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Footwall Deformation and Structural Analysis of the Footwall of the Willard Thrust Fault, Northern Wasatch Range, Utah

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FOOTWALL DEFORMATION AND STRUCTURAL ANALYSIS OF THE FOOTWALL OF THE WILLARD THRUST FAULT, NORTHERN WASATCH RANGE, UTAH.

by

Douglas Scott Neves

A thesis submitted in partial fulfillment
of the requirements for the degree

of

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in

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Douglas Scott Neves

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ABSTRACT

Footwall Deformation and Structural Analysis of the Footwall

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by

Douglas Scott Neves, Master of Science

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

Deformation mechanisms in the footwall of the Willard thrust fault, northern Wasatch Range, Utah, change from dominantly plastic to dominantly cataclastic (both microscopically and macroscopically) in the Ophir Formation and Maxfield Limestone before the thrust begins to ramp laterally upsection southward, just to the north of the North Ogden Canyon field area. This transition in compressional deformation style and mechanism is located within a lateral distance of 3.2-kilometers along the 22-kilometer long trace of the thrust fault.

Between Willard Canyon and North Ogden Canyon penetrative deformation is localized within 200 meters of the thrust surface and is characterized by transposed bedding, solution cleavage parallel to bedding, a northeast- to northwest-dipping foliation, and tight isoclinal folds with axes plunging generally northward. A fracture overprint in the footwall is present throughout the study area. The transition in deformation mechanism and style suggests that footwall deformation is dependent on the sensitive response of limestone and shale to increased pressure and temperature conditions and also the presence of a lateral ramp in the footwall of the Willard thrust. Data from a hangingwall sequence diagram and a stratigraphic displacement diagram suggest the Taylor and Ogden thrusts formed prior to the Willard thrust (the roof thrust) and their sequential geometrical evolution may have been influenced by pre-existing rifts in the underlying crystalline basement rock.

It is proposed that early Cretaceous movement of the Willard thrust sheet over the structurally lower and older Taylor and Ogden thrust sheets resulted in the formation of a recumbent syncline overturned to the east, a southward rising lateral ramp in the footwall of the Willard thrust, a lateral change in footwall deformation, and the anomalous east-west trending canyons that cut through the Willard thrust complex.

(137 pages)

INTRODUCTION

PROBLEM STATEMENT AND OBJECTIVES

The Willard thrust fault is located in the northern Wasatch Mountains northeast of Ogden, Utah (Fig. 1). Previous workers have classified the Willard thrust as the roof thrust of a foreland-dipping duplex or possibly a modified antiformal stack (Fig. 2) in the Willard-Paris thrust system of the Sevier orogenic belt in Idaho, Utah, and Wyoming (Bruhn and Beck, 1981; Schirmer, 1985c).

Bruhn and Beck (1981) and Schirmer (1985c) reported contrasting styles of deformation in the footwall of the Willard thrust between Willard and Ogden canyons. Macroscopic and microscopic footwall deformation observed in the field near Willard Canyon was reported as being predominantly plastic, whereas footwall deformation observed in the field near Ogden Canyon is reported as being predominantly cataclastic.

This study investigates changes in deformation mechanism and style in the footwall of the Willard thrust fault in the same area. The study is important because there are few well-exposed footwalls in thrust systems. The exposed footwall of the Willard thrust and the structurally lower Taylor and Ogden thrusts, provide an opportunity to study footwall deformation in a thrust complex that is unique because it dips to the foreland. Examination of footwall deformation in the Willard thrust will be helpful to the understanding of the propagation and evolution of thrust sheets, hangingwall movement over footwalls, and the sequential geometrical development of the Taylor, Ogden, and Willard thrust sheets. Deformation is hypothesized to change laterally along strike and in the footwall of the Willard thrust between Willard Canyon, which is the

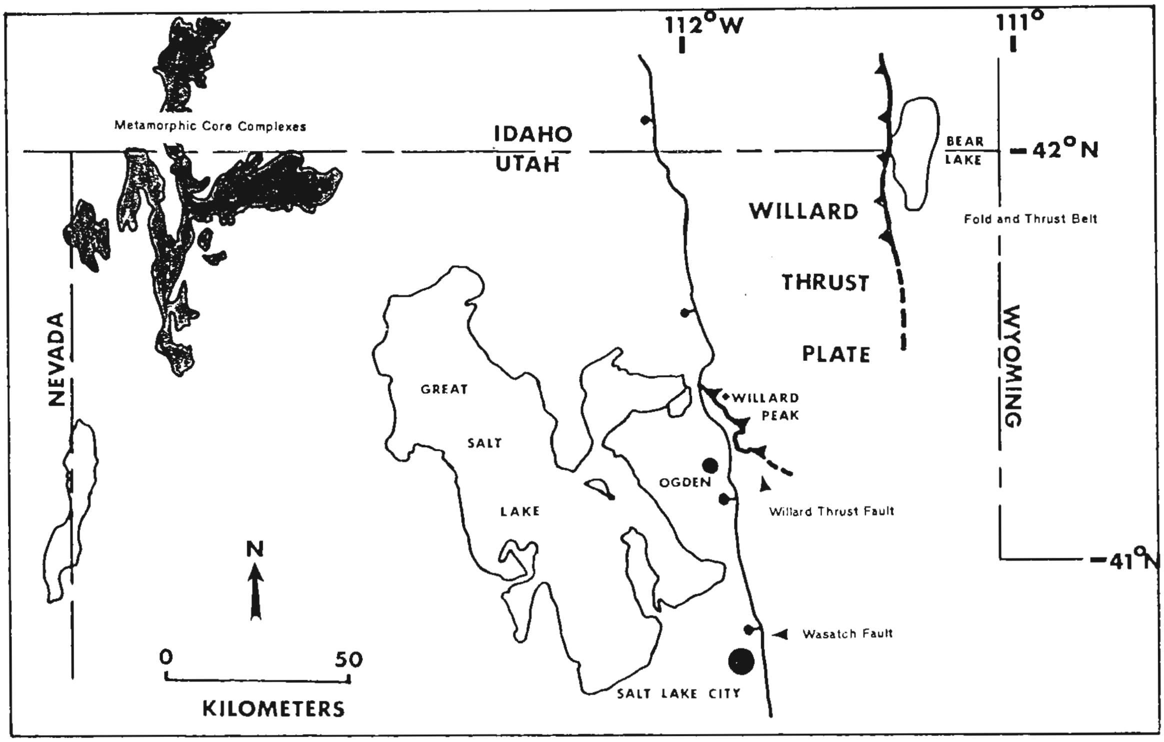


Fig. 1 Location map showing the regional position of the Willard thrust fault relative to the metamorphic core complexes of the Albion, Raft River, and Grouse Creek ranges (to the west) and the fold and thrust belt in Idaho, Wyoming, and Utah (to the east).

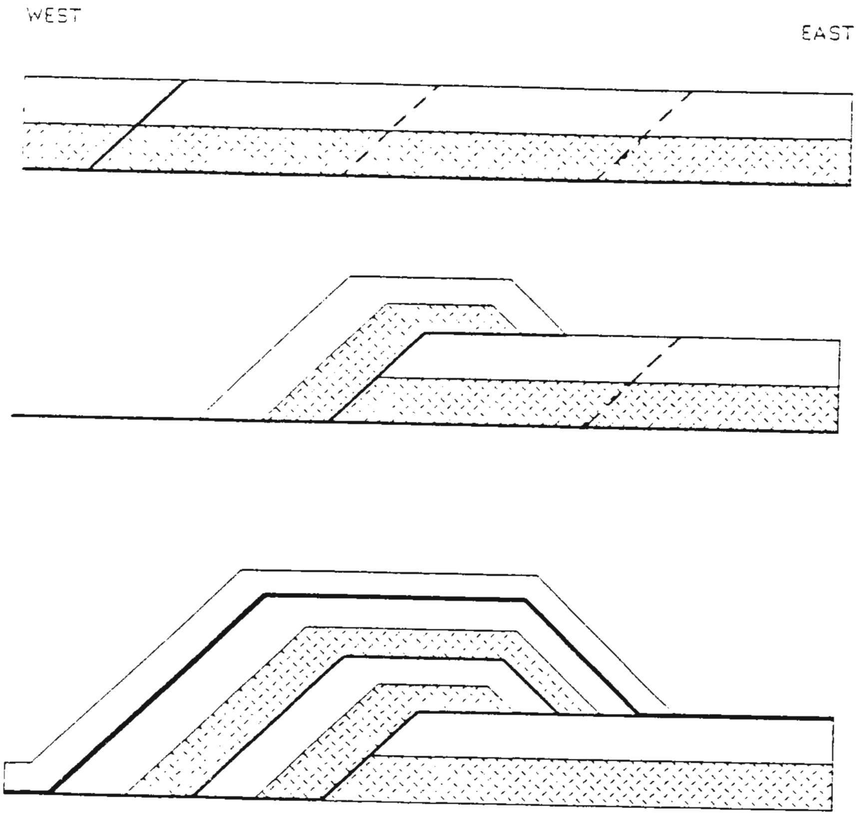


Fig. 2 Schematic diagrams (modified from Boyer and Elliot, 1982) showing developmental geometry of a "classic" foreland-dipping duplex. Older thrust sheets are carried piggyback on younger thrust sheets as the footwall progressively fails (ramping upsection) from left to right.

northernmost exposure of the fault, and Ogden Canyon, which is the approximate southernmost exposure of the fault. The Willard thrust plays an interesting role in that it marks the only known area in the Idaho-Utah-Wyoming Sevier orogenic belt where hinterland basement rock from the west was involved with the foreland fold and thrust belt to the east. This study will provide insight into the kinematics and deformation mechanisms associated with the Willard thrust, as well as the structurally lower Taylor and Ogden thrusts. This is important because it relates the development and evolution of local thrusts to the regional-scale tectonic provinces in the western Rocky Mountains.

The purpose of this study is to identify, map, and interpret deformation in the footwall of the Willard thrust fault between Willard and Ogden canyons. The objectives of the study are to 1) locate the plastic-to-cataclastic transition in footwall deformation along the trace of the fault and map the strain accommodated by the footwall; 2) find the stratigraphic formation or formations that contain the change in deformation style; 3) discover if the transition in deformation takes place on both the microscopic and macroscopic levels; 4) use field data to ascertain possible mechanisms of deformation; 5) develope a sequential footwall chronology of the Taylor and Ogden thrusts and relate it to the emplacement of the Willard thrust and Willard thrust complex; and 6) investigate the relationship between footwall deformation, the geometry of the thrust complex, lateral ramping, a folded portion of the Willard thrust, Precambrian crystalline basement rock, and a possible structural high beneath the Willard thrust, and to compare the results with existing models of thrust-ramp evolution and deformation.

PREVIOUS WORK

Previous workers in this area have included graduate students and professors from Utah State University and the University of Utah, other graduate students and professors, and professionals from the Utah Geological Association and the United States Geological Survey. A detailed list of previous work and workers is provided in Appendix A. and by Schirmer (1985c).

GEOLOGIC SETTING

The Willard thrust fault is located on the western edge of the Idaho-Utah-Wyoming Sevier orogenic thrust belt. Northeast of Ogden, Utah the fault is exposed along an approximate northwest-southeast trace 22-kilometers long that parallels the Wasatch fault. Thrusting has involved Precambrian crystalline basement rocks and Paleozoic sedimentary rocks (Fig. 3).

The Willard thrust fault (Fig. 4) is the oldest and westernmost thrust of the four major thrusts in this region of the Sevier orogenic belt (Armstrong, 1968; Crittenden, 1972; Royse and others, 1975; Blackstone, 1977). More recently Woodward (1988) did not connect the Willard thrust to the Paris thrust. This study will use a working hypothesis similar to Woodward (1988) for the origin of the Willard thrust fault, that is, the assumption is made that the Willard thrust is older than and not connected to the Paris thrust, which is located northeast of the Willard thrust and near the town of Paris, Idaho. Without seismic data this study will not speculate on the subsurface nature of the Willard thrust, either to the north of Willard Canyon or to the south of Pineview Reservoir, where the

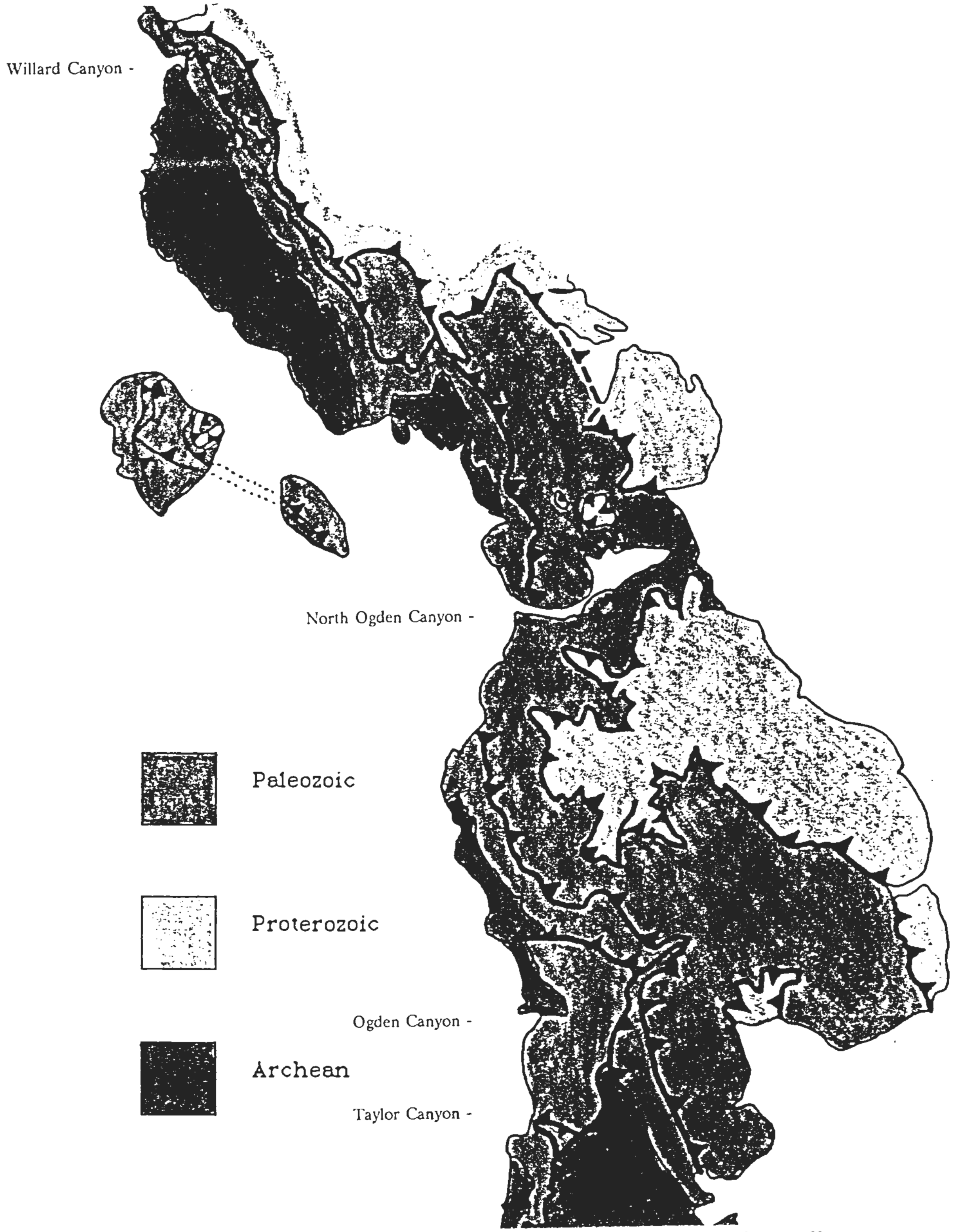


Fig. 3 Generalized geologic map showing footwall (Paleozoic) and hanging wall (Proterozoic) geology of the Willard thrust complex between Willard and Ogden canyons (modified from Schirmer, 1988). Teeth are located on the hanging wall of the thrusts.

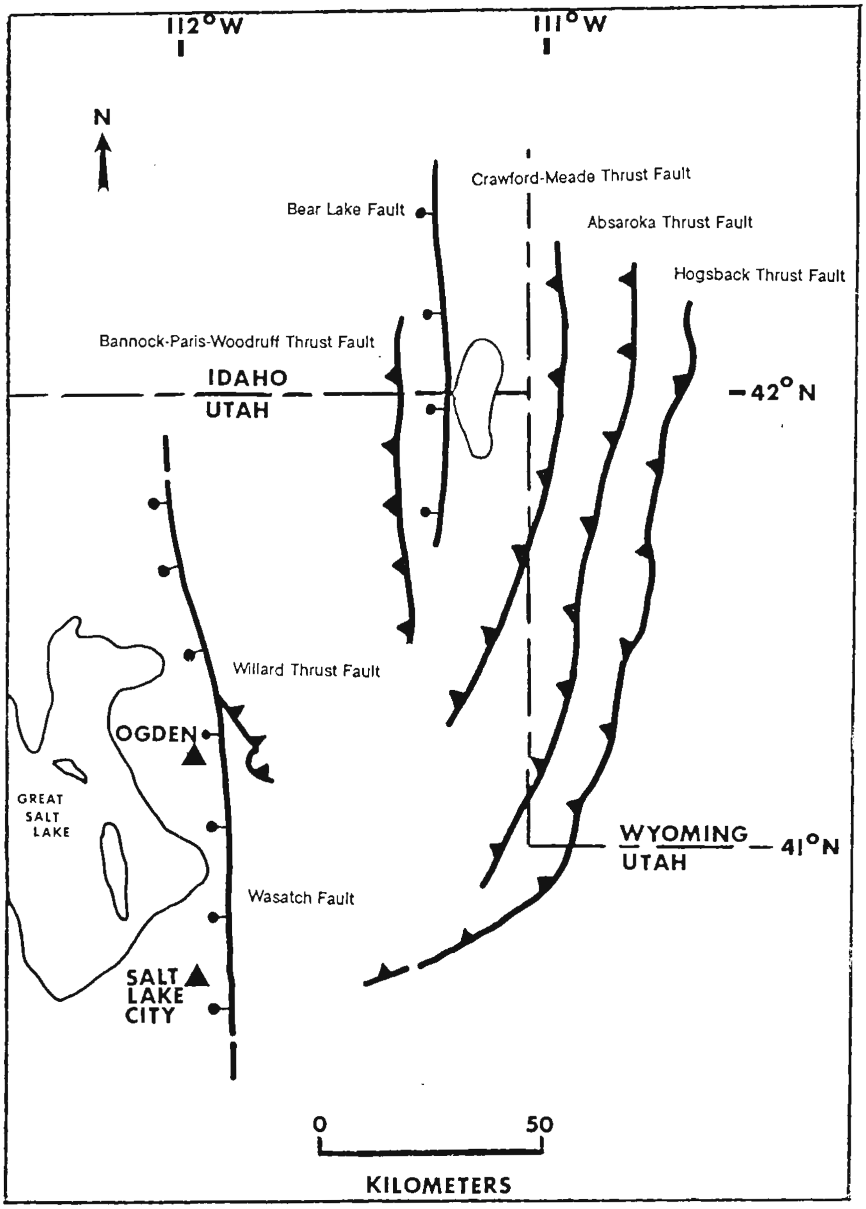


Fig. 4 Location map showing the position of the Willard thrust fault relative to the major thrusts of the Idaho, Wyoming, and Utah thrust belt.

Willard thrust disappears into the subsurface. Schirmer (1985c) classified the Willard thrust and the structurally lower Taylor and Ogden thrusts as a "classic" foreland-dipping "duplex," (Boyer and Elliot, 1982) in which individual thrust sheets dip eastward in the direction of propagation. He named this the Ogden duplex. According to Schirmer (1985c), the "Ogden duplex" developed in a sequential, top to bottom, piggyback manner, causing older thrust sheets to be carried by younger thrust sheets, as compression from the west forced Archean and Proterozoic crystalline basement rock and Early to Middle Paleozoic and Late Proterozoic limestones, dolostones, shales, sandstones, and conglomerates eastward. The eastward or foreland-dipping geometry of the Willard thrust complex, the thrusting of Archean and Proterozoic crystalline basement rock, and the fact that the area marks the transition westward from thin- to thick-skinned deformation, makes the Willard thrust complex unique in the Idaho-Utah-Wyoming thrust belt (Fig. 5). This study will not impose a previous genetic model (e.g., Boyer and Elliot, 1982) on the structural geometry of the Willard thrust fault. Instead, the term thrust complex will be used to describe the Willard thrust sheet and the structurally lower Taylor and Ogden thrust sheets.

West of the Willard thrust, primarily in the northwest corner of Utah, are the metamorphic core complexes of the Albion, Raft River and Grouse Creek ranges. This area is the hinterland of the thrust belt and is characterized by a geologic history of regional metamorphism and ductile deformation in the lower crust followed by a "doming" to the surface of several granitic intrusions. These uplifted domes form the "cores" of the metamorphic complexes. Later, extensional faulting left the cores covered by a shallow, brittle deformation

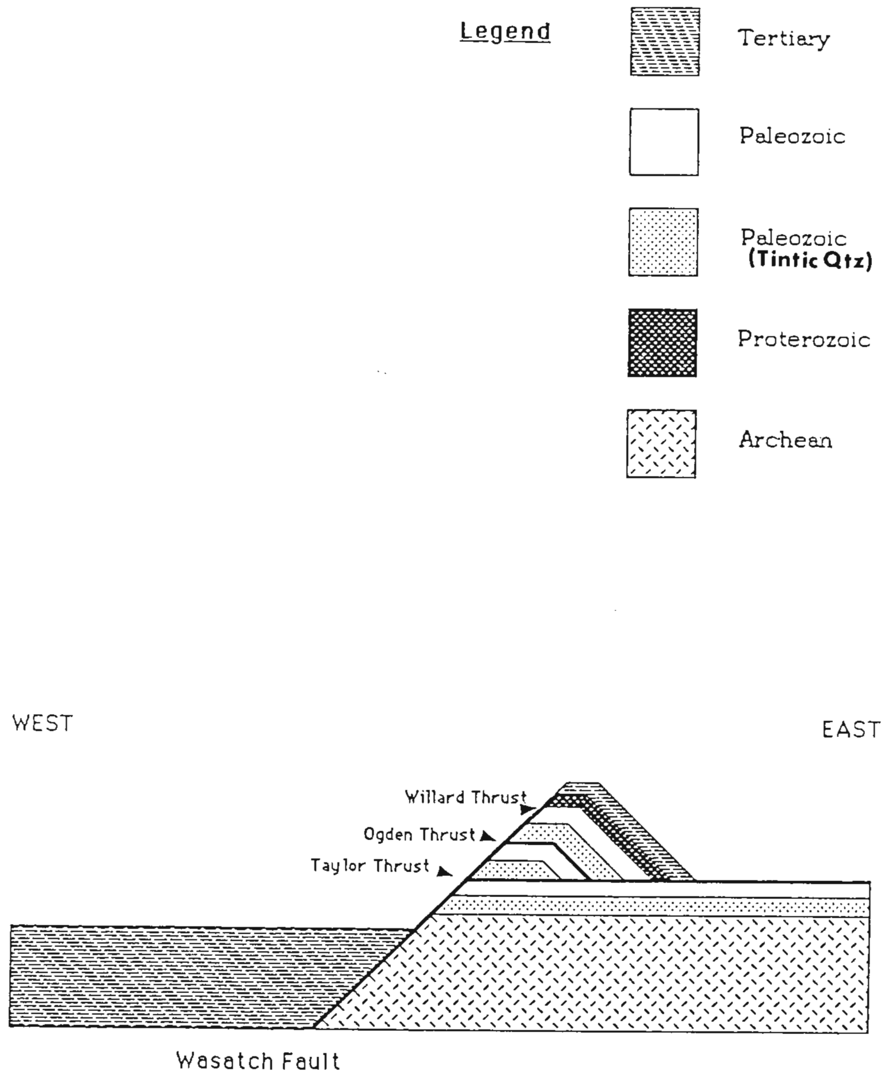


Fig. 5 Schematic diagram showing a generalized conception of the east dipping Willard thrust complex and superimposed Wasatch "normal" fault. The cross-section is oriented west-east and is representative of the geology on the north side of Ogden Canyon.

(Davis and Coney, 1979; Armstrong, 1982; Jordan and others, 1983; Allmendinger and others, 1984; Miller and others, 1986; Malavielle, 1987; Hintze, 1988).

East of the Willard thrust lies the central Rocky Mountain foreland, or fold and thrust belt, which is characterized by four thrusts in the Idaho-Utah-Wyoming thrust belt. The four major thrusts east of the Willard thrust are the Paris, the Crawford-Meade, the Absaroka, and the Hogsback (Armstrong, 1968; Royse and others, 1975). These four thrusts are similar in geometric structure and appearance. That is, they formed as successively younger piggyback imbricates, which developed east of the Willard thrust. According to Spieker (1946), Harris (1959), Armstrong and Cressman (1963), Armstrong and Oriel (1965), Armstrong (1968), Wiltschko and Dorr (1983) and Schmitt (1984), initial movement on the Paris-Willard thrust was believed to have begun in Early Cretaceous (115 to 125 m.y.) or possibly in Late Jurassic and continued through Early Tertiary. Heller and others (1986) have constrained the age of the earliest Sevier thrusting (the Paris-Willard thrust sheet) by examining the distribution of fossil charophytes (a green algae), preserved in the synorogenic Ephraim Conglomerate east of the Willard thrust. Fossil distributions and analyses of subsidence of sedimentary basins east of the thrust belt showed that initial thrusting occurred no earlier than Middle Cretaceous, approximately 110 to 120 m.y. (Heller and others, 1986). Yonkee and others (1989) used sericite grains from phyllonite and cataclasite to obtain $^{40}Ar/^{39}Ar$ ages of 110 to 140 m.y.

Estimates of displacement for the Willard thrust have varied considerably from study to study. The lack of a clear hangingwall cutoff makes estimating displacement difficult. Current minimum estimates range from 10 to 35 kilometers of horizontal eastward displacement on the Willard thrust fault (Crittenden, 1972; Beck, 1982; Schirmer, 1985c). Yonkee and others (1989) used the footwall cutoff near Willard Peak and the hangingwall cutoff near Woodruff Canyon to give an estimate of 35 kilometers of net displacement. This distance is similar to Crittenden's (1972) estimate.

PROBLEM HYPOTHESES AND MODELS

In the footwall of the Willard thrust fault at Willard Canyon, the approximate northernmost exposure of the fault, deformation structures consist primarily of intense folding in the shale and limestone formations. In the footwall of the Willard thrust at Pineview Reservoir, the approximate southernmost exposure of the fault, deformation structures consist entirely of fracturing and cataclasis. The working hypothesis for this study is that a transition in microscopic and macroscopic deformation mechanisms and styles exists in the footwall of the Willard thrust between Willard Canyon and Ogden Canyon. A transition was hypothesized, wherein, plastically deformed footwall rock in the north changes to cataclastically deformed rock in the south. This hypothesis was based on macroscopic field evidence (footwall rock) observed by workers, including this author. The location, characteristics, and mechanisms of the hypothesized transition are dependent on several factors: pressure, temperature, footwall stratigraphy, lithology within stratigraphic formations, and the presence of a lateral ramp. Other hypotheses include the possibility that thrust sheets structurally below the Willard thrust, which may have formed before the Willard thrust, have influenced the final geometry of the Willard thrust. The possibility also exists that a pre-existing subsurface high(s), in the crystalline basement rock, may have influenced initial thrust-sheet movement, sequential development, and emplacement of the Willard thrust complex.

The model proposed in this study for the sequential development of the Willard thrust and the structurally lower Taylor and Ogden thrusts is based on and modified from 1) thrust-fault duplex formation (Boyer and Elliot, 1982); 2) studies of the Taylor, Ogden, and Willard thrusts by Blackwelder (1910), Eardley (1944), Crittenden (1972), Sorensen and Crittenden (1972, 1976, 1979), Crittenden and Sorensen, (1985a, 1985b), Schirmer (1985a, 1985b, 1985c, 1988), and Yonkee and others (1989); 3) the anomalous (Hunt, 1982) east-west trending canyons (i.e., Box Elder, Willard, North Ogden, Ogden, and Taylor's) which cut the thrust complex; 4) the similar geometry of thrust sheets to the south of each of these canyons; 5) the overturned, east- vergent, recumbent syncline below the Willard thrust (Crittenden, 1972); 6) the folded portion of the Willard thrust sheet (between Willard Peak and Ogden Canyon); and 7) the change in footwall deformation between Willard and Ogden canyons.

PROJECT LOCATION AND FIELD AREAS

The project study area is in the northern Wasatch Range of Utah between Willard Canyon and Ogden Canyon, north, northeast, and east of the city of Ogden. The distance along strike between the two canyons is approximately 22 kilometers. Field work was conducted in six areas between Willard and Ogden canyons (Fig. 6). The six areas were chosen based on footwall exposure, quality and quantity of deformation structures in the footwall, and accessibility to the outcrop. The six areas are Willard Canyon, Willard Mountain, North Ogden Canyon, Cold Water Canyon (which includes part of One Horse Canyon), Goodale Creek Canyon, and Pineview Reservoir. Willard Canyon, the northernmost field area, is in section 24, R2W, T8N, in the Willard 1:24,000 topographic quadrangle. The Willard Peak field area is in sections 31 and 32, R1W, T8N and R1W, T7N, in the Mantua 1:24,000 topographic quadrangle. The North Ogden Canyon field area is in sections 23 and 24 of R1W, T7N, in the North Ogden 1:24,000 topographic quadrangle. The Cold Water Canyon field area is in sections 34 and 35 of R1W, T7N, and sections 2 and 3 of R1W, T6N in the North Ogden 1:24,000 topographic quadrangle. The Goodale Creek Canyon and Ogden Canyon field areas are in sections 16, 17, and 18 of R1E, T6N, in the Huntsville 1:24,000 topographic quadrangle.

