AN ABSTRACT OF THE THESIS OF

James Anthony Carpenter for the degree of Master of Science in Geology presented on January 4, 1989.

Title: Structure of the Southern Mormon Mountains, Clark County, Nevada and Regional Structural Synthesis: Fold-Thrust and Basin-Range Structure in Southern Nevada, Southwest Utah, and Northwest Arizona

Abstract approved: Signature redacted for privacy.
Professor R. S. Yeats

Detailed geologic mapping in the Mormon Mountains and new geophysical data provide significant insight into contractional and extensional tectonics in southern Nevada, southwest Utah, and northwest Arizona. The rocks in the region were complexly deformed during two distinct tectonic episodes. Numerous interrelated events occurred within each episode. The first tectonic episode, related to the Sevier orogeny, was characterized by east-west crustal shortening which culminated in thin-skinned decollement style folding and thrusting during the Cretaceous. The Virgin-Beaver Dam Mountains anticline, a Laramide-type basement-involved uplift, represents the only thick-skinned contractional structure in the region. The second tectonic episode, related to basin-range rifting, was characterized by east-west crustal extension which was accommodated by

high-angle normal faults, with dips averaging 60 degrees, in the brittle upper crust. In this area, basin-range rifting initiated in the Oligocene and continued to Recent time.

Relations in the North Muddy Mountains in southern Nevada suggest that the Muddy Mountain thrust sheet advanced and overrode the Weiser syncline during the Cenomanian and may have continued to advance in Turonian time. In the southern Mormon Mountains, the Cambrian Bonanza King Formation lies in the hanging wall flat position in thrust contact with the overturned Petrified Forest Member of the Triassic Chinle Formation at the footwall ramp. The thrust sheet advanced eastward more than 30 km from the place of origin. Thrust imbrication, and probably the formation of hanging wall horses, likely occurred as the Muddy Mountain thrust sheet encountered and ascended up the footwall ramp zone (composed largely of competent carbonate rocks) where slices of the thrust sheet (hanging wall horses) splayed off and accreted to the footwall ramp zone. A detailed retrodeformable (balanced) regional structure section suggests that fold-thrust shortening at the latitude of the Mormon Mountains is a minimum of about 26%.

Extension-related structures overprint older fold-thrust structures in the Mormon Mountains. The west-plunging east-trending Candy Peak syncline is one of a family of fold structures related to basin-range rifting. The syncline formed in pre-Miocene time in association with the northeast-striking Reber Mountain normal fault directly north and the northeast-striking Dry Canyon right-lateral strike-slip fault directly south. The Tortoise Flat synform, which lies southeast of the Dry Canyon fault, developed in Miocene and possibly Pliocene time by right-lateral flexure of early Miocene Horse Spring beds as a result of drag associated with the Dry Canyon fault. The Dry Canyon fault and the Tortoise Flat synform are interpreted to be part of the right-lateral Moapa Peak-Reber Mountain shear zone system in the southern Mormon Mountains. Therefore, the time of formation of the Moapa Peak-Reber Mountain shear zone system is pre-Miocene to possibly Pliocene. The shear zone system formed in response to different amounts of west-directed extension-related movement of the hanging wall block of the high-angle Virgin Beaver Dam Mountains fault, which initiated in the Oligocene. From this, the timing of the Moapa Peak-Reber Mountain shear zone system is interpreted as Oligocene to Miocene, and possibly Pliocene.

The interpretation of 261 km of seismic reflection sections suggests that large-displacement high-angle normal faults, typically with 60 degrees of dip, control horst and graben structure and accommodate extension by simple shear in the upper brittle crust. Such faults likely extend to depths of 15 to 18 km. Below this depth extension is thought to be accommodated by penetrative ductile deformation. A detailed retrodeformable (balanced) regional structure section suggests that basin-range extension at the latitude of the Mormon Mountains is about 17%.

The Virgin-Beaver Dam Mountains high-angle normal fault is a large-displacement master fault in the area, having more than 8,000 m of normal vertical separation at the latitude of the Virgin Valley basin depocenter. Miocene doming and uplift of the Mormon Mountains occurred in response to displacement on the Virgin-Beaver Dam Mountains fault. The Virgin Valley basin formed as the hanging wall block downdropped, and the Mormon Mountains dome formed by relative uplift at the opposite end of the hanging wall block.

Half-grabens, and tilted, folded, and faulted range blocks characterize basin-range crustal structure. Depositional growth relations are interpreted in basins from fanning-upward reflector geometry, and the wedge-shape of Oligocene to Recent syntectonic basin-fill sediments. Non-overlapping opposing east- and west-tilted half-grabens compose the Meadow Valley-California Wash basin.

Seismic sections, gravity data, well data, and geologic mapping demonstrate that the Mormon Peak, Tule Springs Hills, and Beaver Dam/Castle Cliff "detachments," which were thought to be rooted low-angle normal faults, do not exist. The Mormon Peak and Beaver Dam/Castle Cliff low-angle normal faults are denudational fault planes below gravity slid masses. The widely distributed translocated Paleozoic blocks, which were thought to be remnant pieces of large hanging wall sheets ("extensional allochthons"), are disjunct rootless gravity slide blocks of minor tectonic significance. A large number of these rootless slide blocks lie on Pliocene and Quaternary basin-fill deposits. The Muddy Mountain-Tule Springs thrust, of Sevier age, was not reactivated as a crustal penetrating Tule Springs Hills low-angle normal fault, but is affected by small-scale gravity slide features.

Rootless gravity slide blocks, secondary features to high-angle normal faults, commonly occur from instability as a result of the loss of lateral support induced by block faulting and the associated erosion of range blocks.

STRUCTURE OF THE SOUTHERN MORMON MOUNTAINS, CLARK COUNTY, NEVADA AND REGIONAL STRUCTURAL SYNTHESIS: FOLD-THRUST AND BASIN-RANGE STRUCTURE IN SOUTHERN NEVADA, SOUTHWEST UTAH, AND NORTHWEST ARIZONA

by

James Anthony Carpenter

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed January 4, 1989

Commencement June 11, 1989

APPROVED:

Signature redacted for privacy.

Professor of Geology in charge of major

Signature redacted for privacy.

Chairman of Department of Geology

Signature redacted for privacy.

Dean of Graduate School

Date thesis is presented January 4, 1989

ACKNOWLEDGEMENTS

This research is dedicated to the memory of Harold E. Enlows, a Professor of Geology at Oregon State University; and Chester R. Longwell, a geologist who dedicated his life to working on the geology of southern Nevada and northwest Arizona.

I owe a great debt of gratitude to Drs. R. S. Yeats, K. F. Oles, and R. J. Lillie for courses I completed under their enthusiastic instruction, and for serving on the thesis committee. Spence J. Reber (Chevron U.S.A., Inc.), who has 39 years of experience with the geology of the study region, sparked my interest in the structural geology of the area when I worked with him for 15 months at Chevron in San Ramon, CA during 1984-1985. Spence was a constant source of inspiration and structural expertise throughout this study. I am indebted to Spence and his lovely wife, Josephine, and his parents, Spencer and Britta, for their friendship, encouragement, and hospitality. I greatly appreciate the tremendous friendship, intellectual stimulation, logistical expertise, and energized enthusiasm provided by Pat D. Caldwell (Chevron). D. D. Hastings (Chevron) and L. J. Parkinson (Chevron) are appreciated for enlightening discussions about the "great dome" in Nevada and Utah. I am grateful to Dr. J. G. Johnson for his Regional Depo-Tectonics course, J. S. Dixon (Champlin Petroleum

Company) for sharing his fold-thrust belt expertise, M. O. Withjack (Mobil Oil Corporation) and J. A. Helwig (Mobil) for enlightening discussions concerning continental rifting and this study, and L. F. Hintze for his encouragement and sharing of ideas. Dr. R. S. Yeats, S. J. Reber, U. A. Franz (Mobil), A. K. Brandon, and Chevron's 1988 Structure School class of geologists and geophysicists made field visits to the study area. I am grateful to J. P. Earl, A. J. Koch, and R. B. Hiseler, my supervisors at Mobil, for allowing the time and expense for D. G. Carpenter and I to co-lead, along with S. J. Reber, P. Verrall, and C. Kluth, Chevron's 1988 Structure School through southern Nevada, southwest Utah, and northern Arizona. C. Kluth and P. Verrall are appreciated for valuable discussions and much food for thought concerning the thesis study, and for presenting to D. G. Carpenter and I their San Luis rift basin study of south-central Colorado. P. A. Camilleri led the Mobil field team on an enlightening helicopter field trip through her M.Sc. study area in the northwestern part of the Grant Range. B. J. Ellis, W. J. Taylor, M. F. Skelly, and G. J. Axen generously shared unpublished work pertaining to the Mormon Mountains area. B. J. Ellis provided invaluable discussions concerning the geology of here M.Sc. study area in the Mormon Mountains. J. E. Diebert shared his knowledge about the Cenozoic stratigraphy in his M.Sc. study area in the southern part of the Las Vegas Range. I appreciate the knowledge gained from attending, in 1987, a post-Penrose

TABLE OF CONTENTS

LIST OF PLATES
(FILED IN MAP TUBE)

LIST OF TABLES

PREFACE

This thesis is composed in two parts. The first part, Chapter 1, primarily represents the results from seven months of detailed field mapping directed toward the study of contractional fold-thrust structure and extensional basin-range structure in the North Muddy and Mormon Mountains. The second part, Chapter 2, is also field-based but integrates geological and geophysical data into a study of southern Nevada, southwest Utah, and northwest Arizona. Chapter 2 is by the author and Daniel G. Carpenter. It is a region-wide study we undertook above and beyond the initial goals we each outlined for our respective thesis projects in southern Nevada. It was a 50-50 team effort. We incorporated surface, borehole, gravity, and seismic reflection data sets into a regional structural synthesis. In the Chapter 1 Plates and interpretations that are presented in Chapter 2 are referred to, and vice versa. This was done to limit the amount of redundancy between the two chapters.

In the near future, Daniel G. Carpenter and I will combine our respective copyright protected thesis studies. We plan to publish this work as several papers through the American Association of Petroleum Geologists and the Geological Society of America. Here, it is declared that this research is copyright protected such that we retain the legal right to be the first authors to publish this work, and control its distribution. We also plan to write a detailed account of the Phanerozoic stratigraphy of the region. The 1:12,000 scale geologic mapping I completed of the Moapa Peak and Weiser Ridge Quadrangles will be parts of future publications dealing with the Weiser syncline and associated thrusts.

In the course of the field work for the regional study, D. G. Carpenter and I took note of places that exhibit relatively young looking fault-scarps within basin-fill deposits that are in piedmont areas. Chester R. Longwell was the first geologist to recognize such features in this area during his regional reconnaissance projects in the 1920's and 1930's. An active fault-scarp study combined with earthquake data and our work would make a significant contribution to advance the geological understanding of the region, and would hopefully bear on the seismic risk in this tectonically active region. Areas exhibiting faulted basin-fill deposits include: The west side of the Sheep Range, west side of the Muddy and North Muddy Mountains, northwest side of the Virgin Mountains and at Bitter Ridge, west side of the South Virgin Mountains, and the west side of Frenchman Mountain. These areas would be well-suited for a region-wide study. Probably the most efficient way for an interested geologist to attack this problem would be to study all similar work that has been conducted in the Dixie Valley region in Nevada and along the Wasatch Range in Utah.

STRUCTURE OF THE SOUTHERN MORMON MOUNTAINS, CLARK COUNTY, NEVADA AND REGIONAL STRUCTURAL SYNTHESIS: FOLD-THRUST AND BASIN-RANGE STRUCTURE IN SOUTHERN NEVADA, SOUTHWEST UTAH, AND NORTHWEST ARIZONA

CHAPTER 1

INTRODUCTION

The southern Nevada, southwest Utah, and northwest Arizona study area lies in a complex zone of deformation which has been affected by thin-skinned decollement style folding and thrusting (Longwell, 1926, 1928, 1949; Armstrong, 1968), thick-skinned basement-involved folding and faulting (Reber, 1952; Seager, 1970; Moore, 1972; Hintze, 1986; Carpenter et al., 1989), and basin-range high-angle rift faulting (Longwell, 1926, 1928; Longwell et al., 1965; Stewart, 1971; D. Carpenter, 1988; J. Carpenter, 1988; Carpenter et al., 1989).

Much controversy surrounds the geometry and kinematics of basin-range rift faulting and the magnitude of crustal extension in this area, and the Basin-Range as a whole. Crustal extension in the Basin-Range has been accommodated by more than one structural style; e.g., high-angle normal faulting, the "classical" view, and low-angle normal faulting. Some geologists have discounted the classical view of G. K. Gilbert (1874, 1875) altogether, and have attempted to fit the whole of extensional tectonics into a single structural style in which discrete crustal penetrating low-angle normal faults ("detachments") represent the underpinnings of the extensional model. If an analogous attempt was made to fit the whole of contractional tectonics into a single structural style it would fly in the face of decades of arduous research and would be the focus of intense debate.

On the basis of mapping part of the Mormon Mountains, Wernicke (1981, 1982) and Wernicke et al. (1984, 1985) proposed that crustal penetrating (rooted) low-angle normal faults exist in this area. Such faults were thought to initiate at low-angle (5 to 25 degrees), and were interpreted to be the primary type of structure that accommodates crustal extension in the region. This model has been disputed (J. Carpenter, 1988; D. Carpenter, 1988, Carpenter et al., 1989) in this area on the basis of the surface and subsurface data and interpretations presented herein. Because the interpretations drawn from the new evidence presented in this study so markedly differ from Wernicke's low-angle normal fault model it was incumbent upon the writer to also present the arguments that condemn that interpretation. It is noteworthy to realize that the interpretations presented here regarding contractional and extensional tectonics are in general agreement with all work done prior to 1981 and all work completed since that time, with the exception of work that builds on the low-angle normal fault model. The five lines of evidence that dispute the rooted low-angle normal fault model in the study area are: (1) field relations regarding translocated Paleozoic carbonate blocks, (2) condemning timing, and condemning stratigraphic and structural geometries, (3) Bouguer gravity data and physiography, (4) well data, and (5) high-quality seismic reflection profiles.

Most of the geological and all of the geophysical data sets used in this study to examine the region are new. The study integrates 261 km of seismic reflection data, well data, surface data, and Bouguer gravity data. Detailed field mapping was conducted in the North Muddy-Mormon Mountains range block because this range contains key structural and stratigraphic relations for studying the processes of contractional and extensional tectonics. The purpose of the study was to examine the region via the new data sets and integrate them into a cohesive whole.

This study builds primarily on work by Longwell (1926, 1928, and 1949), Reber (1952), Longwell et al. (1965), Tschanz and Pampeyan (1970), Seager (1970), Olmore (1971), Moore, (1972), Wernicke (1982), Wernicke et al. (1984, 1985) Bohannon (1983, 1984), Hintze (1986), J. Carpenter (1986, 1988), D. Carpenter (1986, 1988), Carpenter and Carpenter (1987), Skelly (1987), and Carpenter et al. (1989).

STRUCTURE OF THE SOUTHERN MORMON MOUNTAINS, CLARK COUNTY, NEVADA

ABSTRACT

The rocks in the Mormon Mountains of southern Nevada were complexly deformed during two distinct tectonic episodes. Numerous interrelated events occurred within each episode. The first tectonic episode, related to the Sevier orogeny, was characterized by east-west crustal contraction which culminated in decollement style folding and thrusting during the Cretaceous. The second tectonic episode, related to basin-range rifting, was characterized by east-west crustal extension beginning in the Oligocene and continuing to Recent time.

The Muddy Mountain thrust sheet advanced and overrode the Weiser syncline during the Cenomanian and perhaps continued to advance in Turonian time. The Cambrian Bonanza King Formation lies in the hanging wall flat position in thrust contact with the overturned Petrified Forest Member of the Triassic Chinle Formation at the footwall ramp. Horizontal shortening on the thrust is greater than 30 km (20 mi). Thrust imbrication, and probably the formation of hanging wall horses, likely occurred as the Muddy Mountain thrust sheet encountered the footwall ramp zone (composed largely of hard carbonate rocks) where slices of the thrust sheet (hanging wall horses) splayed off.

The Candy Peak syncline, located at the north end of Reber Mountain, is one of a family of structures related to basin-range rifting. The syncline formed in pre-Miocene time in association with the Reber Mountain normal fault and the Dry Canyon strike-slip fault. The Tortoise Flat synform developed in Miocene and possibly Pliocene time by dextral drag associated with the Dry Canyon fault. The Dry Canyon fault and the Tortoise Flat synform are interpreted to be part of the right-lateral Moapa Peak-Reber Mountain shear zone system in the southern Mormon Mountains. Therefore, the time of formation of the Moapa Peak-Reber Mountain shear zone system is pre-Miocene to possibly Pliocene. The shear system is interpreted to have formed in response to different amounts of west-directed extension-related movement of the hanging wall of the high-angle (60 degrees) Virgin Beaver Dam Mountains fault, which initiated in the Oligocene. Therefore, the timing of the Moapa Peak-Reber Mountain shear zone system is interpreted as Oligocene to Miocene, and possibly Pliocene.

The Mormon Peak low-angle normal fault model does not allow for the existence of the Horse Spring Formation that deposited in the southern Mormon Mountains. The Mormon Peak low-angle normal fault does not exist, and the widely distributed translocated blocks exposed in the Mormon Mountains are disjunct rootless gravity slide blocks.

INTRODUCTION

REGIONAL GEOLOGIC SETTING

STRATIGRAPHIC SETTING

The Mormon Mountains study area lies on the Wasatch-Cordilleran hingeline (Kay, 1951), which separates thick miogeoclinal Precambrian and Paleozoic strata and thick Mesozoic strata to the west from thinner generally coeval (Cambrian through Jurassic) stable platform strata to the east (Longwell, 1926; Kay, 1951; Tschanz and Pampeyan, 1970). Plate 1.1 is a stratigraphic column of the area compiled from work by the author and previous workers.

Precambrian sedimentary rocks do not exist in the study area. The Paleozoic strata are primarily marine deposits, with some continental deposits. They are composed of cherty dolostone, cherty limestone, sandstone, and some gypsum, shale, and siltstone.

The Mesozoic strata are continental and marine deposits composed primarily of siltstone, sandstone, limestone, dolostone, gypsum, conglomerate, and shale.

The Cenozoic strata are continental deposits composed of all the above listed rock types, and volcanic rocks. The Cenozoic rocks are primarily syntectonic basin-fill deposits related to large-scale extensional deformation, which is discussed in Chapter 2. There is a regional unconformity between the youngest Mesozoic rocks and the Cenozoic rocks.

The rocks in the stratigraphic succession from the base of the Cambrian Tapeats Sandstone to the Jurassic Aztec Sandstone are widely distributed units that exhibit minor lateral compositional change and a lack of angular discordance. The Aztec Sandstone is the youngest pre-orogenic unit. Regional layer-parallel sedimentation has not existed in the area since the initiation of tectonism in the Cretaceous.

The pre-Cretaceous rocks vividly display the styles, modes, and sequence of deformation; however, they do not provide information regarding the timing of deformation. Cretaceous and Cenozoic rocks are of equal utility for discerning styles, modes, and the sequence of deformation; and, they also provide information regarding the timing of deformation. Therefore, special attention is given to Cretaceous and Cenozoic rocks, and their interpretive significance is discussed within the Stratigraphy section of this report. The geologic time scale by Palmer (1983) is used herein.

STRUCTURAL SETTING

The study area lies in the southern Nevada sector of the Sevier orogenic belt (Armstrong, 1968), where a zone of intense Cretaceous deformation is characterized by east- and west-vergent folds and thrusts (Longwell, 1949; Longwell et al., 1965; Armstrong, 1968; Carpenter and Carpenter, 1987). The style of thrusting is of the thin-skinned type (Rodgers, 1949), in which folds and thrusts are confined to the stratigraphic succession. The general framework of fold-thrust systems described by Boyer and Elliott's (1982) landmark paper provides useful guiding geometric principles and analogies to apply to southern Nevada.

The Virgin-Beaver Dam Mountains range, located 50 km (30 mi) east of the study area, represents an exception to the thin-skinned type of contractional deformation. The range is a late Mesozoic thick-skinned (Rodgers, 1949) basement-involved uplift genetically related to a west-dipping reverse fault system (Reber, 1952; Seager, 1970; Moore, 1972; Steed, 1980; Hintze, 1986; Carpenter et al., 1989).

The study area lies in the Basin-Range province, where Oligocene to Recent (D. Carpenter, 1988; J. Carpenter, 1988; Carpenter et al.,1989) crustal extension, or "stretching" (Thompson, 1960), is accommodated by high-angle (typically 60 degrees) normal faulting (D. Carpenter, 1988; J.

Carpenter, 1988) and associated strike-slip faulting in the upper brittle crust.

Basin-range structures overprint Mesozoic contractional structures, but do not reactivate the Mesozoic structures to any significant degree.

STRUCTURE AND STRATIGRAPHY OF REBER MOUNTAIN

BACKGROUND

Reber Mountain lies in the Mojave Desert (Hyde, 1987) and is located at the southern terminus of the Mormon Mountains in southern Nevada. Reber Mountain is topographically separated from the Mormon Mountains yet is part of the Muddy-North Muddy-Mormon Mountains horst block (Plates 1.2 and 1.3). The range is bounded on the west by the Meadow Valley basin, a west tilted half-graben at the latitude of Reber Mountain, and on the east by the Virgin Valley basin, an east tilted half-graben positioned beneath Mormon Mesa/Tortoise Flat (Plates 1.2, 1.3, 2.1, and 2.4).

Plate 1.2 shows the structure and stratigraphic units exposed at Reber Mountain. The plate includes a geologic map, an explanation of stratigraphic units and map symbols, a tectonic map, and structure sections A-A' and B-B.'

STRATIGRAPHY

The Phanerozoic sedimentary rocks in the area are well-stratified, distinctive, and commonly are fossiliferous. Plate 1.1 is a generalized stratigraphic column showing gross lithologies and the thickness of each formation. The local stratigraphy, as well as the regional stratigraphy of surrounding basins and ranges, is shown on seismic and structure section interpretations in Chapter 2. Line 6 (Plate 2.4) crosses the Reber Mountain structural trend 1.6 km (1 mi) south of the geologic map (Plate 1.2). In addition to the mapping and study presented here, the author also completed stratigraphic and structural work of similar detail on trend with Reber Mountain, to the south in the North Muddy Mountains, and on trend to the north in the Moapa Peak area of the Mormon Mountains. This additional work provided critically needed insight and on-trend information for the work at Reber Mountain.

The following is a generalized field description of the stratigraphic sequence at and near Reber Mountain based on observations primarily made by the author.

PALEOZOIC ROCKS

A regional nonconformity separates the igneous and metamorphic Precambrian Vishnu Schist basement complex and the overlying Cambrian Tapeats Sandstone. The Vishnu Schist is composed of gneiss, schist, granitoids (including pegmatite), and migmatite.

Olmore (1971), Wernicke (1982), Taylor (1984), Ellis (1984), and Skelly (1987) completed theses in the Mormon Mountains area. These, along with reports by Longwell et al. (1965) and Tschanz and Pampeyan (1970), provide the largest body of information in the surrounding area regarding the Paleozoic stratigraphy. The Tapeats Sandstone (also called the Prospect Mountain Quartzite) is composed primarily of thin- to thick-bedded brownish red medium- to coarse-grained arkosic sandstone. It is overlain by the Cambrian Pioche Shale.

The Pioche Shale (also called the Bright Angel Shale) is composed primarily of thin-bedded yellowish brown and olive gray micaceous siltstone and shale, sandstone, and limestone and dolostone. It is overlain by the Cambrian Bonanza King Formation.

The rocks in the sequence from the Cambrian Bonanza King Formation to the Pennsylvanian-Permian Bird Spring Formation are composed predominantly of thin- to thick-bedded medium to dark gray cherty dolostone, cherty limestone, and argillaceous dolostone. The percentage of dolostone decreases up-section, and the percentage of limestone, evaporites, and clastics increases up-section. The succession includes, from the base of the sequence to the top: Cambrian Bonanza King Formation and Nopah Formation with Dunderberg Shale at the base of the Nopah; Ordovician Pogonip Group and Ely Springs Dolomite; Devonian Muddy Peak Limestone; Mississipian Monte Cristo Limestone (Redwall Limestone); and Pennsylvanian-Permian Bird Spring Formation. This carbonate deposition was interrupted by deposition of Permian Red Beds. Plate 1.1 shows the stratigraphy in a generalized columnar format.

The Red Beds (Longwell, 1949) are composed primarily of iron oxide-stained quartz arenite, and some gypsiferous intervals. The Jurassic Aztec Sandstone looks similar to the Red Beds, but the two units are distinguished by stratigraphic position, and the Red Beds lack the spectacular cross-stratification characteristic of the Aztec Sandstone. Red Bed deposition was followed by renewed carbonate deposition of the Permian Toroweap Formation.

The Toroweap Formation has two members: the Limestone member, and the Gypsum member (Longwell, 1949). The Limestone member is composed of light gray limestone with bedding parallel bands of dark ferruginous nodular chert. The overlying Gypsum member is composed of white gypsum with some intervals bearing red bed siltstone. The Gypsum member is overlain by the Permian Kaibab Limestone.

The Kaibab Limestone is composed of medium gray limestone with bedding-parallel bands of dark ferruginous nodular chert. The Toroweap Limestone looks similar to the Kaibab Limestone, but the two units are distinguished by stratigraphic position, and the Kaibab Limestone is a slightly darker shade of gray.

