MAGNITUDE OF DISPLACEMENT AND STYLES OF DEFORMATION ON THE PARIS AND LAKETOWN THRUST FAULTS, NORTHERN UTAH

RICHARD D. KENDRICK

UTAH STATE UNIVERSITY
1994
MAGNITUDE OF DISPLACEMENT AND STYLES OF DEFORMATION
ON THE PARIS AND LAKETOWN THRUST FAULTS,
NORTHERN UTAH

by

Richard D. Kendrick

A thesis submitted in partial fulfillment of the requirements for the degree
of
MASTER OF SCIENCE
in
Geology

UTAH STATE UNIVERSITY
Logan, Utah
1994
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ABSTRACT

Magnitude of Displacement and Styles of Deformation on the Paris and Laketown Thrust Faults, Northern Utah

by

Richard D. Kendrick, Master of Science
Utah State University, 1994

Major Professor: Dr. James P. Evans
Department: Geology

Surface geology is combined with abundant industry seismic-reflection and drill-hole data in the central Bear River Range and Bear Lake Plateau to depict the forms and interactions of the Paris-Woodruff-Willard, Laketown-Mead-Home Canyon, and Crawford thrust faults. Displacement on the Paris thrust diminished to the south, and died out in splays where displacement was transferred to the Willard thrust. West of Woodruff, Utah, splays of the Laketown thrust deformed a complex footwall imbricate of the Willard thrust. To the east, a major northeast-striking Crawford thrust splay exhibits a change in slip vectors from east to southeast. Reorientation of these slip vectors is recorded by an imbricate stack of thrusts in the Willard thrust footwall to the west. The sharp bend in the surface trace of the Crawford normal fault southeast of Randolph, Utah, reflects the separation of the south-southeast-trending surface traces of the Crawford thrust and this northeast-trending splay.

Cross sections indicate that the Sheep Creek thrust, a major splay off the basal decollement at the base of the Crawford thrust sheet, accommodated displacement during the transition from thrusting on the western thrust system (Paris-Woodruff-
Willard, and Laketown-Meade-Home Canyon) to the structurally lower eastern thrust system (Crawford, Absaroka, and younger thrusts). The Sheep Creek thrust trends northeast and folded the Laketown thrust in the central Bear River Range. Shortening in the northeast part of the study area was accommodated by the Home Canyon thrust along a detachment in the Jurassic Twin Creek Limestone. Several splays from this thrust extensively folded the footwall of the Meade thrust and rocks of the Bear Lake Plateau, and thereby formed a series of hanging-wall anticlines that have been extensively drilled for hydrocarbons.

(151 pages)
INTRODUCTION

General Statement

The magnitude of eastward displacement and the geometrical linkages between the Paris, Willard, and Laketown thrust faults in northern Utah are poorly constrained by regional tectonic studies. Reconstructions of thrusted terranes in other areas of the Idaho-Wyoming-Utah thrust belt have generated estimated values for local displacements on thrust faults (Royse et al., 1975; Evans and Craddock, 1985; Yonkee et al., 1989; Coogan and Royse, 1990), but do not adequately define the east-west component of net slip across the Paris-Laketown thrust system. The lack of data forced broad assumptions to be made about the amount of crustal shortening in the area for regional palinspastic reconstructions (Hintze, 1988; Levy and Christie-Blick, 1989). In addition, little documentation exists on the modes of internal deformation of the Laketown thrust sheet and its linkages with the adjacent Paris, Willard, and Meade thrusts.

This study examines the geometry of deformation and slip of the portions of the Paris, Willard, and Laketown thrust sheets in north-central Utah (Figure 1). These sheets are the westernmost thrust faults in the Idaho-Wyoming-Utah thrust belt. Movement on the Paris thrust fault and the subsequent eastward migration of offset caused extensive deformation in the underlying Laketown thrust sheet, characterized by imbricate thrusts and tight to open folds (Coogan and Royse, 1990; Valenti, 1980), whereas broad, open folds (Williams, 1948; Dover, 1985) developed at the leading edge of the Paris thrust sheet. A palinspastic reconstruction of the thrusted terrane illustrates the distance of transport of the thrust sheets. Field and seismic data gathered for the palinspastic reconstruction were used to construct three deformed-state cross sections of the thrust sheets. Diagrams similar to those of Wiltschko and
Dorr (1983) illustrate temporal and spatial changes in the study area, and model and synthesize events in the tectonic evolution of the Paris-Willard-Laketown thrust system.

**Purpose of Investigation**

The purposes of this research were to: (1) investigate thrust interactions and displacements in the study area, (2) describe the styles of deformation related to thrusting, (3) determine the nature of the transition from basement-involved thrusting in the west to thrusting in progressively younger rocks to the east, and (4) relate the structures in the field area to regional structural trends in the Idaho-Wyoming-Utah thrust belt. These goals were achieved by constructing three balanced and restored east-west cross sections at a scale of 1:100,000, by creating palinspastic maps from the restored cross sections, and by preparing a concealed thrust trace map.

The results yielded well-constrained solutions permitting determination of: (1) the magnitude of eastward displacement of the Paris and Laketown thrust sheets, and (2) the distribution of rocks at present and in the pre-Paris-thrust phase of tectonic evolution. The palinspastic map shows the restored positions of thrust faults prior to shortening. This project builds on previous studies of both thrusting in the southern Idaho-Wyoming-Utah thrust belt by Armstrong and Oriel (1965), Armstrong (1968a), Royse et al. (1975), Allmendinger and Jordan (1981), Dixon (1982), Wiltschko and Dorr (1983), and Heller et al. (1986), and improves the regional palinspastic reconstruction of the Basin and Range province by Levy and Christie-Blick (1989).
Location and Accessibility

The study area (Figure 1) includes approximately 2900 square kilometers of the central Bear River Range, Bear Lake Valley, and Bear Lake Plateau of north-central Utah, shown in figure 2. The large size of the structures in the area dictated the size of the study area. In addition, published data from adjacent areas of Utah, Idaho, and Wyoming were utilized to correlate regional-scale structures.

Access in most of the field area is over unimproved roads. Much of the land is public, administered by either the United States Forest Service or the Bureau of Land Management. Some private land was inaccessible because efforts to contact owners failed. Topography varies from rugged, forested terrain in the Bear River Range in the west to rolling, sage-covered hills on the Bear Lake Plateau. Snow cover prevents field work from November to April in much of the area.

Physiographic Features

The physiography of the study area is largely controlled by the three active normal faults in the area. The East Cache fault, Bear Lake fault, and the Crawford fault are en echelon, west-dipping normal faults with Pleistocene and Holocene offsets, and each exerts considerable structural control of geomorphic features and drainages. From obvious examples like Bear Lake to changes in the sinuosity of the Bear River, normal faults show extensive influence on surficial features.

The Bear River Range is bounded on the west by the East Cache fault zone which offsets Tertiary sedimentary rocks, lake deposits of Pleistocene Lake Bonneville, and post-Bonneville Holocene deposits. Drainage in the range is dominated by the Logan and Blacksmith Fork river systems. Cache Valley, west of the Bear River Range, is a large, north-south trending graben that demarcates the eastern margin of the Basin and Range physiographic province transition zone. Bear
Figure 1. Generalized tectonic map of the Wyoming-Idaho-Utah thrust belt showing major thrust and extensional faults (adapted from Royse et al., 1975).
Figure 2. Generalized geologic map of the field area with fault traces (adapted from Evans, 1990).
Lake Valley and Crawford Valley are predominantly north-trending half-grabens bounded by west-dipping normal faults that may sole into underlying thrust faults (Coogan, 1992). The area south and east of Bear Lake has moderate topographic relief characterized by low rolling hills of bedrock or Tertiary Wasatch Formation, or floodplains of Quaternary alluvium. The Bear Lake normal fault and the Crawford normal fault produced the only major escarpments of this area. The remaining terrain is dominated by low rolling hills or floodplains. Drainage is dominated by Bear Lake and by the meandering north- to northeast-flowing Bear River.
GEOLOGIC SETTING

Previous Work

Considerable research has been conducted on the eastern Idaho-Wyoming-Utah thrust belt. Regional tectonic syntheses by Armstrong and Oriel (1965), Armstrong (1968a), Royse et al. (1975), Allmendinger and Jordan (1981), Dixon (1982), Wiltschko and Dorr (1983), and Heller et al. (1986) delineated the boundaries and overall structural and timing relationships of the region.

Royse et al. (1975) applied modern thrust-belt structural and geometric constraints to the Idaho-Wyoming-Utah thrust belt, and concluded that the thrusts were west-dipping listric faults which sole into a major basal decollement in Archean or Proterozoic rocks. The Willard thrust was interpreted by Crittenden (1972a) to be the westward extension of the Paris thrust. Schirmer (1985a,b; 1988), Yonkee et al. (1989, 1992), and Yonkee (1992) estimated 30-35 km of eastward slip and examined the styles of deformation along the Willard thrust and its linkage with the Ogden duplex. The linkage between the Crawford and Meade thrusts has been investigated by Evans and Craddock (1985). Their balanced and restored cross sections immediately north of the study area revealed 20 km of eastward displacement on the southern portion of the Meade thrust.

Extensive research has produced many estimates for thrust-fault displacements in the region. The considerable range of values is a result of different methods of calculation and changes in eastward displacement laterally along the traces of the faults. Regional estimates are shown in Table 1.

According to Armstrong and Oriel (1965), movement occurred on the Meade thrust 120 Ma and, on the Crawford thrust, 110 Ma. Wiltschko and Dorr (1983) suggested that the Paris thrust moved at the Jurassic-Cretaceous boundary (141 Ma) in
their comprehensive study of the movement and timing of thrust sheets and the
associated sedimentation in the foreland. In contrast, Heller et al. (1986) coupled the
onset of Sevier foreland subsidence during Aptian to Albian time in Wyoming (119 to
97.5 Ma) with the initiation of movement on the Paris thrust. Yonkee (1990) reported
$^{40}$Ar/$^{39}$Ar ages of 140 to 110 Ma from sericite syntectonic vein fills that record
internal deformation of the sheet prior to thrusting on the Willard thrust. Wiltschko
and Dorr (1983) estimated that movement occurred between 85 and 95 m.y. on the
"Crawford-Meade system."

Post-Crawford thrust shortening was accommodated by the Absaroka thrust to
the east. Initial thrusting on the Absaroka thrust is interpreted as Middle to Late
Cretaceous (Late Santonian) by palynological dating of the synorogenic Little Muddy
Creek Conglomerate southwest of Kemmerer, Wyoming (Nichols, 1979; Royse and
Warner, 1987). Movement continued, marked by the progradation of the Ham's Fork
Conglomerate Member of the Evanston Formation in the latest Cretaceous (Late
Campanian or Early Maestrichtian) into southwest Wyoming (Armstrong and Oriel,
1965; Oriel and Tracy, 1970; Royse et al. 1975; Jacobson and Nichols, 1982).

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<tr>
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<td>11 km</td>
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<td>6 km</td>
<td>Royse et al. (1975) section Y-Y'</td>
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<td>Willard</td>
<td>51 km</td>
<td>Levy and Christie-Blick (1989)</td>
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<td>30 km</td>
<td>Schirner (1985a,b; 1988)</td>
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<td></td>
<td>35 km</td>
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<td>Laketown-Meade</td>
<td>20-30 km</td>
<td>Coogan (written commun., 1990)</td>
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<td>19 km</td>
<td>(1975) section X-X'</td>
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</table>
Thrusting continued along a Cambrian shale decollement on the Hogsback, Darby, and Prospect thrusts (Coogan and Royse, 1990). Significant thrusting in the region is marked by the end of displacement along the Prospect thrust near the Paleocene-Eocene boundary (Wiltschko and Dorr, 1983). Minor thrusting continued through the Middle to Late Early Eocene on the La Barge, Bear, Game, and Lookout Mountain thrusts (Wiltschko and Dorr, 1983).

Many hypotheses exist for the subsurface linkages of major thrusts in the southern Idaho-Wyoming-Utah thrust belt. A connection between the Paris and Willard thrusts has long been postulated (Richards and Mansfield, 1912; Armstrong and Oriel, 1965; Crittenden, 1972a,b; Wiltschko and Dorr, 1983). More recently, the Willard thrust was connected to the Meade thrust (Dover, 1983, 1985; Coogan, 1987; Coogan and Royse, 1990). In addition, the Willard thrust was linked with the Woodruff and Meade thrusts by Woodward (1988).

Mapping in the vicinity of Laketown, Utah, by Valenti (1982b) established the similarity between rocks of the Laketown and Meade thrust sheets. The Mississippian section in the Laketown area closely resembles the Mississippian section in the Chesterfield Range at the western edge of the Meade thrust plate. Valenti (1982b) suggested that the Meade thrust trace, exposed immediately north of the Laketown area, merges laterally with the Laketown thrust. The southward-plunging Laketown anticline may represent a termination of the Meade thrust fault or a linkage with the Paris thrust (Valenti, 1982b).

Several regional correlations among thrusts in the study area and others in the thrust belt are possible. Christie-Blick (1982) challenged the Willard-Charleston thrust linkage of Crittenden (1974) and instead linked the Willard thrust with the Canyon Range thrust instead based on similar thrust-sheet stratigraphy. A connection at depth between the Absaroka and the Charleston-Nebo thrusts has been proposed by
Bruhn et al. (1986) and by Levy and Christie-Blick (1989). The southern portion of the Hogsback thrust is thought to merge with the Uinta Mountain bounding thrust (Bruhn et al., 1986). Extensive research, prompted by widespread hydrocarbon production in the Absaroka thrust sheet, has focused on the thrust sheets east of the Paris and Meade thrusts. Significant among these are studies by Dixon (1982), Lamerson (1982), and Valenti (1987), who documented the structural form and origin of petroleum traps, particularly hanging wall anticlines, above Cretaceous footwall source rocks, that contain the most significant reservoirs. The western part of the thrust belt has been investigated by Coogan and Royse (1990), who organized individual thrusts into thrust systems and investigated variations in thrust-sheet stratigraphy. The regional palinspastic reconstruction of crustal shortening and extension, by Levy and Christie-Blick (1989), restored the original configuration of the eastern Great Basin to a pre-thrust state.


Regional Geology

The pre-Eocene structures of the study area are dominated by west-dipping low-angle thrust faults that formed during Sevier folding and thrusting. From west to
east these are the Paris, Willard, Laketown, Meade, and Crawford thrusts (Figure 2). These thrust faults shorten a thick wedge of Late Proterozoic to Late Paleozoic miogeoclinal sedimentary rocks. The Paris and Willard thrusts bring Precambrian sedimentary rocks to the surface, whereas the Meade thrust is probably the oldest thrust with a detachment entirely in the sedimentary cover (Evans and Craddock, 1985). After thrusting ended in the central Idaho-Wyoming-Utah thrust belt in the early Eocene, normal faulting began during the latest Eocene and continues to the present (Miller, 1990).

**Stratigraphy**

The stratigraphy of the study area exerts considerable influence on the structural level of the thrusts and has resulted in a complex ramp-flat geometry of thrusting. The units acting as detachment horizons range from the Late Proterozoic Kelley Canyon Formation to the Jurassic Twin Creek Limestone. Other important thrust-flat horizons include the Cambrian Gros Ventre Formation (Coogan and Royse, 1990), Cambrian Ophir Formation (Schirmer, 1985a,b), and the Mississippian Madison Group (Evans and Craddock, 1985; Woodward, 1988). Many incompetent units that are potential glide planes in the stratigraphic sequence include shales in the Ordovician Bighorn Dolomite and in the basal Permian Phosphoria Formation. Shales, siltstones, and evaporites of the Devonian Darby and Pennsylvanian Amsden Formations, as well as most of the Mesozoic sequence, are structurally weak (Lamerson, 1982). The repetitive localization of thrusting within the same incompetent units resulted in stratigraphically similar thrust plates.

Another important influence of stratigraphy on deformational styles is the response of individual units or packages of units to compression. During cross-section construction, no volume loss was assumed due to layer-parallel shortening.
However, ductile deformation (flow) of some units due to slip on numerous bedding planes was required locally by drill-hole and seismic data. Units apparently prone to flow are the Triassic Ankareh, Dinwoody, and Woodside Formations, and the Jurassic Twin Creek Formation. These formations are thinly bedded limestones and siltstones that can thicken or thin considerably during thrust-associated folding.

Thicknesses of the stratigraphic units in the study area were taken from Dover (1985) and Hintze (1988). In addition, extensive drill-hole data and interpretations of drill-holes (Petroleum Information Corporation, unpubl. data) were used to determine the sequence and thicknesses of subsurface stratigraphic units that crop out east of the study area.

Early local and regional stratigraphic studies were conducted by Eardley (1944). Later work by Stokes (1961, 1963) and Hintze (1973, 1988) assembled stratigraphic data from Utah and surrounding areas to provide references of stratigraphic variations and environments of deposition through time. Sorensen and Crittenden (1979) and Crittenden and Sorensen (1985a,b) supplied additional regional data on thicknesses of subsurface units. Local stratigraphic information was summarized by Oaks and Runnells (1992) from studies by numerous Utah State University master's theses. Together, these provide data for both regional correlations and local variations of stratigraphic units.

A miogeoclinal sedimentary-wedge depositional setting persisted from the Late Proterozoic until the Mississippian followed by the development of the Pennsylvanian-Permian Oquirrh Basin and the associated deposition of thick carbonate rocks (Hintze, 1988). The depositional system changed significantly in the Triassic to an eastward-thickening sedimentary wedge associated with foreland-basin development at the onset of thrusting (Witschko and Dorr, 1983). Thrust faults and folds in much of the study area are overlapped by the Early to Middle Eocene Wasatch Formation, which reflects
an episode of terrestrial deposition in shallow piggyback basins in thrust sheets as they were transported eastward over underlying thrust flats (Oaks and Runnells, 1992; Coogan, 1992).

The stratigraphic sequence exposed in the Bear River Range varies from the Late Proterozoic Mutual Formation to the Pennsylvanian Wells Formation. Mapping by Crittenden and Sorensen (1985a) in the Mantua Quadrangle showed the Bear Canyon thrust at the base of the Late Proterozoic Caddy Canyon Formation. This thrust is interpreted to lie beneath the western portion of the Bear River Range, based on seismic-reflection and stratigraphic data, so that the Caddy Canyon Formation probably is the oldest unit present in the subsurface. If correct, thrust sheets that constitute the Bear River Range contain all units from the Caddy Canyon Formation to the Pennsylvanian Wells Formation. This sequence is similar to the Huntsville stratigraphic section summarized by Hintze (1988).

The stratigraphy underlying the Bear Lake Plateau reflects the early miogeoclinal to cratonic sedimentary environments and the later transition to foreland-basin sedimentation. The oldest rocks exposed east of the surface traces of the Meade, Laketown, and Willard thrusts and west of the Crawford normal fault are the Jurassic Nugget Sandstone and Twin Creek Limestone. These rocks are overlain mostly by the extensive deposits of the Early to Middle Eocene Wasatch Formation and Quaternary sediments. Drill-hole data indicate the presence of rocks as old as the Cambrian Gros Ventre Formation in the hanging wall of the Crawford thrust. In the south part of the study area, these lower Paleozoic rocks overrode Cretaceous rocks, which are exposed east of the leading edge of the Crawford thrust. The Absaroka thrust underlies the Bear Lake Plateau, and contains a thick lower Paleozoic to Cretaceous section. Another significant difference between the stratigraphy underlying the Bear Lake Plateau and the area to the west is the absence of rocks of
Silurian and Middle Ordovician ages. Refer to Appendix A for generalized stratigraphic sections.

These stratigraphic data were used to construct a stratigraphic template in the early stages of cross-section construction, based on known and inferred unit thicknesses. Detachment horizons identified by other workers in the southern Idaho-Wyoming-Utah thrust belt were then examined for their potential to act as thrust horizons, supported by available surface, seismic-reflection, and drill-hole data. This information was used to make a preliminary estimate of the stratigraphic sequences and structures between the surface geologic control and the basal decollement level calculated from seismic-reflection data.