Other field data previously collected from areas structurally below the Willard thrust have been included to help establish and support the proposed model of development of the Willard thrust complex. The field areas are Malans Peak, Taylor Canyon, the "S" fold to the south of the mouth of Ogden Canyon,

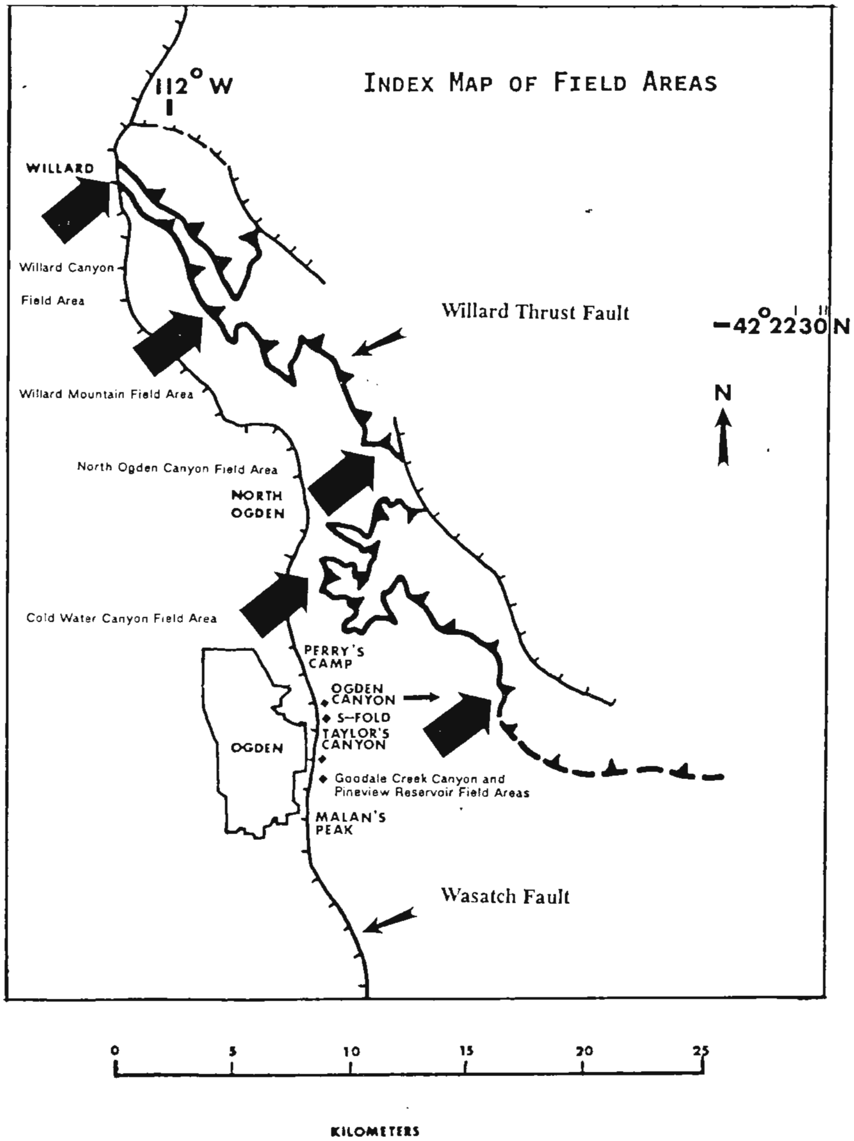


Fig. 6 Location map of individual field areas.

and Perry's Camp (several small houses located just east of the mouth of Ogden Canyon). Malans Peak is in section 35 of R1W, T6N, in the Ogden 1:24,000 topographic quadrangle. Taylor Canyon is in sections 35 and 36 of R1W, T6N, in the Ogden 1:24,000 topographic quadrangle. The "S" fold is located in section 26 of R1W, T6N, in the Ogden 1:24,000 topographic quadrangle. Perry's Camp is located in section 24 of R1W, T6N, in the Ogden 1:24,000 topographic quadrangle.

All of the field areas, because of differences in location, accessibility, and topography, presented unique opportunities and problems during field work. Accessibility to outcrops in each field area was aided by Forest Service trails, old jeep trails, and numerous deer trails. In all but one of the field areas, topography is relatively steep and required strenuous hiking and some climbing. In one field area (Willard Canyon), several outcrops were unreachable because of vertical rock exposures.

METHODOLOGY

DATA

Data used in this study include 1:24,000 and 1:12,000 geologic maps, nine thin sections made from 23 samples collected in the footwall, stereonets of orientations of bedding orientations and deformation structures in the footwall, a stratigraphic displacement diagram, and a hangingwall sequence diagram. The published geologic maps of Bryant (1984), Crittenden and Sorensen (1985a, 1985b), Davis (1985), Hintze (1980), Schirmer (1985c), and Sorensen and Crittenden (1972, 1979) were used in this study; as well as color air photos (1:12,000), topographic quadrangles (1:24,000), and orthophoto quadrangles (1:24,000).

Twenty-three oriented samples were collected from the footwall of the Willard thrust. From each sample, a north-south and west-east "chip," perpendicular to bedding, was cut and prepared for grinding. Of the twenty three samples (now 46 chips) nine west-east oriented chips were chosen for final thin-section preparation. Only chips oriented west-east were chosen for final thin section preparation because deformation fabrics were best seen in west-east cuts of the original field samples.

Stereonet plots of planar and linear orientations of deformation structures as well as bedding were constructed for each of the field areas. The types of stereonet plots include Great Circle Plots, Scatter Plots, and Kamb Contour Plots.

A stratigraphic displacement diagram showing how footwall stratigraphy changes from north to south along strike was constructed from data from Davis'

(1985) 1:100,000 geologic map of the northern Wasatch Front, Utah.

A hangingwall sequence diagram (Elliot and Johnson, 1980; Schirmer, 1988) was constructed from data from Davis' (1985) 1:100,000 geologic map of the Northern Wasatch Front. The diagram is drawn longitudinally from N29W to S29E, which is approximately parallel to the trace of the Willard thrust. The diagram represents a west to east, time-based, schematic sequential development of the Willard thrust complex, based on previous geologic mapping and data incorporated from this study.

FIELD PROCEDURE

Data from deformation structures were collected from the footwall of the Willard thrust at each of the six primary field areas. The types of deformation structures from which data were collected are fractures, solution cleavage, foliations, lineations, folds, and bedding. All deformation data were recorded in a field notebook with sketches of outcrops, color photographs, and identification numbers of samples collected in the field. The process of determining where and what data to collect was decided by the nature of the particular outcrop. The procedure for collecting footwall data at each outcrop was relatively straightforward, and remained the same throughout the study. When a potential outcrop was located, the area was examined to determine outcrop extent and types of deformation structures present. Data were then collected both perpendicular and parallel to the fault surface throughout the outcrop to insure that they were representative of the entire outcrop. Footwall rock is best exposed at the Willard Canyon and Willard Mountain field areas. In these two areas, the approximate stratigraphic thickness of exposed footwall rock where deformation data were collected was about 200 meters (Fig. 7). To the south, in the North Ogden Canyon field area, the exposed thickness of footwall rock is approximately 10 to 20 meters. In the Goodale Creek Canyon and Pineview Reservoir field areas the exposed thickness of footwall rock is approximately 10 meters.

FIELD DATA

Willard Canyon

Data collected from deformation structures in the Willard Canyon field area include orientations of fractures, solution cleavage, fold axes, and footwall bedding (see Appendix B). Rock samples for thin-section analysis of structural fabrics were also collected. Deformation structures are located in the Tintic Quartzite, Ophir Formation, and Maxfield Limestone (Fig. 8). Outcrop rock types include quartzite, limestone, shale, and dolostone (see Appendix C). Because of lateral and vertical thinning and thickening of stratigraphic units in the zone of deformation, it was not possible to determine to which formation the shale and limestone outcrops belonged. Data were collected from the north and south sides of the canyon but primarily from the north side because of better outcrop exposure. All deformation orientations were plotted on equal-area, lower-hemisphere stereonets (Fig. 9). The Ophir Formation and the Maxfield Limestone make up the "zone of deformation" in Willard Canyon. The zone is approximately 200 meters thick from the top of the Tintic Quartzite upward to the base of the Willard thrust sheet (the hangingwall). Because the Tintic

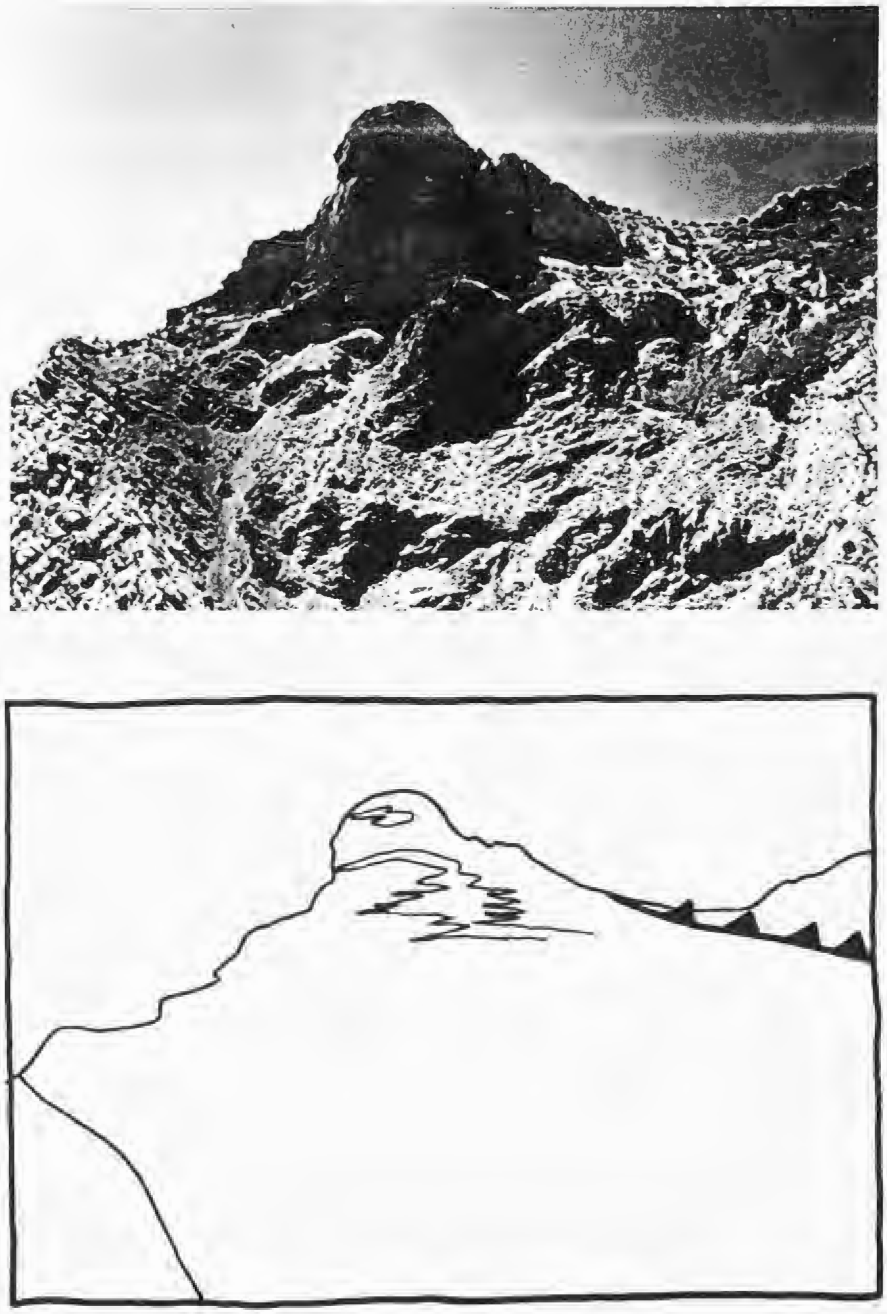
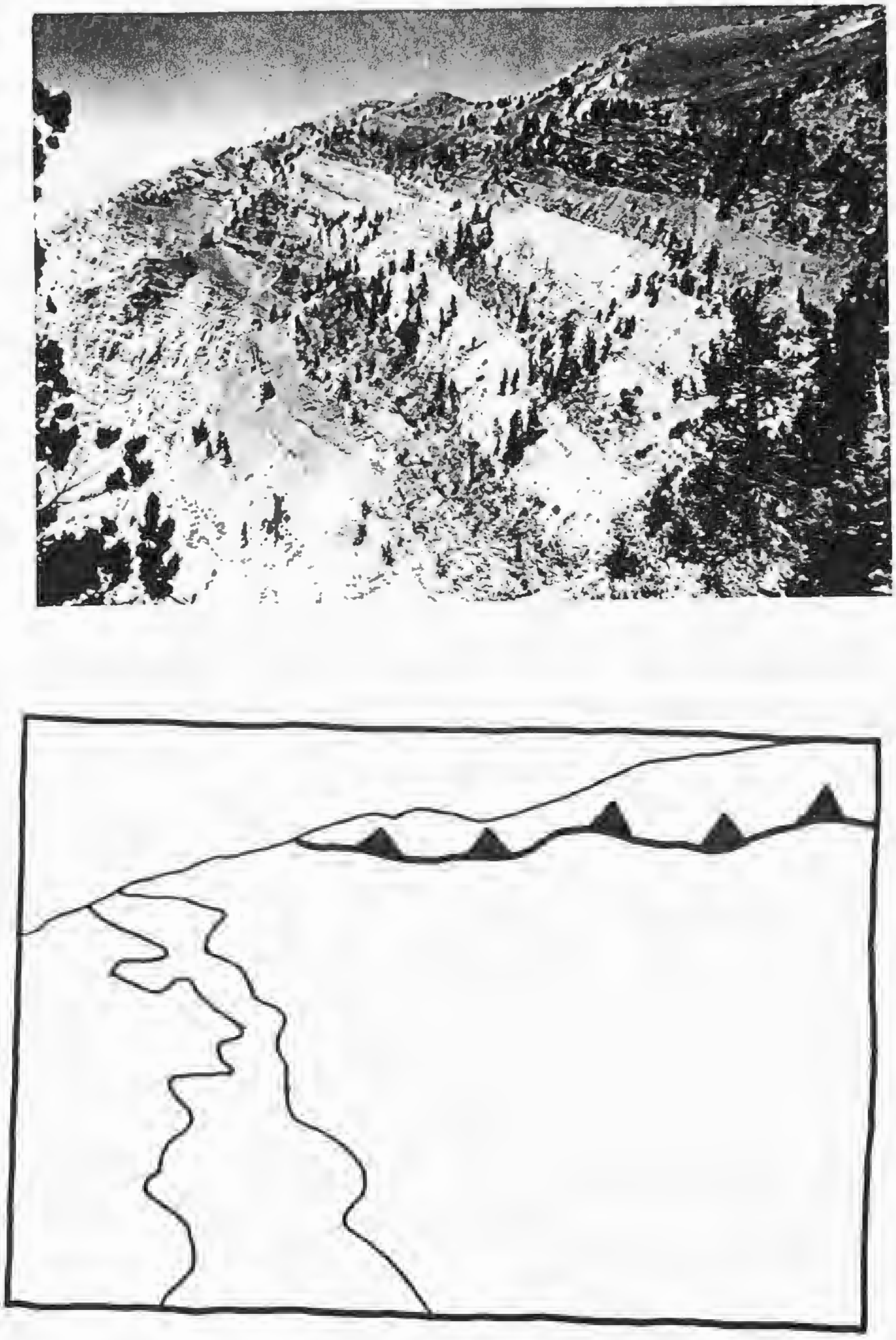
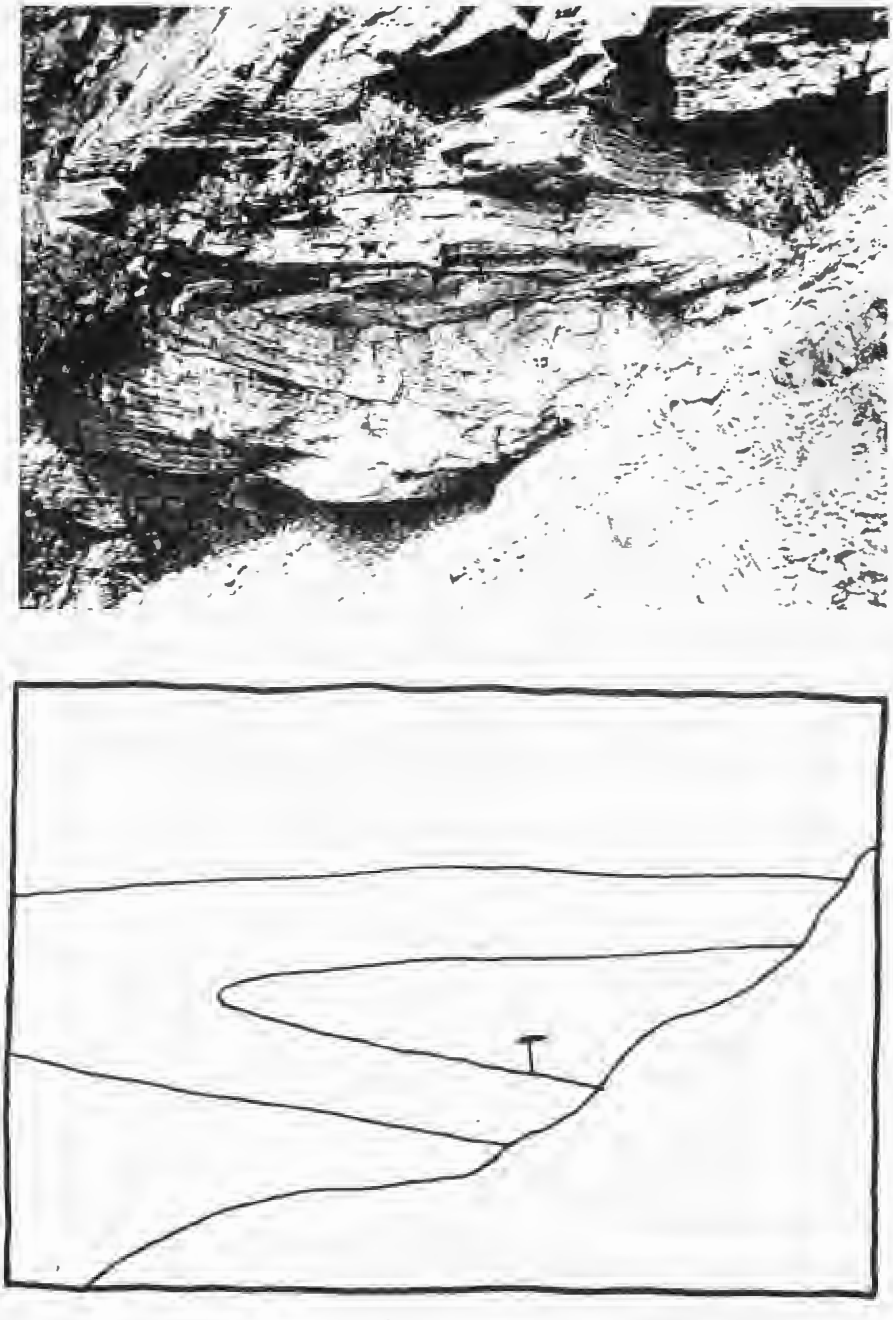


Fig. 7 The zone of deformation at (a) the Willard Canyon field area and (b) the Willard Mountain field area. The view of the Willard Canyon zone of deformation is to the northwest and shows the Tintic Quartzite (lower left), Ophir Formation (lower center), Maxfield Limestone ((knob), and Proterozoic Facer Formation in the hanging wall (upper right). The view of the Willard Mountain zone of deformation is to the north and shows the Tintic Quartzite (lower left), the limestone and shale members ofthe Ophir and Maxfield Formations (central) and the hanging wall of the Willard thrust (upper).



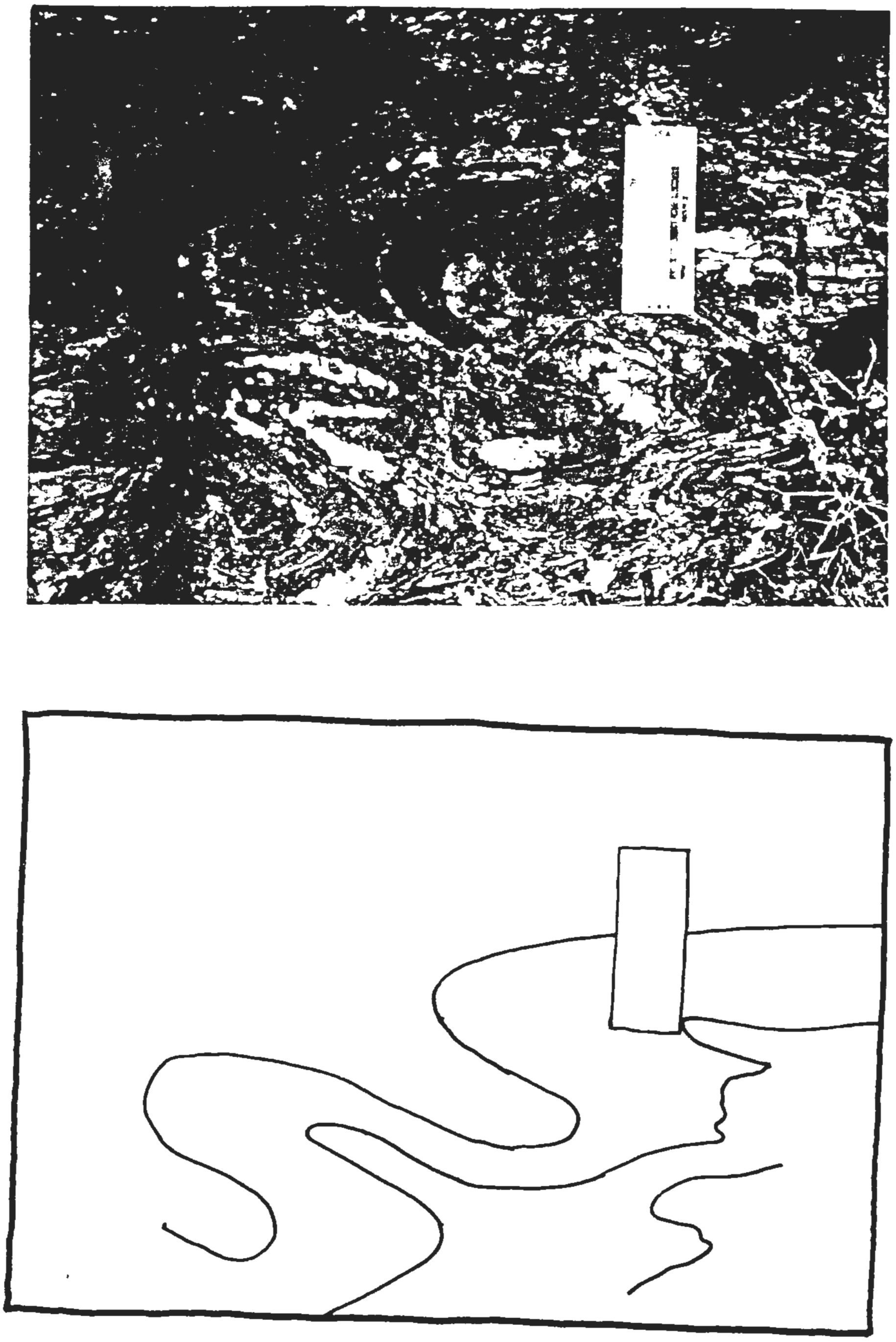
(b)

Fig. 7 (Continued)



(a)

Fig. 8 Examples of macroscopic footwall deformation structures, (a) and (b) at the Willard Canyon field area. Example (a) is a large isoclinal fold that opens to the east. Note rock hammer for scale (view is to the north). Example (b) is a folded limestone surrounded by shale. Dark vertical bar on scale is 10 centimeters long (view is to the north).



(b)

Fig. 8 (Continued)

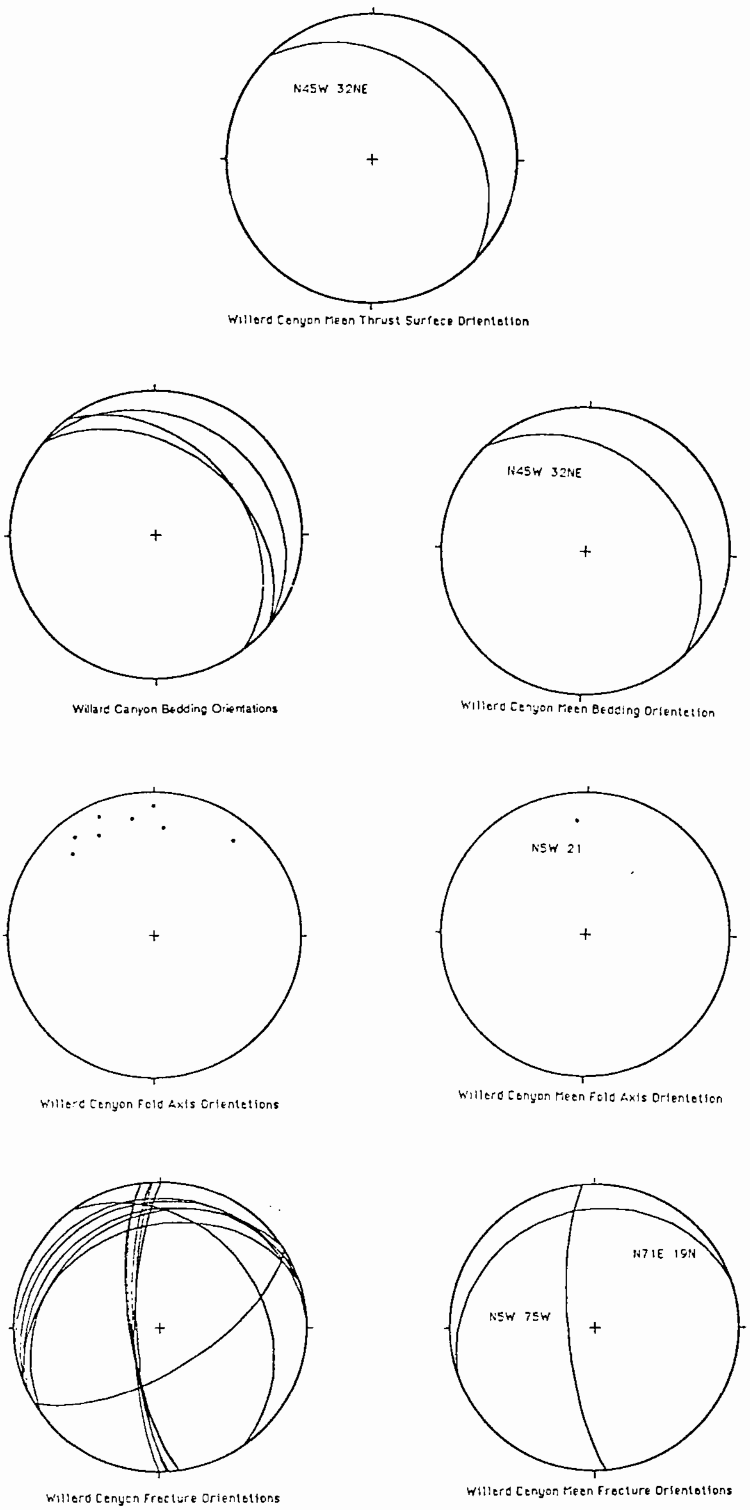


Fig. 9 Stereonet plots of orientations of deformation structures at the Willard Canyon field area. See Appendix B for the number of data points used. Plotted data was visually grouped and means were calculated and plotted from resulting groups.

Quartzite is not part of this zone, its overall bedding geometry (throughout the entire study area) is less deformed than the Paleozoic formations above it and so serves as an excellent marker for recognizing individual thrust sheets in the Willard thrust complex. However, the Tintic Quartzite does contain extensive compressive and tensional cataclastic deformation. Orientations of deformation structures were plotted on stereonets as means (Fig. 9) to simplify data presentation and to present an average orientation of various deformation structures at each field area. The orientation of the Willard thrust surface is approximately N45W 32NE. The mean orientation of footwall bedding for the Tintic Quartzite in this area is the same as that of the thrust surface. Outcrops throughout the field area have been overprinted by fracturing in two separate orientations. The mean orientation of the first group is N5W with a dip of 75 degrees to the west. The mean orientation of the second group is N71E with a dip of 19 degrees to the northwest. Fracturing in this field area is attributed to post-Willard-thrust deformation most likely associated with Basin and Range extensional faulting because fractures generally overprint the other deformation structures.

Axial planar cleavage is abundant, and is associated with most folds in the limestones and shales. Solution cleavage in the Willard Canyon field area is not distinct, but is present in the limestones and shales and is parallel to bedding. It is not distinct because of the penetrative nature of the other structures. Folding in the footwall of Willard Canyon ranges from tight isoclinal to open. Folds open to the west and the east, with neither orientation dominating.

Fold orientations were measured where exposure and accessibility permitted. Many folds could not be measured. Also, many accessible and exposed folds were examined from which no data could be collected. The mean fold axis orientation in the field area trends N5W with a plunge of 21 degrees.

Footwall deformation at the Willard Canyon field area is macroscopically plastic, as evidenced by the folding that is present. It is uncertain how much strain in the footwall was accommodated by pressure solution. Solution cleavage is folded, which indicates an older age than folding and the initiation of footwall deformation prior to frontal or lateral ramping. If solution cleavage is a result of initial movement by the Willard thrust, it must have formed just prior to initiation of folding in the footwall. No structures in the field area were noted that might resolve this question. From all data collected the primary mechanism of deformation in the Willard Canyon field area is the folding of previously stressed (and strained) incompetent rocks in the zone of deformation (i.e., the Ophir Formation and Maxfield Limestone).

