NEW INSIGHTS INTO THE STRUCTURAL GEOLOGY OF THE GILSON AND NORTHERN CANYON MOUNTAINS, CENTRAL UTAH

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Cover Photo: Relatively large-scale fold (Leamington antiform) in Oquirrh Group strata in the common footwall of the Leamington Canyon thrust and the Tintic Valley thrust, southeastern Gilson Mountains.

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Chapter 1

Stratigraphy and Structural Geology of Gilson and Northern Canyon Mountains, Utah—A Review and New View from Detailed Structural Analysis

ABSTRACT

Proterozoic to Paleozoic rocks are exposed in the Gilson and northern Canyon Mountains, which together form one of the first easternmost fault-bounded ranges of the Basin and Range Province west of the Wasatch Front. Within the Gilson Mountains, Sevier-age (Early Cretaceous–Eocene) shortening structures are preserved, though these structures are commonly overprinted by later Tertiary Basin and Range normal faults, and are concealed by Tertiary strata and Quaternary deposits in adjoining valleys. Thus, the Sevier-age fold-thrust structures are obscured and require more detailed study where they are exposed in order to establish a coherent regional framework.

Detailed geologic mapping and structural analyses were used to decipher the Sevier-age structures in the study area. The Leamington Canyon and Tintic Valley thrusts are the major Sevier-age thrusts that are observed in the Gilson Mountains. The antiformally folded Leamington Canyon thrust carried Proterozoic to lower Paleozoic hanging wall rocks over upper Paleozoic footwall strata. The Tintic Valley thrust was also folded into an antiform/synform pair during the emplacement of underlying structures. The Proterozoic hanging-wall rocks correlate with units adapted from the Canyon Range, and include the Pocatello, Caddy Canyon, Inkom, Mutual, and Prospect Mountain Formations. The folded Tintic Valley thrust carried a continuous section of Silurian through Mississippian rocks over Pennsylvanian through Permian rocks of the Oquirrh Group. The Jericho horse, in the footwall of the Tintic Valley thrust in the northeastern Gilson Mountains, contains overturned beds of Mississippian formations thrust over the upright Permian-Pennsylvanian Oquirrh Group. Cambrian carbonates and shales are present in the northern Canyon Mountains, but are not exposed in the Gilson Mountains, while the Ordovician section is only exposed in the Black Mountains, west of the Gilson Mountains.

In the Gilson and northern Canyon Mountains, folding is observed at several scales. Down-plunge projection of the major structures reveals the Jericho antiform in the Tintic Valley thrust sheet has a steep, short forelimb and a long horizontal backlimb that folds the overlying Leamington Canyon thrust and thrust sheet (Leamington Canyon anticline). Second-order, small-scale folds that reflect the large-scale fold geometries are also observed in outcrops of the hanging-wall and footwall rocks of the major thrusts.

INTRODUCTION

This paper has two purposes: (1) to provide an up-to-date review of the stratigraphy in the Gilson and northern Canyon Mountains, and (2) to present a revised description of the structural geology in the Gilson and northern Canyon Mountains based on detailed mapping and structural analyses using modern geological concepts of fold-thrust belts.

The study area covers most of the Gilson Mountains and northern Canyon Mountains (figure 1) in Juab and Millard Counties in central Utah, and includes the Tanner Creek Narrows, Jericho, Lynndyl East, and Champlin Peak 7.5-minute quadrangles (figure 2, plate 1). The Gilson Mountains are south of the town of Jericho and northeast of Leamington and are accessible via dirt roads and 4-wheel-drive trails. The highest elevation in the Gilson Mountains (Champlin Peak) reaches 7,504 feet (2,288 meters [m]) and is about 2,400 feet (730 m) above the surrounding valleys. U.S. Highway 6 passes between the Gilson Mountains and the Black Mountains to the west. Utah State Highway 148 passes between the Gilson Mountains and the East Tintic Mountains that lie to the northeast. Utah State Highway 132 passes between the southern Gilson Mountains and the Canyon Mountains to the south. The Canyon Mountains were formerly known as the Canyon Range.

The Gilson and northern Canyon Mountains are among the easternmost fault-bounded ranges of the Basin and Range Province west of the Wasatch Front in central Utah (figure 1) and are within the Sevier fold-thrust belt. The Gilson Mountains are separated from the northern Canyon Mountains by the Sevier River, which flows through Leamington Canyon (figure 1). Rocks exposed in the northern Canyon Mountains and southern Gilson Mountains are Proterozoic to Tertiary in age.

The Sevier fold-thrust belt (FTB) is an east-verging belt that defines the eastern margin of thin-skinned crustal shortening in the Cordilleran orogen of western North America (Armstrong, 1968; Burchfiel and Davis, 1975; Allmendinger, 1992; Miller and others, 1992) (figure 1a). Within this belt, thrusting displaced the Proterozoic, Paleozoic, and Mesozoic miogeoclinal rocks eastward during the Early Cretaceous to Eocene (140-55 Ma) Sevier orogeny (Armstrong, 1968; Burchfiel and Davis, 1975; Schwartz and DeCelles, 1988). The Sevier FTB is broken up into a series of salients, or segments, and these salients are typically decoupled from one another along east-trending transverse zones (Lawton and others, 1997; Mitra and Sussman, 1997) (figure 1a).

The Gilson Mountains are located at the southern end of the Provo salient, which has a prominent arcuate shape in map view with thrust traces strongly convex toward the foreland (figure 1a); the major thrusts are the Sheeprock thrust (SRT), the Tintic Valley thrust (TVT), the East Tintic-Stockton thrust system (ETT), the Midas thrust (MT), the Charleston-Nebo thrust system (C-NT), and frontal blind thrusts (BT) that form a triangle zone adjacent to the undeformed foreland of the Wasatch Plateau. The Provo salient is separated from the adjoining central Utah salient along the Leamington transverse zone, a prominent ENE-trending oblique transverse zone that includes the Leamington Canyon fault, associated folds, and an out-of-syncline reverse fault (Kwon and Mitra, 2001) (figure 1).

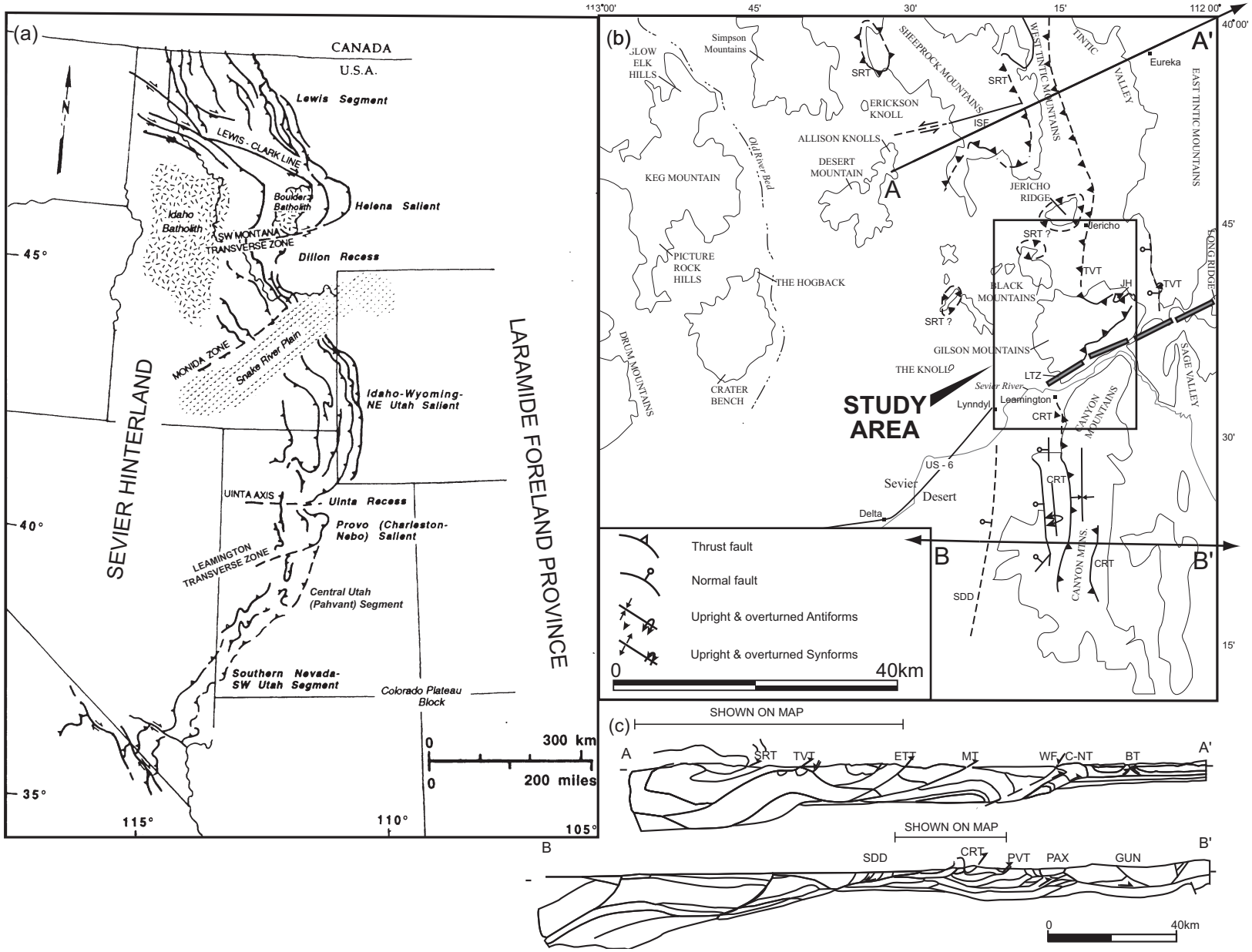

Figure 1. *(a) The Sevier fold-thrust belt of the western U.S. showing the principal salients and recesses located at prominent transverse zones. (b) Generalized structure map of central Utah showing the major Sevier-age structures. Inset box indicates the location of the Gilson and northern Canyon Mountains shown in more detail in figure 2. (c) Regional cross sections along A-A′ (Provo salient) and B-B' (Central Utah segment). Thrusts shown along the Provo salient (A-A′) are Sheeprock (SRT), Tintic Valley (TVT), East Tintic (ETT), Midas (MT), Charleston-Nebo (C-NT) thrusts, and a blind triangle zone (BT). Along the central Utah segment (B-B′) are the Canyon Range thrust (CRT), Pahvant thrust (PVT), Paxton thrust (PAX), and Gunnison thrust (GUN). Also shown are the Wasatch normal fault (WF), Sevier Desert detachment (SDD), Indian Springs fault (ISF), Leamington transverse zone (LTZ), and Jericho horse (JH). Modified from Mitra and Sussman (1997).*

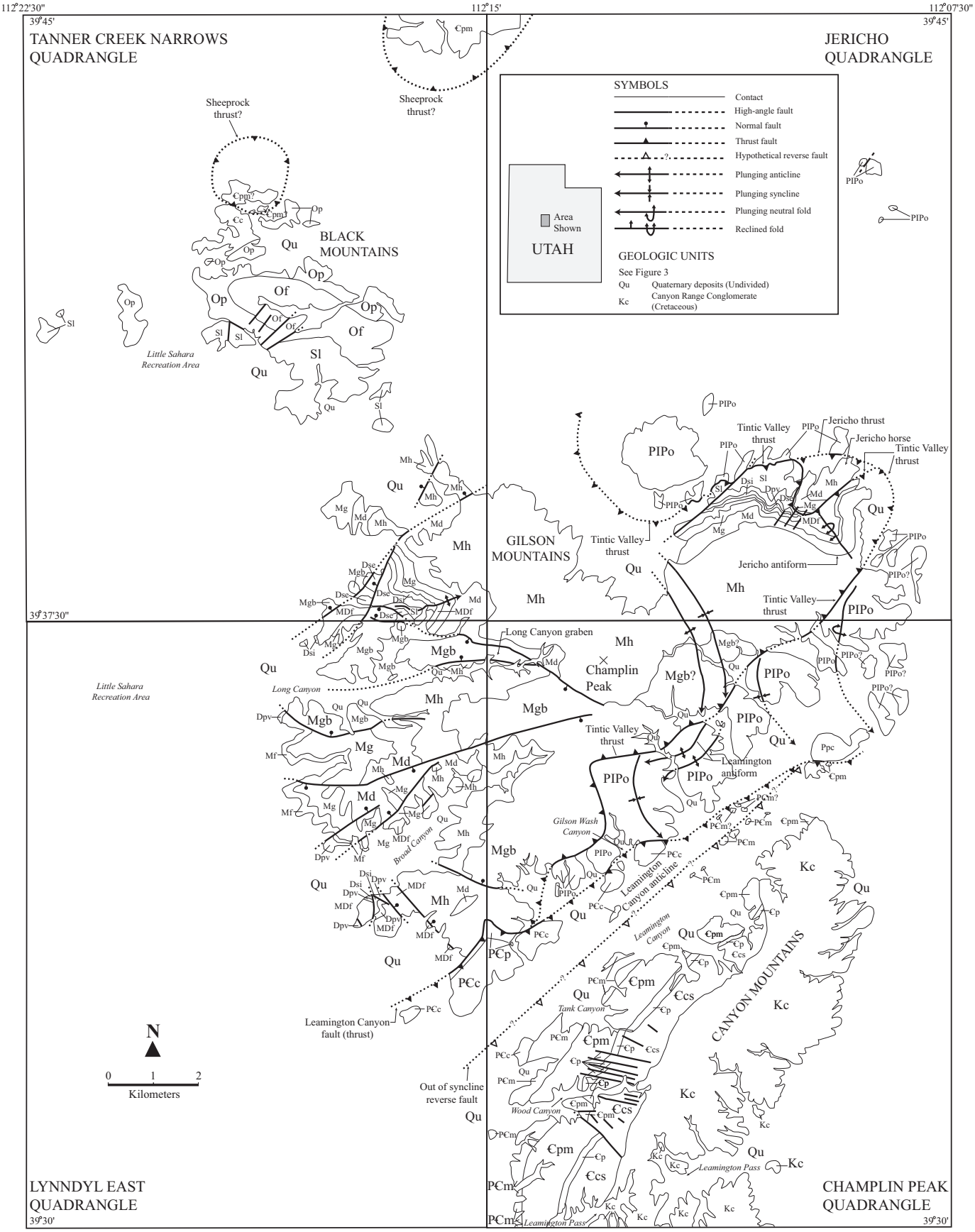

Figure 2. *Generalized geology of the Gilson and northern Canyon Mountains (modified from Costain, 1960; Wang, 1970; Higgins, 1982; Pampeyan, 1989; Kwon and Mitra, 2004). Symbols for map units are shown in figure 3.*

Within the Gilson Mountains, several shortening structures were formed during the Late Cretaceous to Eocene Sevier orogeny (structures shown regionally on figure 1a). The most prominent Sevier-age structures are the Tintic Valley thrust and the Leamington Canyon fault and their associated structures (figure 2). Both the Tintic Valley thrust and the Leamington Canyon fault are folded by underlying structures.

The Leamington Canyon fault, exposed along the southern margin of the Gilson Mountains, is a folded thrust fault (hereafter referred to as the Leamington Canyon thrust) and shows top down-to-the-southeast shear. The Tintic Valley thrust sheet is folded into an anticline-syncline pair by the underlying Jericho horse. The Jericho horse, with overturned beds of upper Paleozoic rocks, is exposed by erosion through the anticlinal portion of the Tintic Valley thrust. The Tintic Valley thrust has a leading branch-line with the Leamington Canyon thrust in the southwestern Gilson Mountains. These older structures are covered by Tertiary rocks and Quaternary deposits.

The conclusions presented here are based on the structural analyses and geological mapping of the Gilson Mountains at 1:24,000 scale in most of the Jericho, Champlin Peak and Lynndyl East, and parts of the Tanner Creek Narrows 7.5-minute quadrangles in central Utah (figure 2, plate 1). In the Tanner Creek Narrows quadrangle, the study covers rocks exposed in the Gilson Mountains but is not extended to the Black Mountains, west of the Gilson Mountains. Previous mapping by Costain (1960), Wang (1970), Higgins (1982), Morris (1987a, 1987b), and Pampeyan (1989) was also taken into account and provided a base for detailed mapping in the study area.

STRATIGRAPHY

The stratigraphy in the Gilson Mountains was first established by Costain (1960), and this scheme was largely followed by Wang (1970), Higgins (1982) and Pampeyan (1989). The stratigraphy of the Upper Proterozoic and Lower Cambrian rocks was revised extensively by Christie-Blick (1982, 1983), Higgins (1982), and Holladay (1984), and was used in a modified form by Pampeyan (1989). The composite and simplified stratigraphic package exposed in the Gilson Mountains and northern Canyon Mountains with map symbols that are used in this paper is summarized in figure 3.

Proterozoic Stratigraphy

Nomenclature of Proterozoic strata of the Gilson and northern Canyon Mountains follows prior studies of the Canyon Range (Higgins, 1982; Holladay, 1984; Millard, 1983), and was initially correlated with units from Pocatello, Idaho, to Beaver Mountain, Utah (Woodward, 1972; Hintze, 1988). This stratigraphic correlation includes the Pocatello Formation, Blackrock Canyon Limestone, Caddy Canyon Quartzite, Inkom Formation, and Mutual Formation. However, Link and others (1993) did not agree with this stratigraphy, and questioned the existence of Pocatello exposures south of the Gilson Mountains. The composite stratigraphy exposed in the area of southern Gilson Mountains and northern Canyon Mountains of the Champlin Peak quadrangle consists of the Pocatello, Caddy Canyon, Inkom, and Mutual Formations (Woodward, 1972; Higgins, 1982; Millard, 1983; Holladay, 1984).

Pocatello Formation

The Pocatello Formation is partially exposed in the hanging wall of the Leamington Canyon thrust northeast of the town of Leamington (figure 2, plate 1). The base of this formation is not exposed because it is bounded by the Leamington Canyon thrust (figure 2, plate 1).

In the Canyon Mountains south of the study area, Holladay (1984) subdivided the upper Pocatello Formation into three distinct members: a lower shale member, a middle quartzite member, and an upper shale and siltstone member. The lower shale member of the upper Pocatello Formation is about 180 m thick. The exposures of the shale member are poor and are typically recognized by a brownish-gray to olive-gray soil. The middle member of the upper Pocatello Formation, about 400 m thick, is mainly made up of resistant quartzite beds; the quartzites appear gray-brown on fresh surfaces and grayish-orange to reddish-brown on weathered surfaces. Finally, the upper member is about 250 m of phyllitic shale and siltstone interbeds.

We think most of the Pocatello Formation exposed adjacent to the Leamington Canyon thrust north of the town of Leamington corresponds to the upper Pocatello Formation of Holladay (1984). In the Leamington Canyon area, the upper shale and siltstone member is poorly exposed above the middle quartzite member of the Pocatello Formation, and the lower shale member is faulted out along the Leamington Canyon thrust.