MESOZOIC ROCKS

The Triassic Moenkopi Formation lies at the base of the Mesozoic sequence. The Moenkopi contains six distinctive members (Plate 1.1). The members are, from the base of the formation to the top: Timpoweap, Lower Red, Virgin Limestone, Middle Red, Shnabkaib, and Upper Red Member.

The Timpoweap Member is composed primarily of cherty light gray limestone, with some green, black, and brown shale, white gypsum, and rare conglomerate. The Lower, Middle, and Upper Red Members are composed of thin- to thick-bedded gypsiferous red bed siltstone, and rare thin sandstone beds. The term, red bed, is used herein as a descriptive term to indicate the red bed association (Krumbein and Sloss, 1963) the soft very fine-grained iron oxide-stained units posses in this area. The Virgin Limestone Member is composed primarily of light to medium gray limestone and some dolostone, and some red, green, black, and brown silty shale beds. The Middle Red Member contains red bed siltstone, sandstone, and silty white gypsum beds. The Shnabkaib Member is composed of silty white gysum, gypsiferous red bed siltstone, and rare thin beds of limestone and dolostone. At the base of the Upper Red Member there is a distinctive thin-bedded dark indurated siltstone about 30 m (100 ft) thick, referred to here as key unit A, or key-A for short. The formation is overlain by the Chinle Formation.

The Triassic Chinle Formation has two members: the Shinarump Member, and the overlying Petrified Forest Member. The Shinarump Member is composed of Paleozoic-derived chert-clast conglomerate, and quartz arenite. I have informally named the Shinarump Member key-B. The Petrified Forest Member is composed of gypsiferous red bed siltstone, purple and violet silty volcanic ash beds, and rare thin silty sandstone beds. Silicified wood is common at and immediately adjacent to the Shinarump-Petrified Forest contact. The formation is overlain by the Moenave Formation.

The Glen Canyon Group is composed of Jurassic rocks of the following formations: Moenave, Kayenta, and Aztec Sandstone.

The Moenave Formation is composed of gypsiferous red bed siltstone. A dark indurated unit, about 90 m (300 feet) thick, lies at the base of the formation. I have named this unit key-C. The formation is overlain by the Kayenta Formation.

The Kayenta Formation is composed of gypsiferous red bed siltstone and is less vivid in its red bed coloration than the Moenave Formation. The formation is overlain by the Aztec Sandstone.

The Aztec Sandstone is composed of iron oxide- and calcite-cemented cross-stratified fine- to medium-grained quartz arenite. The formation is overlain by the Cretaceous Willow Tank Formation.

CRETACEOUS ROCKS

Cretaceous rocks are subdivided into two formations: the Willow Tank Formation, and the overlying Baseline Sandstone. Cretaceous rocks are the oldest deposits in the area to exhibit localized distribution, angular discordance to previous layer-parallel strata, and rapid lateral change in thickness and lithology. The Cretaceous rocks are synorogenic foreland basin deposits of the Sevier orogeny (Longwell, 1949; Armstrong, 1968; Bohannon, 1983; D. Carpenter, 1986, Schmitt and Kohout, 1986; Carpenter and Carpenter, 1987), and are the youngest rocks to be involved in fold-thrust deformation.

The Willow Tank Formation consists of a basal conglomerate and an overlying claystone unit. The conglomerate unit contains clasts of Precambrian, Paleozoic, and Mesozoic rocks. Precambrian clasts are quartzite. Paleozoic clasts are chert, dolostone, limestone, sandstone, and quartzite. Mesozoic clasts are chert, limestone, dolostone, and Shinarump pebble conglomerate and coarse-grained sandstone. The clasts in the conglomerate indicate that it was not derived from local thrust sheets, but rather, was derived from older structurally higher thrust sheets west of the study area (e.g., the Wheeler Pass-Gass Peak thrust system in the Spring Mountains and the Sheep Range)(D. Carpenter, 1986; Schmitt and Kohout, 1986; Carpenter and Carpenter, 1987; D. Carpenter, 1989). The claystone unit is composed of light gray to gray black claystone, tuffaceous claystone, fine-grained sandstone, and biotite-bearing bentonitic claystone.

The age of the conglomerate unit is constrained via stratigraphic bracketing to be post-Jurassic Aztec Sandstone, and pre-Willow Tank claystone unit. An Albian age has been determined for the claystone unit by the occurrence of the fossil tree fern Tempskya minor (Longwell, 1949; Ash and Read, 1976), and by two K-Ar age determinations of 98.4 m.y., and 98.6 m.y. (Fleck, 1970). The uppermost part of the claystone unit extends into early Cenomanian, as indicated by a K-Ar age determination of 96.9 +/- 3.6 m.y. on biotite from a tuff bed at the intertonguing contact (D. Carpenter, 1989) between the uppermost Willow Tank Formation and the White Member of the overlying Baseline Sandstone (Carpenter and Carpenter, 1987).

The Baseline Sandstone has three members. From the base of the formation to the top these are the White Member, Red Member, and Overton Conglomerate Member (Longwell, 1949; Bohannon, 1983). The White Member is composed of white and red-stained quartzite-bearing quartz arenite, conglomerate, rare thin beds of silicified quartz arenite, and rare biotite-bearing tuff beds. The interbedded conglomerate has a composition which includes quartz arenite clasts, westerly-derived Ordovician Eureka Quartzite clasts (D. Carpenter, 1989), and chert clasts. The reworked clasts of quartz arenite suggest that deformation progressed from west to east in time and space, which resulted in cannibalization of foreland basin deposits. The abundance of Eureka Quartzite clasts indicates that the White Member was derived primarily from westerly thrust sheets. The White Member is Cenomanian in age as indicated by two K/Ar dates of 96.9 +/-

3.6 m.y. and 95.8 +/- 3.5 m.y. (Carpenter and Carpenter, 1987).

In the North Muddy Mountains the Red Member overlies the White Member with slight angular discordance (D. Carpenter, 1989). It does not contain Eureka Quartzite clasts. It contains abundant locally-derived rock materials, which represent the first evidence for the beginning of the emergence of local thrust sheets (Longwell, 1949; Carpenter and Carpenter, 1987). The Red Member is composed primarily of medium- to thick-bedded quartz arenite, which has red bed coloration similar to the Jurassic Aztec Sandstone, and thick intercalated beds of conglomerate containing boulders and cobbles of Jurassic Aztec Sandstone and lesser amounts of other Mesozoic and Paleozoic clasts. The Mesozoic and Paleozoic clasts increase in abundance up-section. A K-Ar age determination of 93.1 +/- 3.4 m.y. (Cenomanian) was obtained on a biotite bearing tuff bed in the upper part of the Red Member (Carpenter and Carpenter, 1987), where it intertongues with the Overton Conglomerate Member. Therefore, the Red Member is Cenomanian, and perhaps slightly younger in age.

The Overton Conglomerate Member overlies the Red Member. Conglomerate beds at the base of the Overton Conglomerate Member intertongue with sandstone and conglomerate beds belonging to the upper part of the Red Member. The Overton Conglomerate Member is composed of thick bedded polymictic conglomerate composed of Paleozoic and Mesozoic boulders, cobbles, and pebbles, in a red sandy matrix much like the arenite of the Red Member, and medium- to course-grained sandstone beds. The abundance of Paleozoic clasts in the conglomerate intervals increases up-section. A K-Ar age determination of 93.1 +/- 3.4 m.y. suggests a Cenomanian and perhaps Turonian(?) age (Carpenter and Carpenter, 1987). The top of the Overton Conglomerate Member is overlain, in places, by klippen of the Muddy Mountain thrust sheet which are composed of highly brecciated and recemented dolostone and argillaceous dolostone of the Cambrian Bonanza King and Nopah Formations (J. Carpenter, 1:12,000 geologic map of the Weiser Ridge Quadrangle, in the North Muddy Mountains, in preparation; D. Carpenter, 1989). The klippen are overlain by the basal conglomerate of the Rainbow Gardens Member of the Horse Spring Formation. Predominantly, the top of the Overton Conglomerate Member is overlain by the Tertiary Horse Spring Formation and younger strata without Paleozoic klippen interposed at the contact.

Thrust sheets were progressively elevated and eroded, shedding detritus into the foreland basin. Reverse stratigraphy is recorded by clasts contained in the sequence from the base of the Red Member to the top of the Overton Conglomerate Member (Carpenter and Carpenter, 1987). The first conglomerate clasts, at the base of the Red Member are composed of cannibalized Cretaceous foreland basin rocks, and Aztec Sandstone which were derived from the emergence of the west-vergent Weiser back thrust sheet, and the east-vergent Muddy Mountain thrust sheet. As thrusting progressed older rocks were exposed and shed into the basin. Progressively older clasts are observed up-section in the Red and Overton Conglomerate Members. The first occurrence of clasts, up-section, is as follows: Jurassic Aztec Sandstone, key-C, key-B, key-A, Virgin Limestone, Timpoweap limestone, Kaibab and Toroweap limestone, Permian Red Beds, limestone from the Bird Spring Formation, and limestone and dolostone from progressively older formations until dolostone of the Cambrian Bonanza King and Nopah Formations occurs in abundance in the upper part of the Overton Conglomerate Member.

The Muddy Mountain thrust sheet ultimately overrode all of the rocks in the area, including the Overton Conglomerate Member of the Baseline Sandstone (Carpenter and Carpenter, 1987). The Overton Conglomerate Member is the youngest synorogenic deposit in the study area associated in large part with the Muddy Mountain thrust sheet. It was the last deposit to accumulate in this part of the foreland basin before the basin was tectonically sealed-in by the physical emplacement of the Muddy Mountain thrust sheet. Renewed accumulation of sediments, in the Cenozoic, did not occur for roughly sixty million years, when deposition of the Horse Spring Formation began.

Seismic Line 6 (Plate 2.4) exhibits base-discordant distal downlap geometry (Mitchum, 1977) of Cretaceous stratal reflectors. Such geometry is suggestive of an aggradational depositional system, which agrees with field observations by D. Carpenter (1989). The most complete and best exposed Cretaceous synorogenic section in southern Nevada lies in the North Muddy Mountains where a detailed study was completed by D. Carpenter (1989).

CENOZOIC ROCKS

Cenozoic rocks are subdivided into two formations: (1) Horse Spring Formation; and (2) Muddy Creek Formation. Three seismic reflection profiles (Chapter 2) show these formations. The fanning upward reflector geometry and eastward-thickening wedge geometry indicate that the Horse Spring and Muddy Creek Formations are syntectonic deposits which accumulated in an actively downdropping east-tilted Virgin Valley half-graben (D. Carpenter, 1988; J. Carpenter, 1988; Carpenter et al., 1989). The half-graben formed in association with normal displacement on the Virgin-Beaver Dam Mountains master fault. Cenozoic strata exhibit base-discordant transgressive onlap geometry (Mitchum, 1977) with all pre-Cenozoic strata.

The Horse Spring Formation is primarily a lacustrine deposit (J. Carpenter, 1986; D. Carpenter, 1988) composed of thin- to medium-bedded light pinkish gray to dark gray cherty limestone and dolostone, massive conglomerate, and thin- to thick-bedded sandstone, siltstone, shale, and magnesite, and beds of biotite bearing tuff. In the study area, limestone of the Rainbow Gardens Member of the Horse Spring Formation is present. The Rainbow Gardens Member is the basal member of exposed Horse Spring Formation (Bohannon, 1984), and was the first Cenozoic deposit to accumulate in the study area. Older Cenozoic deposits, however, likely exist to the east in the depocenter of the Virgin Valley basin (Chapter 2).

The limestone exposed in the study area is composed of thin- to medium-bedded light pinkish gray to dark gray cherty limestone. It is predominantly crypalgalaminate cemented by sparry calcite. Algal mounds, assorted fossil debris, and ostracod fossils are abundant (J. Carpenter, 1986). A strong petroliferous odor is emitted from fresh surfaces of dark gray limestone intervals. Minor hematite staining is seen in hand sample and thin section (J. Carpenter, 1986). At the east-projecting prong, where the Jurassic Aztec Sandstone crops out (Plate 1.2), the lowermost meter (3 ft) of the unit contains angular fine to coarse dolostone pebbles of Cambrian Bonanza King and Nopah Formations, minor well-rounded quartz sand derived from the Jurassic Aztec Sandstone, as well as angular fine- to course-grained limestone intraclasts of the Rainbow Gardens Member (J. Carpenter, 1986). Rare patches, typically having dimensions of one-by-three meters, of hydrothermally mineralized breccia composed of limestone of the Rainbow Gardens Member are suggestive of hot spring activity.

The age of the Horse Spring Formation is early late Oligocene to late middle Miocene (Carpenter et al., 1989). Ekren et al. (1977) reported an age of 29.4 m.y. on Horse Spring beds in the Nevada Test Site, and assigned an age of Oligocene and Miocene to these beds and those in the Lake Mead region. 7 km (4.5 mi) south of the geologic map of Reber Mountain (Plate 1.2), there is a tuff bed interval near the base of the Horse Spring Formation that was K-Ar age dated as 19.6 +/- 0.8 m.y. and 21.3 +/- 0.4 m.y. (Anderson et al., 1972), which places it in the early early Miocene. Tschanz (1960) obtained a K-Ar age of 24 m.y. on this same tuff bed interval, which places it in late late Oligocene. However, this date should perhaps be viewed with suspicion because it is an older analysis, done prior to refinements in the K-Ar age dating technique. East of the Virgin Valley basin, in the Virgin Mountains, a date of 24.3 +/- 1.0 m.y. was obtained on a biotite-bearing tuff 100 m (330 ft) above the base of the Cottonwood Wash Formation (Carpenter et al., In press) which is correlative to the Horse Spring Formation (Moore, 1972).

In the study area, the Rainbow Gardens Member of the Horse Spring Formation can for the most part be considered early Miocene in age, although beds below the stratigraphic level of the tuff interval, if present, may be Oligocene. Because the Horse Spring beds in the Reber Mountain area are at a high fringe area of the Virgin Valley basin they are not considered to be representative of Horse Spring beds in the depocenter, where the maximum age certainly equals or exceeds that of exposed beds. The uppermost beds of the Horse Spring are as young as late middle Miocene (Bohannon, 1984). The Horse Spring is always angularly overlain by the Muddy Creek Formation (with the exception of the depocenter of the Virgin Valley basin).

The Muddy Creek Formation is primarily a basin-fill deposit that has the distinction of being the least deformed stratigraphic unit in the southern Nevada region. It is composed of thin to thick bedded gypsiferous red bed siltstone and sandstone, conglomerate, claystone, some thin limestone beds, thin evaporite beds, and rare basalt flows. The Muddy Creek Formation ranges in age from early late Miocene to Quaternary. The oldest exposed Muddy Creek beds are considered to be about 10.6 m.y. (Bohannon, 1984), which is early Late Miocene. Basal beds in the depocenter of the Virgin Valley basin may be slightly older. A significant amount of exposed Muddy Creek beds are Pliocene in age (Bohannon, 1984). Muddy Creek beds are as young as Quaternary, as suggested by the work of Gardner (1972). The Muddy Creek is overlain in many places by Quaternary alluvium and resistant caliche material. The paleoenvironment for deposition of much of the Muddy Creek Formation was probably quite similar to the present-day dry Mojave Desert climatic environment in the region (Kowallis et al., 1986).

STRUCTURAL GEOLOGY

INTRODUCTION

The rocks at Reber Mountain were complexly deformed during two distinct tectonic episodes. Numerous interrelated events occurred within each episode. The first episode, related to the Sevier orogeny (Armstrong, 1968), was characterized by east-west crustal contraction which culminated in decollement folding and thrusting during the Cretaceous. The second episode, related to basin-range rifting (Stewart, 1971, 1978a, 1978b), was characterized by east-west crustal extension which was accommodated by high-angle (60 degrees) normal faulting (block faulting of Gilbert, 1874 and 1875) and associated strike-slip faulting in the brittle crust beginning in the Oligocene (D. Carpenter, 1988; J. Carpenter, 1988; Carpenter et al., 1989) and continuing to the Recent (Moore, 1972).

STRUCTURES OF THE CONTRACTIONAL EPISODE

Fold-thrust structures of the contractional episode represent the first deformational features to affect the stratified rocks in the area.

MUDDY MOUNTAIN THRUST

The Muddy Mountain thrust is the surface above which a regional east-vergent erosion thrust sheet rode (Longwell, 1928; Longwell, 1949; Longwell et al., 1965). In the North Muddy Mountains, the Muddy Mountain thrust sheet (Longwell, 1928; Olmore, 1971) rode over the Cretaceous Red and Overton Conglomerate Members of the Baseline Sandstone. These are synorogenic units shed from the emergent eastward-advancing thrust sheet. The thrust sheet also overrode three local back thrusts (Carpenter and Carpenter, 1987). Displacement on the Muddy Mountain thrust initiated during deposition of the Red and Overton Conglomerate members and continuing after the end of deposition of the Overton Conglomerate Member, when the thrust sheet continued to advance eastward. A K-Ar age determination of 93.1 +/- 3.4 m.y. (Cenomanian) was obtained on a biotite bearing tuff bed in the upper part of the Red Member (Carpenter and Carpenter, 1987) where it intertongues with the Overton Conglomerate Member. The Red Member is Cenomanian and could be slightly younger, and the Overton Conglomerate Member is Cenomanian to perhaps Turonian(?) at the top (Carpenter and Carpenter, 1987). From these dates, it is concluded that the Muddy Mountain thrust sheet began to advance in the Cenomanian. The thrust sheet probably continued to advance until Turonian time, and possibly longer.

Reber Mountain is one of many klippen of the Muddy Mountain thrust sheet (Plate 1.2). The Reber Mountain klippe is faulted on the west side by the East Meadow Valley normal faults. If not for these faults, Reber Mountain could not be considered a klippe. The exposed Muddy Mountain thrust sheet is composed primarily of resistant dolostone of the Cambrian Bonanza King Formation and Nopah Formation (Plate 1.2). These allochthonous rocks are at the surface, in thrust contact, in a hanging wall flat geometry, with lithologically contrasting overturned soft red bed siltstone strata of the Triassic Petrified Forest Member of the Chinle Formation in the footwall ramp (Plate 1.2, Geologic Map, and Structure Sections A-A' and B-B'). Here, the Muddy Mountain thrust sheet is eroded to the footwall ramp position where it roots, albeit interrupted by the East Meadow Valley normal faults, toward the through-going basal decollement in the subsurface. The Muddy Mountain thrust and the land surface at the time of thrusting can be projected onto the Structure Sections (A-A', and B-B') with confidence on the basis of ramp zone geometry, and projection of the thrust from the North Muddy Mountains, on trend to the south. Displacement on the thrust is thought to be greater than 30 km (discussed in Chapter 2).

At the root zone the thrust presently dips 45 degrees westward, toward the hintward down-dip tectonic source area (Plate 1.2, Structure Section B-B'). The thrust has been folded and onlapped by beds of the Horse Spring Formation which now dip about 35 degrees eastward. Restoration of the Horse Spring dip to horizonal increases the dip on the Muddy Mountain thrust at the axial zone of the Candy Peak syncline by about 35 degrees. The resultant angle, about 80 degrees, is anomalous. This high dip is thought to be related to post-thrust - pre-Miocene deformation associated with the Reber Mountain fault, which is discussed below. The thrust surface and the Cambrian beds in the thrust sheet are generally oriented parallel to one another. Overturned footwall ramp cutoffs are present, however, hanging wall ramp cutoffs are not (Plate 1.2). This is because the hanging wall ramp cutoffs must have been transported east of Reber Mountain such that the observed geometry at Reber Mountain is a hanging wall flat juxtaposed with a footwall ramp.

Because there is persistence, along and across strike, in the stratigraphic position of Sevier thrusts, and there is a complete lack of involvement of crystalline igneous and metamorphic basement complex in the major thrust sheets, many geologists assert that thrust sheets of the Sevier belt originate as lift offs from a regional decollement horizon (e.g., Longwell, 1950; Rubey and Hubbert, 1959; Armstrong, 1968). They argue that if thrusts with tens of kilometers of known displacement steepened westward, great uplifts of Precambrian basement rock would be inevitable. Therefore, major Sevier thrusts are thought to "flatten", or shallow, at depth within the relatively incompetent Cambrian and

Precambrian shale-sandstone sequence, rather than in igneous and metamorphic basement complex or competent carbonates. Thus, a stratigraphically controlled through-going regional decollement results, and accommodates thin-skinned decollement style folding and thrusting.

The lowest stratigraphic unit included in the Muddy Mountain thrust sheet is the Middle and Upper Cambrian Bonanza King Formation, composed of dolostone beds. The underlying Pioche Shale, which lies far beneath the range in the footwall is of course not exposed in the range. The Pioche Shale may represent the through-going regional decollement from which the Muddy Mountain thrust sheet originated (See Plate 1.1). This seems likely, because the Pioche Shale is composed predominantly of weak fissile shale and is stratigraphically encased in competent rocks. The Pioche Shale is underlain by competent Cambrian Tapeats sandstone (also called Prospect Mountain Quartzite), and crystalline igneous and metamorphic basement complex; while it is overlain by competent dolostone of the Bonanza King Formation. Different rock types have different mechanical properties. The Pioche Shale is relatively incompetent in comparison with underlying and overlying units, and is suggested here to have a strong predisposition for acting as a fault gathering zone.

In many places, along the trace of the Muddy Mountain thrust, basal Cambrian Bonanza King beds are absent. Instead, stratigraphically higher Bonanza King beds, and even Cambrian Nopah beds are immediately above the Muddy Mountain thrust contact. For example, at Reber Mountain, the lower half of the Bonanza King Formation is absent. This presents a problem: If soft shales of the Pioche Shale acted as a decollement, then all the Bonanza King beds above the decollement of the Muddy Mountain thrust sheet should be present. So, how can we account for this observation? Two alternate interpretations are considered here:

1. Instead of being positioned in soft relatively incompetent shale of the Pioche Shale the decollement is variously positioned within hard significantly more competent dolostone of the Bonanza King and Nopah Formations.

   In this interpretation the problem is addressed by suggesting that the rock broke the hard way, and represents a class of "strong decollement" (Burchfiel et al., 1982).

2. The Muddy Mountain thrust sheet was subjected to intense imbrication and brecciation. Most notably at and proximal to the basal Muddy Mountain thrust contact (See Plate 1.2, Structure Section B-B'), where the thrust imbrication (Dahlstrom, 1970; Dahlstrom, 1969; Jones, 1984) forms a hinterland dipping duplex system (Boyer and Elliott, 1982) composed of an imbricate family of hanging wall horses. The brecciated dolostone has a complex multiphase history in which breccia fragments were healed together with carbonate cement only to be

brecciated again. This process likely occurred throughout the history of thrust displacement. Fault gouge is also observed. Imbrication and brecciation are common in the Muddy Mountain thrust sheet. Such structure is especially evident at the Muddy Mountain footwall ramp, along the west flank of the Muddy and North Muddy Mountains (Longwell, 1949; J. Carpenter, 1:12,000 geologic map of the Weiser Ridge Quadrangle, in preparation), at Reber Mountain, and north of Moapa Peak (Plates 1.3 and 2.1, Peak 6,471') in the Mormon Mountains (Skelly, 1987; J. Carpenter, 1:12,000 geologic map of the Moapa Peak Quadrangle, in preparation). Imbrication, and probably the formation of hanging wall horses, likely occurred as the thrust sheet encountered the footwall ramp zone composed largely of hard carbonate rocks), where slices of the sheet (hanging wall horses) splayed off. This can be viewed as a process of tectonic removal or erosion of the hanging wall, and tectonic accretion to the footwall.

In this interpretation the problem is addressed by suggesting that: (a) the Pioche is in fact the decollement, above which the whole section, including the basal beds of Bonanza King, detached; and (b) on the ascent up the footwall ramp the basal Bonanza King beds in the Muddy Mountain thrust sheet splayed off to form hanging wall horses that remained in the footwall ramp zone.

An analogy can also be considered in regard to this problem. Much thrust imbrication occurs in all the rocks composing the Muddy Mountain thrust sheet at and east of the Muddy Mountain footwall ramp. However, the Cambrian Dunderberg Shale is unique in the association it has to the most intense zones of imbrication. The Dunderberg is composed of about equal amounts of thin bedded silty dolostone and silty shale such that it is as much a dolostone as it is a shale; and is in this regard much more competent than the Pioche Shale. Nevertheless, the Dunderberg had the characteristic of acting as a fault gathering zone at the base of the Nopah Formation (Plate 1.1, and 1.2, Explanation). The expression of this characteristic can be seen as thrust imbrications on the geologic map in the rocks exposed west of Camp Flat, especially in the vicinity of Candy Peak. Thrust imbrications at the horizon of the Dunderberg are also displayed on Structure Sections A-A' and B-B' (Plate 1.2). The thrust imbrications have much less displacement than the basal Muddy Mountain thrust (See Plate 1.2, Structure Section B-B'). In many places, the Dunderberg is intensely brecciated and sheared exhibiting small-scale folds. Small-scale lateral ramps (Boyer and Elliott, 1982) also commonly occur in association with the Dunderberg. This is especially evident in the Cambrian rocks that compose the Candy Peak syncline, where lateral ramps are expressed both in plan view, and structure section view (Plate 1.2, Geologic Map, and Structure Section A-A') as tectonic pinchouts parallel to fault surface and bedding strike.