Willard Mountain

Data collected from deformation structures at the Willard Mountain field area (between Willard Mountain and Willard Peak) include orientations of fractures, pencil cleavage, folds, and footwall bedding (see Appendix B). Rock samples for thin-section analysis of structural fabric were also collected. Deformation data were collected from the Ophir Formation and Maxfield Limestone in this field area. Outcrop rock types include quartzite, limestone, shale, and dolostone (see Appendix C). Orientations of deformation structures were plotted on stereonets and are shown in Figure 10.

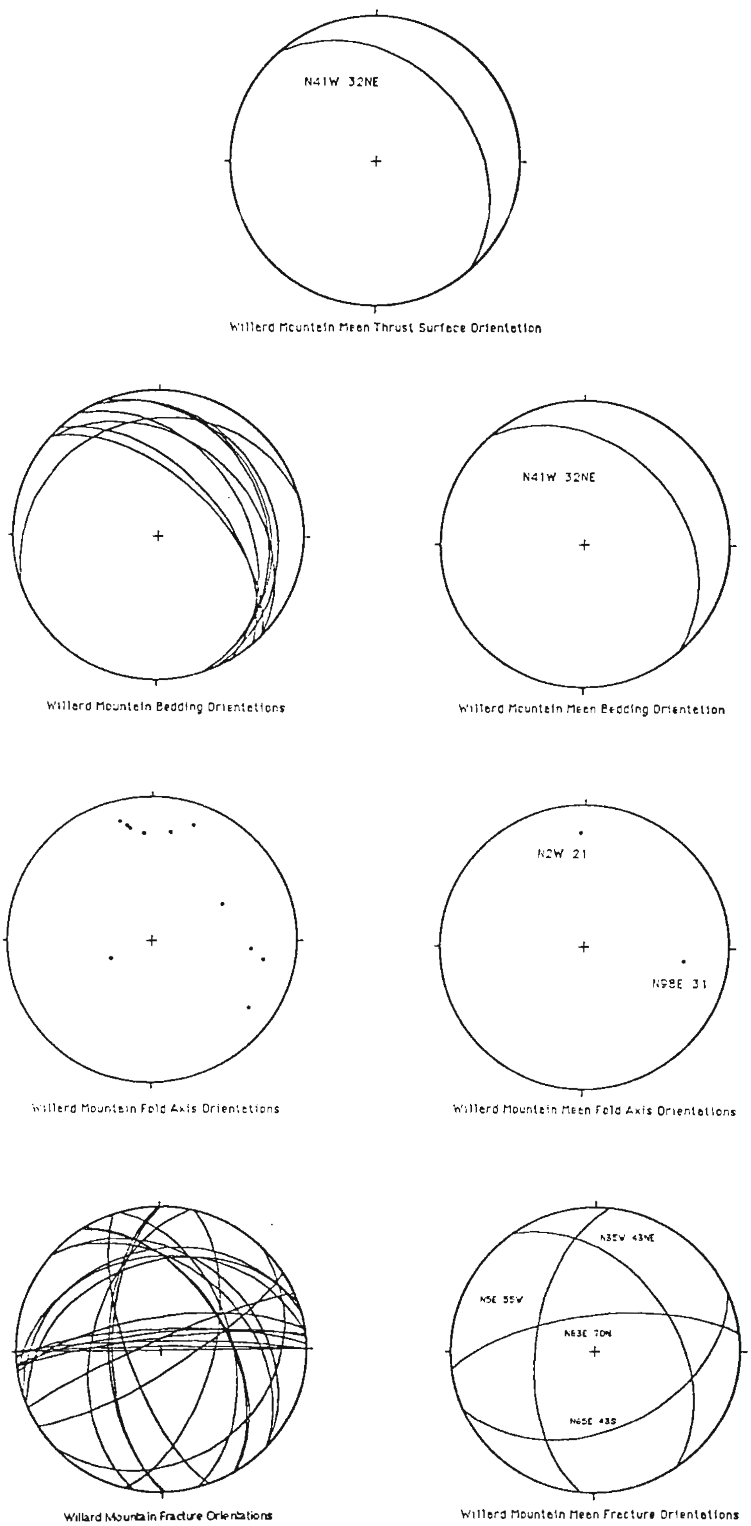
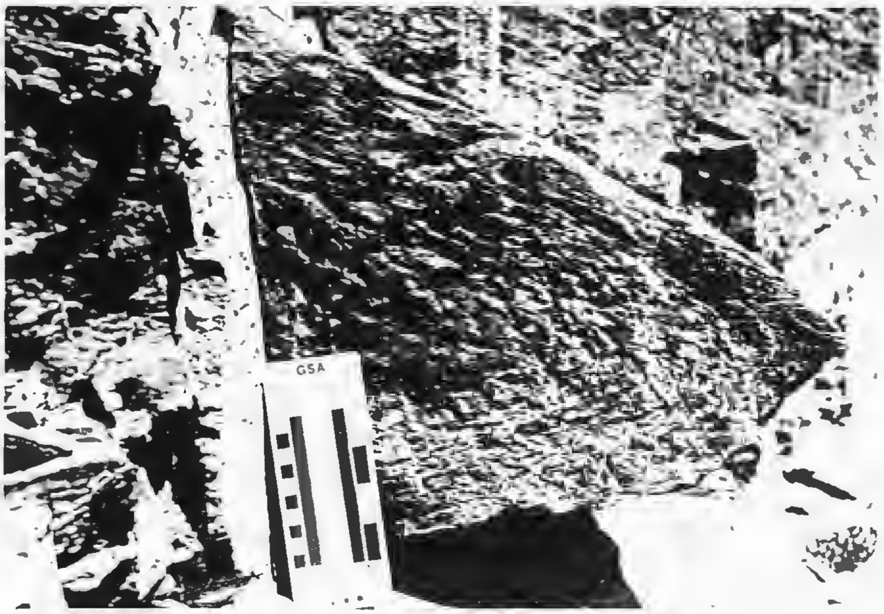


Fig. 10 Stereonet plots of orientations of deformation structures at the Willard Mountain field area. See Appendix B for the number of data points used. Plotted data was visually grouped and means were calculated and plotted from resulting groups.

Footwall deformation at the Willard Mountain field area is located primarily in the Ophir Formation and Maxfield Limestone (Fig. 11), which lie in the zone of deformation . These formations lie in the zone of deformation below the Willard thrust and above the Tintic Quartzite. Unlike the Willard Canyon field area, footwall bedding at the Willard Mountain field area is easier to recognize and to measure. The Willard thrust surface in this area is parallel to footwall bedding. The mean bedding orientation for the Tintic Quartzite, Ophir Formation, and Maxfield Limestone is N41W with a dip of 32 degrees to the northeast.

Outcrops in this field area, like the Willard Canyon field area, have a fracture overprint. Fracture orientations for the Willard Mountain field area fall into four groups. The mean orientation of the first group is N83E with a dip of 70 degrees to the north. The mean orientation of the second group is N65E with a dip of 43 degrees to the southeast. The mean orientation of the third group is N35W with a dip of 43 degrees to the northeast. The mean orientation of the fourth group is N5E with a dip of 55 degrees to the west. The fracture overprint in this field area, like the Willard Canyon field area, is a result of post-Willard thrust extensional tectonics.

Fold-axis orientations in the field area fall into two groups. The mean orientation of the first (dominant) group trends N2W with a plunge of 21 degrees and the mean orientation of the second group trends N98E with a plunge of 31 degrees. Fold axes of the first group are similar to those in the Willard Canyon field area. The first group of fold axes plunges shallowly to the north and indicates a west-to-east compressive stress in the footwall. The second group of



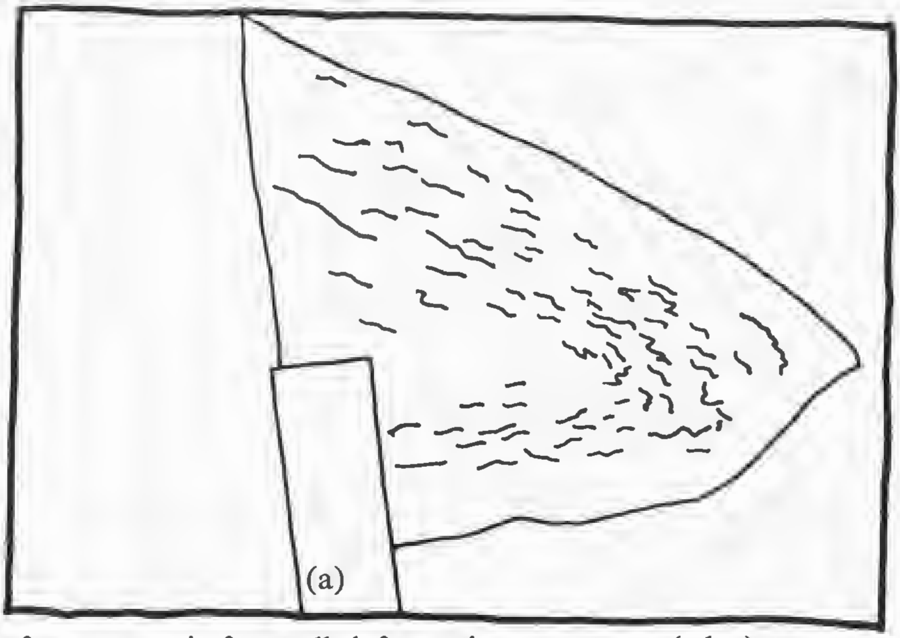
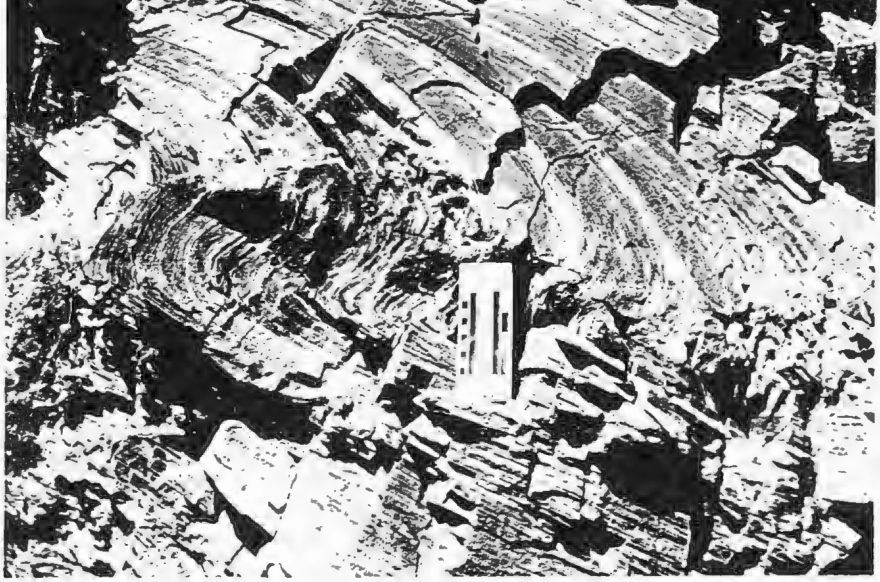
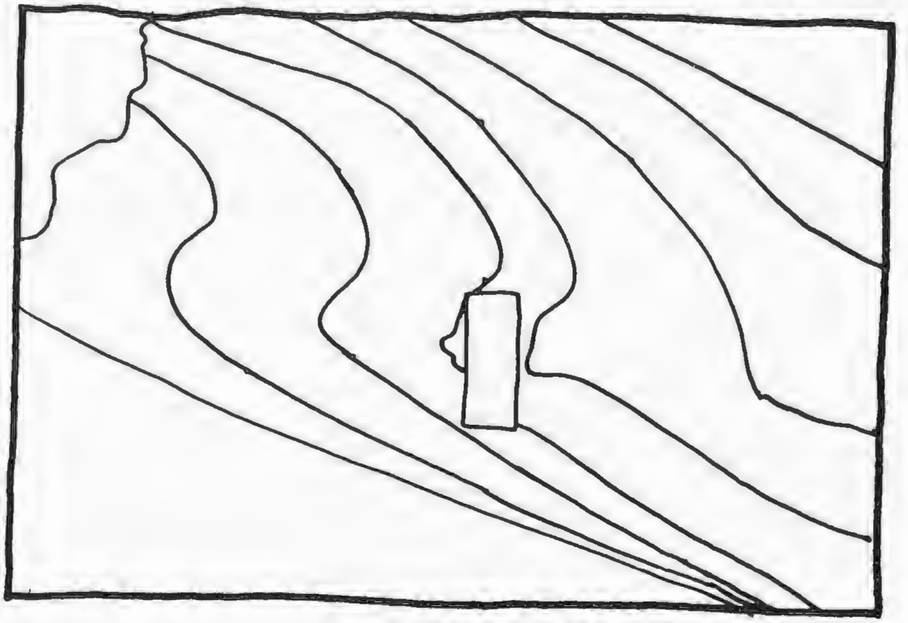


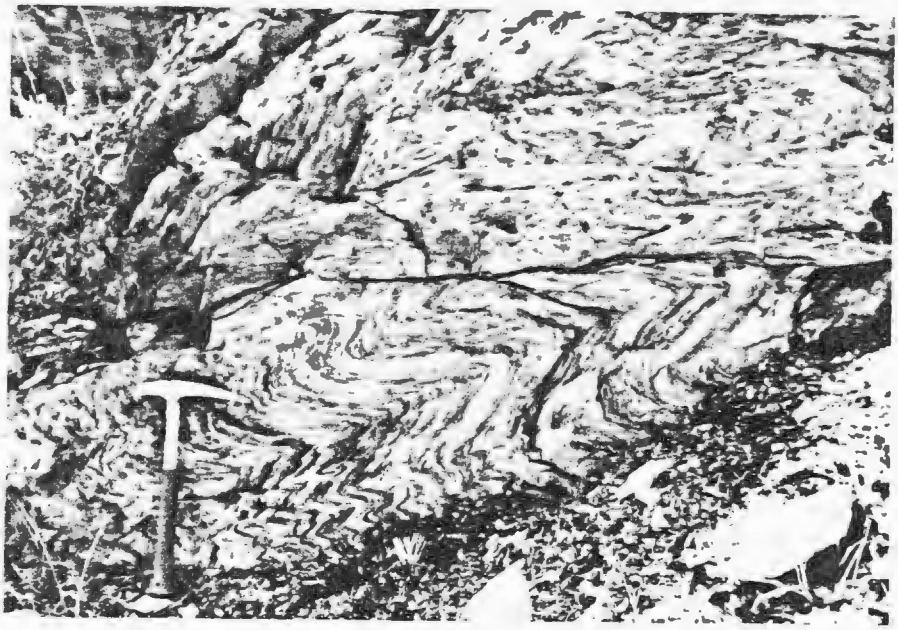
Fig. 11 Examples of macroscopic footwall deformation structures (a,b,c) from the Willard Mountain field area. Example (a) is a small isoclinal fold in limestone that opens to the north (view is to the east). Dark vertical bar on scale is 10 centimeters long. Example (b) is also a folded limstone. Example (c) is a folded unit of shale and limestone alternating shale and limestone

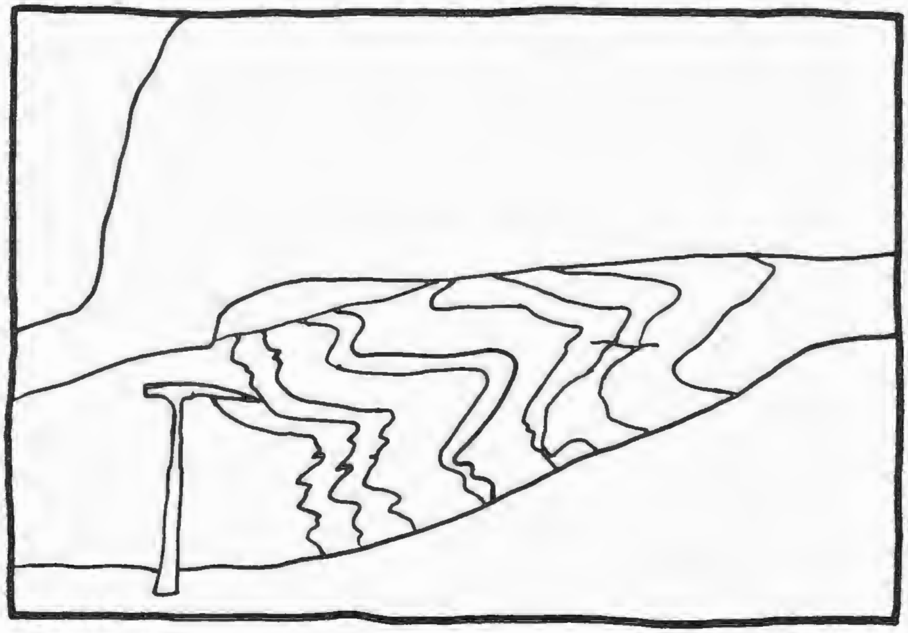




(b)

Fig. 11 (Continued)





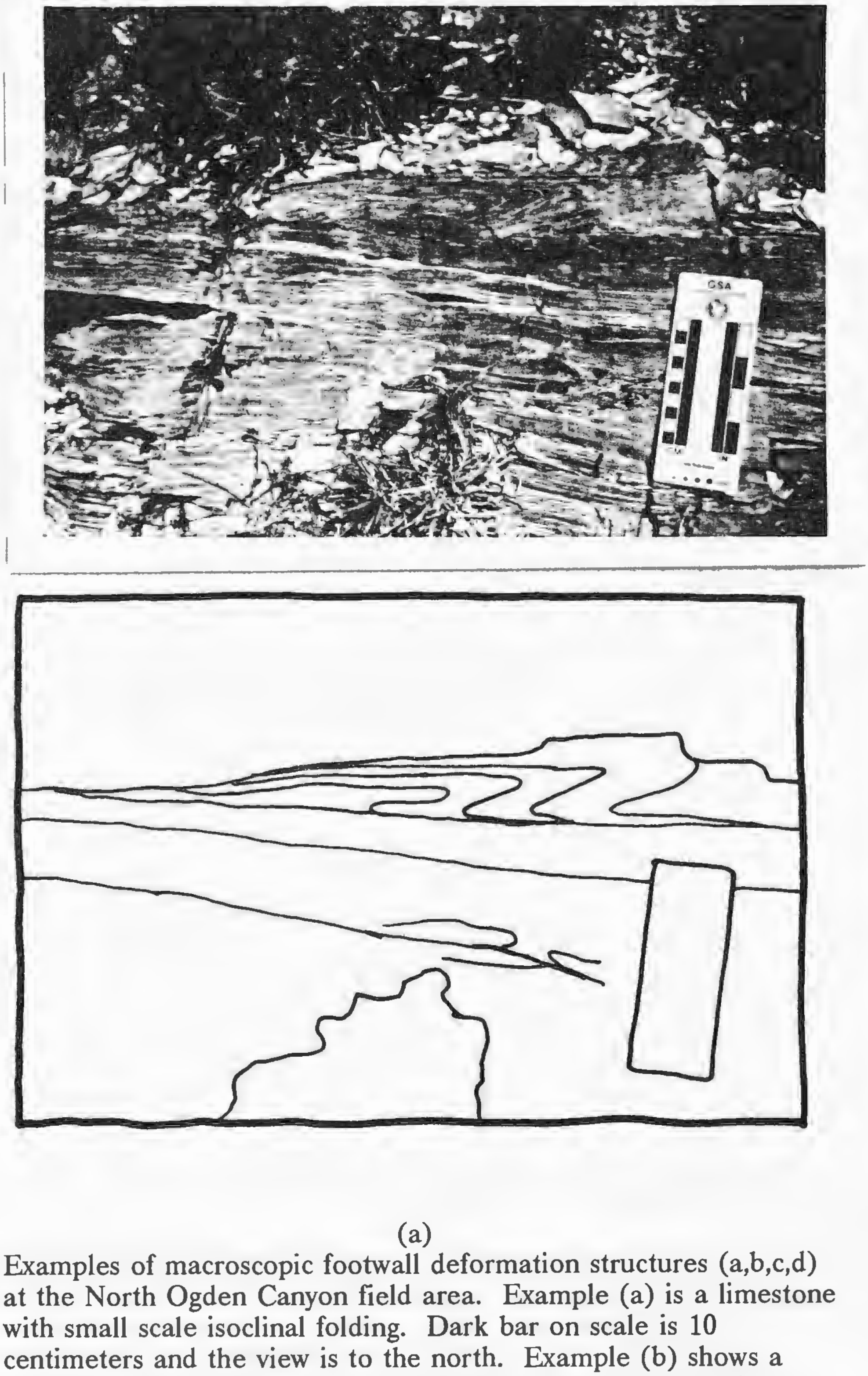
(c)

Fig. 11 (Continued)

fold axes is somewhat anomalous. The anomalous east-plunging orientations are located in an isolated outcrop within the zone of deformation. These fold axes may be evidence for a north-to-south directed component of stress, which Hansen (1980) proposed as following the initial phase of west-to-east directed stress on the Willard thrust plate. Schirmer (1985c) believed that the north-to-south directed lateral stress resulted from uplifting of the margins of thrust-sheet segments (created at lateral ramps) when an adjacent segment climbed up a more distal frontal ramp. The anomalous folds are likely to have been the result of differential stresses within the zone of deformation caused by changing lithologies (within the Cambrian limestones and shales) and east-west directed imbrication in the footwall in this particular field area. Macroscopic footwall deformation at the Willard Mountain field area, like that observed in Willard Canyon, is primarily plastic. Folding is the dominant type of deformation mechanism present, but bedding-parallel pressure-solution cleavage is also common.

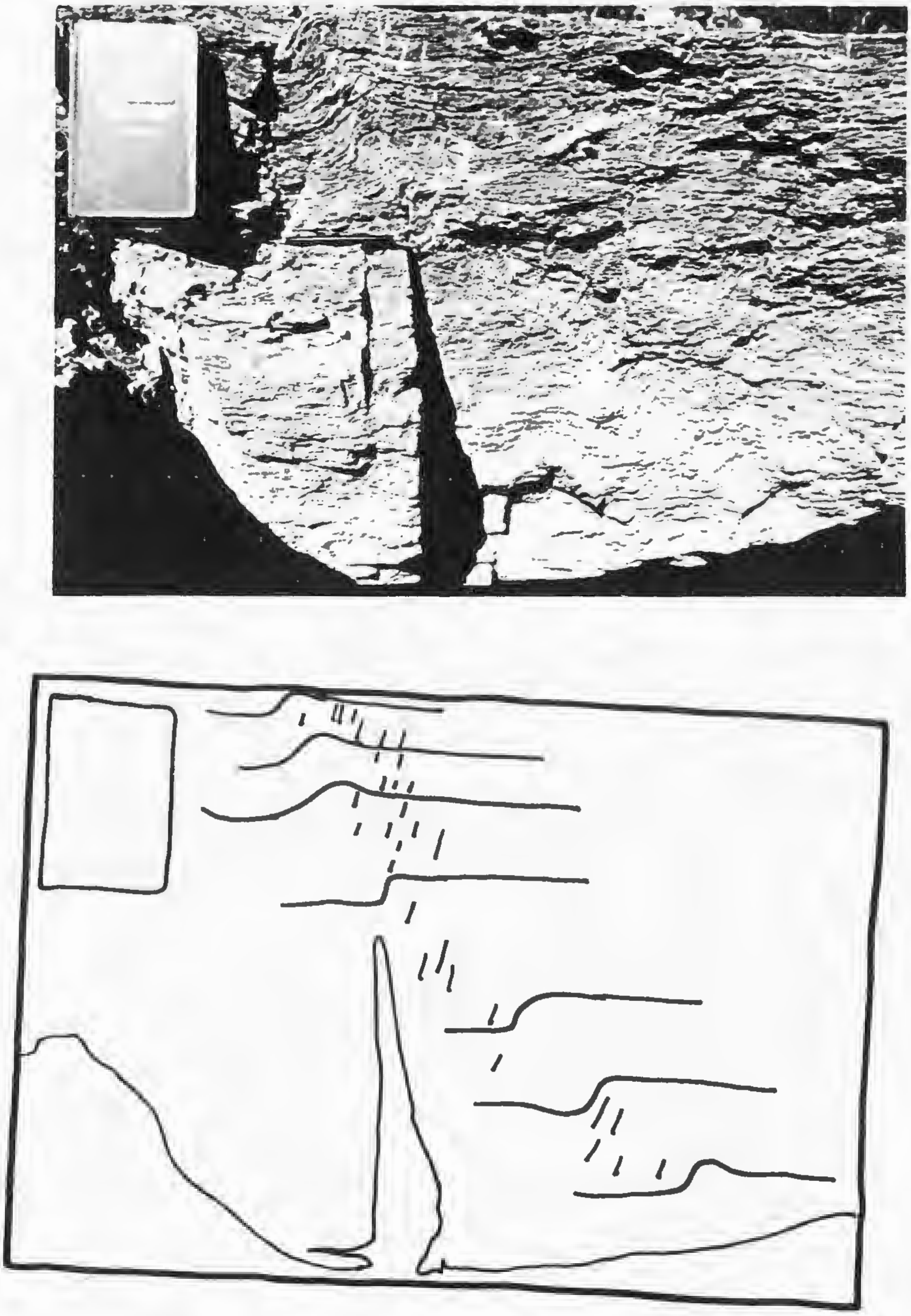
North Ogden Canyon

Data collected from deformation structures at the North Ogden Canyon field area include orientations of fractures, solution cleavage, kink bands, folds, and footwall bedding (see Appendix B). Rock samples for thin-section analysis of structural fabrics were also collected. Data were collected from two areas in the canyon. The first area, Chicken Creek, is on the eastern side of the pass on the north side of the canyon. The second area is along the "Skyline" trail on the northern side of the canyon at the pass. Deformation structures in these two field areas are located in the Tintic Quartzite, Maxfield Limestone, and Ophir Formation (Fig. 12). The zone of deformation present at Willard Canyon and



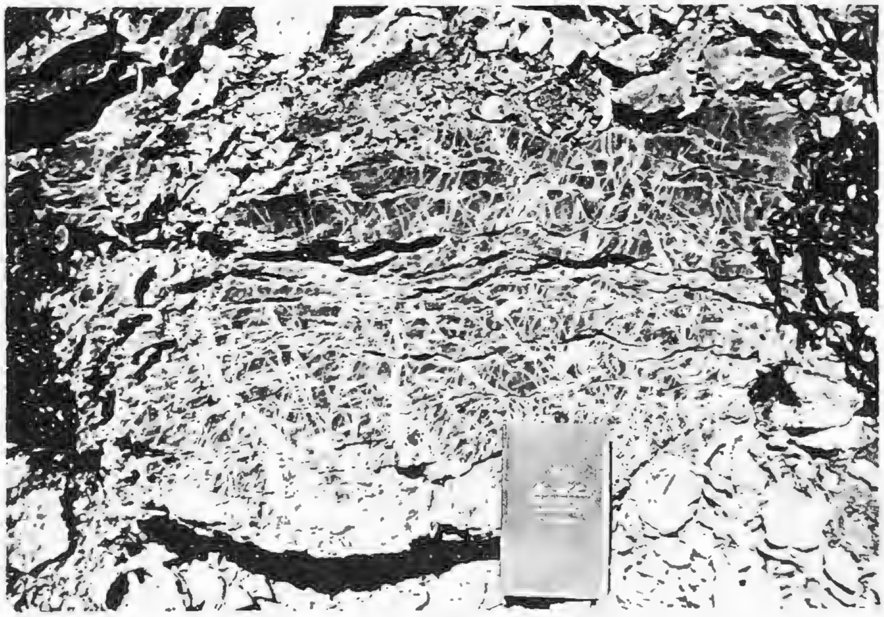
(a)

Fig. 12 Examples of macroscopic footwall deformation structures (a,b,c,d) at the North Ogden Canyon field area. Example (a) is a limestone with small scale isoclinal folding. Dark bar on scale is 10 centimeters and the view is to the north. Example (b) shows a a kink band in limestone. The notebook is 17 centimeters long and the view is to the north. Example (c) and (d) are very fractured limestone and Quartzite outcrops respectively.