The quartzite beds are generally very thick bedded, and individual quartz grains are generally not seen in hand samples. The quartzite is tan to brown on weathered surfaces and light gray on fresh surfaces. Where the rocks are in fault contact with the Leamington Canyon thrust, weakly developed deformation-related foliation, asymmetric folds, and fracture populations (with slickenlines) are seen in this formation. These quartzites below the shales (in the Gilson Mountains) look almost exactly like the Pocatello quartzite (middle) member in the Canyon Mountains, both in outcrop and in thin section.

At the thin-section scale, grain shapes vary from equant to elongated, and the latter are commonly arranged with their long-axes subparallel to each other, defining a foliation by the grain shape-preferred orientation. This foliation is better defined near the Leamington Canyon thrust and less prominent away from the fault. Almost all grains show undulose extinction, and quartz overgrowth texture is commonly observed where the original grains are defined by dust trails. At places, crystal-plastic deformation microstructures such as sweeping undulose extinction, deformation lamellae, serrated grain boundaries, grain boundary migration, intragranular cracks, and stylolites are observed (figure 4a), but elastico-frictional deformation microstructures such as transgranular cracks and zones of cataclasis (with cemented matrix) are also evident (figure 4b).

The lower shale unit of the Pocatello Formation at Pocatello, Idaho, is correlated with the lower member of the Otts Canyon Formation in the Sheeprock and adjacent West

AGE			REGIONAL THICKNESS	MAP SYMBOLS	UNIT AND LOCAL THICKNESS
PALEOZOIC	UPPER	PERMIAN	470-560 m	Ppc	PARK CITY FORMATION (462 - 570 m)
			210-270 m	Pdc	DIAMOND CREEK SANDSTONE (225 - 260 m)
		PENNSYLVANIAN	4560-4930 m	PIPo	OQUIRRH GROUP, UNDIVIDED (1700 m)
	MIDDLE	MISSISSIPPPIAN	910-1230 m	Mgb	GREAT BLUE FORMATION (300 m)
				Mh	HUMBUG FORMATION (190 - 210 m)
				Md	DESERET LIMESTONE (170 - 180 m)
				Mg	GARDISON LIMESTONE (110 m)
				MDf	FITCHVILLE FORMATION (48 - 80 m)
		DEVONIAN	250-290 m	Dpv	PINYON PEAK LIMESTONE AND VICTORIA FORMATION, UNDIVIDED (115 m)
				Dsi	SIMONSON DOLOMITE (42 - 75 m)
				Dse	SEVY DOLOMITE (97 - 110 m)
		SILURIAN	270 m	Sl	LAKETOWN DOLOMITE (265 - 369 m)
	LOWER	ORDOVICIAN	380 m	Of	FISH HAVEN DOLOMITE (Ely Springs) (271 m)
				Op	POGONIP GROUP (273 m)
		CAMBRIAN	850 m	€cs	CARBONATE AND CLASTIC SEDIMENTARY ROCKS, UNDIVIDED (600+ m) (INCLUDES UPPER CAMBRIAN CARBONATES, Cc, 180 m)
			200 m	€p	PIOCHE FORMATION (228 m)
			850 m	€pm	PROSPECT MOUNTAIN QUARTZITE (835 m)
UPPER PROTEROZOIC			580-730 m	P€m	MUTUAL FORMATION (500 - 750 m)
			380 m	P€c	CADDY CANYON QUARTZITE (~300 m) (INCLUDES INKOM FORMATION, 84 - 93 m)
			220-280 m	P€p	POCATELLO FORMATION (UPPER MEMBER, 250 m)

Figure 3. *Composite and simplified stratigraphy of the Gilson and northern Canyon Mountains (Costain, 1960; Wang, 1970; Higgins, 1982; Hintze, 1988; Pampeyan, 1989). Regional thicknesses are based on stratigraphy suggested by Hintze (1988), and Hintze and Davis (2003), and used in figures 15, 22, 26, and 27. Thicknesses in parentheses are local estimates from Costain (1960), Wang (1970), and Higgins (1982). Map symbols are those used in figures 2 and 15.*

Tintic Mountains, and is considered broadly equivalent to the formation of Perry Canyon on Fremont Island (Blick, 1979). The Pocatello Formation is also exposed in the Wah Wah Mountains and Cricket Mountains south of the Canyon Mountains (Hintze and Davis, 2003).

Caddy Canyon Quartzite

The Caddy Canyon Quartzite is one of the most prominent Proterozoic formations in the southern Gilson Mountains, where it is in fault contact with the Oquirrh Group along the Leamington Canyon thrust (figure 2, plate 1). The upper contact is drawn at the top of the highest thick-bedded quartzite unit (Higgins, 1982). The base of the formation is placed on the shale unit corresponding to either the Blackrock Canyon Limestone or the upper part of the Pocatello Formation. The thickness of the Caddy Canyon Quartzite is about 200 m in the southern Gilson Mountains (Higgins, 1982), and about 585 m in the Canyon Mountains (Holladay, 1984). The upper part of the Caddy Canyon Quartzite consists of coarse-grained, thick-bedded, well-sorted quartzites

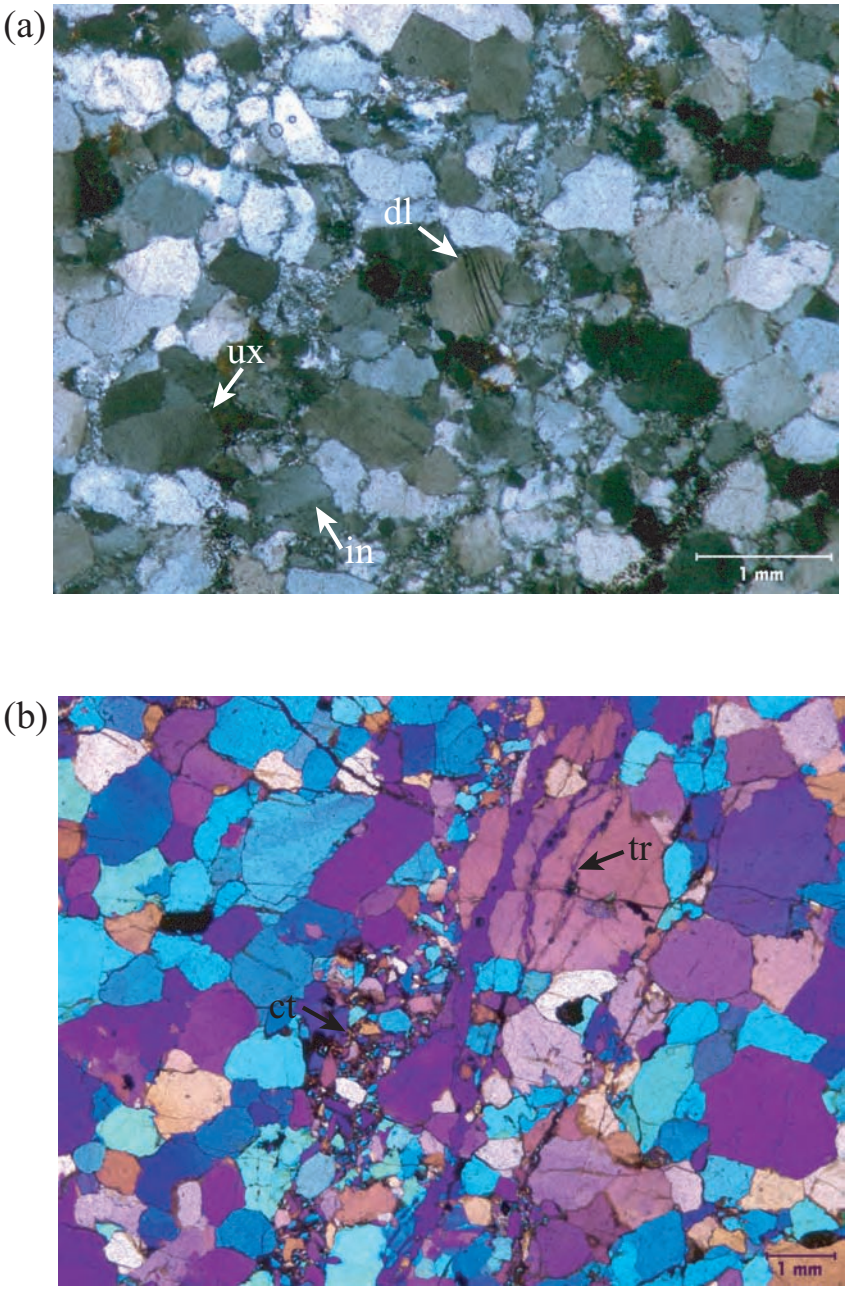

Figure 4. *Photomicrographs showing: (a) crystal plastic deformation features such as deformation lamellae (dl), undulose extinction (ux), and intergranular cracks (in) (cross-polarized light), and (b) cataclastic deformation features such as transgranular fractures (tr) and cataclasite zone (ct) (cross-polarized light with gypsum plate) from the Pocatello Formation close to the Leamington Canyon thrust. All the Proterozoic and Lower Cambrian quartzites in the Gilson Mountains exhibit these characteristics close to the fault.*

with cross-beds and infrequent interbedded pebble conglomerate. The lower part is thin- to medium-bedded, silty quartzites. The quartzites appear white to gray on fresh surfaces, and pale-orange to grayish-pink on weathered surfaces. At most places along the Leamington Canyon thrust, the rocks are strongly deformed, so that bedding and small-scale structures are obscured. Higgins (1982) recognized a 100-meter-thick conglomeratic interbed with 2-cm quartzite pebbles in a poorly sorted quartzite matrix in the rocks north of Leamington Canyon.

Christie-Blick (1982) correlated the Caddy Canyon Quartzite to the upper unit (unit F) of the McCoy Creek group in western Utah and adjacent Nevada. The Caddy Canyon Formation is also exposed in the Sheeprock, Drum, Wah Wah, and Cricket Mountains (Dommer, 1980; Christie-Blick, 1982; Hintze, 1988; Hintze and Davis, 2003).

In thin section, individual quartz grains are defined by dust trails along the grain boundaries. At places, individual grains show smooth, rounded grain boundaries with quartz overgrowths (figure 5), but range in shape from equant to elongated with grain shape-preferred orientation (figure 6). Grain size shows wide variations in the Caddy Canyon Formation. Almost all grains show undulose extinction, and especially close to the Leamington Canyon thrust, the rocks show similar overall microstructures to those described in the Pocatello Formation. The transgranular cracks and cataclasite zones are filled with iron-oxide minerals.

The Caddy Canyon quartzites contain clasts with a pre-existing fabric (figure 7). The individual grains within clasts show either a mylonitic fabric or recrystallized grains with undulose extinction indicating later deformation after recrystallization. These clasts are present in all the Proterozoic

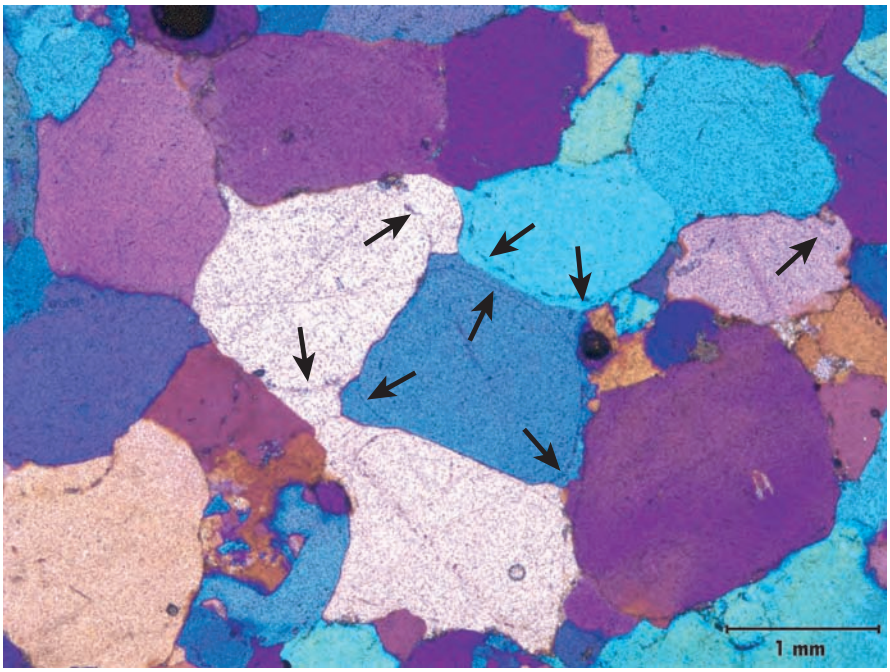

Figure 5. *Photomicrograph (cross-polarized light with gypsum plate) showing overgrowth texture in the quartz grains of the Caddy Canyon Formation. The original boundaries of the quartz grains are defined by dust trails (shown by arrows). This texture is seen in most of the Proterozoic and lower Cambrian quartzites in the Gilson and northern Canyon Mountains.*

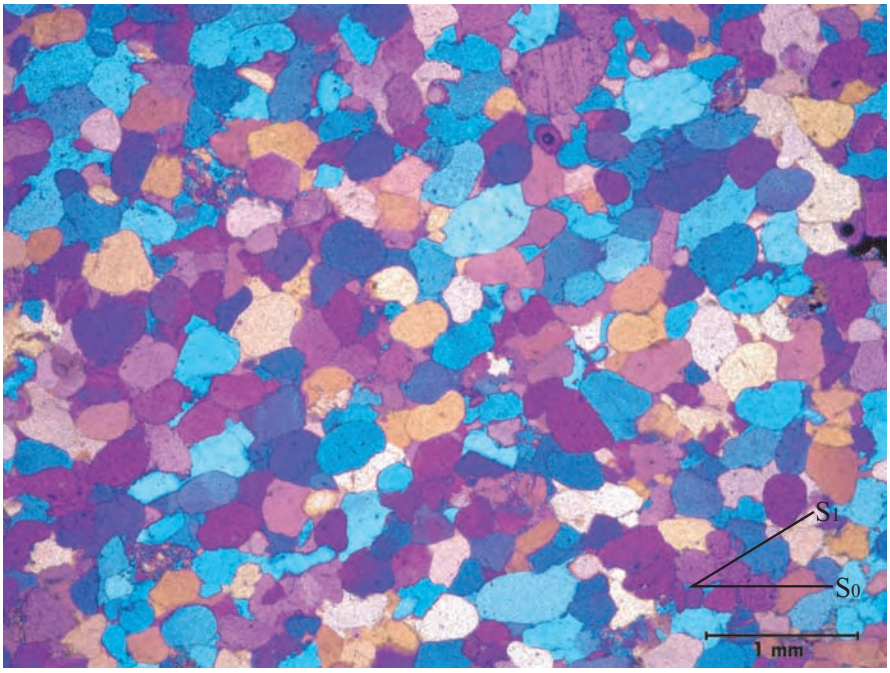

Figure 6. *Photomicrograph (cross-polarized light with gypsum plate) showing grain shape preferred orientations of the quartz grains (S_1) at low angle to bedding (S_0) from the Caddy Canyon Formation. This type of foliation is seen in most of the Proterozoic and lower Cambrian quartzites in the study area.*

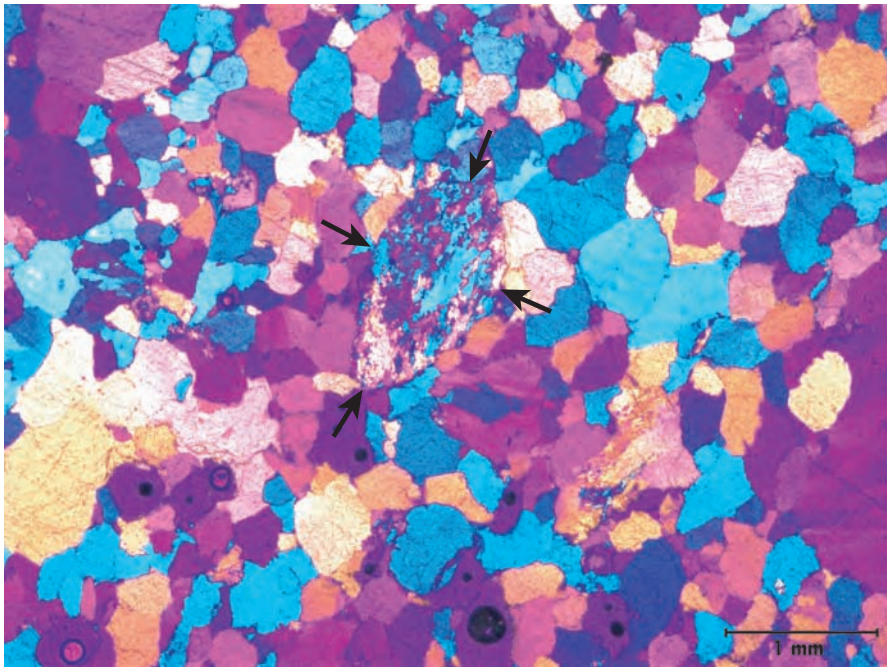

Figure 7. *Photomicrograph (cross-polarized light with gypsum plate) showing clast with pre-existing fabric (shown by arrows) in the Caddy Canyon Formation. Clasts with pre-existing fabric exist in most of the Proterozoic and lower Cambrian quartzites in the study area.*

quartzite units and in the Lower Cambrian Prospect Mountain quartzites. Similar clasts are also reported from the Caddy Canyon Quartzite and Mutual Formation of the Canyon Mountains and the West Tintic Mountains (Sussman, 1995). Clasts with pre-existing fabric are significant because they provide information about the source terrains from which the Proterozoic and the Lower Cambrian quartzites were derived. Mukul and Mitra (1998) estimated that, in the Sheeprock Mountains, the source terrain was shedding sediments for about 500 million years. because these clasts are observed in the entire Proterozoic sequence and in Lower Cambrian rocks. However, they also suggested the possibility that these clasts are reworked and the source terrain did not shed sediments for all 500 million years. Presence of quartz ribbons and recrystallized grains indicates that the deformation temperature in the source terrains corresponded to the upper greenschist to lower amphibolite facies (Tullis, 1983; Simpson, 1985; Tullis and Yund, 1985).

