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**MESOZOIC AND CENOZOIC STRUCTURAL GEOLOGY
OF THE CP HILLS, NEVADA TEST SITE,
NYE COUNTY, NEVADA; AND REGIONAL IMPLICATIONS**

BY

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MASTER

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**Mesozoic and Cenozoic structural geology of the CP Hills,
Nevada Test Site, Nye County, Nevada;
and regional implications.**

Chapter 1

**Mesozoic and Cenozoic structural geology of the CP Hills,
Nevada Test Site, Nye County, Nevada**

Chapter 2

**Mesozoic deformation in the Nevada Test Site
and vicinity; a new perspective from the
CP Hills, Nye County, Nevada**

A thesis submitted in partial fulfillment of the
requirements for the degree of
Master of Science in Geology

by

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August 1991

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October 4, 1991

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Dear Carl:

Enclosed is a copy of John Caskey's newly completed Master of Science thesis, entitled, "Mesozoic and Cenozoic structural geology of the CP Hills, Nevada Test Site, Nye County, Nevada; and regional implications," which was supported by Task 5 of the Yucca Mountain Project of the Center for Neotectonic Studies, UNR, with funds provided by your office.

John's thesis is the first modern structural study of the geometry of Mesozoic structure and prevolcanic normal faulting in the NTS. His work confirmed the importance of west-vergent thrusting and folding of Mesozoic age in the NTS, and has important implications for both the correlation of structures throughout the NTS region and for assessing the magnitude of Cenozoic extension in the vicinity of Yucca Mountain. When considered in conjunction with published maps of areas like Bare Mountain, John's new work provides important constraints for the deep subsurface structure of Yucca Mountain.

Specifically, both east- and west-vergent thrusts must pass at depth beneath the Yucca Mountain area, and their structural relations can be expected to have been complicated by large-magnitude pre-Middle Miocene (pre-15 Ma) extension. **This suggests that faults at depth beneath Yucca Mountain have very different characteristics than those exposed at the surface.** These constraints should be used in future studies for constructing models of deep structure beneath Yucca Mountain both for evaluating flow paths for groundwater and for assessing the seismic potential of faults at Yucca Mountain.

We currently have several structural studies underway to evaluate these kinds of questions and their importance for Yucca Mountain.

This is the fourth recently completed thesis on tectonics and neotectonics supported by Task 5. We are grateful for the support provided by your

office that made these studies possible.

With best regards,

A handwritten signature in cursive script, reading "Rich Schweickert". The signature is written in dark ink and is positioned above the printed name.

Richard A. Schweickert
Professor of Geology

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I thank Dr. Richard A. Schweickert for his guidance, support, encouragement, and reviews of drafts. It has been fun and I thank Rich for all that he has done. I would also like to express thanks to Steve Nitchman for field companionship and assistance, moral support, and many thought provoking discussions. I thank Peter Guth and Jim Cole for introducing me to the geology of the Yucca Flat region. Critical reviews by Patrick Goldstrand and Steve Nitchman improved earlier versions of chapter 2. I also thank John Taylor for many critical discussions. I express my sincere appreciation and gratitude to Maria Ducey whose constant support and patience endured through hectic and sometimes scary times. I greatly appreciate the kindness and friendship of Chuck Rosenbury, Eddie Eubanks, Andy Gile, and Harry Kirkham at RAMATROL. Lastly, I thank my committee members, Dr. M.J. Hibbard and Dr. S.B. Castor. This project was supported by the State of Nevada Nuclear Waste Project Office.

ABSTRACT

Detailed mapping and structural analysis of upper Proterozoic and Paleozoic rocks in the CP Hills of the Nevada Test Site, together with analysis of published maps and cross sections and a reconnaissance of regional structural relations indicate that the CP thrust of Barnes and Poole (1968) actually comprises two separate, oppositely verging Mesozoic thrust systems: 1) the west-vergent CP thrust which is well exposed in the CP Hills and at Mine Mountain, and 2) the east-vergent Belted Range thrust located northwest of Yucca Flat. West-vergence of the CP thrust is indicated by large-scale west-vergent recumbent folds in both its hangingwall and footwall and by the fact that the CP thrust ramps up section through hangingwall strata toward the northwest. Regional structural relations indicate that the CP thrust forms part of a narrow sigmoidal belt of west-vergent folding and thrusting traceable for over 180 km along strike. The Belted Range thrust represents earlier Mesozoic deformation that was probably related to the Last Chance thrust system in southeastern California, as suggested by earlier workers. A pre-Tertiary reconstruction of the Cordilleran fold and thrust belt in the region between the NTS and the Las Vegas Range bears a close resemblance to other regions of the Cordillera and has important

implications for the development of hinterland-vergent deformation as well as for the probable magnitude of Tertiary extension north of Las Vegas Valley.

