impact on controlling the extent of the damage zone by diminishing its size. Evans et al. (2000) and Schlische et al. (1996) also support this by documenting very narrow damage zones around faults in mudstones and jointed granites. This hypothesis might also explain the lack of deformation observed below basal detachments of fault systems (Wernicke, 1981; Xiao et al., 1991; Constenius, 1998) if such detachments follow incompetent units as is typically suggested. Therefore, the influence of fault throw appears to become inconsequential relative to activation along preexisting weaknesses especially once the fault extends over several tens of meters in length.

Opposing ideas have been suggested by McGrath and Davison (1995) who observed greater damage on large faults, and by Caine et al. (1996) who related wide damage zones to faults that had experienced multiple slip events. These contradictory observations and the great variability in other measured damage zones and their symmetry (e.g. Harris et al., 2003; Imber et al., 2003; Kim et al., 2004; Berg and Skar, 2005) lead us to believe that there is a more dominant factor involved in damage zone development.

Knott et al. (1996) presented a fault damage zone model based in part on work done by Muraoka and Kamata (1983), Barnett et al. (1987), and their own outcrop data on faults in north Britain and west Sinai. This model (Fig. 6) shows that hanging wall and footwall damage zone widths on the same fault can vary along its length dependent on the position at which the measurement is made. Knott et al. (1996) state that the



Figure 6. Knott et. al (1996) model depicting damage zone geometry based on outcrop data, and work done by Muraoka and Kamata (1983) and Barnett et. al (1987). The damage zone is widest in the extensional field and narrowest in the contractional field

widest point of a footwall damage zone is found at the lower tip of the fault and that the widest point of the hanging wall damage zone is found at the upper tip of the fault. This model appears to be viable because it describes expected extensional and contractional zones around the fault and fault tip deformation related to fault motion. The model also accounts for the opposing results as well as the trends outlined in the studies above.

Application of the previously discussed damage zone relationships and the Knott et al. (1996) model with consideration of the other observed trends can help to provide an upper bound to the extent of the footwall damage zone in Rock Canyon.

Throughout the following discussion we focus only on the pre-Mesozoic stratigraphic units as data on younger units in the area is lacking. In addition, we assume that the WFZ acts as one large fault (here termed the Wasatch Fault or WF) whose distance from the current eroded mountain front ranges from 0.6 m at the base of the Tintic to 980 m at the top of the unit (estimated from the average earthquake recurrence interval on the Provo segment: McCalpin and Nishenko, 1996; the estimated erosion rate of 0.1cm/yr: Anders and Schlische, 1994; and 1 m displacement/>7.0 magnitude event).

Additional information used in this discussion comes from various authors. This information includes: 1) Stratigraphic unit thicknesses of non-eroded rock units exposed in Rock Canyon (Hintze, 1978) and thicknesses of the now-eroded rock units assumed present at the initiation of Wasatch normal faulting (Hintze and Kowallis, 2009), 2) Depth to the regional detachment (Zoback, 1983; Smith and Bruhn,1984), 3) Dip angle of the Wasatch Fault (Zoback, 1992), and 4) Total displacement on the WFZ (Smith and Bruhn, 1984). All other information is calculated from these data, has been gathered by the authors, or is referenced in the text.

First of all, applying the Shipton and Cowie (2001, 2003) equation to the entire throw of the WFZ in the Provo area yields an unrealistically large damage zone width. Throw calculated from unit thicknesses and fault depth is approximately 15 km and according to Shipton and Cowie's (2001, 2003) equation the WF damage zone would have a total width of about 40 km. However, if we use ideas similar to those applied by Antonellini and Aydin (1995) and measure the throw exclusively on the particular stratigraphic unit of inter-

est, we can apply Shipton and Cowie's (2001, 2003) equation to sandstone units with low clay content. Although slightly metamorphosed, the Tintic Quartzite fits these criteria reasonably well (Lyman, 2001). If we assume that the width-throw relationship is maintained for the length of fault required to completely displace the Tintic from itself, we can calculate the damage zone width by using the individual unit thickness and the angle of the WF. This calculation yields a total damage zone width of approximately 856 m and a half-width of 428 m maximum in the footwall. Remarkably, this figure is very close to our observed width of the damage zone from the fracture analysis.

This half-width damage zone approximation is valid if the Tintic Quartzite lies near the center of the fault dip length or closer to the upper tip of the Wasatch Fault. To determine the approximate location of the Tintic relative to the entire fault length, we apply the Knott et al. (1996) model of deformation distribution. By the relationship: $sin(55^\circ) = 15 \text{ km/x}$ where 55° is the fault dip and 15 km is the throw, we find the total dip length of the fault is 18.31 km. Then we use the same relationship to find the intersection between the fault and the bottom of the Tintic. This yields a distance of 9.77 km from the bottom of the fault (calculations shown in detail in Wald, 2007, Appendix A). This distance is approximately halfway up the fault from its deepest reach. According to the Knott et al. (1996) model, this section of rock would produce a footwall damage zone width midway between the maximum and the minimum widths. Therefore, our half-width approximation of 428 m is viable as an upper bound to the footwall damage zone width within the Tintic Quartzite unit.