Inkom Formation

The Inkom Formation is exposed in the northern Canyon Mountains of the Champlin Peak quadrangle, but is not exposed in the Gilson Mountains (Higgins, 1982). The lower conformable contact is drawn at the top of the upper Caddy Canyon Quartzite, and the upper contact is recognized as the base of the thick-bedded quartzites of the Mutual Formation. The Inkom is predominantly made up of phyllitic shale with minor quartzite interbeds. The shale appears light olive gray at the top of the formation, and grayish red purple at the base. The total thickness of the Inkom Formation is about 84 to 93 m in the northern Canyon Mountains (Hintze and Davis, 2003). The Inkom Formation is also exposed in the Sheeprock, Drum, Wah Wah, and Cricket Mountains (Christie-Blick, 1982; Hintze, 1988; Hintze and Davis, 2003). The Inkom may be an important zone of weakness in the Proterozoic section.

Mutual Formation

The Mutual Formation is about 500 to 750 m thick (Hintze and Davis, 2003), and is exposed in the southern Gilson Mountains and along the northern edge of the Canyon Mountains in the hanging wall of the Leamington Canyon thrust (Higgins, 1982). The contact with the Leamington Canyon thrust, north of the Sevier River, is not exposed. A total thickness of about 750 m is calculated in the northern Canyon Range (Holladay, 1984). The lower conformable contact is drawn above the phyllitic shales of the Inkom Formation. The upper disconformable contact with the Prospect Mountain Quartzite is recognized by a color change from reddish purple to grayish orange pink. The Mutual Formation consists of medium- to coarse-grained, very thick bedded, well-sorted quartzites. Cross-bedding is commonly recognized by variation in color (figure 8). In the Gilson Mountains, several conglomerate interbeds of quartzite pebbles occupy approximately 5 to 10% of the exposed portion of the Mutual Formation (Higgins, 1982; Holladay, 1984).

In thin section, the rock consists of mostly rounded quartz grains with some feldspar and muscovite, but the feldspar grains are mostly altered to sericite. The individual grains are interlocked and equant to elongated with grain shape-preferred orientation. The quartz grains commonly show overgrowth texture where the original grain boundaries are defined by dust trails. Grain size exhibits wide variations in the Mutual Formation.

The Mutual Formation is also exposed in the Sheeprock, Drum, Wah Wah, Cricket, and Wellsville Mountains, and in the Goshen-Long Ridge area (Christie-Blick, 1982; Hintze, 1988; Hintze and Davis, 2003).

Paleozoic Stratigraphy

The Paleozoic section in the Gilson Mountains is about 6.1 kilometers (km) thick. In the study area, the Paleozoic

Figure 8. *Photograph showing the cross-bedding observed in the Mutual Formation (hammer head for scale). Top of bed to bottom of photograph.*

stratigraphy is dominated by carbonate rocks, except for the lowermost Paleozoic Prospect Mountain Quartzite. The Silurian through Mississippian section is observed in the hanging wall of the Tintic Valley thrust, and covers most of the Gilson Mountains. Part of the Mississippian section is also observed within the Jericho horse in the Jericho quadrangle of the northern Gilson Mountains. The Permian-Pennsylvanian Oquirrh Group is exposed in the common footwall of the Leamington Canyon thrust and the Tintic Valley thrust in the Champlin Peak quadrangle, and also exposed in the footwall of the Tintic Valley thrust and the Jericho thrust in the Jericho quadrangle. Cambrian carbonates and shales are exposed in the northern Canyon Mountains (Champlin Peak quadrangle), but not exposed in the Gilson Mountains. The Ordovician section is only exposed in the Black Mountains, west of the Gilson Mountains, in the Tanner Creek Narrows quadrangle.

Cambrian Rocks

The Prospect Mountain Quartzite forms the base of the Cambrian section exposed in the northern Canyon Mountains and the eastern portion of the southern Gilson Mountains in the Champlin Peak quadrangle. Hintze and Robinson (1975) defined the top where shale is predominant in the interbedded quartzite and shale interval, whereas Higgins (1982) defined the top of the Prospect Mountain Quartzite as the base of strata containing phyllitic shale (lower in section). In the northern Canyon Mountains, Champlin Peak quadrangle, Higgins (1982) defined the detailed Cambrian stratigraphy above the Prospect Mountain Quartzite. Above the Pioche Formation, she followed the Cambrian stratigraphic scheme of Hintze and Robinson (1975), originally described from the House Range, which includes the Howell Limestone, Chisholm Formation, Dome Limestone, Whirlwind Formation, Swasey Limestone, and Wheeler Shale. She described the uppermost Cambrian limestones, shales, and sandstones as "carbonate rocks undifferentiated" because she could not identify the formations. To the south, these strata are as young as Late Cambrian (Hintze and Davis, 2003). For simplicity, we depict Cambrian strata above the Pioche Formation as a single unit.

Prospect Mountain Quartzite: The Prospect Mountain Quartzite rests disconformably on the Proterozoic Mutual Formation. The distinction with the Mutual Formation is based on an obvious color change from reddish purple (Mutual Formation) to white and grayish orange pink (Prospect Mountain). However, the weathered color of the Prospect Mountain Quartzite is variable, so that the Prospect Mountain Quartzite looks like Proterozoic quartzites in many places. Cross-bedding is common, and is easily recognized by alternating color changes from gray to grayish red. The Prospect Mountain Quartzite consists mainly of very thick-bedded, medium- to coarse-grained quartzites that appear shaly near the top and conglomeratic at the base. The grain size of the Prospect Mountain quartzites is usually finer than underlying quartzites of the Mutual Formation. Conglomerate interbeds, up to 2 m thick, occupy about 10% of the total thickness of the formation (Higgins, 1982). The upper contact of the Prospect Mountain Quartzite is drawn at the bottom of olive-green, argillaceous, cross-bedded quartzites and green to tan, fissile, micaceous shale of the Pioche Formation (Higgins, 1982).

The Prospect Mountain Quartzite is well exposed in the northern Canyon Mountains with a total measured thickness of about 835 m (Hintze and Davis, 2003), and was further subdivided into lower, middle, and upper units by Sussman (1995), Mitra and Sussman (1997), Ismat and Mitra (2001), and Ismat (2002). It is continuous across the Sevier River, and has a hanging-wall cutoff with the Leamington Canyon thrust in the eastern portion of the southern Gilson Mountains. The Prospect Mountain is also exposed at the northern end of the Jericho and Tanner Creek Narrows quadrangles on Jericho Ridge (figure 2, plate 1).

In thin section, the rock consists mostly of rounded quartz grains with some feldspar grains. The grain boundaries are defined by dust trails, and the rounded quartz grains commonly show overgrowth texture. Most of the feldspar grains are altered to sericite. Grain size exhibits wide variations and individual grains show equant to elongated shape with grain shape-preferred orientation. The grain shape-preferred orientation and the cataclastic deformation are more prominently observed in the rocks close to the Leamington Canyon thrust.

The Prospect Mountain Quartzite was first described in the Eureka district, Nevada (Hague, 1883). Because the formation underlies the lower Middle Cambrian carbonate rocks, most of the Formation is assigned to Early Cambrian age, but the lower part of the Prospect Mountain Quartzite may be Proterozoic (Christie-Blick, 1982). The Prospect Mountain Quartzite is correlated with the Lower and Middle Cambrian Tintic Quartzite in the East Tintic Mountains (Hintze, 1988). The Prospect Mountain Quartzite is also exposed in the Deep Creek Range, Simpson, Sheeprock, Drum, Wah Wah, and Cricket Mountains (Nolan, 1935; Christie-Blick, 1982; Hintze, 1988; Hintze and Davis, 2003).

Pioche Formation: The Pioche Formation is 228 m thick in the northern Canyon Mountains (Higgins, 1982), but not exposed in the Gilson Mountains. It consists of phyllitic shale and calcareous siltstone interbedded with grayish-red-purple to grayish-brown quartzites (2 to 8 m thick). The

shale unit contains trilobites and brachiopods (Holladay, 1984). The siltstone has abundant trace fossils and the quartzite beds have tubular worm burrows (Higgins, 1982). The Pioche Formation has conformable contacts with the overlying Cambrian carbonate and clastic sedimentary rocks (Higgins, 1982).

Cambrian carbonate and clastic sedimentary rocks, undivided: The undifferentiated Cambrian carbonate and clastic sedimentary rock package is one of the most prominent lithologies in the northern Canyon Mountains, but is not exposed in the Gilson Mountains. For our purposes, we have grouped the Middle Cambrian Howell Limestone (~92 m), Chisholm Formation (75 m), Dome Limestone (55 m), Whirlwind Formation (43 m), Swasey Limestone (186 m), and Wheeler Shale (30 m), and Upper Cambrian undifferentiated carbonates (107–360 m) (Higgins, 1982; Hintze and Davis, 2003). Generally, this 600+ m-thick package is made up of limestone with shale interbeds. The rocks appear medium gray on fresh surfaces, and weather yellowish gray in the lower units and brownish gray in the upper units. This rock package contains oncolites, frequently stained with limonite, within the Howell Limestone, *Glossopleura* trilobites within the Chisholm Formation, and *Ehmaniella* trilobites in the Whirlwind Formation (Higgins, 1982). The Wheeler Shale contains rare species of the conodonts *Hertzina bisulcata* and *Ptychagnostus gibbus*, and has many trilobite species in the lower portion of the unit (Higgins, 1982). Costain (1960) measured an incomplete section (180+ m) of Upper Cambrian rocks (he applied the name Ajax Dolomite) in the Black Mountains of the Tanner Creek Narrows quadrangle. However, this name is not appropriate for rocks above the Canyon Range thrust. The upper contact with the Ordovician carbonates is not exposed in the study area, but is exposed in the Black Mountains in the Tanner Creek Narrows quadrangle (figure 2, plate 1).

Ordovician Rocks

Ordovician rocks are not exposed in either the Gilson Mountains or the northern Canyon Mountains, but are exposed in the Black Mountains in the Tanner Creek Narrows quadrangle (figure 2, plate 1). The Ordovician rocks in the Black Mountains include the Pogonip Group and Fish Haven Dolomite (Ely Springs), with a combined thickness of ~544 m (Costain, 1960; Wang, 1970). The rocks are medium gray on fresh surfaces and weather olive to brownish gray. The distinctive Eureka Quartzite and Kanosh Shale were not reported by Costain (1960) or Wang (1970), so the Black Mountains need to be remapped.

Silurian Rocks

Laketown Dolomite: The Laketown Dolomite, which was originally defined in the Bear River Range at the Utah-Idaho border, is the only Silurian unit exposed in the Gilson Mountains, and has a measured thickness of 265 to 369 m (Costain, 1960; Wang, 1970; John Welsh, measured section, 1982, presented in Kwon and Mitra, 2005 [hereafter referred to as Welsh section]). The base of the Laketown is bounded by the Tintic Valley thrust in the northern Gilson Mountains, Jericho quadrangle (figure 2, plate 1). Costain (1960) mapped continuous beds of Silurian Laketown Dolomite in the entire northeastern Gilson Mountains, but parts of these beds were reinterpreted by Wang (1970) as overturned Mississippian section in the footwall of the Tintic Valley thrust (Champlin thrust of Wang, 1970; see also Pampeyan, 1989). These Mississippian beds have recently been further reinterpreted as overturned beds of Mississippian formations that constitute the Jericho horse (Kwon and Mitra, 2001, 2002). Consequently, the Silurian section is only exposed in the western half of the northeastern Gilson Mountains in the hanging wall of the Tintic Valley thrust (Gilson thrust of Wang, 1970) where it is in fault contact with footwall Oquirrh Group rocks (figure 2, plate 1). Small exposures of Laketown Dolomite are also found in the northwestern Gilson Mountains and in the Black Mountains in the Tanner Creek Narrows quadrangle (figure 2).

The Laketown is made up of fine- to coarse-grained, very thick-bedded dolomite with several chert layers and intraformational conglomerates in the upper part of the formation. The Laketown appears light gray to dark gray on a fresh surface, and weathers light blue gray to dark blue gray. Stromatolitic horizons are observed within thin-bedded, crystalline, cherty dolomite with medium- to dark-gray color (figure 9); the existence of these horizons helps to distinguish this unit from other limestones and dolomites in the field. Most of the dolomites are unfossiliferous, although orthid brachiopods and rugose corals occur near the top of the formation, and tabulate corals near the base of the unit (Costain, 1960; Wang, 1970). The Laketown Dolomite is disconformably overlain by a basal conglomerate horizon of the white-weathering Sevy Dolomite.

Devonian Rocks

Devonian rocks are well exposed in the northeastern Gilson Mountains (Jericho quadrangle) and the western edge of the northwestern Gilson Mountains (Tanner Creek Narrows quadrangle) (figure 2, plate 1). Costain (1960) mapped continuous Devonian beds in the northeastern Gilson Mountains, but these beds were reinterpreted by Wang (1970) as part of the Mississippian section in the hanging wall of the Tintic Valley thrust (Champlin thrust of Wang, 1970; see also Pampeyan, 1989). Consequently the Devonian section of the northeast Gilson Mountains is only exposed in the western half, in the hanging wall of the Tintic Valley thrust (Gilson thrust of Wang, 1970). Parts of the hanging-wall Devonian section are in fault contact with overturned Mississippian beds of the underlying Jericho horse (figure 2, plate 1). Small exposures of Devonian rocks are also observed in the western and southwestern Gilson Mountains of the Lynndyl East quadrangle (Costain, 1960; Wang, 1970; see also Pampeyan, 1989) (figure 2, plate 1). The Devonian strata are about 270 m thick and consist of Sevy Dolomite (Lower Devonian), Simonson Dolomite (Middle Devonian), and Pinyon Peak Limestone and Victoria Formation (Upper Devonian).

Sevy Dolomite: The Sevy Dolomite appears gray to olive gray on fresh surfaces, and weathers to grayish white. It is a fine-grained dolomite with scattered grains of frosted clear quartz. Individual beds are about 2 m thick, and a 1.2-meter-thick bed of light-gray quartzose sandstone occurs in the upper part of the formation (Costain, 1960; Wang, 1970). The white-weathering color helps to easily distinguish the

Figure 9. *Photograph showing stromatolitic horizons from the Silurian Laketown Dolomite (lens cap for scale).*

Sevy dolomite from other dolomites in the field. The bottom of the Sevy Dolomite is placed at the base of a poorly exposed conglomerate horizon with small (3 to 10 mm) Sevy-like pebbles in a gray arenaceous matrix. The upper contact is drawn at the base of the medium-gray weathering Simonson Dolomite. The thickness of the Sevy Dolomite in the northern Gilson Mountains is about 97 to 110 m (Costain, 1960; Welsh section). It is also exposed in the Black Mountains, west of the Gilson Mountains.

Simonson Dolomite: The Simonson Dolomite, 42 to 75 m thick in the northern Gilson Mountains (Costain, 1960; Welsh section), has a conformable contact with the underlying Sevy Dolomite. It conformably underlies the Victoria Formation, but locally has disconformable contacts with the Fitchville Formation in the study area where the Pinyon Peak Limestone and Victoria Formation are missing. The Simonson is a fine- to medium-grained, medium-gray, banded dolomite (Costain, 1960; Wang, 1970). Individual beds are about 0.7 m thick. The lower portion of the Simonson Dolomite contains a 2-m zone of laminated dolomite with biscuit-shaped structures that correspond to the "Curley limestone" of Proctor and Clark (1956).

Victoria Formation and Pinyon Peak Limestone: The Victoria Formation, up to about 77 m thick, consists of a basal unit (~7 m thick) of dolomitic breccia and dolomites, a middle unit (~30 m thick) of light-brown, fine- to coarse-grained, thin-bedded quartzose sandstone with cross-bedding, and an upper unit (~40 m thick) of medium- to dark-gray, fine-grained dolomite (Costain, 1960; Wang, 1970). The Victoria Formation is unconformably overlain by the Pinyon Peak Limestone.

The Pinyon Peak Limestone is about 33 to 38 m thick in the Gilson Mountains (Costain, 1960; Welsh section), and shows a uniform sequence of dark-blue, fine-grained, thin- to medium-bedded silty limestone beds. The upper unconformable contact with the Fitchville Formation is placed at the first appearance of thin- to thick-bedded, very silty and very crinoidal limestone (Costain, 1960; Wang, 1970). The fossils included in the Pinyon Peak are corals, brachiopods, foraminifera, and conodonts.

Mississippian-Devonian Rocks

The Mississippian section is the most prominent portion of the Paleozoic section in the Gilson Mountains. It is exposed in the hanging wall of the Tintic Valley thrust in most of the Gilson Mountains. Part of an overturned section makes up the Jericho horse and is exposed in the northeastern Gilson Mountains (112°10′W, 39°39′N) of the Jericho quadrangle. The Mississippian section is about 1 km thick in the study area, and is mostly limestones and sandstones. It consists of the Fitchville Formation (Lower Mississippian-Upper Devonian), Gardison Limestone (Lower Mississippian), Deseret Limestone (Upper Mississippian), Humbug Limestone (Upper Mississippian), and Great Blue Limestone (Upper Mississippian).

Fitchville Formation: The Fitchville Formation is about 48 to 80 m thick (Costain, 1960; Welsh section) and consists of medium-bluish- to dark-gray, fine- to medium-grained limestones and dolomites. Part of the formation in the northern Gilson Mountains is in fault contact with the overturned Mississippian beds of the Jericho horse along the Tintic Valley thrust. Costain (1960) and Wang (1970) suggested that the Fitchville Formation is of Mississippian age as it overlies Upper Devonian rocks, but the lower part of the Fitchville Formation is considered to be Devonian (Hintze, 1988). The dolomite unit in the middle of the Fitchville Formation is a steep cliff-former with 0.6-meter-thick white calcite beds at the base and top of this unit. The top of the Fitchville formation has a "Curley limestone" (Proctor and Clark, 1956) that is defined by the presence of biscuit-shaped structures within beds. The existence of both stromatolitic horizons (figure 10) and 2- to 10-cm cephalopod fossils (figure 11) help to distinguish the formation from other limestones and dolomites in the field. Fossils taken from the Fitchville For-

Figure 10. *Photograph showing stromatolitic horizons from the Mississippian-Devonian Fitchville Formation (lens cap for scale). Note the differences of morphology, color, and weathering from the stromatolitic horizons observed in the Silurian Laketown Dolomite.*

Figure 11. *Photograph of a cephalopod fossil (left of pencil) in the Mississippian-Devonian Fitchville Formation. The presence of both stromatolitic horizons and cephalopod fossils help to distinguish the formation from other limestones and sandstones in the field.*

mation in the Gilson Mountains include brachiopods and corals indicating Early Mississippian age (Costain, 1960; Wang, 1970).