Subsequent to Mesozoic deformation, the CP Hills were disrupted by at least two episodes of Tertiary extensional deformation: 1) an earlier episode represented by pre- middle Miocene low-angle normal faults, and 2) a later, post- 11 Ma episode of high-angle normal faulting. Both episodes of extension were related to regional deformation, the latter of which has resulted in the present basin and range topography of the NTS region. There appears to be a direct correspondence between the regional structural grain of the earlier episode of low-angle faulting and that of (hinterland-vergent) Mesozoic structures. Regional structural relations indicate that both Mesozoic and pre- middle Miocene structures in the CP Hills broadly correlate with those at Bare Mountain. This has important implications for subsurface structural models beneath Yucca Mountain, the candidate high-level nuclear waste repository.

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THESIS INTRODUCTION

The research presented in this thesis encompasses two related projects: 1) detailed mapping and structural analysis of upper Proterozoic rocks in the CP Hills of the Nevada Test Site (NTS) (fig. 1) (Chapter 1), and 2) reconnaissance of regional Mesozoic deformation in the Nevada Test and surrounding regions (Chapter 2). This project was undertaken as a part of an ongoing research program conducted by the Center for Neotectonic Studies, Mackay School of Mines, University of Nevada, Reno, designed to provide the State of Nevada Agency for Nuclear Projects with a comprehensive review and assessment of the tectonic and neotectonic framework of Yucca Mountain (the candidate high-level nuclear waste repository site) and adjacent regions.

Chapter 1, "Mesozoic and Cenozoic structural geology of the CP Hills, Nevada Test Site, Nye County, Nevada," has been submitted to *Nevada Bureau of Mines and Geology Open File Reports* for review. Chapter 2, "Mesozoic deformation in the Nevada Test Site and vicinity; a new perspective from the CP Hills, Nevada Test Site, Nye County, Nevada," is presently submitted to *Tectonics* for review.

A significant concern in characterizing the tectonic framework of the Yucca Mountain region includes the evaluation of previous regional structural interpretations and correlations in the NTS region (e.g. Barnes and Poole, 1968; Wernicke et al., 1988a, 1988b). Barnes and Poole (1968) and Hinrichs (1968) interpreted several thrust faults that place upper Precambrian and lower Paleozoic rocks upon upper Paleozoic strata as remnants of a single, regional, east- to southeast-vergent thrust system. They named this thrust system the CP thrust for exposures in the Control Point (CP) Hills, south of Yucca Flat (fig. 1). In contrast, a published map and cross sections by McKeown et al. (1976) indicate that the CP thrust, where exposed in the CP Hills, is a major west-vergent structure. Subsequent work on the Mesozoic structure in the region has been hindered because of restricted access to the NTS and surrounding regions.

The CP Hills were an important target for detailed field studies for several reasons: 1) As discussed above, significant discrepancies exist between published interpretations of the Mesozoic structure in the Yucca Flat region (e.g. Barnes and Poole, 1968; Wernicke et al., 1988a, 1988b) and published maps and cross sections of the area (e.g. McKeown et al., 1976). 2) Earlier workers correlated Mesozoic structures at Bare Mountain (fig. 1) with

Figure 1- Generalized geologic map and location map of the Nevada Test Site area (modified after Stewart and Carlson (1978). Abbreviations: BM - Banded Mountain; CH - Calico Hills; ER - Eleana Range; GR - Groom Range; MM - Mine Mountain; JR - Jangle Ridge; OSB - Oak Spring Butte; PR - Papoose Range; SR - Syncline Ridge.

those in the Yucca Flat area (Burchfiel et al., 1970; Wernicke et al., 1988a, 1988b). Detailed studies of the magnitude and style of Mesozoic and Tertiary deformation in the CP Hills are required to evaluate previous structural correlations and to provide viable constraints on subsurface (subvolcanic) boundary conditions beneath Yucca Mountain, which lies geographically between Bare Mountain and the CP Hills. In addition, an improved understanding of the Mesozoic structure in the Yucca Flat region may contribute to an overall understanding of the pre-Tertiary tectonic framework of the Mesozoic Cordilleran fold and thrust belt at this latitude.