Additional support for a narrow damage zone is found in the preexisting geology. Preexisting lithological and structural weaknesses also decrease the width of the damage zone. The Tintic Quartzite lies between two incompetent units, the Precambrian Mineral Fork Tillite and the Cambrian Ophir Shale (see Fig. 5). Location of these units on either side of the Tintic would, over time, reduce the shear strength of the fault by producing shale smear along the fault surface. In such a setting, the maximum width of the damage zone would be produced during the first few displacements along the fault (Knott et al., 1996). This supports the ideas of Antonellini and Aydin (1995) and our damage zone width calculated from displacement of the Tintic from itself, as such offset would yield the widest zone of deformation. In addition, preexisting structures could also have a profound effect on the width of the damage zone in the Tintic Quartzite. The Wasatch Fault appears to cut through the major dip domain boundaries in the backlimb of the Rock Canyon anticline. These boundaries would be areas of high deformation developed during Sevier folding producing localized fractures that would lend themselves well to facilitating normal faulting along the Wasatch Range (Paulsen and Marshak, 1999). Usage of the preexisting fractures by the Wasatch Fault would also decrease the width of the damage zone (Evans et al., 2000; Shipton and Cowie, 2003).

Other Wasatch fault studies are consistent with our interpretation of the damage zone width at Rock Canyon. Gravity, magnetic, and seismic surveys conducted by Benson and Mustoe (1995) near Hobble Creek Canyon (east of Springville, Utah) reveal a greater proportion of synthetic faults to antithetic faults (4:1) in the footwall relative to faults seen in the hanging wall. Another characteristic of these synthetic footwall faults is that they are subparallel to the major fault trace. Trench logs from other sites on the WFZ north and south of the Provo area (near Salt Lake City and Nephi) show similar trends in the footwall deformation (Schwartz and Coppersmith, 1984) with the majority of footwall faults being subparallel and synthetic. In Rock Canyon, faults that match these criteria are concentrated within the first 400 m along the canyon wall past which fault style changes indicating a significant change in associated deformation.

In summary, our estimates of the damage zone width in the footwall of the Wasatch Fault correlate well with observations made in other studies. Damage zone width calculations match closely to the 400-m width estimated earlier, and typical damage zone fault styles correspond with deformation within the first 400 m of the canyon. Other factors, such as preexisting weaknesses, position of the rock unit along the fault length, and surrounding shale units producing smear to reduce the shear stress also support development of a narrow damage zone within the Tintic Quartzite at this locale.

Kinematic data

In order to test our interpretation of Basin and Range versus Sevier deformation, fault data from east and west of the 400 m boundary were analyzed separately to observe any variations in transport directions.

Fig. 7a shows slickenline data from normal faults

within 400 m of the canyon mouth. The average transport direction for this section is approximately eastwest corresponding with the regional transport for Recent extension determined by Zoback (1983) and current GPS surveys along the Wasatch front (Harris et al., 2000; Chang et al., 2006). Slickenline data for normal faults east of 400 meters are plotted in Fig. 7b.

Transport direction for these data trends approximately 120°, having a much more SE-NW component. This directional component corresponds more closely to that observed for the pole of the fold axial surface of the Rock Canyon anticline (100°; Fig. 2) than to the WFZ transport.

These variations in kinematic data from each of these sections up the canyon support the idea that each group of faults developed during a different tectonic regime. These data are also consistent with our inferences of damage zone width from the fracture analysis and estimates made from the literature.

Synorogenic and foreland extensional faults

By limiting the width of the Wasatch Fault deformation in Rock Canyon to within 400 m east of the major fault trace we are left with the challenge of explaining the existence of perplexing east-dipping normal faults seen on the forelimb of the Rock Canyon anticline. Slickenline data (Fig. 7b) indicates that movement along these normal faults occurred under a similar farfield stress regime as the Sevier thrust faults. However, the development of pervasive extensional structures in the foreland of a horizontal compressional setting is not generally recognized (Armstrong, 1972; Wiltschko and Dorr, 1983).

A review of the literature leads us to agree with Constenius (1998) who pointed out that many studies conclude or assume that all normal faults occur subsequent to thrusting and many dismiss their importance to fold-thrust belt mechanics in an actively contractile setting (e.g. Armstrong and Oriel, 1965; Wiltschko and Dorr, 1983; Riess, 1985; Schirmer, 1985, 1988; Fossen, 1992; DeCelles and Mitra, 1995; Fossen, 2000).

On the other hand, there have been a growing number of researchers who concede the possibility of extension concurrent with thrusting in a compressional regime.

Early observations

Some of the earliest observations of normal faults in contractional settings were made in connection with

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Figure 7. Fault orientations and slickenline data for normal faults sampled along the canyon wall. (a) shows normal fault data west of 400 meters up the canyon and (b) shows those east of 400 meters. Collected data includes several conjugate faults due to the sparsity of accessible faults particularly east of the 400 meter boundary. The numbers on the plots correspond to the P- and T-axes as calculated by FaultKinWin 1.2.2 (Allmendinger, 2001).

uplift along reverse faults in the Owl Creek Mountains of central Wyoming. Jones (1939) and Wise (1963) concluded that movement of these normal faults located on the outer arc of the tight fold occurred during uplift of the range, which created extension driven by the weight of the uplifted mass. Structural relationships similar to those found in the Owl Creek Mountains have recently been observed by Haddox et al. (2005) in the south flank of the Uinta arch and seem to have developed under comparable conditions.