Gardison Limestone: The Gardison Limestone, exposed only in the Gilson Mountains, conformably overlies the Fitchville Formation in most places, but has unconformable contacts locally. The top of the formation is placed at the base of the first shales and siltstones of the conformably overlying Deseret Limestone. The Gardison Limestone is divided into three distinct units (Costain, 1960; Wang, 1970). The lower unit is a fine-grained gray-blue limestone (~70 m thick) with abundant silicified horn corals in the lower part; the upper part of this unit has a 0.9-meter-thick breccia zone (Costain, 1960), with breccia fragments of dolomite that are lighter colored than the matrix and that range in size from 6 to 150 cm. The middle unit is about 27 m thick and consists mostly of medium-gray, very thick-bedded dolomite with medium to coarse grains. The base of the middle unit has many pockets and lenses of conglomerates, with pebbles of dolomite and chert. Finally, the upper unit, about 12 m thick, is medium-bedded, fine-grained, blue-gray limestone with a thin, black bed of oolites observed in the middle of the unit. The total thickness of the Gardison Formation is about 110 m. The fauna found in the Gardison Limestone in the Gilson Mountains includes brachiopods, gastropods, and tabulate and horn corals (Costain, 1960; Wang, 1970).

Deseret Limestone: The Deseret Limestone is about 170 to 180 m thick in the Gilson Mountains (Costain, 1960; Welsh section) and consists dominantly of fine-grained, thin-bedded limestone with chert nodules and fine-grained, fissile siltstone (Costain, 1960; Wang, 1970). The limestone appears medium dark gray to black, and the siltstone is medium gray blue on fresh surfaces. The conformable upper contact with the overlying Humbug Formation is recognized where sandstone is abundant. The base of the Deseret Limestone is drawn at the contact of the Gardison Limestone with the phosphatic shale of the Deseret Limestone over much of the region. Brachiopods are the only fossils that have been observed in the Deseret Limestone (Costain, 1960; Wang, 1970).

Humbug Formation: The Humbug Formation, about 190 to 210 m thick (Costain, 1960; Welsh section), is one of the most extensively exposed formations, and consists of one of the most distinctive lithologies in the Gilson Mountains. The Humbug Formation has conformable contacts with the overlying Great Blue Limestone and the underlying Deseret Limestone. The base of the formation is drawn below the first sandstone or siltstone bed above the Deseret Limestone. The upper contact is gradational with the lower member of the Great Blue Limestone. The Humbug Formation in the northeastern Gilson Mountains is in fault contact with the Oquirrh Group along the Tintic Valley thrust (figure 2, plate 1). The Humbug Formation consists mainly of silty to arenaceous limestone and quartzose sandstone (Costain, 1960; Wang, 1970). The limestone is fine grained and appears black on fresh surfaces. The sandstone is fine to medium grained, and appears gray to brown gray and black, with light tan to brown weathering. The Humbug Formation is extremely fossiliferous, and foraminifera, gastropods, brachiopods, and corals are particularly abundant (Costain, 1960; Wang, 1970).

Great Blue Formation: The Great Blue is widely exposed in Utah in the Stansbury Mountains, southern Oquirrh Mountains, Sheeprock and West Tintic Mountains, East Tintic Mountains, and the Gilson Mountains. Only the lower part of the Great Blue, about 300 m, is exposed in the Gilson Mountains because most of the limestone is in fault contact with the Oquirrh Group along the Tintic Valley thrust in the southern and southwestern Gilson Mountains (figure 2, plate 1). The formation consists of black to bluish-black, thin- to thick-bedded, slightly silty limestone with fine grains and a fetid odor. The unit also contains some quartzose sandstones that appear brown and gray green, and weather orange brown with platy to flaggy weathering. The stratigraphically higher beds include thick brown-weathering quartzose sandstones and thick conglomerates with pebbles up to 5 cm in diameter. At places, large amounts of horn corals are observed; the size of corals are relatively larger than those observed in other formations. Other fossils observed in the Great Blue include tabulate corals and brachiopods.

Permian-Pennsylvanian Rocks

The Permian-Pennsylvanian rocks, in the common footwall of the Tintic Valley thrust and the Leamington Canyon thrust, are well exposed in the southern Gilson Mountains of the Champlin Peak quadrangle, but not exposed in the northern Canyon Mountains. They are also exposed in the footwall of the Tintic Valley thrust in the northern Gilson Mountains of the Jericho quadrangle. Costain (1960) assigned a Permian age (Park City Formation) to some exposures in the northeastern Gilson Mountains, but these were subsequently reinterpreted by Wang (1970) as Permian-Pennsylvanian Oquirrh Group (see also Pampeyan, 1989). The Park City Formation, therefore, is only exposed in the southern Gilson Mountains (Champlin Peak and Jericho quadrangles). The Permian-Pennsylvanian rocks in the study area include the upper part of the Oquirrh Group (Lower Permian to Pennsylvanian), Diamond Creek Sandstone (Lower Permian), and Park City Formation (Lower Permian).

Oquirrh Group: The lower portion of the undivided Oquirrh Group is not exposed in the Gilson Mountains; the Tintic Valley thrust places the Silurian Laketown Dolomite and Mississippian Humbug Formation and/or Great Blue Limestone against the upper portion of the Permian-Pennsylvanian Oquirrh Group. The upper contact of the Oquirrh with the overlying Diamond Creek Sandstone is not well exposed in the Gilson Mountains. The thickness of the Oquirrh Group as exposed in the Gilson Mountains is about 1700 m, and the unit is characterized by medium- to dark-gray, thin- to thick-bedded, cherty limestone with thin- to thick-bedded, calcareous sandstone interbeds (Costain, 1960; Wang, 1970). The upper part of the Oquirrh Group consists mainly of light-olive-gray to dark-gray, medium-bedded, arenaceous dolomite with interbedded sandstone units that are similar to those in the lower exposed part (Costain, 1960). Many of the dolomite beds contain numerous chert nodules. Fusulinids, brachiopods, corals, and bryozoan fragments are common in this unit in the Gilson Mountains (Costain, 1960; Wang, 1970).

Diamond Creek Sandstone: The Diamond Creek Sandstone is not well exposed in the Gilson Mountains. The lower contact is drawn at the top of cherty dolomite of the

Oquirrh Group and is considered unconformable (Higgins, 1982). The upper contact with the Park City Formation is also not well exposed. The estimated thickness of the Diamond Creek Sandstone is about 225 to 260 m (Costain, 1960; Wang, 1970; Higgins, 1982). The formation consists chiefly of yellowish-gray to grayish-orange, friable sandstone with medium grains. Several lenses of chert beds up to 2 m thick are observed near the top of the formation. We found the Diamond Creek too poorly exposed to map accurately.

Park City Formation: In the southeastern part of the Gilson Mountains, the Leamington Canyon thrust places the Permian Park City Formation (footwall) against Cambrian Prospect Mountain Quartzite (hanging wall). The Park City Formation is 462 to 570 m thick and consists of yellowish-light-gray to medium-gray, fine- to medium-bedded, silty dolomite with fine to medium grains (Costain, 1960; Wang, 1970; Higgins, 1982). The unit contains many chert nodules and some chert beds. The dolomite has a very fetid odor on a fresh surface.

STRUCTURAL GEOLOGY

The geologic setting of the Gilson Mountains and surrounding area has to be interpreted in the context of its regional geological setting (figure 1b). The Tintic Valley thrust is exposed in the northern and southern Gilson Mountains. Morris (1983) suggested that part of the Tintic Valley thrust is also exposed at the south end of the East Tintic Mountains which lie east and northeast of the Gilson Mountains. The Sheeprock thrust is exposed in the West Tintic and Sheeprock Mountains that lie to the northwest of the Gilson Mountains. Across the Leamington transverse zone to the south, in the central Utah segment of the Sevier FTB (figure 1a), the Canyon Range thrust is exposed in the Canyon Mountains (figure 1b and c). The Canyon Range thrust sheet and associated hanging wall rocks are folded into a large syncline that is exposed in the middle and eastern part of the Canyon Mountains (Christiansen, 1952).

Within the Gilson Mountains, Sevier-age (Early Cretaceous-Eocene) shortening structures are preserved, the most prominent of which are the Leamington Canyon thrust and the Tintic Valley thrust. The focus of this study is to examine the structural geology of the Gilson Mountains, which covers most of the Champlin Peak, Lynndyl East, Jericho, and parts of the Tanner Creek Narrows quadrangles. The structures in the area of the Black Mountains of the Tanner Creek Narrows quadrangle were not covered, but the relationship with the northern Canyon Mountains is discussed in this study. The Leamington Canyon thrust, which carries Proterozoic and Lower Paleozoic hanging-wall rocks over Upper Paleozoic footwall rocks, is exposed along the southern edge of the Gilson Mountains (figure 2, plate 1). Upper Paleozoic footwall rocks of the Leamington Canyon thrust, with associated folds, are exposed in the southern Gilson Mountains, and these rocks serve as a common footwall of the Tintic Valley thrust (figure 2, plate 1). In the Jericho and Champlin Peak quadrangles, both the hanging-wall and footwall rocks and structures of the Tintic Valley thrust are exposed. The reclined folds associated with emplacement of the thrusts are exposed in the northeastern Gilson Mountains of the Jericho quadrangle. These older structures are commonly dissected by later normal faults, and covered by Tertiary formations and Quaternary deposits. These younger deposits are not considered in this study, but are shown in maps by Pampeyan (1989) and Kwon and Mitra (2004).

Faults in Gilson Mountains

Faults exposed in the area of the Gilson Mountains can be divided into three broad groups: Sevier thrust faults, older high-angle normal faults, and younger normal faults.

1. Sevier thrust faults include the Leamington Canyon thrust, the Tintic Valley thrust, and the Jericho thrust. These faults formed during crustal shortening related to the Mesozoic to early Cenozoic Sevier orogeny.

2. An older group of high-angle normal faults trend west-northwest (WNW) and east-northeast (ENE) and show small stratigraphic separations. The WNW-trending normal fault north of Long Canyon in the Tanner Creek Narrows and Champlin Peak quadrangles, and the ENE-trending normal fault, north of Broad Canyon in the Lynndyl East and Champlin Peak quadrangles, are the most prominent examples in this group (figure 2, plate 1). These faults commonly formed horst-and-graben type structures with their counterpart normal faults. Several high-angle normal faults that trend approximately WNW to northwest (NW) are also observed in the southwestern part of the Gilson Mountains, south of Broad Canyon in the Lynndyl East quadrangle (figure 2, plate 1). The ENE-trending faults are approximately parallel to the traces of the Leamington Canyon thrust and the Tintic Valley thrust, while the WNW- and NW-trending faults are at high-angle to them. The WNW- and NW-trending normal faults die out at the major thrust faults.

3. A younger group of northeast (NE)-trending normal faults likely formed during mid to late Tertiary, basin-and-range extension. The normal fault that offsets the Tintic Valley thrust in the northern Gilson Mountains in the Jericho quadrangle is an example. Several faults parallel to this trend are also observed in the northern Gilson Mountains in the Jericho quadrangle and in the northwestern Gilson Mountains in the Tanner Creek Narrows quadrangle (figure 2, plate 1). The faults in this group displaced earlier faults in groups 1 and 2.

Sevier Thrusts

In the Gilson Mountains, several thrust faults were successively emplaced during the Sevier orogeny. The Leamington Canyon thrust and the Tintic Valley thrust are the major thrusts in this category, and are superbly exposed in the southern Gilson Mountains (figure 12). The Tintic Valley thrust is also exposed in the northern Gilson Mountains (figure 2, plate 1).

Leamington Canyon thrust: The Leamington Canyon thrust is mostly exposed in the Champlin Peak quadrangle and parts of it are also exposed at the eastern edge of the Lyn-

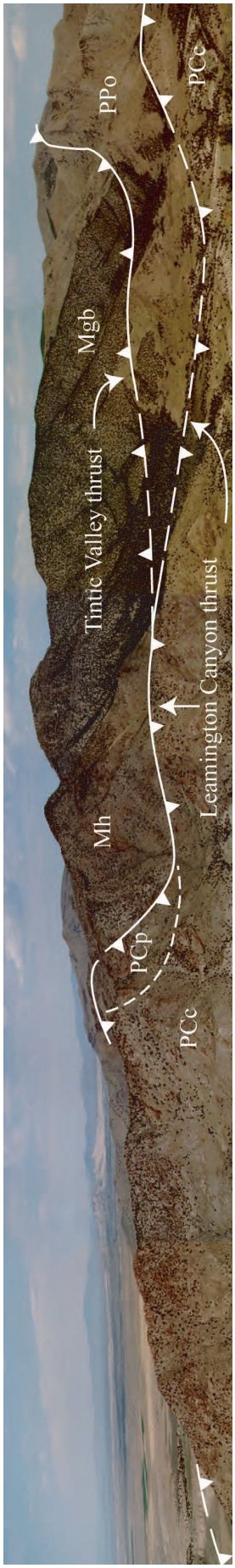

Figure 12. *Panoramic view of the Leamington Canyon area, looking north from Canyon Mountains showing the folded Leamington Canyon thrust and the Tintic Valley thrust. Unit labels from figure 3.*

ndyl East quadrangle (see Chapter 2 for detailed discussion of this fault). The exposure of the thrust can be traced from the western part of the southern Gilson Mountains at Leamington northeastward across the canyons that form north-south drainages in the southern Gilson Mountains. The fault is largely concealed by Tertiary formations and Quaternary deposits northeast of the exposures where it places the Cambrian Prospect Mountain Quartzite over the Permian Park City Formation in the eastern part of the Champlin Peak quadrangle (figure 2, plate 1). At its southwestern extent in the study area, the fault carries hanging-wall Proterozoic quartzite, which we interpret as the Pocatello Formation, over footwall Mississippian Humbug sandstones (figure 13). Beds in the hanging wall of the Leamington Canyon thrust show progressive increase in dip from 30° to 80° from west to east along the fault (figure 2, plate 1), indicating that the fault and its hanging wall are folded into the Leamington Canyon anticline. The hanging-wall rocks, in outcrop-scale, show weakly developed deformation-related foliation, asymmetric folds, and polished fracture surfaces with slickenlines that developed during successive phases of motion on the fault. Although gently dipping fractures are present, the dominant fractures are moderate to steeply dipping toward the southeast. The fault zone is defined by polished fracture surfaces with slickenlines at the outcrop scale (figure 14), and by transgranular cracks and zones of cataclasis that overprint the earlier plastic deformation microstructures at the microscopic scale (figure 4). Both the hanging wall and footwall rocks are more strongly deformed close to the fault.

In summary, Proterozoic through Lower Cambrian rocks are exposed in the hanging wall of the folded Leamington Canyon thrust in the study area, and Mississippian through Permian rocks are exposed in the footwall. Since the youngest rocks exposed in the footwall of the Leamington Canyon thrust are Permian and the fault is concealed by Tertiary formations at its eastern end, the age of thrusting is post-Permian and pre-Tertiary; however, evidence from surrounding areas further constrains the age.

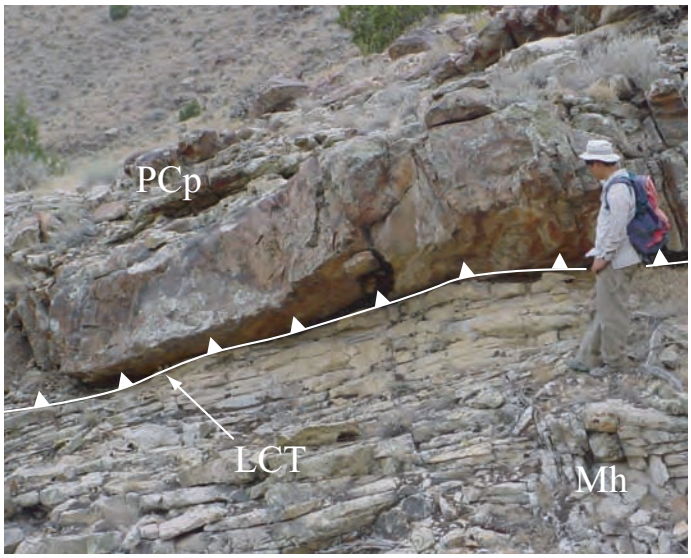

Figure 13. *Field photograph showing the fault contact northeast of Leamington, Utah (plate 1), where the Leamington Canyon thrust (LCT) places the Proterozoic Pocatello Formation (PCp) over the Upper Mississippian Humbug Formation (Mh). Location (39°33′43″, 112°14′52″).*

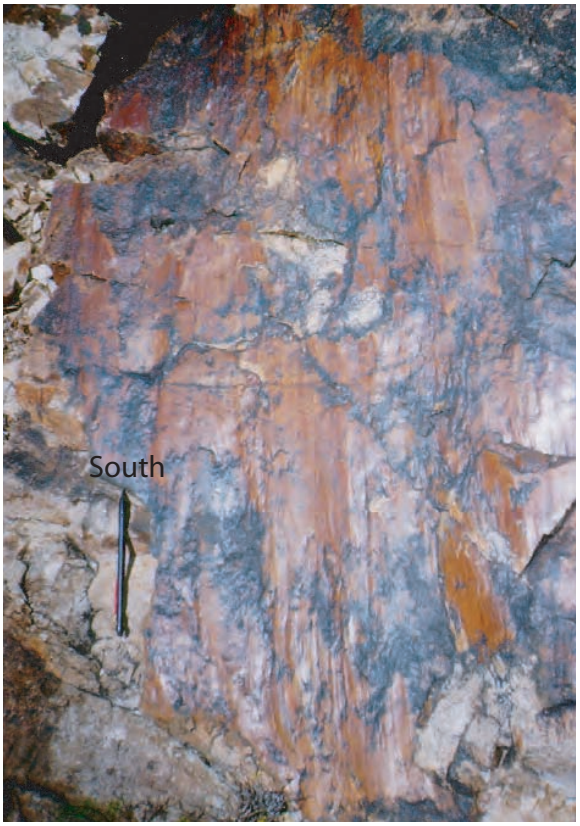

Figure 14. *Photograph, looking down to south, showing the polished surfaces with down-dip slickenlines observed in the Prospect Mountain Quartzite near the Leamington Canyon thrust. Location (39°35′45″, 112° 9′44″). Pencil for scale.*

Tintic Valley thrust: The Tintic Valley thrust is well exposed in the eastern half of the Gilson Mountains in the Jericho and Champlin Peak quadrangles (figure 2), but its position under Tintic Valley in the northern part of the Jericho quadrangle is concealed by later Tertiary formations and Quaternary deposits. The fault is folded into an antiform-synform pair (figures 2, 15). In the western portion of the northeastern Gilson Mountains, the folded fault dips southward at a low angle (average about 10°) and emplaces Silurian Laketown Dolomite southeastward over the Permian-Pennsylvanian Oquirrh Group (figures 2, 15). From there, the trace of the fault swings southward placing the Silurian Laketown Dolomite and Lower Mississippian rocks over the overturned stratigraphic package of Upper Mississippian rocks, and then swings back to the northeast, thereby forming an antiform (figure 2, plate 1). Although the fault is concealed by Quaternary deposits farther to the east in this part of the eastern Gilson Mountains, farther south its continuation can be traced where the fault dips toward the northwest and places Mississippian formations over an overturned section of Oquirrh Group, Diamond Creek Sandstone, and Park City Formation (figure 2, plate 1). The southwestward trending thrust trace crosses the quadrangle boundary and can be continuously traced in most of the southern parts of the Gilson Mountain in the Champlin Peak quadrangle (figure 2, plate 1). The thrust is interpreted to end at a leading branch line with the Leamington Canyon thrust in the western part of the southern Gilson Mountains in the Champlin Peak quadrangle (figure 2, plate 1).