During contraction, the Dunderberg which lies above and parallel to the Pioche Shale may have been in a strain field comparable to that acting on the Pioche. Therefore, since the structural evidence observed at Reber Mountain suggests the Dunderberg Shale is a stratigraphic horizon which acted as a fault gathering zone, and it is composed of incompetent material (e.g., silty dolostone and silty shale) relative to the dolostone above and below, then it is strongly argued that less competent rock types were predisposed to acting as fault gathering zones in the contractional strain field acting on the rocks. By analogy, one can deduce that the Pioche Shale also acted as a fault gathering decollement layer.

Most structural geologists have a general bias in thinking that rocks have the tendency to break where they are weakest. This bias comes from field experience, results from experimental rock deformation, and experiences from relatable day-to-day events. The author shares this general bias and therefore favors the second interpretation: that the Pioche Shale is a weak zone in the stratigraphic succession and is at this longitude a through-going regional decollement, and all of the Bonanza King beds were initially in the Muddy Mountain thrust sheet. The beds that are not present simply splayed off and did not make it up the thrust ramp.

In the North Muddy Mountains area (Plates 1.3 and 2.1) the Muddy Mountain thrust sheet is eroded to a structural level ideally suited for viewing the footwall rocks and structures. The thrust sheet is almost completely removed by erosion. Klippen of the Muddy Mountain thrust sheet provide information regarding what formations are present and constrain the geometry of the thrust surface. Yet, most of the area is part of the readily mappable footwall of the Muddy Mountain thrust. Thus, geologic maps (Longwell, 1949; D. Carpenter, 1989; J. Carpenter, 1:12,000 geologic map of the Weiser Ridge Quadrangle, in preparation) can be viewed as footwall maps directly below the Muddy Mountain thrust. The North Muddy Mountains and parts of the Tule Springs Hills represent two of the most extensive areas along the trend of the Keystone/Red Spring-Muddy Mountain-Tule Springs thrust sheet (Armstrong, 1968) where preservation is at this structural level. The presence of the Muddy Mountain thrust sheet masks the underlying footwall geology in parts of the Tule Springs Hills and the east flank of the central Mormon Mountains (Tschanz and Pampeyan, 1970) and at the Muddy Mountains (Longwell, 1949; D. Carpenter, 1989).

The geology of the North Muddy Mountains (Longwell, 1949; J. Carpenter, 1:12,000 geologic map of the Weiser Ridge Quadrangle, in preparation) can be projected with confidence on-trend northward to Reber Mountain. This is greatly facilitated by exposures of distinctive stratigraphic units in the footwall of the Muddy Mountain thrust. The fault-bend anticlinal fold (Suppe, 1983) depicted on Structure Section B-B' is projected from the North Muddy Mountains, to the south (Plate 1.3 and 2.1). The Cretaceous Overton Conglomerate, in the footwall of the Muddy Mountain thrust, and the Weiser back thrust are also projected.

Relations between Cambrian formations of the Muddy Mountain-Tule Springs thrust sheet (Armstrong, 1968) and Jurassic formations of the autochthon support the continuation of the thrust sheet toward the north part of the Beaver Dam Mountains. Hanging wall cutoffs are not preserved for the Muddy Mountain thrust system in Nevada. Thus, only poorly constrained minimum estimates of displacement on the thrust can be estimated. However, there is a large thrust klippe in the Beaver Dam Mountains in southwest Utah that may be the Muddy Mountain thrust sheet. If so, displacement can be approximately determined. On this basis, it is estimated that the Muddy Mountain thrust system records more than 30 km of shortening. This is discussed in Chapter 2.

WEISER SYNCLINE

The Weiser syncline (Plate 1.3 and 2.4) (Longwell, 1949) is a regional east-vergent structure having a minimum north-south trend-length of 55 km (35 mi), starting in the south at the Buffington Window in the southwest part of the

Muddy Mountains (D. Carpenter, 1989), and continuing northward to the Moapa Peak area in the Mormon Mountains (Olmore, 1971)(Plates 1.3 and 2.1). The Weiser syncline is an overturned fold and in many places is recumbent. The panel of overturned beds in the upper limb of the fold measures up to 6 km in an east-west direction. In the North Muddy Mountains the fold is subdivided into two segments by a subparallel back thrust, the Weiser back thrust (Longwell, 1949; Carpenter and Carpenter, 1987; J. Carpenter, geologic map of the Weiser Ridge Quadrangle, In preparation). The fold is positioned in a complex zone of contractional structure, as it lies in the footwall of the Muddy Mountain thrust, the hanging wall of the North Buffington back thrust (Carpenter and Carpenter, 1987), and is involved in a triangle zone between the east-vergent Muddy Mountain thrust and the west-vergent Weiser back thrust (Carpenter and Carpenter, 1987). These large-scale structural relations are depicted in simplified form on Line 6 (Plate 2.4).

Cambrian through Cretaceous rocks comprise the exposed limb of the Weiser syncline in the Muddy and North Muddy Mountains (Longwell, 1949; D. Carpenter, 1989). In the Moapa Peak area, exposed rocks composing the syncline include strata from the Devonian Muddy Peak Limestone to Triassic Chinle Shinarump Member (J. Carpenter, 1:12,000 geologic map of the Moapa Peak Quadrangle, in preparation). The Reber Mountain exposure of the overturned limb of the Weiser syncline includes beds of the Moenave Formation and

Aztec Sandstone (Plate 1.2). As noted previously, these beds form an overturned section of footwall cutoffs to the Muddy Mountain thrust (Plate 1.2, Geologic Map, Structure Sections A-A' and B-B'). The Cambrian units of the Muddy Mountain thrust sheet at Reber Mountain are positioned on top of the Weiser Syncline. The inverted section of strata comprising the overturned limb of the Weiser syncline on the west side of Structure Section A-A' were projected on the basis of mapping in both the Moapa Peak area (Longwell et. al, 1965; Skelley, 1987; J. Carpenter, geologic map of the Moapa Peak Quadrangle, in preparation) and the North Muddy Mountains (Longwell, 1949; J. Carpenter, geologic map of the Weiser Ridge Quadrangle, in preparation), and on the basis of firm constraints provided by the Muddy Mountain footwall rocks that crop out on the west side of Camp Flat (Plate 1.2). The Weiser syncline is of considerably greater amplitude than Longwell (1949) thought it was (See Plate 2.4). The reason for this is because he believed the Aztec Sandstone was removed by erosion prior to folding and therefore is not in the axis of the fold, and in the North Muddy Mountains, he confused the key-C, at the base of the Jurassic Moenave, for key-B, the Triassic Shinarump conglomerate, which he thought was the upright limb of the fold.

Field relations from the North Muddy Mountains and the Moapa Peak area in the Mormon Mountains, suggest that the kinematic mechanisms accommodating folding of the syncline include: (1) flexural slip faulting, especially along siltstone, shale and gypsum layers, in the Permian through Jurassic section; (2) east- and west-directed inverted limb thrusts and reverse faults (these are faults which formed in overturned strata such that younger strata are thrusted over older strata); and (3) tectonic attenuation and thickening of beds (Longwell, 1949; J. Carpenter, geologic map of the Weiser Ridge Quadrangle, in preparation; J. Carpenter, geologic map of the Moapa Peak Quadrangle, in preparation).

The syncline formed as a result of two opposing contractional structures, the North Buffington back thrust, and the Muddy Mountain thrust (Plate 2.4) (Carpenter and Carpenter, 1987). The first stage of synclinal folding occurred with the inception of the west vergent North Buffington back thrust, which resulted in an east-dipping panel of hanging wall rocks above the east-dipping ramp. At this stage, overturning of beds did not arise, and the syncline existed as a fault-bend (Suppe, 1983) synclinal fold. The final stage of formation of the Weiser syncline was related to the inception of the Muddy Mountain thrust, which ultimately overrode the North Buffington back thrust, and overturned the west limb of the synclinal fold. Inception of the Weiser back thrust followed. The Weiser back thrust (Plate 1.2, Structure Section, A-A') is a back-limb imbricate thrust to the North Buffington back thrust (Plate 2.4) (Carpenter and Carpenter, 1987). The Weiser back thrust is a fault that cut both the lower and upper (overturned) limbs of the Weiser syncline (Plate 2.4), which indicates that it cut through the Weiser syncline after the syncline was fully developed approximately to the present geometry. The Weiser back thrust was overridden and, in places, it and the Narrows anticline (Longwell, 1949) (Plate 1.2, Structure Section A-A') were overturned by the Muddy Mountain thrust (J. Carpenter, 1:12,000 geologic map of the Weiser Ridge Quadrangle, in preparation) (Plate 2.4). The age of associated synorogenic rocks, as previously discussed, places this episode of deformation in the Cenomanian (Carpenter and Carpenter, 1987), although eastward advancement of the Muddy Mountain thrust sheet likely continued into the Turonian.

STRUCTURES OF THE EXTENSIONAL EPISODE

Cretaceous fold-thrust structures did not influence later basin-range structure at Reber Mountain. However, Cenozoic basin-range extensional structures complexly deformed the earlier fold-thrust structures.

CANDY PEAK SYNCLINE

The Candy Peak syncline is a prominent east-west-trending, west-plunging structure exposed for 2.5 km at the northern part of Reber Mountain (Plate 1.2, Geologic Map, Formline Structural Elements map, and Structure Section A-A', and Plate 1.3). The beds composing the fold limbs crop out for 2 km in a north-south direction. The down-plunge view (Mackin, 1950) of the syncline indicates that it is an open fold with an interlimb angle of about 120 degrees. The fold axis plunges 40 +/- 5 degrees to the west. The axial surface typically is vertical, although on the west side of the syncline, where the axis is closer to the Reber Mountain fault, it dips 66 degrees northwest (Plate 1.2, Geologic Map). The rocks forming the syncline are composed of carbonates of the Cambrian Bonanza King and Nopah Formations, contained in the Muddy Mountain thrust sheet. The overturned footwall rocks which compose the Weiser Syncline are likely re-folded with the same geometry as the Cambrian units, in an orientation perpendicular to the trend of the Weiser syncline (Plate 1.2, Structure Section A-A'). At and near the surface, the overturned footwall rocks form a west plunging synformal anticline, which is similar to the west plunging Reber Mountain antiformal syncline located about 1 km north of the Candy Peak synformal anticline.

The limestone unit of the Rainbow Gardens Member of the Horse Spring Formation onlaps the Candy Peak syncline but does not mimic the synclinal geometry exhibited by the Cambrian units (Plate 1.2, Geologic Map, and Structure Section A-A'). This critical relation demonstrates that the syncline was formed prior to deposition of the Horse Spring Formation. The timing of the formation of the Candy Peak syncline is constrained to be post-thrusting (post-Cenomanian and possibly Turonian) and pre-Horse Spring (pre-Miocene) deposition. There are many lines of evidence which indicate post-thrust timing. The most compelling evidence is the fact that it is an east-west-trending syncline, not north-south-trending as would be anticipated with east-west crustal shortening. Also, the numerous thrust imbrications which are folded in the Cambrian units forming the syncline would not form with such an orientation during thrusting. Evidence is presented below which argues for the syncline to have formed in association with Cenozoic structural features (a down-to-the-south east-northeast-trending fault system south of the Moapa Peak area and the East Mormon Mountains), which also constrains the timing of formation as Cenozoic. The next question is: When in the Cenozoic did the syncline form? As noted, the syncline was formed prior to depositional onlap of the Horse Spring, which constrains the timing to be pre-Miocene. The syncline most likely formed during the Oligocene when the Virgin-Beaver Dam Mountains normal fault was initiated and the Horse Spring basin developed. This timing interpretation is discussed in later sections of this report.

The Candy Peak syncline was further deformed since it was depositionally onlapped by the Horse Spring. The structural features that have affected it since that time include the Dry Canyon fault, a set of north-trending faults within the Candy Peak syncline north of the Dry Canyon fault, and the East Meadow Valley high-angle fault system on the west side of the range (Plate 1.2). These structures are discussed below. Also, the Reber Mountain horst block has been tilted to the east, at least in the Miocene and probably somewhat in Pliocene to Recent time, by the the Subbasin fault and the Virgin Beaver Dam Mountains fault (Plate 2.6), which are discussed in Chapter 2.

REBER MOUNTAIN FAULT

The Reber Mountain fault is part of a system of down-to-the-south normal faults which separate the south part of the Mormon Mountains and the East Mormon Mountains from the Virgin Valley basin. The evidence for these faults comes from several observations: (1) surface mapping (Olmore, 1971; Longwell et al., 1965; J. Carpenter, geologic map of the Moapa Peak Quadrangle, in preparation) showing such faults; (2) a Bouguer gravity anomaly which exhibits a steep negative gradient into the Virgin Valley basin (Kane et al., 1979) in response to low density Cenozoic basin fill; (3) a profound topographic anomaly of the range in contrast to the basin; and (4) the extreme structural relief on the Muddy Mountain thrust. The relief is demonstrated by the realization that the Muddy Mountain thrust projects over the top of the Weiser syncline at Moapa Peak (Plates 1.3 and 2.1), in the Mormon Mountains where it is greater than 6,471 ft (1,972 m) in elevation. This elevation is conservative because the thrust sheet is eroded and the comparable part of the Muddy Mountain footwall ramp lies in the subsurface at Reber Mountain. At Reber Mountain the thrust is at an elevation of 2,500 ft (762 m) (Plate 1.2).

The dip of Cambrian units increases near the Reber Mountain fault (Plate 1.2, Geologic Map), and the axial trace of the Candy Peak syncline is deflected from a west-northwest trend to a west-southwest trend. Consequently, the Candy Peak syncline is interpreted to have formed in part by normal drag associated with the Reber Mountain fault (Plate 1.2, Geologic map, and Formline Structural Elements Map). Steep topography exists at the Reber Mountain fault as a result of differential erosion of the rocks at and near the surface on either side of the fault. On the northern upthrown side of the fault, the beds that underlie the alluvium are composed of overturned Permian Red Beds through Triassic Moenkopi Upper Red Member (Plate 1.2, Structure Section A-A'). These units are more readily eroded than the Cambrian units on the south-downthrown side of the fault. Consequently, the downthrown hanging wall of the fault forms the high topography which delineates a fault-line scarp. Note that Structure Section A-A' is a vertically oriented section through Reber Mountain and is drawn more-or-less parallel to strike across a dipping sequence of rocks at the Candy Peak syndline. This is evident by the apparent stratigraphic thicknesses of units shown in the Candy Peak syncline and apparent offset across the Reber Mountain fault (Compare Structure Section A-A' to B-B' on Plate 1.2). These geometries are a result of the two-dimensional aspect of the structure section.

Because the Reber Mountain fault is thought to be associated with the formation of the Candy Peak Syncline, which formed in pre-Miocene time, the timing is also interpreted as pre-Miocene. At least one other pre-Miocene down-on-the-south normal fault is present at Reber Mountain. The fault is located immediately west of the anticline that occurs within the southernmost exposure of the Horse Spring (See Plate 1.2, Geologic Map, and Formline Structural Elements Map). The fault trends through a topographic divide in the range, where it offsets Cambrian units. There is no indication of offset of the Horse Spring by such a fault, which suggests the time of displacement was pre-Miocene. The cause of the formation of the Reber Mountain fault and related down-to-the-south normal faults is likely associated with Cenozoic doming and uplift of the Mormon Mountains (See Plate 1.3, and Chapter 2). In this context, the Reber Mountain fault and related faults represent flank faulting to the Mormon Mountains domal uplift. Doming of the Mormon Mountains is further discussed in Chapter 2, where seimsic section interpretations are used as supportive evidence.

TORTOISE FLAT FOLD BELT

A complex belt of open to tight folds distributed within the Horse Spring is here named the Tortoise Flat fold belt (Plate 1.2, Geologic Map, Formline Structural Elements Map, and Structure Section A-A'). Folding was accommodated by flexural-slip faulting, decollement zones at various stratigraphic levels, and apparently, brecciation within the Cambrian Bonanza King Formation as evidenced in the axis of the Tortoise Flat anticline (Plate 1.2, Structure Section A-A'). The most significant fold of the Tortoise Flat fold belt is a west-northwest-trending syncline located at about the central area of exposed Horse Spring, immediately south of the Tortoise Flat anticline and the Dry Canyon fault

(Plate 1.2, Geologic Map). This fold, here named the Tortoise Flat syncline, is part of a broader synformal feature named the Tortoise Flat synform. The distinction between the Tortoise Flat synform and syncline is that the syncline is part of the broader synform. The synform has a broad synclinal shape (which is mimicked by the basal Horse Spring unconformity) upon which many shorter wavelength folds are superimposed (See Plate 1.2, Geologic Map and Formline Structural Elements Map). The strike of a 1-2 km-wide panel of Horse Spring beds changes from generally north-south, south of the synformal axis, to east-northeast, north of the synformal axis. Thus, the beds north of the synformal axis record right-lateral flexure to the east. The intensity and tightness of folding increases in the proximity of the Dry Canyon fault (Plate 1.2, Geologic Map). Consequently, most of the folds, including the Tortoise Flat synform, are thought to be related to the Dry Canyon fault. Folds at the southern third of exposed Horse Spring beds (Plate 1.2) may have formed by different mechanisms. For example, the anticline at the southern part of exposed Horse Spring beds may be a rollover structure related to the down-on-the-east normal faults west of the fold. The timing of folding is constrained as post-Horse Spring and pre-Muddy Creek deposition, which is indicative of Miocene and possibly Pliocene time.

DRY CANYON FAULT

A vertical near-linear fault, here named the Dry Canyon fault, bounds the north end of the Tortoise Flat fold belt (Plate 1.2). The fault is exposed in the range for a distance of 1.5 km. Because the fault is vertical and is thought to have caused right-lateral flexure of Horse Spring beds, it is interpreted to be a right-lateral strike-slip fault (See Plate 1.2, Formline Structural Elements Map). The fault zone is generally 1-2 meters wide. It is easily recognized at places where Bonanza King dolostone and Horse Spring limestone crop out on either side of the fault. The fault appears to have down-on-the-south displacement as well. This is based upon the generally thicker section of Horse Spring beds on the south side of the fault, but this relation does not hold everywhere, apparently because of the predominantly strike-slip component of displacement (See Plate 1.2, Structure section A-A' and the Geologic Map). The fault strikes northeast in the range, and is interpreted to strike more easterly at Camp Flat, where it is not exposed. This change in fault orientation is interpreted because the dip of Horse Spring beds increases in the direction of the eastward projecting prong, where a south dip of 55-65 degrees is attained. It is assumed that this high dip is related to the proximity of the Dry Canyon fault or related faults. This assumption is indirectly supported by the occurrence of linear east-trending brecciated epithermal alteration zones on the north side of the east projecting prong.

It has been established that the Candy Peak syncline likely formed in Oligocene time. The south limb of the Candy Peak syncline is bounded by the Dry Canyon fault (Plate 1.2, Geologic Map, and Formline Structural Elements Map). Cambrian beds south of the fault do not mimic the synformal shape of the Candy Peak syncline. Thus, the evidence indicates the south limb of the syncline formed in association with the Dry Canyon fault. Consequently, the Dry Canyon fault is interpreted to have experienced pre-Miocene, probably Oligocene, displacement. Evidence for this is the angular overlap of Horse Spring beds on the south limb of the syncline (Plate 1.2, Geologic Map and Structure Section A-A'). It was also previously established that many of the folds in the Tortoise Flat fold belt formed in association with the Dry Canyon fault. Horse Spring beds are folded, indicating post-Horse Spring folding. From this, displacement on the Dry Canyon fault is constrained to be Miocene, and possibly Pliocene. Consequently, it is concluded from two different lines of evidence that the Dry Canyon fault experienced (1) pre-Miocene, probably Oligocene, displacement, and (2) Miocene and possibly Pliocene displacement. Syntectonic deposition of the Horse Spring may have occurred near the Dry Canyon fault. This may be true, however, evidence such as growth structures or coarse clastic materials in the Horse Spring near the fault were not observed in the field.

A system of small-displacement oblique-slip faults offsets Cambrian beds that compose the south limb of the Candy Peak syncline (Plate 1.2, Geologic Map). The structural history of these faults is not well constrained, however, one of the faults juxtaposes Horse Spring beds with Cambrian beds, and is accompanied by folding of the Horse Spring beds (Plate 1.2, Geologic Map and Structure Section B-B'). Therefore, this fault experienced Miocene or younger displacement, i.e., post-Horse Spring deposition. Displacement on these faults dies out to the north away from the Dry Canyon fault, which may suggest they are related to the Dry Canyon fault. They may have formed as a result of crowding related to movement on the Dry Canyon fault. Crowding and accomodating structures associated with the Dry Canyon fault are further discussed below.

The existence and orientation of folds in the Tortoise Flat fold belt suggest there is a restraining bend (Crowell, 1974) associated with a change in the strike of the Dry Canyon strike-slip fault. Evidence for this comes from fold and fault orientations (Plate 1.2, Geologic Map). Many of the fold axes proximal to the Dry Canyon fault are oriented roughly east-west. Others are oriented northeast-southwest. Still others are oriented east-west but are deflected to a northeast-southwest orientation in the proximity of the Dry Canyon fault. The pattern of east-west fold axes suggests the general direction of maximum contraction was oriented roughly north-south, whereas the northeast-southwest fold axes suggest the direction of contraction was oriented roughly northwest-southeast. The deflected folds are thought to have initially formed in the north-south oriented strain field. Continued displacement on the Dry Canyon fault presumably brought the folds toward the restraining bend where they were flexed to a northeast-southwest orientation in the northwest-southeast direction of contraction. This seems reasonable for most of the folds of the Tortoise Flat fold belt. However, there are anomalies, e.g., the Tortoise Flat anticline (Plate 1.2, Structure Section A-A'), which maintains an east-west trend for the entire length of the fold axis.

The amount of right-lateral strike-slip displacement on the Dry Canyon fault cannot be determined from observed offset on corresponding features on either side of the fault. As previously noted, the right-lateral sense of displacement is interpreted from the right-lateral flexure of Horse Spring beds on the south side of the fault. However, the amount of strike-slip displacement probably does not exceed 5-10 km. This is suggested because the Jurassic rocks that crop out north and south of the fault are not noticeably disrupted from the outcrop pattern that would be expected for the overturned limb of the Weiser syncline (Plate 1.2). If the Dry Canyon fault did have a great amount of offset, then it is fortuitous that the rocks on either side of the fault are what would be expected for the overturned limb of the Weiser syncline without the fault, or with little offset on the fault.

MOAPA PEAK-REBER MOUNTAIN SHEAR ZONE SYSTEM

Olmore (1971) suggested the Moapa Peak shear zone, located at the south end of the Mormon and East Mormon Mountains (Plate 1.3), was a Cretaceous thrust-related feature which formed as a result of differential shortening north and south of the northeast-southwest-trending shear zone. However, the evidence for timing that he provided does not preclude a younger age. The shear zone is evidenced by dextral oroflexure, i.e., mountain bend (Albers, 1967), of the Weiser syncline (Plate 1.3), which formed in the Cenomanian. Axen and Skelley (1984) and Skelley (1987) suggested the Moapa Peak shear zone is a Tertiary feature related to low-angle normal faults in the Mormon Mountains. In a later section and in Chapter 2, evidence is presented for a gravity-slide origin for the translocated Paleozoic blocks in the Mormon Mountains. This interpretation disputes rooted low-angle normal faulting in this area and any interpretations built on that misinterpretation. Skelly (1987) viewed the east-trending folds in the Horse Spring, at Reber Mountain, as indirect evidence for the timing of the Moapa Peak shear zone. The amount of right-lateral motion in the Moapa Peak shear zone north of Reber Mountain was estimated to range from 10 to 20 km (Olmore, 1971).

The newly-discovered Tortoise Flat synform, the right-lateral flexure of Horse Spring beds, and the associated Dry Canyon strike-slip fault are the first features to be discovered that provide direct evidence bearing on the timing of shear zone deformation. Here, these features are thought of collectively as the Reber Mountain shear zone system.

The Moapa Peak and Reber Mountain shear zones are parallel to one another and have the same sense of displacement (Plate 1.3). These similarities in strain suggest the two areas experienced a similar paleostrain field. By this association, the timing of the Moapa Peak shear zone is interpreted to be the same as that for the Reber Mountain shear zone. Therefore, the timing of formation of the Moapa Peak-Reber Mountain shear zone system (Plate 1.3) is pre-Miocene (probably Oligocene), and Miocene, and possibly Pliocene.

Plate 1.3 shows the Moapa Peak-Reber Mountain shear zone system in a regional tectonic context. The sinusoidal Virgin-Beaver Dam Mountains fault is a major basin-range high-angle normal fault which initiated in the Oligocene and has been active up to the Recent (Chapter 2). The fault is evidenced by Basin-Range physiography, a steep Bouguer gravity gradient across the trace, offset of Holocene fan deposits, and seismic reflection profiles (Chapter 2).

Here, the Virgin-Beaver Dam Mountains fault is interpreted to be responsible for the developement of the Moapa Peak-Reber Mountain shear zone system. Consequently, the Moapa Peak-Reber Mountain shear zone system is interpreted to have initiated in the Oligocene.