Other Laramide structures found in the Wind River Basin and Teapot Dome in central Wyoming show normal faults in close proximity to thrust fault tips in interpreted seismic sections (Gries and Dyer, 1985; Mc-Bride et al., 2005).

Friedman et al. (1976) tested these relationships by producing drape folds over reverse faults in the laboratory and found that stress orientations could change drastically between fold domains causing shortening in some and extension in others. They also determined that the zone of normal faults was located at the point of maximum curvature in the fold. Similarly, many of the east-dipping normal faults observed in Rock Canyon propagate from the point of maximum curvature of the anticline toward the foreland (Fig. 4).

Synorogenic hinterland extension

More recently, research on synorogenic extension has focused on normal faulting within the hinterland of fold-thrust belts or collisional orogens (e.g. Burchfiel and Royden, 1985, Martínez Catalán et al., 2003; Harris 2006). Armstrong (1972) refuted several studies that had speculated on pre-Tertiary normal faulting in the Cordilleran hinterland stating that evidence for extension concurrent with shortening was lacking.

This was the general consensus until several years later when research and technology brought to light new information. Studies of the Tibetan Plateau have revealed northward spreading against north to south thrusting of the Asian plate over the Indian Plate (Burg et al., 1984; Burchfiel and Royden, 1985; Herren, 1987; Hodges et al., 1996). Several authors cite basal detachment of the Himalayan orogenic wedge, which causes it to become unstable and collapse under the vertical stresses produced by its weight (Burchfiel and Royden, 1985; Herren, 1987; Fossen, 1992; Hodges et

al., 1996).

This model is consistent with work on the extensional collapse of orogens presented by Dewey (1988) who states that orogenic collapse during and after convergence is determined by the boundary forces and elevation of the wedge. Since these early reports of the Himalayas have recognized coeval extension within an active convergent setting, more research in orogenic belts has produced similar interpretations for extensional structures found in other convergent hinterlands. These studies have focused on areas such as the Variscan belt in NW Spain (Aranguren and Tubía, 1992; Martínez Catalán et al., 2003), the Alps (Dewey, 1988), the Alboran Sea in southern Spain (Platt and Vissers, 1989), the Carpathians (Dewey, 1988) the Banda Sea (Harris, 2006), and the North American Cordillera (e.g. Coney and Harms, 1984; Yin and Kelty, 1991; Hodges and Walker, 1992).

Because many of these compressional and extensional processes can be observed currently, there is little dispute over whether or not extension of this nature can occur during horizontal compression of the orogen. Thus, most researchers focus on the mechanisms responsible for this phenomenon and its characteristics. As these mechanisms may also be active in a foreland fold-thrust belt, we identify processes and conditions in the convergent hinterland and compare them to those seen in the Wasatch Range.

Mechanisms of synorogenic extension

Basal detachment of the orogenic wedge is often cited as the major cause of extension in the hinterland concurrent with a compressional regime. Several authors attribute this basal detachment and the resulting instability of the wedge to the emplacement of plutons (Allmendinger and Jordan, 1981; Coney and Harms, 1984; Aranguren and Tubía, 1992; Hodges and Walker, 1992) whereas others see such extension simply as a response to overriding vertical stresses produced by thickening of the wedge during and/or after shortening (Burg et al., 1984; Burchfiel and Royden, 1985; Dewey, 1988; Fossen, 1992; Hodges et al., 1996; Constenius, 1998; Fossen, 2000; Martínez Catalán et al., 2003).

Platt's (1986) dynamic wedge theory agrees with the latter group of authors by demonstrating that extension can occur as a natural (and probably cyclical) response to wedge thickening. Therefore, it appears that although pluton emplacement can encourage extension of the orogenic wedge, it is not a necessary component to extensional collapse.

Other mechanisms that have been suggested to induce decoupling of the orogenic wedge include: 1) Underplating of the crust (Burchfiel and Royden, 1985; Martínez Catalán et al., 2003), 2) Convective erosion (Dewey, 1988), and 3) Changes in wedge taper (Davis et. al, 1983).

However, hinterland studies have found that more localized extensional stresses can be induced by any or a combination of any of the following factors: 1) Decoupling along weak zones produced by fractures or a change in rheology of the deformed rock units (Dewey, 1988; Hodges and Walker, 1992; Martínez Catalán et al., 2003), 2) Internal adjustments to the wedge (Platt and Vissers, 1989; Fossen, 1992), 3) Tectonic or isostatic uplift (Cross and Pilger, 1982), and 4) Subduction zone rollback (Coney, 1987; Fossen, 2000). These factors could all have had an equally large impact on stresses within the hinterland as they could on those within the foreland fold-thrust belt during the Sevier Orogeny.

Other processes that have shown to produce localized tensional stresses are 1) Flexural flow folding with bounding surfaces subject to a shear traction (Engelder and Peacock, 2001), and 2) Neutral surface folding (Ramsay and Huber, 1987).