Jericho thrust: In the northeastern Gilson Mountains of the Jericho quadrangle (112°10′W, 39°39′N), the overturned stratigraphic package of older Mississippian formations is carried over the younger Permian-Pennsylvanian Oquirrh group along the Jericho thrust (figure 2, plate 1). The fault-bounded slice of Mississippian strata is interpreted to be a small-scale horse, the Jericho horse (Kwon and Mitra, 2001, 2002, 2006). This horse is also visible in down-plunge projection (figure 15).

Older High-Angle Normal Faults

Broadly, two different orientations of high-angle normal faults with relatively small stratigraphic-separations are observed in the Gilson Mountains: (1) WNW- to ENE-trending normal faults that are approximately parallel to the trace of the major thrusts, and (2) roughly WNW- to NW-trending normal faults that trend at high-angle to the trace of the major thrusts, and die out against them.

Several WNW- to ENE-trending normal faults are present in the hanging wall of the Tintic Valley thrust in the western half of the Gilson Mountains (figure 2, plate 1). The traces of these faults are relatively straight, suggesting that they are nearly vertical faults. However, the faults appear to be non-planar at places where the wavy fault traces indicate opposite dip directions (Costain, 1960) (figure 2, plate 1). Small, outcrop-scale, fault-related-drag folding is observed near these faults. The WNW- to ENE-trending faults are often in conjugate orientations and form horst-and-graben type structures (figure 2, plate 1). The WNW-trending normal fault in the Tanner Creek Narrows and the Champlin Peak quadrangles and the ENE-trending normal fault in the Lynndyl East and the Champlin Peak quadrangles are the largest examples (figure 2, plate 1). In the Tanner Creek Narrows and Champlin Peak quadrangles, north of Long Canyon, the WNW-trending normal fault places the Silurian Laketown Dolomite against the Mississippian-Devonian Fitchville Formation. Its stratigraphic separation decreases eastward as the fault climbs in its footwall from the Silurian Laketown Dolomite to the Mississippian Great Blue Limestone (figure 2, plate 1). This fault forms the northern boundary of the ENE-trending Long Canyon graben. The fault also dissects earlier box-type folds in the Tanner Creek Narrows quadrangle and is dissected by Tertiary NE-trending normal faults at its western end (figure 2, plate 1). Another example in this group of faults is the normal fault north of Broad Canyon in the Lynndyl East and Champlin Peak quadrangles (figure 2, plate 1). This fault also forms a graben structure with conjugate ENE-trending normal faults northwest of Broad Canyon (figure 2, plate 1); this fault has relatively small stratigraphic-separation compared to the fault north of Long Canyon.

Several high-angle normal faults trending approximately WNW to NW are also present in the southwestern part of the Gilson Mountains in the Lynndyl East quadrangle (figure 2, plate 1). The traces of these faults are nearly straight indicating that they are almost vertical faults, and they have relatively small stratigraphic-separations (figure 2, plate 1). The fault traces are at high-angle to the trend of the major thrust faults; a couple of them can be traced to the major thrusts and die out at the Leamington Canyon thrust and the Tintic Valley thrust (figure 2, plate 1).

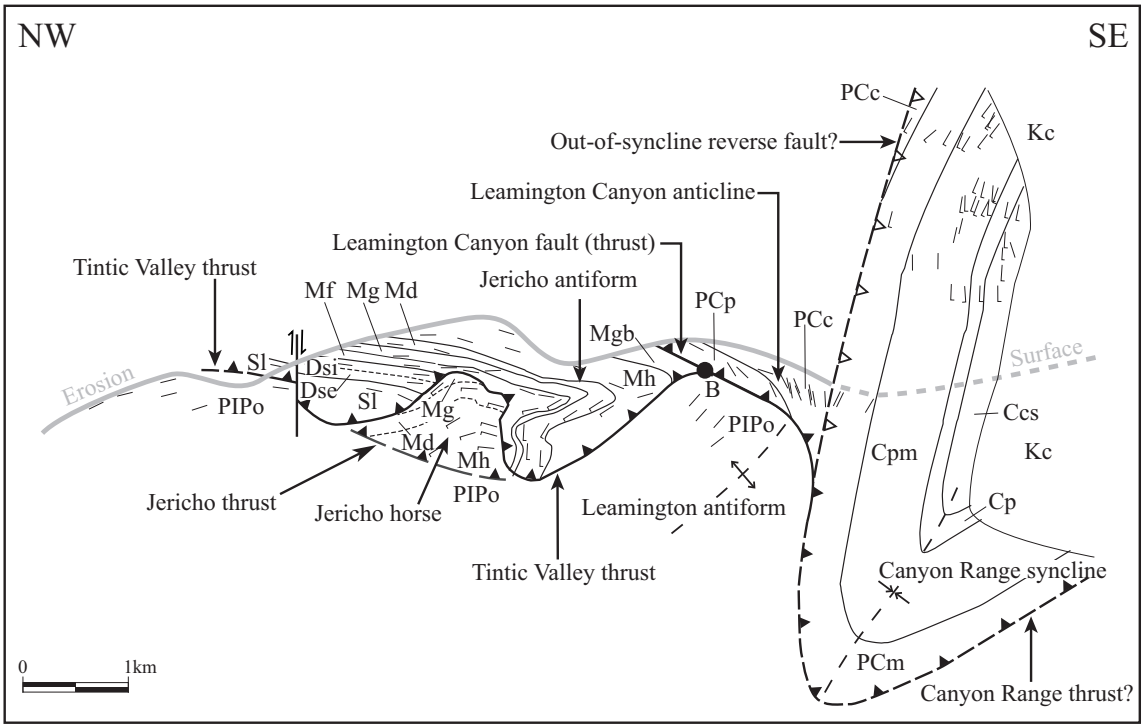

Figure 15. *Down-plunge projection showing major structures, bedding rakes, and lithologic contacts in the Gilson Mountains. The Leamington Canyon thrust has a leading branch line (B) with the Tintic Valley thrust and is folded by the underlying Tintic Valley thrust sheet and the Jericho horse. The Jericho horse causes the reclined folding in the southeastern part of the Tintic Valley thrust sheet. No vertical exaggeration. Unit labels from figure 3. Kc is the Canyon Range Conglomerate.*

Younger Normal Faults

Steeply dipping, NE-trending Tertiary normal faults truncate the Sevier-age structures in the Gilson Mountains. The older structures are commonly dissected by these basin-and-range normal faults and these faults are topographically conspicuous (figure 2, plate 1). For example, the Tintic Valley thrust shows offset by a nearly vertical normal fault in the Jericho portion of northeastern Gilson Mountains. These faults also dissect the earlier WNW-trending high-angle normal fault in the Tanner Creek Narrows and Champlin Peak quadrangles, north of Long Canyon (figure 2, plate 1). Tertiary normal faults with this trend are also observed in the Black Mountains in the Tanner Creek Narrows quadrangle (figure 2, plate 1).

Fold Geometries in Gilson Mountains

In the Gilson Mountains, folds are developed at several scales, and formed pre-, syn- and post-emplacement of major thrust faults. As described in the previous section, the major thrust faults observed in the study area are folded, so that the earlier fault-related folds show very complicated patterns in certain places. In this section, the geometries of the folds observed in the Gilson Mountains and their relation to the other structures (i.e., major thrust faults) will be discussed.

Folds in Hanging Wall of Antiformally Folded Leamington Canyon Thrust

In the hanging wall of the Leamington Canyon thrust, folding is observed on several scales. As previously discussed, the bedding in antiformally folded hanging-wall rocks progressively increase in dip from 30° to 80° from west to east along the fault (plate 1), giving a fold-axis that plunges gently to the southwest (19°, 218°) (figure 16). The large-scale structure of the Leamington Canyon thrust sheet is therefore best observed in down-plunge projections, and the geometry of folding on this scale in the hanging wall of the Leamington Canyon thrust (figure 15) shows an anticline (Leamington Canyon anticline) with a steep to overturned forelimb and long horizontal backlimb. Relatively small, outcrop-scale folding observed near the southwestern extent of the Leamington Canyon thrust (figure 17) reflects the geometry of the large-scale anticline observed in the hanging wall of the Leamington Canyon thrust.

In the down-plunge projection, it is interesting to note that the bedding orientations of the hanging-wall rocks in the northwest limb of the synform are plotted relatively higher than those in the antiform of the folded Leamington Canyon thrust; this is interpreted as the result of out-of-syncline reverse faulting (figures 2, 15). Therefore, the Caddy Canyon Quartzite that is observed in the western parts of the northern Canyon Mountains (south of Leamington Canyon) (figure 2, plate 1) is displaced along the out-of-syncline reverse fault relative to the beds observed in the southern Gilson Mountains (north of Leamington Canyon) (figure 2, plate 1). Parts of the Leamington Canyon thrust were reactivated as this reverse fault. Because Precambrian and Lower Cambrian hanging-wall strata of the Leamington Canyon thrust that show cutoffs in the eastern parts of the southern Gilson Mountains can be traced continuously to the northern Canyon Mountains (figure 2, plate 1), the synformally-folded Leamington Canyon thrust (figure 15) probably corre-

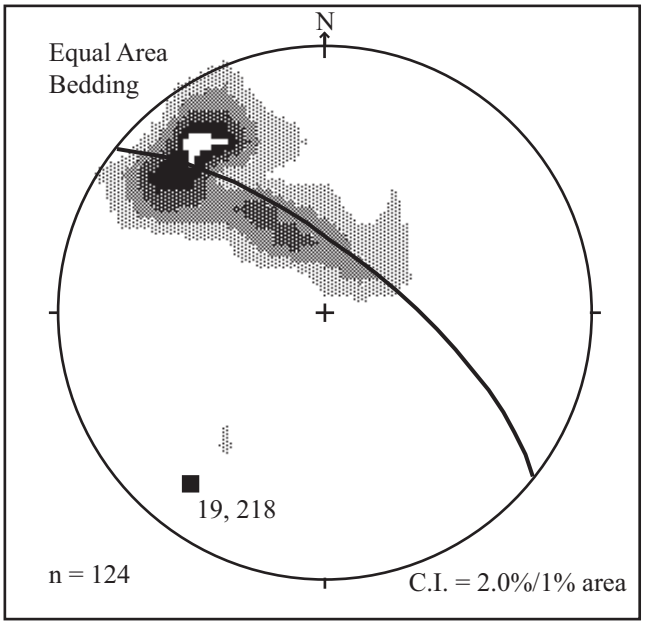

Figure 16. *Lower hemisphere, equal-area plot of poles to bedding in the hanging wall of the Leamington Canyon thrust. Overall, bedding in the sheet is folded along an axis plunging 19° toward 218°. Number of poles indicated by* n *and C.I. is contour interval.*

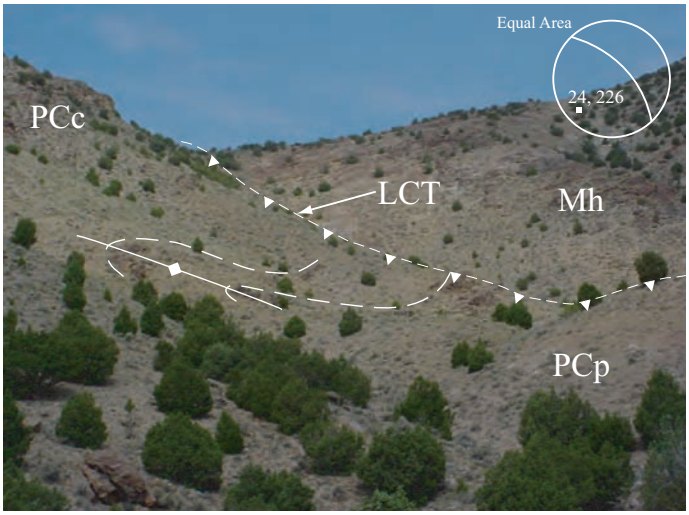

Figure 17. *Photograph, looking northeast, showing a second-order, small-scale antiform with a long horizontal backlimb and short, steep to overturned forelimb in the Pocatello Formation (PCp) and Caddy Canyon Quartzite (PCc) near the Leamington Canyon thrust (LCT). Location (39°33′43″, 112°14′52″). This small-scale fold reflects the geometry of the large-scale antiform that is visible in down-plunge projection. The fold-axis plunge and trend (24°, 226°) is shown in upper right corner.*

sponds to the northern parts of the folded Canyon Range thrust in the Canyon Range syncline (Lawton and others, 1997; Ismat and Mitra, 2001; Kwon and Mitra, 2001; Kwon and Mitra, 2006) (figure 15).

Folds in Folded Tintic Valley Thrust Sheet

In the northern part of the Jericho quadrangle portion of the Gilson Mountains, the hanging-wall rocks of the Tintic Valley thrust dip at moderately low angles to the north or south; but farther to the east, the beds are overturned with moderate- to high-angle dips to the west and northwest (plate 1). This change in strike and dip indicates the presence of an overturned antiform (Jericho antiform) that has a fold-hinge with low plunge and southwesterly trend (12°, 219°) (figure 18). Part of this fold is observed in the Lower Mississippian hanging-wall rocks (figure 19) in the Jericho portion of the northeastern Gilson Mountains (figure 2, plate 1), and its geometry is clear in the down-plunge projection (figure 15); it is a reclined fold that has a broadly folded long horizontal backlimb and a steep to overturned forelimb with smaller-scale folds (figure 15). The steep to overturned forelimb is also folded (figure 15).

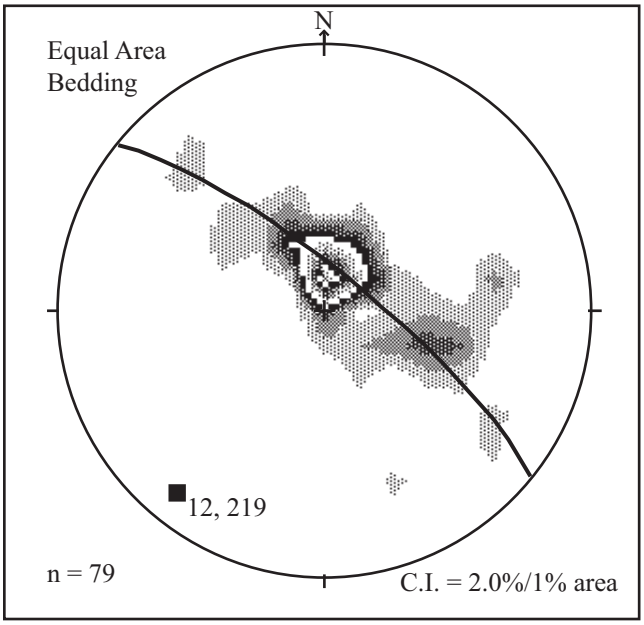

Figure 18. *Lower hemisphere, equal-area plot of poles to bedding in the hanging wall of the Tintic Valley thrust. Overall, bedding in the sheet is folded with low plunge and southwesterly trend (12°, 219°). Number of poles indicated by* n *and C.I. is contour interval.*

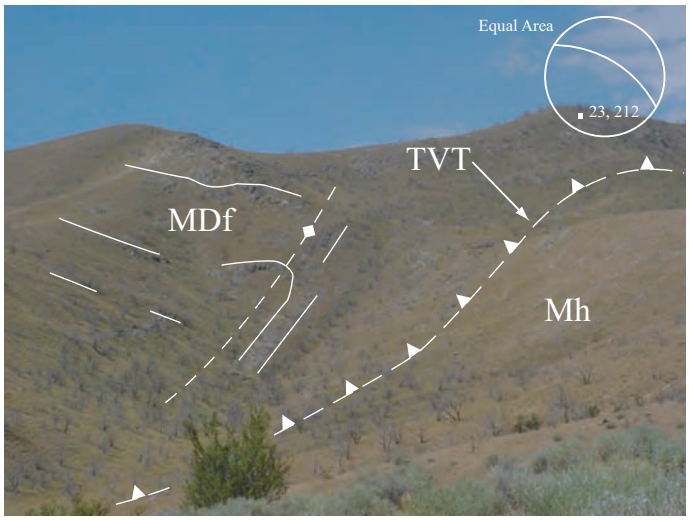

Figure 19. *Photograph looking north, showing part of the reclined fold (Jericho antiform) observed in the Lower Mississippian hanging wall rocks close to the Tintic Valley thrust. Location (39°39′17″, 112°9′20″). The fold-hinge plunge and trend (23°, 212°) is shown in upper right corner.*

Folds in Common Footwall of Leamington Canyon and Tintic Valley Thrusts

A large-scale upright antiform (Leamington antiform), and related, smaller (outcrop-scale) folds are present in the common footwall rocks of the Leamington Canyon thrust and the Tintic Valley thrust (Permian-Pennsylvanian Oquirrh Group) (figures 2, 20). The Leamington antiform has two antiformal fold-hinges, thereby forming a box-type fold (figure 2, plate 1); the fold-hinge (22°, 231°) is almost parallel to the trend of the major thrusts (figure 21a). Farther west, the fold-hinge of the adjoining synform changes trend toward the south (30°, 189°) (figure 21b). A smaller-scale antiform (figure 20b) is upright, and its relationship to the Leamington antiform, and the parallelism of the fold-traces to the major thrusts indicates that these folds formed in relation to the emplacement of the major thrusts.

On the west side of the Permian Park City Formation outcrops in the eastern portion of the southern Gilson Mountains, the bedding in the footwall rocks is steeply dipping to the south. However, on the eastern side of the formation, bedding is overturned with steep dips to the north, indicating the presence of a neutral fold (figure 2, plate 1).

DISCUSSION

Relative Timing of High-Angle Normal Faults in Gilson Mountains

Several older high-angle to almost vertical normal faults in the southwestern part of the Gilson Mountains are at high angle to the trend of the major thrusts and die out at these faults (e.g., Leamington Canyon thrust and the Tintic Valley thrust) (figure 2, plate 1). However, one of the prominent older high-angle normal faults displaces an earlier box-type antiform at the Tanner Creek Narrows quadrangle in the northwestern Gilson Mountains (figure 2, plate 1), and it is cut by later Tertiary (NE-SW) normal faults (figure 2, plate 1). These observations suggest that the high-angle faults were formed later than the folds, but they were probably active during the emplacement of the major thrusts. Because the development of most early folds in the Gilson Mountains are presumably closely related to the emplacement of major thrusts, the high-angle normal faults were probably active during a later phase of emplacement of the major thrusts. Therefore, these high-angle normal faults that end along the major thrusts are probably related to later phases of the Sevier orogeny (Costain, 1960).