**Pre-Cretaceous Deformation in the Region**

The form, style, and interrelationships of the thrust faults and synorogenic deposits in the Idaho-Wyoming-Utah thrust belt have been investigated by many authors. The miogeoclinal formed as a result of rifting of the Archean and Early Proterozoic craton during the Late Proterozoic according to Stewart (1972) and Stewart and Poole (1974). The new continental margin was the site of marine deposition through the middle Triassic, ranging in thickness from 11 to 15 km (Hintze, 1988). East of the miogeoclinal, cratonic sedimentation totaled approximately 2 km in total thickness throughout this period (Miller, 1990).

Tectonic quiescence in the miogeoclinal was interrupted several times during the Paleozoic and Mesozoic. The Late Devonian to Mississippian Antler orogeny (Speed and Sleep, 1982) and the Pennsylvanian-Permian Ancestral Rocky Mountain uplifts and basins along with associated subsidence of the Oquirrh Basin (Jordan and Douglas, 1980) significantly altered regional depositional patterns, but produced no structures in the study area. The Early Triassic Sonoma orogeny described by
Collinson et al. (1976) created a regional unconformity between mid-Permian and Triassic strata. The deposition of marine sediments in the miogeoclone ended in the Late Triassic in this area.

Tectonic activity west of the field area was widespread in the hinterland during the Jurassic. Late Jurassic plutons, most commonly alkali-enriched granodiorite, were emplaced in eastern Nevada, cutting structures associated with regional shortening. The ages of the plutons range from 150 to 155 Ma based on K-Ar biotite dating (Miller, 1990). Middle and Late Jurassic sedimentary rocks in northeast Utah thicken westward. They are interpreted to be foreland-basin sediments derived from a magmatic highland to the west (Jordan, 1985). Despite indications of thrusting, no examples of major thrusts of Jurassic age that ramped to the surface have been found. Indeed, many examples of extensional faults cutting thrust structures indicate an interval of extension in the Late Jurassic, related to local extension near plutons, or fracturing and faulting of cooling lithosphere (Miller, 1990).

Early Cretaceous tectonic activity is characterized by scattered faulting and hinterland ductile deformation. West of the field area, minor thrusts and folding in the Blue Springs Hills and Samaria Mountains (Allmendinger and Platt, 1983; Allmendinger et al., 1984; Jordan et al., 1988) record east-directed pre-Paris thrust shortening. Farther west, the younger-over-older Manning Canyon detachment accommodates up to 60 km of displacement along a decollement in Mississippian and Pennsylvanian shales (Allmendinger and Jordan, 1981) in the Jurassic. Altered black shales of the Mississippian Great Blue Limestone in the Oquirrh Mountains associated with Manning Canyon detachment deformation yield K-Ar ages of 193 to 122 Ma (Wilson and Parry, 1990).

Jurassic and/or Early Cretaceous hinterland tectonism is recorded by greenschist- and amphibolite-facies metamorphism in the Albion, Grouse Creek, and
Raft River Mountains (Armstrong, 1968b, 1982). These highly strained metamorphic rocks lie above nearly undeformed Archean basement and may represent a thick, subhorizontal shear zone (Sabisky, 1985) acting as the sole decollement for thrusts ramping to the surface in the east. Shallow, younger-over-older faults in the hinterland may represent a decollement or extensional fault horizons above the deformed metamorphic complex (Miller, 1990).

**Thrust Timing**

The ability to date the movements of thrusts both absolutely and relatively gives important clues to the evolution of the Idaho-Wyoming-Utah thrust belt. Absolute dating allows for the determination of thrust-plate velocities when combined with estimated displacements. However, absolute dating relies on radiometric dating of synorogenic conglomerates shed from uplifted thrust sheets which have so far provided ages that are widely spaced, both spatially and stratigraphically. Relative dating of thrust-associated sediments provides a more useful, if less accurate, timing scheme. Many data exist relating particular sedimentary units to various intervals of specific thrusting events.

Furthermore, it is unclear which sedimentary deposits should be used in dating fault movement. Some workers think conglomerates date fault movement, whereas others think the deposition of fine-grained deposits equates with the onset of thrusting (Heller et al., 1988). An excellent reference of regional correlations can be found in Wiltschko and Dorr (1983). Figure 3 illustrates the tectonic events and sedimentological records of the thrust belt.

Timing of the Paris thrust, the oldest and westernmost of the major documented thrusts east of the Manning Canyon detachment, has proven to be difficult. According to Heller et al. (1986), movement began on the Paris and Willard
thrusts approximately 115 Ma. Early Paris thrust movement is recorded by the upper member of the Ephraim Conglomerate, which contains nonmarine fossils, charophytes and ostracodes. These fossils in the conglomeratic upper member mark the onset of coarse-grained deposition as Albian or slightly older, an age that corresponds to widespread Sevier foreland-basin coarse-grained sedimentation of Aptian-Albian age (Heller et al., 1986). Sedimentological changes between the upper and lower members of the Ephraim Conglomerate were correlated with similar changes in the Morrison Formation and the overlying Cloverly Formation by Furer (1970). The hiatus between the lower and upper members of the Ephraim Conglomerate may represent up to 40 m.y. (Dodson et al., 1980).

Estimates for the duration of Paris thrusting reach 50 m.y. based on the assumption of several intervals of movement, which could explain the separate origins of the Ephraim, Bechler, Thomas Fork, Quealy, and Coalville conglomerates (Wiltschko and Dorr, 1983). The Coalville Conglomerate, the youngest unit associated with thrust uplift of the Paris thrust sheet, is preserved only in northeast Utah. This evidence suggests that the duration of thrusting and thrust displacement was not uniform across the broad Paris thrust front. Latest displacement on the Paris thrust possibly was restricted to the southern part of the fault (Wiltschko and Dorr, 1983). In more recent studies, the presence of clasts derived from the Paris thrust sheet in uppermost Cretaceous to Paleogene conglomerates is thought to be the result of uplift of the Paris thrust sheet on younger thrust ramps. Schmitt and Steidtmann (1990) termed this mechanism "interior ramp-supported uplift" and used it to explain the intermittent deposition of coarse-grained deposits previously assumed to be the result of movement on the Paris thrust. Acceptance of this model would significantly diminish the duration of active thrusting attributed to the Paris thrust to a length similar to others, and thus bring its estimated duration of movement more in line with other
thrusts in the area. Thus, the very low slip rates calculated in Wiltschko and Dorr (1983) for the Paris thrust would be revised upward. Application of the model in the study area appears reasonable due to the uplift of the Paris and Willard thrusts by underlying thrust faults based on cross sections (Evans, writ. commun., 1990; this study), and the work of Bruhn et al. (1983), Schmitt (1985), and DeCelles (1988).

Timing of movement on the Willard thrust is also constrained by the Lower Cretaceous Ephraim Conglomerate and its equivalent to the southeast, the Kelvin Formation (Yonkee, 1992). Although the Paris and Willard thrusts are spatially separate, they are both dated by the Ephraim Conglomerate or its equivalent, suggesting coeval development and a linkage in the subsurface. Yonkee et al. (1989) indicated radiometric ages of 110 to 140 m.y. of sericite grains in vein systems in the Willard thrust sheet. They interpreted these veins to result from shortening of the thrust sheet just prior to, and at the onset of, thrusting that resulted in the synorogenic deposition of the upper part of the Ephraim Formation and the Kelvin Formation (Yonkee et al., 1992).

Establishing the relative ages of slip on the Laketown, Meade, and Crawford thrusts is difficult. Many workers have linked the activity of the Laketown and Meade thrusts, or the Crawford and Meade thrusts. Deposition of the Upper Cretaceous Echo Canyon Conglomerate in northeastern Utah has been attributed to thrusting on the Crawford or Meade thrusts. Also, Oriel and Armstrong (1986) equated deposition of the Late Albian Wayan Formation with movement on the Meade thrust. In contrast, the Meade thrust cuts the Albian Wayan and Sage Junction Formations in several places in eastern and southeastern Idaho, which dates the event as post-Early Cretaceous (Wiltschko and Dorr, 1983) and provides strong evidence that the Wayan Formation is not a synorogenic product of the Meade thrust. If correct, this would
Figure 3. Tectonic events and sedimentological responses of the thrust belt (adapted from Wiltschko and Dorr, 1983). Note that Heller et al. (1986) reevaluated the age of the Upper Ephraim Formation, and argue that it is no older than Aptian.
suggest that Meade thrusting predated movement on the Crawford thrust, instead of
the two being nearly contemporaneous as suggested by Royse et al. (1975).

Cross-cutting relationships for dating the Crawford thrust exist near Cokeville,
Wyoming, where the Crawford thrust cuts and is thrust over the Quealy and Sage
Junction Formations (Rubey, 1973; Wiltschko and Dorr, 1983). The Quealy
Formation was correlated with the upper part of the Wayan in eastern Idaho, which is
also equated to the Early Cretaceous Dakota Sandstone of eastern Wyoming based on
fossil evidence (Rubey, 1973). An upper age of thrusting is provided by Rubey et al.
(1980) by interpreting the Crawford thrust in the subsurface to be overlain, west of
Cokeville, by the Silem Member of the Fowkes Formation. The Bulldog Hollow
Member of the Fowkes, immediately above the Silem Member, yielded a K-Ar date of
47.7 ± 1.5 Ma (Oriel and Tracy, 1970). This Middle Eocene date for the Silem
Member constrains movement on the Crawford thrust between post-Early Cretaceous
and pre-Middle Eocene time.

Minor, late phase Crawford thrusting is manifested by break-back thrust
development near Cokeville, Wyoming, and frontal imbricates east of the study area
that offset the Eocene Wasatch Formation (Lamerson, 1982; Coogan, oral comm.,
1988; Salat and Steidtmann, 1991). DeCelles (1988) strongly linked the deposition of
the Coniacian-Santonian Echo Canyon Conglomerate with movement on the Crawford
thrust. The lack of precise timing data for the Crawford and Meade thrusts leaves their
relationship open to question, but does show that they post-date the initial and
probably renewed thrusting on the Paris thrust (Wiltschko and Dorr, 1983).

These timing questions suggest two possible geometric links between the
Crawford and Meade thrusts. If deposition of the Late Albian Wayan Formation is
coupled with slip along the Meade thrust (Oriel and Armstrong, 1986), two distinct
thrusts are required by the large disparity in timing of the thrusts. Alternately, if they
are nearly contemporaneous, the two thrusts probably resulted from the same episode of regional shortening. Coeval development seems more likely, since this explanation avoids the problem of the apparent absence of thrust structures between the overlapping distal ends of the two thrusts.

**Extension**

Regional thrusting ended in the Early Eocene and was replaced by pre-Basin and Range extension in the latest Eocene (Miller, 1990). Large amounts of extension occurred in the Mesozoic hinterland metamorphic belt, indicating gravity-driven extension of the highlands (Coney and Harms, 1984). The mechanism to accommodate this deformation was apparently similar to the large, low-angle detachment faults of Wernicke (1981). Basin and Range faulting began 15 to 17 Ma (Davis, 1979; Zoback et al., 1981) due to high heat flow and consequent broad uplift and crustal stretching (Miller, 1990). Miller (1990) suggested the origin of the thermal disturbance was mantle upwelling, manifested by the Snake River Plain volcanics.

Much Basin and Range extension east of Cache Valley was accommodated by normal movement on pre-existing thrust faults. Royse et al. (1975) noted that many normal faults throughout the Idaho-Wyoming-Utah thrust belt are located near thrust ramps and have the following characteristics: (1) normal faults lie west of and are approximately parallel major thrusts with which they are associated; (2) normal faults may merge downward with, but do not cut, major thrusts; and (3) sediments deposited after thrusting on the downthrown side of normal faults are rotated until they dip into the plane of the normal fault (reverse drag).

More recent work has characterized the geometry of these normal faults. East of the East Cache and Wasatch faults in northern Utah, seismic data indicate that normal faults are restricted to the thrust plates above the regional decollement, and
basement rocks are not cut by normal faulting (Coogan and Royse, 1990). Based on seismic-reflection data, some normal faults in the study area dip more gently in the subsurface than the steep fault scarps in surficial deposits would suggest. Considerable debate exists over the shape of the normal-fault surfaces, but some apparently are steep near the surface and gradually flatten westward into an underlying thrust ramp to form a listric geometry. This is manifested at the surface by a half-graben, a valley bounded on one side by a major listric normal fault. The East Cache normal fault does not sole into an underlying thrust, but some portions of the fault appear to have a listric geometry (Smith and Bruhn, 1984; Evans, 1991). Local values of crustal extension have been estimated at 10-15% along a line from the Wellsville Mountains, west of the study area, to the Wyoming-Utah border (Evans, 1991).
DATA

Field Data

Initial field reconnaissance was conducted in the spring of 1991 and more detailed field work was undertaken in the summer of 1992. Field work consisted of strip mapping along seismic lines where no detailed surface data existed. These data were collected to provide control for the interpretation of seismic-reflection lines and ultimately for the construction of cross sections.

Structural data recorded during field mapping included: orientations of faults and of bedding, formation contacts, and cleavage. Lithologic information included: rock type, bedding thickness, sedimentary structures, grain sizes, colors, and fossil type. Field equipment consisted of a Brunton Pocket Transit and a tape measure 50 feet long.

Structural information was transferred to a 1:100,000 scale base map with topography and generalized geology, compiled by Evans (1990). Data from many sources of published mapping and unpublished Utah State University master’s theses were also transferred to the base map, as were all locations of seismic-reflection lines and drill-holes for which data had been obtained. References to specific work will be made where appropriate in the following discussions.

Drill-Hole Data

Drill-hole data were obtained for 24 wells drilled in the Bear River Range, Bear Lake Valley and Plateau, and Cache Valley. These data provided important local information on thrust-sheet stratigraphy, thickness, and detachment horizons that was utilized in the interpretation of nearby seismic-reflection lines and in construction of
Table 2. Drill-hole locations and total depths.

<table>
<thead>
<tr>
<th>well name</th>
<th>location</th>
<th>total depth</th>
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<tbody>
<tr>
<td>American Quasar 18-1</td>
<td>T9N R6E Sec. 18</td>
<td>3337m</td>
</tr>
<tr>
<td>American Quasar 19-1</td>
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<td>2808</td>
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<td>American Quasar Duck Creek</td>
<td>T12N R7E Sec. 7</td>
<td>2583</td>
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<td>American Quasar Eden 12-1</td>
<td>T14N R6E Sec. 12</td>
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<td>5110</td>
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<td>T13N R7E Sec. 17</td>
<td>3271</td>
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<tr>
<td>American Quasar Hogback R. 28-1</td>
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<td>Amoco Lynn Reese</td>
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<tr>
<td>Christmann Bridger Creek</td>
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<td>Sohio Sugar Loaf</td>
<td>T10N R6E Sec. 11</td>
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</tr>
</tbody>
</table>

cross sections. Table 2 summarizes well locations and total depths. Original well logs were reinterpreted by the Petroleum Information Corporation (unpubl. data).

These reinterpreted well logs were the best subsurface information for the interpretation of the seismic-reflection lines. Other sources of drill-hole data included Valenti (1982a,b) for the Marathon Otter Creek well, and Ott and Kreckel (1982) for the Marathon Thousand Dollar well. These authors provided alternate interpretations for these two wells. Data were in the form of depth in feet from the Kelly bushing to faults and to the top of each formation. The thickness of each unit and the positions of contacts relative to mean sea level were calculated in meters.
Seismic Data

Seismic-reflection data were the primary factor in determination of the location of cross sections. These data provided two-way travel times to major thrusts, to the basal decollement, and to prominent lithologic changes in the stratigraphic sequence. The interpreted seismic-reflection data were used to construct cross sections, structure-contour maps, and isochore maps of the study area. Seismic-reflection data were analyzed from 21 seismic-reflection profiles in the Bear River Range, Bear Lake Valley, and the Bear Lake Plateau to determine the geometries and extents of thrust faults in the study area.

Three formats of industry seismic-reflection profiles were examined: tracings of major reflectors, photocopies, and time-to-reflectors at individual shot points. Sources of these data were the Exxon Corporation, Texaco Incorporated, American Quasar Petroleum, Amoco Corporation, Placid Oil Company, and the Overthrust Belt Consortium. All original data were measured in time, and, where appropriate, reflectors were measured to the nearest .005 second. These data were plotted with the computer program Kaleidagraph, version 2.0, from Abelbeck Software, with shot points on the x-axis and time on the y-axis, to represent unscaled working reproductions of the seismic lines. In this format, reflectors were correlated from one seismic line to another.

Calculation of the depths to reflectors was accomplished by assigning velocities to intervals based on the ages of the units involved. Depths to known reflectors in drill-hole data and published cross sections of the area were converted to time using the parameters in Table 3. These time intervals were then used to assign
Figure 4. Map of field area showing locations of seismic-reflection lines and drill-holes used in this study.
probable velocity values for the same intervals, identified by lateral correlation on the seismic-reflection profiles, for conversion to depth. Depth with respect to mean sea level, used later to construct cross sections, was calculated from known or datum horizons. Datum horizons were known for 19 of the 21 lines. The other two were estimated by comparison of the seismic-reflection profiles with adjacent profiles and available drill-hole data.

The method used to compute depth from two-way travel time depended on the complexity of the stacking regime. The formula and logic capabilities of the Kaleidagraph program were used to calculate depths in areas of simple, stacked packages of rocks. Structurally complex areas exceeded capabilities of the spreadsheet program and computations were done by hand.

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**Table 3.** Velocities used for conversion of time to depth.

<table>
<thead>
<tr>
<th>Strata</th>
<th>Velocity (feet/second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tertiary Wasatch Fm. and Tertiary sediments</td>
<td>10,000</td>
</tr>
<tr>
<td>Mesozoic and upper Paleozoic</td>
<td></td>
</tr>
<tr>
<td>less than 1 second thick</td>
<td>15,000</td>
</tr>
<tr>
<td>greater than 1 second thick</td>
<td>17,000</td>
</tr>
<tr>
<td>Lower Paleozoic and Proterozoic</td>
<td></td>
</tr>
<tr>
<td>less than 0.5 second thick</td>
<td>16,000</td>
</tr>
<tr>
<td>greater than 0.5 second thick</td>
<td>19,000</td>
</tr>
</tbody>
</table>

Note: the base of the Mississippian Lodgepole Limestone was used as the boundary between upper and lower Paleozoic.
METHODS

Structural Analysis

Studies in the Appalachians (Rich, 1934; Perry, 1978), in the Canadian Rockies (Bally et al., 1966; Dahlstrom, 1969; Price and Mountjoy, 1970), in the Moine thrust belt (Elliott and Johnson, 1980), in the Alps (Trumpy, 1960; Boyer and Elliott, 1982), and in the Idaho-Wyoming-Utah thrust belt (Armstrong and Oriel, 1965; Armstrong, 1968a; Royse et al., 1975; Blackstone, 1977; Dixon, 1982; Lamerson, 1982; Witschko and Dorr, 1983; Coogan and Royse, 1990) show how thrust belts develop and how thrust faults interact. The geometric and mechanical behavior of thrust-fault development in thin-skinned thrust belts is largely governed by the following "rules":

(1) Thrust faults have a ramp-flat geometry with long, flat detachment horizons in incompetent units and short, steep ramps in more competent units.

(2) Major thrust faults are younger in the transport direction; thrust propagation toward the foreland takes place due to progressive footwall failure.

(3) Thrusts cut upsection both parallel (frontal ramps) and perpendicular (lateral ramps) to the direction of transport

(4) Folding is generally concentric and is mainly the result of frontal and lateral ramping

(5) Thrust-sheet geometry is determined by the location of underlying thrust ramps.