The Wasatch Range is replete with examples that such fold mechanisms were present during development of the wedge.

Sevier fold and thrust belt extension

Although several of these studies have discussed extension produced during active convergence in the Cordilleran hinterland, research on extension within the Sevier fold and thrust belt foreland is lacking, especially that found in the forelimbs of the Sevier anticlines. Constenius' (1996, 1998) is one of the few who proposes a pre-Basin and Range extensional event (Paleogene in age) during which the fold-thrust hinterland and foreland developed collapse features. However, his research of the foreland focuses on the west-dipping normal faults that sole into thrusts formed during the Sevier, and he does not address the east-dipping normal faults farther inland.

Other structural studies of the Wasatch region have acknowledged the existence of major and minor eastdipping normal faults in the foreland, but have failed to directly address the timing and/or nature of their development (Zoback, 1983; Schirmer, 1985, 1988; Yonkee, 1997).

Schirmer (1985, 1988) attempts an explanation of some of the normal movement to the east by citing bedding-parallel faults as thrusts rotated by subsequent folding. This process has also been interpreted as a mechanism for structures found in the Alberta foothills by Jones (1971) and in the Lewis allochthon in Montana by Yin and Kelty (1991). Mitra (1986) also recognizes this phenomenon and attributes rotation of upper sheet structures to movement along structurally lower thrusts. Yin and Kelty (1991) provide the best discussion on east-dipping normal faults and state that such extension is due to a combination of shear traction on the basal thrust to produce a low-angle detachment which then produced higher angle normal faults by movement on the two major faults.

They also propose that the Coulomb wedge model discussed by Dahlen (1984) could be used to adequately describe the fault interactions and relate them to regional and local stresses.

Strain analyses conducted by Mukul and Mitra (1998), Kwon and Mitra (2004), and Bruhn and Beck (1981) also provide evidence for pre-Basin and Range extension within the North American Cordillera. Mukul and Mitra (1998) studied finite strain accumulations within the Sheeprock thrust sheet (southwest of study area) by analyzing quartzites throughout the sheet. Their results demonstrated a significant component of stretching in the forelimb of the sheet in the direction of transport.

Bruhn and Beck (1981) found two extensional axes in their strain analysis of two domains within the Ogden thrust sheet to the north of our study area. By collecting fault slip data in these areas they discovered two subhorizontal extensional axes near the synclinal hinge (also the anticlinal forelimb) that trended 095° and 005°.

Kwon and Mitra (2004) produced a three-dimensional finite element model of the Provo salient foldthrust wedge. Modeling of the wedge produced maximum compressive stresses that plunged toward the foreland. This component of dip toward the foreland of the wedge was interpreted to be the result of gravity boundary conditions.

The studies discussed above cite examples of extensional structures and features observed in contractional settings and give credence to our interpretation for Sevier-age forelimb extension in Rock Canyon. Many also provide mechanisms for such opposing regional and local stress regimes. These mechanisms include: gravitational instabilities due to uplift, basal decoupling of the orogenic wedge, flexural flow folding, neutral surface folding, and underplating.

Rock Canyon forelimb extension

Based on the evidences and mechanisms discussed above, the E-dipping normal faults observed in Rock Canyon appear to have formed during late-stage Sevier folding in the foreland fold-and-thrust belt. Those who speculate that E-dipping normal faults in the Wasatch Range are associated with Basin and Range extension often imply that they are a conjugate set to the WFZ. However, there are several indications that such is not the case. First of all, conjugate faults are found approximately 60° off of the main fault, whereas the majority of Rock Canyon's E-dipping normal faults are around 90° to the WFZ. Second, the spatial distribution of Rock Canyon's E-dipping normal faults are spread out in the anticlinal forelimb with each normal fault propagating from the tightest point in the fold (Fig. 5).

Additionally, there is currently no evidence to suggest that the normal faults cut down the stratigraphic section out of the shaly units into which the sole. Future research should focus on determining the subsurface position and structure of these normal faults.

Other observations indicate that the formation of these E-dipping normal faults occurred during active folding. The fanning fracture pattern in the forelimb of the fold adjacent to the core suggests that some of the faults were formed prior to complete rotation of the units in which they are found (Fig. 4; Wibberley, 1997; Yonkee et al., 1997). Furthermore, there is evidence of flexural slip, which caused at least some movement of beds toward the east in Rock Canyon and other areas throughout the Wasatch Range. A westward-verging fold can be seen on the south side of Rock Canyon demonstrating active folding while the overlying and underlying beds experienced opposite senses of shear.

This phenomenon is also very apparent in the westwardverging Bridal Veil Falls Fold in Provo Canyon just to the north of Rock Canyon. The E-dipping normal faults in the Wasatch Range could have originated at points where such flexural slip initially produced eastward movement between layers (Bruhn and Beck, 1981).

Our damage zone width estimates from the literature and kinematic data provide some of the most convincing data that supports our hypothesis for Sevi-

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er-aged forelimb extension. As has been discussed at great length in this text, the balance of the evidence suggests that the WFZ damage zone does not exceed the 400 meter boundary up the canyon. Kinematic data on faults to the east of this boundary, including the Edipping normal faults in question, indicate a transport direction that corresponds more closely to the transport direction for Sevier folding than the direction of movement on the WFZ.