Nature of Upright Fold and Neutral Fold in Common Footwall of Major Thrusts

Because of the lack of subsurface information such as seismic data and drill holes in the study area, the formation and relative timing of the upright fold and the neutral fold (a fold with a nearly horizontal hinge surface) with respect to the major thrusts in the study area is uncertain. However, Kwon and Mitra (2001) suggested that the Tintic Valley thrust initially developed with a fault propagation fold in the Paleozoic section; the fault eventually broke through, cutting up through the Paleozoic sequence, and carried the sheet over the ramp to form a fault-bend fold (figure 22), as was the case in other thrust faults such as the Sheeprock (Mukul and Mitra, 1998), Midas (Tooker, 1983) and Nebo (Smith and Bruhn, 1984) thrusts in the Provo salient. From this argument, two alternative kinematic interpretations are possible for the formation of the upright Leamington antiform and the neutral fold observed in the common footwall of the Leamington Canyon thrust and the Tintic Valley thrust (fig-

Figure 20. *Photographs looking northwest showing: (a) relatively large-scale fold (Leamington antiform) in Oquirrh Group strata in the common footwall of the Leamington Canyon thrust and the Tintic Valley thrust (inset indicates the area for [b]) (39°34′48″—39°35′48″, 112°12′8″—112°13′), and (b) small-scale, upright antiform (39°35′45″, 112°12′8″).*

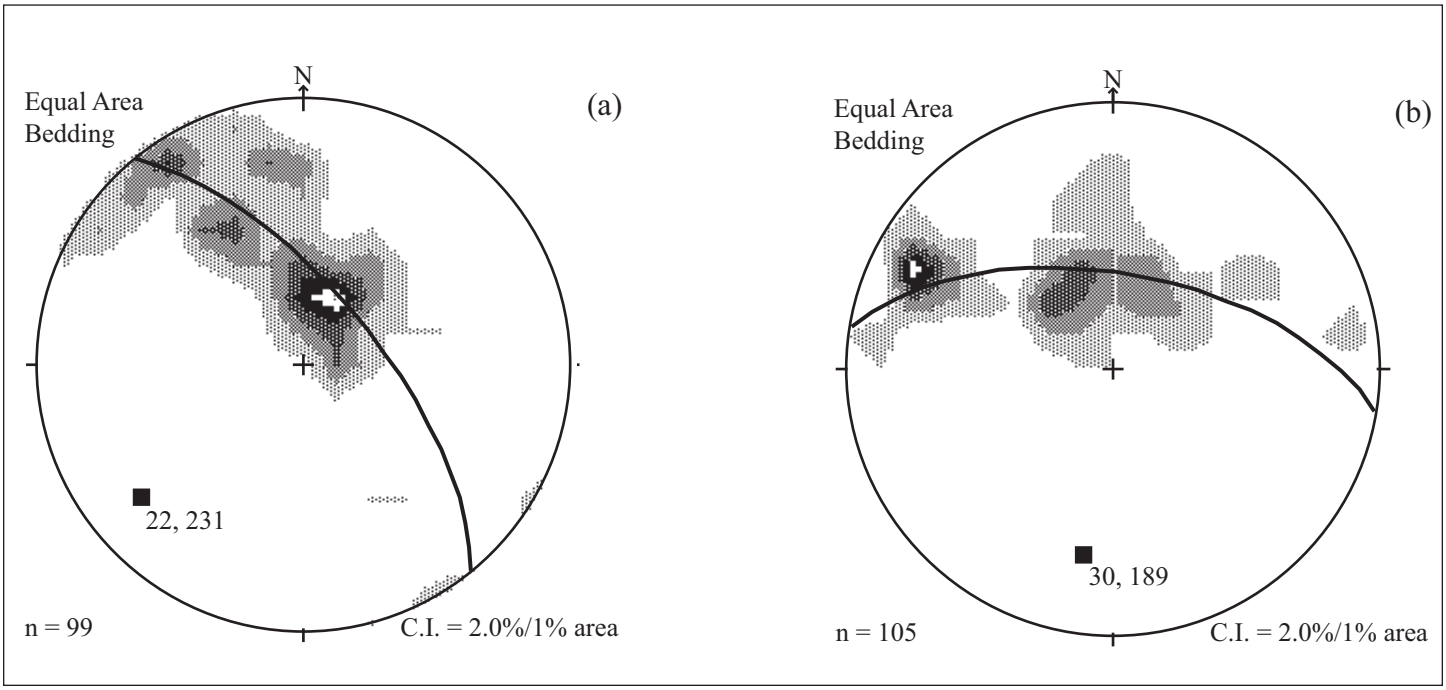

Figure 21. *Equal-area plots of poles to bedding from the relatively large-scale folds in the Oquirrh Group in the common footwall of the Leamington Canyon thrust and the Tintic Valley thrust. (a) Fold-axis of the Leamington antiform, plunging moderately to the southwest (22°, 231), representing orientation of the fold-axis before refolding event. (b) Fold-axis from the adjoining synform, plunging moderately to the south (30°, 189°), indicating the orientation of the fold-axis after refolding. Number of poles indicated by* n *and C.I. is contour interval.*

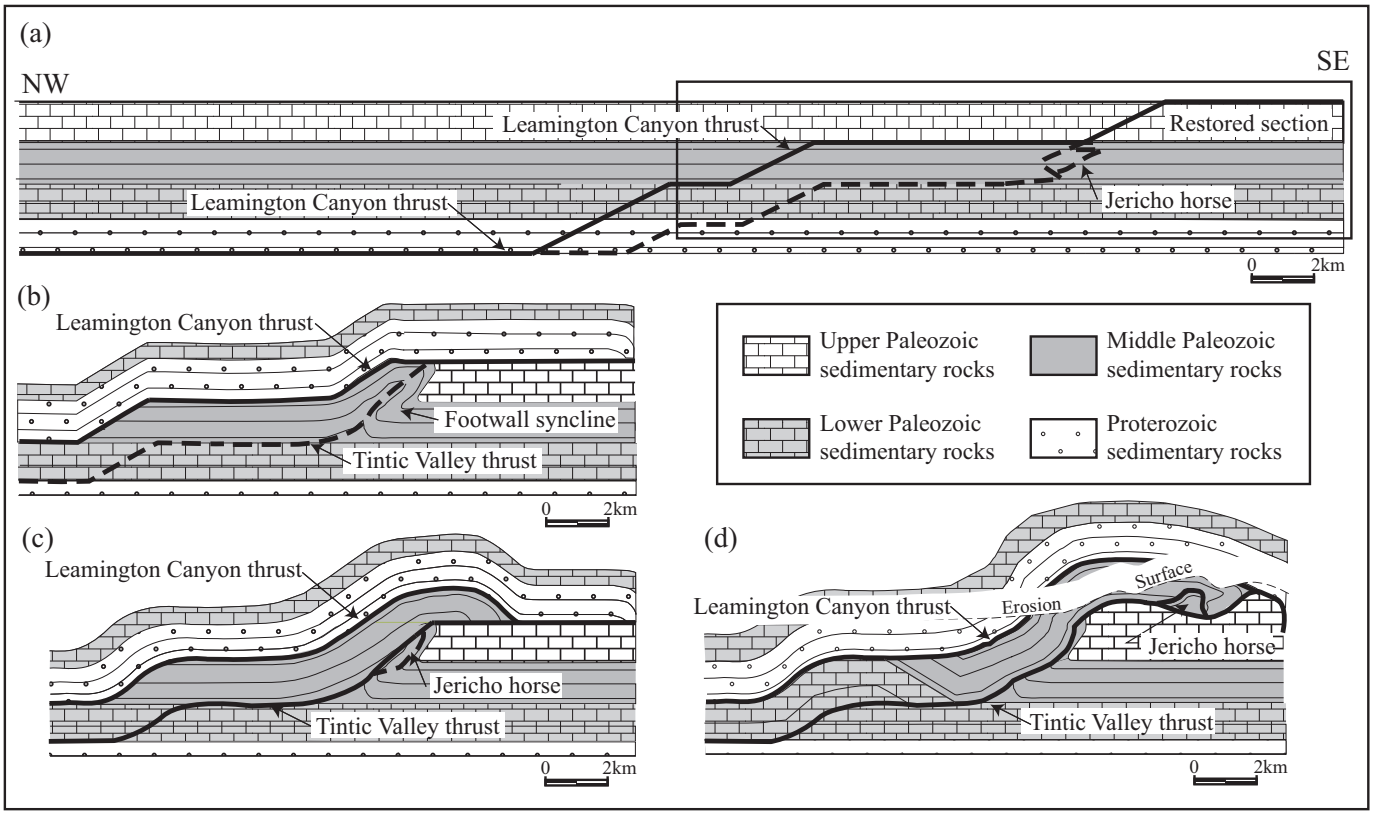

Figure 22. *Step-wise restorations of major structures in the Gilson Mountains (after Kwon and Mitra, 2006). Thrusts shown are Leamington Canyon thrust, Tintic Valley thrust, and Jericho horse. No vertical exaggeration. (a) Restored section (Early Cretaceous) where the restoration is carried out for most of the major structures. (b) Emplacement of Leamington Canyon thrust and developing Tintic valley thrust sheet by fault-propagation folding. (c) Emplacement of Tintic Valley thrust sheet by fault-bend folding forming Jericho horse at the footwall syncline of fault-propagation folds. (d) Emplacement of Jericho horse caused reclined folding at Tintic Valley thrust (present day).*

ures 2 and 15, plate 1). The first possibility is that the formation of the Leamington antiform was related to the fault propagation folding of the Tintic Valley thrust. In this case, the fold can be interpreted as the remnant of a footwall fold that was formed during fault propagation folding. The second interpretation is that the Leamington antiform formed at the tip of a blind thrust during its emplacement. As indicated by folded fold-hinge lines, the earlier upright antiform experienced progressive changes in fold-axis associated with three-dimensional motion of the thrust sheet over an oblique ramp and/or later emplacement of underlying structures such as the Jericho horse and blind thrusts. The neutral fold probably formed at the same time or later than the refolding of the box-type fold.

CONCLUSIONS

Detailed structural geologic mapping together with review of previous studies shows that it is possible to decipher the complex Sevier-age shortening structures in the rocks exposed in the Gilson Mountains, even though earlier structures are commonly dissected by later Tertiary basin-and-range normal faults, and are concealed by Tertiary formations and Quaternary deposits.

Structural analysis and detailed geologic mapping show the presence of Sevier-age thrusts with associated folds. The Sevier-age thrusts observed in the Gilson Mountains are the Leamington Canyon thrust, the Tintic Valley thrust, and the Jericho horse. The Leamington Canyon thrust carried Proterozoic and Lower Cambrian hanging-wall rocks over the Upper Paleozoic footwall strata, and is folded into an anticline (i.e., Leamington Canyon anticline) plunging gently to the southwest. Part of the thrust was later reactivated as an out-of-syncline reverse fault related to the fold tightening of the synformal pair of the antiform (south of the Leamington Canyon anticline), which corresponds to the northern Canyon Range syncline. The Tintic Valley thrust is also folded into an antiform/synform pair, and carries Silurian through Mississippian rocks over Pennsylvanian to Permian rocks. The Jericho horse underlies the Tintic Valley thrust in the northeastern Gilson Mountains and brings overturned beds of Mississippian formations during its emplacement over the Permian–Pennsylvanian Oquirrh Group.

Our work also shows that the WNW-, ENE-, and NW-trending, high-angle faults that die out along the Leamington Canyon thrust and the Tintic Valley thrust are normal faults probably formed during Sevier thrusting, rather than Tertiary basin-and-range normal faults.

Construction of a down-plunge projection shows large-scale folds in the hanging wall and footwall of the Leamington Canyon and the Tintic Valley thrusts. A large-scale anticline (Leamington Canyon anticline) with a steep forelimb and long horizontal backlimb is present in the hanging wall of the Leamington Canyon thrust, with its fold-axis almost parallel to the trend of the Leamington Canyon thrust. In the hanging-wall Proterozoic rocks near the southwestern end of the Leamington Canyon thrust, a small-scale fold is visible; this fold is a lower-order fold that reflects the geometry of the large-scale folding. A large-scale, reclined fold with steep to overturned short limb and long horizontal backlimb (Jericho antiform) is also present in the Tintic Valley thrust sheet. It has a fold-hinge with low plunge and southwesterly trend. Part of this folding is observed in the Lower Mississippian hanging-wall rocks in the Jericho portion of the northeastern Gilson Mountains. Both the steep to overturned forelimb and the gentle, long horizontal backlimb of the fold are broadly folded. The large-scale, upright Leamington antiform was observed in the Oquirrh Group near the Tintic Valley thrust in the common footwall of the Leamington Canyon thrust and the Tintic Valley thrust. The Leamington antiform shows a folded fold-hinge indicating a refolding event in this area. A small-scale upright antiform, with a fold-axis almost parallel to the trend of the major thrusts, developed as part of the relatively large-scale, fault-related folding (Leamington antiform).

Chapter 2

Controversies in Structural Geology of Gilson and Northern Canyon Mountains, Sevier Fold-Thrust Belt, Central Utah—A Re-Examination From New Evidence

ABSTRACT

Proterozoic to lower Paleozoic sedimentary rocks in the southern Gilson Mountains in central Utah were deformed and transported southeastward along the Leamington Canyon thrust during the Sevier orogeny. Evidence from a stratigraphic-separation diagram, a lateral cross section of the predeformational basin, down-plunge projection of major structures, microstructural observations, and finite strain data indicate that the Leamington Canyon thrust and the Canyon Range thrust, south of the Leamington Canyon thrust, are essentially the same fault. The Leamington Canyon thrust sheet is folded into the Leamington Canyon anticline by underlying structures such as the Tintic Valley thrust sheet. Parts of the Leamington Canyon thrust were reactivated as an out-of-the-syncline reverse fault, and this faulting is related to tightening of the northernmost Canyon Range syncline, which forms a fold-pair with the antiformally folded Leamington Canyon thrust.

The Tintic Valley thrust, north of the Leamington Canyon thrust in the Gilson Mountains, is the next-emplaced thrust in a foreland-stepping sequence, and it has a leading branch line with the Leamington Canyon thrust in the southwestern part of the Gilson Mountains. Evidence from our detailed mapping and analysis of structural geometry of the Tintic Valley thrust indicates that the fault is also folded into an antiform/synform pair by the underlying Jericho horse, and the emplacement of this horse caused reclined folding within the Tintic Valley thrust sheet.

Overall, the Leamington Canyon thrust and associated structures, which define the Leamington transverse zone, constitute a complex slip transfer zone between two prominent salients (Provo salient and central Utah segment) of the Sevier fold-thrust belt.

The Sevier-age structures are commonly dissected by later steeply dipping Tertiary normal faults in the Gilson Mountains.

INTRODUCTION

The main structures exposed in the Gilson and northern Canyon Mountains are: (1) the Tintic Valley thrust (north of Leamington Canyon fault), (2) the Canyon Range thrust (south of Leamington Canyon fault), and (3) the Leamington Canyon fault, which is exposed along the southern edge of the Gilson Mountains. The Leamington Canyon fault is part of the Leamington transverse zone, which extends about 50 km between the towns of Leamington and Nephi (figure 1). The zone transfers slip between the Provo salient (to the north) and the central Utah (Pahvant) segment (to the south) of the Sevier fold-thrust belt in the North American Cordillera (figure 1). In the southern Gilson Mountains, the Leamington Canyon fault serves as a boundary for the Tintic Valley thrust and the Canyon Range thrust (figure 2, plate 1). The Tintic Valley thrust sheet, an internal thrust sheet of the Provo salient, makes up the main part of the Gilson Mountains; the Canyon Range sheet of the central Utah segment makes up much of the Canyon Mountains to the south.

Costain (1960) first described the Leamington Canyon fault along the southern margin of the Gilson Mountains. The fault was later reinterpreted by many workers (e.g., Morris and Shephard, 1964; Eardley, 1969; Wang, 1970; Burchfiel and Hickcox, 1972; Higgins, 1982; Morris, 1983), but the nature of the Leamington Canyon fault remained uncertain. Costain (1960) also identified two high-angle reverse faults (North Gilson fault and South Gilson fault) in the Gilson Mountains; these were later referred to as the Tintic Valley thrust by Morris and Kopf (1969), although there are controversies regarding the exact exposure of the Tintic Valley thrust in the Gilson Mountains (Costain, 1960; Wang, 1970; Higgins, 1982; Morris, 1987a, 1987b; Pampeyan, 1989).

CONTROVERSIES OF LEAMINGTON CANYON FAULT AND TINTIC VALLEY THRUST

Three major problems complicate interpretations of the structural geology of the Gilson Mountains. First, what is the nature of motion along the Leamington Canyon fault? Second, what is the relationship between the Leamington Canyon fault and the Canyon Range thrust? Third, what is the structural geometry of the Tintic Valley thrust and how is it related to the Leamington Canyon fault? Answers to these questions have important ramifications for the geometry and kinematics of the thrust sheets at the bounding transverse zone and are examined in detail in this chapter.

Nature of Motion along Leamington Canyon Fault (Tear Fault Versus Thrust Fault)

Costain (1960) first recognized the Leamington Canyon fault as a thrust fault dipping 30° to the southeast. He postulated that the Canyon Range thrust sheet was carried toward the northwest along the Leamington Canyon fault and overrode the rocks of the Gilson Mountains. Subsequent workers recognized the ENE-WSW trace of the Leamington Canyon fault, but questions remained unanswered about its relationship with the Tintic Valley and Canyon Range thrusts, and the sense of motion on the fault. Morris and Shepard (1964), Crittenden (1964), Eardley (1969), and Morris (1983) all interpreted the Leamington Canyon fault as a tear fault even though they disagreed about its sense of motion. Morris and Shepard (1964), Crittenden (1964), and Morris (1983) interpreted the fault to be a right-lateral, large displacement feature along which the Charleston-Nebo thrust sheet moved farther east than rocks south of the tear fault; Eardley (1969), on the other hand, described the fault as left-lateral with com-

paratively small displacement. Wang (1970) and Burchfiel and Hickcox (1972) agreed with the right-lateral tear fault interpretation. Higgins (1982) considered the Leamington Canyon fault to be a thrust fault with top-to-the-northwest motion, but did not rule out the alternative possibility of top down-to-the-southeast motion. Irrespective of its original nature, the fault has likely undergone complex reorientation during thrusting and subsequent folding in this area.