These rules have been used in this study to provide the basis of interpretation for structural and stratigraphic relationships in the study area and for the construction of balanced cross sections.
Cross section balancing techniques were originally developed by Bally et al. (1966) in their study of the Alberta foothills. Working in the same area, Dahlstrom (1969) established assumptions for balancing that included constant volume and thickness of the rocks involved, and concentric folding. Based on these principles, rules for balancing cross sections were proposed: (1) the length of units in a cross section must be consistent, and (2) adjacent cross sections should have comparable amounts of shortening (Dahlstrom, 1969). Dahlstrom further indicated that variations in shortening among cross sections can be the result of nearby lateral ramps, tear faults, differential movement on sole thrusts, and decollements.

Dahlstrom (1969, p. 757) reviewed the utility of balanced cross sections and concluded:

It should be emphasized that a cross section which passes the geometric tests is not necessarily correct, because completely ridiculous cross sections can be drawn which abide by the law of conservation of volume. However, if a cross section passes the geometric tests, it could be correct, and if it has been drawn with due regard for the "local ground rules" it probably is correct. On the other hand, a cross section that does not pass the geometric tests could not possibly be correct.

Several concepts regulated the construction of the cross sections in the study area in addition to the general rules of thrust faulting:

(1) Thrust displacement was eastward on all thrusts except in the southeastern part of the study area, where an east-southeast transport direction was assumed.

(2) Simple strain or layer-parallel shortening was assumed to be negligible in all sections so that there was no net loss of material due to strain-related dissolution.

(3) Lateral variations in shortening and unit thicknesses between adjacent cross sections are the result of lateral ramps and splaying of thrust faults.
(4) Geometries depicted on the cross sections represent the least complex structures that can be balanced.

(5) Cross sections must honor all available surface data.

Folding

Shortening in thrust belts commonly produces fault-related folds classified by their geometry. Models to construct and interpret individual structures were presented by Suppe (1983) and Suppe and Medwedeff (1990). These models apply geometric constraints to fold shape by interrelating ramp angle, interlimb angle, and thickness changes in the forelimb. Use of this interpretation technique produces folds that exhibit conservation of volume, which is an objective of cross section balancing (Jamison, 1987).

Fault-bend folding (Jamison, 1987, p. 210) occurs when hanging wall rocks are thrust over a footwall ramp. Rich (1934) introduced this fold model to explain the Pine Mountain Thrust in the southern Appalachians. The forelimb of the fold lies toward the foreland relative to the underlying ramp and the ramp formed prior to the development of the fold.

Fault-propagation folding (Jamison, 1987, p. 209) is also related to thrust ramping. This fold type develops progressively during ramp formation with the fold hinge located at the terminus of the thrust ramp. Displacement on the underlying thrust decreases to zero at the terminus of the ramp. A fault-propagation fold is the result of the strain accumulation at the termination of a thrust fault (Jamison, 1987).

A third model of fold development in thrust terranes is the "break-thrust" model of Willis and Willis (1934), wherein folding occurs prior to faulting. Commonly, an anticline-syncline pair forms with the syncline lying on the foreland side. A subsequent thrust propagates through the limb shared by the folds to form an
out-of-the-syncline thrust with a resulting hanging wall anticline and footwall syncline (Suppe and Medwedeff, 1990).

The locations of these three fold types relative to the thrust fault are characterized by Boyer (1986), who suggested that folds form in three main settings, each with a characteristic geometry:

(1) Trailing-edge ramp anticlines contain two kink bands that develop above footwall ramps. Such anticlines may reflect late movement on a thrust fault where imbricate thrusts initiating at a footwall ramp form a compound anticline (duplex).

(2) Intraplate folds, which accommodate shortening of the thrust plate, are often formed by imbricate thrusts splaying from the underlying thrust detachment. Fold shape varies from a chevron geometry near the core of the fold to a box-like structure with two kink bands higher in the fold.

(3) Leading-edge folds form when folding precedes thrusting, as suggested by Elliott (1976). This is the fault-propagation fold of Suppe and Medwedeff (1984).

**Duplexes**

Duplex development is a result of stress accumulation at thrust ramps and the resulting failure of the footwall. Failure of the footwall ramp produces a horse, a commonly lozenge-shaped unit of rock that is bounded on all sides by faults (Elliott and Johnson, 1980; Boyer and Elliott, 1982). Successive ramp failure toward the foreland results in the formation of a duplex. Boyer and Elliott (1982) presented a model for duplex formation that incorporates footwall failure and the subsequent abandonment of the thrust on top of the horse with the transfer of displacement to the younger thrust underlying the horse. Transport of the horse up a new ramp and the repetitive propagation of another new thrust ramp into the footwall produce a true duplex geometry. The definition of a duplex is "...a thrust system with an imbricate
family of subsidiary contraction faults asymptotically curving downward to a sole or
floor thrust and upward to a roof thrust" (Boyer and Elliott, 1982, p. 1199).

Three types of duplexes are recognized based on their form and the relative
amounts of slip on the subsidiary faults compared to the lengths of the horses. In
order of increasing ratio of slip to horse length, duplex types are (1) hinterland-
dipping duplex, (2) antiformal-stack duplex and, (3) foreland-dipping duplex. These
structures are illustrated by Boyer and Elliott (1982, fig. 12). Cross sections
constructed in thrust belts commonly incorporate duplexes to allow for cross section
balancing.

Hinterland-dipping duplexes are characterized by an imbricate series of
subsidiary thrusts that dip toward the hinterland. This structure forms when slip on
the subsidiary faults is less than the length of the horses involved. The net effect is to
move branch lines, the lines where a subsidiary thrust splays from the major thrust,
closer together (Boyer and Elliott, 1982).

Approximate equality of horse length and subsidiary fault slip results in
clustering of branch lines and stacking of horses atop one another in an antiformal-
stack geometry (Boyer and Elliott, 1982). Folding of each successively higher horse
occurs as they are thrusted over structurally lower, previously formed horses.

In a foreland-dipping duplex, thrusting on the subsidiary faults continues to a
point that each overlying branch line is transported beyond the underlying one.
Structurally higher branch lines that have been thrusted past previous branch lines
result in a network of subsidiary faults that dip toward the foreland. A characteristic
of this structure is the transfer of branch lines that formed on the floor thrust to the
roof thrust (Boyer and Elliott, 1982).
Cross Sections

Cross-sections A-A', B-B', and C-C' were constructed at a scale of 1:100,000 from seismic-reflection data, drill holes, surface geologic data, and published cross sections (Figure 4, Plates 1-3). Cross sections are perpendicular to the surface traces of the major thrust faults in the area. A north-south strike section, D-D', was drawn through the east-west cross sections after the east-west sections were balanced and restored (Figure 2). Stratigraphic thicknesses of Precambrian and Mesozoic units were assumed to be constant across the study area, whereas the Paleozoic rocks were inferred to thin eastward approximately 1%, the result of tectonic quiescence of the miogeocline. The Suppe method (Suppe, 1983) was used to construct the deformed-state cross section geometrically. This technique permitted the seismic-reflection data to be honored in most cases. Adherence to rigid geometric constraints of deformation precluded the inclusion of some seismic-reflection data in the cross sections. Thus, in structurally complex areas, discontinuous or isolated reflectors occasionally were discarded or modified to comply with models of individual thrust structure development of Jamison (1987). These data were considered anomalous due to velocity pull-ups, inadequate processing, or bends in the surface trace of the seismic-reflection line.

Cross-section A-A' was drawn by plotting depth versus shot-point location with Kaleidagraph, and then was scaled to 1:100,000 with no vertical exaggeration using Claris CAD. Cross-section A-A' is a reinterpretation of a cross section by Coogan (1992, Fig. 2).

Cross-section B-B' incorporates seismic-reflection data from four seismic lines. Data points from two seismic-reflection lines were normalized into the line of section. Corrections to these data to project them onto the cross section were necessary to mitigate the effects of a southerly dip of the units. The angle of dip was
calculated from parallel seismic-reflection lines. The greater the distance of the actual position of a shot point from its normalized position, the greater the correction necessary. Cross-section B-B' is a reinterpretation of cross-section 3c by Evans (1991), and includes a reinterpretation of a cross section by Coogan and Royse (1990, Fig. 18) and a cross section by Chidsey (Link et al., 1985, fig. 13). Cross-section C-C' changes orientation at the trace of the Willard thrust, in order to be perpendicular to the Willard thrust, to the Laketown thrust imbricates, and to the Crawford thrust splay to the southeast. This cross section contains data from seven seismic-reflection lines.

The sole thrust on all cross sections is shown as a simplified, planar surface dipping 4° west. In many cases, seismic-reflection lines from which the elevation and form of the sole thrust were taken show considerable local variations in elevation, commonly 200 meters between adjacent shot points. The simplification to a planar surface was based on the assumption that the variations were mostly the result of the data processing and changes in the orientation of the seismic-reflection line relative to the position of the sole thrust. The position of the sole thrust was established on the cross sections by drawing a best-fit straight line through the reflector representing the detachment. The decollement is assumed to dip 3 to 5° to the west based on seismic data and regional cross sections (Coogan and Royse, 1990; Evans, J. P., writ. comm., 1990; Coogan, 1992).

The cross sections have been restored to ensure that they reflect a permissible pre-thrust geometry. These restored cross sections reveal original thrust trajectories and lateral changes in stratigraphic thicknesses when packages of thrust rocks are restored by pulling back the thrust sheets (Dahlstrom, 1969). Line-length balancing of key horizons was the dominant method used. Areas of complex footwall and hanging wall folds, thrust imbricates, and duplexes were balanced by incrementally
reproducing the original area of key stratigraphic intervals in that particular complex
structure or geometry (Cooper and Trayner, 1986; Protzman and Mitra, 1990). Sigma
Scan, version 3.90, from Jandel Scientific, was used to balance areas of the cross
section using a Hitachi digitizer.

All folds are drawn with a kink geometry. Earlier work in thrust belts showed
folds as concentric, cylindrical structures (Dahlstrom, 1969). However, exposed
folds northeast of the Bear Lake Plateau exhibit distinctive kink geometry (Coogan,
wrft. comm., 1991; Oaks, 1993, oral comm.). The techniques of Busk (1929) were
used to project surface data to depth to create a sinusoidal fold and to maintain constant
unit thickness (Boyer, 1986). Studies by Faill (1969, 1973), Laubscher (1977), and
Roeder et al. (1978) indicate most fold-and-thrust belts exhibit kink folding. The
incorporation of the kink style of folding during cross section construction allows the
use of the kinematic modeling technique of Jamison (1987). This method uses three
variables, interlimb angle, ramp dip, and forelimb thickness, to determine the form of
the fold and the initial fold-thrust interaction (Couples et al., 1987).

The strike section (D-D') trends north-south along longitude 111°30'. It was
drawn through the other three cross sections after they were balanced. Construction
of a strike section perpendicular to balanced sections automatically results in a
balanced strike section (Woodward et al., 1985).

Restored Cross Sections

The cross sections were restored to their pre-thrust geometries. These
geometries represent the undeformed miogeoclinal wedge. When thrust displacements
are removed and the original stratigraphy is reconstructed, the original positions of
thrust ramps and flats are restored (Dahlstrom, 1969; Woodward et al., 1985). The
deformed-state cross sections at a scale of 1:100,000 were balanced, then restored,
and subsequently reduced in size to a scale of 1:200,000. The present erosional profile is shown as a dashed line.

Restoration of the deformed-state cross sections provides an estimate of the total shortening that has occurred across this portion of the thrust belt. Also, the shortening ratio, the present length of a deformed block divided by its pre-thrust length, can be calculated. This indicates the degree of internal deformation of an allochthonous block (Dixon, 1982). Calculated thrust displacements represent a minimum distance based on restoration relative to the East Cache Fault. The East Cache Fault represents a loose line, or marker, to record amounts of slip on each stratigraphic horizon in the thrust sheets during restoration. Hanging wall cutoff angles at the leading edge of the thrust sheets were used to reconstruct the angles of thrust ramps west of the East Cache Fault.

Structure-Contour and Isochore Maps

Structure-contour and isochore maps were created from seismic, drill-hole, and surface data. Locations of these data were plotted on the base map at a scale of 1:100,000. These points were then digitized to determine their coordinates. These coordinates were entered into a file to be utilized by the program Gridzo (Rockware, Inc). A file consisted of x and y coordinates denoting map location, a label for the point specified, and a value for z representing elevation above or below mean sea level or isochore thickness in meters. The map location was specified to the nearest meter.

The creation of contour lines by Gridzo entailed several steps. The contour interval was set to 400 meters, and all data were included for each surface of interest. The program created a 20 by 20 cell grid scaled to include all of the data points. Intersections of grid lines served as statistical nodes on which the calculations were made for the paths of the contour lines. The inverse-distance method of gridding
assigns a value to a grid node based on the weighted average of nearby data points. Weighting is determined by the inverse of the distance of adjacent data points from the node.

In order to create maps of large areas at a scale of 1:100,000, some maps plots were scanned using an Apple scanner. Rockware automatically overrides the desired scale settings if the map would be wider than one page. The image was imported into Claris CAD, version 2.0, and scaled to 1:100,000. This process considerably degraded the detail of the original image. Because of this loss of detail, all structure-contour and isochore maps also were traced onto acetate from the rescaled plots. Each map was reduced on a photocopier to a scale of 1:200,000 or 1:400,000 (see appendices). Minor distortions of the structure-contour and isochore maps result from the photo-reduction.

**Concealed Thrust Trace Map**

A concealed thrust trace map was constructed to show structures in relation to exposed bedrock and beneath widespread Tertiary and Quaternary sediments. This map is a valuable tool in unraveling the tectonic evolution of the region (Rodgers and Janecke, 1992). The concealed thrust trace map shows the structures that immediately underlie the lowest Tertiary rocks. Data were taken from deformed-state cross sections, drill-holes, seismic-reflection lines, and both published and unpublished geologic maps. Published maps include Richardson (1941), Mullens and Izett (1963), Ott and Kreckel (1982), Valenti (1982a,b), Walker (1982), Davis (1985), Dover (1985), Blackstone and DeBruin (1987), Evans (1990), Oaks and Runnels (1992), and petroleum-industry geologic maps. Sources of unpublished mapping include Hafen (1961), Hansen (1964), Smith (1965), Blau (1975), Rauzi (1979), and Kienast (1985).
**Palinspastic Maps**

Palinspastic maps were constructed from the restored cross sections to illustrate the approximate pre-thrust geologic conditions in the Middle Cretaceous. The amounts of shortening restored on the thrusts were taken from Table 4. The surface traces of the restored thrust faults are plotted to show their original positions and sequential geometric relationships with other thrust faults.

Several assumptions were necessary in the construction of the palinspastic maps. The direction of Cenozoic extension and earlier thrusting was assumed to parallel the cross sections. The locations of structures in adjacent restored cross sections were connected with roughly north-south lines between structures in each section. The palinspastic map constrains an area of uncertainty in the regional palinspastic reconstructions of Levy and Christie-Blick (1989). They relied heavily on prior studies of thrusting in north-central Utah (Royse et al., 1975; Dixon, 1982; Yonkee et al., 1989). This study provides a more detailed estimate of thrusting for Levy and Christie-Blick's regional reconstruction.

**Analysis of Surface Data**

Surface data across the southern portion of the field area were analyzed to determine the orientation of fold axes. Figure 5 shows a Kamb contour and scatter plot of fold-axis orientations near the southern boundary of the field area. Sources of these data include published maps (Dover, 1985), and unpublished maps by Hafen (1961), Hansen (1964), Smith (1965), Blau (1975), Rauzi (1979), and Kienast (1985). Bedding orientations were traced from these maps onto overlays and then grouped by similar orientations. Adjacent groups of bedding data were combined to
Figure 5. Scatter plot and Kamb contour of fold axes near the south boundary of the study area.

determine the orientation of the fold axes (see Appendix B, Table 7). The locations and orientations of folds identified from surface data and their positions relative to thrusts are shown in Appendix B, Figure 22. The computer program Stereonet, version 4.1, was used in the analysis. These data were used to define the fold shape and orientation and to relate it to thrusts in the subsurface. Bedrock data proved useful in this regard, but orientation data from the Tertiary Wasatch Formation were too scarce to yield valid results.

A Kamb contour and scatter plot of the data indicate that fold orientations fall into two subsets. The mean vector of each subset plots similar to the orientation of the Logan Peak syncline. The stereonet indicates an east-southeast orientation of principle stress. Cross sections suggest the principal stress direction was constant during
shortening on the Paris and Willard thrusts, and that folding associated with the Bear River duplex resulted from a similar principal stress orientation.

**Thickness of Tertiary Sediments**

The thickness of Tertiary rocks was estimated in one of two ways. A maximum thickness of 457m (1500 feet) was assumed for the Eocene Wasatch Formation throughout the study area based on seismic-reflection and drill-hole data. Where depth to pre-Tertiary rocks exceeded 457m, the balance was assumed to be comprised of younger Tertiary strata. Where well control was dense, isochore maps were constructed to estimate the thickness of Tertiary rocks between nearby seismic-reflection lines. However, in most areas, sparse drill-hole data made less precise methods of estimating thicknesses necessary. The elevation of each shot point was estimated from topographic maps. The elevation of the top of pre-Tertiary rocks with respect to mean sea level was either picked or estimated from the seismic-reflection profile depending upon the quality of the data. In all areas of Tertiary rock outcrops, the Tertiary thicknesses were estimated at each shot point in this manner.

**Cross-section A-A’**

Cross-section A-A’ extends 41.75 km from 111° to 111°30’ West longitude, just south of latitude 42° North. Eight thrusts are depicted, most of which step down-to-the-west with a ramp-flat geometry. In the west, the Paris and Willard thrusts and a Laketown thrust splay are folded into a broad anticline. The leading edge of the Meade thrust is cut by the Bear Lake normal fault and overturned by the formation of a large fault-bend fold in its footwall associated with the Home Canyon thrust. The hanging wall of the normal fault is buried by thick Cenozoic sediments. In the east, the Crawford thrust climbs a series of ramps to a Mesozoic detachment.
The hanging wall of the Paris thrust consists of a section of Cambrian-
Precambrian Geertsen Canyon through Ordovician strata. The thrust is exposed near
the western shore of Bear Lake. The Paris thrust is underlain by the Willard thrust,
which is shown to have a similar geometry to the Paris thrust. The Willard thrust plate
is inferred to consist of Cambrian-Precambrian Geertsen Canyon Quartzite at the base
overlain by lower Paleozoic rocks. The Willard thrust ramps over Triassic rocks just
prior to surfacing beneath the Tertiary sediments of Bear Lake.

The Paris and Willard thrusts are folded by the underlying Laketown thrust.
Two splays of the Laketown thrust repeat upper Paleozoic strata. Splaying of the
Laketown thrust near its northern extent provides the necessary stratigraphic thickness
to fill the interval between the Laketown thrust and the overlying Willard thrust.
Folding of the Paris and Willard thrusts into the east-dipping limb of the broad
syncline shown in the western part of the section is a result of fault-bend fold
development at depth. This fold formed as a result of the Laketown thrust ramping to
a higher detachment in the upper Paleozoic section and the subsequent pinning of the
lowest Paleozoic rocks on the fault plane, followed by folding of the hanging wall
rocks. Slip on the Laketown thrust was transferred to a detachment in the middle of
the upper Paleozoic section. This detachment accommodates slip on the imbricates
above the main Laketown thrust fault. These upper Paleozoic rocks ramp over
Triassic sediments to a flat atop the Jurassic Nugget Sandstone until the thrust surfaces
beneath the lacustrine sediments of the east-central portion of Bear Lake.