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CHAPTER 1

**Mesozoic and Cenozoic structural geology
of the CP Hills, Nevada Test Site,
Nye County, Nevada**

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ABSTRACT

Recent detailed mapping and structural analysis of upper Proterozoic and Paleozoic rocks in the CP Hills of the Nevada Test Site (NTS) indicate that the CP thrust of Barnes and Poole (1968), where exposed in the CP Hills, is a major west-vergent Mesozoic thrust fault. This is indicated by large-scale west-vergent recumbent folds in both the hangingwall and footwall of the CP thrust and by the fact that the CP thrust ramps upsection through hangingwall strata toward the northwest. While the interpretation of west-vergence is consistent with a published map and cross sections by McKeown et al. (1976) many workers have interpreted the CP thrust as an east- to southeast-vergent structure. Structural relations indicate that the CP thrust correlates with the Mine Mountain thrust located northwest of the CP Hills. Net displacement along the CP thrust is poorly constrained, but field relations require a minimum stratigraphic separation of 8.5 km. Structural analysis of mesoscopic folds within rocks of the CP parautochthon suggests that at least one episode of folding affected these strata prior to the development of large-scale west-vergent folds.

Subsequent to Mesozoic deformation the CP Hills were disrupted by at least two episodes of Tertiary extensional deformation; 1) an earlier episode

represented by pre- middle Miocene low-angle normal faults, and 2) a later post- 11 Ma episode of high-angle normal faulting. Both episodes of extension were related to regional deformation, the latter of which has resulted in the present basin and range topography of the NTS region. There appears to be a direct correspondence between the regional structural grain of the earlier episode of low-angle faulting and that of (hinterland-vergent) Mesozoic structures. Regional structural relations indicate that both Mesozoic and pre- middle Miocene structures in the CP Hills broadly correlate with those at Bare Mountain. This has important implications for subsurface structural models beneath Yucca Mountain the candidate high level nuclear waste repository.

INTRODUCTION

Regional Setting

The CP Hills of the Nevada Test Site (NTS) (fig. 1) lie within the dominantly east-vergent Mesozoic Sevier orogenic belt (Armstrong, 1968) near one of the thickest known parts of the Cordilleran Paleozoic miogeocline (Ekren, 1968). Throughout most of the NTS region, the Mesozoic structural framework has been disrupted by at least two major episodes of Cenozoic

Figure 1- Generalized geologic map and location map of the Nevada Test Site area (modified after Stewart and Carlson (1978)). Abbreviations: BM - Banded Mountain; CH - Calico Hills; ER - Eleana Range; GR - Groom Range; MM - Mine Mountain; JR - Jangle Ridge; OSB - Oak Spring Butte; PR - Papoose Range; SR - Syncline Ridge.

extensional faulting (Ekren et al., 1968; Schweickert and Caskey, 1990), the youngest of which has resulted in the present basin and range topography characteristic of the entire Great Basin. Extensive middle to upper Miocene volcanic rocks of the southwest Nevada volcanic field (Christiansen et al., 1977) (fig. 1) blanket most of the NTS region. Although these rocks are highly faulted locally, they postdate and therefore conceal much of the evidence for earlier Tertiary extensional faulting (Schweickert and Caskey, 1990) as well as many details of the Mesozoic fold and thrust belt.