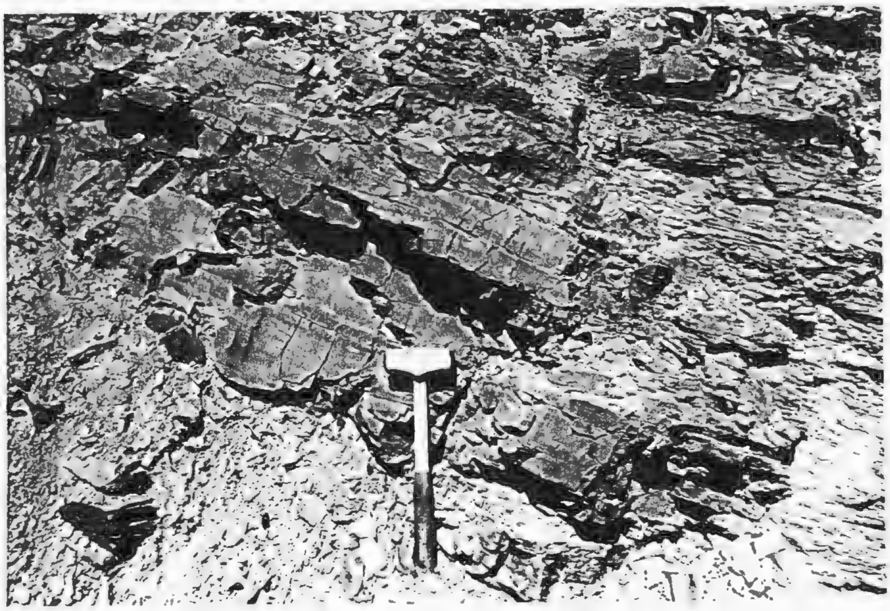


(b)

Fig. 12 (Continued)



(c)



(d)

Fig. 12 (Continued)

Willard Mountain is less distinct and stratigraphically thinner in this field area. Outcrop rock types include quartzite, limestone, shale, and dolostone. Figure 13 contains stereonet plots of North Ogden Canyon deformation orientations. The orientation of the thrust surface in this field area is N44W with a dip of 52 degrees to the northeast. The mean bedding orientation at the North Ogden Canyon field area is N76E with a dip of 36 degrees to the northwest. The change in footwall-bedding orientation relative to thrust-surface orientation is significant. This change may be due to the geometric relation of the thrust sheet to the underlying upper limb of an overturned syncline, mapped by Sorensen and Crittenden (1972) and Crittenden and Sorensen (1985b), which is first exposed in North Ogden Canyon. Because the trace of the Willard thrust is approximately northwest-southeast, and movement of the Willard thrust plate is assumed to have been to the east, it follows that folds forming in the footwall should have axes that are perpendicular to the direction of hangingwall movement. If the overturned syncline below the Willard thrust has formed in this manner, and both the upper and lower limbs of the fold are exposed, then according to this reasoning, footwall bedding should dip in either of two distinct directions that will depend on the exposed stratigraphic thickness of the footwall, the tightness of the fold, and the position of the thrust surface relative to the lateral ramp (Fig. 14). As well as could be determined by this author footwall bedding orientations measured in this area were from the upright (lower) limb of the syncline. Footwall bedding that is part of the upright limb of the syncline should dip to the northeast (i.e., the same as bedding at the Willard Canyon and Willard Mountain field areas). Footwall bedding that is part of the overturned limb of the syncline

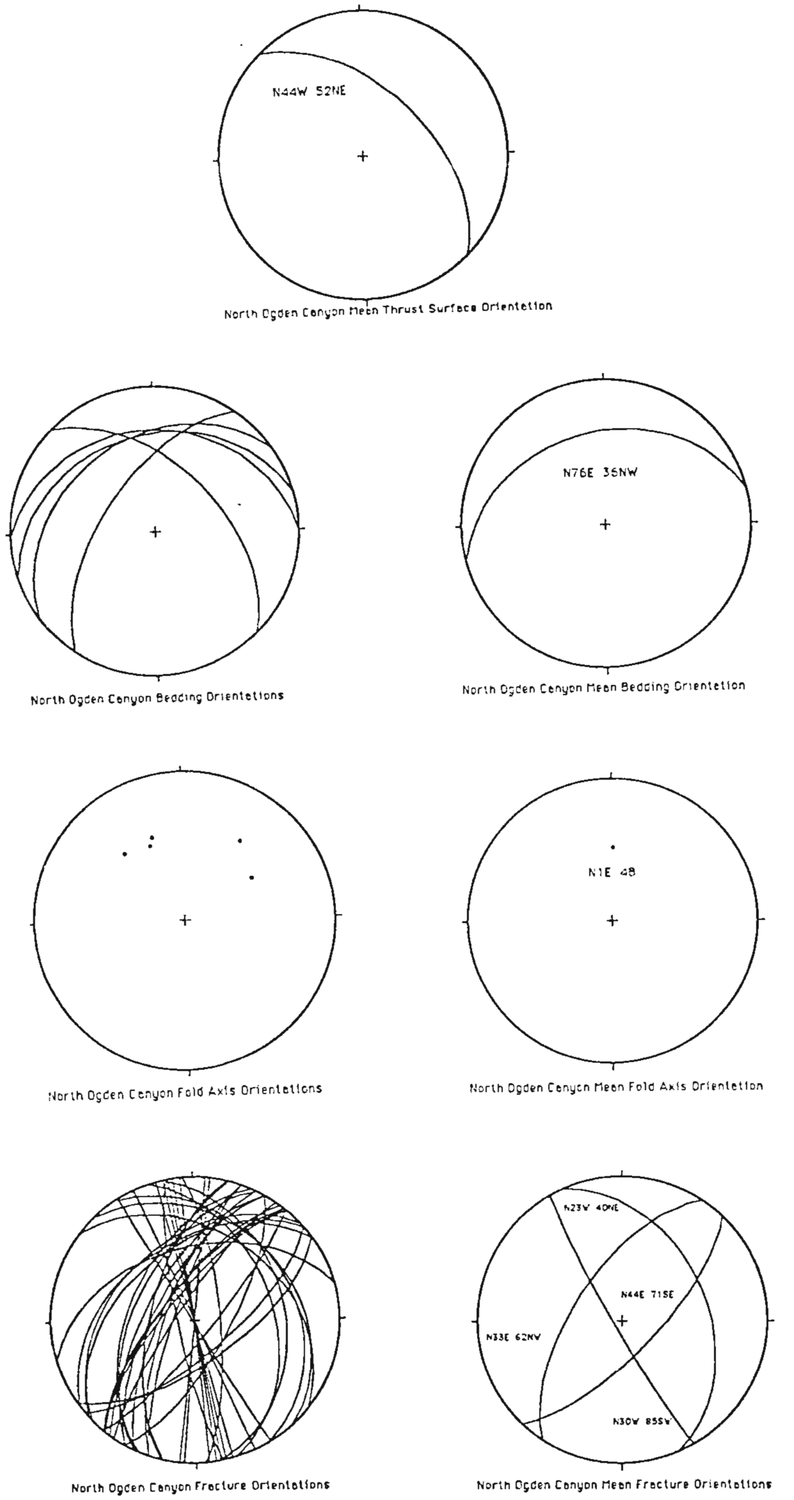
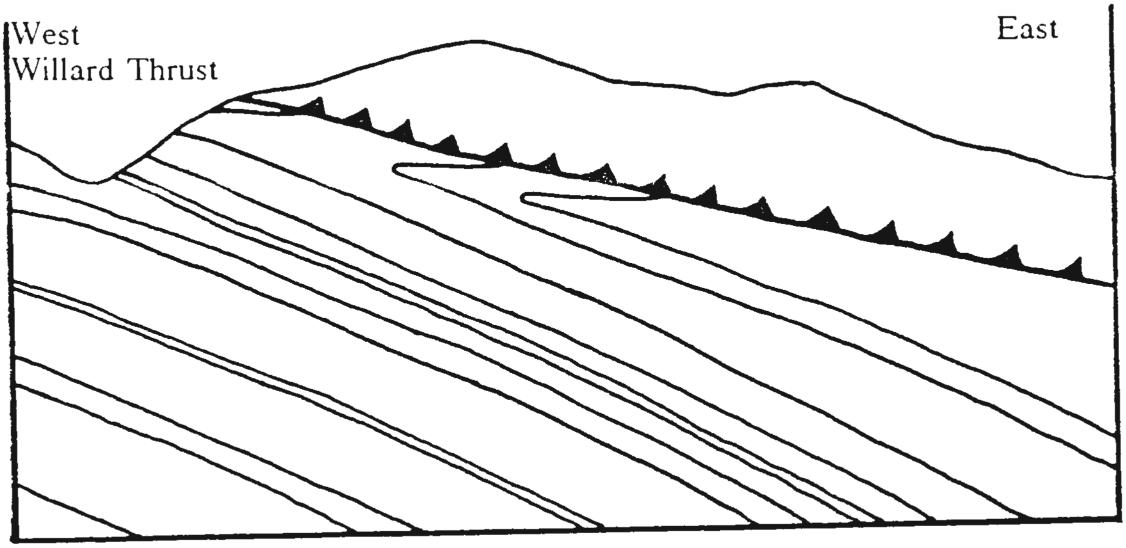
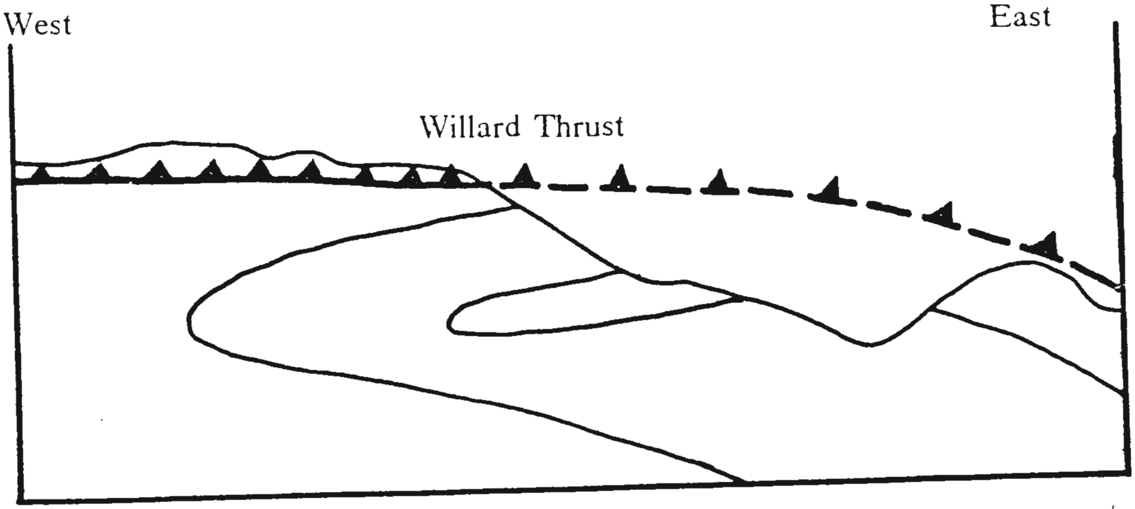


Fig. 13 Stereonet plots of orientations of deformation structures at the North Ogden Canyon field area. See Appendix B for the number of data points used. Plotted data was visually grouped and means were calculated and plotted from resulting groups



(a)



(b)

Fig. 14 Schematic cross sections modified from (a) Crittenden and Sorensen (1985b) and (b) Hansen (1980) showing the overturned to the east recumbent syncline near the Goodale Creek Canyon field area. Cross section scales are 1:24,000 and 1:17,500 respectively and oriented approximately west-east.

may dip to the southwest or northeast. However, footwall bedding directly below the thrust in the North Ogden Canyon field area does not dip southwest, but strikes N64E and dips 40 degrees to the northwest. This orientation indicates that some other deformation event, prior to movement of the Willard thrust, has influenced the orientation of footwall bedding. Several possibilities exist which may explain this situation: 1) the overturned-to-the-east syncline may be a conical fold which opens eastward and southward, 2) upright and overturned limb geometries of the syncline may not be as geometrically straightforward as a simple conical fold which opens in two directions, and 3) variations in lithology and stratigraphy may be influencing footwall-bedding geometry. However, this study proposes that the thrusts structurally below the Willard thrust (i.e., Taylor and Ogden thrusts) are older than the Willard thrust, and their sequence of eastward displacement and emplacement history may have influenced by pre-existing variations, discontinuities, or rifts (faults) in subsurface basement rocks. Reasons for this model will be given in the "DISCUSSION" and "IMPLICATIONS" sections. This change in the orientation of footwall bedding coincides with the location of the lateral ramp in the footwall, and where microscopic and macroscopic footwall deformation mechanisms begin to change southward from plastic to cataclastic, in the Ophir Formation and Maxfield Limestone as the thrust surface begins to cut upsection southward.

Orientations of the fracture overprint in the footwall, like those at Willard Mountain, are separated into four groups (Fig. 13). The mean orientation of the first group is N33E with a dip of 62 degrees to the northwest. The mean orientation of the second group is N30W with a dip of 85 degrees to the southwest. The mean orientation of the third group is N23W with a dip of 40 degrees to the northeast. The mean orientation of the fourth group is N44E with a dip of 71 degrees to the southeast. Solution cleavage is less distinct, but parallel to bedding in this field area.

Folding in the North Ogden Canyon field area consists of scattered smaller scale folds and some kink bands. The primary deformation mechanism in the North Ogden Canyon field area is folding, with some compressional fracturing appearing in the footwall.

Cold Water Canyon

Data collected from deformation structures in the Cold Water Canyon field area consists of bedding orientations only (see Appendix B) from the Maxfield Limestone, the Calls Fort Shale Member of the Bloomington Formation, and the Nounan Dolomite. Outcrop rock types in this field area consist of limestone, dolostone, and shale. Deformation structures within this field area include an extensional fracture overprint, compressional fracturing, and an overturned, east-vergent syncline (Sorensen and Crittenden, 1972) whose fold axis trends approximately parallel to the strike of the Willard thrust surface. Superimposed on this deformation and the Willard thrust sheet is another set of folds. This younger set of folds is located in the Cold Water Canyon area of Sorensen and Crittenden's (1972) map. Folding has involved footwall rock, the thrust surface, and the hangingwall of the Willard thrust. Bedding orientations were collected in this area only to determine the orientations of these younger fold axes. Results of mapping and stereonet analysis indicate the presence of 3 large conical folds in this field area (Fig. 15). The axis of the first fold trends N41W, plunges 78 degrees, and is located between North Ogden Canyon and Cold Water Canyon. The axis of the second fold trends N9E, plunges 86 degrees, and is located in Cold Water Canyon. The axis of the third fold trends N44E, plunges 81 degrees, and is located between Cold Water Canyon and One Horse Canyon. Sorensen and Crittenden (1972) mapped an overturned recumbent syncline in the stratigraphic formations below the Willard thrust, between Chicken Creek (in North Ogden Canyon) and Pineview Reservoir. The axial trace of the overturned syncline in their geologic map has been folded, as well as the surface of the Willard thrust fault. This field area (between North Ogden Canyon and One Horse Canyon; approximately 2-3 kilometers to the south) contains a folded (Cold Water Canyon data), overturned, east-vergent recumbent syncline, which may have formed during the eastward propagation of the structurally lower Taylor and Ogden thrust sheets, or contemporaneously as the Willard thrust moved over the structurally lower Taylor and Ogden thrusts.

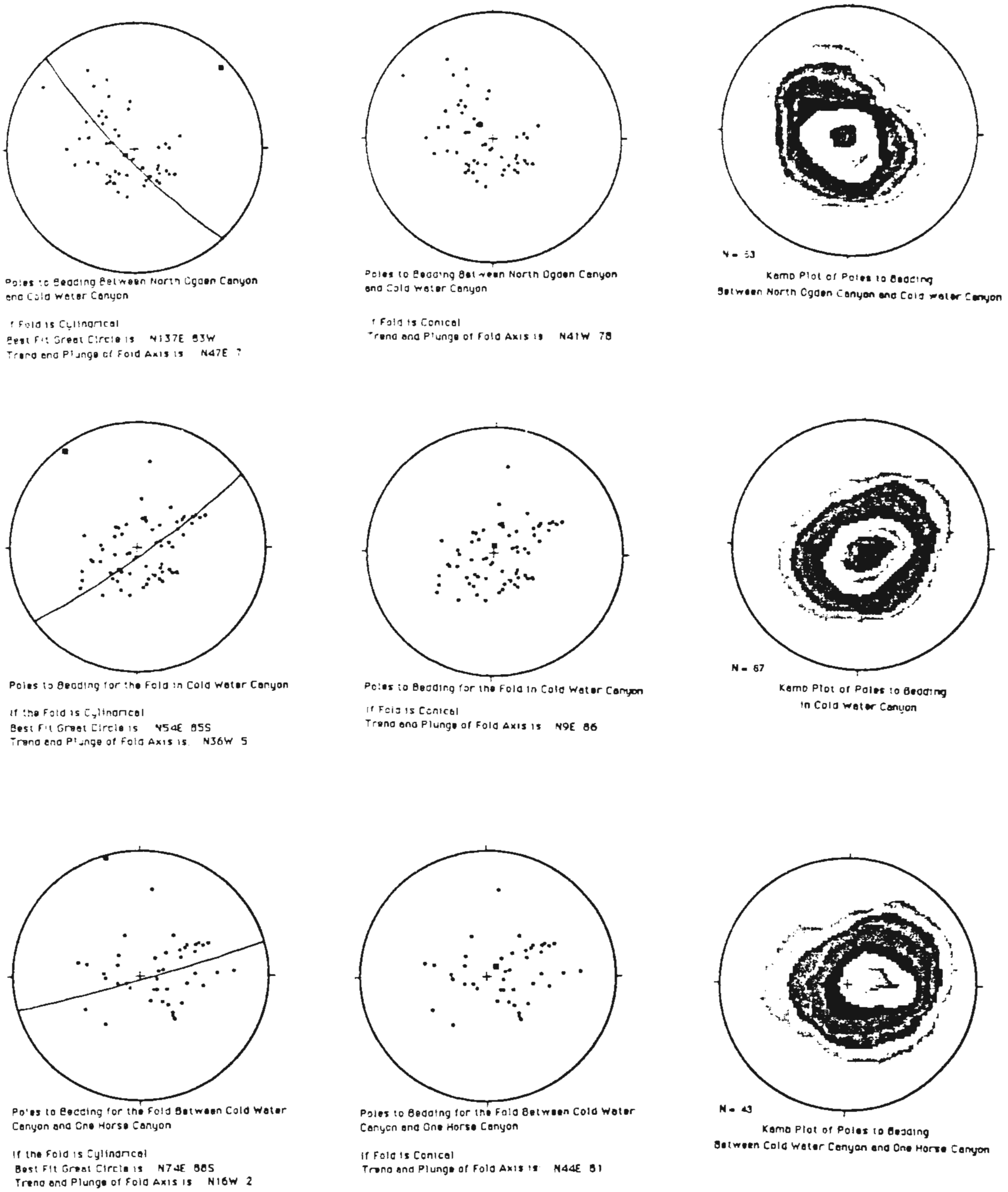


Fig. 15 Stereonet plots of orientations of poles to bedding at the Cold Water Canyon field area.

Goodale Creek Canyon

Data collected from deformation structures in the Goodale Creek Canyon field area include orientations of fractures, folds, and footwall bedding (see Appendix A). Rock samples for thin-section analysis of structural fabrics were also collected. Stereonet plots of orientations of deformation structures are shown in Figure 16.

Deformation structures at the Goodale Creek Canyon field area consists of fracturing in the Garden City Formation, the Fish Haven Dolomite, the Water Canyon Formation, the Hyrum Dolomite, the Beirdneau Sandstone, the Lodgepole Limestone, the Deseret Limestone, and the Humbug Formation. Differentiating between post-Willard thrust cataclastic footwall overprinting and footwall cataclasis due to movement of the Willard thrust was difficult and not attempted in this area. The surface of the Willard thrust fault in this field area is oriented N56W with a dip of 51 degrees to the northeast. The mean bedding orientation in the field area is N62E with a dip of 33 degrees to the northwest. This orientation is similar to the orientation of footwall bedding at the North Ogden Canyon field area. The reason for this may be due to the large overturned syncline in the footwall, which caused footwall bedding geometry to change, but may be a result of rifts or faults in subsurface basement rocks that influenced the development of the Taylor and Ogden thrusts which then influenced the Willard thrust.

Fracture orientations in this field area fall into two groups. The mean orientation of the first group is N45W with a dip of 81 degrees to the southwest.

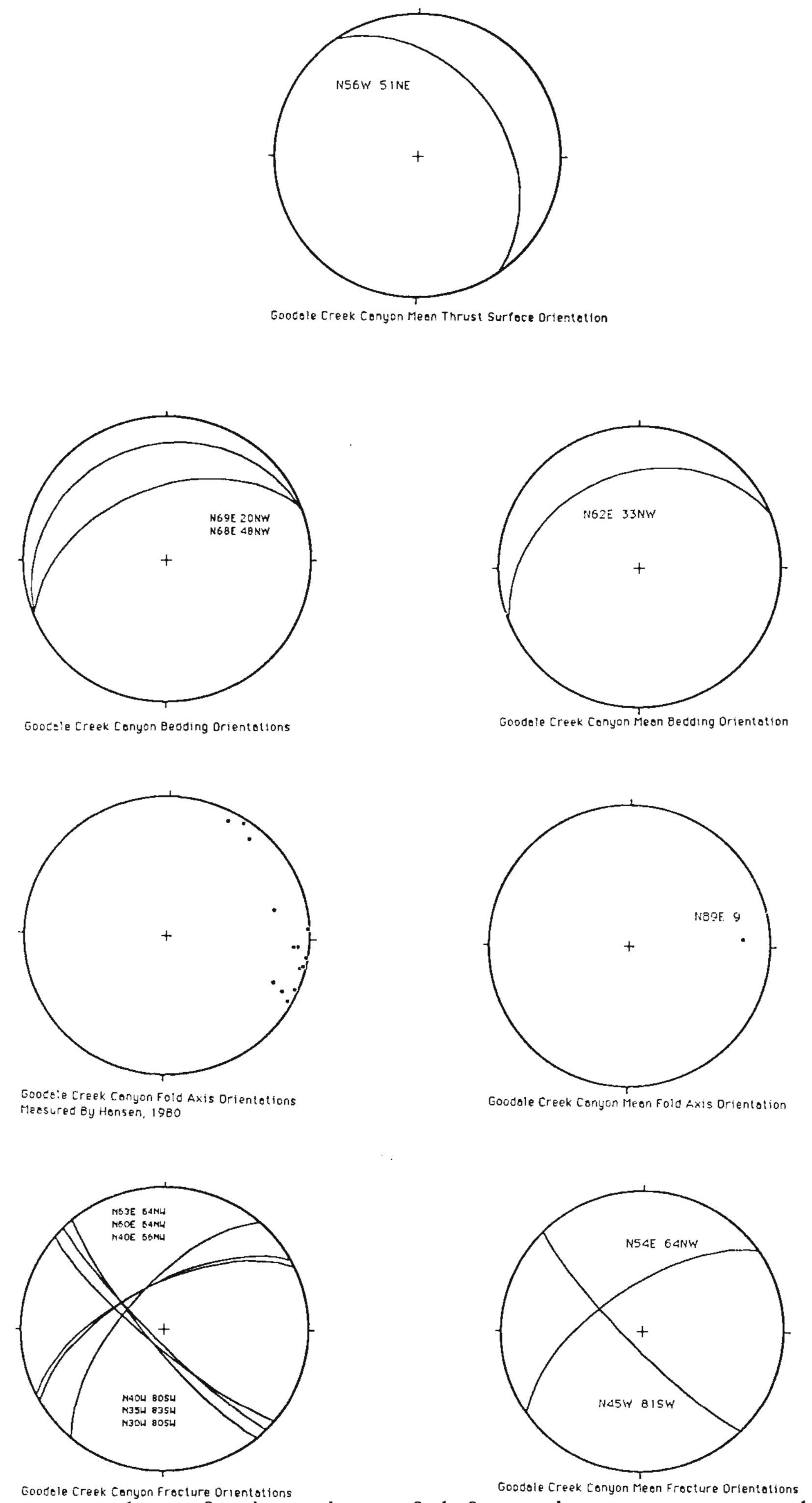


Fig. 16 Stereonet plots of orientations of deformation structures at the Goodale Creek Canyon field area. See Appendix B for the number of data points used. Plotted data was visually grouped and means were calculated and plotted from the resulting groups.

The mean orientation of the second group is N54E with a dip of 64 degrees to the northwest. These two groups of fracture orientations are similar to two of the four groups of orientations from the North Ogden Canyon field area. The mechanism for footwall fracturing in this field area is caused by changing pressure and temperature conditions brought about by upward lateral ramping southward in the footwall, as well as later extensional overprinting. Smaller scale folds such as those in Willard Canyon and at Willard Mountain were not seen in this field area, but Hansen (1980) did map some small-scale folds. The mean orientation of Hansen's fold axis trends North 89 East and plunges 9 degrees. The overturned syncline in the footwall is still present in this field area (Sorensen and Crittenden, 1972).

Pineview Reservoir

Data collected from deformation structures at the Pineview Reservoir field area include only bedding orientations (see Appendix B). Rock samples for thin-section analysis of structural fabrics were also collected. Outcrops in this field area are very fractured so fracture orientations were not measured. Figure 17 contains stereonet plots of bedding orientations for the Pineview Reservoir field area.

The orientation of the thrust surface is N24W with a dip of 51 degrees to the northeast. The mean bedding orientation in the footwall is N34W with a dip of 39 degrees to the northeast. In the three field areas where footwall bedding and thrust-surface orientation are approximately the same (i.e., Willard Canyon, Willard Mountain, and Pineview Reservoir) footwall bedding is the "flat" either

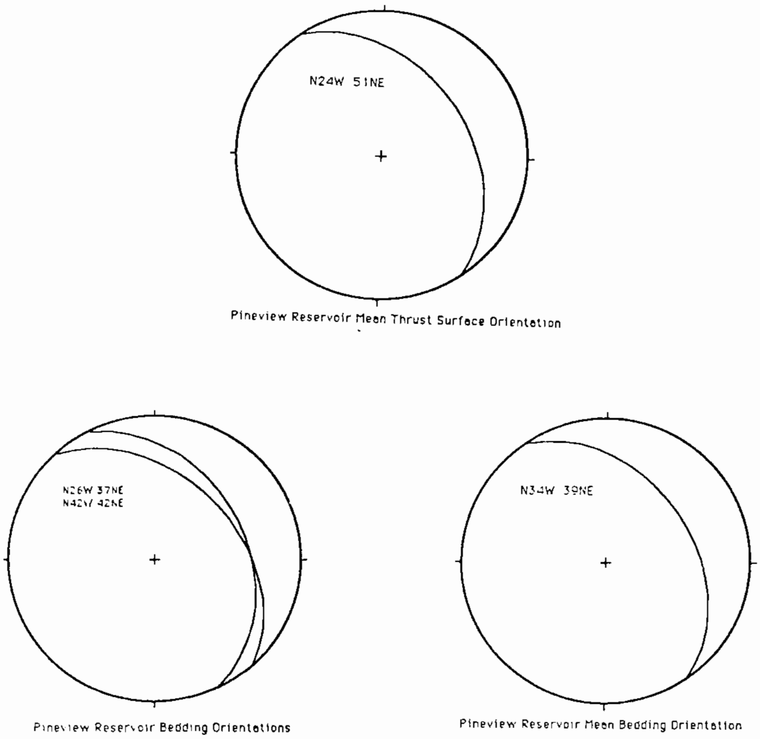


Fig. 17 Stereonet plots of orientations of deformation structures at the Pineview Reservoir field area. See Appendix B for the number of data points used. Plotted data was visually grouped and means were calculated and plotted from resulting groups.

below or above the ramp lateral ramp. In the two field areas where footwall bedding and thrust-surface orientation are not the same (i.e., North Ogden Canyon and Goodale Creek Canyon) the change in footwall-bedding orientation represents the "ramp" of the lateral ramp. It is not possible to distinguish between compressional fracturing and extensional fracturing in this field area and throughout the other field areas. However, fracturing caused by movement of the Willard thrust probably dominates in this field area because fracturing is only present close to the thrust surface.

Malans Peak

Field data from Malans Peak consist of bedding orientations collected around the limb of a large, basement-cored monoclinal fold in the Tintic Quartzite and Ophir Formation (see Appendix B). Figure 18 contains stereonet plots of Tintic Quartzite bedding orientations.

At Malans Peak, bedding of the Tintic Quartzite forms a large monocline that has been faulted downward to the north into Taylor Canyon. Numerous smaller folds are present within bedding near the peak. The monoclinal fold begins just to the north of Malans Peak where bedding begins to dip into Taylor Canyon. A best fit great circle drawn through poles to bedding is orientated N34E and dips 82 degrees to the northwest. The pole to the great circle gives a trend of N24E and a plunge of 8 degrees if the Malans Peak fold is cylindrical. If the fold is conical the trend is N99E and the plunge is 82 degrees.

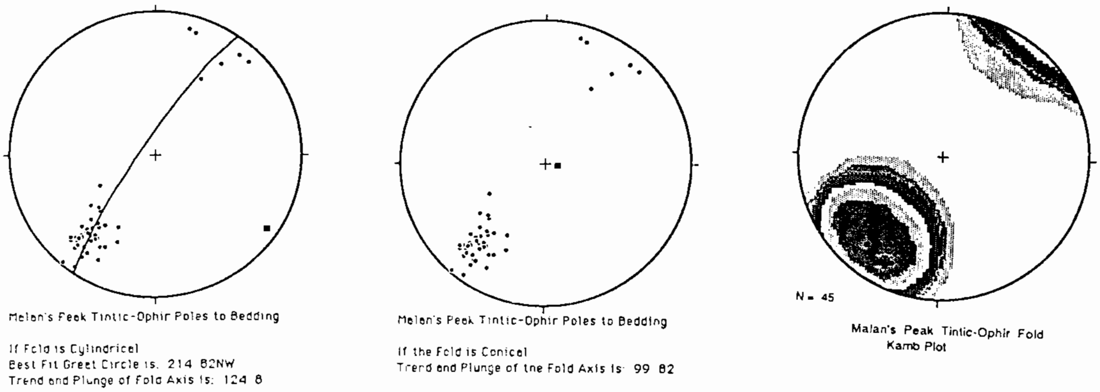


Fig. 18 Stereonet plots of orientations of poles to bedding around the limb of the basement-cored monocline at Malans Peak. Field mapping indicates the fold to be cylindrical.

Taylor Canyon

Field data collected on the south side of Taylor Canyon include orientations of fractures, solution cleavage, fold axes, and bedding (see Appendix B). Deformation structures are located in the Tintic Quartzite, the Ophir Formation, and the Maxfield Limestone. Outcrop rock types in this area include limestone, shale, and quartzite. Figure 19 contains stereonet plots of deformation orientations in Taylor Canyon. Bedding orientations fall into two groups. The mean orientation of the first group is N44W with a dip of 60 degrees to the northeast. The average orientation of the second group is S61E with a dip of 43 degrees to the south. The trend and plunge (fold axis) of the pole to the great circle that was drawn through poles to bedding is oriented North 129 East and dips 13 degrees. This orientation is similar to that of the fold axis of the Malans Peak fold. Smaller folds which were observed but not measured have axes which trend and plunge to the east. Deformation on the south side of Taylor Canyon is a result of localized stress in the limestones and shales above the Tintic Quartzite, caused by adjustments in the units to folding.