The normal fault depicted in the Tertiary and Quaternary sediments of Bear
Lake is taken from the work of Skeen (1975). Detailed, shallow seismic-reflection
surveys of the graben-fill indicate that the normal faults are a late stage product of
extension on the main Bear Lake normal fault. Displacement on these normal faults is
\leq 100$ meters.
The Laketown and Meade thrusts branch from the sole thrust onto a common detachment approximately 4.1 km east of 111°30'. The Meade thrust sheet consists of uppermost Paleozoic rocks overlain by Triassic and Jurassic strata. The detachment beneath the upper Paleozoic rocks is at the same stratigraphic level as found in the Laketown thrust plate. The Meade thrust ramps over Mesozoic rocks and surfaces 5.2 km east of the Bear Lake fault. The easternmost portion of the Meade thrust is overturned to the east where it is underlain by an anticline in the hanging wall of the Home Canyon thrust. The small east-dipping fault that surfaces 1.15 km west of the Meade thrust is interpreted as a minor back-thrust associated with later movements on the Home Canyon thrust. A syncline in the hanging wall of the Meade thrust has an east-dipping to nearly vertical west limb. Farther south, the west limb is overturned to the east. This folding is the result of a steep Meade thrust splay that now accommodates the normal fault movement of the Bear Lake fault. Normal fault slip is estimated at 4.85 km from the cross section. This normal fault effectively beheads the toe of the Meade thrust and continues downward and occupies a thrust ramp on the underlying Home Canyon thrust.

The Home Canyon thrust ramps Paleozoic rocks from the sole thrust to a flat atop upper Paleozoic rocks. This deep ramp is reactivated by the Bear Lake normal fault and transfers Cenozoic extension from the surface to the regional decollement on a listric normal fault. The Home Canyon thrust ramps beneath the surface exposure of the Bear Lake normal fault to a detachment atop the Jurassic Nugget Sandstone in the Gypsum Springs Member of the Jurassic Twin Creek Limestone. The lower Paleozoic rocks become pinned on the ramp, transferring slip to the overlying upper Paleozoic units. The upper Paleozoic rocks and the overlying Mesozoic units become locked on the flat to produce an upper Paleozoic-cored anticline that is overturned to the east. This hanging wall fold has a generally concentric geometry based on
seismic-reflection and drill-hole data, and the work of Coogan (1992). Continued slip on the Home Canyon thrust results in several thrust splays that generally flatten to the east. Deformation associated with thrusting on these splays is accommodated by widespread disharmonic folding in the thinly bedded siltstones and limestones of the Jurassic Twin Creek Limestone. The Home Canyon thrust continues along the top of the Jurassic Nugget Sandstone and surfaces to the base of the Tertiary Wasatch Formation near the east end of the cross section.

The Crawford thrust underlies these structures and begins ramping from the sole thrust beneath the surface exposure of the Bear Lake fault. The thrust carries lower Paleozoic through Jurassic rocks over a long ramp of lower Paleozoic rocks through the Jurassic Twin Creek Limestone in the footwall. A small Crawford thrust splay branches near the end of the ramp. This splay deforms overlying strata, forming a fault-propagation fold, the Pegram anticline. The Crawford thrust occupies a gently west-dipping flat in the Jurassic Twin Creek Limestone before ramping to the surface off the east end of the section.

The footwall of the Crawford thrust is transported eastward along the sole detachment. The Absaroka thrust branches from the sole decollement approximately 17.7 km west of the Utah-Wyoming border, which is beyond the scope of this work.

**Cross-section B-B’**

This cross section extends from the Range 1 West / 1 East boundary 77.1 km east to 111° West longitude. The East Cache Fault dominates the west end of the section, cutting several thrusts and a large duplex in its footwall. Ten west-dipping thrusts are divided into two thrust systems. The older, structurally higher thrust system consists of the Bear Canyon, upper and lower Paris, and Willard thrusts. The Bear River duplex, Laketown, Meade, Home Canyon, Sheep Creek, and Crawford
thrusts comprise the lower thrust system. The Laketown thrust sheet is folded by imbricates of the underlying Meade thrust. The Home Canyon thrust is similarly folded by a large fault-propagation fold atop the Sheep Creek thrust. The Crawford thrust climbs to the surface near the Utah-Wyoming border. The listric Crawford normal fault soles into the Crawford thrust, indicating reactivation of the thrust by Cenozoic extension.

The geometry of the East Cache fault is taken from a nearby cross section from Evans (1991). The initial 70° dip of the fault plane is interpreted to flatten with depth to a listric geometry based on the interpretation of seismic-reflection lines in Cache Valley. These data also indicate the amount of eastward dip of the Paleozoic rocks underlying the Tertiary and Quaternary basin fill.

The Bear River duplex (here named) underlying the western Bear River Range is not conclusively indicated on seismic-reflection lines. Its existence is inferred to explain the east-dipping limb of the Logan Peak syncline and to fill a stratigraphic gap. The Cambrian to Pennsylvanian rocks exposed at the surface of the syncline and the stratigraphic thicknesses of the underlying Late Proterozoic rocks do not fill the area down to the basal decollement. A single, thick horse consisting of Late Proterozoic Facer Formation to the base of the Late Proterozoic Mutual Formation was originally hypothesized to fill the gap. This single horse geometry required very low-angle hanging wall cutoffs. A foreland-dipping duplex, consisting of two horses, was judged more likely based on more reasonable hanging wall cutoff angles and favorable location of potential detachment horizons. The presence of a duplex is supported by Williams (1948) and Evans (1990) who suggest that present-day Cache Valley was occupied by a broad anticline before Basin and Range extension based on restoration of Paleozoic rocks on either side of the East Cache fault and pre-Tertiary subcrop patterns between the Wasatch and Bear River Ranges.
An alternative hypothesis for the origin of the Logan Peak syncline is flexure of the footwall of the East Cache fault to form the west limb of the fold. The orientation of Tertiary sediments with underlying Paleozoic rocks in the western Bear River Range does not support this idea. Brummer (1991) identified gravity-emplaced slide-blocks of the Tertiary Salt Lake Group overlying lower Paleozoic rocks in the west limb of the syncline as the only possible depositional contact.

The highest thrust on the cross section is the Bear Canyon thrust, transported on a decollement in the Late Proterozoic Papoose Creek Formation. The basic evidence for the Bear Canyon thrust is the presence of a strong reflector at the approximate base of the Late Proterozoic Papoose Creek Formation and the surface exposure of the thrust southwest of Mantua, Utah (Crittenden and Sorensen, 1985a). Thrust displacement decreases to zero where the interbedded shales in the Papoose Creek Formation and overlying lower Caddy Canyon Quartzite have been completely thinned by transport along the thrust fault. Near longitude 111°30', the Bear Canyon thrust sheet is folded into a hanging wall anticline due to uplift on underlying thrusts. A series of down-to-the-east normal faults, with slip ranging from 100 to 150 meters, are shown on seismic-reflection data to sole into the Bear Canyon thrust. The Bear Canyon thrust forms a horse where it terminates against the underlying upper Paris thrust.

The Paris thrust is inferred to splay into an upper and lower fault based on seismic-reflection data. The upper Paris Thrust carries a section of Late Proterozoic Papoose Creek Formation through Cambrian-Precambrian Geertsen Canyon Formation that ramps onto a flat atop lower Paleozoic rocks. A thrust splay offsets overlying Bear Canyon thrust plate rocks and was reactivated as a normal fault during Cenozoic extension. The thrust surfaces approximately 2.8 km east of 111°30' in Strawberry Valley, where Cenozoic normal fault displacement is now accommodated.
on the reactivated thrust fault. The upper Paris thrust plate forms the lower horse in a
gameology resembling a hinterland-dipping duplex in conjunction with the overlying
Bear Canyon thrust sheet.

The lower Paris thrust branches from the upper Paris thrust at a point west of
the East Cache fault. The lower Paris thrust follows a flat atop lower Paleozoic rocks,
transporting the Late Proterozoic Mutual Formation and overlying units along the fault
until it surfaces near 8.2 km east of 111°30'. The near surface lower Paris thrust ramp
is reactivated by a normal fault surfacing 4.5 km east of 111°30' and accommodates
approximately 350 meters of normal slip.

The Willard thrust places a Cambrian-Precambrian Geertsen Canyon Quartzite
through lower Paleozoic section over upper Paleozoic footwall rocks along its length,
except the leading edge where Geertsen Canyon Quartzite overlies Triassic rocks. The
Willard thrust branches from the lower Paris thrust approximately 8.8 km west of
111°30' in the subsurface, and follows a long flat in upper Paleozoic rocks. The
thrust ramps through the rest of the upper Paleozoic section and overlying Triassic
rocks and surfaces 12.6 km east of 111°30'.

The Laketown thrust branches from the sole thrust approximately 13.4 km east
of the East Cache fault. The Cambrian through upper Paleozoic section initially ramps
over lower Paleozoic footwall rocks at a low angle. The thrust climbs to a flat in
upper Triassic rocks followed by a flat atop the Jurassic Nugget Sandstone. The
Laketown thrust surfaces near the location of the Marathon Otter Creek well as a series
of splays based on drill-hole data from the Petroleum Information Corporation
(unpubl. data). The imbricate stack of thrusts alternates packages of lower Paleozoic
and Jurassic rocks. This structure resembles an imbricate pattern interpreted
approximately 22 km north of the section, at the mouth of South Eden Canyon, where
Coogan and Royse (1990) documented a decollement within the Gypsum Springs
member of the Jurassic Twin Creek Limestone. They concluded that the tight, disharmonic folds "...represent shortening in front of and beneath the Laketown thrust sheet that formed as the thrust plane cut upsection from a Pennsylvanian through Triassic decollement level to the decollement in the Gypsum Springs seen at Laketown" (Coogan and Royse, 1990, p. 113). The most eastward splay rises to the base of the overlying Tertiary Wasatch Formation approximately 16.6 km west of the Utah-Wyoming border.

Approximately 6.2 km east of the point where the Laketown thrust branches from the regional decollement, the Meade thrust separates from the sole thrust at a low angle. The thrust occupies a flat atop the upper Paleozoic, only to ramp up a greatly thinned section of Triassic rocks at a very gentle angle. As the thrust overrides the Jurassic Nugget Sandstone in the footwall, a series of thick imbricates of Paleozoic hanging wall rocks form in a break-forward sequence. Successive formation of these imbricates uplifts and folds the overlying Laketown thrust sheet into a broad, open anticline. In addition, the Triassic section is greatly thickened east of the imbricates. The thinly bedded siltstones and limestones of the Triassic section are assumed to flow during thrusting.

East of the imbricated leading edge of the Meade thrust, the Home Canyon thrust displaces Triassic and Jurassic rocks along the top of the Jurassic Nugget. The Triassic rocks carried on the thrust are thinned as a result of the tendency for Triassic rocks to be "smeared out" (Link et al., 1985, p. 280) during thrusting. The Home Canyon thrust ramps through the Jurassic Twin Creek Limestone and surfaces approximately 10 km west of the Utah-Wyoming border, based on poor seismic-reflection data and geologic mapping (Coogan, 1991).

The Sheep Creek thrust splays from the sole 5.6 km east of 111°30'. The relatively steep ramp angle decreases in upper Triassic rocks where brittle thrust
deformation gives way to the development of a large fault-propagation fold. The east limb of the resulting hanging wall anticline is nearly vertical to overturned to the east. Development of the fold thinned the Triassic rocks in the trailing limb and thickened the Triassic rocks in the forelimb. Footwall Triassic rocks were also thickened by a combination of thrust imbrication and footwall folding. The Sheep Creek thrust folds the overlying Home Canyon thrust and creates a thick package of the Jurassic Twin Creek Limestone in the Home Canyon thrust sheet.

The Crawford thrust transports a section of Paleozoic and Mesozoic rocks. The thrust ramps steeply from the sole thrust at a point 21.4 km west of the Utah-Wyoming border until occupying a flat in the Jurassic Twin Creek Limestone. The toe of the Crawford thrust sheet is deformed by several thrust imbricates and the formation of a hanging wall anticline. A model for the formation of these structures is found in the splay off the Crawford thrust on cross-section C-C'. Fault-propagation folds formed in the hanging wall followed by continuing propagation and splaying of the thrust. These thrust splays have been reactivated by slip on the Crawford normal fault 1.8 km west of the Utah-Wyoming border on the west flank of the Crawford Mountains. The footwall of the ramp consists of a thick section of Paleozoic through Cretaceous rocks. Estimated displacement on the listric, west-dipping normal fault of 2300 meters was followed by the accumulation of approximately 1100 meters of graben fill.

The Absaroka thrust ramps upward from the sole decollement approximately 12.1 km west of the Utah-Wyoming border and surfaces east of the section. The Absaroka thrust plate consists of a thick Paleozoic through Cretaceous sequence. The Paleozoic and Mesozoic footwall rocks are the trailing edge of the Hogsback thrust sheet.
**Cross-section C-C'**

Cross-section C-C' extends 44.7 km east-southeast from the Range 1 West / 1 East boundary to the buried leading edge of the Willard thrust, where the section changes orientation to the southeast and continues 29 km to the Utah-Wyoming border. The west end of the section is the East Cache Fault zone. The normal faulting offsets several thrusts and a duplex at depth. Seven thrusts are organized into an upper thrust system (Bear Canyon, upper and lower Paris, and Willard thrusts), and a lower system (Laketown, Crawford, and Absaroka thrusts). Fault-bend folding is the dominant style of deformation on the structurally highest thrusts. The footwall of the Willard thrust consists of a foreland-dipping duplex and a thrust imbricate. The southernmost splays of the Laketown thrust underlie the imbricate. Splays of the Crawford thrust branch steeply from the main thrust several kilometers southeast of the Laketown splays. Near the Utah-Wyoming border, a Cenozoic normal fault soles into the reactivated Crawford thrust.

The stratigraphy underlying Cache Valley and the geometry of the East Cache fault is described in Evans (1991). The thickness of the Tertiary and Quaternary basin fill sediments is estimated at 2235 meters based on seismic-reflection lines and drill-hole data from the Amoco Lynn Reese well. Cross-section C-C' shows 2800 meters of Tertiary and younger sediments atop the underlying Paleozoic rocks. The East Cache fault is not depicted as a single, discrete fault plane. The fault splays at the south end of Cache Valley, distributing movement on multiple planes creating a zone of faulting with a cumulative net slip of 7.6 to 8.1 km (Evans, 1991). The fault dips at nearly 70° near the surface (Evans, 1991) and the angle decreases to approximately 35° at depth.
The formation of the Logan Peak syncline in the westernmost Bear River Range is attributed to a large duplex at depth as a result of a stratigraphic gap between the sole thrust and the units oldest exposed at the surface. Seismic-reflection data indicate the west limb of the fold dips east at approximately 20° and corresponds generally to surface orientations. The horses are located in the Crawford thrust plate and are comprised of upper and lower Paleozoic rocks. The shape of the syncline gradually tightens to the south based on comparison with section B-B'. The horse folds the overlying Bear Canyon, Paris, and Willard thrusts. The interlimb angle of the horse indicates a ramp angle of approximately 17° based on the work of Jamison (1987).

The Bear Canyon thrust is the structurally highest thrust in the section and it is transported on a detachment in the Late Proterozoic Papoose Creek Formation. Seismic-reflection data indicate normal faults in the vicinity of South Cottonwood Canyon, T10N, R3E, are relatively shallow and sole into a ramp on the Bear Canyon thrust. Slip on these normal faults range from approximately 75 to 300 meters. The decollement in the Papoose Creek Formation accommodates both shortening and extension. The Bear Canyon thrust is folded into an anticline with the axis just west of Ant Valley. The Bear Canyon thrust terminates against the underlying upper Paris thrust, forming the uppermost horse of a very large hinterland-dipping duplex.

The horse underlying the Bear Canyon thrust is the upper Paris thrust plate. The upper Paris thrust carries a section of Late Proterozoic Papoose Creek Formation through Cambrian-Precambrian Geertsen Canyon Formation that ramps onto a flat atop the Late Proterozoic Mutual Formation. A splay from this flat cuts through overlying Bear Canyon thrust plate rocks at a high angle with minimal displacement, on the order of 175 meters. The thrust continues along the flat until it is inferred to ramp to the surface through upper Proterozoic and lower Paleozoic rocks 1.7 km west
of 111°30'. This fault plane now accommodates Cenozoic normal fault displacement of approximately 100 meters. The overall geometry of the upper Paris thrust plate is a fault-bend fold. Later thrusting has uplifted and tilted the thrust sheets toward the hinterland. The original geometry of these two thrust plates resembled an antiformal-stack to foreland-dipping duplex. The present geometry is that of a hinterland-dipping duplex.

The lower Paris thrust branches from the older upper Paris thrust 12.2 km west of 111°30'. The lower Paris thrust follows a decollement at the base of the Late Proterozoic Caddy Canyon Formation to a long flat atop the lower Paleozoic rocks. The hanging wall is composed of Late Proterozoic to Silurian rocks that form a hanging wall anticline as a result of fault-bend folding. This is the structurally lowest horse in the large hinterland-dipping duplex composed of the Bear Canyon thrust plate, and the upper and lower Paris thrust plates.

The Willard thrust carries a Late Proterozoic Mutual Formation through lower Paleozoic section. The Willard thrust branches from the Paris thrust system at a point beneath the Logan Peak syncline. The thrust initially follows a flat atop upper Paleozoic rocks, but later ramps over lower Triassic rocks 8.5 km west-northwest of 111°30'. The Triassic rocks are apparently bounded on all sides by the Willard thrust forming a duplex geometry based on seismic-reflection data and the absence of lower Triassic rocks in the Willard thrust imbricate to the west. Based on the magnitude of net slip on the Willard thrust and the length of subsidiary faults, the lower Triassic rocks in the duplex underlying the Willard thrust are inferred to have a foreland-dipping geometry. The Willard thrust plate is carried to the surface on an increasingly steep series of ramps. The Willard thrust surfaces to the base of the Tertiary Wasatch Formation at the bend in section C-C', 12 km east-southeast of 111°30'. The footwall of the thrust is a highly deformed imbricate stack.
As the Willard thrust climbed through the Mesozoic section, displacement was transferred to a series of detachments in the Triassic rocks in a break-forward sequence. A relatively undeformed wedge of Mesozoic footwall rocks caps a thick upper Triassic section where the Willard thrust hanging wall overlays the Jurassic Twin Creek Limestone. The formation of the structurally highest thrusts in the imbricate package in the Triassic Ankareh and Thaynes Formations correspond to duplex development in the underlying Triassic Dinwoody and Woodside Formations. The thrusts repeatedly splay from a detachment in lower Triassic rocks and climb to the top of the Nugget Sandstone. A greatly thickened section of upper Triassic rocks rests atop a doubled thickness of Jurassic Nugget Sandstone (Ott and Kreckel, 1982). This records the failure of early footwalls in the formation of the duplex. The presence of the lower Triassic decollement enabled the foreland-dipping duplex to form in the footwall of the Willard thrust, and promoted the formation of the imbricate stack of thrusts immediately southeast of the Willard thrust leading edge.

During movement on the Laketown thrust, a thrust climbed to a detachment atop the Jurassic Nugget Sandstone, pushing a beam of competent Nugget Sandstone along this fault plane, doubling Nugget thickness. The Twin Creek Limestone is a proven decollement horizon (Coogan and Royse, 1990) that here accommodates early Laketown thrust movement. Slip on the lowest thrusts folded overlying thrusts, forming a small footwall anticline. The thrusts that surface southeast of the American Quasar 19-1 well, and those that form the anticline below the well, are the south portions of the Laketown thrust.

The Crawford thrust carries a thick section of Paleozoic rocks in the west and a Paleozoic section, minus the lower Cambrian, plus Mesozoic rocks in the east. The hanging wall rocks are passively transported east of the duplex underlying the western Bear River Range until lower Cambrian rocks become pinned on a ramp opposite
Cretaceous footwall rocks. The locking of lower Cambrian rocks forms a fault-bend fold in the hanging wall and initiates the development of a series of thrust imbricates that surface at a point 10 to 10.8 km southeast of the bend in section. Fault-propagation folding is the dominant style of deformation in the hanging wall. Hanging wall and footwall rocks are folded into an anticline-syncline pair that is cut by thrusting. The Crawford thrust ramps gradually to the east over Cretaceous rocks until it climbs to the base of overlying Tertiary and Quaternary sediments 3.8 km northwest of the Utah-Wyoming border. This steep ramp has been reactivated by the west-northwest-dipping Crawford normal fault and is composed of Cretaceous rocks. Cenozoic slip and subsequent sedimentation of the half-graben has resulted in the accumulation of approximately 700 meters of Tertiary and Quaternary sediments.