Fold model and thrust geometry

Major structural features seen in both the largescale photo sections and the balanced cross section correlate well with the modeled geometry of a faultbend fold with a duplex (Suppe, 1983) (Fig. 8). The balanced cross section was undeformed to its pre-Basin and Range state with other major late Sevier-age offsets also removed to better interpret the geometry of the fold prior to brittle deformation. This fold geometry was tested against a fault-propagation fold model (Suppe, 1985) and several fault-bend fold models with vertical forelimbs (Suppe, 1983).

When fitting restored Rock Canyon geometries to the fault-propagation fold model, there are additional dip domain angles in Rock Canyon making it a more gradual fold than would likely be produced by a faultpropagation fold. The model that best matches the observed Rock Canyon fold geometry has seven inflection lines in the fold and one or more duplex structures. The average bedding dips of each dip domain in Rock Canyon match closely with those seen in the model. Creating the most controversy is undoubtedly the overturned forelimb.

Overturned forelimbs are commonly associated with fault-propagation folds (Suppe, 1985; van der Pluijm and Marshak, 1997) and may be the basis for such interpretations in other areas in the Wasatch region (Reiss, 1985; Mukul and Mitra, 1998). However, overturned forelimbs can be and have been associated with fault-bend folds and are related to 1) Fault propagation/fault-bend fold hybridization, 2) Thrust duplexing, and 3) Out-of-sequence thrusting. These processes are discussed in more detail below.

Fold hybridization

Mitra (1986) defined a hybrid duplex as a fault propagation fold that was subsequently carried up and over a fault-bend fold ramp. This combination of processes produces very complex structures and high



Figure 8. Fault-bend fold model with one imbrication after Suppe (1983). This model fits best the observed Rock Canyon geometry.

structural relief and also provides a mechanism for an overturned limb characteristic of a fault-propagation anticline but with the underlying geometry of a faultbend fold. Mitra (1986) gives several examples of hybrid duplexes in the Appalachian Valley and Ridge province that show overturned forelimbs truncated against the upper footwall flat. These hybrid duplexes also depict the major fault propagation thrust running along the footwall ramp and extending up into the fold. We contend, however, that these same relationships can be contrived by means of a combination of the following two processes.

Thrust duplexing

Suppe (1983) demonstrates in his work on faultbend fold geometry that steep or overturned limbs in such fold models are geometrically feasible. However, steep and overturned limbs would not fit a simple faultbend fold model but instead are most often associated with the development of at least one duplex structure. This is because emplacement of these duplex structures will increase the forward and back dip angles of the overlying anticline (Suppe, 1983).

Several other authors have observed that folding and brittle deformation in the upper thrust sheet is a response to emplacement of underlying horses (Jones, 1971; Schirmer, 1985; Boyer, 1986; DeCelles and Mitra, 1995; Wibberley, 1997; Yonkee et al., 1997).

Some examples of such folds are seen in Suppe's (1980,1983) interpretation of the subsurface structure of the Nanliao anticline in southern Taiwan and Constenius' (1998) interpretation of the Oil Hollow anti-

cline in the eastern Sevier foreland.

The various types of deformation produced in the upper horse of a thrust duplex all involve similar and related mechanisms. Major deformational features include: steepened limb angles (e.g. Suppe, 1983; Mitra, 1986), fanning fracture sets related to rotation (Wibberley, 1997; Yonkee, et al., 1997), out-of-sequence thrusts (Mitra, 1986; Yin and Kelty, 1991), and uplift (Schirmer, 1985; DeCelles and Mitra, 1995; Yonkee, 1997). All of these types of deformation are used to accommodate internal shortening of the thrust belt (Morley, 1988; DeCelles and Mitra, 1995), and have been directly correlated with a sticking point or buttress in the front of the propagating thrust (Schirmer, 1985; Mi-tra, 1986; Morley, 1988).

Thrust duplexing is a common occurrence in foldthrust belts (Evans and Neves, 1992) and has been especially well documented in the Wasatch Range. Duplexes have been observed and used to interpret several areas in the Sevier fold-thrust belt throughout the Willard-Ogden thrust system (Bruhn and Beck, 1981; Schirmer, 1985, 1988; DeCelles and Mitra, 1995; Yonkee, 1997; Yonkee et al., 1997; Paulsen and Marshak, 1999;) and the Charleston-Nebo thrust system (Constenius, 1996, 1998).

Out-of-sequence thrusting

According to Morley (1988), out-of-sequence thrusts occur in fold-thrust belts much more commonly than many may believe. Such thrusts occur to maintain critical taper of the orogenic wedge and to accommodate stresses transferred as a result of buttressing or a change in lithology in the front of the wedge (Morley, 1988). Out-ofsequence thrusts will most often reactivate thrust ramps of earlier-formed in-sequence faults and then cut upward to accommodate internal shortening (Morley, 1988). Movement along such a thrust would accentuate uplift of the wedge and transfer slip of the upper sheet towards the foreland (Morley, 1988).