"S"-Fold

Field data from the "S" fold consist of orientations of lineation and bedding structures orientations from the lower, middle, and upper limbs of the fold (see Appendix B). The "S" fold is located in the Maxfield Limestone in the upper portion of the first ravine south of the mouth of Ogden Canyon. Outcrop rock types are limestone and shale. Figure 20 contains stereonet plots of

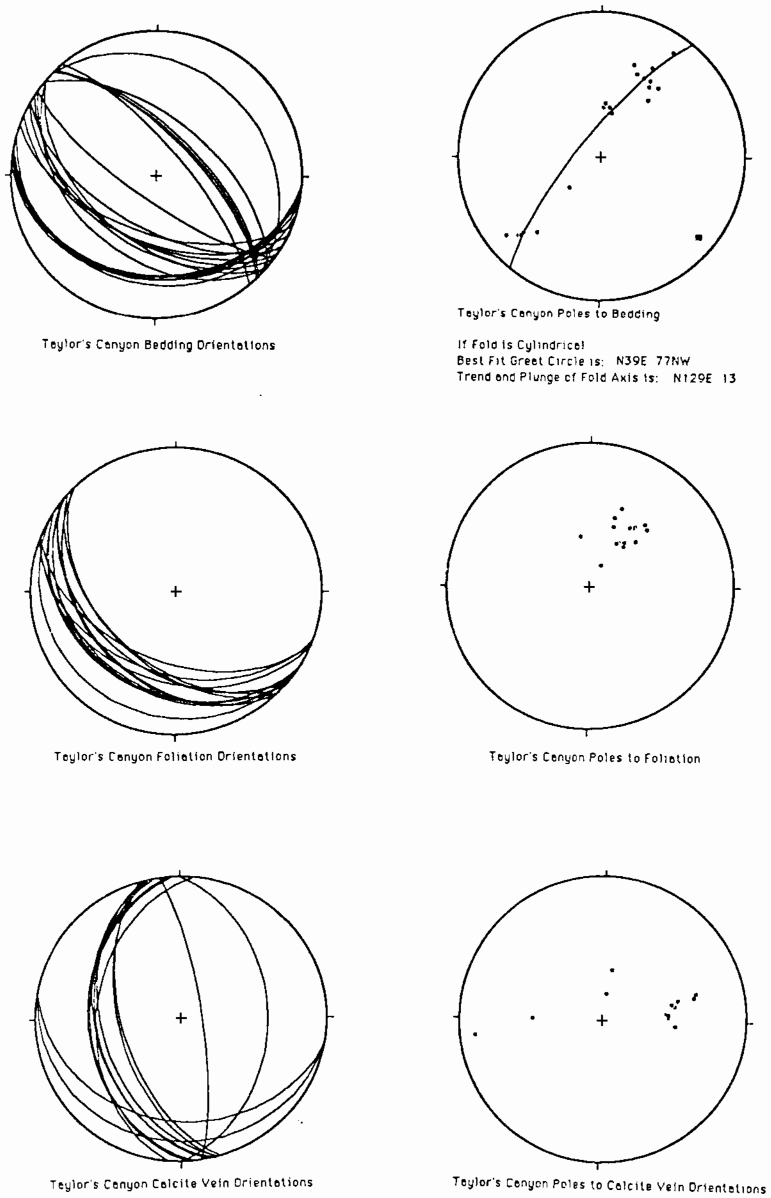


Fig. 19 Stereonet plots of orientations of deformation structures at the Taylor Canyon field area. See Appendix B for the number of data points used.

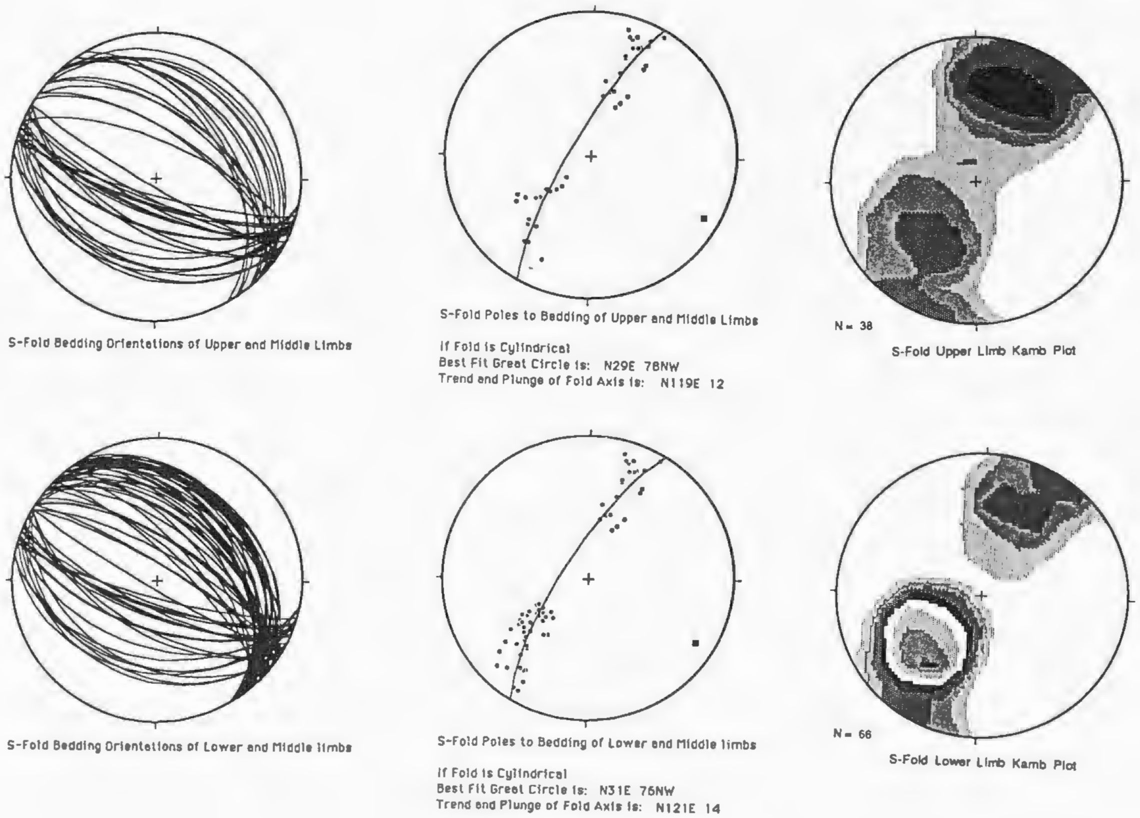


Fig. 20 Stereonet plots of orientations of bedding for the upper, middle, and lower limbs of the "S" Fold. See Appendix B for the number of data point used.

orientations of the upper, middle, and lower limbs of the "S" fold. A best-fit great circle through poles to bedding for the lower and middle limbs is orientated N31E and dips 76 degrees to the northwest. The pole to this great circle defines a fold axis that trends N121E with a plunge of 14 degrees. A best fit great circle through poles to bedding for the upper and middle limbs is oriented N29E and dips 78 degrees to the northwest. The pole to this great circle defines a fold axis that trends N119E with a plunge of 12 degrees. The "S" fold south of Ogden Canyon formed when limestones and shales above the Tintic Quartzite were locally strained as the Tintic Quartzite folded downward and northward into Ogden Canyon.

Perry's Camp

Data collected from deformation structures at Perry's Camp include orientations of folds, solution cleavage, and bedding (see Appendix B). The outcrops are located on the north side of the canyon, just east of Perry's Camp, approximately 1 to 2 kilometers up Ogden Canyon. Deformation is located in the Ophir Formation and Maxfield Limestone. Outcrop rock types include shales and limestones. Figure 21 contains great circle stereonet plots of deformation data at Perry's Camp.

The mean bedding orientation is N37W with a dip of 50 degrees to the east. Fold-limb orientations from Perry's Camp fall into two groups. The mean fold-limb orientation of the first group trends S31E with a plunge of 8 degrees. The mean orientation of the second group trends N22W with a plunge of 18 degrees. The trend and plunge (fold axis) of the pole to the great circle of poles to fold limb orientations is N118W and 28 degrees. Deformation in this area is a result of localized strain, due to movement of overriding thrust sheets, within the incompetent Ophir Formation and Maxfield Limestone.

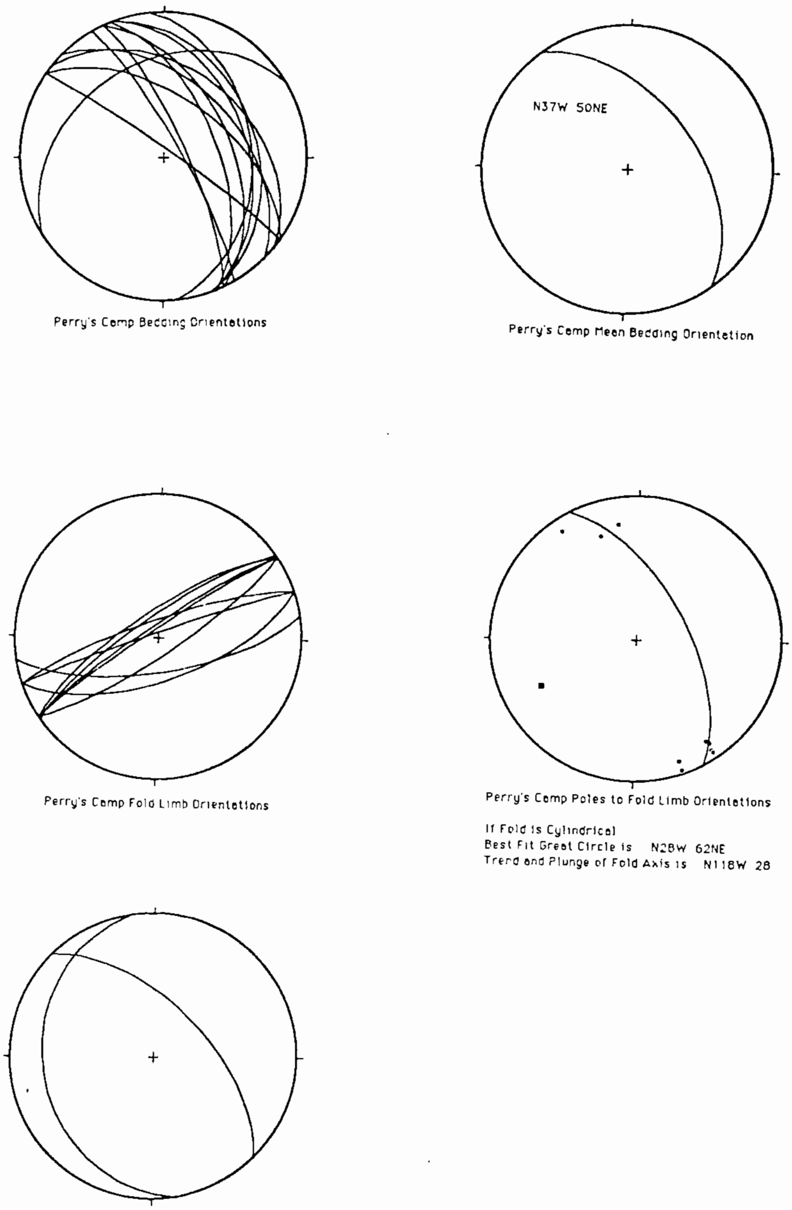
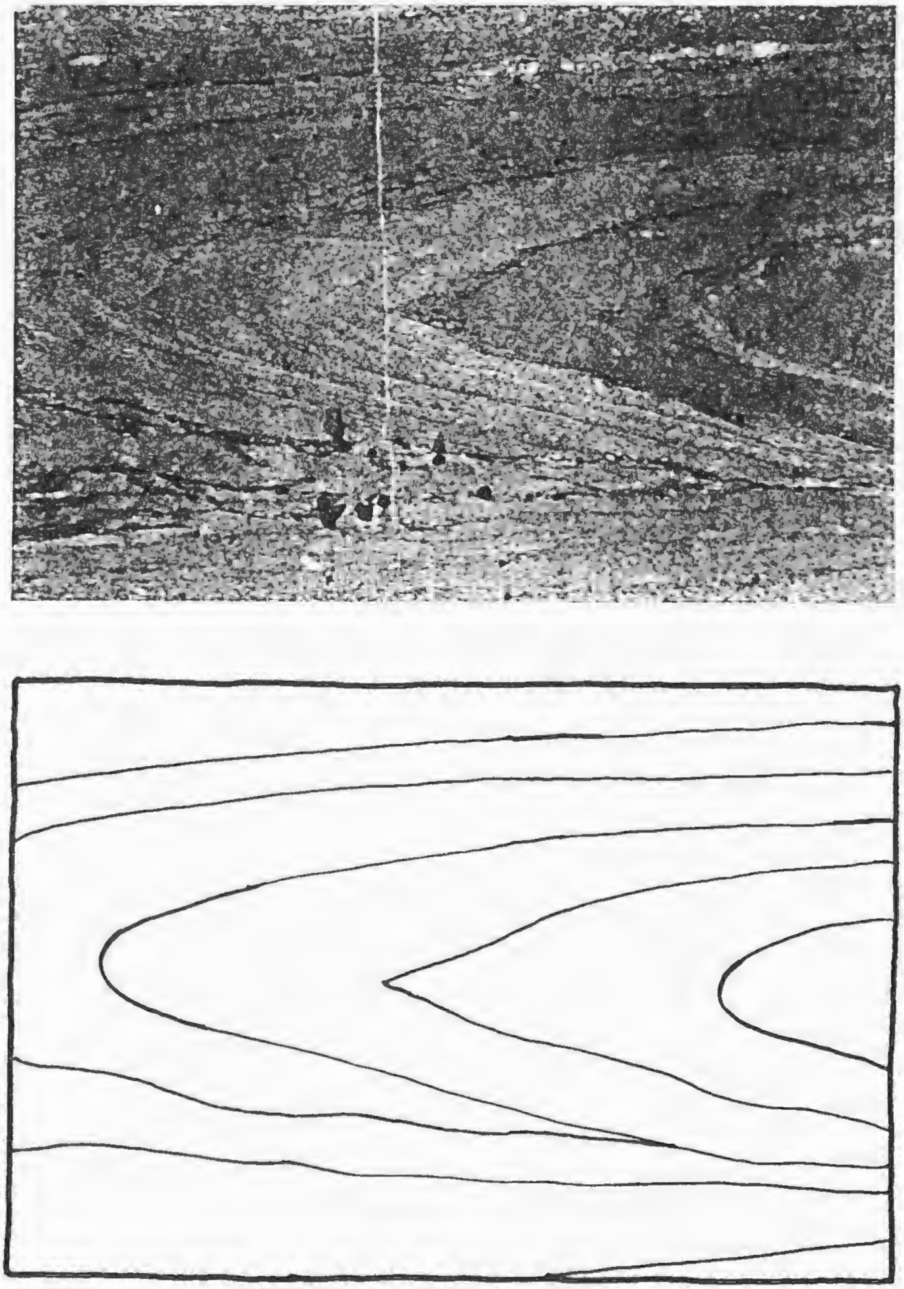


Fig. 21 Stereonet plots of orientations of deformation structures at the Perry's Camp field area. See Appendix B for the number of data points used. The mean bedding orientation was calculated from all bedding data.

RESULTS

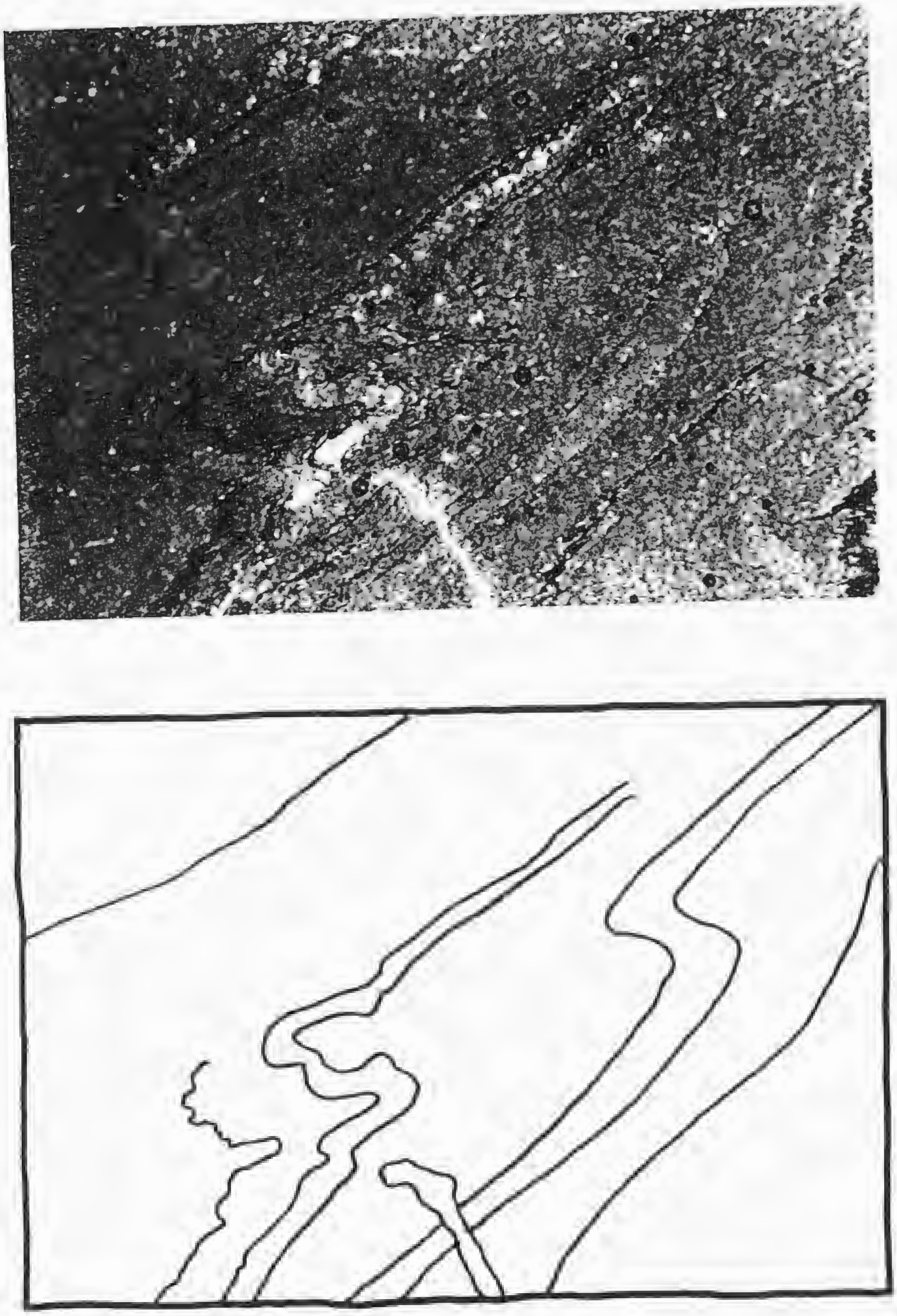
THIN SECTIONS

Thin sections are useful in structural geology for studying the texture, the mineralogy, and the structural fabrics of rocks. Nine thin sections were made from samples collected in the field areas. Preliminary examination showed that microscopic deformation textures and fabrics show up best in thin sections that are oriented west-east and cut perpendicular to bedding. Thin sections cut in this way show an apparent dip of structural fabric to the east. The "true" dip of bedding, fold limbs, and other structures which look similar to s-c shearing in Weber Canyon (Yonkee and Bruhn, 1986) is to the northeast. The most important area for thin- section analysis is between Willard Mountain and North Ogden Canyon. It is this segment in the footwall of the thrust where deformation mechanisms in the footwall change from plastic to cataclastic. Thin sections from these areas are from the Ophir Formation and Maxfield Limestone. The best examples of microscopic plastic and cataclastic deformation come from the Willard Mountain and North Ogden Canyon field areas (Figs. 22 and 23). The dominant mechanism of microscopic plastic deformation in this field area is folding of limestone accompanied by dynamic recrystallization of calcite grains, the development of solution cleavage parallel to bedding, and mineral alteration of the shale in the limestone. The original clay minerals in the shale have been altered to what appears to be sericite. To the south, in the North Ogden Canyon field area, microscopic folding structures are less pronounced in outcrop and thin section. Dynamic recrystallization of calcite, solution cleavage, and the initiation



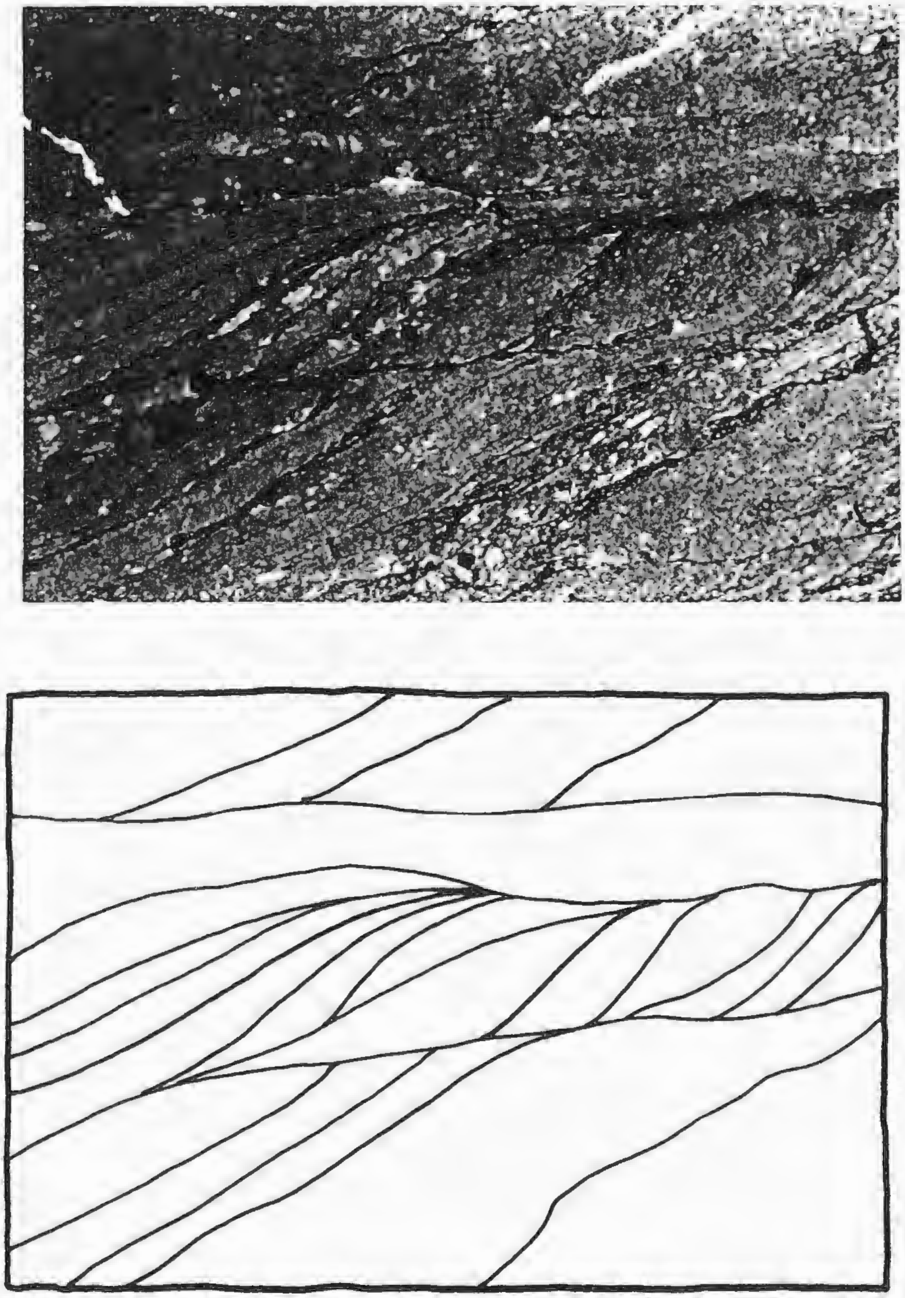
(a)

Fig. 22 Examples of microscopic footwall deformation structures (a,b,c) from the Willard Mountain field area. Thin sections are cut west-east and perpendicular to bedding. Example (a) is a folded limestone. Example (b) is a folded limestone. Example (c) contains alternating layers of limestone and shale that have been folded (diagonal lines) and sheared (horizontal lines). Examples (a), (b), and (c) are 18 millimeters wide.



(b)

Fig. 22 (Continued)



(c)

Fig. 22 (Continued)

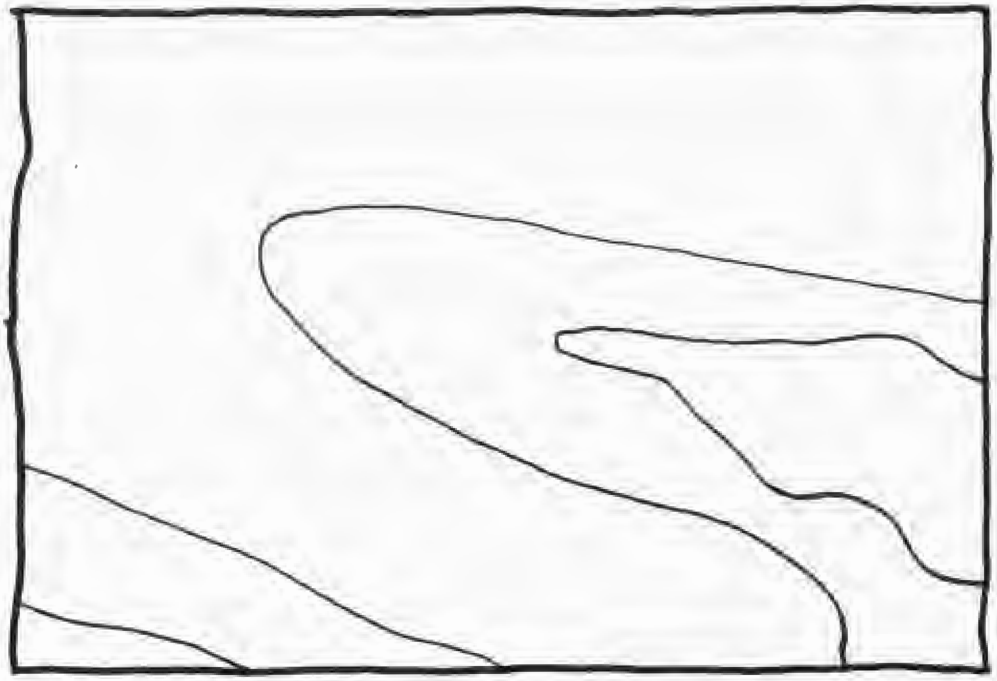
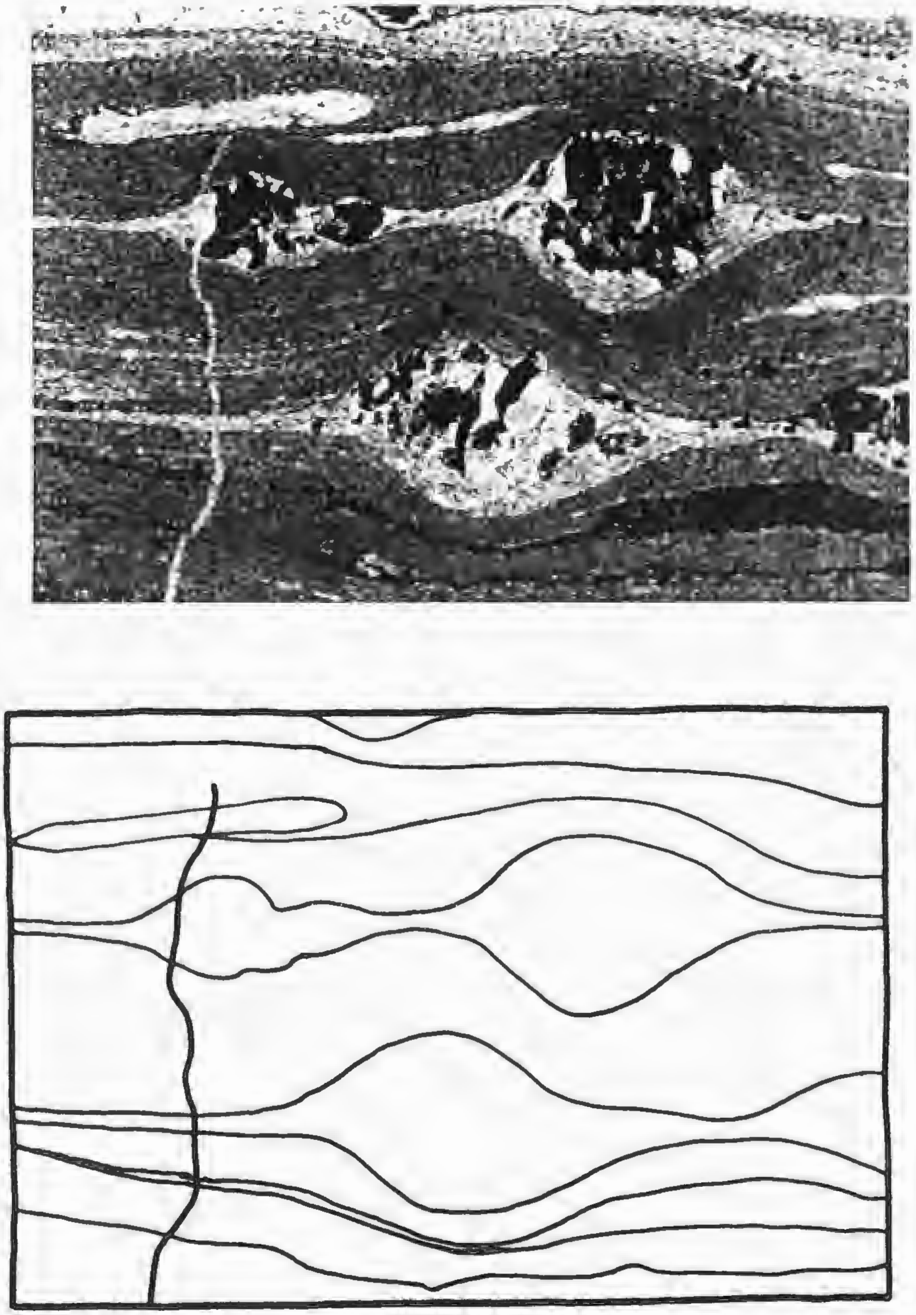
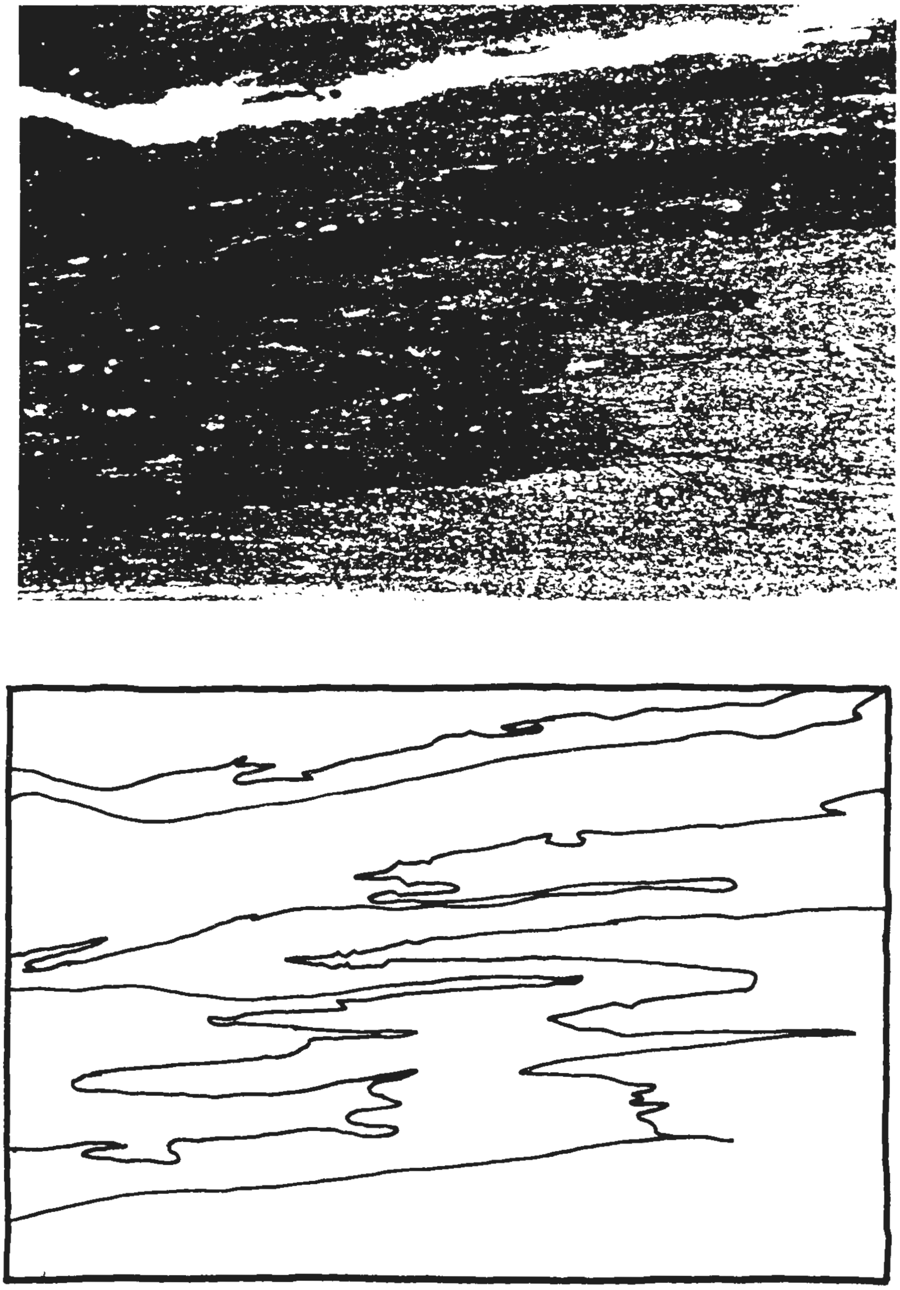