The area surrounding Yucca Flat offers a rare, and by far the most extensive, window through Cenozoic volcanic rocks within the NTS (fig. 1). In this region, exposures of upper Precambrian through upper Paleozoic rocks reveal important aspects of the tectonic history of the region. The Paleozoic stratigraphic framework which is well known for this region (e.g. Nolan, 1929; Hazzard, 1937; Cornwall, 1972; Ekren, 1968; Stewart, 1970; Stewart and Poole, 1972) provides a good foundation for interpreting locally complicated Mesozoic and Tertiary structure. All seven systems of the Paleozoic are represented in the NTS region and these, together with Precambrian strata form a generally conformable stratigraphic section nearly 12,000 m (nearly 38,000 ft) thick (fig. 2).

Figure 2 - Generalized stratigraphic column for upper Proterozoic and Paleozoic rocks in the Nevada Test Site region (modified after Ekren, 1968).

Previous work

Detailed geologic studies of the NTS region were initiated in 1956, when the United States began to investigate the feasibility of underground testing of nuclear devices. Johnson and Hibbard (1957) laid much of the geologic groundwork for the NTS (then the Atomic Energy Commission Nevada Proving Grounds) with a reconnaissance study of the stratigraphy and structure of the Yucca Flat and Frenchman Flat areas (fig. 1). By 1966, ten years of NTS research culminated in a technical session of the 18th Annual Meeting of Rocky Mountain Section Geological Society of America (GSA), held in Las Vegas, Nevada, which focussed on the hydrology, volcanology, and general geology of the NTS. Born from this session, and published in 1968, was GSA Memoir 110. In this volume, Barnes and Poole (1968) and Hinrichs (1968) interpreted several thrust faults that place upper Precambrian and lower Paleozoic rocks upon upper Paleozoic strata as remnants of a single, regional, east- to southeast-vergent thrust system. They named this thrust system the CP thrust for exposures in the Control Point (CP) Hills, south of Yucca Flat (fig. 1). Subsequent work on the Mesozoic structure in the region has been hindered because of restricted access to the NTS and surrounding regions. Later discussions of the regional structural setting of

the NTS (e.g. Sinnock, 1982; Carr, 1984; Wernicke et al., 1988a, 1988b; Snow and Wernicke, 1990) have therefore relied to some extent on these earlier interpretations.

Recent studies in the CP Hills and Mine Mountain area (fig. 1) (discussed in this report) together with published maps and cross sections by Orkild (1968) and McKeown et al. (1976) and a reconnaissance study of regional structural relations (Caskey and Schweickert, in review), suggest that the CP thrust of Barnes and Poole (1968) actually comprises two separate, oppositely-vergent thrust systems: 1) the west-vergent CP thrust, which is well exposed in the CP Hills and at Mine Mountain, and 2) the southeast-vergent Belted Range thrust, located northwest of Yucca Flat (Caskey and Schweickert, in review) (fig. 1). The CP thrust forms part of a narrow sigmoidal belt of west-vergent folds and thrust faults traceable for at least 180 km along strike (Caskey and Schweickert, in review). The Belted Range thrust probably represents early Mesozoic deformation related to the Last Chance thrust system in southeastern California (Burchfiel et al., 1970; Wernicke et al., 1988a, 1988b).

Purpose and Scope

This project was undertaken as a part of an ongoing research program conducted by the Center for Neotectonic Studies, Mackay School of Mines, University of Nevada, Reno, designed to provide the State of Nevada Agency for Nuclear Projects with a comprehensive review and assessment of the tectonic and neotectonic framework of Yucca Mountain (the candidate high-level nuclear waste repository site) and adjacent regions. The CP Hills were an important target for detailed field studies for several reasons: 1) As discussed above, significant discrepancies exist between published interpretations of the Mesozoic structure in the Yucca Flat region (e.g. Barnes and Poole, 1968; Wernicke et al., 1988a, 1988b) and published maps and cross sections of the area (e.g. McKeown et al., 1976). One goal of this study was to help resolve these discrepancies. 2) Earlier workers correlated Mesozoic structures at Bare Mountain (fig. 1) with those in the Yucca Flat area (Burchfiel et al., 1970; Wernicke et al., 1988). Detailed studies of the magnitude and style of Mesozoic and Tertiary deformation in the CP Hills are required to evaluate previous structural correlations and to provide viable constraints on subsurface (subvolcanic) boundary conditions beneath Yucca

Mountain which lies geographically between Bare Mountain and the CP Hills.