The Absaroka thrust branches from the sole decollement approximately 13.3 km northwest of the Utah-Wyoming border. The Absaroka thrust plate consists of a thick Paleozoic through Cretaceous section that ramps to the surface southeast of the section. The footwall rocks are the trailing edge of the Hogsback thrust plate.

**Strike Section D-D’**

The strike section illustrates structural and stratigraphic relationships at longitude 111°30’West. The Willard thrust separates the upper thrust system (upper and lower Paris thrust, Willard thrust), which carries Late Proterozoic to lower Paleozoic rocks, from the lower thrust system (Laketown, Meade, and Crawford thrusts) that transports lower Paleozoic through Triassic rocks. Lateral ramps are more prominent in the lower thrust system. At the south end of the section all beds and thrusts, except the lower splay of the Willard thrust, have a component of north dip reflecting uplift of the Ogden duplex to the south. To the north, there is no consistent dip direction.
The upper Paris thrust cuts downsection slightly to the south in the hanging wall in Late Proterozoic rocks. The underlying lower Paris thrust similarly cuts downsection to the south from a point 5.1 km north of the center cross section where it merges with the Willard thrust. North of the intersection point, the Willard thrust carries an uppermost Late Proterozoic and Paleozoic section as it laterally ramps up in the footwall over repeated upper Paleozoic footwall rocks of the imbricated Laketown thrust hanging wall. The folding in the Willard thrust plate is not reflected in the overlying upper Paris thrust sheet. This suggests that the upper Paris thrust may post-date the Willard thrust. However, no additional evidence supports this possibility of younger thrusting farther from the craton. South of the point of intersection, the Willard thrust cuts downsection in the hanging wall and footwall to include Late Proterozoic Mutual Formation in its hanging wall as it rises gradually to the south. At the south end of the section, the Willard thrust bounds a duplex of lower Triassic rocks immediately south of the intersection of the Willard and Laketown thrusts. The Willard thrust cuts steeply across the Paleozoic rocks of the footwall.

At longitude 111°30', the Laketown thrust transports a hanging wall flat of Paleozoic rocks that ramps up to the south in the footwall until it intersects the overlying Willard thrust. At the north end of the section, the Laketown and Meade thrusts share a common thrust plane. They diverge as the Laketown thrust dips more shallowly southward than the underlying Meade thrust, which ramps down to the south in the footwall. The Paleozoic rocks of the Meade thrust sheet thicken considerably to the south and become the Crawford thrust plate. The Meade and Crawford thrusts share a common basal detachment, branching from the sole thrust at a point approximately 7.9 km from the south end of the section. The Crawford thrust ramps up in the footwall to the south over Paleozoic and lower Triassic rocks. The
regional decollement ramps upward from the center of the section, gently to the north and slightly more steeply to the south.

**Restored Cross-section A-A'**

Restoration of cross-section A-A' removes the thrust displacement, thrust sheet deformation, and the structural complexities introduced by large-scale normal faulting overprinting stacked and folded thrusts. The pin line is located approximately 1.75 km from the east end of the deformed-state cross section. This location marks the easternmost limit of relatively little-deformed Crawford thrust hanging wall rocks. No restoration of the Paris and Willard thrusts was attempted due to a lack of data west of 111°30'West. The base of the 3.85 km thick thrust sheet which rests atop the Crawford thrust ranges from lower Paleozoic up to the top of the Jurassic Nugget Sandstone. From the east end of the restored section, three Home Canyon thrust splays branch from the main thrust with interthrust angles between 41° and 43°. The Home Canyon thrust rises from the sole thrust at an initial angle of 16° as it ramps through Paleozoic rocks to a flat at the base of the Triassic rocks. The Home Canyon thrust ramps up from the lower Paleozoic to Jurassic Nugget Sandstone over a shorter distance than the Meade thrust.

The Meade thrust overlies the Home Canyon thrust and shares a ramp from the regional decollement with the Laketown thrust. The ramp maintains a 19° angle with the sole thrust until reaching a flat in the upper Paleozoic section. A short ramp connects this flat with another at the base of the Triassic rocks. From this flat, the Meade thrust splays into two thrusts, one with a 28° initial ramp angle that now accommodates normal fault movement as the Bear Lake fault, and another with a 14° ramp that steps up to a detachment atop the Jurassic Nugget Sandstone.
The next structurally higher thrust on cross-section A-A' is the Laketown thrust. As stated above, the Laketown thrust shares the initial ramp and flat from the sole thrust with the Meade thrust. The Laketown thrust ramps up to a flat above the Jurassic Nugget Sandstone in a short distance in contrast to the more gently dipping Meade thrust. Only the lowest Laketown thrust splay was restored.

The restored cross section indicates important detachment horizons in the Jurassic Twin Creek Limestone, in lower Triassic rocks, and at the base of the Cambrian section. Another detachment in middle upper Paleozoic rocks accommodates displacement on the Laketown and Meade thrusts. Branch angles of thrusts from the sole thrust range from 13-15°, whereas thrusts propagating through Mesozoic rocks branch from the lower Triassic detachment at angles of 16 to 19°. Steep splays of the Home Canyon thrust are the result of progressive uplift of older splays by younger splays.

**Restored Cross-section B-B'**

The restoration of cross-section B-B' produces a lengthy model of the reconstructed miogeoclinal wedge. The pin line is located in the Crawford thrust plate approximately 16 km from the east end of the section. The pin line spans a 3.4 km thick lower Paleozoic through lower Jurassic section in the Crawford thrust sheet and Mesozoic rocks of the Home Canyon thrust sheet.

West of the pin line, the Sheep Creek thrust ramps up from the lower Paleozoic up to the middle Triassic. The ramp branches from the sole at an angle of 15°, but the angle decreases to approximately 7° in the middle Triassic before the thrust terminates in upper Triassic rocks.

The Home Canyon and Meade thrusts share an initial 15° ramp from the regional decollement and a flat atop the upper Paleozoic. The next ramp
accommodates both the imbrication of the Meade thrust hanging wall and later thrusting on the Home Canyon thrust to a long flat atop the Jurassic Nugget Sandstone. The Meade thrust ramps from lower Paleozaic rocks to the Jurassic over a much shorter distance along cross-section B-B’ than A-A’.

The next structure toward the hinterland is the Bear River duplex. The duplex is shown to consist of two horses of Paleozaic rocks. Hanging wall cutoff angles indicate the upper horse was thrust up a 36° ramp, whereas the lower horse was transported across a 7° ramp. Development of the duplex occurred approximately 9 km east of the ramp which separates the Laketown thrust from the sole thrust.

The Laketown thrust cuts through lowest Paleozaic rocks at an angle of 5°. This ramp angle increases to 15° approximately 500 meters above the base of the lower Paleozaic, until a long flat atop the upper Paleozaic is reached. A 17° ramp angle through Triassic rocks decreases due to flowage of Triassic rocks in the footwall to an angle of about 12°. A short, steep ramp leads to a flat on the Jurassic Nugget Sandstone. A shallow, 3.5° ramp through the overlying Jurassic Twin Creek Limestone is shown as the base of the imbricate thrust complex at the leading edge of the Laketown thrust.

Willard thrust separates from the sole thrust along an 11° ramp at the base of the Cambrian-Precambrian Geertsen Canyon Quartzite to reach a flat in middle Cambrian rocks. A short ramp up to a detachment in the middle-upper Paleozaic rocks leads to the steep remnant of a ramp into the overlying Triassic rocks. The Willard thrust is the easternmost thrust in the study area to involve a decollement in rocks older than lower Cambrian and is the deepest fault of the upper thrust system. From the Willard thrust westward, each fault separates from the sole thrust at progressively deeper stratigraphic levels.
The lower Paris thrust transports a sheet comprised of Late Proterozoic Mutual Formation at the base through uppermost lower Paleozoic up a 10° ramp. A flat atop the Cambrian-Precambrian is followed by a 12° ramp to a flat near the top of the lower Paleozoic. The upper Paris thrust carries a Late Proterozoic Perry Canyon Formation through Cambrian-Precambrian Geertsen Canyon Quartzite section up a 35° ramp to a detachment atop the Geertsen Canyon Quartzite. The thrust sheet is transported up a 12° ramp to a flat atop the lower Paleozoic.

The Bear Canyon thrust exhibits several similarities with the upper Paris thrust. A section of Late Proterozoic Perry Canyon Formation through upper Paleozoic rocks is thrust up a steep, 47° ramp to at least the Cambrian-Precambrian Geertsen Canyon Quartzite where the thrust terminates along a flat.

Restoration of thrusting highlights key detachment levels in the Jurassic Twin Creek Limestone, lower Triassic and basal Cambrian rocks, and at the base of the Cambrian-Precambrian Geertsen Canyon Quartzite, and Late Proterozoic Mutual and Papoose Creek Formations. Minor detachment horizons exist in the upper Triassic, middle upper Paleozoic, and uppermost lower Paleozoic rocks. Thrusts separate from the sole thrust through Late Proterozoic and Paleozoic rocks at angles less than 15° east of the upper Paris thrust sheet, except for the steep 35° Bear River duplex. The upper Paris thrust and Bear Canyon thrust angles range from 35° to 47° based on hanging wall cutoff angles.

**Restored Cross-section C-C'**

Restored cross-section C-C' is characterized by long ramps and detachments in the east and center, compared to shorter ramps and flats in the west. The pin line is located approximately 11 km west-southwest of Woodruff, Utah, in the hanging wall of the Crawford thrust splay. The pin line is drawn through a 3.5-km thick section of
Ordovician through Jurassic rocks. The Crawford thrust splay carried these units up a steep 47° ramp that is now shallower due to footwall deformation. The main Crawford thrust steps down to a long detachment at the base of the Cambrian across a short ramp 6.2 km west of the splay.

Splays of the Laketown thrust overlie the Crawford thrust fault. These splays separate from the older Willard thrust and share a ramp with the Willard thrust up to their present level in Triassic rocks. Together, these splays southeast of the complex Willard thrust footwall imbricate account for 21.3 km of shortening. This Laketown thrust deformation is accommodated entirely within Mesozoic rocks.

The Willard thrust steps downsection to the west and transports a section of Late Proterozoic Mutual Formation through upper Cambrian rocks up a long ramp to the surface with an initial angle of 23°. The ramp angle shallows slightly where lower Triassic rocks comprise the footwall, but approaches an angle close to the initial value as it climbs higher in the section. Considerable shortening is accommodated by the formation of an imbricate stack of five thrusts, and a thrust with a relatively undeformed section of Mesozoic rocks in the hanging wall, in the Willard footwall.

The lower Paris thrust displaces Late Proterozoic Caddy Canyon Quartzite through lower Paleozoic rocks up a 26° ramp to a long flat near the top of the lower Paleozoic. The upper Paris thrust carries a Late Proterozoic Kelley Canyon Formation through Geertsen Canyon Quartzite section up a 23° ramp to a short flat atop the Late Proterozoic Mutual Formation.

The Bear Canyon thrust plate consists of a Late Proterozoic Kelley Canyon Formation through upper Paleozoic section. The thrust sheet was transported up a short, 35° ramp. A flat atop the Late Proterozoic Inkom Formation is followed by a ramp to a detachment atop the Geertsen Canyon Quartzite.
The restored section shows important thrust horizons in the lower Triassic, lower Paleozoic, basal Cambrian rocks, and at the base of the Late Proterozoic Caddy Canyon and Kelley Canyon Formations. A secondary detachment is found in uppermost lower Paleozoic rocks. Thrust fault branch angles with the sole thrust are generally greater than the cross sections to the north, ranging from 23° to 47°
RESULTS

Thrust Kinematics

Restoration of cross-sections A-A', B-B', and C-C' enabled the estimation of thrust displacements. Values for displacements were obtained, wherever possible, by measuring hanging wall cut-off separation along the fault plane. In some cases it was impossible to restore thrust movement along a simple ramp-flat geometry. These areas consisted of complex imbricates or fault-propagation folds. Lateral and horizontal displacements were estimated by dividing the area of a key stratigraphic interval in the hanging wall by its average thickness. Table 4 summarizes these calculations. Figure 6 illustrates the changes in thrust displacement along strike. The thrust displacements from Table 4 are plotted to show the variations in shortening along each major thrust as measured from the restored cross sections.

Table 4. Thrust displacements.

<table>
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<th>Thrust</th>
<th>North</th>
<th>Center</th>
<th>South</th>
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<tr>
<td>Sheep Creek</td>
<td>1.0</td>
<td>14.4</td>
<td>0</td>
</tr>
<tr>
<td>Home Canyon</td>
<td>15.4</td>
<td>NC</td>
<td>0</td>
</tr>
<tr>
<td>Meade</td>
<td>18.8</td>
<td>23.2</td>
<td>0</td>
</tr>
<tr>
<td>Bear River Duplex</td>
<td>NC</td>
<td>23.7</td>
<td>NC</td>
</tr>
<tr>
<td>Laketown</td>
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<td>31.2</td>
<td>21.3</td>
</tr>
<tr>
<td>Willard</td>
<td>NC</td>
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<tr>
<td>Paris(lower)</td>
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</tr>
<tr>
<td>Paris(upper)</td>
<td>NC</td>
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<td>9.3</td>
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<tr>
<td>Bear Canyon</td>
<td>NC</td>
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<table>
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<tr>
<th>Totals</th>
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<th>230.1km</th>
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<tr>
<td>% Shortening</td>
<td>63.7%</td>
<td>79.4%</td>
<td>71.4%</td>
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Variations in thrust displacement along strike

Explanation
- Sheep Creek thrust (SCT)
- Home Canyon thrust (HCT)
- Meade thrust (MT)
- Bear River duplex (BRD)
- Laketown thrust (LT)
- Willard thrust (WT)
- Paris thrust (lower) (PT(L))
- Paris thrust (upper) (PT(U))
- Bear Canyon thrust (BCT)

Figure 6. Plot of changes in displacement along strike determined from restoration of cross sections.
Slip Rates

Dating of thrust movements and displacement data allows calculation of slip rates. Table 5 summarizes calculations of slip rates from thrusts in the study area. Displacements on individual thrusts in the study area were averaged when two or more measured displacements were available. The duration of thrusting was calculated from estimates of time of movement from cross sections (this study), stratigraphic data, and published work (Royse, et al., 1975; Wiltshko and Dorr, 1983; Heller et al., 1986; Yonkee, 1992). Figure 7 is a plot of thrust displacements versus time of the data in Table 5. Values for the Absaroka, Darby, and Prospect thrusts were taken from Wiltshko and Dorr (1983; Figure 4). The plot shows: 1) the amount of displacement and duration (or age bracketing) of thrusting decreases toward the craton; 2) slip on thrusts stops, or nearly so, prior to motion on the next thrust (Wiltshko and Dorr, 1983). Also, the midpoints of the durations of thrusting can be connected to form a gently curved line (time-displacement line), with the exception of the Laketown thrust and Ogden duplex, which represent an interval of transition between thrust systems and slip vectors.

A generalized trend of internal strain is plotted alongside the line connecting the midpoints of intervals of active thrusting (time-displacement line). Shifts to the left in the time-displacement line during intervals of duplex development are matched by increases in internal strain of the thrust belt. In general, early periods of higher internal strain coincide with deeper, more ductile thrusting and deformation of the Late Proterozoic miogeoclinal wedge. Later, strain decreases toward the craton as thrust development occurs at shallower crustal levels in cratonic sedimentary rocks in the eastern Wyoming-Idaho-Utah thrust belt, reflecting the dominance of brittle deformation.
Slip Vectors

The four deformed-state cross sections were used to construct a map of thrust fault branch lines and post-Willard thrust folds (Appendix C, Figure 24). Bold branch lines are drawn between branch points from the sole thrust. Lighter branch lines are drawn between a branch point from the sole thrust and the westernmost point where the thrust splays from a younger thrust above the decollement. Each branch line is numbered relative to the order of thrust formation. A general orientation of the principal stress direction (slip vector) during each period of thrusting can be interpreted as perpendicular to the trend of the branch line. Applied only to bold branch lines, this technique yields the general slip vector orientations in Table 6. A similar method was used to estimate the principal stress direction from the trends of fold axes east and south of Bear Lake. The slip vector was estimated to lie perpendicular to the trends of the major hanging wall folds in the Meade, Home Canyon, Sheep Creek, and Crawford thrust sheets as summarized in Table 6. Figure 8 shows the slip vectors relative to the present thrust traces in the field area. Rotation of slip vectors through time is shown in figure 9.

Structure-Contour Maps

The structure-contour maps were drawn to show the geometries and extents of the thrust-fault surfaces (Appendix D, Figures 25-30). Subsurface control is provided in most areas by an extensive network of seismic-reflection lines, closely spaced drill-holes, or a combination of the two. The three balanced, east-west cross sections and the strike section provide further control for the maps. However, deep subsurface data are lacking in two areas: from Randolph, Utah, west to 111°30'W; and from the east shore of Bear Lake west and southwest to 111°30'W. In both areas, the Gridzo
Figure 7. Plot of thrust duration, displacement, and corresponding changes in internal strain in the thrust belt. Values for the Prospect (PrT), Darby (DT), and Absaroka thrusts (AT) are taken from Wiltschko and Dorr (1983).
Table 5. Summary of thrust displacements, durations, and slip rates.

<table>
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<tr>
<th>Thrust</th>
<th>Mean Displacement (km)</th>
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<th>Slip rate (cm/yr)</th>
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<td>Prospect</td>
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<td>2</td>
<td>.5-.1.0</td>
</tr>
<tr>
<td>Darby</td>
<td>17.5</td>
<td>7</td>
<td>.3-.6</td>
</tr>
<tr>
<td>Absaroka</td>
<td>29</td>
<td>18</td>
<td>.2</td>
</tr>
<tr>
<td>Bear River duplex</td>
<td>23.7</td>
<td>10</td>
<td>.24</td>
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<tr>
<td>Crawford</td>
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<td>.15</td>
</tr>
<tr>
<td>Home Canyon</td>
<td>7.7</td>
<td>2.5</td>
<td>.15</td>
</tr>
<tr>
<td>Meade</td>
<td>21</td>
<td>10</td>
<td>.21</td>
</tr>
<tr>
<td>Laketown</td>
<td>22</td>
<td>10</td>
<td>.22</td>
</tr>
<tr>
<td>Ogden duplex</td>
<td>30</td>
<td>10</td>
<td>.3</td>
</tr>
<tr>
<td>Willard</td>
<td>60.6</td>
<td>20</td>
<td>.3</td>
</tr>
<tr>
<td>Paris</td>
<td>43.3</td>
<td>20</td>
<td>.22</td>
</tr>
<tr>
<td>Bear Canyon</td>
<td>26.4</td>
<td>10</td>
<td>.26</td>
</tr>
</tbody>
</table>

Table 6. Slip vectors for post-Willard thrust structures.