Relationship Between Leamington Canyon Fault and Canyon Range Thrust (Tear Fault Versus Lateral Ramp)

A controversy also exists about the relationship between the Leamington Canyon fault and the Canyon Range thrust. In contrast to the interpretation of the Leamington Canyon fault as a right-lateral strike-slip tear fault (Morris and Shepard, 1964; Crittenden, 1964; Wang, 1970; Burchfiel and Hickcox, 1972), other geologists (e.g., Royse, 1993; Pequera and others, 1994; Mitra and Sussman, 1997; Lawton and others, 1997) have suggested that the Leamington Canyon fault may be a lateral ramp of the folded Canyon Range thrust to the south. Sussman (1995) and Lawton and others (1997), from the stratigraphic correlation of the hanging-wall strata, further suggested that the Leamington Canyon fault is a continuous fault with the Canyon Range thrust, so that it corresponds to a folded hanging-wall ramp of the Canyon Range thrust that cuts up-section eastward from the Proterozoic Caddy Canyon Quartzite to the Cambrian Prospect Mountain Quartzite.

Geometry and Relations of Tintic Valley Thrust

The Tintic Valley thrust is well exposed in the eastern half of the Gilson Mountains and its position under the Tintic Valley is variously interpreted (Costain, 1960; Wang, 1970; Higgins, 1982; Pampeyan, 1989). Costain (1960) first recognized two high-angle reverse faults (North Gilson fault and South Gilson fault) in the Gilson Mountains; these were later interpreted as the synformally folded southern end of the Tintic Valley thrust by Morris and Kopf (1969), Wang (1970), Higgins (1982), and Morris (1987a, 1987b), although there is some controversy regarding the exact location of the fault trace. Morris and Kopf (1969) suggested the possibility that both the North Gilson fault and the South Gilson fault are the southern continuation of the Tintic Valley thrust. Wang (1970) agreed with this thrust fault interpretation, but with two different thrust traces (Gilson and Champlin thrusts). He suggested that the Gilson thrust (North Gilson fault of Costain, 1960) swings to the south at the eastern end of the Gilson Mountains and has a branch line with the Leamington Canyon fault in the eastern part of the southern Gilson Mountains. He further suggested that the South Gilson fault of Costain (1960) is a separate thrust (Champlin thrust) that swings northward at the eastern end of the Gilson Mountains and lies above the Gilson thrust. In the northern Gilson Mountains, Wang (1970) placed the fault where the Devonian dolomites and Lower Mississippian formations in the hanging wall are in contact with the Silurian Laketown Dolomite and Lower Mississippian formations in the footwall (see also Pampeyan, 1989). However, this thrust trace is problematic because it places younger Devonian dolomites over older Silurian Laketown Dolomite. Other geologists (Morris and Kopf, 1969; Higgins, 1982) suggested that the Tintic Valley thrust has a leading branch-line with the Leamington Canyon fault at the western end of the southern Gilson Mountains (near the town of Leamington). Morris (1987a, 1987b) modified the traces of both the Gilson and the Champlin thrusts of Wang (1970), but he agreed with Higgins (1982) regarding the location of the branch line with the Leamington Canyon fault (see also Pampeyan, 1989). However, the modified trace of the Champlin thrust of Wang (1970) by Morris (1987a, 1987b) and Pampeyan (1989) remains problematic because it still places younger Devonian dolomites over older Silurian dolomite in the western portion of the northeastern Gilson Mountains.

Considerable recent study in the Gilson Mountains (Kwon and Mitra, 2001, 2002; Kwon, 2004; Kwon and Mitra, 2006) and mapping of the Jericho 7.5-minute quadrangle (Kwon and Mitra, 2005) suggest that both the North and South Gilson faults (Costain, 1960) are essentially the same fault, namely the Tintic Valley thrust that is folded into a syncline (figures 2 and 15; plate 1). The Tintic Valley thrust is also exposed at the south end of the East Tintic Mountains (Furner Ridge quadrangle) where it is also folded into a syncline. Considering the map patterns (Costain, 1960; Morris, 1987a) of the synclinally folded thrust fault (wider in Gilson Mountains and narrower in East Tintic Mountains), we can surmise that the Tintic Valley thrust exposed in the Gilson Mountains lies on the down-thrown side of the range-front normal fault bounding the East Tintic Mountains (figure 1b).

NEW EVIDENCE AND INTERPRETATIONS

New lines of evidence (first noted in Kwon and Mitra, 2001) are described below and can be used to address the controversies.

Nature of Motion along Leamington Canyon Fault

The Leamington Canyon fault is superbly exposed at the south end of the Gilson Mountains (figure 2, plate 1), near the town of Leamington. The hanging-wall rocks show a weakly developed deformation-related foliation, and display asymmetric folds and fracture populations with slickenlines developed during successive phases of motion on the fault. Here the Leamington Canyon fault dips 30° to the southeast and places Proterozoic quartzites on top of Lower Mississippian sandstones of the Humbug Formation (figure 2, plate 1). From here toward the east along the trace of the Leamington Canyon fault, the fault shows progressive increase in dip from 30° to 80°, indicating that it is folded into an anticline (referred to as the Leamington Canyon anticline) with a fold-axis approximately parallel to the trend of the Leamington Canyon fault (figure 23a). Although gently-dipping fractures are present in the hanging wall and footwall of the Leamington Canyon fault, the dominant fracture sets are moderate to steeply dipping toward the southeast (figure 23b).

For a single tectonic episode, the kinematics of movement between fractures in such a population is best demonstrated by plotting the poles to the motion planes (M-poles)

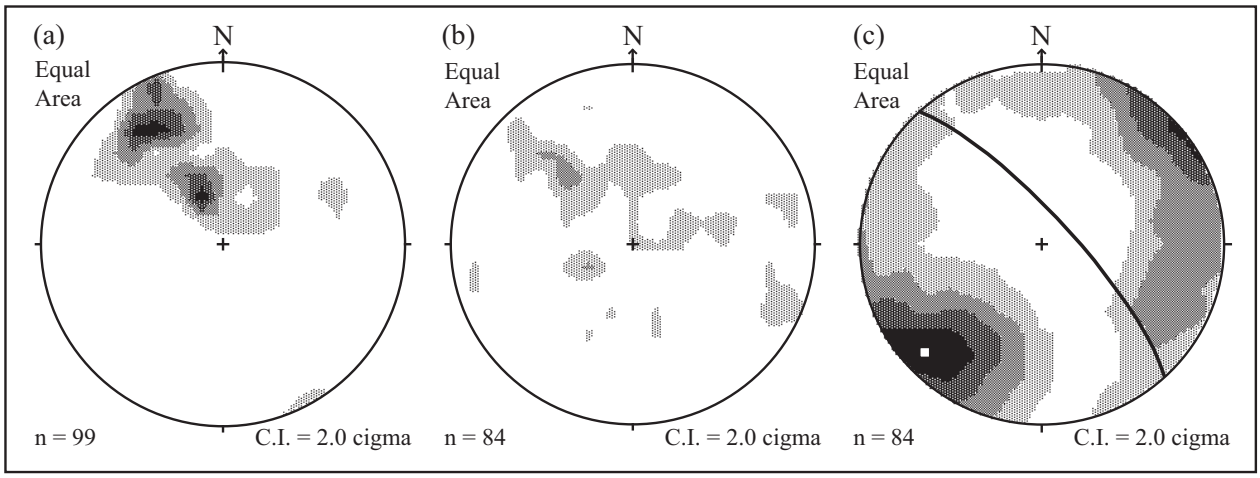

Figure 23. *Lower hemisphere, equal-area projections from the hanging wall of the Leamington Canyon fault showing: (a) poles to bedding, (b) fracture poles, and (c) M-poles with associated motion plane. The plane of motion is steeply dipping and trends northwest-southeast;* n *is number of data points and C.I. is contour interval.*

on a stereographic projection (Arthaud, 1969; Wojtal, 1982; Aleksandrowski, 1985; Goldstein and Marshak, 1988; Mitra, 1993; Ismat, 2001). The motion plane (M-plane) is defined by the plane that contains the pole to the fault plane and the direction of slickenlines on the fault; thus the M-plane is perpendicular to the λ_2 axis and contains λ_1 and λ_3 axes (Reches, 1978, 1983). The orientations of fractures with slickenlines from the hanging wall of the Leamington Canyon fault give a consistent M-plane that is steeply dipping and trends NW-SE (figure 23c). This indicates that the Leamington Canyon fault has transported the Proterozoic hanging-wall rocks over the middle Paleozoic footwall rocks toward either the northwest or the southeast, almost perpendicular to the trend of the Leamington Canyon fault. This interpretation is further supported by southeast-verging outcrop-scale folds that have fold-axes parallel to the trend of the Leamington Canyon fault (Higgins, 1982). In order to determine the sense of motion on the M-plane, we measured the lattice-preferred orientation of quartz grains from quartzites (Pocatello Formation) in the hanging wall of the Leamington Canyon fault. The measured pattern of quartz C-axes shows asymmetric type I cross girdle (Passchier and Trouw, 1996), indicating top down-to-the-southeast shear (figure 24). This interpretation agrees with the sense of shear determined from acute angles of cleavage-bedding intersections. In summary, the evidence presented above indicates that the Leamington Canyon fault is a folded thrust fault (Leamington Canyon thrust hereafter) with top down-to-the-southeast shear.

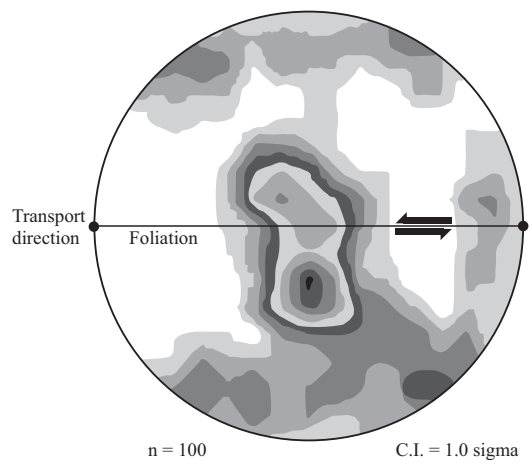

Figure 24. *Equal-area stereograms of quartz C-axis fabrics viewed toward the southwest from the hanging-wall quartzite (Pocatello Formation) of the folded Leamington Canyon thrust showing top-to-the southeast down-dip shear. Note that this is consistent with down-dip motion of the folded Canyon Range thrust to the south. Number of data indicated by* n *and C.I. is contour interval.*

Relationship Between Leamington Canyon Thrust and Canyon Range Thrust

Syn- to post-thrusting normal faults are present in the Gilson Mountains, and these normal faults displace the lithologic boundaries and earlier structures (figure 2, plate 1). Parts of the thrust sheets are also covered by Cenozoic sedimentary deposits. The normal faults and later deposits are "removed" to make a simplified geologic map of the study area (figure 25). Even though the later Tertiary basin-and-range normal faulting and surficial deposits obscure direct relationship between the Leamington Canyon thrust and the Canyon Range thrust, NE-striking Precambrian, Cambrian and Cretaceous hanging-wall strata south of the folded Leamington Canyon thrust bend to a north-trending strike along the western flank of the Canyon Mountains, where they form the hanging wall of the folded Canyon Range thrust (Sussman, 1995; Lawton and others, 1997; Kwon and Mitra, 2001; Kwon and Mitra, 2006) (figure 25). The steeply dipping, NE-trending hanging-wall strata of the Leamington Canyon thrust have cutoffs at the eastern end of the southern Gilson Mountains (figures 2, 25). The relationship between the Leamington Canyon and Canyon Range thrusts is determined using several lines of evidence.

Stratigraphic-Separation Diagram and Lateral Cross Section

A strike-parallel, stratigraphic-separation diagram constructed from the western limb of the folded Canyon Range thrust to the folded Leamington Canyon thrust (figure 25)

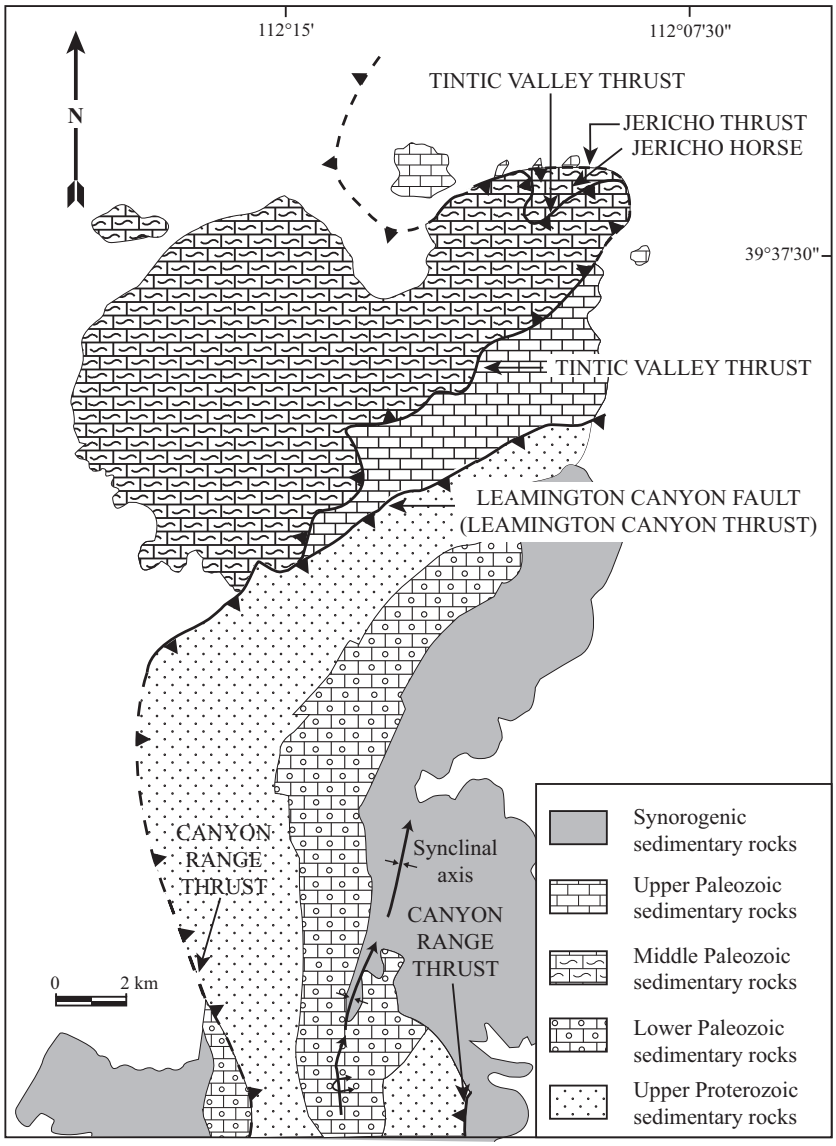

Figure 25. *Simplified geologic map of the Gilson and northern Canyon Mountains. Normal faults and Cenozoic rocks and deposits have been removed.*

records an increase in the stratigraphic-separation from south to north (figure 26). The continuous stratigraphic section in the hanging wall suggests that these two faults are essentially the same fault. The stratigraphic-separation diagram further shows the possible stratigraphic position of a southward-dipping, large footwall oblique (or lateral) ramp, where the fault climbs up-section over a lateral distance of 10 km from lower Paleozoic sedimentary rocks (Prospect Mountain Quartzite of the Canyon Range footwall) to middle Paleozoic sedimentary rocks (Humbug Formation of the Leamington Canyon footwall) (figure 26). Considering that the Leamington transverse zone is an old crustal boundary that defines the southern margin of the Permian-Pennsylvanian Oquirrh basin (Peterson, 1977; Royse, 1993), the oblique ramp should dip northward, toward the deeper part of the basin. This northward-dipping oblique ramp along the old crustal boundary is better seen on a regional lateral cross-section of the predeformational basin drawn based on lateral stratigraphic variations (Hintze, 1988) across the Leamington zone from the Canyon Mountains of the central Utah segment to the Sheeprock Mountains of the Provo salient (figure 27). From this, we can reasonably interpret that the stratigraphic position of the footwall oblique ramp in the local stratigraphic-separation diagram at Leamington (figure 26) may not be a simple 'thrust-ramp' in terms of flat-ramp-flat geometry. More likely, the southward-dipping footwall oblique ramp represents variations in stratigraphic cutoffs along the fault that formed where the horizontal Leamington Canyon/Canyon Range thrust cut through a northward-dipping stratigraphic section from lower Paleozoic to middle Paleozoic sedimentary rocks (figure 27). The bending of the strike of the hanging-wall strata from northeast-southwest to north-south from the folded Leamington Canyon thrust to the folded Canyon Range thrust can be explained by cross-folding of the hanging-wall rocks at the oblique ramp (Pequera and others, 1994).