Fig. 23 Examples of microscopic footwall deformation structures (a,b,c,d,e) from the North Ogden Canyon field area. The thin sections are all limestones and cut east-west perpendicular to bedding. Example (a) shows a folded calcite vein. Example (b) shows a "plastic flow" fabric around rigid inclusions. Example (c) shows folding in the same thin section as example (b). Example (d) shows a "plastic-flow" fabric that was overprinted by fracturing. Example 9e) shows only fractured limestone. Examples (b), (d)., and (e) are 18 millimeters wide. Examples (a) and (c) are 0.45 millimeters wide.



(b)

Fig. 23 (Continued)

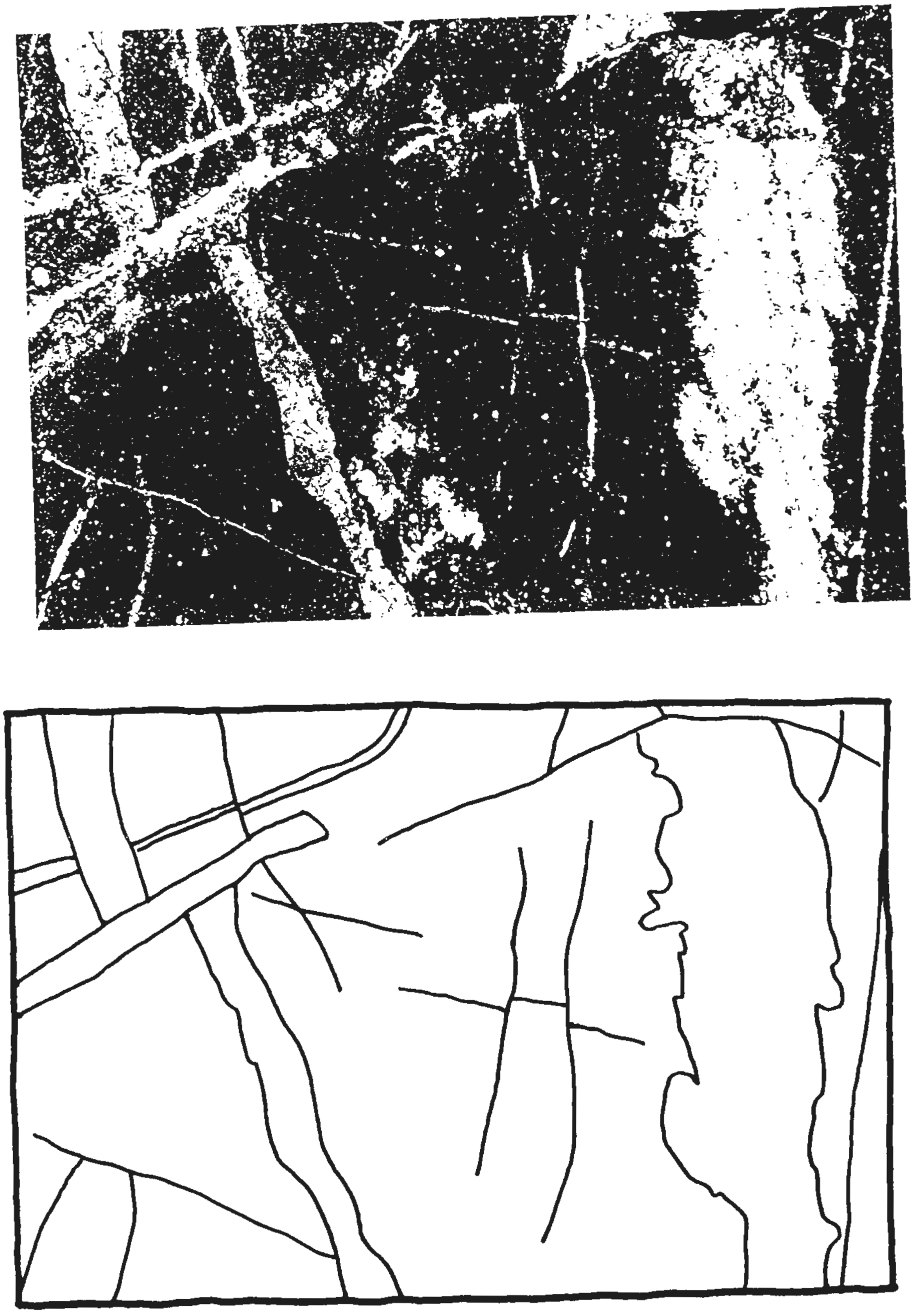


(c)

Fig. 23 (Continued)

(d)

Fig. 23 (Continued)



(e)

Fig. 23 (Continued)

of microscopic fracturing is visible. Thin sections provide confirmation that microscopic deformation as well as macroscopic (outcrop-scale) deformation changes from plastic to cataclastic between the Willard Mountain and North Ogden Canyon field areas. Thin sections from these areas reveal interesting structural and textural fabrics. Figure 22 shows several examples of plastic footwall deformation from the Willard Mountain field area. Structures that can be identified include isoclinal folding (Figs. 22a and 22b) and folding accompanied by shearing (Fig. 22c). Figure 22c show a distinctive difference in limestone and shale composition. No laboratory analysis was performed to determine a chemical or mineralogical composition of the two types of layers, but using a petrographic microscope the layers appear to differ by the percentage of limestone or shale they contain. The structural fabric in Figure 22c is the same as the structural fabric of s-c mylonites found in the Weber Canyon shear zone (Yonkee and Bruhn, 1986). Figure 23 shows examples of plastic and cataclastic deformation from the North Ogden Canyon field area. Structures that can be identified include isoclinal folding (Fig. 23a), a "plastic-flow" texture of calcite, deforming by dynamic recrystallization, flowing around rigid inclusions (23b and 23c), cataclasis overprinted on a "plastic-flow" texture (Fig. 23d), and cataclasis only (Fig. 23e). The origin of the inclusions within the plastic-flow structure is unknown, but deformation around the inclusions is plastic. The thin section with the cataclasis (Fig. 23d) also contains very small veins of calcite which have been folded (Fig. 23a). The combination of plastic deformation and cataclastic deformation at the same scale in the same thin section suggests that this field area lies in the area of transition of footwall deformation. This idea is supported by thin sections collected north of the North Ogden Canyon field area, which show only plastic deformation at the same scale, and thin sections from south of the North Ogden Canyon field area, which show only cataclastic deformation at the same scale.

STEREONETS

The projection of three-dimensional line and plane field data (i.e., fold axes and bedding) to solve geometric problems in structural geology can be graphically depicted using a two-dimensional equal-area coordinate net (Schmidt net). The resulting stereonet is useful because it preserves geometric field orientations of lines and planes without regard to the spatial orientation of the structures (Davis, 1984; Suppe, 1985). The stereonets used in this study were constructed using "STEREONET" version 3.6, an academic shareware computer plotting program for the Macintosh computer. The program was written by Richard W. Allmendinger of the Department of Geological Sciences at Cornell University.

Stereonets constructed from field data reveal several significant geometrical relationships. The most interesting and possibly the most important is the changing relationship between the orientation of footwall bedding and the orientation of the thrust surface (Figs. 9, 10, 13, 16, 17). The change may be a clue to subsurface structure(s) which influenced the geometry of the top of the footwall thereby causing deformation in the footwall as the thrust complex developed. Another geometrical relationship seen on the stereonets is the orientation of footwall fold axes relative to the orientation of the thrust surface.

Footwall fold-axis orientations suggest that movement of the hangingwall of the Willard thrust was approximately due east. Schirmer (1985c) also used the geometry of the thrust sheets to determine the direction of movement. Other stereonet relationships include post-Willard-thrust fracture patterns, which can be approximately correlated from one field area to the next, and bedding-parallel solution cleavage which may be pre-Willard deformation, syn-Willard deformation, or a combination of the two.

MAPS

Previously published geologic maps of the study area contain many structural features associated with the Willard thrust fault. Some of these features include: 1) bedding-plane thrusts, 2) imbrication of the main thrust, 3) folding of the thrust surface, 4) a large overturned syncline in the footwall of the thrust, and 5) a lateral change in stratigraphy at the top of the footwall from north to south. Bedding-plane thrusts and main-thrust imbrication are primarily between Willard Canyon and North Ogden Canyon. Folding of the Willard thrust surface and exposure of the large overturned syncline in the footwall are best displayed between North Ogden Canyon and Cold Water Canyon. The lateral change in footwall stratigraphy is most dramatic between Cold Water Canyon and Pineview Reservoir, where the thrust cut upsection from Cambrian in the north to Mississippian in the south. Possible explanations for the change in stratigraphic formation, the over-turned syncline, and the folded trace of the thrust will be discussed below.

STRATIGRAPHIC DISPLACEMENT DIAGRAM

Stratigraphic displacement diagrams (Chapman and Williams, 1984; Woodward, 1987) are used to locate graphically stratigraphic changes of thrust faults. This helps to identify frontal and lateral ramps, and to quantify shortening and stretching between the hangingwall and footwall of a thrust. The stratigraphic displacement diagram constructed for this study (Fig. 24) shows the longitudinal stratigraphic position of the Willard thrust surface relative to footwall stratigraphy along the strike of the fault surface from the Willard Canyon field area to the Pineview Reservoir field area. Very generally, the displacement diagram shows that at about North Ogden Canyon the Willard thrust surface begins to cut upsection laterally from north to south. The displacement diagram also shows a peculiar set of peaks just south of North Ogden Canyon in the area of Cold Water Canyon. The cause of these peaks is unclear but they may be a result of: 1) thrust-surface folding and subsequent differential erosion, 2) footwall remnants with little or no meaning, 3) footwall imbricates which laterally appear and disappear along the trace of the thrust surface, or 4) areas where the thrust fault actually cuts up and down in footwall stratigraphy.

HANGINGWALL SEQUENCE DIAGRAMS

Hangingwall sequence diagrams are two-dimensional longitudinal cross sections showing, through time, the initiation, progressive footwall deformation, and sequential development of a series of related thrust sheets. Constructed

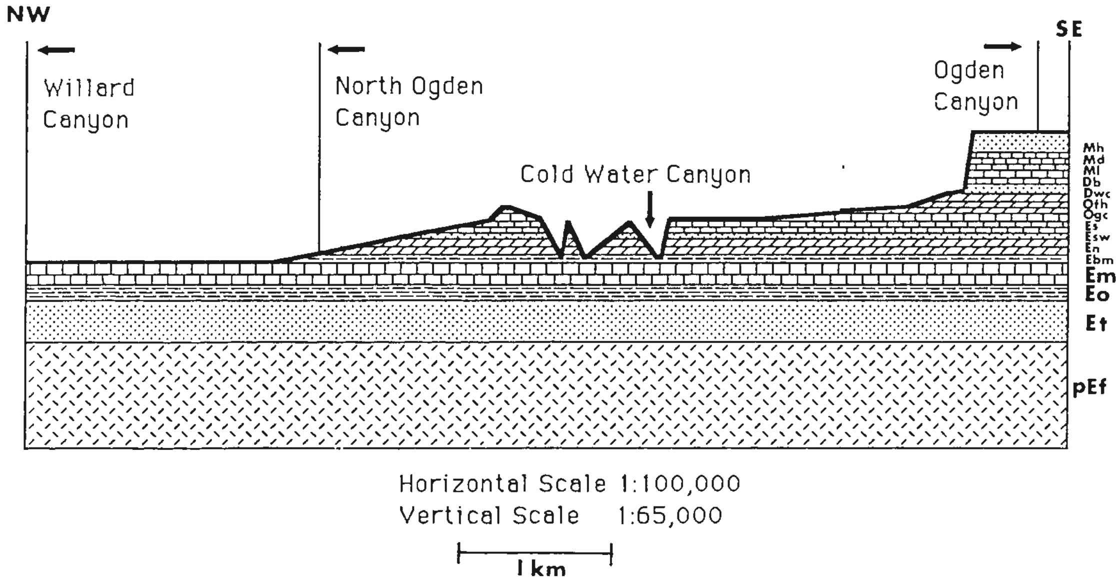


Fig. 24 Stratigraphic Displacement Diagram showing the change in footwall geology, from north to south (left to right), along the trace of the Willard thrust fault. Stratigraphic units on this diagram correspond to the stratigraphic columns in Appendix C. The units are pEf-Farmington Canyon Complex, Et-Tintic Quartzite, Eo-Ophir Formation, Em-Maxfield Limestone, Ebm-Calls Fort Member of Bloomington Formation, En-Nounan Dolomite, Esw-Worm Creek Quartzite, Es-St. Charles Limestone, Ogc-Garden City Formation, Ofh-Fish Haven Dolomite, Dwc-Water Canyon Formation, Db-Beirdneau Sandstone, Ml-Lodgepole Limestone, Md-Deseret Limestone, Mh-Humbug Formation.

diagrams are subjective in nature, model-dependent, and based on available maps and collected field data. The hangingwall-sequence diagrams constructed for this study (Fig. 25) show a simplified development of the Willard thrust complex. The diagram is oriented northwest-southeast (because the trace of the fault is approximately northwest-southeast) and uses the Tintic Quartzite formation as a marker horizon. The diagram shows the Taylor Canyon thrust developing first, followed by the Ogden thrust and then the Willard thrusts (possibly a "roof" thrust). The significance of the diagram is that unlike previous studies in this area (Eardley, 1944; Bell, 1952; Bruhn and Beck, 1981; Schirmer, 1985c) the idea being proposed here is that the Taylor and Ogden thrusts are older than the Willard thrust. The idea for the proposed sequential development is based on the geometry of thrust plates near the four major canyons in the area (only three of which are shown on the diagram), the possible existence (?) of north-south and east-west rifts in subsurface basement rock (not shown in Fig. 25), the North to South change in footwall deformation mechanism and structure, and the presence of a lateral ramp in the footwall of the Willard thrust. It is proposed that pre-existing discontinuities and rifts in subsurface basement rocks influenced where and how thrust faults developed and that continued displacement along these discontinuities further deformed the evolving thrust complex.

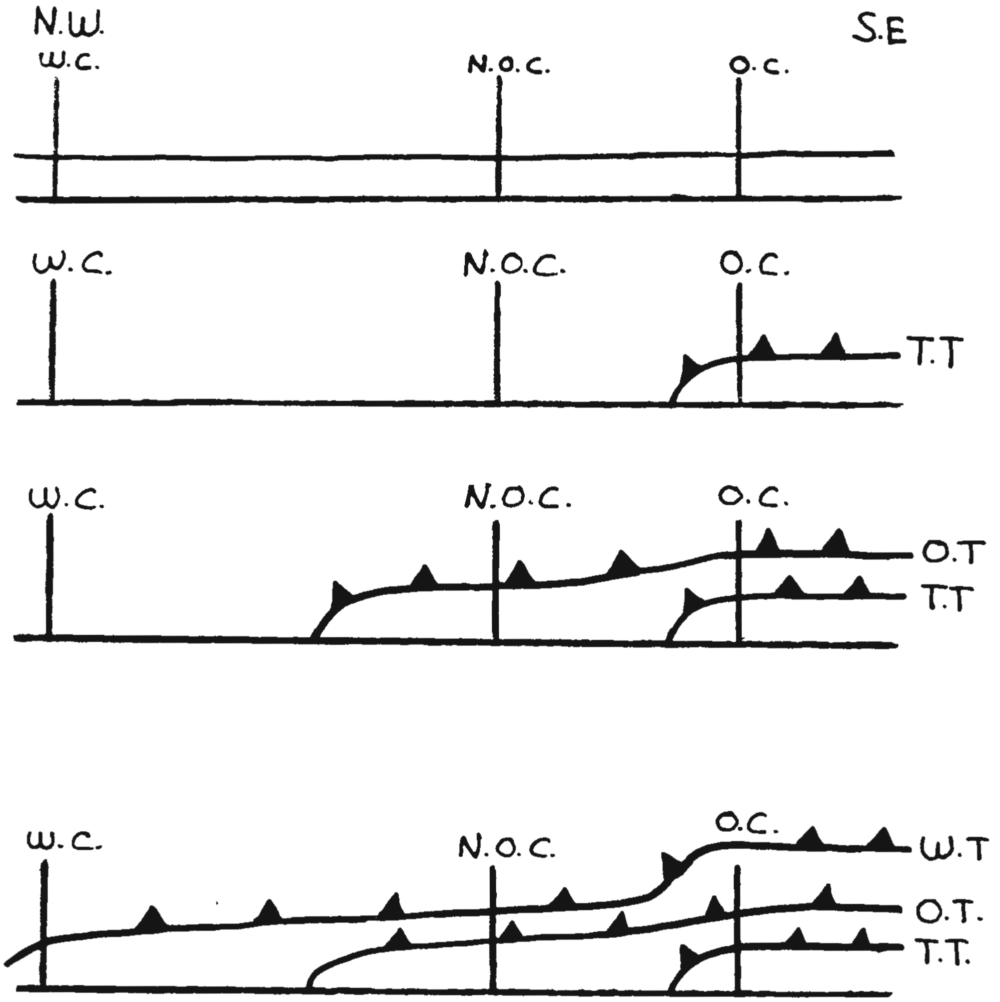


Fig. 25 Hangingwall sequence diagrams showing a simplified longitudinal development (NW-SE) of the Willard "thrust complex." Horizontal scale is 1:100,000. N.W.-Northwest, S.E.-Southeast, W.C.-Willard Canyon, N.O.C.-North Ogden Canyon, O.C.-Ogden Canyon, T.T.-Taylor Thrust, O.T.-Ogden Thrust, W.T.-Willard Thrust.

DISCUSSION

INTERPRETATION OF FOOTWALL DEFORMATION

Analysis of footwall deformation and thrust-complex geometry below the Willard thrust fault provides additional insights into the relationship between hangingwall movement and resulting footwall strain and pre-existing footwall geometry and resulting hangingwall geometry.

The direction of tectonic transport of the Willard thrust sheet over its footwall might be determined by assuming that fold axes (of folds formed in the footwall) form perpendicular to the direction of transport. The direction of tectonic transport is approximated by adding 90 degrees to the trend of the mean fold axis orientation at field areas where folding has occurred in the footwall. Corrections are based on the assumption that thrusting was generally from west to east, which is confirmed by regional data, and the "Z" fold (Crittenden, 1972; Pavlis and Bruhn, 1988) at the head of Ogden Canyon. The mean fold-axis orientation in the footwall of the Willard Canyon field area trends N5W with 21 degrees of plunge, this implies a tectonic transport direction of N85E or almost due east for the Willard thrust sheet in this area. The mean fold axis orientation in the footwall at the Willard Mountain field area trends N2W with 21 degrees of plunge, this implies a tectonic transport direction of N88E. An isolated stress field, whose origin may due to intraformational lithological variation and imbricate bedding-plane thrusts in the detachment zone below the Willard thrust, is present in this area and has a mean fold-axis orientation of N98E with 31 degrees of plunge. The mean fold-axis orientation in the North Ogden Canyon field area is N1E with 48 degrees of plunge which gives a tectonic transport direction of N91E. Although no folds were discovered in the Goodale Creek Canyon field area during this study, Hansen (1980) measured 15 small isoclinal folds near this field area. The mean fold-axis orientation for Hansen's data is N25W which suggests a tectonic transport direction of N65E for the Willard thrust sheet. No folds were observed at the Pineview Reservoir field area, but the strike of footwall bedding, which closely approximates thrust surface orientation, is oriented N34W 39NE. This indicate a general tectonic transport direction of N56E. All field data collected in this study indicates a direction of movement of west to east for the Willard thrust sheet. Other evidence for eastward movement includes an overturned to the east, recumbent syncline (Sorensen and Crittenden, 1972), which lies below the Willard thrust fault between the North Ogden Canyon and Pineview Reservoir field areas, and the "Z" fold exhibiting eastward drag at the head of Ogden Canyon. Studies by Hammond (1971), Hammond and Parry (1972), Sadeghi (1972), Hansen (1980), Beck (1982), and Schirmer (1985c) also concluded that tectonic movement was from west to east.

Footwall deformation due to movement of the Willard thrust sheet is both plastic and cataclastic. Penetrative plastic deformation at both the macroscopic and microscopic scales is present in the Willard Canyon, Willard Mountain, North Ogden Canyon, and Goodale Creek Canyon field areas. Cataclastic deformation is present in the North Ogden Canyon, Goodale Creek Canyon, and Pineview Reservoir field areas. All six of the field areas contain an extensional fracture overprint. The extensional cataclastic overprint was caused by post-Willard thrust tectonism (i.e., Basin and Range faulting). The transition in deformation styles begins just north of the North Ogden Canyon field area (Fig. 26) and continues southward past the North Ogden Canyon field area. All footwall deformation north of this point is plastic, with folding the dominant mechanism of deformation. Solution cleavage and tectonic thinning and thickening of footwall formations are primarily present in the northern field areas (i.e., Willard Canyon, Willard Mountain, North Ogden Canyon), but exactly how strain was accommodated by pressure solution is difficult to determine. Solution cleavage in the limestones and shales however is important because they provide rough constraints on temperature and pressure conditions during deformation (e.g., for limestone pressure solution doesn't usually form at $<120°C$). From the North Ogden Canyon field area southward the abundance of plastic deformation in the footwall decreases and cataclastic deformation becomes more dominant. South of the Goodale Creek field area plastic deformation is not present in the footwall of the Willard thrust. The transition from plastic to cataclastic deformation takes place within the Ophir Formation and Maxfield Limestone where plastic strain begins to give way to cataclastic strain. The transition happened at this point because the Maxfield Limestone was able to record differing styles of deformation, due to changing pressure and temperature conditions brought about by the lateral ramp, which begins to cut upsection (southward) near the transition in footwall deformation. A possible relationship between lateral ramping, the overturned to the east syncline in the footwall, and possible influences from subsurface structures will be discussed next.

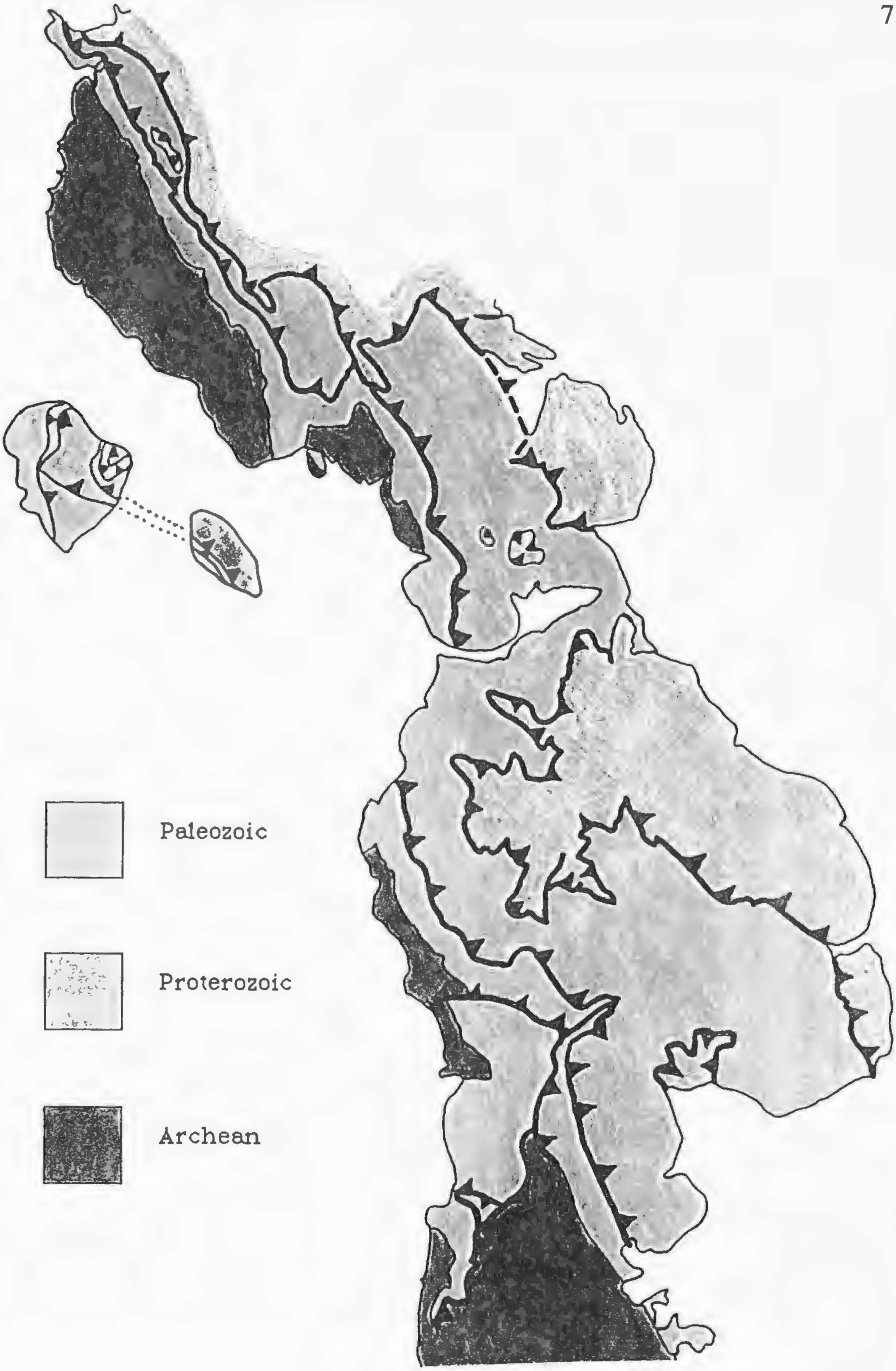


Fig. 26. Generalized geologic map showing the area (box) where footwall deformation begins to change from plastic to cataclastic. Map scale is 1:125,000.