The trace of the Virgin-Beaver Dam Mountains fault (Plate 1.3) is north-south at the north segment, is arcuate with a concave-west geometry at the north-central segment, is arcuate with a convex-northwest geometry at the south-central segment, and is again north-south at the south segment (Plate 1.3). The change in orientation of the fault along the four segments is quite abrupt, especially for a fault with such large displacement (Chapter 2). The sinusoidal shape of the fault is thought to be the cause for different amounts of westward movement of the downdropped Virgin Valley hanging wall block. The shape of the Virgin Valley graben is primarily attributable to the shape of the Virgin-Beaver Dam Mountains fault. The gross shape of the basin is also sinusoidal. The southwest part of the basin projects toward the North Muddy Mountains and the southern terminus of the Mormon Mountains. The Moapa Peak-Reber Mountain right-lateral shear zone system is interpreted to have developed as a result of greater westward movement of the hanging wall block south of the shear zone system, at the north part of the projection of the hanging wall block.

Where the trace of the Virgin-Beaver Dam Mountains fault changes abruptly from the north-central segment to the south-central segment it has oblique slip with a component of dip slip displacement and a component of left-lateral strike-slip displacement. The Arrowhead left-lateral shear zone system (D. Carpenter, 1989) is interpreted to have developed as a result of the left-lateral component of displacement on the Virgin-Beaver Dam Mountains fault. In this case, the greatest amount of westward movement of the hanging wall block was on the north side of the shear zone system (D. Carpenter, 1989).

EAST MEADOW VALLEY AND OVERTON HIGH-ANGLE FAULT SYSTEMS

The East Meadow Valley and Overton high-angle normal fault systems border the west and east sides of Reber Mountain, respectively (Plate 1.2). The faults are mapped based on surface exposures, where present, seismic data, steep gravity gradients (Kane et al., 1979), and the physiography which is approximately mimicked by the contact between bedrock and basin-fill. The interpretation of Seismic Line 6 (Plate 2.4) shows these high-angle normal faults. The Meadow Valley fault system truncates the west side of Reber Mountain, and is therefore constrained to be post-Horse Spring and post-shear system deformation. Most of the displacement on these faults is likely Pliocene and younger, although displacement may have initiated in Miocene time.

DENUDATION FAULTS

Small-scale gravity slide blocks and slump masses have been observed throughout southern Nevada, southwest Utah, and northwest Arizona by many different field geologists. The study area contains many of these features, which are especially prevalent within Horse Spring beds. Most of the gravity slide blocks and all the slump masses are too small to adequately show on the Geologic Map (Plate 1.2). The bodies of rock lie above rootless denudation faults that are oriented parallel, subparallel, and even perpendicular to bedding. The dip on the faults is typically 10 to 35 degrees, but ranges from horizontal to vertical; sometimes on a single fault surface. Listric geometry is common. The displacement on the faults typically is small at Reber Mountain, usually only 5 to 100 ft. The distinctive feature of these faults is that they do not root into the subsurface. This can often be directly observed in the field. It is thought that these small-scale structures result from instability under the influence of gravitational force. The instabilty is caused by the removal of lateral support as a consequence of basin-range faulting and associated erosion (J. Carpenter, 1988; Carpenter et al., 1989). Most of the faults cause the omission of stratigraphic section, although some are responsible for the duplication of stratigraphic section.

REINTERPRETATION OF THE MORMON PEAK LOW-ANGLE NORMAL FAULT

Geophysical and geological information, presented in Chapter 2, provides strong evidence in support of a high-angle (60 degrees) normal fault style of crustal extension, and suggests that rooted low-angle normal faults do not exist in the area (D. Carpenter, 1988; J. Carpenter, 1988, Carpenter et al., 1989). However, it is noteworthy to consider here some of the implications of the rooted low-angle (5-25 degrees) normal fault model proposed by Wernicke (1981, 1982), and how these implications condemn such a model. In his model, based on mapping part of the central Mormon Mountains (Plates 1.3 and 2.1), Wernicke proposed the idea that crustal extension occurs by means of simple shear between rigid blocks on a very shallowly-dipping fault. The crust above the fault, or "extensional thrust" (Wernicke, 1981), moves in the down-dip direction, thereby representing the extensional analogue of large thrust faults of contractional regimes. The primary difference between this model and Gilbert's (1874, 1875) model is the fault angle. Wernicke proposed that normal faults initiate at angles of 5 to 25 degrees, whereas Gilbert and hundreds of other geoscientists have constrained fault angles to generally be about 60 degrees from field observations, seismic reflection profiles, and constraints provided by gravity modeling.

Wernicke (1982) and Wernicke et al., (1984, 1985) proposed that a west-dipping low-angle (20-25 degrees) normal fault, the "Mormon Peak detachment", lies on the west flank of Reber Mountain, in the position where I map the East Meadow Valley high-angle faults (Plate 1.2). This interpretation is based on the occurrence of the wide-spread distribution of translocated blocks of Paleozoic strata that veneer the Mormon Mountains. The small translocated blocks were interpreted to be remnant pieces of a single large hanging wall sheet that moved west. Furthermore, Wernicke et al., (1985) interpreted all major elements of the the modern topography between the Meadow Valley Mountains and the East Mormon Mountains as being directly attributable to low-angle normal faults.

In this interpretation Reber Mountain is in the footwall, and Meadow Valley basin and the Meadow Valley Mountains are in the hanging wall of the Mormon Peak low-angle normal fault. In other words, the Meadow Valley Mountains and Meadow Valley basin faulted from off the top of Reber Mountain and moved west 20 km. The 20 km of west-directed displacement of the hanging wall, the "Mormon Peak extensional allochthon", was proposed to have occurred in the middle to late Miocene, and perhaps into the Pliocene. The timing is interpreted from the occurrence of imbricately normal-faulted mid- to late Miocene extrusive volcanic rocks, including ash-flow tuffs and basaltic andesite, which are truncated by a low-angle fault structure (the "Mormon Peak detachment") (Wernicke et al., 1985). This fact alone is cause for great concern, because there is not a way to account for extrusive (i.e., surficial) volcanic deposits lying in contact with the footwall of what is interpreted to be a large hanging wall sheet. The question is: How did the volcanic deposits avoid the hanging wall and move down to the structural level of the footwall? It could be argued that the volcanic rocks were faulted down onto the footwall as distension occurred in the westward moving hanging wall. I believe such an argument is well beyond the bounds of reason, and a simpler explanation is given here that solves this problem: The volcanic rocks were deposited at, or very near, the present structural level in the range, and were subsequently involved in deformation associated with a rootless gravity slide mass. As will be shown below, the above alternate interpretation, although viable, is a moot point in comparison to a more critical issue concerning the extrusive volcanic rocks and the low-angle normal fault model itself. The volcanic rocks were used by Wernicke (1982) to interpret the timing on his Mormon Peak low-angle normal fault. There are problems with his timing interpretation, but even more importantly, there are serious structural geometry problems with the low-angle normal fault model.

The Meadow Valley Mountains lie 18 km west of Reber Mountain (Plates 1.3 and 2.1). The implication of the low-angle fault model put forth by Wernicke (1982) and

Wernicke et al. (1984, 1985), is that the rocks composing the Meadow Valley Mountains and the rock composing the Meadow Valley basin faulted from off the top of Reber Mountain and the Virgin Valley basin (J. Carpenter, 1988). The Meadow Valley Mountains are composed of Paleozoic rocks as young as Pennsylvanian at the latitude of Reber Mountain (Longwell et al., 1965). Until the removal of the hanging wall rocks had occurred, (i.e., the "Mormon Peak extensional allochthon"), via 20 km of west-directed displacement in middle to late Miocene time, Reber Mountain was covered by the rocks that now compose the east flank of the Meadow Valley Mountains and Meadow Valley basin (Plate 1.3). This is not possible because at Reber Mountain and the North Muddy Mountains (Plates 1.2, 1.3, and 2.1) the Horse Spring Formation, of early Miocene (possibly late Oligocene) age (i.e., older than the age invoked for the Mormon Peak low-angle normal fault), was deposited on Cambrian to Cretaceous rocks. The Horse Spring lacustrine beds (Bohannon, 1984; J. Carpenter, 1986) could not have been deposited if prior to extension the rock composing the Meadow Valley Mountains and the Meadow Valley basin had been on top of Reber Mountain. Consequently, Wernicke's Mormom Peak low-angle fault model does not allow for the existence of the Horse Spring Formation that deposited at Reber Mountain. Tschanz and Pampeyan (1970) and Olmore (1971) were the first geologists to map the Mormon Mountains. Because thrusts are so prevailent in this sector of the

Sevier orogenic belt, they interpreted many low angle fault structures exposed in the Mormon Mountains as thrusts, despite their realization that many of these structures omit section (like a normal fault) rather than duplicate section. Spence J. Reber (1979, Chevron U.S.A, Inc., 1:48,000 Company mapping) mapped these low-angle faults as rootless denudational faults across which section is omitted, and above which gravity slide blocks or masses had moved. Wernicke (1981) also noted that section was omitted across these low-angle faults but interpreted them to be rooted crustal penetrating low-angle normal faults even though there is no evidence supporting such an interpretation, and there is evidence to the contrary. Also, a much simpler explanation for the low-angle faults and the translocated blocks of Paleozoic strata observed in the Mormon Mountains (Tschanz and Pampeyan, 1970; Reber, 1979, Chevron mapping; Wernicke, 1982; J. Carpenter, 1988) is that they are denudation faults associated with locally derived disjunct gravity slide blocks (Reber, 1979, Chevron mapping; J. Carpenter, 1988). The same conclusion has been reached by numerous field geologists working in other areas in the region. J. Carpenter (1988) reinterpreted the translocated blocks to have source areas within the Mormon Mountains that require only 0.5 to 4 km of displacement. The gravity slide blocks moved, under the influence of gravitational force, in various downslope directions on rootless denudation faults. This occurred because of instability created by the removal of lateral support as a consequence of high-angle basin-range faulting and associated erosion. Also, the easternmost gravity slide block reveals east-vergent structural features, including west dipping overturned beds, rather than west vergent as necessary in Wernicke's Mormon Peak low-angle normal fault model (J. Carpenter, 1988)

The overwhelming problem with Wernicke's Mormon Peak low-angle normal fault model ("detachment" model) is that there is a multitude of resultant implications and observations that are condemning; the model invokes complications and numerous problems with regional and local geology, and does not serve to remedy geologic problems. This is discussed in greater detail in Chapter 2.

DISCUSSION AND CONCLUSIONS

The rocks in the stratigraphic section from the Cambrian Tapeats Sandstone to the Jurassic Aztec Sandstone are widely distributed units that exhibit minor lateral compositional change and a lack of angular discordance. The Aztec Sandstone is the youngest pre-orogenic unit. Regional layer-parallel sedimentation has not existed in the area since the initiation of tectonism in Albian and Cenomanian time. The deformed rocks in the Mormon Mountains record two distinct tectonic episodes. Numerous interrelated events occurred within each episode. The first tectonic episode, related to the Sevier orogeny (Armstrong, 1968) was characterized by contractional decollement style folding and thrusting that initiated in the Cenomanian and may have continued into Turonian time. The second tectonic episode was characterized by Oligocene to Recent basin-range extensional rifting which was accomodated in the upper brittle crust by high-angle normal faulting and associated strike-slip faulting.

Fold-thrust structures of the contractional episode represent the first deformational features to affect the stratified rocks in the area. The Weiser syncline, which lies below the Muddy Mountain thrust ramp, is one of a family of structures that were overridden by the eastward advancing Muddy Mountain thrust sheet during Cenomanian and perhaps Turonian time. This timing also applies to the correlative Keystone thrust in the Spring Mountains (Longwell et al., 1965). Jurassic Aztec Sandstone crops out near the axial core of the Weiser syncline in the southern Mormon Mountains. This relation, and the recognition of other distinctive stratigraphic units in the axis, suggests that the Weiser syncline is a broad generally concentric fold having much greater amplitude than previously thought by Longwell (1949). Consequently, the Weiser back thrust, which cut through the Weiser syncline immediately after it was fully formed, has a greater amount of displacement than previously thought. In the southern Mormon Mountains only the upper half of the beds composing the Cambrian Bonanza King Formation are present in the Muddy Mountain thrust sheet. The Bonanza King beds that are present lie in the hanging wall flat position in thrust contact with the overturned Petrified Forest Member of the Triassic Chinle Formation at the footwall ramp. Thrust imbrication, and probably the formation of hanging wall horses, likely occurred as the Muddy Mountain thrust sheet encountered and ascended up the footwall ramp zone (composed largely of competent carbonate rocks) where slices of the thrust sheet (hanging wall horses) splayed off and accreted to the footwall ramp.

Many Cenozoic extension-related structures of the second tectonic episode overprint older fold-thrust structures of the first tectonic episode. The Candy Peak syncline in the Mormon Mountains is one of a family of such structures. The west-plunging east-trending syncline formed in pre-Miocene time in association with the Reber Mountain normal fault, on the north, and the Dry Canyon strike-slip fault on the south. The initiation of displacement on the Virgin-Beaver Dam Mountains normal fault began in the Oligocene. Because the Dry Canyon fault and the formation of the Candy Peak syncline are associated with the Virgin-Beaver Dam Mountains fault, it is reasonable to interpret the time of initiation of the formation of the Dry Canyon fault and the Candy Peak syncline as Oligocene. The Tortoise Flat synform, southeast of the Dry Canyon fault, developed in Miocene and possibly Pliocene time by right-lateral flexure of Horse Spring beds associated with the Dry Canyon fault. The Dry Canyon fault and the Tortoise Flat synform are interpreted to be part of the right-lateral Moapa Peak-Reber Mountain shear zone system. Therefore, the time of formation of the Moapa Peak-Reber Mountain shear zone system is pre-Miocene to possibly Pliocene. The shear system is interpreted to have formed in response to different amounts of west-directed movement of the hanging wall of the high-angle Virgin-Beaver Dam Mountains normal fault, which initiated in the Oligocene. Consequently, the Moapa Peak-Reber Mountain shear zone system is interpreted to have initiated in the Oligocene.

Wernicke (1981, 1982) proposed that the rock composing the Meadow Valley Mountains and the Meadow Valley basin faulted from off the top of the Mormon Mountains in the hanging wall of the Mormon Peak low-angle normal fault. This is not possible for many reasons; one reason being that the model does not allow for the existence of the Horse Spring Formation that deposited in the southern Mormon Mountains. Consequently, the Mormon Peak low-angle normal fault is interpreted to be nonexistent (J. Carpenter, 1988). The lacustrine beds of the Horse Spring Formation exposed in the southern Mormon Mountains deposited on Cambrian to Cretaceous rocks. These lacustrine beds of early Miocene age are much older than the middle to late Miocene age invoked for the Mormon Peak low-angle normal fault and could not have been deposited if prior to extension the rocks composing the Meadow Valley Mountains and Meadow Valley basin (i.e., the Mormon Peak extensional allochthon) had been on top of the Mormon Mountains. The widely distributed translocated Paleozoic blocks exposed in the Mormon Mountains, which were thought to be remnant pieces of a single large hanging wall sheet (the "Mormon Peak extensional allochthon"), are disjunct rootless gravity slide blocks (J. Carpenter, 1988).

REFERENCES CITED

Albers, J. P., 1967, Belt of sigmoidal bending and right-lateral faulting in the western Great Basin: Geological Society of America Bulletin, V. 78, p. 143-156.

Anderson, R. E., C. R. Longwell, R. L. Armstrong, and R. F. Marvin, 1972, Significance of K-Ar ages of Tertiary rocks from the Lake Mead region, Nevada-Arizona: Geological Society of America Bulletin, V. 83, p. 273-288.

Armstrong, R. L., 1968, Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin, v. 79, p. 429-458.

Ash, S. R., and C. B. Read, 1976, North American Species of Tempskya and their stratigraphic significance: U. S. Geological Survey Professional Paper 874, 69 p.

Axen, G. J., and M. F. Skelly, 1984, Folding and low-angle faulting of Mesozoic and Tertiary age, Moapa Peak-Glendale area, southern Nevada: GSA abstract, v. 16. no. 6, p. 434.

Bohannon, R. G., 1983, Mesozoic and Cenozoic tectonic development of the Muddy, North Muddy, and northern Black Mountains, Clark County, Nevada: Geological Society of America Memoir 157, p. 125-148.

Bohannon, R. G., 1984, Nonmarine sedimentary rocks of Tertiary Age in the Lake Mead region, southeastern Nevada and northwestern Arizona: USGS Professional Paper 1259, 72 p.

Boyer, S. E., and D. Elliott, 1982, Thrust systems: AAPG Bulletin, v. 66, p. 1196-1230.

Burchfiel, B. C., B. P. Wernicke, J. H. Willemin, G. J. Axen, and C. Scott Cameron, 1982, A new type of decollement thrusting: Nature, v.300, p. 513-515.

Carpenter, D. G., 1986, Diagenesis of the synorogenic Baseline Sandstone, North Muddy Mountains, Clark County, Nevada: SEPM, Abstract, v. 3, p. 18-19.

Carpenter, D. G., 1988, Basin-and-range structure in the southern Nevada-Utah-Arizona region via borehole, seismic reflection, and Bouguer gravity data: Insights on Hydrocarbon potential: AAPG, Abstract, v. 72/2, p. 168

Carpenter, D. G., 1989, Geology of the North Muddy Mountains, Clark County, Nevada and regional structural synthesis: fold-thrust and basin-range structure in southern Nevada, southwest Utah, and northwest Arizona: M.Sc. thesis, Oregon State University, Corvallis, Oregon.

Carpenter, D. G., and J. A. Carpenter, 1987, New K/Ar ages from the Baseline Sandstone (Cenomanian), Clark County, Nevada: Isochron/West, No. 49, p. 3.

Carpenter, D. G., and J. A. Carpenter, In preparation, New K/Ar ages from the Horse Spring Formation, Clark County, Nevada, and the Cottonwood Wash Formation (Oligocene), Mohave County, Arizona.

Carpenter, D. G., J. A. Carpenter, M. D. Bradley, U. A. Franz, and S. J. Reber, 1989, **Comment** on: On the role of isostasy in the evolution of normal fault systems, by Wernicke, B. P., and G. A. Axen: Geology, v. 16, p. 848-851.

Carpenter, J. A., 1986, Depositional and diagenetic history of the Rainbow Gardens Member of the Tertiary Horse Spring Formation, Clark County, Nevada: SEPM, Abstract, v. 3, p. 19.

Carpenter, J. A., 1988, Reinterpretation of the Mormon Peak detachment in the Mormon Mountains, southern Nevada: AAPG, Abstract, v. 72/2, p. 168-169.

Crowell, J. C., 1974, Origin of Late Cenozoic basins in southern California, in Dickinson, W. R., ed., Tectonics and Sedimentation: SEPM Special Publication No. 22, p. 190-204.

Dahlstrom, C. D. A., 1969, Balanced cross-sections: Canadian Journal of Earth Science, v. 6, p 743-757.

Dahlstrom, C. D. A. 1970, Structural geology in the eastern margin of the Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geology, v. 18, p. 332-406.

Ekren, E. B., P. P. Orkild, K. A. Sargent, and G. L. Dixon 1977, Geologic map of Tertiary rocks, Lincoln County, Nevada: U. S. Geological Survey Misc. Geol. Inv. Map I-1041.

Ellis, B. J., 1984, Thin-skinned extension superposed on frontal Sevier thrust faults, Mormon Mountains, southern Nevada: Unpublished M.Sc. thesis, Syracuse University, Syracuse, N. Y., 80 p.

Fleck, R. J., 1970, Tectonic style, magnitude, and age of deformation in the Sevier orogenic belt in southern Nevada and eastern California: GSA Bulletin, v. 81, p. 1705-1720.

Gardner, L. R., 1972, Origin of the Mormon Mesa Caliche, Clark County, Nevada: Geological Society of America Bulletin, v. 83, p. 143-156.

Gilbert, G. K., 1874, Preliminary geologic report, expedition of 1872: U.S. Geog. and Geol. Surveys W. 100th Mer. (Wheeler) Progress Rept., p. 48-52.

Gilbert, G. K., 1875, Report on the geology of portions of Nevada, Utah, California, and Arizona, examined in the years 1871 and 1872: U.S. Geog. and Geol. Surveys W. 100th Mer. (Wheeler) Rept., v.3, p. 17-187.

Hintze, L. F., 1986, Stratigraphy and structure of the Beaver Dam Mountains, southwestern Utah, in Griffen, D. T., and Phillips, W. R., eds., Thrusting and extensional structures and mineralization in the Beaver Dam Mountains, southwestern Utah: Utah Geological Association Publications 15, p. 1-36.

Hyde, Philip, 1987, Drylands: The deserts of North America: Harcourt Brace Jovanovich, Publishers, Orlando, Florida, 173 p.

Jones, P. B., 1984, Sequence of formation of back-limb thrusts and imbrications-implications for the development of the Idaho-Wyoming thrust belt: AAPG Bulletin, V. 68, p. 816-818.

Kane, M.F., D. L. Healey, D. L. Peterson, H. E. Kaufman, and D. Reidy, 1979, Bouguer gravity map of Nevada: Las Vegas Sheet, Nevada Bureau of Mines and Geology, Map 61.

Kay, M., 1951, North American geosynclines: Geological Society of America Memoir 48, 143 p.

Kowallis, B. J., and B. H. Everett, 1986, Sedimentary Environments of the Muddy Creek Formation near Mesquite, Nevada in Griffen, D. T., Phillips, W. R., eds., Thrusting and extensional structures and mineralization in the Beaver Dam Mountains, southwestern Utah: Utah Geological Association Publication 15, p. 69-76

Krumbein, W. C., and L. L. Sloss, 1963, Stratigraphy and Sedimentation: W. H. Freeman and Company, San Francisco, 660 p.

Longwell, C. R., 1926, Structural studies in southern Nevada and western Arizona: Bulletin of the Geological Society of America, v. 37, p. 551-584.

Longwell, C. R., 1928, Geology of the Muddy Mountains, Nevada, with a section through the Virgin Range to the Grand Wash Cliffs, Arizona: U. S. Geological Survey Bulletin 198, 152 p.

Longwell, C. R., 1949, Structure of the northern Muddy Mountain area, Nevada: Bulletin of the Geological Society of America, v. 60, p. 923-968.

Longwell, C. R., 1950, Tectonic theory viewed from the Basin Ranges: Geological Society of America Bulletin, v. 61, p. 413-434.

Longwell, C. R., E. H. Pampeyan, B. Bowyer, and R. J. Roberts, 1965, Geology and mineral deposits of Clark County, Nevada: Nevada Bureau of Mines and Geology, Bulletin 62, 218 p.

Mackin, J. H., 1950, The down-structure method of viewing geologic maps: Journal of Geology, v. 58, p. 55-72.

Mitchum, R. M. 1977, Seismic stratigraphy and global changes of seal level, Part 11: Glossary of terms used in seismic stratigraphy, <u>in</u> C. E. Payton, ed., Seismic stratigraphy - applications to hydrocarbon exploration: AAPG Memoir 26, p. 205-212.

Moore, R. T., 1972, Geology of the Virgin and Beaver Dam Mountains, Arizona: Arizona Bureau of Mines Bulletin, 65 p.

Olmore, S. D., 1971, Style and evolution of thrusts in the region of the Mormon Moutnains, Nevada: Ph.D. thesis, University of Utah, 213 p.

Palmer, A. R., 1983, The Decade of North American Geology 1983 Geologic Time Scale: Geology, v. 11, p. 503-504.

Reber, S. J., 1952, Stratigraphy and structure of the Beaver Dam Mountains, Utah: Intermountain Assoc. of Petroleum Geologists Guidebook 7, p. 101-108.

Rodgers, J., 1949, Evolution of throught on structure of the middle and southern Appalachians: AAPG Bulletin, v. 33, p. 1643-1654.

Rubey, W. W., and M. K. Hubbert, 1959, Overthrust belt in geosynclinal area of western Wyoming in light of fluid-pressure hypothesis: Geological Society of America Bulletin, v. 70, p. 167-206.

Schmitt, J. G., and J. B. Kohout, 1986, Early Cretaceous sedimentary evolution of the Sevier foreland basin, Muddy and North Muddy Mountains, Nevada: Geological Society of America, Abstract, v. 18, p. 181.

Seager, W. R., 1970, Low-angle gravity glide structures in the Northern Virgin Mountains, Nevada and Arizona: Geological Society of America Bulletin, V. 81, p.1517-1538.

Skelly, M. F., 1987, The Geology of the Moapa Peak area, southern Mormon Mountains, Clark and Lincoln Counties, Nevada: M.Sc. Thesis, Northern Arizona University.

Steed, D. A., 1980, Geology of the Virgin River Gorge, Northwest Arizona: Brigham Young University Geology studies, v. 27, p. 96-115.

Stewart, J. H., 1971, Basin and Range structure: A system of horsts and grabens produced by deep-seated extension: Geolocial Society of America Bulletin, v. 82, p. 1019-1044.

Stewart, J. H., 1978a, Basin-range structure in western North America: A review, in Smith, R. B., and G. P. Eaton, eds., Cenozoic tectonics and regional geophysics of the western cordillera, Geological Society of America Memoir 152, p. 1-32.

Stewart, J. H., 1978b, Rift systems in the western United States: Tectonics and Geophysics of Continental Rifts: D. Reidel Publishing Company, p. 89-110.

Suppe, J., 1983, Geometry and kinematics of fault-bend folding: Am. Jour. of Sci., v. 283, p. 684-721.

Taylor, W. J., 1984, Superposition of thin-skinned normal faulting on Sevier orogenic belt thrusts, northern Mormon Mountains, Lincoln County, Nevada: Unpublished M.Sc. thesis, Syracuse University, N. Y., 78 p.