DeCelles and Mitra's (1995) study throughout the Sevier orogenic belt led them to conclude that out-ofsequence thrusting was part of the cyclical pattern involved in thrusting for the region. In addition, several cross sections through the Willard-Ogden thrust system by Schirmer (1985) and others through the Charleston-Nebo thrust sheets by Reiss (1985) and Constenius (1998) show thrust splays located near thrust ramps on the lower duplexes also indicating that out-ofsequence thrusting could be a common process within the Wasatch Range.

By examining major structural features along the canyon sections and reviewing related research, we can make a better estimation of the structural evolution in this section of the Wasatch Range.

STRUCTURAL EVOLUTION

Based on the previous discussion, canyon data, and observations on digital photomontages, we interpret the structural evolution of Rock Canyon to have occurred with the following general sequence of events:

- 1) Initial folding and thrusting along the upper thrust,
- 2) Development of the lower thrust to form a duplex,
- 3) Buttressing of the thrust sheets,
- 4) Deformation in the upper sheet with final emplacement of the lower horse,
- 5) Propagation of an out-of-sequence thrust along the upper sheet footwall ramp,
- 6) Normal faulting, shale flowage, and overturning in the anticlinal forelimb,
- 7) Normal faulting of the Wasatch fault.

These events are depicted in Figs. 9a-f and outlined in detail below.

Initial folding and thrusting along the upper thrust

Thrusting in the Wasatch region began in the Mid-Cretaceous (120-70 Ma) (Heller et al., 1986). Thrust movement toward the east in the Rock Canyon area is inferred to have occurred along several decollements within the stratigraphic sequence. This is consistent with ideas proposed by Jones (1971) and Armstrong (1968), and interpretations throughout the Willard-Ogden thrust system by Schirmer (1985,1988).

These decollements were localized in the upper section of the Precambrian Big Cottonwood Formation, the Cambrian Ophir Shale and the Mississippian Manning Canyon shale. Several others have observed detachments along these incompetent units in this region (e.g. Allmendinger and Jordan, 1981; Bruhn and Beck, 1981; Yonkee, 1997). Although movement likely occurred along each of these planes, the major thrust propagated through the Precambrian Big Cottonwood Formation and ramped upward through the Cambrian Tintic Quartzite. Movement along this main thrust caused folding of the overlying sediments as well as









Figure 9. Structural evolution of Rock Canyon depicting the major steps in the interpreted sequence of events (Cambrian Ophir Shale highlighted in gray): (a) is the restored section. (b) shows initial folding and thrusting of the upper sheet with development of the lower thrust and buttressing of the thrust sheets. (c) demonstrates emplacement of the thrust sheets. (d) shows transfer of movement to the upper sheet with the formation of an out-of-sequence thrust above the lower horse. (e) exhibits normal faulting and shale flowage from the top of the anticline toward the overturned forelimb. (f) shows normal faulting along the Wasatch Fault at approximately 1.2 Ma.



the decollements within the shale units.

Folding also produced zones of higher-density fractures between fold dip domains along inflection lines. These fractures have little to no displacement and served to accommodate the strain produced at points of tighter bending. This relationship between fold structure and strain distribution has been observed by Ramsay and Huber (1987).

Development of the lower thrust to form a duplex

Duplexes typically form in regions where slip along the active detachment is impeded by frictional resistance, usually due to a change in lithology or an old fault block (Schirmer, 1985; Mitra, 1986; Morley, 1988). This obstruction causes stresses to transfer forward for propagation of a lower thrust (Jones, 1971; Morley, 1988). In the Provo region this initial buttressing could have occurred along the Precambrian rift margin and/or Paleozoic basin margins, which have often been interpreted to control the shape of the Provo Salient (e.g. Zoback, 1983; Reiss, 1985; Yonkee et al., 1997; Paulsen and Marshak, 1999).

There is very convincing evidence that large changes in the thicknesses of Paleozoic basin sediments, especially those of the Oquirrh basin, could have also caused or contributed to buttressing along the propagating foreland (Hintze and Kowallis, 2009; Paulsen and Marshak, 1999; Lyman, 2001).

This stalling of the initial thrust appears to have been only temporary. Uplift of the upper sheet by the lower horse may have initiated continued propagation of the initial major thrust. At this point the lower horse adhered to the base of the upper sheet (a process also observed by Schirmer, 1985) and moved upward and to the east with the overlying unit.

Buttressing of the thrust sheets

As the upper sheet folded over the footwall flat, the sheet encountered another barrier to eastward propagation. Very likely this was due to the large vertical stress in the front of the fold due to the weight of the forelimb and the increase in frictional resistance between the hanging wall ramp and the footwall flat (Dahlen, 1984; van der Pluijm and Marshak, 2003; Kwon and Mitra, 2004). As sticking occurred in the frontal limb of the upper sheet, movement again shifted to the lower horse until it also was impeded by buttressing of the upper sheet. Evidence of this sticking point is seen in internal deformation of the anticline (discussed below) and the subsequent rotation of the vertical beds in the forelimb to become overturned.