LATERAL RAMPS

Between the North Ogden Canyon field area and the Pineview Reservoir field area the Willard thrust cuts laterally up-section from the Lower Cambrian Maxfield Limestone (in the north) to the Upper Mississippian Humbug Formation (in the south). The proposed mechanism most cited for this occurrence is the presence of a lateral ramp in the footwall of the thrust (Schirmer, 1985c; Bruhn and Beck, 1981). The overturned-to-the-east recumbent syncline, which lies below the thrust, is only exposed where the Willard thrust cuts upsection along the ramp between North Ogden Canyon and Pineview Reservoir. The fold is not exposed north of the North Ogden Canyon field area because the upper and lower limb are cut off by the thrust surface. Crittenden and Sorensen (1985b) left few written details concerning the evolution of the recumbent syncline which he mapped below the Willard thrust (Fig. 14). Hansen (1980) described the axis of the overturned syncline in Goodale Creek Canyon as trending north-northwest with most of the overturned limb truncated by the Willard thrust. He also noted that bedding in the upright (lower) limb of the syncline is dips east, whereas bedding in the overturned (upper) limb dips west. Schirmer (1985c) also described the change in geometry of the syncline between North Ogden Canyon and Ogden Canyon. He described the fold as changing from overturned isoclinal in the north to tight in the south where the syncline opens as the thrust cuts upsection. Possibilities for the origin of the fold are: 1) Paleozoic strata were uplifted, overturned, and folded as movement on the Willard thrust fault initiated, 2) Paleozoic strata were overturned and folded as a result of drag underneath the Willard thrust sheet as it moved eastward (a footwall fault-propagation fold), or 3) some combination of 1 and 2.

Another possibility, for which no evidence exists, is that a pre-Willard-thrust tectonic event folded the strata. Previous workers (Bruhn and Beck, 1981; Schirmer, 1985c) have concluded the Taylor and Ogden thrusts are younger than the Willard thrust. The presence of the recumbent syncline poses several problems. Did the syncline form prior to movement on the Willard thrust or did it form contemporaneously with the Willard thrust? Could its presence be the result of structural highs in the subsurface? If the shape of the recumbent syncline is conical (Fig. 10), that is, closed in the north (North Ogden Canyon field area) and opening to the south and east, then one possible explanation (if the fold is pre-Willard thrust) is that the Willard thrust fault is ramping upsection laterally southward because of the large fold in its footwall. The syncline also opens southward and may or may not have been influenced by a subsurface basement structure. If the fold was contemporaneous with the Willard thrust and formed as the thrust moved eastward then a pre-existing, sub-fold, basement structure may have influenced the location of formation of the recumbent syncline and thereby caused the Willard thrust fault to cut upsection southward.

The geometry of the footwall between the North Ogden Canyon field area and the Pineview Reservoir field area has been carefully described and mapped by Schirmer (1985c) as a frontal ramp that cuts upsection eastward and a lateral ramp that cuts upsection southward. The sequential development of Schirmer's Ogden duplex accounts for the fact that the Willard thrust fault cuts upsection from Cambrian to Mississippian age rocks.

The idea proposed in this study is that multiple smaller ramps or steps may be present in the footwall of the thrust complex (i.e., structurally below the Taylor thrust). Evidence for these lateral steps includes the presence of the "anomalous" east-west-trending canyons (Hunt, 1982) that cut the Willard thrust and Willard thrust complex in the study area, and the large basement-cored anticline in the Tintic Quartzite, Ophir Formation, and Maxfield Limestone south of Taylor's Canyon, which Bruhn and Beck (1981 p. 203) stated "...could be a 'step' fold caused by oblique movement across an east-trending tear fault at depth." The three anomalous canyons in question are North Ogden Canyon, Ogden Canyon, and Taylor's Canyon. As Hunt (1982) pointed out, the origin of these canyons is not well understood. Evidence for the multiple lateral steps is present in the geometry of the footwall of the Willard thrust fault and underlying thrust complex in each of these canyons. At each of the three canyons the Tintic Quartzite is a marker horizon, and changes in duplex geometry are reflected in changes in its bedding orientation. Part of the evidence for the multiple lateral steps is that bedding geometry of the Tintic Quartzite is similar at each canyon. To the south of each canyon (approximately 3 to 6 kilometers) the overall bedding orientation in the Tintic Quartzite dips eastward in the east-dipping thrust complex. Near the south side of each canyon, bedding in the Tintic Quartzite bedding begins to fold downward toward the canyon. The anticlinal fold that has developed in each of the canyons is most obvious at Malans Peak (south of Taylor Canyon), where Precambrian crystalline basement rock from the Farmington Canyon Complex is exposed in the core of the fold. The Malans Peak fold is unique because rocks from the Farmington Canyon Complex also have been uplifted on the north side of Taylor's Canyon to form an "apparent" high-angle reverse fault with "reverse" drag in the downthrown block south of the canyon. The fold on the south side of the canyon has been called a basement-cored anticline by Bruhn and Beck (1981) and Schirmer (1985c). This fold and the east-west trending reverse fault in the canyon floor may represent the reactivation of east-west rifts in the Precambrian basement followed by the initial movement of the Taylor thrust. South of Ogden Canyon bedding in the Tintic Quartzite bedding changes from east dipping to north-northeast dipping. The major difference at Ogden Canyon is that the Tintic Quartzite dips below ground level before it actually reaches the canyon. The Ogden Canyon fold is unique because it is cored by Precambrian crystalline basement rock and because above the crystalline basement rock the Tintic Quartzite is faulted. This east-west "tear" fault was first mapped by Gilbert (1890). Above the tear fault, in the Maxfield Limestone, faulting has given way to folding. This is the location of the "S" fold. The presence of the tear fault and the "S" fold are attributed here to the change in overall geometry as the east-dipping units in the footwall and in the overlying thrust complex changed to north dipping closer to Ogden Canyon. North of Ogden Canyon the Tintic Quartzite dips to the east, and is part of the thrust complex beneath the Willard thrust fault. Farther north near North Ogden Canyon the Tintic Quartzite in the footwall is folded, dips to the north, and gradually disappears into the subsurface. This fold is similar to the fold just south of Ogden Canyon because it also disappears into the subsurface before reaching the canyon. A similar structure in the Tintic Quartzite is present farther north at the northernmost exposure of the Willard thrust fault (i.e., north of

Willard Canyon). South of Willard Canyon the Tintic Quartzite is part of the east-dipping thrust complex. Where the Tintic Quartzite approaches Willard Canyon, it begins to dip to the north, and eventually disappears into the subsurface before it reaches Box Elder Canyon, east of Brigham City. This study proposes that the change in thrust complex geometry to the south of Taylor Canyon, Ogden Canyon, North Ogden Canyon, and Box Elder Canyon may be due to three or more east-west lateral steps in the lowest footwall of the thrust complex. A possible origin for these lateral steps will be discussed in the "IMPLICATIONS" section.

Other evidence that supports the presence of lateral ramps is the relative orientation of footwall bedding to thrust-surface orientation (Figs. 9, 10, 13, 15, 16, 17). At the Willard Canyon and Willard Mountain field areas both footwall bedding and thrust-surface orientation strike northwest and dip to the northeast. To the south, at the North Ogden Canyon field area, where the plastic to cataclastic transition is associated with a southward climbing lateral ramp, footwall bedding is oriented approximately northeast and dips to the northwest, whereas the orientation of the thrust surface strikes northwest and dips to the northeast. The same divergence is present in the Goodale Creek Canyon field area, where bedding strikes northeast and dips to the northwest and the Willard thrust fault strikes northwest and dips to the northeast. At the Pineview Reservoir field area, the approximate southernmost exposure of the Willard thrust, bedding is once again oriented approximately the same as the Willard thrust surface. The change in footwall-bedding orientation may be an indication not only of lateral ramping but also of possibly pre-Willard-thrust thrusting.

DEVELOPMENT OF THE WILLARD THRUST FAULT

The development of the Willard thrust complex in northern central Utah, in a very general sense, is relatively straightforward when viewed regionally. That is, west to east tectonic compression during Middle Cretaceous time forced Archean, Late Proterozoic and Paleozoic miogeosyncline sedimentary basin rock from the hinterland, onto rock of the adjoining eastern shelf, or foreland (Wheeler and Krystinik, 1988). In a more restricted sense, the development of the Willard thrust complex does not fit well with previously conceived models for the evolution of thrust faults and classic duplexes. The problems are that the Taylor, Ogden, and Willard thrust sheets dip in the direction of propagation (the foreland) and the amount of deformation in the footwall is more than what is predicted in other models (Boyer and Elliot, 1982; Suppe, 1985). The exception to this occurs between Taylor's Canyon and Ogden Canyon (below the Ogden thrust) where a segment of the Tintic Quartzite forms an anticlinal structure that dips both west and east. How did the overall structure of the thrust complex end up dipping to the east if thrust sheet movement was from west to east? Schirmer (1985c, 1988) modified Boyer and Elliot's (1982) classic models of foreland-dipping duplexes and antiformal stacks in addition to using hangingwall-sequence diagrams to describe the Willard thrust sheet and structurally lower Taylor and Ogden thrust sheets, which he named the Ogden Duplex. Schirmer (1988) concluded that the Ogden Duplex formed in a sequential piggyback manner, as older thrust sheets (horses) are placed on top of and folded over younger and structurally lower thrust sheets as thrusting propagated eastward.

Then, normal faulting along the Wasatch fault zone downdropped the western half of the duplexes to a position now buried by valley fill. If correct, the Ogden Duplex would constitute an "antiformal stack duplex" locally or a "foreland dipping duplex" overall in the classification of Boyer and Elliot (1982).

This study suggests the term "thrust complex" be used to describe the Willard thrust fault and structurally lower Taylor and Ogden thrust faults in order to avoid any inference of genetic models of multiple, sequential stacking and development, of thrust sheets. The Willard thrust complex as proposed by this study developed as part of the eastward-propagating Sevier orogeny. A décollement or zone of deformation formed in Cordilleran miogeosyncline rocks far to the west of the current Wasatch Front (Fig. 27). Continued eastward displacement along the zone of deformation combined with the possible existence of pre-existing east-west and north-south structures (located approximately where the Wasatch Fault exists today), caused the Taylor and Ogden thrust sheets to ramp upsection from west to east and then the Willard thrust sheet formed as the "roof thrust" of the thrust complex. This study's proposed development of the thrust complex is similar to previous models (Dahlstrom, 1970) which do not require progressive failure of the footwall frontal ramp (fig. 2). Most of the recent thrust-fault duplex models (i.e., Boyer and Elliot, 1982) have proposed progressive failure of the footwall ramp, so that younger and structurally lower thrusts develop beneath older thrusts. Figure 27 shows a décollement or zone of deformation forming at the base of miogeosyncline shelf sediments to the west. To the east rifts in the cratonic shelf may have influenced the detachment surface to ramp upward. As thrusting continued new thrusts developed by ramping

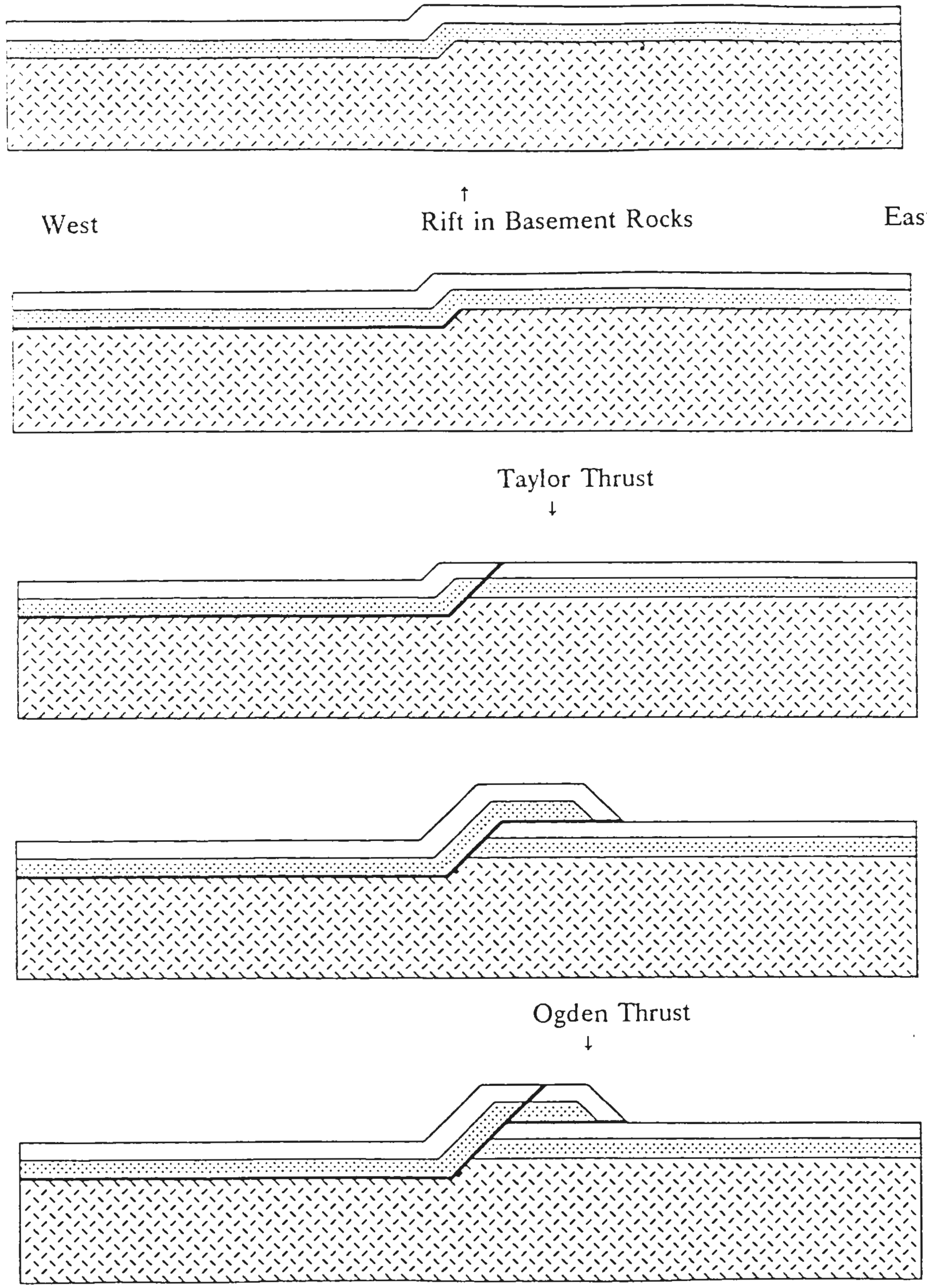


Fig. 27 Proposed schematic development of the Willard thrust complex.

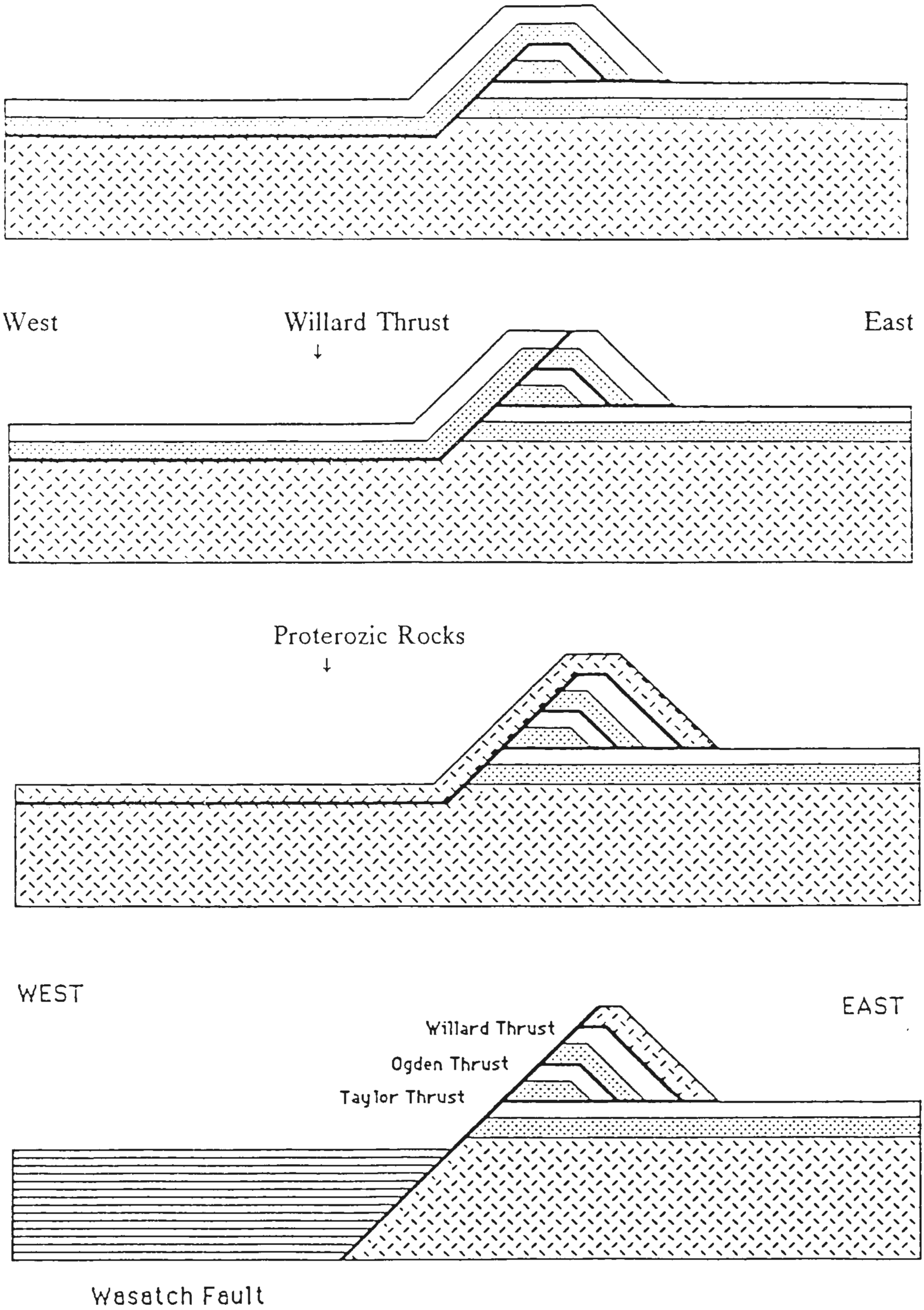


Fig. 27 (Continued)

upsection along the same initial frontal ramp and then overriding older thrusts. This eliminates the need for younger thrusts to develop their own frontal ramp structurally beneath the initial frontal ramp. In this model the Taylor thrust sheet was the first to form. The Ogden thrust sheet was the second to form. The final thrust or roof thrust was the Willard thrust sheet which carried Proterozoic rock in its base. Finally, the entire thrust complex was eroded and followed by Cenozoic extension and normal faulting (reactivation of Precambrian extension ?) which enhances the eastward dipping nature if the thrust complex.

Other factors have also influenced the final geometry of the Willard thrust complex. In addition to the west-to-east frontal ramp, north-to-south lateral ramps of the Willard thrust fault also formed. Lateral ramps are assumed to be related to east-west Precambrian rifts in cratonic shelf sediments. The combination of frontal ramps, lateral ramps, and other possible structures in the subsurface help explain the complex thrusting, thrust imbrication, and bedding-plane thrusts below the Willard thrust sheet between Willard Canyon and Pineview Reservoir, the approximate southern exposure of the Ogden thrust. The model proposed in this study, with the exception of the proposed sequence of progressive failure in the footwall, still adheres to the basic rules of development of thin-skinned thrust faults and their resulting geometries and structures (Dahlstrom, 1970; Jones, 1971; Perry, 1978; Elliot and Johnson, 1980; Boyer and Elliot, 1982; Mitra, 1986).

IMPLICATIONS

SUBSURFACE STRUCTURES

One of the problems that workers in this area of the Idaho-Wyoming-Utah thrust belt have to deal with is trying to interpret Cretaceous-age thrusting overprinted by Cenozoic extension. This apparent complication may potentially be more helpful than complicating. Prior to Cenozoic extension, Cretaceous thrusting during the Sevier orogeny, and Proterozoic development of a passive continental margin (and the sediments of the Cordilleran miogeosyncline that accumulated on the margin), the area was subjected to numerous episodes of Precambrian rifting (Wheeler and Krystinik, 1988). Rifting and associated extension and thinning in Late Proterozoic time helped form a continental margin that extended between the present location of Alaska and Mexico. So, to unravel the history of Cretaceous thrusting in this study area, it is important to try to understand the influence of pre-Cretaceous subthrust structures (e.g., Late Proterozoic extension). These subthrust structures may be just as important in unraveling Cretaceous thrusting as is the Cenozoic extension which overprints the thrust complex in this area. The hypothesis states that thrusts of the Sevier orogeny overrode the older and rifted passive margin. Wheeler and Krystinik (1988) stated that when compared to other thrust systems, the resulting thrust complex should "...contain numerous faults of diverse strikes, dips, and degrees of interconnection" (Boyer and Elliot, 1982; Perry and others, 1984). Wheeler and Krystinik (1988) used gravity data, aeromagnetic data, earthquake-epicenter data, topographic data, and geologic data in addition to other studies by Stewart

(1972), Stewart and Poole (1974), Zoback (1983, 1987), Bruhn and Smith (1984), Christie-Blick (1984), Smith and Bruhn (1984), Pricha and Gibson (1985), and Bryant and Nichols (1988) to infer the existence of normal faults, extending both north-south and east-west, in Precambrian rock beneath the thrust sheets exposed in the Wasatch Front. Wheeler and Krystinik (1988) made a correlation between Precambrian extensional faults and possible segmentation boundaries along the Wasatch Fault.

One of the objectives of this study, which these previous studies have not directly focused on, is the influence of pre-existing structures in the passive continental margin on thrust complex geometry and evolution. A point to keep in mind is that seismic-reflection profiles of the area in question are scarce.

HYPOTHESES AND MODELS

The hypotheses and proposed models for the development and evolution of the Willard thrust complex in this study are based on direct and indirect lines of evidence from published literature, map analyses, lab work, and field work. The implication of this research, in a broad sense, is that plastic to brittle changes in deformation in the footwall of the Willard thrust fault should not be thought of as a single tectonic event, but as a continuous and interrelated sequence of overlapping tectonic events. That is, a plastic-to-brittle transition in the footwall of the Willard thrust fault is not only a function of the thrust fault ramping laterally upsection southward, but also a function of footwall topography (e.g., the overturned syncline) and thrust complex geometry below the Willard thrust, which in turn may be a function of pre-existing rifts or faults in passive continental-margin rocks. On a smaller scale however, the transition from plastic to brittle footwall deformation within the same stratigraphic units (Ophir Formation and Maxfield Limestone) where the thrust fault ramped upsection laterally southward implies that deformation style is controlled not only by the changing geometry of a thrust sheet, but by the physical, chemical, and mineralogical properties of the stratigraphic formations in the footwall.

CONCLUSIONS

The Willard thrust fault is the roof thrust of an east-dipping thrust complex in the northern Wasatch Mountains, east, northeast, and north of Ogden, Utah. The thrust complex is made up of three separate thrusts which include the Willard thrust and the structurally lower and older Taylor and Ogden thrusts. The proposed model of development and evolution for the Willard thrust complex is that an eastward-propagating thrust (décollement or zone of deformation) during the Sevier orogeny encountered rifts or possibly faults (both west-east and north-south) in the crystalline basement rock and miogeosyncline sediments of the passive continental margin. These rifts caused the Taylor, Ogden, and Willard thrust sheets to ramp upward (both parallel and perpendicular to the direction of thrust-sheet transport) and form an east dipping thrust complex. This study proposes that the Taylor thrust fault developed first and that the Ogden thrust developed second and overrode the Taylor thrust. The timing of these two thrusts is difficult to determine as is the timing of the Willard thrust fault which formed shortly thereafter as a roof thrust that carried the Late Proterozoic Facer and Perry Canyon formations.

This study investigated microscopic and macroscopic changes in deformation mechanism and style in the footwall of the Willard thrust fault between Willard Canyon and Ogden Canyon. Deformation structures in the Willard Canyon and Willard Mountain field areas are dominantly plastic and formed by mechanisms of folding, pressure solution, and dynamic recrystallization of calcite. Intensely folded shales and limestones of the Ophir Formation and

Maxfield Limestone can be seen in outcrop and thin section. Thin sections revealed dynamic recrystallization of calcite, styolitic textures, folding, shearing, and possible mineral alteration in the shale. Deformation structures in the North Ogden Canyon field area are both plastic and cataclastic. At the outcrop scale folding is less distinct and at a smaller scale than at the Willard Canyon or Willard Mountain field areas. At the microscopic scale, folding, pressure solution, and dynamic recrystallization of calcite are present, but the plastic deformation is overprinted by fracturing. The presence of both plastic and cataclastic deformation structures, the fact that the thrust begins to cut up section in this area, and the lack of plastic deformation structures to the south indicates this is the location of the transition in footwall deformation. The transition from plastic to cataclastic footwall deformation begins approximately 3 kilometers north of the North Ogden Canyon field area in the Ophir Formation and the Maxfield Limestone. It is in this area of the footwall, between Willard Canyon and Ogden Canyon, where plastic mechanisms of deformation give way to cataclastic mechanisms of deformation. The transition in deformation appears most prominent in the Maxfield Limestone.

Understanding how the deformation in the footwall of a thrust sheet relates to the total displacement of the thrust sheet is important to the history of how the thrust sheet and its associated thrust complex evolved. Deformation structures and mechanisms in the footwall of the Willard thrust discussed in this study present some interesting ideas. Footwall deformation structures observed in this study represent strain that was accommodated just prior to and during frontal ramping, lateral ramping, and the sequential geometrical evolution of the Willard thrust complex. This idea states that deformation in the footwall of the Willard thrust is not representative of the total strain accommodated during the total net displacement of the Taylor, Ogden, and Willard thrust sheets. Rather, footwall deformation in the Willard thrust represents a record of thrust complex development and specifically how thrust sheets interacted as they were thrust eastward and upward on top of one another. Results of this study are important because they show that footwall deformation can be used to determine a specific thrust complex chronology and relate the resulting geometry of the thrust complex to deformation mechanisms working within the deforming thrust sheets.

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APPENDICES

APPENDIX A. PREVIOUS WORK

Blackwelder (1910) was one of the first workers to describe geologic structures between Weber Canyon (south of Ogden) and Willard Canyon (east of Willard). Later workers (Eardley, 1933, 1939, 1944, 1949, 1952, 1962, 1963, 1969, 1972; Eardley and Hatch 1940a, 1940b; Bell, 1951, 1952; Thomas, 1940; Granger, 1953; Williams, 1948; Crittenden, Sharp, and Calkins 1952; Hanson, 1953; Hardy and Williams, 1953; Crittenden 1959, 1961, 1967, 1972, 1974, 1980; Crittenden, Mckee, and Peterson, 1971; Crittenden, Schaeffer, Trimble, and Woodward, 1971; Crittenden and Christie-Blick, 1980; Maxey, 1958; Hintze, 1959, 1960, 1973, 1988; Rigo, 1968; Bryant, 1980; Hedge, Stacey, and Bryant, 1983; Chidsey, 1984) described stratigraphy, lithology, and structure of both the Willard-Paris thrust and the surrounding geology of the north-central Wasatch Mountains. More recently, the Sevier orogenic belt has been studied in detail by workers such as Armstrong and Hansen (1966), Condie (1966, 1969), Armstrong (1967, 1968), Compton (1969), Mullens and Crittenden (1969), Temple (1969), Tooker and Roberts (1971), Coney (1972, 1973), Roberts (1972), Beutner (1977), Burchfiel and Davis (1972, 1975) Hollet, (1979), Allmendinger and Jordan (1981), Jordan (1981); Standlee, (1982, 1983), Bruhn, Picard, and Beck (1983), Bruhn, Picard, and Griffey (1983), Yonkee and Mitra (1982), Heller and others (1986), Christie-Blick (1983, 1984), Kulik and others (1983), Miller (1983), Naeser, Bryant, Crittenden, and Sorensen (1983), Tooker (1983), Villien and Kligfield (1983), Wiltschko and Dorr (1983), Mitra and others (1984), Mitra and Yonkee (1985), Christie-Blick and Levy (1985, 1988), Lawton (1985), Yonkee and Bruhn (1986, 1987, 1988), Dunlap (1988), and Neuhauser, (1988). More specifically, workers such as Eriksson (1960), Hammond (1971), Hammond and Parry (1972), Bruhn and Beck (1981), Beck (1982), Beck and Bruhn (1983), Cashman and others (1986), Crittenden (1972), Crittenden and others (1971a), Eardley (1969, 1972), Hansen (1979, 1980), Heller and others (1986), Schirmer (1982, 1984, 1985a, 1985b, 1985c, 1988), have conducted detailed studies in the Willard thrust. Studies by Heller and others, (1986), Pavlis and Bruhn (1988), and Yonkee and others (1989) have focused on time of thrusting and hangingwall deformation. Other investigations that were helpful to this study were: 1) studies of thrust-ramp mechanics and thrust-ramp deformation by Berger and Johnson (1980), Bombolakis (1986), Ori and Friend, (1984), Boyer (1986), Butler (1982a, 1982b, 1985), Groshong and Usdansky (1986), Mitra and Boyer (1986), Williams (1987), Wiltschko (1979a, 1979b), and Wiltschko and Eastman (1983); 2) thin-skinned structures and deformational features in thrust plates by Armstrong and Dick (1974), Boyer and Elliot (1982), Byerlee (1968), Chapple (1978), Davis and others (1983), Elliot (1976a, 1976b), Mitra (1984), Mitra and others (1984), Mitra and others (1985), Bruhn and Kligfield (1983), Morley (1986), Jamison (1987), and Royse and others (1975); and 3) subsurface influences on thrust sheet geometry and emplacement by Pricha and Gibson, (1983, 1985), Wiltschko and Eastman (1983, 1988), Schedl and Wiltschko (1987), Bryant and Nichols (1988), Chester and others, (1988), Kulik and Schmidt (1988), Wheeler and Krystinik (1988), and Woodward (1988).