Thompson, G. A., 1960, Problem of Late Cenozoic structure of the Basin Ranges: Copenhagen, 21st International Geological Congress Proceedings, Section 18, p. 63-68.

Tschanz, C. M., and E. H. Pampeyan, 1970, Geology and mineral deposits of Lincoln County, Nevada: Nevada Bureau of Mines and Geology, Bulletin 73, 188 p.

Wernicke, B. P., 1981, Geology of the Mormon Mountains, Lincoln and Clark Counties, Nevada: Geological Society of America Abstracts with Program, v. 13, p. 113-114.

Wernicke, B. P., 1982, Processes of extensional tectonics:

Ph.D. thesis, Massachusettes Institute of Technology, 170 p.

Wernicke, B. P., P. L. Guth, and G. J. Axen, 1984, Tertiary extension in the Sevier thrust belt of southern Nevada, in Western Geological Excursions Guidebook, edited by Lintz, J. P., Mackay School of Mines, Reno, v. 4, p. 473-510.

Wernicke, B. P., J. D. Walker, and M. S. Beaufait, 1985, Structural discordance between Neogene detachments and frontal Sevier thrusts, central Mormon Mountains, southern Nevada: Tectonics, v. 4, p. 213-246.

REGIONAL STRUCTURAL SYNTHESIS: FOLD-THRUST AND BASIN-RANGE STRUCTURE IN SOUTHERN NEVADA, SOUTHWEST UTAH, AND NORTHWEST ARIZONA

CHAPTER 2

ABSTRACT

New seismic reflection, gravity, well, and surface geologic data provide significant insight into contractional and extensional tectonics in southern Nevada, southwest Utah, and northwest Arizona. The rocks in the region were complexly deformed during two distinct tectonic episodes. Numerous interrelated events occurred within each episode. The first tectonic episode, related to the Sevier orogeny, was characterized by east-west crustal shortening which culminated in thin-skinned decollement style folding and thrusting during the Cretaceous. The Virgin-Beaver Dam Mountains anticline, a Laramide-type basement-involved uplift, represents the only thick-skinned contractional structure in the region. A detailed retrodeformable (balanced) regional structure section suggests that fold-thrust shortening at the latitude of the Mormon Mountains is a minimum of about 26%.

The second tectonic episode, basin-range rifting, was characterized by east-west crustal extension accommodated by

large-displacement, high-angle normal faults, typically with 60 degrees of dip, in the upper brittle crust. Such faults control the horst and graben structure and accommodate extension by simple shear in the upper brittle crust. Tilted, folded, and faulted horst and graben blocks characterize the crustal structure. A horizontal decoupling zone below the upper brittle crust is estimated to occur at depths between 15 and 18 km, below which lower crustal extension is accommodated by generally uniform penetrative ductile stretching. In this area, basin-range rifting initiated in the Oligocene and continued to Recent time. A detailed retrodeformable (balanced) regional structure section suggests that basin-range extension at the latitude of the Mormon Mountains is about 17%.

Syntectonic sediments began filling the Virgin Valley half-graben in the Oligocene in response to movement on the Virgin-Beaver Dam Mountains high-angle normal fault. A growth relation is interpreted from the fanning-upward seismic reflector geometry and a westward-thinning sedimentary wedge of Oligocene to Recent basin-fill sediments. The syntectonic sediments are more than 8,000 m thick at the basin depocenter. Tertiary strata in the North Muddy Mountains and the Virgin Mountains, with late Miocene and Oligocene K-Ar ages, are in part correlative with those composing the westward thinning syntectonic sedimentary wedge. Older Tertiary strata likely exist in the basin depocenter.

The Virgin Beaver Dam Mountains fault is the largest fault in the area, having more than 8,000 m of normal vertical separation at the latitude of the Virgin Valley basin depocenter. Doming and uplift of the Mormon Mountains occurred primarily in Miocene time in response to displacement on the Virgin-Beaver Dam Mountains fault. As the hanging wall block downdropped it formed the Virgin Valley basin, whereas the Mormon Mountains, at the opposite end of the hanging wall block, were relatively uplifted and deformed into a broad dome.

The Meadow Valley-California Wash basin is composed of three non-overlapping opposing half-grabens, as supported by seismic reflection sections and gravity data. Such data, including well data, and geologic mapping demonstrate that rooted low-angle normal faults ("detachment faults") are nonexistent in this area. The Mormon Peak, Tule Springs Hills, and Beaver Dam/Castle Cliff "detachments," which were thought to be rooted low-angle normal faults, are reinterpreted to be the denudational fault planes above which disjunct rootless gravity slide blocks moved.

Rootless gravity slide blocks, common secondary surficial features in this high-angle normal fault terrane, result from instability induced by the loss of lateral support inherent in block faulted terranes, and from the erosion of range blocks.

INTRODUCTION

The southern Nevada, southwest Utah, and northwest Arizona study area lies primarily in the Basin and Range province. The area lies in the Mojave Desert east of and in the rain shadow of the Sierra Nevada (Hyde, 1987). The area generally has a north-northeast to south-southwest structural and physiographic grain (Plate 2.1). Cenozoic high-angle normal faults overprint and deform earlier Mesozoic contractional structures. Seismic sections and Bouguer gravity data delineate the basin and range geometries produced by the normal faults (D. Carpenter, 1988; J. Carpenter, 1988; Carpenter, et al., 1989). Such data also document the strikes of major basin-bounding faults and the thickness of Cenozoic basin-fill deposits.

Structures in this complex region include Mesozoic thrust faults, high-angle Cenozoic normal and strike-slip faults, and related folds. Gravity slide blocks which have been recognized for more than 50 years in this area have recently caused considerable confusion. Surficial slide blocks move above denudation faults because of the loss of lateral support inherent in high-angle normal fault terranes (D. Carpenter, 1988; J. Carpenter, 1988; Carpenter et al., 1989). The denudation faults can be variously oriented but tend to project down-slope and outward toward the free air-rock interface, and as a result often shallow to low angles. They are in many respects similar to landslides.

Based on mapping part of the central Mormon Mountains in southern Nevada, Wernicke (1981, 1982) proposed a model in which large-displacement, low-angle normal faults accommodate crustal extension. In his model, the faults dip 5 to 25 degrees. To be viable in southern Nevada, the model must be compatible with the regional trend of the Mesozoic fold-thrust belt, the Cordilleran miogeoclinal stratigraphic trend, and geophysical-geologic mapping of Cenozoic basins. We have disputed the model as a viable explanation of the crustal structure in southern Nevada, southwest Utah, and northwest Arizona (D. Carpenter, 1988; J. Carpenter, 1988; Carpenter, et al., 1989) on the basis of the evidence presented herein. This new evidence supports the older tilted block, half-graben, pure-shear, extension model (Stewart, 1971, Stewart, 1980; Gans and Miller, 1983). This model, first conceived in its preliminary form by G. K. Gilbert in 1871, suggests that high-angle normal faults border basins and ranges (Gilbert, 1874 and 1875). The model explains the observed tilting in ranges and basins, the sharply defined linear north-trending range boundaries, and the geological-geophysical data presented herein.

Davis (1979) stated that Basin-Range crustal extension has been explained traditionally by high-angle normal faulting, and he suggested that greater attention be given to other extensional styles, e.g. igneous diking, low-angle normal faults, and ductile flow within the crust. Since 1979, attention has been directed toward styles other than high-angle normal faulting. Low-angle normal faulting (detachment faulting) has in recent years received the greatest amount of attention because these structures were not well-studied until the last 10 or 15 years, although they had been recognized and mapped for decades.

We envision a Basin-Range province that involves different types of crustal extension through time and space. Such a scenario includes acceptance of both high-angle and low-angle normal faulting styles as viable in different places at different times, and superposed one on the other.

In the study area, we show that the tilted block-listric fault pure-shear extension model (Stewart, 1971, Stewart, 1980; Gans and Miller, 1983; Lister et al., 1986) is in general agreement with our new data sets. There is a one-to-one correlation between major high-angle normal faulting (delineated by seismic, gravity, and surface geology data) and basin-range physiography in the region, with only two known exceptions. Also, associated with the half-grabens, bounded by high-angle normal faults, are a number of shear zones and strike-slip faults.

REGIONAL TECTONIC SETTING

The Sevier orogenic belt (Armstrong, 1968) trends through southern Nevada and southwest Utah (Longwell et al., 1965; Armstrong, 1968; Heller et al., 1986). In the North Muddy Mountains (Plates 2.1 and 2.4), the fold-thrust deformation is Cenomanian and perhaps Turonian in age, as determined by K-Ar age dating of synorogenic rocks (Fleck, 1970; Carpenter and Carpenter, 1987) and fossil studies (Longwell, 1949). The determination of provenance and dating of the synorogenic rocks show a west-to-east progression of Sevier thrusting in southern Nevada (Longwell, 1949; Fleck, 1970; Burchfiel et al., 1974; D. Carpenter, 1986; Schmitt and Kohout, 1986; Carpenter and Carpenter, 1987; D. Carpenter, 1989).

Oligocene to Recent (J. Carpenter, 1988; J. Carpenter, 1988, Carpenter et al., 1989) extensional structures overprint older fold-thrust structures (Longwell, 1949; Longwell et al., 1965; Tschanz and Pampeyan, 1970; Bohannon, 1983; D. Carpenter, 1988, Carpenter et al., 1989). Large-scale Cenozoic structures include high-angle normal faults, strike-slip and oblique-slip faults, antithetic faults, rollover anticlines associated with high-angle normal faults, and broad antiformal structures, such as the Mormon Mountains. The antiformal structures form as a result of uplift on the distal end of the hanging wall of a high-angle normal fault system. This is explained in a later section of this paper.

Previously, the initiation of crustal extension was thought to be mid-to-late Miocene (Brenner and Glanzman, 1979; Bohannon, 1984). However, several Oligocene dates on the Horse Spring Formation and the Cottonwood Wash Formation (Tschanz, 1960; Ekren et al., 1977; Carpenter et al., 1989) suggest the onset of crustal extension in the Lake Mead area began, in places, in the Oligocene. This interpretation is supported by the fact that these Oligocene units correlate with fanning-upward (syntectonic) basinal reflectors on seismic sections which have been tied into a synthetic seismogram from the Mobil Virgin River #1-A well.

BASAL CENOZOIC UNCONFORMITY AND CENOZOIC STRATIGRAPHY

Late Oligocene beds may exist in the North Muddy Mountains (Tschanz, 1960), and are documented in the Virgin Mountains (Carpenter et al., 1989). Fluvial-lacustrine sedimentary wedges of Cenozoic age thicken dramatically across many of the downdropped half-grabens. This relation was previously unknown in this area. The Horse Spring and correlative formations were not considered to be syntectonic deposits associated with rifting. Lacustrine algal limestone of the Horse Spring Formation (Bohannon, 1984; J. Carpenter, 1986) and other limestone units of the Horse

Spring and Muddy Creek Formations are evidence for periods when extensive lakes existed.

The Oligocene and Miocene Horse Spring Formation of the North Muddy and Muddy Mountains and Cottonwood Wash Formation of the Virgin Mountains (Moore, 1972) contain conglomerate, silty shale, sandstone, siltstone, lacustrine limestone, evaporites, and a variety volcanic rocks.

The Miocene to Quaternary Muddy Creek Formation consists primarily of sandstone, siltstone, claystone, conglomerate, limestone, evaporites, air-fall tuff, and basalt flows. The rock types reflect an alluvial, fluvial, and lacustrine depositional environment.

Quaternary pediments, wadi-fluvial, and alluvial fan-bajada gravels, sands, and silts dominate the present depositional processes and can be considered a modern analogue of the Muddy Creek Formation. On the seismic interpretations the Quaternary sediments are included with the Muddy Creek Formation.

The Horse Spring Formation unconformably onlaps Cretaceous and older beds in the North Muddy and Mormon Mountains. At the surface, the unconformity dips east between 20 and 30 degrees. In the subsurface (Virgin Valley basin) the unconformity has an east dip between 20 and 27 degrees. Dipmeter data from the Mobil Virgin River #1-A well also demonstrate an east dip between 20 and 30 degrees in the basin. Cretaceous beds occur below Cenozoic beds in parts of the basin as imaged on the seismic lines and confirmed by the Virgin River #1-A well (Plate 2.3).

Other constraints for the unconformity and its geometry in the Virgin Valley basin, include: (1) a synthetic seismogram of the Mobil Virgin River #1-A well (Plate 2.3) which ties into Line 6 (Plate 2.4); (2) a downdropped part of the Muddy Mountain-Tule Springs thrust sheet, imaged on Line 5 (Plate 2.5) which is angularly overlapped by fanning-upward Cenozoic deposits; (3) fanning upward reflector geometry observed on all seismic sections; and (4) gross basin wedge geometry.

SUBSURFACE INFORMATION

WELL DATA

The Mobil Virgin River #1-A wildcat well (drilled in 1980) (M on Plate 2.1), the only well located in the Virgin Valley basin, penetrates the Cretaceous-Cenozoic unconformity at 2,050 m. Cenozoic, Mesozoic, and Paleozoic beds were penetrated as far as the Cambrian Bonanza King Formation. The well reached a total depth of 5,960 m in Precambrian igneous and metamorphic basement complex.

GRAVITY DATA

Bouguer gravity lows are recorded over basins with considerable basin-fill, compared to higher values over adjacent ranges. High-relief (10 to 80 mGals), asymmetric gravity profiles delineate the major bounding faults of many of the basins and are attributed to the juxtaposition of high-density beds in range blocks against low-density basinal strata across the faults. For example, asymmetric Bouguer gravity profiles (Plates 2.4, 2.5, 2.6, and 2.8), recorded across the Virgin Valley basin, demonstrate a half-graben geometry that is confirmed by seismic data. Density data for the rocks in the region come primarily from sources at Chevron U.S.A., Inc. Cenozoic beds are juxtaposed against Precambrian rocks, 2.65 g/cc, along the eastern margin of the basin by the Virgin-Beaver Dam Mountains fault. The density contrast (.31 to 1.03 g/cc) contributes to the significant Bouguer anomaly along the fault (Plates 2.4, 2.5, 2.6, and 2.8, and Table 2.2). A seismic velocity analysis and a density versus depth plot (Plate 2.7) in the Virgin Valley depocenter, SP #1069, Line 4-4A (Plate 2.6; Table 2.1) indicate that surficial Quaternary beds have a density of 1.62 g/cc, and the remaining Cenozoic beds increase to 2.34 g/cc at a depth of 7,930 m. These low-density Cenozoic beds, imaged on the seismic sections (Plates 2.4, 2.5, and 2.6) cause the significant density contrast across the Virgin-Beaver Dam Mountains fault.

SEISMIC REFLECTION DATA

The stratigraphic units shown on the seismic interpretations (Plate 2.2) are correlated to surface geologic information and subsurface well information (Plate 2.3). A widespread, normally angular, unconformity at the base of the Cenozoic sequence is seismically imaged within the Virgin Valley basin (Plates 2.4, 2.5, and 2.6). The unconformity separates 15 to 35 degree east-dipping beds of the Horse Spring Formation from the overlying beds of the Muddy Creek Formation, which dip gently eastward 1 to 8 degrees. Rosendahl and Livingstone (1983) suggest that prominent, basin-wide reflectors on seismic sections in continental rift basins may constitute depositional pulses related to tectonic events. This may apply in the Virgin Valley basin because there is a considerable angular unconformity imaged between the Horse Spring Formation and the Muddy Creek Formation.

Diffractions on Line 4-4A at 3 3/4 s two-way travel time, SP 1070 (Plate 2.6) allow the dip angle of the Virgin-Beaver Dam Mountains normal fault to be examined. Calculations using the obliquity of the seismic line and fault trace (30 degrees) and the apparent dip between the diffractions and the surface trace of the fault (45 degrees by migration and depth conversion) indicate a true dip of about 60 degrees. Because of drag or depositional dip, downdropped Cenozoic beds juxtaposed along the fault dip to the west. When converting unmigrated points to migrated positions they migrate updip, in this case, eastward, resulting in a steeper apparent fault angle. Conversion to depth expands the faster velocity beds deeper in the basin, where the diffractions occur, relative to the near surface low velocity beds. The expansion results in a steeper dip angle as well. These calculations bring the 40 degree west dip on the unmigrated section to 45 degrees by migration and depth conversion, which corresponds to 60 degrees of true dip on the fault. The diffracted energy likely resulted from a point-source termination of a stratal reflector(s). Stratal reflectors represent the fault surface only if they are terminated by it, because they can abruptly end as the result of lateral facies changes to coarse-grained alluvial fan debris before reaching the fault. Consequently, the diffraction point represents a conservative estimate of the dip of the fault surface. Overall, the seismic lines and gravity profiles suggest an average fault dip of 60 degrees. The Virgin-Beaver Dam Mountains fault is approximately planar from 0 to about 6100 m.

STRUCTURAL INTERPRETATION

SEISMIC INTERPRETATION

The locations of the seismic lines are shown on the index map (Plate 2.1). The three lines span a distance of 261 km. Line 4-4a and Line 5-5a (Plates 2.6 and 2.5) cross the Basin and Range province and the Transition Zone (Moore, 1972) into the Colorado Plateau. Line 4-4A (Plate 2.6) is 104 km in length and traverses the Virgin Valley basin oblique to strike. On the west and east ends of Line 5-5A (Plate 2.5), which spans 77 km, structure sections with no vertical exaggeration, and explanations are included. The structure sections show important off-line structures. Line 5-5A and Line 6 (Plate 2.5 and 2.4) are approximately perpendicular to the strike of the Virgin Valley basin. Line 6 (Plate 2.4) spans 80 km. The major structures in the juncture area between the North Muddy and Mormon Mountains are projected into the line of section based on geologic mapping and well data (D. Carpenter and J. Carpenter, unpublished mapping, 1985 to 1988). Uninterpreted stacked seismic sections are shown at the top of each display with the corresponding interpretation and Bouguer anomaly profile shown below. Stratigraphic units for the seismic lines are shown on the explanation (Plate 2.2).

Table 2.2 is a synopsis of information derived from the seismic section interpretations and gravity data. The information contained in the table is discussed in the following descriptions of the Cenozoic basins.

VIRGIN VALLEY BASIN

The Virgin Valley basin is 24 to 32 km wide and is 113 km long (Plate 2.1). Displacement on the Virgin-Beaver Dam Mountains normal fault produced the east-tilted, asymmetric, half-graben geometry of the basin (Plates 2.4, 2.5, 2.6, and 2.8). The vertical component of displacement on the Virgin-Beaver Dam Mountains fault is greater than 8,000 m at the basin depocenter. The Piedmont fault is a deeply rooted splay of the Virgin-Beaver Dam Mountains fault, which offsets Holocene fan deposits (Moore, 1972), shown on the structure section on the east side of Line 5-5A (Plate 2.5). East-dipping, antithetic faults bound the west side of the basin.

Lillie (1984) interpreted half-graben geometry for crust extended during continental rifting and presented examples from the Rio Grande rift (New Mexico), the Keweenawan Rift (Kansas), the Basin and Range Province (Utah), the U.S. Atlantic passive margin, and the Bay of Biscay. Bounding faults for the half-grabens have normal vertical separation as great as 7,000 m (Lillie, 1984). Armstrong (1968) suggested that some high-angle normal faults in the Basin-Range province may have normal vertical separation as great as 9,000 m. These values are similar to those obtained for the Virgin-Beaver Dam Mountains fault.

An asymmetric Bouguer gravity profile, with 50 to 65 mGals of Bouguer gravity relief, is recorded over this segment of the basin, along Line 4-4A (Plate 2.6). Farther north, the relief over an asymmetric profile is over 60 mGals (Plate 2.5). At the latitude of the Mormon Mountains, an asymmetric Bouguer anomaly with 30 to 40 mGals of relief is observed (Plate 2.8). The overall anomaly, up to 70 mGals in places, averages more than 40 mGals. Velocity calculations suggest that more than 8,000 m of Cenozoic deposits have accumulated in the basin since the Oligocene. The Mormon Mountains domal uplift is visible as a relative Bouguer anomaly low. Precambrian basement rocks (2.65 to 2.70 g/cc) are juxtaposed against higher density, Paleozoic miogeoclinal carbonate rocks (2.70 to 2.80 g/cc). The resulting density contrast from 0.10 to 0.05 g/cc can account for the observed gravity anomaly (Plate 2.8).

The North Muddy Mountains horst block (Plate 2.4, SP 725 to 905), exhibits eastward tilt in response to rotation associated with the Virgin-Beaver Dam Mountains fault. The fault exhibits less offset at the latitude of the North Muddy Mountains than it does along strike to the northeast. This is demonstrated by a thicker sequence of syntectonic sediments at the basin depocenter (Plates 2.5 and 2.6). The Arrowhead fault and the Moapa Peak-Reber Mountain shear zone systems are thought to reflect different amounts of west-directed movement of the hanging wall block of the Virgin-Beaver Dam Mountains fault.

The Horse Spring Formation is represented by prominent reflectors from SP 101 to SP 1170 on Line 4-4A (Plate 2.6). The reflectors are flexed by normal drag and truncated along the Virgin-Beaver Dam Mountains fault. They similarly truncate against the high-angle Subbasin fault at SP 425 to 497 (Plate 2.6), and other minor offset faults.

Tertiary volcanic rocks (Plate 2.2) from SP 1230 to 660 on Line 5-5A (Plate 2.5) contain intercalated limestone beds similar to that observed in the Horse Spring Formation (Tschanz and Pampeyan, 1970). Reflections from the Horse Spring Formation, Muddy Creek Formation, and Tertiary volcanic rocks show that these formations thicken in the eastern part of the basin (Plates 2.4, 2.5, and 2.6), as well as in the Virgin Valley subbasin (Plate 2.6). These units show decreasing eastward dip with decreasing age, producing a fanning-upward, wedge-shaped geometry. Such features, typical of growth faulting, demonstrate the syntectonic relation between Cenozoic beds and the Subbasin fault, as well as the Virgin-Beaver Dam Mountains fault.

A contrast in the character of the reflectors marks the contact between the Horse Spring Formation and the overlying Muddy Creek Formation. The contact is an angular unconformity except at the depocenter. This suggests that at the margins of the Cenozoic basin sedimentation was not continuous, while at the subsiding depocenter it was more continuous. The reflectors in the Muddy Creek Formation are generally not as distinct nor as laterally continuous as those in the Horse Spring Formation; however, between SP 1001 and 1160 (Plate 2.6), and at a number of other places, they are distinct. The last movement on the Subbasin fault is older than the Muddy Creek beds which overlap it (SP 497; Plate 2.6). Therefore, the last movement was likely in pre-Quaternary time, probably in the Pliocene.

The Gourd Spring high-angle normal fault mapped on Line 4-4A (Plate 2.6) is interpreted as the southern continuation of the Gourd Spring fault mapped in the East Mormon Mountains (Tschanz and Pampeyan, 1970; Olmore, 1971). It bounds the eastern side of the East Mormon Mountains range block (Plate 2.1). The fault exhibits a growth relation with the Horse Spring Formation and the lower part of the Muddy Creek Formation at SP 533 to 605 (Plate 2.6).

The Muddy Mountain-Tule Springs thrust sheet, SP 510 to 245, is downdropped into the Virgin Valley basin (Plate 2.5) (D. Carpenter, 1988). The prominent reflectors of the thrust sheet downdropped into the basin are similar in character to reflectors at SP 510 to 420 (Plate 2.5) which correspond to the mapped thrust sheet (Tschanz and Pampeyan, 1970).

CENOZOIC SEISMIC SEQUENCE BOUNDARY

Abrupt angular unconformities which exist within the Horse Spring Formation in surface exposures and on Line 6 (Plate 2.4) at the margin of the basin, do not exist in the deeper part of the basin. The relation is observed on seismic lines (Plate 2.4, SP 941 to 1121; 2.5 and 2.6). The angular unconformitites between sequence units on the seismic lines resulted from: (1) episodes of extension; (2) erosional periods, followed by (3) renewed depositional periods. The basal Cenozoic unconformity and several unconformities observed within the Cenozoic section record discrete pulses of crustal extension in the area. Seismic sequence stratigraphic units (Mitchum and Vail, 1977), bounded by unconformities, are packages of rock interpreted to represent distinct periods of normal faulting and deposition. Fanning-upward reflector geometry and lateral thickness variations confined to a single formation or stratigraphic sequence delineate a single period of normal faulting.

Cenozoic syntectonic beds in the Virgin Valley basin occur in at least two uninterrupted reflector packages that are bordered and controlled by high-angle normal faults. The two major Cenozoic packages are defined as the Horse Spring and Muddy Creek seismic sequences (Plate 2.4, SP 905 to 1121). Other less significant seismic sequences occur in the Horse Spring sequence on Line 6 (Plate 2.4). Cenozoic stratal reflectors exhibit base-discordant, transgressive, onlap geometry (Mitchum, 1977) in relation to pre-Cenozoic units. Two Cretaceous seismic sequences are interpreted as the Willow Tank/White Member, and the Red Member/Overton Conglomerate Member sequences (Plate 2.4, SP 833 to 977). These sequences exhibit base-discordant distal downlap geometry (Mitchum, 1977) of stratal reflectors suggestive of an aggrading depositional system.