Emplacement of the lower horse

Emplacement of the lower horse would have caused deformation and geometrical changes in the fold of the upper horse (Mitra, 1986). In our structural model, the lower horse in Rock Canyon caused uplift, steepened limb angles, and some rotation in the top and forelimb of the anticline. Evidence for this is seen in the fracture orientations found above the interpreted position of the duplex. Directly above the anticlinal core is a large concentration of vertical-subvertical fractures indicative of a vertical maximum stress orientation (Fig. 3).

Other faults seen in the same section are high-angle reverse and normal faults. On the forelimb of the fold can be seen a very distinct fanning fracture pattern that is found in other thrust systems with duplexes (see Fig. 5; and Wibberley, 1997; Yonkee, et al., 1997). This style of fanning fracture pattern has been related to rotation and uplift resulting from lower duplex emplacement (Wibberley, 1997).

In other locations along the Wasatch Front, Schirmer (1985), DeCelles and Mitra (1995), and Yonkee (1997) have observed uplift and passive folding of the upper sheet of the Willard and Ogden thrust sheets.

Mitra's (1986) duplex fault-bend fold model was applied to the Rock Canyon anticline based on fracture patterns and the geometrical constraints of the fold. However, it is interesting to note that a very similar cross section was constructed by Schirmer (1985) just north of the Provo area through the Willard and Weber thrust sheets. The Willard and Weber thrusts cut through similar units within a nearly-identical stratigraphic sequence to the one in Rock Canyon. One major difference between Schirmer's (1985) cross section through the northern segment and our constructed section is that the forelimb has vertical fold limbs but they are not overturned. In addition, there is no out-ofsequence thrust propagating from the top of the lower horse as in our model.

According to our interpretation (discussed below), the lack of the out-of-sequence thrust is directly correlated to the absence of overturned beds in the forelimb.

Propagation of the out-of-sequence thrust

As movement along the thrusts ceased due to buttressing of the fold front, initiation of an out-ofsequence thrust internally accommodated compres-

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sive stresses with continued propagation of the upper thrust and thickening of the orogenic wedge (Morley, 1988; van der Pluijm and Marshak, 2003). This outof-sequence thrust reactivated the footwall ramp of the upper sheet and propagated up into its anticlinal hinge (Fig. 10). Offset along the tip of this thrust can be seen along the base of Rock Canyon with significant apparent offset superposing the Mineral Fork Tillite against the Tintic Quartzite.

Kinematic data on the fault trace shows a very high angle on thrust movement toward the east with a transport direction trending at about 120°, matching closely the transport directions seen in other Sevier-age deformation.

Thrust splays like this out-of-sequence thrust are seen in several other cross sections along the range (Schirmer, 1985) and discussed by several other researchers (DeCelles and Mitra, 1995; Yonkee, 1997; Constenius, 1998). They are found in analogous structural positions along footwall ramps, accommodate internal shortening, and they produce sharp bedding angles on either side of the thrusts. In addition, Paulsen and Marshak (1999) also suggested stalling and internal shortening within the Provo salient based on its relatively small indentation to the east compared to that of the Wyoming salient. This stalling affected significant propagation of even lower and eastward thrusts such that strain had to be accommodated internally.

Another interesting feature found to the west of this thrust is what looks like a pop-up structure bounded on either side by reverse faults (Fig. 11). At this location, the Precambrian Mineral Fork Tillite intrudes into the base of the Tintic Quartzite in a wedge shape. Slicken-line data of associated faults and cleavage data of this outcrop indicate that one component of the maximum stress orientation was at ~ 110° and sigma 3 was at a very high angle (65°-80°). This indicates its association with other Sevier deformational features and supports uplift of the anticlinal hinge interpreted to have occurred by emplacement of the underlying horse.

Normal faulting, shale flowage, and overturning of the



Figure 10. Detail of anticlinal core showing the interpreted out-of-sequence thrust that offsets the Mineral Fork Tillite and the Tintic Quartzite. Location in the canyon is shown on the unbalanced section in Figure 4. Thrust data on equal area lower hemisphere stereo-plots for this location are also shown demonstrating the large vertical component of sigma 1.

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Figure 11. Detail of pop-up structure just west of the anticlinal core. Location in the canyon is shown on the unbalanced section in Fig. 4. Fault kinematic data and cleavage orientations on equal area lower hemisphere stereo-plots for this location are plotted indicating a near-vertical sigma 3 orientation.

anticlinal forelimb

Uplift and rotation of the upper sheet resulting from movement on the out-ofsequence thrust caused reactivation of inflection line fractures and of the folded thrust detachments in the incompetent units (e.g. Ophir and Manning Canyon shale units). Fold dip domains also provided zones weakened by earlier fracturing that occurred with active folding. Normal faults reactivated these zones through the competent layers and then soled into the rotated thrusts in the incompetent layers. Due to their steepened angle and uplift of the wedge, these thrusts were reactivated as normal faults with motion to the east. This extension toward the foreland of the fold-thrust belt could have been caused by several of factors: 1) Uplift of the wedge had exceeded the critical taper (Dahlen, 1984), 2) Rotation of the upper sheet produced inclined weak units such that their frictional strength was exceeded and the overlying units were decoupled (Hodges and Walker, 1992; Constenius, 1998), and 3) Vertical stresses became greater than the horizontal compressive stress (Burg et al., 1984; Platt and Vissers, 1989). Most likely, extension to the east was a result of a combination and interaction between all

three of these factors in the Rock Canyon area.