APPENDIX B. FIELD DATA

Willard Canyon

Fracture orientations in Willard Canyon occur in two dominant groups. Orientations of the first group range from N35W to N0W, with dips ranging from 73 to 77 degrees to the west. Orientations from the second group range from N55E to N85E, with dips ranging from 11 to 30 degrees to the north. Lineation data from Willard Canyon consists almost entirely of fold axis orientations. Fold axis trends range from N44W to N39E, with plunges ranging from 10 to 25 degrees. Bedding data collected in the Willard Canyon field area is from the Tintic Quartzite. Bedding in the Tintic Quartzite ranges from N50W to N36W, with dips ranging from 20 to 40 degrees.

<u>Sample Numbers</u>:
7-25-88-1
7-27-88-1

Fold Axes:	Lineations:	Fractures:	Solution Cleavage:	En Echelon Veins:
N44W 22	N78E 18	N0W 76W	N55E 24N	N40W
N10W 18		N8W 74W	N35W 30N	N40W
N28W 22		N3W 77W	N70E 30N	N44W
N38W 14		N8W 73W		
N0W 10		N4W 75W		
N5E 25		N85E 11N		
N24W 10		N70E 14N		
N39E 15		N65E 20N		

Willard Mountain

Bedding orientations range from N72W to N20W, with dips ranging from 20 to 57 degrees to the northeast. Fracture orientations in the field area fall into four groups. Orientations of the first group range from N67E to N90E, with dips ranging from 30 to 90 degrees to the north. Orientations from the second group range from N15E to N58E, with dips ranging from 24 to 78 degrees to the southeast. Orientations from the third group range from N15W to N47W, with dips ranging from 34 to 52 degrees to the northeast. Orientations from the fourth group range from N5W to N12E, with dips ranging from 50 to 65 degrees to the west. Other foliation data collected at Willard Mountain includes axial planar cleavage and pencil cleavage. Lineation data collected on Willard Mountain includes fold axes, slickenlines, and lines of intersection of two planes. Fold-axis trends on Willard Mountain fall into two groups. The range of trends for the first group is N15W to N20E, with plunges ranging from 15 to 24 degrees. The range of trends for the second group is N63E to N125E, with plunges ranging from 18 to 44 degrees.

Sample Numbers:	Bedding:	Fold Axes:	Slickenlines:	Pencil Cleavage:
7-18-88-1	N72W 20N	N20E 15	S65W 65	N47W 34N
7-19-88-1	N42W 53N	N63E 44		N12E 50W
7-28-88-1	N20W 24N	N10E 24		
7-28-88-2	N25W 20N	N10W 21		
	N20W 26N	N12W 19		
	N47W 57N	N15W 15		
	N47W 34N	S80E 22		
	N32W 39N	S85E 31		
		S55E 18		

Willard Mountain (continued)

Fractures:

N88E 78N	N46E 24S	N15W 49N	N15E 60S	N74E 30N
N31W 51N	N85E 80N	N46W 41N	N0W 62W	N47W 34N
N12E 50W	N1W 60W	N82W 71N	N67E 84N	N90W 90N
N90E 85N	N84E 83N	N90W 88N	N58E 78S	N19W 71S
N5W 65W	N83E 34N	N30W 52N		

North Ogden Canyon

Bedding orientations in the North Ogden Canyon field area range from N35E to N90E, with dips ranging from 33 to 60 degrees to the north. Fracture orientations in North Ogden Canyon, like those on Willard Mountain, fall into four groups. Orientations from the first group range from N14E to N75E, with dips ranging from 43 to 74 degrees to the northwest. Orientations from the second group range from N31W to N8W, with dips ranging from 89 to 90 degrees to the southwest. Orientations from the third group range from N51W to N4W, with dips ranging from 30 to 75 degrees to the northeast. Orientations from the fourth group range from N5E to N55E, with dips ranging from 65 to 90 degrees to the southeast. Lineation data collected at the field area includes fold axes, kink band axes, and slickenline orientations. Trends of fold axes and kink bands range from N40W to N60E, with plunges ranging from 40 to 45 degrees.

Sample Numbers:		Bedding:	Fold Axes:
6-23-1	7-4-88-1	N35E 60N	N23W 44
6-24-1	7-6-88-1	N44W 52N	N40W 40
6-24-2	7-11-88-T	N74E 33N	N20W 40
6-24-3		N90E 30N	N60E 45
		N55E 35W	N37E 35

Fracture Data:

N20E 73N	N35E 80N	N37E 71N	N75E 47N	N30E 67N	N26E 55N
N30E 62N	N24E 52N	N49E 48N	N20E 78N	N14E 64N	N15E 64N
N55E 44N	N47E 43N	N4W 75E	N51W 37N	N11W 37N	N42W 30N
N31W 31N	N17W 44N	N40E 74N	N40E 71N	N39E 71N	N26E 71N
N24W 90S	N11W 37N	N31W 89S	N15W 90S	N5W 90S	N5E 90S
N10W 90S	N24W 90S	N12W 90S	N8W 90S	N50E 70S	N30E 70S
N40E 80S	N55E 65S	N7E 90S			

Goodale Creek Canyon

Bedding orientations in Goodale Creek Canyon range from N68E to N69E, with dips ranging from 20 to 48 degrees to the northwest. Goodale Creek Canyon fracture data falls into two groups. Orientations from the first group range from N30W to N40W, with dips ranging from 80 to 83 degrees to the southwest. Orientations from the second group range from N40E to N63E, with dips ranging from 64 to 66 degrees to the northwest.

Sample Numbers:	Bedding:	Hammond's Fold Axes:		Fracture Data:
6-20-1-G	N69E 20N	N26E 8	N38E 11	N40W 80S
6-20-2-G	N68E 48N	N32E 4	N86 1	N60E 64N
6-21-1		N94E 9	N94E 12	N35W 83S
		N112E 3	N103E 4	N63E 64N
		N115E 11	N75 24	N30W 80S
		N98E 1	N102E 2	N40E 66N
		N118E 4	N113E 20	
		N110E 1		

Pineview Reservoir

Bedding orientations at the field area range from N26W to N42W, with dips ranging from 37 to 42 degrees to the northeast.

Sample Numbers:	Bedding:	Slickenlines:
7-7-88-1	N26W 37N	S65W 60
7-7-88-2	N42W 42N	

Cold Water Canyon

Fold #1 Bedding Orientations:

N54W 26N	N45W 24N	N16W 31N	N70E 22N	N42E 13S	N47E 17S
N44E 20N	N23W 25N	N34E 31N	N36E 19N	N55E 28N	N75E 25N
N36W 8N	N65E 14N	N56E 25N	N38E 28N	N60W 19N	N87W 7N
N50W 24N	N38W 6N	N8W 20S	N0W 22W	N2W 15W	N15W 30W
N46E 23N	N61E 21N	N42E 20N	N36E 25N	N62W 26N	N70W 30N
N82W 32N	N78W 8N	N52W 19N	N75W 18N	N52W 29N	N40E 26S
N44E 31S	N11E 36S	N30E 36S	N14E 30S	N0W 44E	N15W 40N
N15E 16S	N10E 18S	N60E 61S	N65E 38S	N75E 35S	N82E 26S
N58E 49S	N86E 31S	N50E 27S	N50E 32S	N69E 49S	

Fold #2 Bedding Orientations:

N62W 26N	N70W 30N	N82W 32N	N78W 8N	N52W 19N	N75W 18N
N54W 26N	N45W 24N	N16W 31N	N42E 13S	N47E 17S	N44E 20N
N34E 31N	N36E 19N	N55E 28N	N70E 22N	N23W 25N	N75E 25N
N36W 8N	N65E 14N	N56E 25N	N38E 28N	N60W 19N	N87W 7N
N50W 24N	N38W 6N	N8W 20S	N0W 22W	N2W 15W	N15W 30W
N34E 30N	N65E 16S	N95E 32S	N46W 20N	N85W 20S	N80W 19S
N72W 18S	N46E 23N	N61E 21N	N42E 20N	N36E 25N	N24W 38S
N34W 36S	N33W 34S	N30W 43S	N14W 12S	N15W 15S	N82E 27N
N19W 30N	N37W 46N	N24W 39N	N20W 15N	N12E 35S	N3E 23S
N44E 19S	N26E 16S	N5W 22N	N32W 42N	N55W 39N	N50E 22N
N34W 30S	N26W 49S	N29W 41S	N26W 45S	N82W 59S	N49W 15S
N25W 28S	N51W 34S				

Fold #3 Bedding Orientations:

N24W 38S	N34W 36S	N33W 34S	N30W 43S	N14W 12S	N15W 15S
N20W 15N	N12E 35S	N3E 23S	N44E 19S	N26E 16S	N5W 22N
N32W 42N	N55W 39N	N50E 22N	N34W 30S	N26W 49S	N29W 41S
N26W 45S	N82W 59S	N49W 15S	N25W 28S	N51W 34S	N2W 50S
N2W 35S	N42W 22S	N70E 28S	N45E 13N	N52E 33N	N47E 26N
N28E 19N	N50W 10N	N30W 10N	N11E 11N	N40E 14N	N10E 30N
N3W 62S	N10E 41N	N50E 32N	N53E 36N	N35E 32N	N67E 18N
N12E 41S					

Malans Peak

Bedding Orientations:

N30W 36N	N46W 45N	N39W 47N	N44W 44N	N64W 47N	N53W 53N
N55W 50N	N56W 60N	N51W 52N	N50W 57N	N46W 53N	N49W 61N
N52W 61N	N67W 56N	N54W 59N	N55W 72N	N53W 70N	N46W 72N
N62W 72N	N50W 57N	N60W 64N	N48W 59N	N55W 61N	N45W 60N
N50W 74N	N48W 69N	N55W 76N	N48W 65N	N49W 65N	N47W 68N
N50W 61N	N45W 70N	N62W 62N	N48W 67N	N54W 64N	N50W 71N
N56W 72N	N55W 85N	N50W 88N	S54E 66S	S50E 79S	S45E 79S
S59E 51S	S72E 78S	S75E 80S			

Taylor Canyon

Bedding orientations fall into two groups. Orientations from the first group range from N50W to N40W, with dips ranging from 25 to 74 degrees to the north. The second group of orientations range from S87E to S50E, with dips ranging from 25 to 76 degrees to the south. Fracture cleavage orientations from Taylor Canyon fall into three groups. Orientations from the first group range from S16E to S3E, with dips ranging from 37 to 57 degrees to the west. Orientations from the second group range from S80E to S81E, with dips ranging from 15 to 29 degrees to the south. Orientations from the third group range from N0W to N8W, with dips ranging from 40 to 78 degrees to the north. Foliation orientations from Taylor Canyon range from S80E to S44E, with dips ranging from 14 to 49 degrees to the south. Fold axes in Taylor Canyon trend approximately east-west and plunge to the east.

Fracture Orientations:

S68E 49S	S68E 37S	S70E 42S	S48E 48S	S45E 47S	S44E 36S
S44E 37S	S52E 43S	S53E 43S	S57E 30S	S50E 30S	S52E 32S
S58E 29S	S60E 14S	S80E 29S	N55W 42S	N54W 42S	N56W 41S

Calcite Vein/Joint Orientations:

S11E 42S	S15E 45S	S13E 41S	S16E 57S	S14E 55S	S3E 38S
N0E 40S	S5E 37S	S4E 38S	S5W 42N	N8W 78N	S80E 29S
S81E 15S					

"S" Fold

Bedding orientations range from N72W to N30W and S60E to S80E, with dips ranging from 18 to 85 degrees. Lineation trends range from S48E to S70E, with plunges ranging from 6 to 19 degrees.

Lower and Middle Limb Orientations:

N36W 34E	N34W 45E	N36W 47E	N36W 53E	N40W 32E	N36W 53E
N40W 32E	N36W 30E	N33W 32E	N37W 35E	N45W 28E	N30W 32E
N34W 40E	N51W 30E	N46W 35E	N30W 31E	N40W 35E	N36W 45E
N45W 32E	N32W 38E	N31W 42E	N45W 32E	N35W 33E	N40W 41E
N45W 45E	N47W 51E	N57W 40E	N43W 48E	N54W 41E	N40W 46E
N46W 49E	N45W 56E	N51W 54E	N50W 53E	N58W 66E	N57W 67E
N55W 67E	N60W 74E	N58W 81E	N60W 81E	N50W 72E	N40W 61E
N51W 60E	N42W 68E	N46W 76E	S73E 75S	S75E 80S	S60E 40S
S72E 61S	S72E 62S	S80E 35S	S64E 74S	S60E 62S	S60E 59S
S67E 71S	S68E 70S	S70E 69S	S72E 74S	S80E 44S	S60E 85S
S75E 38S	S65E 31S	S62E 34S	S72E 39S	S72E 51S	S70E 77S
S64E 78S					

Upper and Middle Limb Orientations:

S64E 78S	S73E 75S	S75E 80S	S60E 40S	S72E 61S	S72E 62S
S80E 35S	S64E 74S	S60E 62S	S60E 59S	S67E 71S	S68E 70S
S70E 69S	S72E 74S	S80E 44S	S60E 85S	S75E 38S	S65E 31S
S62E 34S	S72E 39S	S72E 51S	S70E 77S	N55W 64E	N67W 69E
N57W 63E	N55W 52E	N50W 54E	N49W 51E	N50W 24E	N48W 27E
N44W 18E	N42W 37E	N35W 44E	N30W 47E	N34W 50E	N40E 31E
N44W 30E	N40W 39E				

Perry's Camp

Bedding orientations range from N58W to N20W, with dips ranging from 35 to 80 degrees to the east. Fold Axis orientations from Perry's Camp fall into two groups. Fold axis trends from the first group range from S36E to S20E, with plunges ranging from 5 to 15 degrees. Fold axis trends from the second group range from N35W to N10W, with plunges ranging from 10 to 25 degrees.

Bedding Orientations:

N51W 38E	N45W 46E	N55W 55E	N55W 85E	S58W 34W	N5W 38E
N20W 35E	N25W 51E	N20W 41E	N22W 59E	N25W 77E	N30W 80E

Fracture Orientations:

S10E 24S	N45W 60N

Fold Axes:

S36E 12	N35W 10	S20E 3	S20E 10	S35E 15	S35E 7
S35E 7	N10W 20	N20W 25	S35E 7	S35E 5	

APPENDIX C. GENERAL STRATIGRAPHY

The geologic units below the Willard thrust range in age from Precambrian to Mississippian. Figures 28, 29, 30, and 31 are generalized stratigraphic columns of Willard Canyon, Willard Mountain, North Ogden Canyon, and Ogden Canyon. The following lithologic and stratigraphic descriptions are general descriptions only. The reason for this is due to extensive lateral and vertical facies changes within local formations and because lateral tectonic thinning and thickening has occurred in the incompetent formations. The oldest unit below the Willard thrust is the Precambrian Farmington Canyon Complex (Eardley and Hatch, 1940a; Bruhn and Beck, 1981; Hedge and others, 1983; Bryant, 1980, 1984, 1988). The Farmington Canyon Complex is exposed in both Ogden Canyon and Willard Canyon, but not in North Ogden Canyon. Bryant (1988) divided the complex into four principle map units. The four units are quartz monzonite gneiss, migmatite, schist and gneiss, and schist, gneiss, and quartzite. In general the complex is a light gray, pinkish gray, and yellowish gray quartz monzonite gneiss with thick lenses of greenish black amphibolite; medium gray mica schist; light gray, pinkish gray, and pale orange pegmatite; and also white to pale yellowish green coarse-grained meta-quartzite. The formation is approximately 1,220 meters thick in the North Ogden quadrangle. Ages from Rb-Sr and Sm-Nd isotopes show that protoliths from these layered, metamorphic crustal rocks range in age from 2,800 to 3,600 m.y. old. The protoliths underwent metamorphism approximately 2,600 m.y. ago. Isotopic studies along with modal and chemical compositions indicate the quartz monzonite gneiss

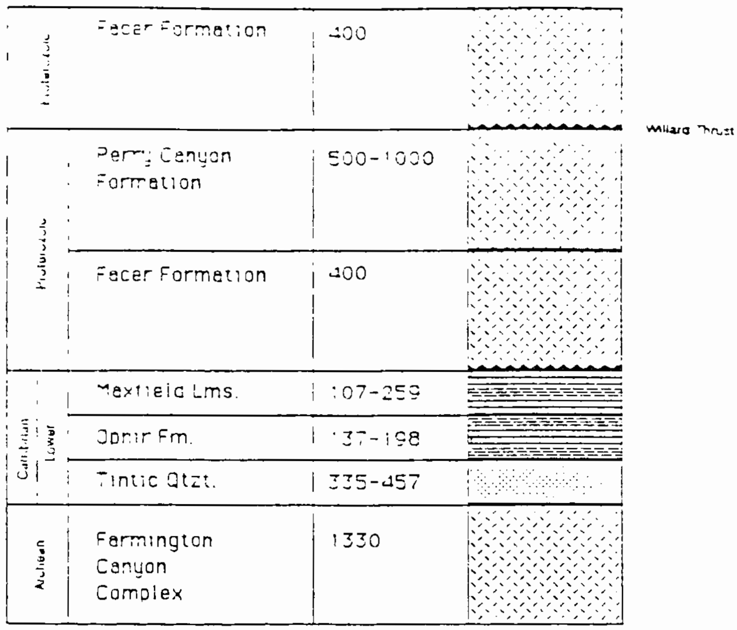

Fig. 28 Generalized stratigraphic column of Willard Canyon. Unit thicknesses are reported in meters from Hintze (1988).

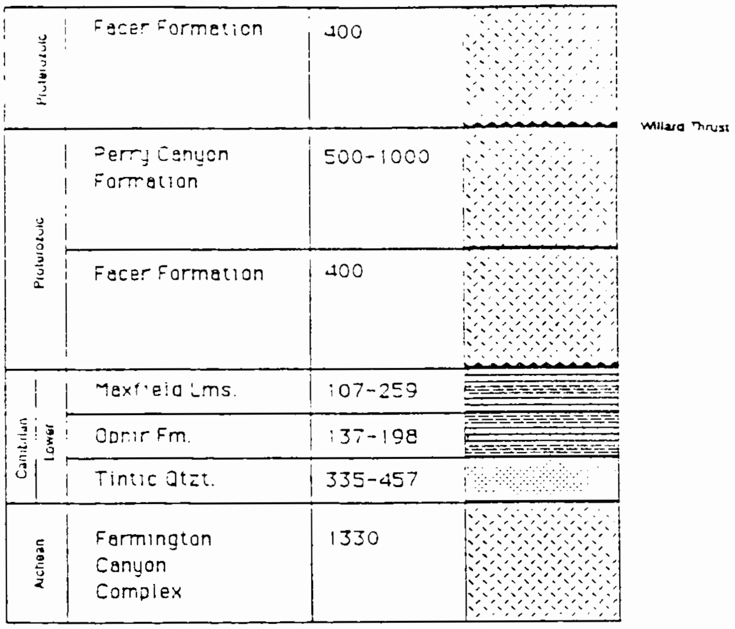

Fig. 29 Generalized stratigraphic column of Willard Mountain. Unit thicknesses are reported in meters from Hintze (1988).

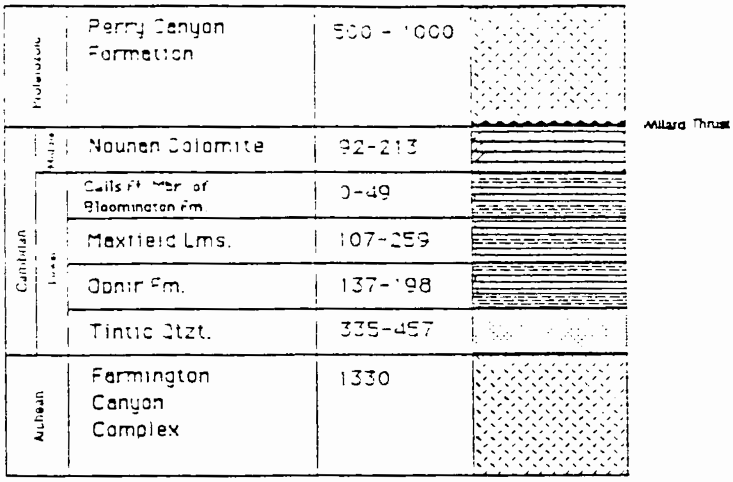

Fig. 30 Generalized stratigraphic column of North Ogden Canyon. Unit thicknesses are reported in meters from Hintze (1988).

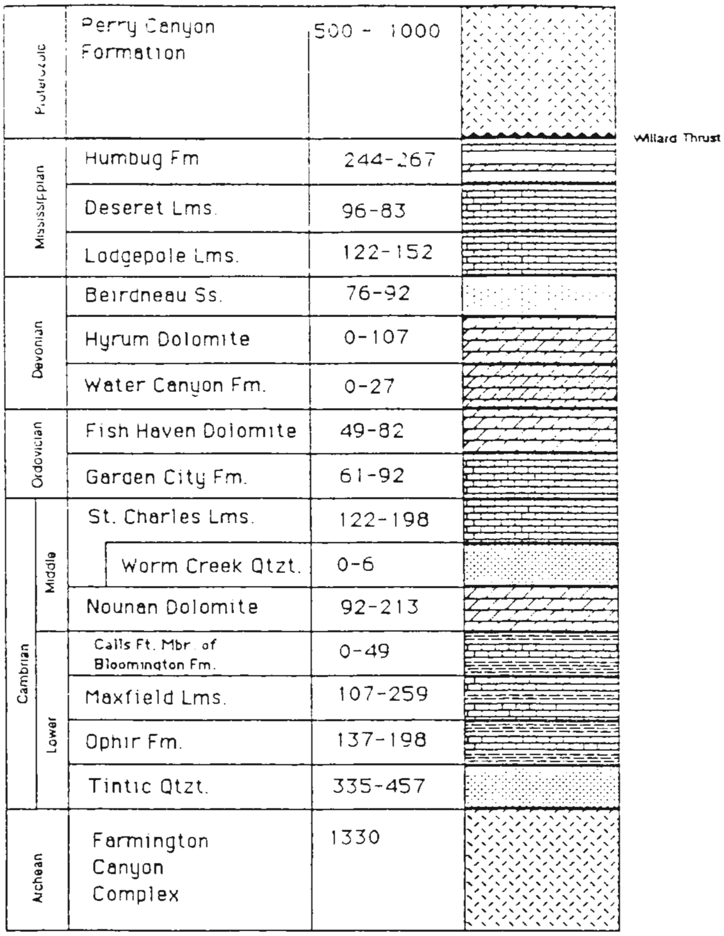

Fig. 31 Generalized stratigraphic column of Ogden Canyon.
Unit thicknesses are reported in meters from Hintze (1988).

formed approximately 1,790 m.y. ago when upper crustal rocks melted (Hedge and others, 1983).

The Lower Cambrian Tintic Quartzite lies nonconformably above the Farmington Canyon Complex. The Tintic Quartzite is exposed in Ogden, North Ogden, and Willard canyons. The Tintic Quartzite is a white, pink, buff, and tan, medium- to coarse-grained, medium to thick, cross-bedded quartzite, in which layers and zones of quartz-pebble conglomerate increase in abundance downward. The unit is approximately 335 to 427 meters thick in the North Ogden quadrangle (Bryant, 1984; Crittenden and Sorensen, 1985a, 1985b; Davis, 1985).

Above the Tintic Quartzite is the Middle Cambrian Ophir Formation, which is exposed only in Ogden and North Ogden canyons. This shale is divided informally into three parts (Rigo, 1968; Sorensen and Crittenden, 1972; Bryant, 1984). The lower part is a light brown to olive drab micaceous shale, with locally abundant worm tracks and linguloid brachiopods; the middle part is a fine-crystalline blue gray limestone, and commonly has tan to orange brown, silty limestone; the upper part is an olive drab to greenish olive drab shale, with some limestone and shaly limestone, approximately 137 to 183 meters thick in the North Ogden quadrangle (Sorensen and Crittenden, 1972, 1976; Bryant, 1984; Crittenden and Sorensen, 1985a, 1985b; Davis, 1985).

Above the Ophir Formation is the Middle Cambrian Maxfield Limestone. The Maxfield Limestone is exposed in Ogden, North Ogden, and Willard canyons. Like the Ophir Formation, the Maxfield Limestone is also divided informally into three parts. Both the lower part and the upper part consist of medium to dark gray, thin-bedded, fine-crystalline, cliff-forming dolostone and limestone, commonly with intercalated light gray silty limestone. Both lower and upper parts include laminated dolostone and dark gray mottled limestone. The middle part contains an olive drab to greenish brown micaceous shale and an interbedded, medium to dark gray limestone, which are overlain by a medium to dark gray, cliff-forming platy limestone. The Maxfield Limestone is approximately 259 meters thick in the North Ogden quadrangle (Rigo, 1968; Sorensen and Crittenden, 1979; Crittenden and Sorensen, 1985a, 1985b; Bryant, 1984; Davis, 1985).

Above the Maxfield Limestone is the Nounan Dolomite and St. Charles Formation. Davis (1985) showed these units as one undivided map unit. These formations crop out only in Ogden and North Ogden canyons. Rigo (1968), Sorensen and Crittenden (1972, 1976), and Sorensen and Crittenden (1979) mapped these formations as separate units, as well as placing the Calls Fort Member of the Bloomington Formation (a shale) at the base of the Nounan Dolomite and the Worm Creek Quartzite at the base of the St. Charles Formation. The Nounan Formation is a thin- to thick-bedded, fine-crystalline, light to medium gray, cliff-forming dolostone, that is approximately 240 meters thick in Ogden Canyon. The Worm Creek Quartzite Member is a thin-bedded, fine- to medium-grained, medium to dark gray, brown-weathering, calcareous quartzite. Detrital grains in the Worm Creek Quartzite Member are commonly well sorted and well rounded. The St. Charles Formation is a thin- to thick-bedded, fine- to medium-crystalline, white to light gray, cliff-forming dolostone, that is approximately 610 meters thick.

The following six units have been mapped in Ogden Canyon, but not in

North Ogden or Willard canyons: The Lower Ordovician Garden City Formation, the Upper Ordovician Fish Haven Dolomite, the Lower Devonian Water Canyon Formation and Hyrum Dolomite, the Upper Devonian Beirdneau Sandstone, the Mississippian Lodgepole Limestone, Deseret Limestone, and the Upper Mississippian Humbug Formation (Rigo, 1968; Hintze, 1973; Sorensen and Crittenden, 1972, 1976, 1979; Crittenden and Sorensen, 1985a, 1985b; Bryant, 1984; Davis, 1985).

The Garden City Formation is a medium to pale gray and tan, thin- to thick-bedded limestone and dolomitic limestone, with interbedded intraformational conglomerate. The unit commonly contains sandy streaks and lenses, with interbedded and intercalated, thinly laminated, medium gray to tan, and tan- weathering siltstone. In places the siltstone contains nodules and lenses of dolomite. The unit is approximately 44 meters thick.

The Fish Haven Dolomite is a dark gray, medium- to coarse-crystalline, medium- to thick-bedded, cliff-forming dolomite. Remnants of horn corals and crinoids are common.

The lower part of the Water Canyon Formation is thin-bedded to laminated, fine-crystalline, medium to pale gray dolostone and silty dolostone. The upper part is a medium to dark gray dolostone.

The Hyrum Dolomite is a dark gray to black, dark to light gray-weathering, thin to thick-bedded, fine- to medium-crystalline cliff-forming dolostone with lenses of intraformational dolostone breccia and some minor intercalated gray limestone and limy siltstone.

The Beirdneau Sandstone is a tan-, orange-, and brown-weathering, fine- to medium-grained sandstone, and laminated to medium-bedded dolomitic sandstone and dolostone. The formation is approximately 76 to 92 meters thick in Ogden Canyon.

The Lodgepole Limestone and Deseret Limestone are dark gray, thick-bedded, contain medium gray dolostone with lenses of chert, and contain a dark gray to black, thin- to medium-bedded, light blue gray- weathering, platy, fossiliferous limestone.

The Humbug Formation is a medium-bedded, tan and gray siltstone and fine-grained sandstone. The unit is interbedded with dark to medium gray, medium-bedded limestone and dolostone and is approximately 245 meters thick (Rigo, 1968; Hintze, 1973; Sorensen and Crittenden, 1972, 1976, 1979; Crittenden and Sorensen, 1985a, 1985b; Bryant, 1984; Davis, 1985).

Other stratigraphic units below the Willard thrust that do not crop out in Ogden Canyon include the Precambrian Facer Formation, the Precambrian Perry Canyon Formation, and the Lower Cambrian Geertsen Canyon Quartzite (equivalent to the Tintic Quartzite). In Willard Canyon only the Facer Formation and the Perry Canyon Formation crop out. In North Ogden Canyon only the Geertsen Canyon Quartzite and the Perry Canyon Formation crop out.

The Facer Formation is a white to light gray metaquartzite. The formation also contains a pale greenish gray and grayish purple schist; lustrous quartz-muscovite schist; a dark green to greenish black amphibolite (in sills); a creamy white gneiss, and a light gray quartzose conglomerate. Some localized gray limestone and dolostone are present. Partially measured sections total approximately 750 meters thick (Crittenden, 1980; Bryant, 1984; Davis, 1985).

The Perry Canyon Formation contains brown and gray to dark green micaceous siltstone, brown quartzitic sandstone, and gray to dark green argillite. The lower part of the formation is a gray to black diamictite (tillite ?) with some limestone and minor pillow lava near the base. The entire formation is approximately 460 meters thick (Sorensen and Crittenden, 1979, Crittenden and Sorensen, 1985a; Davis, 1985).

The Geertsen Canyon Quartzite is a white, gray, pink, and light green, medium- to coarse-grained metaquartzite in the upper part, and a tan, white, maroon, and green metaquartzite in the lower part. The formation is approximately 1,220 to 1,340 meters thick in the Huntsville quadrangle (Bryant, 1984; Davis, 1985).