Geologic mapping (D. Carpenter, 1989) demonstrates that the Arrowhead fault, a left-lateral oblique-slip fault, had Miocene displacement. Five zircon fission track ages for the Red Sandstone unit (onlaps fault) were recorded in this age range within 25 km of the Arrowhead fault (Bohannon, 1984). The Red Conglomerate and Red Sandstone units (Bohannon, 1984) angularly overlie Mesozoic units north of the Arrowhead fault and Paleozoic units south of the Arrowhead fault, constraining the timing of primary displacement to earlier than 11.0 +/- 0.9 to 15.6 +/- 0.9 Ma. The Horse Spring Formation is involved in oroflexural folding by the Arrowhead fault, constraining displacement on the fault as post 19.6 +/- 0.8 Ma (Horse Spring dates from Armstrong et al., 1972). Field evidence in the Mormon Mountains (J. Carpenter, 1989) suggests the Moapa Peak-Reber Mountain shear zone system is similarly onlapped by the Horse Spring Formation and is interpreted as Oligocene to Miocene, but possibly as young as Pliocene in age. These faults were apparently active during deposition of the

Oligocene to Miocene Horse Spring Formation and may have continued to experience displacement during deposition of the Muddy Creek Formation, albeit to a much lesser degree.

The Virgin-Beaver Dam Mountains fault appears to be potentially active. Fault scarps in Holocene basin-fill deposits, visible even on Landsat small-scale imagery, show minor degradation in the field. The fault may have a very long history. It possibly formed as a normal fault during Precambrian rifting, was later reactivated as a reverse fault during Laramide contraction, and subsequently was reactivated again as a Cenozoic normal fault. The Front fault, exposed 8 km to the east in the Virgin Mountains, experienced this history of reactivation (Moore, 1972).

The California Wash fault is exposed on the west side of the North Muddy Mountains and Muddy Mountains. It exhibits a fault scarp juxtaposing footwall Miocene-Pliocene Muddy Creek Formation and "older" Quaternary alluvium in the hanging wall. The "young" alluvium that now occupies the drainages is not cut by the fault. Thus, the last offset could be as young as Pleistocene. Other non-active faults are onlapped by undeformed beds such as the upper part of the Miocene, Pliocene, and Quaternary Muddy Creek Formation.

MEADOW VALLEY BASIN

The Meadow Valley basin is 15 to 25 km wide and 90 to 120 km long. The basin consists of a series of non-overlapping opposing half-grabens. Each half-graben is shown on seismic sections and asymmetric Bouguer gravity anomalies. The half-graben units may be separated by strike-slip accommodation zones. The terms "non-overlapping half-grabens" and "strike-slip accommodation zones" are borrowed from rift terminology recently developed at the East African Rift (Rosendahl, 1987). Displacement on the East Meadow Valley fault, SP 990 to 930 (Plate 2.5) to the north resulted in a east-tilted half-graben. Farther south, displacement on the West Meadow Valley fault (Plate 2.8; and Plate 2.4, SP 509 to 581) resulted in a west-tilted half-graben. Still farther south, at the latitude of the Muddy Mountains, Chevron proprietary seismic reflection data show an east-tilted half-graben.

About 20 mGals of Bouguer gravity relief are recorded across the Meadow Valley half-graben along Structure Section A-A' (Plate 2.8). Farther south along Line 6, 20 mGals of Bouguer relief are observed for the Meadow Valley basin, SP 437 to 761 (Plate 2.4).

Westward tilting of the Horse Spring Formation and Muddy Creek Formation is observed on Line 6 (Plate 2.4). Small displacement antithetic faults, confined to the Horse Spring Formation, oppose the West Meadow Valley fault at SP 509 to 581. The basin is filled with an eastward-thinning Cenozoic sedimentary wedge (Plate 2.4), and gravity and seismic velocity data suggest that these sediments are from 1,800 to 2,100 m thick (Table 2.2).

The Arrow Canyon Range, SP 230 to 460, lies in the hanging wall of the Dry Lake thrust (Longwell et al., 1965) and is a horst block bounded by high-angle normal faults (Plates 2.1 and 2.4). Several east-dipping, high-angle normal faults at SP 401-509 suggest widening of the Meadow Valley half-graben block by step-faulting. The Meadow Valley Mountains, SP 1235 to 1110, are an east-tilted horst block (Plate 2.4) (Tschanz and Pampeyan, 1970). To the south and north of the line, Mesozoic and Paleozoic formations crop out. Geologic mapping (Tschanz and Pampeyan, 1970) confirms a general east-tilt to the range.

The Clover and Mormon Mountains horst block, SP 930 to 840 (Plate 2.5), is bounded by two normal faults, the West Tule Desert fault and the East Meadow Valley fault.

The West Meadow Valley fault has perhaps stepped to the west of the former basin bounding fault, SP 617, which suggests widening of the basin (Plate 2.4). Small antithetic faults are observed adjacent to some larger faults, e.g., the East Meadow Valley fault (Plate 2.4).

Several small structures on the seismic section (e.g., Line 6 at SP 653 to 689 and SP 1121) in the Horse Spring Formation are interpreted as gravity slide structures which rest on rootless denudation faults (Plate 2.4). Similar structures observed in the Horse Spring Formation on the east side of the North Muddy Mountains exhibit small-scale forethrusts, back thrusts, and east-vergent (down-slope) contractional folds, in the toe area, above a glide horizon.

Below the glide horizon the beds dip east and are otherwise undeformed.

COYOTE SPRING BASIN

The Coyote Spring basin is 8 to 16 km wide and 64 to 80 km long. Displacement on the Kane Springs Wash fault system, SP 113 to 149 (Plate 2.4 and 2.8) produced the asymmetric form of the basin. 10 to 15 mGals of Bouguer gravity relief are illustrated across the basin (Plate 2.4).

The basin is widened by west-dipping, listric, high-angle normal faults, SP 110 to 257 (Plate 2.4). Several small-displacement listric step faults are observed on the eastern margin of the basin between SP 185 to 221 (Plate 2.4). East-tilted reflectors in the Muddy Creek Formation are apparent on the faults. Basin-fill deposits are imaged as a westward-thinning Cenozoic wedge deposited on a downdropped half-graben block (Plate 2.4). The basin-fill deposits are about 1,070 m thick (Table 2.2) based on gravity and seismic velocity data.

TULE DESERT BASIN

The Tule Desert basin is 8 to 13 km wide and 24 to 32 km long. Displacement on the West Tule Desert fault, SP 840 to 780 (Plate 2.5) produced the slightly asymmetric geometry of the basin.

The West Tule Desert fault is an east-dipping high-angle normal fault with moderate displacement (Plate 2.5). The Tule Springs Hills and Jumbled Mountain area, SP 420 to 660, represents an east-tilted horst block (Tschanz and Pampeyan, 1970) bounded by the East Tule Desert fault and the Tule fault. The Tule Desert basin appears to be a slightly east-tilted half-graben that exhibits only about 15 mGals of Bouguer gravity relief because of minimal basin-fill deposits and the presence of thick interbedded volcanic flows (Plate 2.5). The density contrast between thick interbedded volcanic flows in the basin (2.2 to 2.8 g/cc) and Mesozoic and Paleozoic rocks in the range blocks (2.5 to 2.8 g/cc) is, of course, low. The Cenozoic beds are estimated to be 1,220 m thick from gravity and seismic velocity data (Table 2.2).

CENOZOIC DOMING AND UPLIFT OF THE MORMON MOUNTAINS

The Mormon Mountains are a broad domal rollover anticline associated with the Carp Road fault, the East Mormon fault, and most notably, with the Virgin-Beaver Dam Mountains fault (Plate 2.8). The Virgin Beaver Dam Mountains fault is the largest fault in the area, having more than 8,000 m of normal vertical separation at the latitude of the Virgin Valley basin depocenter. Doming and uplift of the Mormon Mountains occurred primarily in Miocene time in response to displacement on the Virgin-Beaver Dam Mountains fault. As the hanging wall block downdropped and formed the Virgin Valley basin, the opposite end of the hanging wall block, i.e., the Mormon Mountains, were relatively uplifted as a broad domal antiform.

Detailed field mapping, regional structure section construction (Plate 2.8), and the study of unconformities in Cenozoic syntectonic deposits on seismic sections (Plates 2.4, 2.5, and 2.6), suggest that the Mormon Mountains domal uplift formed primarily in Miocene time. Motion associated with movement on the Virgin-Beaver Dam Mountains fault (Table 2.1 and Plate 2.6) caused the uplift. To visualize the kinematics of the uplift, consider a wooden board floating quietly in a pond when suddenly a water turtle climbs up on one end. The board tilts toward the side the turtle is on and the opposite end of the board rises. The Mormon Mountains are on the side that rises and the Virgin

Valley basin is on the down-side of the kinematic system, i.e., where the turtle is.

Hanging walls of large-displacement high-angle fault systems experience downdropping near the fault, and are relatively uplifted on the end farthest from the master fault. This concept has been applied elsewhere to explain geologic relations that reflect extreme uplift in the basin-range. For example, in the Cherry Creek Range in east-central Nevada (Phil Gans, personal communication, 1987), and in the Roberts Mountains in east-central Nevada (D. and J. Carpenter, 1987 and 1988 Mobil company work).

We employ this kinematic model to explain features in our seismic sections, gravity data, and surface mapping. The features are: (1) the Tule Desert Basin antiform (Plate 2.5); (2) the Mormon Mountains domal uplift (Plates 2.6, and 2.8); and (3) the North Muddy Mountain-Mormon Mountain antiform (breached Tertiary beds) (Plate 2.4). These antiforms are interpreted to be the result of counterbalancing and uplift relative to the downdropping Virgin Valley half-graben. These relations can be observed in a north to south, linear progression for about 100 km. The antiformal trend occurs about 30 to 50 km west of and subparallel to the trace of the Virgin-Beaver Dam Mountains fault, which is more than 120 km in length. The amount of uplift diminishes at latitudes that correspond with the north and south ends of the Virgin Beaver Dam Mountains fault where it loses displacement. The antiform is as close as 30 km to the Virgin-Beaver Dam Mountains fault on the north and south ends. The middle segment of the fault, with the greatest displacement, corresponds to the Cenozoic basin depocenter. The fault displays the maximum divergence with the antiform, about 48 km to the west at this segment. Also, the antiform, i.e., the Mormon Mountains horst block, exhibits the greatest amount of structural relief. This observation may be the result of a relation between the amount of displacement on the high-angle normal fault, the amount of domal uplift, and the fact that the Mormon Mountains lie at the location where the effect of the fault is focused as a result of its arcuate trace.

GRAVITY SLIDE BLOCKS

Areas that experience rapid relative uplift by faulting, tilting on high-angle normal faults, antiformal development on the distal ends of normal fault hanging wall blocks, and plutonic uplifts exhibit gravity sliding. Many geologists who have worked in southern Nevada, southwest Utah, and northwest Arizona have recognized that structural relief created as a result of normal faulting and/or doming has resulted in gravity sliding (Longwell, 1937, 1951; Mackin, 1960; Burchfiel et al., 1974; Hintze, 1986; D. Carpenter, 1988; J. Carpenter, 1988; Carpenter et al., 1989).

Longwell (1937) cited examples of "gigantic landslide breccias" on the west side of the Virgin Mountains with individual blocks more than 30 m long. He demonstrated that some blocks were at least 6.5 km from their bedrock source area. The blocks lie on Pliocene(?) basin-fill deposits and are much like the Castle Cliff slide mass (discussed later). Longwell (1951) described another megabreccia body nearly 5 km wide which lies on Cenozoic lavas, Miocene-Pliocene Muddy Creek Formation (basin-fill), and on Precambrian metamorphic and granitic rocks west of the Black Mountains. The megabreccia is composed of the same Precambrian rocks which are its bedrock source. He pointed out that the lower surface of the megabreccia is planar with striae which trend generally downslope. Longwell (1937; 1951) interpreted the megabreccias as denudation products of rising range blocks. In the Spring Mountains, gravity slide blocks were described as thoroughly brecciated blocks which moved by gravity downslope (Burchfiel et al., 1974).

LOW-ANGLE NORMAL FAULT MODEL FOR CRUSTAL EXTENSION

The Meadow Valley Mountains and translocated Paleozoic blocks in the Mormon Mountains are considered to be part of a west-directed Mormon Peak extensional allochthon by Wernicke (1982) and Wernicke et al. (1984; 1985). The Meadow Valley Mountains are interpreted to be faulted from off the top of the Mormon Mountains and to have moved 20 km to the west on a 20-25 degree, west-dipping, low-angle normal fault (the Mormon Peak detachment) in middle to late Miocene, and perhaps into Pliocene time (Wernicke, 1982; 1985; Ellis et al., 1985). The projection of the Mormon Peak low-angle normal fault and two other low-angle normal faults (Wernicke et al., 1984, Fig. 10) are shown on our seismic reflection interpretation mosaics (Plates 2.4, 2.5, and 2.6), to show them in the context of our interpretation.

We interpret the blocks of the "Mormon Peak extensional allochthon," which veneer the Mormon Mountains as disjunct gravity slide blocks (J. Carpenter, 1988). The slide blocks (Plate 2.8) originated in the Mormon Mountains and moved along glide horizons 0.5 to 5 km down-slope as the result of broad folding, attendant faulting, and the loss of lateral support as a result of high-angle normal faulting and associated erosion (J. Carpenter, 1988). The slide blocks moved in various downslope directions on rootless denudation faults; they exhibit internal structures which strongly argue for downslope displacement.

RECONSTRUCTION

Structure Section A-A' (Plate 2.8) extends from the Meadow Valley Mountains, on the west, to the Beaver Dam Mountains, on the east. Surface geologic data used across the structure section were derived from many authors (Reber, 1951 & 1952; Tschanz and Pampeyan, 1970; Olmore, 1971; Ekren et al., 1977; Wernicke, 1982; Wernicke et al., 1985; Hintze, 1986; Carpenter and Carpenter, unpublished mapping). A generalized version of this structure section is shown in Plate 2.9. In the following section, we use this structure section to illustrate that the "Mormon Peak detachment" does not gradually cut down-section to the west, nor does it have 20 km of lateral displacement.

Two other low-angle normal faults have been suggested to exist in the study area: The Tule Springs Hills low-angle normal fault (Wernicke et al., 1984; 1985) and the Beaver Dam low-angle normal fault (Wernicke et al., 1984; 1988). These faults, along with the Mormon Peak low-angle normal fault, are shown on Plate 2.9. Plate 2.9 shows our high-angle normal fault model and the Wernicke et al. (1984; 1985) and Wernicke and Axen (1988) low-angle normal fault model.

The restored up-dip source area for Paleozoic blocks of the Mormon Peak extensional allochthon (Wernicke, 1982; Ellis et al., 1985; Wernicke et al., 1985) now exposed in the Mormon Mountains would be at elevations in excess of

7,000 to 10,000 m above the North Muddy Mountains, Tule Springs Hills, and the Virgin Valley basin (Plates 2.4, 2.5, 2.6, and 2.8) according to Wernicke's (1982) low-angle normal fault model. The Virgin Valley basin had already accumulated several thousand meters of Cenozoic sediments for about 20 m.y. prior to the proposed time (i.e., middle to late Miocene), of initiation of the Mormon Peak low-angle normal fault. This presents a dilemma, because, according to Wernicke's model the source area (7,000 to 10,000 m elevation) for klippen of the Mormon Peak extensional allochthon could only have existed above a downdropping Cenozoic basin. Clearly, this is not possible.

On Wernicke's palinspastically restored section, blocks of the Mormon Peak extensional allochthon were not indicated by formational nomenclature (Wernicke, 1982; Wernicke et al., 1985), instead they were shown only as solid rock bodies. On our structure section (Plate 2.8), we show: (1) A simpler interpretation for a local source area for slide blocks; (2) The restored position of Paleozoic strata to updip source areas; (3) The restored position in Wernicke's model of the easternmost block (from point B to point B', is 20 km); and (4) The stratigraphic content of each of the blocks of Wernicke's (1985) "Mormon Peak allochthon" (at surface level). We conclude:

1. There is no up-dip (easterly) source area for beds within the easternmost and most elevated block, in partly restored position, in which the

rollover anticline and associated faults of the Eastern Imbricate Normal Fault Belt are restored. For example, there is no possible source area for the Monte Cristo limestone up-dip on the Mormon Peak low-angle normal fault.

2. Restoring point B, 20 km up-dip (eastward) to point B' along a 20 degree west-dipping fault plane results in a source area elevation of over 10,700 m above the Tule Springs Hills and the Virgin Valley basin.

3. Point A locates a slide mass which lies on a carbonate-pebble conglomerate of unknown age, which Wernicke (1982) suggests is a Cretaceous synorogenic deposit. If so, it represents the only occurrence of Cretaceous synorogenic rocks deposited upon the Muddy Mountain-Tule Springs-Keystone thrust sheet. Seven other exposures of Cretaceous synorogenic rocks occur in the Muddy, North Muddy, and southern Mormon Mountains. Without exception, these deposits accumulated on top of Mesozoic rocks and are autochthonous with respect to the Muddy Mountain-Tule Springs-Keystone thrust sheet. We consider a new alternate hypothesis for Wernicke's (1982) undated carbonate-pebble conglomerate: The deposit represents a Cenozoic pebble conglomerate above which a rootless gravity slide block moved. This type of evidence was considered by Longwell (1937, 1951), Cook (1960) and

Hintze (1986) to be crucial evidence for conclusively demonstrating the slide block character of translocated rock masses (Carpenter et al., 1989). "Extensional allochthons," because they are supposed to be rooted slabs of rock, should not involve Cenozoic basin-fill in footwall positions. Rootless gravity slide blocks readily explain such occurrences.

4. The westernmost blocks of the Mormon Peak extensional allochthon could not have been derived from 20 km up-dip on the "Mormon Peak detachment." Demonstrable lateral displacement away from source beds at higher elevations in the range, is at most 5 km in a down slope direction. At the westernmost exposure of the Mormon Peak low-angle normal fault, where it is thought to cut down into Precambrian basement (Wernicke, 1982; Wernicke et al., 1985), the Cambrian Tapeats Sandstone in the hanging wall of the Mormon Peak detachment is displaced from the footwall source area by less than 500 m (Plate 2.8). This close spacial relation between a small slide block and a source certainly does not require 20 km of offset on a low-angle normal fault. It could be argued that this piece of Cambrian Tapeats Sandstone represents a footwall horse of the Mormon Peak low-angle normal fault, by restoring the source terrane 500 m up-dip. However, if this argument is made, then it supports our simpler interpretation of locally derived gravity slide blocks, rather than

klippen of a low-angle normal fault.

5. The easternmost block (Plate 2.8, at point B) of the Mormon Peak extensional allochthon exhibits eastward down-slope overturning of beds near the basal fault contact, which argues strongly for vergence to the east. We do not observe west-vergent structural features that are required in Wernicke's low-angle normal fault model. Displacement on the Mormon Peak low-angle normal fault has been interpreted as mid- to late-Miocene, possibly, continuing into the Pliocene (Wernicke, 1982; Wernicke et al., 1985). This implies the source area would be positioned above the Cenozoic Virgin Valley basin. Because the formation of the Virgin Valley basin predates the low-angle normal faulting invoked by Wernicke (1981, 1982), and Wernicke et al., (1985), there is not an elevated eastern source area for the translocated Paleozoic blocks.

In summary, our seismic sections image thick Cenozoic basin-fill deposits that, along with physiography and Bouguer gravity profiles, constrain the faults to be high-angle (Plates 2.4, 2.5, 2.6, 2.8, and 2.9). To be lower angle than shown on our interpretations, it would be required that the Cenozoic reflectors be offset by such faults. Deep diffractions tie the faults, e.g., the Virgin Beaver Dam Mountains fault, to depths as great as 5,700 m, that corresponds to 3 3/4 seconds two-way travel time assuming an average velocity of 10,000 ft/second (Plate 2.6).

THRUST TRENDS

Many authors (Longwell, 1960; Longwell et al., 1965; Armstrong, 1968; Johnson, 1981; Hintze, 1986; Carpenter and Carpenter, 1987) have recognized a major thrust belt from southeast California to southwest Utah, between the Red Spring-Keystone, Muddy Mountain-Glendale, Tule Springs, and Square Top Mountain thrusts. The Square Top Mountain thrust is interpreted as the northeast continuation of the Muddy Mountain thrust system (Hintze, 1986). In the Muddy Mountains, preserved Cambrian through Mississippian formations are thrust over Mesozoic formations and over the North Buffington back thrust (Carpenter and Carpenter, 1987). In the North Muddy Mountains and southern Mormon Mountains, relations show Cambrian beds thrust over Mesozoic and Paleozoic formations. In the Mormon Mountains, Cambrian beds are thrust over late Paleozoic and early Mesozoic formations. At the Tule Springs Hills thrust Cambrian beds are thrust over Triassic and Jurassic formations. Finally, to the north, the Square Top Mountain segment of the thrust exhibits Permian and Pennsylvanian formations thrust over Mesozoic formations. Thus, the Muddy Mountain-Tule Springs Hills thrust cuts up-section to the east in the hanging wall and footwall as it should along the 135 km trace.

The right-lateral Las Vegas Valley shear zone offsets the Muddy Mountain thrust system and is also suggested to separate an area of upper crustal extension, on the north, from a relatively stable tectonic block, the Spring Mountains (Wernicke, 1982), on the south. In the northern "extended" terrane, four large-scale low-angle normal faults were mapped as the primary structural elements accommodating crustal extension (Wernicke et al., 1984). The Mormon Peak low-angle normal fault is positioned between the Muddy Mountain-Tule Springs thrust and the Gass Peak thrust. The Muddy Mountain-Tule Springs thrust correlates with the Keystone thrust (Longwell, 1960), and the Gass Peak thrust was correlated to the Wheeler Pass thrust (Burchfiel, 1965). The spacing between the Gass Peak thrust and the Muddy Mountain-Tule Springs thrust north of the shear zone and the Wheeler Pass thrust and Red Spring thrust to the south of the shear zone ranges from 40 to 50 km for both segments (Guth, 1981). For this reason, Wernicke (1982) and Wernicke et al., (1985) believed that the Keystone thrust trend must be disrupted at the Mormon Mountains and that the "Mormon thrust" must be a separate entity. This relation (Longwell et al., 1965; Armstrong, 1968) demonstrates that the Mormon Peak low-angle normal fault either has little or no offset, or does not exist. More recently, Wernicke et al., (1988) have accepted the Keystone, Muddy Mountain, Tule Springs Hills thrust trend which contradicts their previous interpretation.

Structure section A-A' (Plate II.8) was constructed using well data (Plate 2.3), gravity data, a low-density isopach map of Cenozoic beds, seismic sections (Line 4-4A and 5-5A), and surface geologic data (Tschanz and Pampayan, 1970; Olmore, 1971; Wernicke, 1982; Hintze, 1986; and Carpenter and Carpenter, unpublished mapping). The structure section crosses the central Mormon Mountains (Plate 2.1) and illustrates relative uplift and normal faulting of older Sevier thrusts and dramatic thickening of Paleozoic units to the west, across the Cordilleran hinge. Dahlstrom's (1969) method of balancing sections was employed to refine the retrodeformable interpretation and constrain the amount of extension and shortening. Palinspastic restoration of the Cenozoic high-angle normal faults and associated folds demonstrates extension of about 17% (111 km present length; 95 km retro-extended length), while restoration of contractional structures indicates minimum shortening of 26% (95 km shortened length; 129 km pre-thrust length). Using the hanging wall ramp Permian stratigraphic cutoff at the Square Top Mountain thrust in the Beaver Dam Mountains (Hintze, 1986) and the Mormon Mountain window footwall Permian cutoff (Tschanz and Pampeyan, 1970), and projecting them parallel to major contractional fold axes, thrust shortening of 34 km, about 26% was also determined in the eastward direction of tectonic transport. Displacement between 25 km and perhaps 50 km was suggested for the

Keystone-Muddy Mountain thrust by Johnson (1981), and generally agrees with our results.

The age of the thrust system is constrained in the North Muddy Mountains by Potassium-Argon dating of synorogenic rocks as 93.1 +/- 3.4 Ma (Carpenter and Carpenter, 1987), and in the northern Beaver Dam Mountains where synorogenic rocks have been fission track age dated as 80.0 +/- 10 Ma (Hintze, 1986). Thus, the age of thrusting is constrained to the late Cretaceous between Cenomanian to perhaps Maastrichtian(?).

TULE SPRINGS THRUST SHEET

Wernicke, (1982) and Wernicke et al. (1985) suggest that the Tule Springs thrust sheet, exposed in the Tule Springs Hills (Plates 2.4, 2.5, 2.6, and 2.8), is part of another low-angle normal fault that underlies the Mormon Mountains. This was suggested to account for the doming of the range Wernicke, 1982; Wernicke et al., 1984; 1985). On the basis of clast-rotated breccia at the contact between the Muddy Mountain-Tule Springs thrust sheet (Mormon thrust sheet of Wernicke, 1984) and the underlying Mesozoic units, at the Tule Springs Hills (Plate 2.1), and small imbricate normal faults in the Muddy Mountain-Tule Springs thrust sheet; it was suggested that the Tule Springs thrust was reactivated as the Cenozoic Tule Springs Hills low-angle normal fault (Plate 2.5) resulting in doming of the Mormon

Mountains (Wernicke, 1982; Wernicke et al., 1984; 1985). A significant problem with the interpretation is that the thrust sheet was already in place prior to extension and does not enter the subsurface until it is in the Mormon Mountains (Plate 2.5 and 2.8). Since the thrust root zone is itself high-and-dry in the range it could not have caused doming of the Mormon Mountains, as it would be required that it lie below the Mormon Mountains in order to cause them to dome. Additionally, the Tule Springs Hills low-angle normal fault is not imaged on seismic data where it was projected (Wernicke et al., 1984, Fig. 10), at SP 1049 to 1085 (Plate 2.4). In fact, between SP 833 and 1157, east-dipping Tertiary stratal reflectors show no evidence of a low-angle normal fault but rather a deep half-graben filled by Cenozoic sediments.