<table>
<thead>
<tr>
<th>Thrust or fold</th>
<th>Slip vector (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laketown thrust</td>
<td>041*</td>
</tr>
<tr>
<td>Meade Thrust -north</td>
<td>108</td>
</tr>
<tr>
<td>Meade Thrust -south</td>
<td>060</td>
</tr>
<tr>
<td>Meade Thrust -average</td>
<td>084</td>
</tr>
<tr>
<td>Meade Thrust sheet anticline</td>
<td>101</td>
</tr>
<tr>
<td>Meade Thrust+anticline average</td>
<td>090*</td>
</tr>
<tr>
<td>Home Canyon Thrust</td>
<td>109*</td>
</tr>
<tr>
<td>Sheep Creek Thrust</td>
<td>114*</td>
</tr>
<tr>
<td>Crawford Thrust -north</td>
<td>096</td>
</tr>
<tr>
<td>Crawford Thrust -south</td>
<td>145</td>
</tr>
<tr>
<td>Crawford Thrust -average</td>
<td>120.5</td>
</tr>
<tr>
<td>Crawford Thrust sheet anticline</td>
<td>116</td>
</tr>
<tr>
<td>Crawford Thrust+anticline average</td>
<td>119*</td>
</tr>
<tr>
<td>Bear River duplex-north</td>
<td>102</td>
</tr>
<tr>
<td>Bear River duplex -south</td>
<td>089</td>
</tr>
<tr>
<td>Bear River duplex -average</td>
<td>95.5*</td>
</tr>
<tr>
<td>Absaroka Thrust</td>
<td>090*</td>
</tr>
</tbody>
</table>

* denotes value used in Figure 9.
Figure 8. Map of thrust traces and post-Willard thrust slip vectors.
Figure 9. Plot of thrust displacement, duration, and slip vector rotation. This figure combines data from figures 7 and 8 to show temporal and spatial variations in slip vectors in the study area. The orientations of the slip vectors, in degrees, are noted by the arrows. A general rotation of slip vectors through time from northeast to southeast to east is indicated.
contouring program, using simple linear interpolation, was relied upon to fill the gap in the data for the structure-contour and isochore maps. Structure-contour maps were constructed for the Meade, Laketown, Willard, upper and lower Paris, and Bear Canyon thrusts (Appendix C, Figures 25-30). The approximate surface traces of the thrust faults, and their geometry at depth, shown on the structure-contour map, delineate the geometric linkages of the faults in the subsurface. Ramps and flats on the structure-contour maps are denoted by the letters R and F, respectively.

The structure-contour map of the Meade thrust (Figure 25) shows the thrust surface is curved with northeast-, north-, and northwest-striking segments. The thrust fault dips steeply to the west to a depth of approximately -2000 meters. Westward, this steep ramp is only documented in the north part of the study area, and is inferred to die out quickly to the south, where the geometry of the fault changes from a ramp-flat to a buried thrust-fault imbricate in the south. A very broad, gently dipping ramp is shown in the north, and reflects the listric motion on the Bear Lake normal fault that has rotated the earlier steeper thrust ramp. The broad flat persists laterally for approximately 8 km until it impinges on a long, steep ramp.

The Laketown thrust fault (Figure 26) is a gently west-dipping thrust in the north, where the Bear Lake fault has downdropped the structure approximately 2500 meters. Southward, the northern portion of the Laketown thrust salient has a shallow westward dip. The salient formed where the thrust surface is domed by movement on the underlying Meade thrust imbricate. This thrust steps down to the west. Southward, this salient merges with a rather steep ramp that flattens near -4000 meters and extends to below -10,000 meters.

The Willard thrust fault (Figure 27), like the underlying Meade and Laketown thrusts, shows the influence of the Bear Lake normal fault. A flat is present just east of 111°30'W, and the leading edge of the fault has been downdropped up to several
thousand meters in the north, from its position prior to normal-faulting. Southward, in the area of Laketown Canyon, the thrust appears to flatten somewhat, reflecting movements on the Laketown thrust. The overall geometry is that of a southwest-dipping ramp in the north that changes to the south into a ramp dipping north-northwest off the Ogden duplex. Near section B-B', the Willard thrust nearly merges eastward with the underlying Laketown thrust.

The lower Paris thrust (Figure 28) has a steep ramp along and immediately west of the mostly concealed map trace. In the north, this ramp continues westward, but flattens below -8000 meters. To the south, the ramp separates into three steps separated by three flats that widen to the south. The gross geometry of the fault is transformed from west-dipping in the north to nearly northwest-dipping in the south. A steep north-dipping lateral step is present between -6800 and -9200 meters in the west. This geometry probably represents folding of the thrust above underlying duplexes in the Willard thrust sheet.

The upper Paris thrust (Figure 29) is a generally west-northwest-dipping surface. A flat, present in the south between -4400 and -4800 meters, widens to the south like those on the underlying lower Paris thrust surface. Minor curvature of the contours indicates limited influence of folding over duplexes at depth.

The Bear Canyon thrust geometry (Figure 30) is a ramp widening to the south, similar to the upper and lower Paris thrusts. A flat salient between -2000 and -2400 meters may result from folding over underlying structures, or could be a remnant geometry from the origin of the thrust as a large fault-bend fold.

**Isochore Maps**

The isochore maps (Appendix D, Figures 31-35) show variations in vertical thickness of each thrust sheet. Where thickness decreases to zero, the bounding-fault
surfaces merge to share the same detachment. Thicknesses of duplexes and splays are included in the isochore thickness of each thrust sheet. Isochore maps were constructed for the Meade, Laketown, Willard, and upper and lower Paris thrust sheets. These maps were derived from the intersections of structural contours of the thrust surfaces that bound each thrust sheet.

The Meade thrust plate (Figure 31) thins to zero in the northwest where the thrust merges with the overlying Laketown thrust (Plate 3, section D-D'). The sheet thickens to the southeast. There it reaches an estimated maximum thickness of 4000 meters where a thrust imbricate repeats the hanging wall section. The lateral extent of the imbricate is shown by a series of elongate, closely spaced contours stretching north from the area of maximum thickness. In the northeast, the sheet thickness varies greatly where movement on the underlying Home Canyon thrust has formed an overturned-to-the-east hanging wall anticline (Plate 2, section A-A').

The Laketown thrust sheet (Figure 32) thickens from zero in the southeast portion of the sheet, where it merges laterally the Willard thrust, to 5600 meters in the northwest. Thickness data under southeastern Bear Lake are not available, but to the south, contour patterns indicate considerable influence of the underlying Meade thrust imbricate. Generally north-south trending thickness domains in the west result from duplexing beneath the Laketown thrust and suggest the westward extent of the duplexes.

The Willard thrust sheet (Figure 33) thins to nearly zero toward the northwest, south of cross-section B-B', where it merges with the lower Paris thrust. It reaches a maximum thickness of 4000 meters near its present eastern limit. In the west part of the sheet, the thrust generally thickens to the south. This thickening represents the rise to the south of the overlying lower Paris thrust, and the decline in altitude of the Willard thrust to the south (see section D-D').
The lower Paris thrust sheet (Figure 34) attains a maximum thickness of 5600 meters in the north below the trace of the overlying upper Paris thrust. The plate thins to zero in the southwest where the upper Paris thrust merges with the lower Paris thrust. From the zero line, the sheet thickens rapidly to the north and east. The upper Paris sheet (Figure 35) thickens to 3200 meters in the southwest and thins to zero in the east where the upper and lower Paris thrusts join (Plate 3, section C-C').

The thickness of the Bear Canyon thrust sheet reached a probable maximum of 10.65 km at the time of thrusting during the Cretaceous. The thickness of the plate was estimated by averaging thickness values from measured sections (Appendix A, Figures 16-20) in the Bear River, Wellsville, and Malad Ranges described in Utah State University master's theses. Thicknesses for rocks not exposed were taken from Hintze (1988; Huntsville section).

Concealed Thrust Trace Map

The concealed thrust trace map (Plate 1) is a valuable tool for depicting structural relationships in the field area that are concealed by overlying Tertiary and Quaternary units. The features of particular importance shown on the map are the points where the Willard and Laketown thrusts splay, the traces of the upper and lower Paris thrusts, and the many thrust splays underlying the Bear Lake Plateau.

The trace of the upper Paris thrust, concealed beneath the Bear Canyon thrust, curves to the southwest from section B-B'. The thrust now accommodates normal-fault displacement, and places Cambrian rocks over Cambrian footwall rocks. Dover (1985) depicted a complicated, anastomosing network of normal faults along the trace of the upper Paris thrust where it is located by this study. These normal faults may be the product of reactivation of an upper Paris thrust ramp during Cenozoic extension, and thus now delineate the approximate trace of the thrust. The lower Paris thrust lies
to the east, buried along its entire length within the study area by the Tertiary Wasatch Formation. The trace of the thrust is generally convex to the east, with a pronounced eastward bulge near the boundary of T11N and T10N. In the south portion of area, Dover (1985) mapped normal faults to the west of, and approximately parallel to, the concealed trace of the lower Paris thrust. Cross sections indicate that the lower Paris thrust trace lies just east of this linear zone of normal faults. These normal faults are interpreted to merge with a ramp of the lower Paris thrust. To the north, this anastomosing pattern is interrupted by small normal faults intersecting the trace of the lower Paris thrust. These minor faults are interpreted to have formed as a result of imbrication of the Meade thrust at depth, which is more clearly manifested by transverse faulting east of Laketown, Utah. The units cropping out in the hanging wall of the lower Paris thrust range in age from Cambrian to Silurian.

The Willard thrust trace trends approximately north-south. It is almost completely concealed by the Tertiary Wasatch Formation along its length. The only exposed portion of the fault in the study area is at the easternmost location of the fault, in Old Laketown Canyon, south-southwest of Laketown, Utah. In the south, west of Birch Creek reservoir, the Cambrian-Precambrian Geertsen Canyon Quartzite is present in the hanging wall. Exposures to the north indicate that the fault cuts upsection because the Cambrian Langston and Ute Formations are the oldest identified in the hanging wall. In Old Laketown Canyon, the Willard thrust places the Langston Formation over the Cambrian St. Charles Formation. In the south, stratigraphic offset is much greater along Birch Creek, west of Woodruff, Utah. There, the Cambrian-Precambrian Geertsen Canyon Quartzite in the Willard thrust hanging wall lies only 1.4 km west of exposures of the Jurassic Nugget Sandstone in the Willard footwall.

The trace of the main Laketown thrust diverges from the Willard thrust near New Canyon, approximately 14.5 km west of Randolph, Utah. The thrust trends
northeast to the present boundary of T11N and T12N, where the thrust curves slightly
to a north-northeast trend. The thrust curves abruptly westward at the boundary of
T12N and T13N. In this segment of the fault two transverse faults are present north
of Laketown Canyon (Valenti, 1982a,b). The transverse faults may result from uplift
of the overlying Laketown thrust plate by the underlying, imbricated leading edge of
the Meade thrust. These transverse faults are discussed in detail later. The portion of
the Laketown thrust that is in the hanging wall of the Bear Lake normal fault trends
north-south.

The Laketown and Willard thrusts are characterized by many thrust imbricates,
based on seismic-reflection and drill-hole data. These imbricates are depicted on
cross-section B-B' east of the Marathon Otter Creek well, and on cross-section C-C'
immediately east of the Willard thrust. In the south half of the field area, the
approximate leading edges of these imbricates are denoted by the buried thrust
symbols east of the Laketown and Willard thrusts. To the north the thrust geometries
become more complex with the interaction of the Meade and Home Canyon thrusts.

The Meade thrust crops out east of Bear Lake in a series of scattered surface
exposures. This pattern of discontinuous exposures in the vicinity of South Eden
Canyon result from a backthrust in Jurassic rocks in the footwall of the Meade thrust.
The backthrust, indicated by surface exposures and seismic-reflection data, probably
was caused by steepening of the Meade footwall on several imbricates of the
underlying Home Canyon thrust. Displacement on the Bear Lake normal fault just
west, also indicated by seismic-reflection and surface data, further complicates the
local geology. East of the main Bear Lake fault, the largest concealed normal fault
appears to branch from the leading edge imbricates of the Laketown thrust in Sec. 2,
T12N R6E.
Several splays of the Home Canyon thrust are depicted on the concealed thrust trace map. Due to a lack of surface exposures of this thrust, it is unclear if the Home Canyon thrust splays penetrate Mesozoic sediments and thus ramp to the base of the Tertiary Wasatch Formation within the field area. The thrust splays are included on the concealed thrust trace map based on the extensive folding of the Jurassic Twin Creek Limestone that resulted from pervasive thrust-splay displacements. As plotted, the concealed traces of the Home Canyon thrust splays represent the approximate limits of thrust displacement based on published cross sections (Coogan, 1992) and abundant seismic-reflection and drill-hole data. Some displacement on the Home Canyon thrust is inferred to be coeval with movement on imbricates of the Laketown thrust. Evidence for this includes: (1) gross geometric similarities among the thrusts, so that older, overlying thrusts could shuffle forward incrementally; (2) position of these thrusts immediately east of major thrusts; and (3) a long duration of development of thrust imbricates in the footwall of the Willard thrust in the south that recorded shortening across a broad thrust front in the field area. The main Home Canyon thrust ramps to the base of overlying Quaternary sediments near the east end of cross-section A-A’, approximately 3.2 km east of the Wyoming-Utah border.

The remaining structures west of the Crawford normal fault are the major imbricate splay from the Crawford thrust and its folded hanging wall and footwall. The splay is inferred to join with the Crawford thrust to the northeast based on seismic-reflection and drill-hole data. The sharp bend in the trace of the Crawford normal fault southeast of Randolph, Utah, suggests interaction with a pre-existing structure. The increase in the sinuosity of the Bear River in the vicinity of the concealed trace of the Crawford thrust splay probably indicates decreased stream gradient due to normal-fault displacement and eastward tilting of the area. The Crawford thrust accommodates normal-fault displacement along much of its length.
The southward bend in the trace of the Crawford normal fault appears to transfer the
normal-fault displacement to the main Crawford thrust, and possibly the southeast-
trending splay, coinciding with the area of maximum sinuosity of the Bear River.

Much of the Crawford thrust is exposed in the area of the Crawford Mountains
and east of the Wyoming-Utah border further north. Several concealed fault traces are
indicated on the subcrop map. These traces are taken from the map of Evans (1990)
except for the thrust noted near the center of the east boundary of the map, which is
joined with a thrust at depth indicated on a seismic-reflection line along Wyoming
Highway 89.

**Transverse Faulting**

Transverse faulting is present in the field area. Valenti (1982b) described a
minor right-lateral transverse fault striking northwest in the northeast quarter of section
29, T13N R6E, near Laketown, Utah. Offset along the fault appears slight, although
the fault itself is not exposed. A more pronounced west-striking, left-lateral tear fault
lies in the southwest quarter of the same section. The fault separates north-striking
Devonian Hyrum Formation from northwest-striking Jurassic Nugget Sandstone
along its exposed length of 300 meters. Valenti (1982b, p. 864) speculated on the
significance of these transverse faults:

> This transverse fault might be a tear fault offsetting the
elsewhere concealed trace of the north-south striking Meade(?)
Thrust Fault in a left-lateral manner. Alternatively, the transverse
fault may be a part of a reentrant in the Meade(?) Thrust.
Although the lack of drag effects adjacent to the fault might
support the latter interpretation, lack of adequate exposures
prevents discrimination between the two alternatives.

The work of Royse et al. (1975), on the linkage between the Darby, Prospect,
and Hogsback thrusts, indicates another possibility. A tear fault exists east of a
transverse footwall step in the Prospect fault plane. The older Darby thrust is folded
north of the underlying Prospect lateral ramp. South of the ramp, the Prospect thrust and Darby thrust join, which transferred younger Prospect displacement onto the pre-existing Darby thrust plane and created the Hogsback thrust (Royse et al., 1975). This situation is similar to the fault relationships seen near Laketown, where the tear faults are present near the traces of the Laketown and Meade thrusts. A north-northwest dipping lateral ramp in the Meade thrust plane below the south shore of Bear Lake and a temporal overlap in the displacement on the two thrusts could explain the surface relationships. According to Dahlstrom (1970), tear faults are common features at the margin of a deformed hanging wall panel.

**Palinspastic Maps**

Palinspastic maps in figures 10-13 illustrate the structural geometry of north-central Utah at specific intervals during thrusting on the Paris, Willard, Laketown, Meade, and Crawford thrust faults. Present positions of the thrust faults shown in figure 10 are taken from the concealed thrust trace map (Plate 1). Shortening values in Table 4 are restored incrementally on the thrusts to depict two periods in the tectonic evolution of the area.

The first palinspastic map (Figure 11) shows the restored positions of the Paris, Willard, and Laketown thrusts after reconstruction of the underlying thrusts. Displacement on the Sheep Creek, Home Canyon, and Meade thrusts was removed, as well as two-thirds of total Crawford thrust shortening (Table 4). The Crawford thrust apparently was active through a considerable period of time, as evidenced by the presence of fewer thrusts separating the Willard and Crawford thrusts in the south than in the north. The only structures to restore in the Willard-to-Crawford thrust interval in the south are the small Crawford thrust splay and the thrusts and folds in
Figure 10. Present position of major thrusts in the study area.
Figure 11. Palinspastic map showing thrust locations following restoration of post-Laketown thrust displacement.
the footwall of the Willard thrust associated with movement on the Laketown thrust. These two structures accounted for 27.4 km of shortening along cross-section C-C', while much more shortening was accommodated to the north with the development of the Home Canyon and Sheep Creek thrusts. Inclusion of a portion of Crawford thrust slip in the restoration solves a kinematic problem of thrusting within the Ogden duplex south of section C-C' contemporaneous with slip on the Laketown thrust to the north. Yonkee (1992, p. 457) reported that the Ogden thrust system "...continued farther east as the regional decollement of the frontal Crawford, Absaroka, and Hogsback thrusts, marking a fundamental change from basement involved deformation." Activity in the Ogden duplex was directly connected to movement on the Crawford thrust.

The palinspastic restoration in figure 12 illustrates changes in local structural geometries through the restoration of movement on the Laketown thrust, Bear River duplex, and on the partially restored Crawford thrust in the south. The lack of data to the north required the restoration to project shortening values from cross-section B-B' onto an imaginary western extension of cross-section A-A'. This assumption is reasonable because thrusting took place on the Laketown thrust, in cross-section A-A', and duplexing can be inferred to continue in the western Bear River Range because of the northward lateral continuity of tectonic folds (Logan Peak syncline, Red Banks anticline) and of sedimentary rocks of the Bear Canyon thrust sheet in the Bear River Range west of cross-section A-A'.

Seismic-reflection data across the northern Bear River range indicate that duplexing at depth is permissible (Coogan, 1990, oral comm.). The arcuate map trace of the Laketown thrust (Figures 10 and 11) is attributed to uplift and folding by the underlying Meade thrust, so restoration of the Meade thrust removes this bend. Crawford thrust shortening restored during this interval on cross-section C-C' is limited to one-third of total Crawford thrust displacement, in order to preserve the
Figure 12. Palinspastic map showing thrust locations following restoration of post-Paris, and post-Willard thrust displacement.
approximate pre-Crawford thrust geometry, and is coupled with restoration of the Bear River duplex and the Laketown thrust imbricate in the footwall of the Willard thrust (Figure 12). The palinspastic map indicates that the Paris and Willard thrust faults trended approximately northwest-southeast in the south part of the field area, prior to the development of the underlying fault system.

The prominent bend to the southeast of the thrust traces on section C-C' reflects a missing piece of data for the restoration. The amount of slip accommodated by the Ogden duplex to the south is not accounted for in figure 12. Near Ogden, Utah, the formation of the Taylor Canyon and Ogden thrusts post-dates slip on the Willard thrust. These thrusts bound the Ogden duplex, a thick sequence of repeated Late Proterozoic and Early Paleozoic units. In the north, much of the displacement carried thrust sheets toward the east, whereas displacement in the south was accommodated by duplex development. Schirmer (1988) estimates 8 to 12 km of slip accommodated by the Ogden duplex. Yonkee (1992, p. 457) estimated "... slip of about 30 km within the Ogden system largely transferred eastward into slip on the Crawford thrust, early movement on the Absaroka thrust, and internal shortening."

Figure 13 shows an alternate restoration of post-Willard thrusting, except that restoration of the Laketown thrust imbricates in the footwall of the Willard thrust on cross-section C-C' is omitted. The unreasonable geometry of thrusts in this reconstruction suggests that the imbricate formed as a result of slip on the Laketown thrust, rather than slip on the Willard thrust.

The palinspastic reconstructions differ from the estimates of Levy and Christie-Blick (1989). The present study restores total regional shortening and extension across the eastern Great Basin by utilizing closely spaced, detailed cross sections to reconstruct thrust geometries during specific intervals of thrust-belt evolution. Levy and Christie-Blick (1989) estimated a ratio of shortening to extension of 1:2 based on
Pre-Laketown Thrust (alternate)

Idaho

No restoration of the 21.3 kilometers of displacement on the Laketown Thrust imbricate on cross-section C-C'.