Two major normal faults are seen in the anticlinal forelimb along the Ophir and Manning Canyon shale units and several smaller normal faults are seen in the forelimb of the Tintic Quartzite and interspersed throughout the thick Mississippian limestones. The Tintic normal faults are interpreted to be the result of rotation and collapse of the steepened forelimb resulting from propagation of the out-of-sequence thrust. Preexisting weaknesses along bedding planes and earlier-formed fractures were used to accommodate movement. This is evidenced by the abundance of slickenlines along bedding planes in the Tintic and by second- and third-order eastward-verging folds produced from eastward slip on the overlying bed (Fig. 12).

Normal faults within the Mississippian limestones also follow preexisting planes of weakness in the interbedded shaly limestones. These normal faults often continue up into the overlying limestone beds to produce offset and movement on these faults provided space for thickening of the shale into the fold forelimb (Fig. 3).

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Although a pervasive mechanism seen throughout the canyon, shale flowage is most pronounced in the Ophir Shale. By measuring this unit along the canyon floor, we approximated a thickness of 420 meters in the thickened forelimb. This is about five and half times thicker than Hintze's (1978) estimate of the Ophir shale thickness for the area (76 meters) and it is remarkably thicker than other portions of the Ophir exposed in the canyon. Thickening and thinning within the Ophir Shale is a very common occurrence throughout the Wasatch Range interpreted to be caused by flowage or imbricate slices (e.g. Schirmer, 1985; Yonkee, 1997).

In Rock Canyon it appears that thickening of this unit occurred by massive flowage into the forelimb induced by normal movement on the overturned detachment within the shale layer. This idea has been proposed by Boyer (1986) who stated that slip along incompetent units may create a void between the competent layers; this void will then be filled either with minerals crystallized from mobile fluids or by flowage of the incompetent unit into the space. This mechanism has also been used by Schirmer (1985) in various locations in the Willard-Ogden thrust system.

We do not accept the flexural flow model of relative hinge thickening because the Rock Canyon anticline does not meet the model criteria given by Ramsay and Huber (1987) and Hudleston et al. (1996). According to these studies, flexural flow folds produce relative thickening in the hinge by means of continuous simple shear parallel to bedding. However, the process does not increase the thickness of the deformed layer so the hinge retains its original thickness. This is obviously not the case in the Rock Canyon anticline, which displays extensive thickening in the forelimb of the fold and attenuation in the hinge region.

According to our structural model, another effect of movement on the out-ofsequence thrust was rotation of the upper part of the anticline toward the east. This instigated the normal fault movement and shale flowage, which also facilitated overturning of the bedding in the forelimbs. With the forelimb of the Tintic buttressed at the fold front, movement was confined to the upper portions of the fold to become overturned. Mississippian limestones riding on the Ophir shale may have been mobile enough to open up a gap between them and the Tintic into which the shale could flow and thicken. These units then stalled along their base and overturned, aided by the interbedded shaly limestones throughout the section.

Normal faulting of the Wasatch Fault

Although initial extension of the Rock Canyon backlimb toward the hinterland was likely contemporaneous with that in the forelimb (Constenius, 1998), movement along the WFZ has a different stress signature (Fig. 7), was much more extensive, and its effects



Figure 12. Detail of anticlinal forelimb showing east-dipping normal faults and east-verging folds.

are more apparent. The position of the WFZ consistently on the backlimbs of the Wasatch anticlines indicates some structural control inherent in the preexisting conditions. We interpret that propagation of the normal fault began by utilizing preexisting weakness along fold inflection line fractures at the top of the Rock Canyon anticline, then moving bedding-parallel along the incompetent Ophir Shale, across Tintic Quartzite bedding, and finally connecting with Sevier detachments. As faulting occurred along the WFZ, isostatic equilibrium produced a 15° eastward rotation of the range.

CONCLUSIONS

Preexisting structures play a large role in determining structural mechanisms and deformation styles seen in subsequent tectonic events. Reactivation processes along weak planes are especially prevalent in the Wasatch region near Provo, Utah. Our structural evolution model of Rock Canyon exhibits several episodes of deformation, the majority of whose characteristics were determined by interaction with previously-formed structural and lithologic features. Thrusts initially developed within major incompetent units of the sedimentary sequence taking advantage of the weakness of the layers.

The Paleozoic basin margins and/or the Precambrian rift zone then served to localize thrust ramps and buttressed the major active thrust during its initial propagation. This in turn caused duplexing and an increase in the vertical component of wedge development. As the duplexes were emplaced, an out-of-sequence thrust accommodated compressive stresses by reactivating the footwall ramp of the upper thrust. The vertical stresses created with this thrusting enhanced fracturing along the earlier-deformed fold dip domain boundaries. These stresses also reactivated rotated bedding-parallel thrusts within the shale units to form eastward-dipping normal faults on the anticlinal forelimb and initial extension of the backlimb toward the west.

During later Basin and Range collapse the WFZ reactivated this zone of extension and followed lines of weakness along fractured dip domains, bedding planes, and thrust ramps.

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