If the Muddy Mountain-Tule Springs thrust had been reactivated, it would not be a "primary" rooted low-angle normal fault. The Bouguer anomaly profile and Line 5-5A (Plate 2.5) suggest that the Muddy Mountain-Tule Springs thrust sheet exposed at the surface and the downdropped portion in the Virgin Valley basin are adjacent (Plate 2.5). No demonstrable renewed displacement has occurred during the Cenozoic.

The Tule Springs low-angle normal fault which must surely offset prior Sevier structures apparently does not offset the trace of the Muddy Mountain thrust system nor does it offset Mesozoic folds. The Muddy Mountain thrust system continues directly across the interpreted hanging wall and footwall portions of the Tule Springs "extensional allochthon."

CORDILLERAN HINGE STRATIGRAPHIC TRENDS

The Mormon Mountains are positioned on the Cordilleran Hinge line. Beds in the Mormon Mountains are of almost cratonal thickness (Olmore, 1971; Wernicke, 1982, Wernicke et al., 1985; Ellis, 1984; Taylor, 1984), whereas to the west a miogeosynclinal thickness is encountered (Tshanz and Pampeyan, 1970). If according to Wernicke's interpretation, the Meadow Valley Mountains had been displaced westward from off the top of the Mormon Mountains, then the stratigraphy and section thickness in the Meadow Valley Mountains should be similar to that in the Mormon Mountains (J. Carpenter, 1988).

A brief outline (Table 2.3) shows the stratigraphic thickness and stratigraphic section in the Meadow Valley Mountains (Tschanz and Pampeyan, 1970; Langenheim, 1963), and the Mormon Mountains (Wernicke, 1982; Ellis, 1984; Taylor, 1984). The stratigraphic section from the Ordovician Pogonip group to the Permian-Pennsylvanian Bird Spring Formation is 3,420 m thick in the Meadow Valley Mountains, while in the Mormon Mountains the same stratigraphic interval is only 1,410 m thick. The Meadow Valley Mountains section is 243% greater in thickness than in the Mormon Mountains (J. Carpenter, 1988). Also, several key formations that exist in the Meadow Valley Mountains die out into unconformities and do not exist in the Mormon Mountains. The formations are: Silurian Laketown Dolomite, Devonian Simonson Dolomite and Sevy Dolomite, Mississippian-Devonian Pilot Shale, and the Mississippian Chainman Shale and Scotty Wash Sandstone. The contrast is so striking, in comparison to the normal westward thickening transition into the miogeocline, that thrust-shortening was suggested to account for it (Langenheim, 1963). If the Meadow Valley Mountains are restored up-and-to-the-east on the Mormon Peak detachment to a position on top of the Mormon Mountains, the thickness contrast is even more profound. The contrast demonstrates that the Mormon Mountains are not a source area for the stratigraphic section in the Meadow Valley Mountains.

CASTLE CLIFF GRAVITY SLIDE SYSTEM

A gravity slide system mapped in the Virgin-Beaver Dam Mountains (Reber, 1951; Cook, 1960; Jones, 1963; Hintze, 1986, Carpenter et al., 1989) has been named the Castle Cliff gravity slide mass (Hintze, 1986), which is underlain by the Castle Cliff denudational fault. Recently, the fault underlying the gravity slide mass has been reinterpreted by Wernicke et al. (1984) and Wernicke and Axen (1988) as a major rooted low-angle normal fault, called the "Virgin-Beaver Dam breakaway detachment."

Field relations argue that the Castle Cliff structure is not a major normal fault, but a rootless denudational fault system at the base of a gravity slide mass now represented by more than 30 blocks (Cook, 1960; Jones, 1963; Hintze, 1986, Carpenter et al., 1989). Brecciated Paleozoic blocks of the slide mass lie 4 to 6 km downslope from the source area on both sides of the Virgin-Beaver Dam Mountains fault (Plate II.8). At least 15 of the slide blocks rest on the Muddy Creek Formation and younger basin-fill deposits (Hintze, 1986), indicating Pliocene to Recent displacement. Hintze (1986) determined that all lines of evidence suggest the structure is the result of gravity sliding. Hintze (1986) and Carpenter et al., (1989) noted the similarity between the Castle Cliff slide mass and the structures exposed in the Mormon Mountains. Similar slide blocks were mapped and interpreted to the south in the Virgin Mountains (Longwell, 1937; Seager, 1970) and to the west in the East Mormon Mountains (Olmore, 1971), and in the Mormon Mountains (J. Carpenter, 1988).

Wernicke and Axen (1988) proposed that during crustal extension, footwalls of low-angle normal faults isostatically rebound and fold at large amplitude-to-wave-length ratios. The Virgin-Beaver Dam Mountains are their "type area" for this style of deformation. They call upon the Castle Cliff denudation fault system (Hintze, 1986) to be a major west-dipping low-angle normal fault, which they refer to as the Virgin-Beaver Dam breakaway zone (VBBZ). In their breakaway fault-detachment model, west-directed displacement of an extensional allochthon, above the VBBZ, resulted in isostatic uplift and folding of the footwall.

Structural and stratigraphic relations clearly demonstrate that the Virgin-Beaver Dam Mountains anticline is a late Mesozoic contractional basement-involved fault-propagation fold (Plate 2.5 and 2.8) genetically related to the west dipping Jackson Wash, Cedar Wash, Front, and Cottonwood Wash reverse fault trend, shown by Reber (1951, B-B' to O-O'), Moore (1972, Structure Sections B-B' to O-O'), Steed (1980, Structure Section A-A'), and Hintze (1986, Structure Section C-C'; Carpenter et al., 1989, Structure Section A-A'). Eastward fold vergence and overturned beds dipping as shallow as 30 degrees to the west, provide evidence of profound east-directed compression (Reber, 1951, Structure Section D-D'; Hintze, 1986, Structure Section C-C'). The Virgin-Beaver Dam Mountains anticline is truncated by a north-south trending segment of the Virgin-Beaver Dam Mountains fault (Reber, 1951), demonstrating that it predates and is therefore not an isostatic response to low-angle normal faulting.

Wernicke and Axen (1988) interpret the age of the Virgin-Beaver Dam Mountain anticline as middle to late Miocene. However, field relations indicate otherwise. In the Virgin Mountains, the Tertiary Cottonwood Wash Formation lies angularly on the Cretaceous Jacobs Ranch Formation, onlaps and truncates it, and often rests directly on the Jurassic Navajo Sandstone (Moore, 1972). Our K-Ar date on biotite from a vitric tuff 100 m above the base of the Tertiary section was 24.3 +/- 1.0 Ma, indicating pre-late Oligocene folding and erosion (Carpenter et al., 1989). The Virgin-Beaver Dam Mountains anticline is angularly overlapped by the near horizontal Muddy Creek Formation. Furthermore, Hintze (1986) documented that the east-directed contractional structures in the Virgin-Beaver Dam Mountains were eroded and overlapped by Paleocene(?) and younger deposits. Clearly, "middle and late Miocene" folding does not affect post Mesozoic beds as suggested by Wernicke and Axen (1988).

Line 4-4A (Plate 2.6) shows the relation between the Castle Cliff gravity slide mass and the Virgin-Beaver Dam Mountains fault. The seismic lines and gravity data do not support the existence of a "Beaver Dam detachment," a rooted low-angle normal fault, but rather a surficial gravity slide block that has a source area up-slope in the Beaver Dam Mountains (Carpenter et al., 1989). The slide block slid downslope over basin-fill deposits and the high-angle Virgin Beaver Dam Mountains normal fault. Autochthonous rocks should be relatively older than rocks of the downdropped extensional allochthon which moved down over the lower plate. Such Miocene-Pleistocene(?) basinal sedimentary rocks should not exist below an extensional allochthon.

Many of the potential "extensional allochthons" in southern Nevada, southwest Utah, and northwest Arizona lie on such Cenozoic basinal sediments, a characteristic which precludes the possibility that they represent low-angle normal faults penetrating the crust. The Bouguer anomaly attests to the high-angle fault which is interpreted on Seismic Line 4-4A (Plate 2.6). An 8-10 million year old Miocene extensional allochthon involving surface Miocene-Quaternary(?) rocks in its autochthon does not account for field relations. However, a gravity slide block, which slid over Paleozoic and Pliocene rocks, created in response to instability resulting from the loss of lateral support and erosion during downdropping of the Virgin Valley half-graben, is consistent with observed relations (Carpenter et al., 1989).

The Virgin Valley basin is suggested to have formed from 8 to 10 Ma to Recent time in response to a west-dipping low-angle normal fault (Castle Cliff gravity slide mass) which is exposed on the western flank of the Beaver Dam Mountains (Wernicke et al., 1984; Wernicke and Axen, 1988). We interpret an earlier origin for the formation of the Virgin Valley basin (D. Carpenter, 1988; J. Carpenter, 1988) (see Virgin Valley Basin discussion). The Castle Cliff gravity slide mass slid downslope off west flank of the Beaver Dam Mountains footwall fault block, and moved out onto basin-fill deposits which lie in the downdropped hanging wall block (Carpenter et al., 1989).

DISCUSSION AND CONCLUSIONS

Cenozoic crustal structure is characterized by half-grabens, and tilted, folded, and faulted range blocks in the southern Nevada region. High-angle normal faults exert primary control over crustal structure, while gravitational sliding on denudation faults are secondary surficial (rootless) features of minor significance.

A decoupling zone between the upper and lower crust is estimated to lie between 15 and 18 km depth. The decoupling zone separates a zone of brittle deformation in the upper crust accommodated by high-angle normal faulting and a zone of extension which is accommodated by ductile stretching of the lower crust.

The Meadow Valley-California Wash basin represents a system of non-overlapping opposing half-grabens. Seismic lines record the switch from west to east-tilting half-grabens. Bouguer gravity data confirm at least three gravity troughs bounded by highs suggestive of strike-slip accommodation zones.

Seismic and gravity data demonstrate the east-tilted half-graben geometry of the Virgin Valley basin and the tremendous thickness of Cenozoic basin-fill. The Cenozoic basin-fill deposits are imaged as a fanning upward sequence exhibiting dramatic westward thinning geometry.

The Virgin Beaver Dam Mountains fault has more than 8,000 m of normal vertical separation at the latitude of the

Virgin Valley basin depocenter. Miocene doming and uplift of the Mormon Mountains occurred in response to displacement on the Virgin-Beaver Dam Mountains fault. The Virgin Valley basin was produced as the hanging wall block downdropped, and the Mormon Mountains were relatively uplifted at the opposite end of the hanging wall block.

Cenozoic syntectonic deposits documented within the basins are directly related to basin bounding high-angle normal faults. Many ranges contain gravity slide structures, some of which have been recognized for decades. Such structures have been recently misinterpreted as "extensional allochthons." Many of the potential "extensional allochthons" in southern Nevada, southwest Utah, and northwest Arizona lie on Cenozoic basinal sediments, a characteristic which precludes the possibility that they represent low-angle normal faults penetrating the crust.

REFERENCES CITED

Anderson, R. E., C. R. Longwell, R. L. Armstrong, and R. F. Marvin, 1972, Significance of K-Ar ages of Tertiary rocks from the Lake Mead region, Nevada-Arizona: Geological Society of America Bulletin, V. 83, p. 273-288.

Armstrong, R. L., 1968, Sevier orogenic belt in Nevada and Utah: GSA Bulletin, v. 79, p. 429-450.

Bohannon, R. G., 1983, Mesozoic and Cenozoic tectonic development of the Muddy, North Muddy, and northern Black Mountains, Clark County, Nevada: in Tectonic and stratigraphic studies in the eastern Great Basin, eds., D. M. Miller, V. R. Todd, and K. A. Howard: GSA Memoir 157, p. 125-148.

Bohannon, R. G., 1984, Nonmarine sedimentary rocks of Tertiary Age in the Lake Mead region, southeastern Nevada and northwestern Arizona: USGS Professional Paper 1259, 72 p.

Brenner, E. F., and R. K. Glanzman, 1979, Tertiary sediments in the Lake Mead area, Nevada: RMAG-UGA, Basin and Range symposium, p. 313-323.

Burchfiel, B. C., 1965, Structural geology of the Specter Range quadrangle, Nevada and its regional significance: GSA Bulletin, v. 76, p. 175-192.

Burchfiel, B. C., R. J. Fleck, D. T. Secor, R. R. Vincelette, and G. A. Davis, 1974, Geology of the Spring Mountains: GSA Bulletin, v. 85, p. 1013-1022.

Carpenter, D. G., 1986, Diagenesis of the Baseline Sandstone, North Muddy Mountains, Clark County, Nevada: SEPM, abstract, v. 3, p. 18-19.

Carpenter, D. G., 1988, Basin-and-range structure in the southern Nevada-Utah-Arizona region via borehole, seismic reflection, and Bouguer gravity data: Insights on Hydrocarbon potential: AAPG, abstract, v. 72/2, p. 168.

Carpenter, D. G., 1989, Geology of the North Muddy Mountains, Clark County, Nevada and regional structural synthesis: fold-thrust and basin-range structure in southern Nevada, southwest Utah, and northwest Arizona: M.Sc. thesis, Oregon State University, Corvallis, Oregon.

Carpenter, D. G., and Carpenter, J. A., 1987, New K/Ar ages from the Baseline Sandstone (Cenomanian), Clark County, Nevada: Isochron/West, No. 49, p. 3.

Carpenter, D. G., and Carpenter, J. A., In preparation, New K/Ar ages from the Horse Spring Formation (Miocene), Clark County, Nevada, and the Cottonwood Wash Formation (Oligocene), Mohave County, Arizona.

Carpenter, D. G., J. A. Carpenter, M. D. Bradley, U. A. Franz, and S. J. Reber, 1989, Comment on: On the role of isostacy in the evolution of normal fault systems, by B. P. Wernicke, and G. A. Axen: Geology, v. 16, p. 848-851.

Carpenter, J. A., 1986, Depositional and diagenetic history of the Rainbow Gardens Member of the Tertiary Horse Spring Formation, Clark County, Nevada. SEPM Abstract, v. 3, p. 19.

Carpenter, J. A., 1988, Reinterpretation of the Mormon Peak detachment in the Mormon Mountains, southern Nevada: AAPG, Abstract, v. 72/2, p. 168-169.

Carpenter, J. A., 1989, Structure of the southern Mormon Mountains, Clark County, Nevada and regional structural synthesis: fold-thrust and basin-range structure in southern Nevada, southwest Utah, and northwest Arizona: M.Sc. thesis, Oregon State University, Corvallis, Oregon.

Cook, E. F., 1960, Breccia blocks (Mississippian) of the Welcome Spring area, southwestern Utah: GSA Bulletin, v. 71, p. 1709-1712.

Dahlstrom, C. D. A., 1969, Balanced cross sections: Canadian Jour. of Earth Sci., v. 6, p. 743-757.

Davis, G. A., 1979, Problems of intraplate extensional tectonics, western United States, with special emphasis on the Great Basin: in RMAG-UGA Basin and Range Symposium, eds., G. W. Newman, and H. D. Goode, p. 41-54.

Ekren, E. B., C. L. Rogers, R. E. Anderson, and P. P. Orkild, 1977, Age of Basin and Range normal faults in Nevada Test Site and Nellis Air Force Range, Nevada: Nevada Test Site, p. 247-250.

Ellis, B. J., 1984, Thin-skinned extension superposed on frontal Sevier thrust faults, Mormon Mountains, southern Nevada: Unpublished M.Sc. thesis, Syracuse University, N. Y., 80 p.

Ellis, B. J., W. J. Taylor, and B. Wernicke, 1985, Structural sequence in the northern Mormon Mountains, southern Nevada: GSA Abstract with programs, v. 17, no. 6.

Fleck, R. J., 1970, Tectonic style, magnitude, and age of deformation in the Sevier orogenic belt in southern Nevada and eastern California: GSA Bulletin, v. 81, p. 1705-1720.

Gans, P. B., and E. L. Miller, 1983, Style of mid-Tertiary extension in east-central Nevada: Utah Geol. and Mineral Survey Spec. Studies 59, Guidebook Part I - GSA Rocky Mountain and Cordilleran Sections Meeting, p. 107-160.

Gilbert, G. K., 1874, Preliminary geologic report, expedition of 1872: U.S. Geog. and Geol. Surveys W. 100th Mer. (Wheeler) Progress Rept., p. 48-52.

Gilbert, G. K., 1875, Report on the geology of portions of Nevada, Utah, California, and Arizona, examined in the years 1871 and 1872: U.S. Geog. and Geol. Surveys W. 100th Mer. (Wheeler) Rept., v.3, p. 17-187.

Guth, P. L., 1981, Tertiary extension north of the Las Vegas shear zone, Sheep and Desert Ranges, Clark Conty, Nevada: GSA Bulletin, v. 92, p. 763-771.

Heller, P. L., S. S. Bowdler, H. P. Chambers, J. C. Coogan, E. S. Hagen, M. W. Shuster, N. S. Winslow, and T. F. Lawton, 1986, Time of initial thrusting in the Sevier orogenic belt, Idaho-Wyoming and Utah: Geology, v. 14, p. 388-391.

Hintze, L. F., 1986, Stratigraphy and structure of the Beaver Dam Mountains, southwestern Utah, in Griffen, D. T., and W. R. Phillips, eds., Thrusting and extensional structures and mineralization in the Beaver Dam Mountains, southwestern Utah: Utah Geological Association Publication 15, p. 1-36.

Hyde, Philip, 1987, Drylands: The deserts of North America: Harcourt Brace Jovanovich, Publishers, Orlando, Florida, 173 p.

Johnson, M. R. W., 1981, The erosion factor in the emplacement of the Keystone thrust sheet (South East Nevada) across a land surface: Geol. Mag., v. 118, p. 501-507.

Jones, R. W., 1963, Gravity structures in the Beaver Dam Mountains, southwestern Utah: Intermountain Assoc. Petroleum Geologists Guidebook 12, p. 90-95.

Langenheim, R. L., Jr., 1963, Mississippian stratigraphy in southwestern Utah and adjacent parts of Nevada and Arizona in Geology of southwestern Utah: Intermountain Assoc. Petroleum Geologists, 12th Ann. Field Conf. 1963, Guidebook: Salt Lake City, Utah Geol. and Min. Survey, p. 30-41.

Lillie, R. J., 1984, Tectonic implications of subthrust structures revealed by seismic profiling of Appalachian-Ouachita orogenic belt: Tectonics, v. 3, p. 619-646.

Lister, G. S., M. A. Etheridge, and P. A. Symonds, 1986, Detachment faulting and the evolution of passive continental margins: Geology, v. 14, p. 246-250.

Longwell, C. R., 1937, Sedimentation in relation to faulting: GSA Bulletin, v. 48, p. 433-442.

Longwell, C. R., 1949, Structure of the northern Muddy mountain area, Nevada: GSA Bulletin, v. 60, p. 923-968.

Longwell, C. R., 1951, Megabreccia developed downslope from large faults: Am. Jour. of Sci., v. 249, p. 343-355.

Longwell, C. R., 1960, Possible explanation of diverse structural patterns in southern Nevada: American Journal of Science, v. 258-A, p. 192-203.

Longwell, C. R., E. H. Pampeyan, B. Bowyer, and R. J. Roberts, 1965, Geology and mineral deposits of Clark County, Nevada: Nevada Bureau of Mines and Geology, Bulletin 62, 218 p.

Mackin, J. H., 1960, Structural significance of Tertiary volcanic rocks in southwestern Utah: Am. Jour. Sci., v. 258, p. 81-131.

Miller, E. L., P. B. Gans, and J. Garing, 1983, The Snake Range decollement: An exhumed mid-Tertiary ductile-brittle transition: Tectonics, v. 2, p. 239-263.

Mitchum, R. M. 1977, Seismic stratigraphy and global changes of seal level, Part 11: Glossary of terms used in seismic stratigraphy, in C. E. Payton, ed., Seismic stratigraphy - applications to hydrocarbon exploration: AAPG Memoir 26, p. 205-212.

Mitchum, R. M., Jr., and P. R. Vail, 1977; Seismic stratigraphy and global changes of sea level, Part 7: Seismic stratigraphic interpretation procedure: in Seismic stratigraphy -- applications to hydrocarbon exploration, ed., C. E. Payton: AAPG Memoir 26, p. 135-143.

Moore, R. T., 1972, Geology of the Virgin and Beaver Dam Mountains, Arizona: Arizona Bureau of Mines Bulletin, 65 p.

Olmore, S. D., 1971, Style and evolution of thrusts in the region of the Mormon Mountains, Nevada. University of Utah, Ph.D. thesis, 213 p.

Reber, S. J., 1951, Stratigraphy and structure of the south-central and northern Beaver Dam Mountains, Washington County, Utah: BYU unpublished M.S. thesis, 68 p.

Reber, S. J., 1952, Stratigraphy and structure of the Beaver Dam Mountains, Utah: Intermountain Assoc. of Petroleum Geologists Guidebook 7, p. 101-108.

Rosendahl, B. R., 1987, Architecture of continental rifts with special reference to East Africa: Ann. Rev. Earth Planet. Sci., v. 15, p. 445-503.

Rosendahl, B. R., and D. A. Livingstone, 1983, Rift lakes of East Africa: New seismic data and implications for future research: Episodes, v. 1, p. 14-19.

Schmitt, J. G., and J. B. Kohout, 1986, Early Cretaceous sedimentary evolution of the Sevier foreland basin, Muddy and North Muddy Mountains, Nevada: Geological Society of American, Abstract, v. 18, p. 181.

Seager, W. R., 1970, Low-angle gravity glide structures in the Northern Virgin Mountains, Nevada and Arizona: Geological Society of America Bulletin, v. 81, p. 1517-1538.

Steed, D. A., 1980, Geology of the Virgin River Gorge, Northwest Arizona: Brigham Young University Geology studies, v. 27, p. 96-115.

Stewart, J. H., 1971, Basin and Range structure: A system of horsts and grabens produced by deep-seated extension: Geolocial Society of America Bulletin, v. 82, p. 1019-1044.

Stewart, J. H., 1980, Regional tilt patterns of late Cenozoic basin-range fault blocks, Western United States: GSA Bulletin, v. 91, p. 460-464.

Taylor, W. J., 1984, Superposition of thin-skinned normal faulting on Sevier orogenic belt thrusts, northern Mormon Mountains, Lincoln County, Nevada: Unpublished

M.Sc. thesis, Syracuse University, N. Y., 78 p.

Tschanz, C. M., 1960, Regional significance of some lacustrine limestones in Lincoln County, Nevada recently dated as Miocene: USGS Professional Paper 400-B, p. 293-295.

Tschanz, C. M., and Pampeyan, E. H., 1970, Geology and mineral deposits of Lincoln County, Nevada: Nevada Bureau of Mines Bull. 73, 188 p.

Wernicke, B. P., 1981, Low-angle normal faults in the Basin and Range Province: Nappe tectonics in an extending orogen; Nature, v. 291, p. 645-648.

Wernicke, B. P., 1982, Processes of extensional tectonics, Ph.D. thesis, Massachusettes Institute of Technology, 170 p.

Wernicke, B. P., 1985, Uniform-sense normal simple shear of the continental lithosphere: Canadian Journal of Earth Sciences, v. 22, p. 108-125.

Wernicke, B. P., and G. J. Axen, 1988, On the role of isostasy in the evolution of normal fault systems: Geology, v. 16, p. 848-851.

Wernicke, B. P., G. J. Axen, and J. K. Snow, 1988, Basin and Range extensional tectonics at the latitude of Las Vegas, Nevada: GSA Bulletin, v. 100, p. 1738-1757.

Wernicke, B. P., P. L. Guth, and G. J. Axen, 1984, Tertiary extension in the Sevier thrust belt of southern Nevada, in Western Geological Excursions Guidebook, edited by Lintz, J. P., Mackay School of Mines, Reno, v. 4, p. 473-510.

Wernicke, B. P., J. D. Walker, and M. S. Beaufait, 1985, Structural discordance between Neogene detachments and frontal Sevier thrusts, central Mormon Mountains, southern Nevada: Tectonics, v. 4, p. 213-246.

BIBLIOGRAPHY

Albers, J. P., 1967, Belt of sigmoidal bending and right-lateral faulting in the western Great Basin: Geological Society of America Bulletin, V. 78, p. 143-156.

Anderson, R. E., C. R. Longwell, R. L. Armstrong, and R. F. Marvin, 1972, Significance of K-Ar ages of Tertiary rocks from the Lake Mead region, Nevada-Arizona: Geological Society of America Bulletin, V. 83, p. 273-288.

Armstrong, R. L., 1968, Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin, v. 79, p. 429-458.

Ash, S. R., and C. B. Read, 1976, North American Species of Tempskya and their stratigraphic significance: U. S. Geological Survey Professional Paper 874, 69 p.

Axen, G. J., and Skelly, M. F., 1984, Folding and low-angle faulting of Mesozoic and Tertiary age, Moapa Peak-Glendale area, southern Nevada: GSA abstract, v. 16. no. 6, p. 434.