Figure 13. Palinspastic map showing thrust locations following restoration of post-Paris, and post-Willard thrusting without restoration of the 21.3 km of Laketown thrust displacement on cross-section C-C'.
104 km of shortening along their northern Utah transect and approximately 250 km of extension. This study estimates 210.5 km of shortening along a similar line of section from restoration of cross-section C-C' and Plate V from Lamerson (1982). By using their value for extension, these data suggest the ratio more closely approximates 1:1. This new shortening data and the implications of internal strain in regional shortening calculations affects the results of the previous study. The orientation of the Late Proterozoic-Early Cambrian basin would shift more to the north-northwest if the south part of Levy and Christie-Blick's restoration remains fixed. Though differing in scale and timing, both studies show the restored positions of thrusts and so are valuable tools to unravel thrust linkages and kinematics.

Regional Shortening

Regional shortening across the thrust belt was estimated by combining cross-section C-C' (this study) and a cross section to the east (Lamerson, 1982, Plate V). These sections were chosen because together they span all known thrusts along that latitude and their endpoints nearly coincide (Figure 14). Shortening estimates based on Lamerson (1982) are 21 km on the Hogsback thrust and 31.3 km on the Absaroka thrust. The section was restored by pinning the undeformed footwall of the Hogsback thrust east of the surface trace of the thrust, and by restoring the Hogsback and Absaroka thrusts to a loose line drawn at the Utah-Wyoming border. The Medicine Butte and Bridger Hill thrusts, structurally higher than the Absaroka thrust, were not restored due to a lack of footwall cutoffs on the west end of Lamerson's cross section (Plate V). Displacements on these thrusts, however, appear to be minor. Combined total shortening along C-C' and Plate V is 210.5 km of an original 327.4 km undeformed length, or 64.3% regional shortening. Royse et al. (1975, cross-section
Figure 14. Location of field area and cross sections used in regional shortening calculation (adapted from Royse et al., 1975).
Y-Y') estimated 83.7 km of shortening from an original 178.6 km width along a similar latitude across the thrust belt, or 47% shortening across the additional thrusts or thrust splays and the interpretation of greater offset on those thrusts included in the Royse et al. (1975) study. This establishes the significant role of smaller thrusts and of detailed estimates of thrust displacement in determining regional shortening values.
IMPLICATION FOR HYDROCARBON EXPLORATION

Source Rocks

Several units within the study area are potential hydrocarbon source rocks. According to Valenti (1987) these include:

(1) organic-rich, phosphatic black shale within the Permian Phosphoria formation; (2) similar, but thinner and less well-studied black shale within the underlying Mississippian section (present within the Paris and Meade sheets, and possibly present within the western Crawford sheet); (3) dark-colored, fetid shale intervals within the Triassic Thaynes; (4) possibly, shale in Jurassic Twin Creek.

In addition, the northeast-trending Crawford Thrust ramp overrides Cretaceous rocks in the south and east part of the study area. These units are the source rocks for the prolific oil and gas fields located in the Absaroka thrust plate. Those units identified as source rocks are the Gannet Group, and Wayan, Bear River, Aspen, and Frontier Formations.

The quality and maturity of these potential source rocks vary greatly. The Triassic and Jurassic shale source rocks in the Crawford and Meade thrust plates are of poor quality due to their limited distribution and low organic carbon (Valenti, 1987). The Thaynes contains petrolierous concretions in the Laketown area (Valenti, 1982a,b). However, the Phosphoria Formation is organic-rich and present through much of the area. Thermal-maturity data indicate that the Phosphoria is very mature to post-mature in the Crawford thrust sheet. Dry gas produced from the Hogback Ridge field and gas shows from the Crawford thrust plate are probably evidence of late-stage Phosphoria hydrocarbon generation. Oil-stained cuttings of Pennsylvanian-Permian Crawford hanging wall rocks record early Phosphoria hydrocarbon generation and migration (Warner, 1982). Sheldon (1967) and Stone (1967) postulated Late Jurassic generation of hydrocarbons from the Phosphoria followed by migration eastward up
regional dip and subsequent trapping in foreland structures. In the Paris thrust sheet, the Phosphoria is apparently less mature due to earlier development of the Paris thrust and consequent uplift of the Phosphoria before reaching the high TTI (Temperature Index) values seen to the east (Valenti, 1987).

**Reservoir Rocks**

The stratigraphic section in the study area contains many regionally proven reservoir intervals. All units from the lower Mississippian Lodgepole to the Jurassic Twin Creek, except the Triassic Ankareh Formation, have documented reservoir potential in the Overthrust Belt (Valenti, 1982b). Many of these data are from the extensive oil and gas fields located on the Absaroka thrust plate to the southeast. Many factors limit the lateral extent of positive reservoir qualities encountered there. Significant among these are lateral facies changes, calcite cementation, and the presence of thick, brittle upper Paleozoic carbonates that undergo extensive fracturing and imbrication during thrusting. Thick Mississippian carbonates in large-scale thrust imbricates in several locations in the study area are possible reservoirs. However, the large amounts of Paleozoic carbonates and overlying Mesozoic limestones involved in thrusting accommodated much shortening by dissolution that resulted in widespread, pervasive calcite cementation. Facies changes show isolated cases of positive differences between lithologies of formations in the Absaroka thrust plate and their equivalents in north-central Utah, but this factor is apparently secondary to calcite cementation. Although many intervals present in the study area are proven reservoirs in the region, local potential is decreased by cementation. According to Valenti (1987, p. 264), "...poor fluid recoveries on drill-stem tests throughout much of the Crawford plate indicate that poor reservoirs may be a fundamental problem in the area."
The Hogback Ridge field began production of dry gas in August, 1978, from an anticline in the hanging wall of the Crawford thrust sheet. The sole producing well in the study area, American Quasar 20-1, was completed in the Triassic Dinwoody Formation. The lithology varies from "...a basal, silty limestone, a middle heterogeneous unit of gray limestone and shale, and an uppermost unit of tan siltstone, gray limestone, and some shale" (Walker, 1982, p. 585). The Dinwoody is not considered a good reservoir in the Absaroka plate because the reservoir lithofacies are absent. The DST (drill stem test) of the Dinwoody flowed 15,886,000 cf/day. The well was completed for 22,400,000 cf/day of sweet gas from fractured carbonates. The Phosphoria Formation recovered 9,900,000 cf/day of dry gas containing 0.019 mol% H₂S. Also, a slight gas show in the Triassic Thaynes accompanied 2,300 feet of fluid recovery from the Jurassic Nugget, while the Jurassic Twin Creek tested tight (Walker, 1982).

The Marathon Thousand Dollar Well penetrated a highly imbricated series of steeply dipping Triassic Ankareh in the Crawford thrust hanging wall. Small gas shows were detected from the Ankareh, which is not considered a good reservoir. A DST recovered 83 MCFPD of flammable gas (Ott and Kreckel, 1982).

Reservoir Seals

The role of faults varies in trapping accumulations of hydrocarbons. Bishop (1982) found considerable evidence in the Absaroka thrust plate that faults have acted as barriers and as channels to fluid migration. Some of these characteristics can be extrapolated to the study area based on structural and stratigraphic similarities. Faults with impermeable gouge would be expected to act as barriers. While precluding the movement of hydrocarbons into suitable reservoirs above or updip of such a boundary, the potential exists for the formation of many small traps along the fault
plane due to irregularities in the fault surface. Alternately, some faults can act as channels or at least semi-permeable membranes for hydrocarbon migration between stratigraphic packages. Evidence for this is found at the Hogback Ridge field (Walker, 1982). During initial testing, both the Triassic Dinwoody and the Permian Phosphoria were thought capable of production. The well was completed in the Dinwoody Formation, which produced sweet gas that became progressively more sour through time. Depletion of the Dinwoody reservoir forced an attempt to recomplete the well in the underlying Phosphoria. The Phosphoria, which originally contained sour gas, was depleted of viable amounts of gas. These two units are separated by a detachment in the Triassic Woodside Formation.

**Petroleum Prospects**

Eight areas have been identified as potential hydrocarbon traps. Their locations are plotted on the concealed thrust trace map. Location 1 is an updip anticline in the Jurassic Nugget at a kink fold in the overlying Home Canyon thrust fault along the crest of the Pegram anticline (Plate 2, section A-A'). The Exxon Sweetwater well is just west of this structure.

Location 2 is the approximate position of an updip pinchout of the Jurassic Nugget against the base of the Laketown thrust. This structure was produced by the development of splay faults of the Meade thrust that folded the overlying Laketown thrust. The Nugget pinchout is at a thrust ramp that is upturned on the east limb of a broad anticline. Location 3 lies slightly west on the same anticline where potential Triassic reservoir rocks underlie lower Paleozoic rocks at the folded Laketown thrust. Locations 2 and 3 overlap significantly.

Locations 4 and 5 are parts of an overturned anticline formed by thrusting on the Sheep Creek thrust. Location 4 is a normal section of Jurassic Nugget to lower
Paleozoic rocks overturned to the east. The Home Canyon thrust overlies the Nugget and is also folded, creating a possible reservoir seal. Location 5 denotes the approximate trace of the Jurassic Nugget forming the hinge of the anticline.

Location 6 is an anticline of Jurassic Nugget and Triassic Ankareh overlain by thrust splay s east of the Willard thrust, and imbricates of the Laketown thrust. This structure was drilled by the American Quasar 18-1 well.

Location 7 denotes an area of possible closure in an anticline in the hanging wall of a major splay off the Crawford thrust. The area of potential closure is in middle to upper Paleozoic rocks of an anticline that was initially a fault-propagation fold that was later thrusted. The anticline is probably breached by erosion in at least part of its extent. Location 8 is an updip pinch-out in the footwall of the same structure. A normal section of Jurassic Nugget down to the lower Paleozoic is upturned and cut-off by the Crawford thrust splay. Cretaceous rocks underlying this structure create a possible source-to-reservoir setting. The Sohio Birch Creek well and the American Quasar 23-1 well both penetrated this structure.

Locations 2 through 5 are of special interest since several potential traps exist and both are updip from the Permian Phosphoria Formation, a proven source rock, and Mississippian shales. Favorable TTI histories would allow this large source area to produce a great deal of hydrocarbons. Coupled with the existence of significant trapping structures up-dip, further study is warranted.
CONCLUSIONS

(1) Thrust interactions and displacements in the study area:

Thrusts in the study area are organized into two thrust systems. The upper system is comprised of the Bear Canyon, Upper and Lower Paris, and Willard thrusts. The Lower Paris thrust and the Willard thrust developed coevally (Figure 15) and are shown to merge in the field area. The lower thrust system consists of the Laketown, Meade, Home Canyon, Sheep Creek, Crawford, and Absaroka thrusts, and the Bear River duplex. The Laketown and Meade thrusts are separate thrusts that share a detachment. The Meade and Home Canyon thrusts have a similar relationship. The Meade and Crawford thrusts are not equivalent, but are relatively closely spaced in time. Displacements are summarized in Table 4. See figure 15 for a revised timing of tectonic events.

(2) Styles of deformation related to thrusting:

The progression in structural style of deformation can be evaluated by comparison of the geometries of the Laketown, Meade, and Sheep Creek thrusts, and the Crawford thrust splay. The first step involves imbrication and transfer of displacement to many subsidiary thrust faults in the footwall of the Willard thrust as the Willard thrust shuffled forward through progressive failure of the footwall. Displacement on the Laketown thrust is confined to a single thrust plane in the center of the field area that splays both north and south. The displacement decreases to the north and south, from a maximum in the center. The Meade thrust dies out southward into a series of imbricates in its hanging wall. To the north, total shortening increases on the Meade, where the Laketown thrust splays join with the Meade thrust. As regional slip vectors changed orientation to a slightly more southeast direction between
Figure 15. Revised timing of tectonic events and sedimentological responses of the thrust belt incorporating data from this study (adapted from Wiltschko and Dorr, 1983).
movement on the Paris and Willard thrusts and the Crawford thrust, a new
deformation geometry formed. The Sheep Creek thrust, which cores a deep fault-
propagation fold, accommodated deformation at the intersection of east-southeast
directed slip vectors in the north, and east directed slip vectors in the south. The final
stage in the transition of slip vectors is recorded by the Crawford thrust splay and its
faulted anticline-syncline geometry.

A general pattern emerges of imbricate-thrust development at the beginning of
slip-vector changes when an oblique slip on faults predominates. Fault-propagation
folds form when slip probably is nearly perpendicular to the ramp. Near-
perpendicular shortening encourages folding prior to thrusting. A succession of
deformational styles indicates changes in the orientation of regional shortening.

(3) Nature of the transition from basement-involved thrusting in the west to
thrusting in progressively younger rocks to the east:

The area of northern Utah encompassing the western Bear River Range and the
Bear Lake Plateau is a complexly deformed structural terrane. Cretaceous thrusting
during the Sevier Orogeny translated miogeoclinal sediments eastward by thrusting
and produced thrust-associated folds. Models of thin-skinned thrust faulting only
apply to part of this region, as complications arise from the influence of pre-existing
structures and later thrust-to-thrust interactions.

Thrust-fault development in the field area began with the Bear Canyon thrust.
This author links the structurally highest thrust indicated on seismic-reflection lines in
the western Bear River Range with the Bear Canyon thrust and associated duplexing
in the Portneuf Range (Kellogg and Skipp, 1988; Kellogg, 1992) based on similar
thrust-plate stratigraphies and geometries. The Bear Canyon thrust can be traced on
seismic-reflection lines through the western Bear River Range beneath a stratigraphic
package that can be traced well into Idaho.
Regional thrusting continued by eastward failure of the footwall, recorded by the formation of the Paris and Willard thrusts. The Paris thrust splay s into an upper and lower strand, ramps to the surface to the south, and parallels the Willard thrust west of Bear Lake. These two thrusts formed separately but coeval ly (Figure 15). The form of the Willard thrust shows the influence of rift-initiated thrust development, whereas the Paris thrust may have formed from lithologic-controlled thrust inception due to the absence of great thicknesses of Late Proterozoic rocks in the hanging wall.

Later displacement is transferred to the Laketown and Meade thrusts. The Laketown thrust is folded by the Meade thrust, which indicates that the Meade thrust propagated into the field area after emplacement of the Laketown thrust. The Laketown thrust is seen as a pivotal local feature that transferred slip laterally when reorientation of regional slip vectors took place across the region. Evidence for the role of the Laketown thrust as a lateral hinge is found in its genetic relationship to the complex imbricate thrust structure and duplexing at depth in the footwall of the Willard thrust in the south (section C-C'), and the presence of imbricates at its base and within the underlying Meade thrust northward (section B-B'). Later, in the same pivotal area, the Sheep Creek thrust accommodated displacement in the area between the buttress of the northern Utah highland (Ogden duplex) to the south, and a newly oriented east-southeast direction of regional thrusting. The limited apparent lateral extent of the Sheep Creek thrust illustrates its role as a transitional structure accommodating changes in slip vectors between major episodes of thrusts.

The geometry and lateral extent of the main Crawford thrust indicate the end of transitional thrusting in the area and the resumption of major regional thrusting. The splay branching from the Crawford thrust ramp near Woodruff, Utah, reflects the late stage of shifting regional stress axes and the drag effects of the Archean-Proterozoic Ogden duplex.
(4) Relationships of structures in the field area to regional structural trends in the Idaho-Wyoming-Utah thrust belt:

The different structures and interrelations of faults represent classic examples of thin-skinned thrusting, influence of pre-existing topography, and changing orientations of thrust-plate vectors. Structures in the area are extensions of regional features or transitional structures accommodating changes in regional deformation patterns.

The southwest boundary of the study area abuts the basement-involved duplex beneath the Willard thrust sheet (Bell, 1952; Schirmer, 1985; Yonkee, 1992), named the Ogden duplex (Schirmer, 1985a,b; 1988). The sharp bends in the trace of the Willard thrust (Figure 1) are attributed to the duplex, which uplifts the south portion of the thrust sheet. Schirmer (1985a,b) indicated that the Ogden duplex dies out southward. Cross sections of this study identify similar duplex structures north in the footwall of the East Cache fault. The Bear River duplex consists of Late Proterozoic through upper Paleozoic rocks, whereas the Ogden duplex involves Archean Farmington Canyon Complex. The origin of duplexing in the study area is a northward extension of the thick, rift-filling sequence of Late Proterozoic rocks (Wheeler and Krystnik, 1988) in which ramps of the Willard thrust and thrusts in the Ogden duplex formed (Schirmer, 1985a,b; Neves, 1989).

Where regional thrusting encountered the Ogden culmination, older thrust faults were forced to ramp up laterally in the south, forming a bend to the northeast in their surface traces. The surface traces of younger thrusts in the lower thrust system that do not show this bend indicate incorporation of the uplifted basement obstacle in the allochthon. The period of transition from the active culmination to a passive hinterland uplift is also recorded by the interrelationships of the thrust faults in the field area with the duplex to the south. The strike section at 111°30'W longitude
shows that splays of the Paris thrust thicken the section southward onto the Ogden duplex, and the splays rise to the surface. The Willard thrust rises gently upward to the south and overlies a duplex of Triassic rocks at depth eastward.

Formed coevally with the Ogden duplex (Figure 15), the Laketown thrust dips to the north off the Ogden duplex, and then remains nearly horizontal to the north, where it joins with the Meade thrust a short distance south of cross-section A-A'. East of the Laketown thrust, on section B-B', the Meade thrust forms a large hanging wall imbricate that accommodates shortening at the south end of the thrust. Displacement nearly doubles to 37 km north of Bear Lake (Evans and Craddock, 1985) as that portion of the Meade thrust sheet is not induced to expend eastward slip for thrust sheet thickening in the wake of the Ogden duplex far to the south. The Home Canyon thrust ramps up in the footwall from the sole thrust (section A-A') to the top of the Jurassic Nugget Sandstone (section B-B'). To the southeast, the Sheep Creek thrust cores a large fault-propagation fold that trends northeast, similar to the orientation of the Crawford thrust splay. The Crawford, Absaroka, and Hogsback thrusts trend north-northeast, indicating the end of slip within the Ogden duplex.

Figure 2 shows the orientations and extents of these concealed structures as determined by cross sections (this study). These transitional structures represent the reorientation of the slip vectors between movement on the Paris-Willard and Absaroka thrusts in the interval of slip accommodation by uplift and internal strain within the Ogden duplex.
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APPENDICES
Appendix A. Stratigraphic Descriptions.

The geologic units involved in thrusting in the study area range in age from Late Proterozoic to Cretaceous. Published stratigraphic sections in the area from Hintze (1988) are found in figures 16-20. Figure 21 illustrates generalized east-west stratigraphic variations in thickness and facies changes. The general lithologic and stratigraphic descriptions of the geologic units that follows are based on the work of many authors.

Late Proterozoic

The Brigham Group (Crittenden et al., 1971) includes the following units:

The Formation of Perry Canyon (Upper Proterozoic) consists of two members. The upper member is a medium- to dark-gray, tan-weathering, medium- to fine-grained graywacke, and a gray to dark-green, tan-weathering, micaceous siltstone. The lower member is a gray to black, tan-weathering diamictite containing pebble- to boulder-sized quartzitic and granitic clasts. The matrix is a black, medium-to fine-grained sand.

The Maple Canyon Formation (Upper Proterozoic) consists of three members. The upper member contains a white, coarse-grained, locally conglomeratic quartzite underlain by a olive-drab to silvery-gray, laminated argillite. The base of the upper member is a white to pale-gray conglomeratic quartzite, containing white quartz and white, gray, or pale-pink quartzite clasts of pebble- to cobble-size. The middle member is a pale-green, massively bedded, arkosic sandstone with intercalated quartzitic conglomerates near the base. The lower member is an olive-drab, locally gray, thin-bedded silty argillite and siltstone. Contains a middle interval of greenish-gray arkosic sandstone.
The Kelley Canyon Formation (Upper Proterozoic) consists of three different intervals. The upper part is an olive-drab siltstone interbedded with a tan- to brown-weathering, thin-bedded quartzite. The middle part is a gray to lavender argillite intercalated with and enclosing a pinkish-gray, thin-bedded, silty limestone. The lower part is a lavender-gray, purple-gray, or olive-drab shale and thin-bedded, greenish, fine-grained sandstone at top.