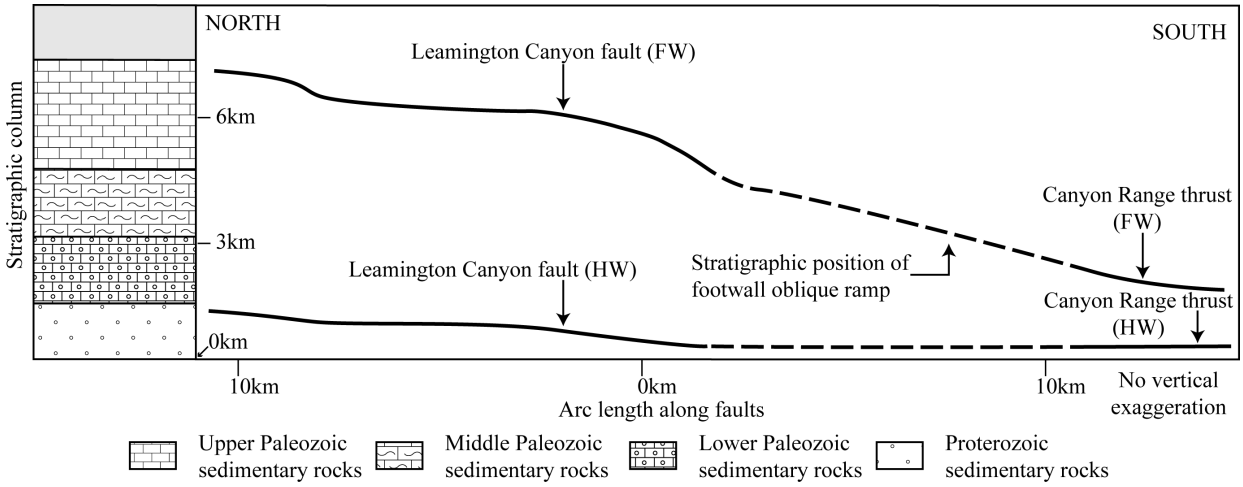

Figure 26. *Strike-parallel, stratigraphic-separation diagram drawn from the western limb of the folded Canyon Range thrust to the folded Leamington Canyon thrust. The stratigraphic separation increases continuously from south to north as the fault climbs section in its footwall from Lower Paleozoic sedimentary rocks along the Canyon Range thrust to Middle Paleozoic sedimentary rocks along the Leamington Canyon thrust, indicating the existence of a footwall oblique ramp. Patterns used in the stratigraphic column are the same as in figure 25. FW is footwall, HW is hanging wall.*

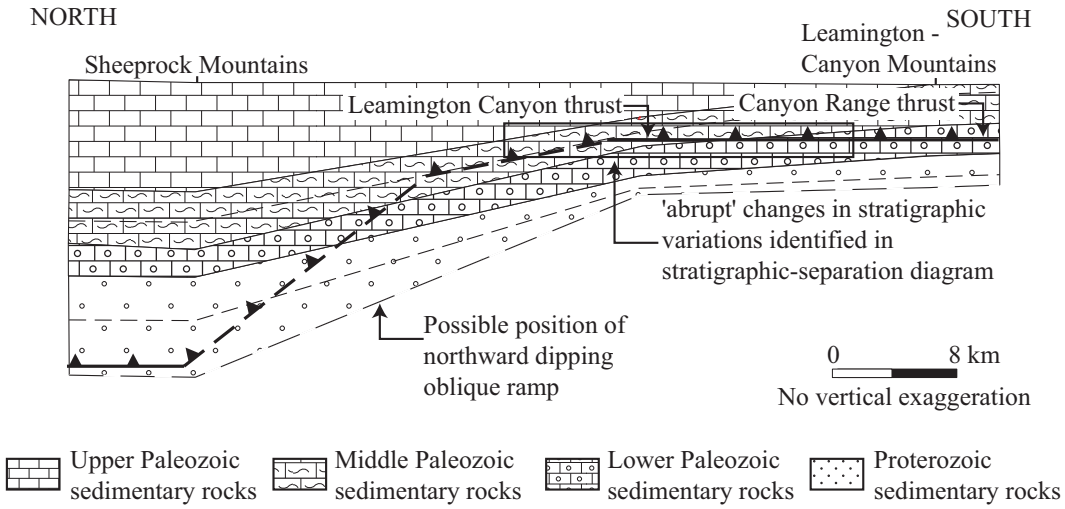

Figure 27. *Diagrammatic cross section drawn across Leamington Canyon showing variations in stratigraphy within the predeformational basin shape with the possible position of a northward dipping low-angle oblique ramp that is defined by an old crustal boundary, and 'ramp' type structure that is identified in the stratigraphic-separation diagram (figure 26). Patterns used in the stratigraphic column are the same as in figure 25.*

Down-Plunge Projection

Down-plunge projection of the major structures in the Gilson Mountains and northern Canyon Mountains exhibits geometries that are similar to the folded Canyon Range thrust sheet (figure 15). The map patterns, kinematic indicators, and a stratigraphic-separation diagram together suggest that the Leamington Canyon thrust is an antiformally folded thrust fault. The folded Leamington Canyon thrust and related major structures in the Gilson Mountains are best seen on a down-plunge projection (figure 15). The plotted down-plunge projection shows that the Leamington transverse zone consists of the antiformally folded Leamington Canyon thrust, associated folds, and an out-of-syncline reverse fault (figure 15). The folded Leamington Canyon thrust cuts up stratigraphic section to the southeast placing Precambrian strata over Paleozoic strata. The fault itself is folded into an antiform by underlying structures (the Tintic Valley thrust and the Jericho horse), and the synclinal fold south of the antiformally folded Leamington Canyon thrust probably corresponds to the northern end of the synclinally folded Canyon Range thrust (figure 15). Southeast-verging, small-scale folds with moderately plunging fold-axes that trend parallel to the Leamington Canyon thrust-trace support the southeastward transport direction (plate 1). Part of the Leamington Canyon thrust was reactivated as a possible out-of-syncline reverse fault (figure 15, plate 1), and this was probably related to tightening of the northern end of the Canyon Range syncline. This overall structural geometry with the Leamington Canyon thrust folded by underlying structures is consistent with structures of the Canyon Range thrust to the south, which is also folded by an underlying duplex (Mitra and Sussman, 1997).

Microstructural and Strain Evidence

Microstructural observations in the Proterozoic quartzites from the hanging wall of the Leamington Canyon thrust (Kwon and Mitra, 2001) indicate similar deformation microstructures and mechanisms as those from the hanging-wall quartzites of the Canyon Range thrust (Sussman, 1995). Undulose extinction, deformation lamellae, serrated grain boundaries, grain boundary migration, intragranular cracks, and stylolites are all seen in both thrust sheets, indicating that quasi-plastic deformation by more than one deformation mechanism was active during Sevier deformation. Transgranular cracks and zones of cataclasis (with cemented matrix) are also present in samples from both thrust sheets and these cross-cut the quasi-plastic deformation features, indicating that the rocks were overprinted by elastico-frictional deformation. Later phase unstable cracks cross-cut the previous features in wider cataclastic deformation zones. The overprinting relationships of these microstructures indicate crystal plastic deformation followed later by dominant cataclasis as the rocks were brought closer to the surface by uplift and erosion during progressive deformation.

Finite strain computations using the Modified Normalized Fry Method (McNaught, 1994) on the Proterozoic quartzites from the hanging wall of the Leamington Canyon thrust yield similar strain ratios to the finite strain values from the hanging wall of the Canyon Range thrust. Finite strain values measured in the transport plane from the hanging wall of both the Leamington Canyon thrust and the Canyon Range thrust (unpublished data from Tanikawa, 1997) show similar axial ratios ranging from 1.04 to 1.50 with low shear strain ($\gamma = 0.1 - 0.25$) and low stretch ($\alpha = 0.8 - 1.1$) (figure 28). Therefore, the similarities of both deformation microstructures and finite strain characteristics further support our interpretation that the two faults are essentially the same fault.

DISCUSSION

Structural Geometry of Tintic Valley Thrust and Its Relationship to Leamington Canyon Thrust

As we described above, there is some controversy regarding the exact location of the Tintic Valley thrust in the Gilson Mountains (Costain, 1960; Wang, 1970; Higgins, 1982; Pampeyan, 1989). Differences of opinion are apparently the result of a poor understanding of the structural geometry of the Tintic Valley thrust and its relation to other structures such as the Leamington Canyon thrust. To examine the two-thrust hypothesis favored by Wang (1970) and Pampeyan (1989), one of the cross sections drawn by Wang (1970), which crosses both the Gilson and the Champlin thrusts, must be considered. In his cross section, Wang (1970) showed that the Champlin thrust carried Mississippian hanging-wall rocks over the Silurian through Permian footwall rocks that constitute the hanging wall of the Gilson thrust. But most of the trace of the Champlin thrust in the cross section is problematic because it places younger Mississippian rocks over older Silurian rocks; thus this portion of the "thrust" is more likely a normal fault, if it even exists. In addition, Wang (1970) left as an open question the relationship between the overturned package of Mississippian beds

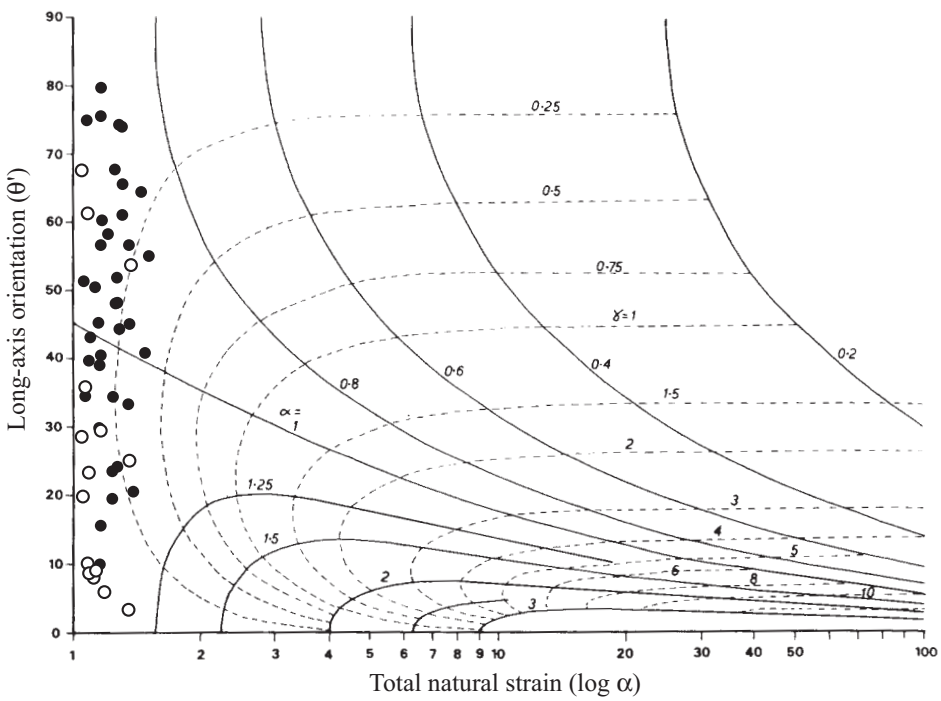

Figure 28. *Axial ratios and angle of long-axis orientations with respect to the fault planes from the hanging wall of the folded Canyon Range and Leamington Canyon thrusts on a plot containing simple shear strains (γ for dotted lines) and stretch (α for solid lines) contours (Sanderson, 1982). Finite strains in both the hanging wall of the Canyon Range (open circle) and Leamington Canyon (filled circle) thrusts show similar strain values of low shear strains ($\gamma = 0.1 - 0.25$) and low stretch ($\alpha = 0.8 - 1.1$).*

and the Permian-Pennsylvanian Oquirrh Group, and interpreted the boundary between the Silurian and Mississippian rocks in the Champlin footwall as a high-angle fault (Jericho fault) in the Gilson thrust sheet that dies out at the Champlin thrust.

From our detailed mapping of the entire Gilson Mountains (figure 2, plate 1) we have defined the course of the Tintic Valley thrust, which differs in detail from the previously mapped fault trace. The fault dips at a low angle (about 10° on average) in the western portion of the northeastern Gilson Mountains, where the Tintic Valley thrust (Gilson thrust of Wang, 1970) places the older Silurian Laketown Dolomite over the younger Permian-Pennsylvanian Oquirrh Group (figure 2, plate 1). Here it is important to note that the hanging wall of the fault has continuous stratigraphic section, so that the Champlin thrust does not exist in this part of the Gilson Mountains (figure 2, plate 1). Farther to the east, the Tintic Valley thrust is folded into an antiform where Devonian dolomites and Mississippian formations are in fault contact with an overturned stratigraphic package of Mississippian rocks (figure 2, plate 1); thus the Jericho fault of Wang (1970), and Pampeyan (1989), is actually a part of the Tintic Valley thrust. The fault swings to the southwest, where the Mississippian formations are in fault contact with Permian-Pennsylvanian Oquirrh Group (figure 2, plate 1). The overturned stratigraphic package of Mississippian formations constitutes a slice that is also in fault contact with Permian-Pennsylvanian Oquirrh Group; this is interpreted as a small-scale horse (Jericho horse), which caused the folding of the overlying Tintic Valley thrust (figures 2a, 25). The trace of the Gilson thrust in the southeastern Gilson Mountains as described by Wang (1970), where he placed the fault between the Oquirrh Group and the Park City Formation in the southeastern part of his cross-section, does not exist. Instead the Tintic Valley thrust has a branch line with the Leamington Canyon thrust in the southwestern part of the Gilson Mountains as suggested by Higgins (1982), Morris (1987a, 1987b), and Pampeyan (1989). The Tintic Valley thrust is offset by a later normal fault in the western portion of the northeastern Gilson Mountains (figure 2, plate 1).

The structural geometry of the Tintic Valley thrust and its relation with the Leamington Canyon thrust can be best demonstrated in down-plunge projection of the major structures in the Gilson Mountains (figure 15). The Tintic Valley thrust sheet is folded as an antiform/synform pair by the underlying Jericho horse, and has a leading branch line with the Leamington Canyon thrust in the southeastern part of the section (figure 15). We interpret the Tintic Valley thrust to have been emplaced later than the Leamington Canyon thrust as an imbricate fault in a duplex structure based on three lines of evidences: (1) the Tintic Valley thrust has a much smaller stratigraphic separation than the Leamington Canyon thrust, (2) the fault has a leading branch line with the Leamington Canyon thrust, and (3) the Leamington Canyon thrust is folded by underlying structures. The roof thrust of the duplex is the Leamington Canyon thrust (Kwon and Mitra, 2001, 2006) and the floor thrust is in the subsurface and not exposed anywhere. The reclined fold with a steep short limb and long horizontal backlimb within the Tintic Valley thrust sheet (figure 15) is interpreted to be the result of refolding of a pre-existing fault-bend fold, which was formed during emplacement of the Tintic Valley thrust (Kwon and Mitra, 2001). The reclined fold has a fold-trace with a southeasterly trend and the fold-axis has a low westerly plunge.

The overturned stratigraphic package observed in the Jericho horse can be explained as the result of formation of the horse by plucking of the overturned limb of the footwall syncline under the Tintic Valley thrust, by a mechanism similar to that suggested by McNaught and Mitra (1993).

CONCLUSIONS

Our kinematic analyses show that the Proterozoic sedimentary rocks in the southern Gilson Mountains in central Utah were deformed and transported southeastward along the Leamington Canyon thrust during the Sevier orogeny. The Leamington Canyon thrust is the first-emplaced thrust in the Gilson Mountains and is folded into an antiform due to motion along younger underlying structures (the Tintic Valley thrust and the Jericho thrust). This overall structural geometry of the folded Leamington Canyon thrust is consistent with the geometry of the Canyon Range thrust, which was also folded into an antiform cored by an underlying duplex (Mitra and Sussman, 1997). A variety of evidence, including a stratigraphic-separation diagram, down-plunge projection, microstructures, and finite strain characteristics suggest that the Leamington Canyon thrust is essentially the same fault as the Canyon Range thrust to the south. Part of the Leamington Canyon thrust was reactivated as a possible out-of-syncline reverse fault related to fold-tightening of the adjoining synform south of the Leamington Canyon antiform; this synform corresponds to the northernmost end of the Canyon Range syncline.

The Tintic Valley thrust was the next-emplaced thrust in the Gilson Mountains in a foreland-stepping sequence, and has a leading branch line with the Leamington Canyon thrust in the western portion of the southern Gilson Mountains. The Tintic Valley thrust sheet was also folded into an antiform/synform pair by the underlying Jericho horse, which caused a fault-bend fold pair within the Tintic Valley thrust sheet to be refolded into reclined folds.

The Leamington Canyon thrust and associated structures define the Leamington transverse zone in the study area, and the zone serves as a slip transfer zone at the boundary of the central Utah segment and the Provo salient of the Sevier fold-thrust belt.

The Sevier-age structures are commonly dissected by later steeply-dipping Tertiary basin-and-range normal faults in the Gilson Mountains.

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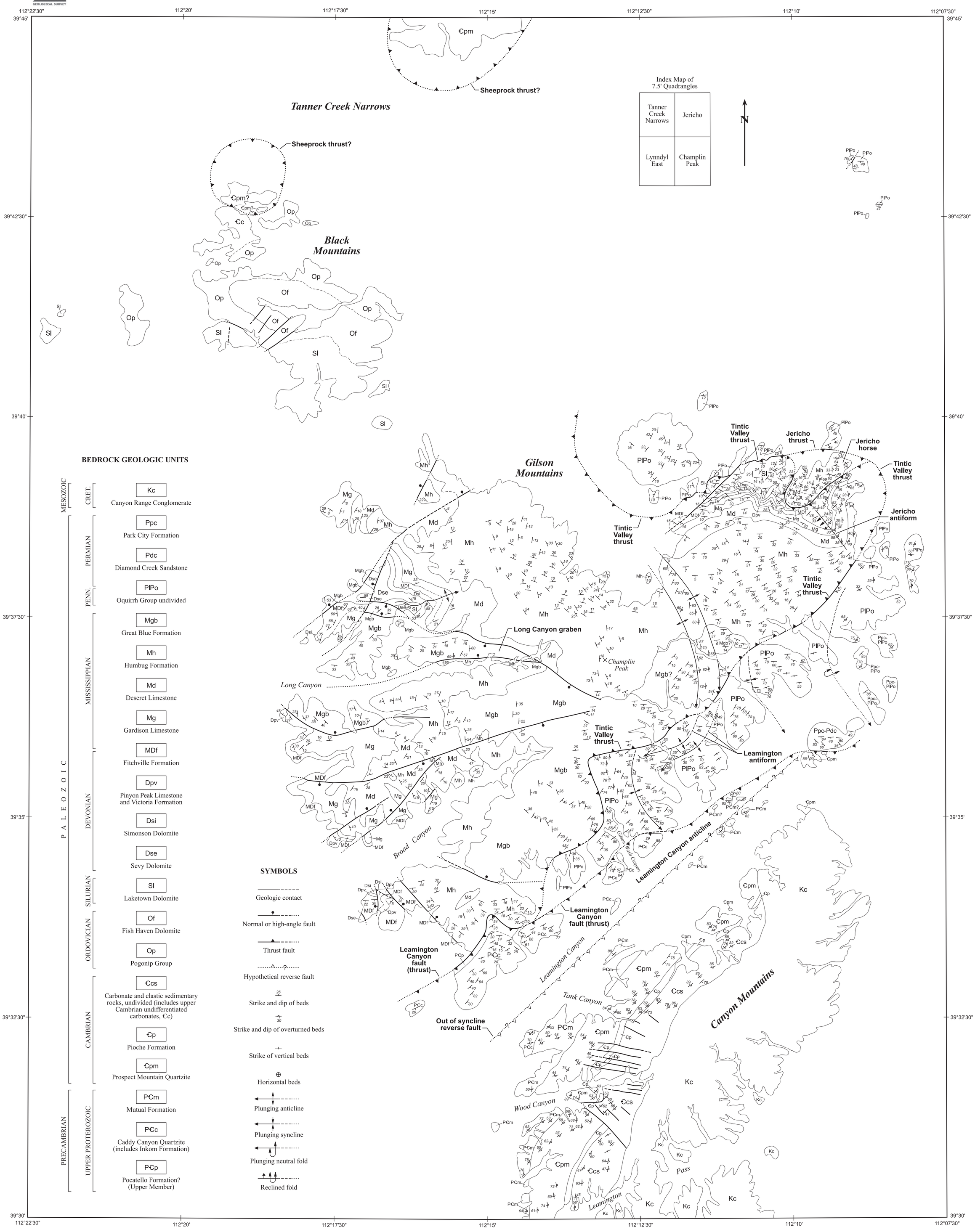

STRUCTURAL GEOLOGIC MAP OF THE GILSON AND NORTHERN CANYON MOUNTAINS, CENTRAL UTAH

by
Sanghoon Kwon and Gautam Mitra

2007