Bohannon, R. G., 1983, Mesozoic and Cenozoic tectonic development of the Muddy, North Muddy, and northern Black Mountains, Clark County, Nevada: in Tectonic and stratigraphic studies in the eastern Great Basin, eds., D. M. Miller, V. R. Todd, and K. A. Howard: GSA Memoir 157, p. 125-148.

Bohannon, R. G., 1984, Nonmarine sedimentary rocks of Tertiary Age in the Lake Mead region, southeastern Nevada and northwestern Arizona: USGS Professional Paper 1259, 72 p.

Boyer, S. E., and D. Elliott, 1982, Thrust systems: AAPG Bulletin, v. 66, p. 1196-1230.

Brenner, E. F., and R. K. Glanzman, 1979, Tertiary sediments in the Lake Mead area, Nevada: RMAG-UGA, Basin and Range symposium, p. 313-323.

Burchfiel, B. C., 1965, Structural geology of the Specter Range quadrangle, Nevada and its regional significance: GSA Bulletin, v. 76, p. 175-192.

Burchfiel, B. C., R. J. Fleck, D. T. Secor, R. R. Vincelette, and G. A. Davis, 1974, Geology of the Spring Mountains: GSA Bulletin, v. 85, p. 1013-1022.

Burchfiel, B. C., B. P. Wernicke, J. H. Willemin, G. J. Axen, and C. Scott Cameron, 1982, A new type of decollement thrusting: Nature, v.300, p. 513-515.

Carpenter, D. G., 1986, Diagenesis of the synorogenic Baseline Sandstone, North Muddy Mountains, Clark County, Nevada: SEPM, Abstract, v. 3, p. 18-19.

Carpenter, D. G., 1988, Basin-and-range structure in the southern Nevada-Utah-Arizona region via borehole, seismic reflection, and Bouguer gravity data: Insights on Hydrocarbon potential: AAPG, Abstract, v. 72/2, p. 168

Carpenter, D. G., 1989, Geology of the North Muddy Mountains, Clark County, Nevada and regional structural synthesis: fold-thrust and basin-range structure in southern Nevada, southwest Utah, and northwest Arizona: M.Sc. thesis, Oregon State University, Corvallis, Oregon.

Carpenter, D. G., and J. A. Carpenter, 1987, New K/Ar ages from the Baseline Sandstone (Cenomanian), Clark County, Nevada: Isochron/West, No. 49, p. 3.

Carpenter, D. G., J. A. Carpenter, M. D. Bradley, U. A. Franz, and S. J. Reber, 1989, **Comment** on: On the role of isostacy in the evolution of normal fault systems, by Wernicke, B. P., and G. A. Axen: Geology, v. 16, p. 848-851.

Carpenter, D. G., and Carpenter, J. A., In preparation, New K/Ar ages from the Horse Spring Formation (Miocene), Clark County, Nevada, and the Cottonwood Wash Formation (Oligocene), Mohave County, Arizona.

Carpenter, J. A., 1986, Depositional and diagenetic history of the Rainbow Gardens Member of the Tertiary Horse Spring Formation, Clark County, Nevada. SEPM Abstract, v. 3, p. 19.

Carpenter, J. A., 1988, Reinterpretation of the Mormon Peak detachment in the Mormon Mountains, southern Nevada: AAPG, Abstract, v. 72/2, p. 168-169.

Carpenter, J. A., 1989, Structure of the southern Mormon Mountains, Clark County, Nevada and regional structural synthesis: fold-thrust and basin-range structure in southern Nevada, southwest Utah, and northwest Arizona: M.Sc. thesis, Oregon State University, Corvallis, Oregon.

Cook, E. F., 1960, Breccia blocks (Mississippian) of the Welcome Spring area, southwestern Utah: GSA Bulletin,

v. 71, p. 1709-1712.

Crowell, J. C., 1974, Origin of Late Cenozoic basins in southern California, in Dickinson, W. R., ed., Tectonics and Sedimentation: SEPM Special Publication No. 22, p. 190-204.

Dahlstrom, C. D. A., 1969, Balanced cross-sections: Canadian Journal of Earth Science, v. 6, p 743-757.

Dahlstrom, C. D. A. 1970, Structural geology in the eastern margin of the Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geology, v. 18, p. 332-406.

Davis, G. A., 1979, Problems of intraplate extensional tectonics, western United States, with special emphasis on the Great Basin: in RMAG-UGA Basin and Range Symposium, eds., G. W. Newman, and H. D. Goode, p. 41-54.

Ekren, E. B., P. P. Orkild, K. A. Sargent, and G. L. Dixon 1977, Geologic map of Tertiary rocks, Lincoln County, Nevada: U. S. Geological Survey Misc. Geol. Inv. Map I-1041.

Ekren, E. B., C. L. Rogers, R. E. Anderson, and P. P. Orkild, 1977, Age of Basin and Range normal faults in Nevada Test Site and Nellis Air Force Range, Nevada: Nevada Test Site, p. 247-250.

Ellis, B. J., 1984, Thin-skinned extension superposed on frontal Sevier thrust faults, Mormon Mountains, southern Nevada: Unpublished M.S. thesis, Syracuse University, Syracuse, N. Y., 80 p.

Ellis, B. J., W. J. Taylor, and B. Wernicke, 1985, Structural sequence in the northern Mormon Mountains, southern Nevada: GSA Abstract with programs, v. 17, no. 6.

Fleck, R. J., 1970, Tectonic style, magnitude, and age of deformation in the Sevier orogenic belt in southern Nevada and eastern California: GSA Bulletin, v. 81, p. 1705-1720.

Gans, P. B., and E. L. Miller, 1983, Style of mid-Tertiary extension in east-central Nevada: Utah Geol. and Mineral Survey Spec. Studies 59, Guidebook Part I - GSA Rocky Mountain and Cordilleran Sections Meeting, p. 107-160.

Gardner, L. R., 1972, Origin of the Mormon Mesa Caliche, Clark County, Nevada: Geological Society of America Bulletin, v. 83, p. 143-156.

Gilbert, G. K., 1874, Preliminary geologic report, expedition of 1872: U.S. Geog. and Geol. Surveys W. 100th Mer. (Wheeler) Progress Rept., p. 48-52.

Gilbert, G. K., 1875, Report on the geology of portions of Nevada, Utah, California, and Arizona, examined in the years 1871 and 1872: U.S. Geog. and Geol. Surveys W. 100th Mer. (Wheeler) Rept., v.3, p. 17-187.

Guth, P. L., 1981, Tertiary extension north of the Las Vegas shear zone, Sheep and Desert Ranges, Clark Conty, Nevada: GSA Bulletin, v. 92, p. 763-771.

Heller, P. L., S. S. Bowdler, H. P. Chambers, J. C. Coogan, E. S. Hagen, M. W. Shuster, N. S. Winslow, and T. F. Lawton, 1986, Time of initial thrusting in the Sevier orogenic belt, Idaho-Wyoming and Utah: Geology, v. 14, p. 388-391.

Hintze, L. F., 1986, Stratigraphy and structure of the Beaver Dam Mountains, southwestern Utah, in Griffen, D. T., and W. R. Phillips, eds., Thrusting and extensional structures and mineralization in the Beaver Dam Mountains, southwestern Utah: Utah Geological Association Publication 15, p. 1-36.

Hyde, Philip, 1987, Drylands: The deserts of North America: Harcourt Brace Jovanovich, Publishers, Orlando, Florida, 173 p.

Johnson, M. R. W., 1981, The erosion factor in the emplacement of the Keystone thrust sheet (South East Nevada) across a land surface: Geol. Mag., v. 118, p. 501-507.

Jones, P. B., 1984, Sequence of formation of back-limb thrusts and imbrications-implications for the development of the Idaho-Wyoming thrust belt: AAPG Bulletin, V. 68, p. 816-818.

Jones, R. W., 1963, Gravity structures in the Beaver Dam Mountains, southwestern Utah: Intermountain Assoc. Petroleum Geologists Guidebook 12, p. 90-95.

Kane, M.F., D. L. Healey, D. L. Peterson, H. E. Kaufman, and D. Reidy, 1979, Bouguer gravity map of Nevada: Las Vegas Sheet, Nevada Bureau of Mines and Geology, Map 61.

Kay, M., 1951, North American geosynclines: Geological Society of America Memoir 48, 143 p.

Kowallis, B. J., and B. H. Everett, 1986, Sedimentary Environments of the Muddy Creek Formation near

Mesquite, Nevada <u>in</u> Griffen, D. T., Phillips, W. R., eds., Thrusting and extensional structures and mineralization in the Beaver Dam Mountains, southwestern Utah: Utah Geological Association Publication 15, p. 69-76

Krumbein, W. C., and Sloss, L. L., 1963, Stratigraphy and Sedimentation: W. H. Freeman and Company, San Francisco, 660 p.

Langenheim, R. L., Jr., 1963, Mississippian stratigraphy in southwestern Utah and adjacent parts of Nevada and Arizona <u>in</u> Geology of southwestern Utah: Intermountain Assoc. Petroleum Geologists, 12th Ann. Field Conf. 1963, Guidebook: Salt Lake City, Utah Geol. and Min. Survey, p. 30-41.

Lillie, R. J., 1984, Tectonic implications of subthrust structures revealed by seismic profiling of Appalachian-Ouachita orogenic belt: Tectonics, v. 3, p. 619-646.

Lister, G. S., M. A. Etheridge, and P. A. Symonds, 1986, Detachment faulting and the evolution of passive continental margins: Geology, v. 14, p. 246-250.

Longwell, C. R., 1926, Structural studies in southern Nevada and western Arizona: Bulletin of the Geological Society of America, v. 37, p. 551-584.

Longwell, C. R., 1928, Geology of the Muddy Mountains, Nevada, with a section through the Virgin Range to the Grand Wash Cliffs, Arizona: U. S. Geological Survey Bulletin 198, 152 p.

Longwell, C. R., 1937, Sedimentation in relation to faulting: GSA Bulletin, v. 48, p. 433-442.

Longwell, C. R., 1949, Structure of the northern Muddy Mountain area, Nevada: Bulletin of the Geological Society of America, v. 60, p. 923-968.

Longwell, C. R., 1950, Tectonic theory viewed from the Basin Ranges: Geological Society of America Bulletin, v. 61, p. 413-434.

Longwell, C. R., 1951, Megabreccia developed downslope from large faults: Am. Jour. of Sci., v. 249, p. 343-355.

Longwell, C. R., 1960, Possible explanation of diverse structural patterns in southern Nevada: American Journal of Science, v. 258-A, p. 192-203.

Longwell, C. R., E. H. Pampeyan, B. Bowyer, and R. J.

Roberts, 1965, Geology and mineral deposits of Clark County, Nevada: Nevada Bureau of Mines and Geology, Bulletin 62, 218 p.

Mackin, J. H., 1950, The down-structure method of viewing geologic maps: Journal of Geology, v. 58, p. 55-72.

Mackin, J. H., 1960, Structural significance of Tertiary volcanic rocks in southwestern Utah: Am. Jour. Sci., v. 258, p. 81-131.

Miller, E. L., P. B. Gans, and J. Garing, 1983, The Snake Range decollement: An exhumed mid-Tertiary ductile-brittle transition: Tectonics, v. 2, p. 239-263.

Mitchum, R. M. 1977, Seismic stratigraphy and global changes of sea level, Part 11: Glossary of terms used in seismic stratigraphy, in C. E. Payton, ed., Seismic stratigraphy - applications to hydrocarbon exploration: AAPG Memoir 26, p. 205-212.

Mitchum, R. M., Jr., and P. R. Vail, 1977; Seismic stratigraphy and global changes of sea level, Part 7: Seismic stratigraphic interpretation procedure: in Seismic stratigraphy -- applications to hydrocarbon exploration, ed., C. E. Payton: AAPG Memoir 26, p. 135-143.

Moore, R. T., 1972, Geology of the Virgin and Beaver Dam Mountains, Arizona: Arizona Bureau of Mines Bulletin, 65 p.

Olmore, S. D., 1971, Style and evolution of thrusts in the region of the Mormon Moutnains, Nevada: Ph.D. thesis, University of Utah, 213 p.

Palmer, A. R., 1983, The Decade of North American Geology 1983 Geologic Time Scale: Geology, v. 11, p. 503-504.

Reber, S. J., 1951, Stratigraphy and structure of the south-central and northern Beaver Dam Mountains, Washington County, Utah: BYU unpublished M.S. thesis, 68 p.

Reber, S. J., 1952, Stratigraphy and structure of the Beaver Dam Mountains, Utah: Intermountain Assoc. of Petroleum Geologists Guidebook 7, p. 101-108.

Rodgers, J., 1949, Evolution of throught on structure of the middle and southern Appalachians: AAPG Bulletin, v. 33, p. 1643-1654.

Rosendahl, B. R., 1987, Architecture of continental rifts with special reference to East Africa: Ann. Rev. Earth Planet. Sci., v. 15, p. 445-503.

Rosendahl, B. R., and D. A. Livingstone, 1983, Rift lakes of East Africa: New seismic data and implications for future research: Episodes, v. 1, p. 14-19.

Rubey, W. W., and M. K. Hubbert, 1959, Overthrust belt in geosynclinal area of western Wyoming in light of fluid-pressure hypothesis: Geological Society of America Bulletin, v. 70, p. 167-206.

Schmitt, J. G., and J. B. Kohout, 1986, Early Cretaceous sedimentary evolution of the Sevier foreland basin, Muddy and North Muddy Mountains, Nevada: Geological Society of America, Abstract, v. 18, p. 181.

Seager, W. R., 1970, Low-angle gravity glide structures in the Northern Virgin Mountains, Nevada and Arizona: Geological Society of America Bulletin, v. 81, p. 1517-1538.

Skelly, M. F., 1987, The Geology of the Moapa Peak area, southern Mormon Mountains, Clark and Lincoln Counties, Nevada: M.S. Thesis, Northern Arizona University.

Steed, D. A., 1980, Geology of the Virgin River Gorge, Northwest Arizona: Brigham Young University Geology studies, v. 27, p. 96-115.

Stewart, J. H., 1971, Basin and Range structure: A system of horsts and grabens produced by deep-seated extension: Geolocial Society of America Bulletin, v. 82, p. 1019-1044.

Stewart, J. H., 1978a, Basin-range structure in western North America: A review, <u>in</u> Smith, R. B., and G. P. Eaton, eds., Cenozoic tectonics and regional geophysics of the western cordillera, Geological Society of America Memoir 152, p. 1-32.

Stewart, J. H., 1978b, Rift systems in the western United States: Tectonics and Geophysics of Continental Rifts: D. Reidel Publishing Company, p. 89-110.

Stewart, J. H., 1980, Regional tilt patterns of late Cenozoic basin-range fault blocks, Western United States: GSA Bulletin, v. 91, p. 460-464.

Suppe, J., 1983, Geometry and kinematics of fault-bend folding: Am. Jour. of Sci., v. 283, p. 684-721.

Taylor, W. J., 1984, Superposition of thin-skinned normal faulting on Sevier orogenic belt thrusts, northern

Mormon Mountains, Lincoln County, Nevada: Unpublished M.Sc. thesis, Syracuse University, N. Y., 78 p.

Thompson, G. A., 1960, Problem of Late Cenozoic structure of the Basin Ranges: Copenhagen, 21st International Geological Congress Proceedings, Section 18, p. 63-68.

Tschanz, C. M., 1960, Regional significance of some lacustrine limestones in Lincoln County, Nevada recently dated as Miocene: USGS Professional Paper 400-B, p. 293-295.

Tschanz, C. M., and E. H. Pampeyan, 1970, Geology and mineral deposits of Lincoln County, Nevada: Nevada Bureau of Mines and Geology, Bulletin 73, 188 p.

Wernicke, B. P., 1981, Geology of the Mormon Mountains, Lincoln and Clark Counties, Nevada: Geological Society of America Abstracts with Program, v. 13, p. 113-114.

Wernicke, B. P., 1981, Low-angle normal faults in the Basin and Range Province: Nappe tectonics in an extending orogen; Nature, v. 291, p. 645-648.

Wernicke, B. P., 1982, Processes of extensional tectonics: Ph.D. thesis, Massachusettes Institute of Technology, 170 p.

Wernicke, B. P., 1985, Uniform-sense normal simple shear of the continental lithosphere: Canadian Journal of Earth Sciences, v. 22, p. 108-125.

Wernicke, B. P., and G. J. Axen, 1988, On the role of isostasy in the evolution of normal fault systems: Geology, v. 16, p. 848-851.

Wernicke, B. P., G. J. Axen, and J. K. Snow, 1988, Basin and Range extensional tectonics at the latitude of Las Vegas, Nevada: GSA Bulletin, v. 100, p. 1738-1757.

Wernicke, B. P., P. L. Guth, and G. J. Axen, 1984, Tertiary extension in the Sevier thrust belt of southern Nevada, in Western Geological Excursions Guidebook, edited by Lintz, J. P., Mackay School of Mines, Reno, v. 4, p. 473-510.

Wernicke, B. P., J. D. Walker, and M. S. Beaufait, 1985, Structural discordance between Neogene detachments and frontal Sevier thrusts, central Mormon Mountains, southern Nevada: Tectonics, v. 4, p. 213-246.

APPENDICES

APPENDIX 1

TABLES

TABLE 2.1

VELOCITY ANALYSIS SP #1069, LINE 4-4A

TIME (twtt)	STACK VELOCITY (ft/s)	INTERVAL VELOCITY (ft/s)	INTERVAL (twtt)
0.00	4,000	4,001.6	0.000
.88	4,300	4,300.1	0.875
1.04	4,900	7,314.4	0.165
1.61	5,800	7,150.4	0.570
1.80	6,250	9,249.6	0.190
2.70	7,600	9,741.6	0.900
5.00	11,400	14,661.6	2.300

THICKNESS (ft)	ESTIMATED DENSITY (g/cc)	TOTAL DEPTH (ft)
0	1.63	0
1,881	1.64	1,881
603	1.69	2,484
2,038	1.81	4,522
878	1.86	5,400
4,384	2.14	9,784
16,860	2.32	26,644

TABLE 2.2

BASIN CONFIGURATIONS

	Gravity (mGals)	TWTT (s)	GEOMETRY
VIRGIN VALLEY BASIN			East-tilted half-graben with between 4,600 and 8,500 m of Cenozoic basin-fill at, and near, the depocenter.
Line 4-4A	65	5-5.5	
Line 5-5A	60	~4.5	
Line 6	40	2.6	
SS A-A'	30-40	-	
VIRGIN VALLEY SUBBASIN			East-tilted half-graben with ~5,800 m of Cenozoic basin-fill on the seismic section.
Line 4-4A	25-30	3	
MEADOW VALLEY BASIN (north)			West-tilted and East-tilted half-grabens with between 1,800 and 2,100 m of Cenozoic basin-fill on seismic sections.
Line 5-5A	20	1.5	
Line 6	15	1.6	
SS A-A'	20	-	
COYOTE SPRING BASIN			East-tilted half-graben with ~1,000 m of Cenozoic basin-fill on the seismic section.
Line 6	30	1	
SS A-A'	15	-	
TULE DESERT BASIN			East-tilted half-graben with ~1,200 m of Cenozoic basin-fill on the seismic section.
Line 5-5A	20	1.2	

TWTT - Two-way travel times for seismically imaged Cenozoic basin-fill deposits at maximum depths imaged on the seismic lines.

mGals - The mGals of gravity represents the relief associated with the basins on each particular line of section.

TABLE 2.3

MEADOW VALLEY MOUNTAINS

MIOGEOSYNCLINAL CARBONATE AND DETRITAL PROVINCE

Permian-Pennsylvanian Bird Spring Formation	4,274 ft
Mississippian Chainman Shale and Sandstone	1,375 ft
Mississippian Joana Limestone	1,500 ft
Mississippian-Devonian Pilot Shale	150 ft
Devonian Guilmette Formation	1,350 ft
Devonian Simonson Dolomite	400 ft
Devonian Sevy Dolomite	275 ft
Silurian Laketown Dolomite	330 ft
Ordovician Eureka Quartzite	20 ft
Ordovician Pogonip Group	1,100 ft
TOTAL = 3,422 m/11,224 ft)	

This stratigraphic section, in the Meadow Valley Mountains, is 243% thicker than the equivalent section in the Mormon Mountains.

MORMON MOUNTAINS

SHELF CARBONATE PROVINCE

Permian-Pennsylvanian Bird Spring Formation	1,800 ft
Mississippian Chainman Shale	0 ft
Mississippian Monte Cristo Limestone	915 ft
Mississippian-Devonian Pilot Shale	0 ft
Devonian Muddy Peak Limestone	708 ft
Silurian Laketown Dolomite	0 ft
Ordovician Ely Springs Dolomite	354 ft
Ordovician Eureka Quartzite	13 ft
Ordovician Pogonip Group	834 ft
TOTAL = 1,410 m/4,624 ft)	

This stratigraphic section, in the Mormon Mountains, is only 41% as thick as the equivalent section in the Meadow Valley Mountains.

APPENDIX 2

PLATE CAPTIONS

Plate 2.1. Physiographic index map showing the Lines 4-4A, 5-5A, and 6, and regional Structure Section A-A'. M = Mobil (1980) Virgin River No. 1-A well (TD = 19,562').

Plate 2.2. Stratigraphic nomenclature used on Seismic Lines 4-4A, 5-5A, and 6.

Plate 2.3. Synthetic seismic trace showing the acoustic impedance contrasts generated across seismically fast and slow rocks penetrated by the Mobil Virgin River #1-A well. Reflectivity and acoustic impedance determined from the sonic log were convolved with a Ricker wavelet, to generate the observed trace. Field seismic data, Line 6, and well information are included in the interpretation.

Plate 2.4. Seismic Line 6, shows the southern representation of the Virgin Valley half-graben. Sevier fold-thrust structures are projected into the seismic interpretation from geologic mapping north and south of the traverse in the North Muddy and Mormon Mountains juncture area, and in the Black Ridge area of the Virgin-Beaver Dam Mountains.

Plate 2.5. Seismic Line 5-5A, shows a perpendicular transect across Virgin Valley half-graben, a downdropped Sevier thrust, the Tule Springs Hills bascule dome, the Meadow Valley half-graben, and the Virgin-Beaver Dam Mountain fault-propagation anticline.

Plate 2.6. Seismic Line 4-4A, obliquely crossing the Virgin Valley half-graben. Note the reverse drag anticline and the unconformity between the Muddy Creek and Horse Spring Formation. The line shows the Virgin Valley Subbasin half-graben, the North Muddy and Mormon Mountains juncture, and the Virgin-Beaver Dam Mountains fault-propagation anticline.

Plate 2.7. Density versus depth plot showing calculated values of density and interval velocity from seismic stacking velocities.

Plate 2.8. Structure Section A-A,' showing the Virgin

Valley half-graben, Mormon Mountains (rollover anticline), Meadow Valley half-graben, Coyote Spring half-graben, and the Virgin-Beaver Dam Mountains basement-involved fault-propagation anticline.

Formational units on Structure Section A-A': **pCb** = metamorphic and igneous basement complex, **pCs** = undiff. siliciclastics, **Cpm** = Prospect Mountain Quartzite, **Ctba** = Tapeats Sandstone and Bright Angel Shale, **Cclp** = Chisholm Shale, Lyndon Limestone, and Pioche Shale, **Cb** = Bonanza King Formation, **Cn** = Nopah Formation, **SOu** = Pogonip Group-Eureka Quartzite-Ely Springs Dolomite-Laketown Dolomite, **Oep** = Pogonip Group-Eureka Quartzite-Ely Springs Dolomite, **Sl** = Laketown Dolomite, **Dssg** = Sevy Dolomite-Simonson Dolomite-Guilmette Formation, **Dm** = Muddy Peak Limestone, **MDp** = Pilot Shale, **Mj** = Joana Limestone, **Mm** = Monte Cristo LImestone, **Mr** = Redwall Limestone, **Mcs** = Chainman Shale-Scotty Wash Sandstone, **PPb** = Bird Spring Formation, **Pc** = Callville LImestone, **Pp** = Pakoon Dolomite, **Prb** = Red Beds, **Pq** = Queantoweap Sandstone, **Pt** = Toroweap Formation, **Pk** = Kaibab Formation, **TRm** = Moenkopi Formation, **TRc** = Chinle Formation, **JRmka** = Moenave Formation-Kayenta Foramation-Aztec Sandstone, **K** = undifferentiated siliciclastics, **Ths** = Horse Spring Formation, **Tv** = undifferentiated extrusive volcanic rocks, conglomerate, and freshwater limestone of Oligocene to Pliocene age, **QTm** = Muddy Creek Formation and younger basinal deposits of Miocene to Quaternary age.

PLATE 2.9. High-angle normal fault and low-angle normal fault models proposed for crustal extension in the southern Nevada, southwest Utah, and northwest Arizona region at the latitude of the Mormon Mountains. The high-angle normal fault model is supported by field mapping, Bouguer gravity data, well data, and seismic reflection data. The low-angle normal fault model was proposed on the basis of field mapping of translocated blocks of Paleozoic strata. Many geologists, including the authors, have examined the translocated blocks in the field and concluded that they are rootless surficial gravity slide blocks of no tectonic significance. They are of significance in regard to denudational processes in a tectonically active region. Many of these gravity slide blocks lie on top of Pliocene and Quaternary basin-fill sediments.
See text for details.