The Caddy Canyon Quartzite (Upper Proterozoic) is a white to tan, medium-grained, vitreous quartzite. The lower portion of the unit is commonly tan- to pale-brown weathering and light-colored near the top, commonly contains intercalated red siltstone at base.

The Inkom Formation (Upper Proterozoic) is a purple and olive-drab to light-green, thin-bedded argillite and quartzite. The upper part is commonly purple, while the lower portion is olive-drab to pale green. The unit contains a silver weathering, thin tuff and sandy tuff.

The Mutual Fm (Upper Proterozoic) is a grayish-red to pale-purple or pink, coarse- to medium- grained, commonly gritty or locally pebbly, quartzite and feldspathic quartzite with abundant cross-bedding.

The upper portion of the Geertsen Canyon Quartzite consists of a buff, white, pale-pink, coarse-grained, thick- to massive bedded, locally cross-bedded quartzite, arkose, grit, and conglomerate with subrounded pebble- and cobble-sized clasts of quartz, quartzite, and minor jasper. Arkosic rocks lower part contain broken crystals of green and pink microcline up to 1 cm in length (Dover, 1985).
Cambrian

The Langston Formation is described by Valenti (1982a) as a dusky blue to medium-gray, yellowish-brown to light-gray weathering, limestone and dolomite. The unit outcrops as ledges and small cliffs.

The Ute Formation is a gray to blue, locally green, pink, or red, laminated to thin-bedded, locally oolitic, limestone. The limestone contains an intraformational conglomerate and is bounded above and below by thick-bedded dolomite and limestone (Valenti, 1982a).

The Blacksmith Dolomite is a gray to blue, thick-bedded, sugary weathering, dolomite. Interbedded cross laminated siltstone and oolitic intervals are also present (Valenti, 1982a).

The Bloomington Formation is a light- to dark-bluish-gray limestone and olive-green to light-brown shale, with interbedded pale-yellow-orange silty limestone. An intraformational conglomerate is common throughout this unit (Sorensen and Crittenden, 1972, 1979; Bryant, 1979).

The Nounan Formation is a medium-gray, thin- to thick-bedded, fine-crystalline dolostone. White, twiggy structures are common throughout the unit (Sorensen and Crittenden, 1972, 1979).

The St. Charles Formation consists of a lower member, the Worm Creek Quartzite, and an upper dolomitic member. The Worm Creek member is a medium- to dark-gray, tan- to brown-weathering, thin-bedded, calcareous quartzite (Sorensen and Crittenden, 1979). The upper member is a white- to light-gray, thin- to thick-bedded, fine- to medium- grained dolostone (Bryant, 1979).

The Gros Ventre Formation (Upper and Middle Cambrian) is a gray and tan, partially oolitic limestone containing a green micaceous shale in the middle (Oriel and Platt, 1980).
The Gallatin Group (Upper Cambrian) is described by Oriel and Platt (1980) as "a gray and tan mottled limestone" that is 120 meters thick in southeastern Idaho.

**Ordovician**

The Garden City Limestone (Middle and Lower Ordovician) is separated from underlying Cambrian rocks by a disconformity. It is a medium- to pale-gray, grayish-orange-weathering, thin- to medium-bedded dolostone, commonly interbedded with sandy lenses and a medium- to yellowish-gray, thinly laminated siltstone (Bryant, 1979; Sorensen and Crittenden, 1972, 1979).

The Swan Peak Quartzite (Middle Ordovician) is described by Dover (1985) as a white- to pale-reddish-brown, well-sorted, well-rounded, fine- to medium-grained, fucoidal quartzite or quartz sandstone that thins and pinches out in the southeast of the study area. Oaks et al. (1977) reported thicknesses ranging from 0-150 meters.

The Fish Haven Dolomite (Upper Ordovician) and its Bighorn Dolomite equivalent is a medium- to pale-gray, medium- to thick-bedded, fine- to medium-grained dolostone (Bryant, 1979). The unit contains corals and crinoid columnals, and small white twiggy structures throughout (Sorensen and Crittenden, 1972, 1979).

**Silurian**

The Laketown Dolomite (Upper and Middle Silurian) is a consists of two members according to Budge (1966). The lower member is described as a light gray dolomite and the upper member is a dark-gray, very thick-bedded dolomite. The Laketown Dolomite forms large cliffs (Valenti, 1982a).

**Devonian**

The Devonian Water Canyon Formation (Jefferson Formation equivalent) disconformably overlies the Ordovician rocks. The Water Canyon Formation consists
of a medium- to pale-gray, pale- to yellowish-weathering, thin- to very thin-bedded, fine-grained dolostone, silty dolostone, and sandy dolostone (Sorensen and Crittenden, 1979).

The Upper and Middle Devonian Hyrum Dolomite (Jefferson Formation equivalent) is a dark-gray to black, dark- to light-gray-weathering, thin- to thick-bedded, fine- to medium-crystalline dolostone (Sorensen and Crittenden, 1972, 1979; Bryant, 1979).

The Darby Formation, equivalent of the Three Forks and Beirdneau Sandstone, is a grayish-orange weathering, medium- to very thin-bedded, fine- to medium-grained sandstone, dolomitic sandstone, and dolostone. The unit is interbedded with limestone, mudstone, shale, orthoquartzite, and intraformational conglomerate (Sorensen and Crittenden, 1979).

**Mississippian**

The Lodgepole Limestone (Lower Mississippian), lowest unit of the Madison Group, is a gray, thin- to thick-bedded, partly cherty, fossiliferous limestone (Dover, 1985).

The Little Flat Formation correlates with the lower Brazer Limestone of Richardson (1913) and the Mission Canyon (Upper and Lower Mississippian). The base of the unit is a brown shale, oolitic phosphorite, and cherty limestone. This interval is overlain by a brown weathering, medium- to thick-bedded, calcareous quartz sandstone, and interbedded sandy, cherty dolomite and limestone (Valenti, 1982a).

The Monroe Canyon Limestone (Upper Mississippian) is divided into three intervals by Valenti (1982a). The upper portion is described as a light gray weathering, thick-bedded bioclastic limestone. A middle interval of cherty limestone
is overlain by a bluish gray, phaneritic dolomite. The Monroe Canyon Limestone is a cliff-former (Valenti, 1982a).

**Pennsylvanian**

The Amsden Formation (Pennsylvanian and Upper Mississippian) is equivalent to the Morgan Formation. It is described by Oriel and Platt (1980) as a "red and gray cherty limestone and yellow siltstone, sandstone and conglomerate."

The Wells Formation (Pennsylvanian and Permian) is the western equivalent of the Weber and Tensleep Formations. The Wells is described by Sando et al. (1959) as a "fine- to medium-grained quartzite sandstone and sandy dolomite with minor interbeds of coarse-grained limestone breccia and fine-grained dolomite."

**Permian**

The Phosphoria Formation (Permian) is divided into two members. The lower member is a brown phosphatic shale and the upper member is an olive-gray to yellowish-orange chert (Valenti, 1982a).

**Triassic**

The Dinwoody Formation (Lower Triassic) is an interbedded gray limestone and greenish-brown to olive-green siltstone (Oriel and Platt, 1980).

The Woodside Shale (Lower Triassic) is primarily a red siltstone and shale containing an interbedded minor sandstone and gray limestone (Oriel and Platt, 1980).

The Thaynes Limestone (Lower Triassic) consists of a middle interval of olive-gray, calcareous siltstone and shale, and a brown weathering shale between massive limestones above and below. Fossils are found throughout including ammonoid cephalopods and gastropods (Valenti, 1982a).
The Ankareh Formation (Upper Triassic) "consists primarily of reddish shales and siltstone and gray to red limestones; these lithologies appear to grade into one another both laterally and vertically. The middle portion of the formation contains several hundred feet of friable sandstone, the color of which ranges from white, yellow, orange, red, to maroon" (Valenti, 1982a). Valenti (1982a) also noted a lens of gritstone that is possibly correlatable to the Higham Grit.

**Jurassic**

The Nugget Sandstone (Upper Triassic to Lower Jurassic) is a red to grayish-white, fine- to medium-grained, medium to thickly cross-bedded, well-rounded quartz sandstone (Valenti, 1982a).

The Twin Creek Limestone (Middle Jurassic) is a medium- to light-gray, thin- to medium-bedded limestone and argillaceous limestone. The unit contains a minor reddish-brown mudstone (Dover, 1985).

The Stump Sandstone and Preuss Redbeds (Upper and Middle Jurassic) consist of glauconitic siltstone, limestone, and sandstone, and reddish-brown evaporite-bearing siltstone and sandstone (Dover, 1985).

**Cretaceous**

Two members of the Gannet Group (Lower Cretaceous) and other Cretaceous units are encountered in drill-holes in the southeastern portion of the study area. The Ephraim Conglomerate is a red to maroon chert-pebble conglomerate and mudstone with a brown to tan crossbedded sandstone (Oriel and Platt, 1980). The Bechler Formation is a "red to purplish-gray mudstone, sandstone, and chert-pebble conglomerate" (Oriel and Platt, 1980).

The Cokeville Formation (Lower Cretaceous) is a tan to gray sandstone containing beds of tan sandstone, limestone, claystone, coal, porcelanite, and
bentonite (Oriel and Platt, 1980). The Bear River Formation is the equivalent of the Cokeville Formation.

The Kelvin Formation (Lower Cretaceous) is the equivalent of the Gannet Group and Bear River Formation (Lamerson, 1982).

The Aspen Shale (Lower Cretaceous) is a dark- to light-gray claystone and siltstone with intervals of quartz sandstone and porcelanite (Oriel and Platt, 1980).

The Frontier Formation (Upper Cretaceous) is a "brown to white sandstone and dark-gray shale" according to Oriel and Platt (1980). Oyster beds in the upper part of the formation are termed the Oyster Ridge Member on well logs that further note the Coalville Conglomerate Member and Allen Hollow Shale Member.

The Hilliard Shale (Upper Cretaceous) is a tan to dark-gray sandy shale, siltstone, and claystone with a tan sandstone increasing in thickness to the west and north (Oriel and Platt, 1980).

**Tertiary**

The Wasatch Formation contains three distinct lithologies described by Oaks and Runnells (1992). The principal lithology is a mudstone and mud-rich diamicton containing boulders and cobbles in a matrix of un laminated mud. Also common throughout the Wasatch Formation are calcite cemented, conglomeratic sandstones to sandy orthoconglomerates containing cobbles (Oaks and Runnells, 1992). The Cowley Canyon Member is an oncolitic limestone that reaches thicknesses greater than 60 meters near the southeast corner of Bear Lake (Coogan, 1992).
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<td>Geertsen Canyon Quartzite</td>
<td>1067</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Browns Hole Fm.</td>
<td>107</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mutual Fm.</td>
<td>732</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inkom Fm.</td>
<td>305</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Caddy Canyon Quartzite</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Papoose Creek Fm.</td>
<td>343</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kelley Canyon Fm.</td>
<td>213</td>
<td></td>
</tr>
</tbody>
</table>

Figure 16. Generalized stratigraphic column of the Wellsville, Utah area (adapted from Hintze, 1988).
<table>
<thead>
<tr>
<th></th>
<th>Depth (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-P</td>
<td></td>
</tr>
<tr>
<td>Monroe Canyon Limestone</td>
<td>168</td>
</tr>
<tr>
<td>Little Flat Fm.</td>
<td>308</td>
</tr>
<tr>
<td>Lodgepole Limestone</td>
<td>198</td>
</tr>
<tr>
<td>Leachap Fm.</td>
<td></td>
</tr>
<tr>
<td>Bonneville Sandstone</td>
<td>526</td>
</tr>
<tr>
<td>Hyrum Dolomite</td>
<td></td>
</tr>
<tr>
<td>Water Canyon Fm.</td>
<td></td>
</tr>
<tr>
<td>Sil</td>
<td>417</td>
</tr>
<tr>
<td>Laketown Dolomite</td>
<td></td>
</tr>
<tr>
<td>Ord</td>
<td>546</td>
</tr>
<tr>
<td>Fish Haven Dolomite</td>
<td></td>
</tr>
<tr>
<td>Swan Peak Fm.</td>
<td></td>
</tr>
<tr>
<td>Garden City Fm.</td>
<td></td>
</tr>
<tr>
<td>St. Charles Fm.</td>
<td>281</td>
</tr>
<tr>
<td>Nounan Dolomite</td>
<td>305</td>
</tr>
<tr>
<td>Cambrian</td>
<td></td>
</tr>
<tr>
<td>Bloomington Fm.</td>
<td>457</td>
</tr>
<tr>
<td>Blacksmith Fm.</td>
<td>157</td>
</tr>
<tr>
<td>Ute Fm.</td>
<td>183</td>
</tr>
<tr>
<td>Langston Fm.</td>
<td>139</td>
</tr>
<tr>
<td>?</td>
<td></td>
</tr>
<tr>
<td>Brigham Group</td>
<td>777</td>
</tr>
<tr>
<td>Geertsen Canyon Quartzite</td>
<td></td>
</tr>
<tr>
<td>Mutual Fm.</td>
<td>792</td>
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</table>

Figure 17. Generalized stratigraphic column of the Logan-Bear River Range, Utah area (adapted from Hintze, 1988).
Figure 18. Generalized stratigraphic column of the Laketown, Utah area (adapted from Hintze, 1988).
<table>
<thead>
<tr>
<th></th>
<th></th>
<th>500 meters</th>
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<tbody>
<tr>
<td>Park City Fm.</td>
<td>274</td>
<td></td>
</tr>
<tr>
<td>Wells Fm.</td>
<td>183</td>
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</tr>
<tr>
<td>Round Valley Limestone</td>
<td>182</td>
<td></td>
</tr>
<tr>
<td>Monroe Canyon Limestone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Little Flat Fm.</td>
<td>274</td>
<td></td>
</tr>
<tr>
<td>Lodgepole Limestone</td>
<td>274</td>
<td></td>
</tr>
<tr>
<td>Berdineau Sandstone</td>
<td>336</td>
<td></td>
</tr>
<tr>
<td>Hyrum Dolomite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Canyon Fm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laketown Dolomite</td>
<td>259</td>
<td></td>
</tr>
<tr>
<td>Fish Haven Dolomite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Garden City Fm.</td>
<td>290</td>
<td></td>
</tr>
<tr>
<td>St. Charles Fm.</td>
<td>282</td>
<td></td>
</tr>
<tr>
<td>Nounan Dolomite</td>
<td>183</td>
<td></td>
</tr>
<tr>
<td>Bloomington Fm.</td>
<td>99</td>
<td></td>
</tr>
<tr>
<td>Blacksmith Dolomite</td>
<td>259</td>
<td></td>
</tr>
<tr>
<td>Ute Fm.</td>
<td>176</td>
<td></td>
</tr>
<tr>
<td>Langston Dolomite</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>Brigham Group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geertsen Canyon Quartzite</td>
<td>1189</td>
<td></td>
</tr>
<tr>
<td>Browns Hole Fm.</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Mutual Fm.</td>
<td>366</td>
<td></td>
</tr>
<tr>
<td>Inkom Fm.</td>
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</tr>
<tr>
<td>Caddy Canyon Quartzite</td>
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</tr>
<tr>
<td>Papoose Creek Fm.</td>
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<td>Kelley Canyon Fm.</td>
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<td>Maple Canyon Fm.</td>
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<td>Fm. of Perry Canyon</td>
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<td>Facer Fm.</td>
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</tbody>
</table>

Figure 19. Generalized stratigraphic column of the Huntsville, Utah area (adapted from Hintze, 1988).
Figure 20. Generalized stratigraphic column of the Preston-Pocatello, Idaho area
(adapted from Hintze, 1988).
Figure 21. Generalized diagram illustrating east-west stratigraphic variation across the study area. The stratigraphic columns adapted from Hintze (1988).
Appendix B. Strike and Dip Data.

Table 7. Orientations of fold axes across the south boundary of the field area.

<table>
<thead>
<tr>
<th>Fold #</th>
<th>limb code</th>
<th>fold type</th>
<th>trend</th>
<th>plunge</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A + B</td>
<td>SYN</td>
<td>214</td>
<td>05 SW</td>
</tr>
<tr>
<td>2</td>
<td>B + O</td>
<td>ANT</td>
<td>213</td>
<td>05 SW</td>
</tr>
<tr>
<td>3</td>
<td>C + D</td>
<td>SYN</td>
<td>209</td>
<td>07 SW</td>
</tr>
<tr>
<td>4</td>
<td>E + F</td>
<td>SYN</td>
<td>345</td>
<td>20 NW</td>
</tr>
<tr>
<td>5</td>
<td>F + G</td>
<td>ANT</td>
<td>355</td>
<td>22 NW</td>
</tr>
<tr>
<td>6</td>
<td>G + H</td>
<td>SYN</td>
<td>350</td>
<td>14 NW</td>
</tr>
<tr>
<td>7</td>
<td>H + W</td>
<td>ANT</td>
<td>195</td>
<td>00</td>
</tr>
<tr>
<td>8</td>
<td>I + J</td>
<td>ANT</td>
<td>238</td>
<td>02 SW</td>
</tr>
<tr>
<td>9</td>
<td>J + K</td>
<td>SYN</td>
<td>072</td>
<td>10 NE</td>
</tr>
<tr>
<td>10</td>
<td>L + R</td>
<td>SYN</td>
<td>031</td>
<td>08 NE</td>
</tr>
<tr>
<td>11</td>
<td>M + P</td>
<td>SYN</td>
<td>024</td>
<td>15 NE</td>
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<td>ANT</td>
<td>042</td>
<td>07 NE</td>
</tr>
<tr>
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<td>N + Q + S</td>
<td>ANT</td>
<td>358</td>
<td>01 NW</td>
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<td>SYN</td>
<td>030</td>
<td>07 NE</td>
</tr>
<tr>
<td>17</td>
<td>R + S</td>
<td>SYN</td>
<td>015</td>
<td>13 NE</td>
</tr>
<tr>
<td>18</td>
<td>Q + S</td>
<td>ANT</td>
<td>031</td>
<td>11 NE</td>
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<tr>
<td>19</td>
<td>S + U</td>
<td>ANT</td>
<td>341</td>
<td>04 NW</td>
</tr>
<tr>
<td>20</td>
<td>T + X</td>
<td>ANT</td>
<td>184</td>
<td>03 SW</td>
</tr>
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<td>03 SW</td>
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<td>ANT</td>
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<td>09 SW</td>
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<tr>
<td>23</td>
<td>Y + Z</td>
<td>SYN</td>
<td>217</td>
<td>11 SW</td>
</tr>
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</table>
Figure 22. Fold orientations in thrust fault hanging walls and locations of dip domains. Circled letters correspond to limb codes in Table 7.
Sources of surface data across the south part of the field area

Figure 23. Sources of surface data along the south boundary of the study area.
Appendix C. Slip vector data.

Figure 24. Map of thrust fault branch lines and major post-Willard thrust hanging wall folds.
Appendix D. Structure-contour and isochore maps.

Figure 25. Structure-contour map of the Meade thrust.
Figure 26. Structure-contour map of the Laketown thrust.
Figure 27. Structure-contour map of the Willard thrust.
Figure 28. Structure-contour map of the Lower Paris thrust.
Figure 29: Structure-contour map of the Upper Paris thrust.
Figure 30. Structure-contour map of the Bear Canyon thrust.
Figure 31. Isochore map of the Meade thrust.
Figure 32. Isochore map of the Laketown thrust.
Figure 33. Isochore map of the Willard thrust.
Figure 34. Isochore map of the Lower Paris thrust.
Figure 35. Isochore map of the Upper Paris thrust.