This report summarizes the results of geologic mapping and structural analysis of upper Precambrian and Paleozoic rocks and, to a lesser extent, Tertiary volcanic rocks exposed in the CP Hills south of Yucca Flat (fig. 1). Field studies were initiated in the spring of 1988, and fieldwork was carried out in the fall of 1988, the fall of 1989, and the winter of 1991. The geology was mapped on a 1:12,000 scale topographic base and in part, on 1:24,000 scale natural color aerial photographs. Areas in the western and northwestern part of the study area which are devoid of structural data (see plate 1) were interpreted by analysis of aerial photographs and mapping by McKeown et al. (1976). All mapping was compiled on a 1:12,000 scale topographic base (plate 1). The intention was not to redo a commendable mapping job by McKeown et al. (1976). However, it was advantageous to remap large portions of the CP Hills at a larger scale to examine more carefully the structural relations. Some minor revisions have been made of the surface geology mapped by McKeown et al. (1976), although subsurface structure has been substantially reinterpreted.

STRATIGRAPHY

The upper Proterozoic and Paleozoic Cordilleran miogeocline forms a wedge of clastic and carbonate strata that thickens regionally from east to west from less than 1400 m in northwestern Arizona (McNair, 1951) to nearly 12,000 m in the NTS region (Ekren, 1968). Upper Precambrian and Lower Cambrian rocks are composed dominantly of clastic, craton-derived sediments which represent the initial deposits of the Cordilleran miogeocline (Stewart, 1970, 1972). Middle Cambrian through Upper Devonian rocks are predominantly carbonates which broadly represent passive continental margin carbonate shelf deposition. Uppermost Devonian and Mississippian rocks consist of carbonate shelf deposits in areas east of the NTS. However, within the NTS, rocks of these systems are dominantly siliciclastic foreland basin deposits derived from the Late Devonian and Mississippian Antler orogenic highlands to the northwest (Poole, 1974). The Pennsylvanian and Permian(?) systems largely represent a return to carbonate platform deposition in the NTS region.

The following section outlines the lithologic characteristics, ages, and areas of occurrence of those upper Precambrian and Paleozoic stratigraphic

units exposed within the study area (plate 1). Tertiary volcanic rocks exposed in the CP Hills and vicinity are also discussed in less detail.

Cambrian

Wood Canyon Formation

The Wood Canyon Formation is the oldest stratigraphic unit exposed in the CP Hills. This formation was named by Nolan (1929) for exposures in Wood Canyon, in the northern Spring Mountains. Exposures of the Wood Canyon Formation in the CP Hills consist of reddish-brown weathering thinly laminated micaceous shale, siltstone and fine sandstone, rusty-orange weathering planar- and cross-laminated silty quartzite, minor amounts of pale red planar- and cross-laminated medium-to-coarse grained quartzite, and several-meter-thick bed(s) of light-to-medium grey dolomite. Locally abundant *Skolithos* tubes are common within sandstones and quartzites. Bedding surfaces of shales and siltstones contain locally abundant worm tracks and borings.

In its type location, the Wood Canyon Formation is approximately 640 m thick (Nolan, 1929). Neither the base nor the top of the Wood Canyon Formation is exposed in the CP Hills. However, field relations suggest that a

maximum of 200 m, presumably in the upper part of the formation, is exposed within the study area.

The age of the upper part of the Wood Canyon Formation is considered to be Early Cambrian, based on occurrences of olenellid trilobites and archeocyathids (Stewart, 1970). The middle and lower parts of the Wood Canyon Formation (which may not be exposed in the CP Hills) are considered to be Precambrian because they lie below the lowest occurrences of these fauna in the stratigraphic sequence (Stewart, 1970).

The Wood Canyon Formation is distinguished in the field by its dominantly clastic lithologies and its overall dark reddish-brown hue. However, this formation does contain pure quartzites which are lithologically similar to those within the Cambrian Zabriskie Quartzite and the Mississippian Eleana Formation (discussed below). The Wood Canyon Formation is best exposed at the southern edge of the study area (plate 1) where it lies in high-angle fault contact with the Pennsylvanian Tippipah Limestone. The formation is poorly exposed just northwest of the mapped trace of the CP thrust in the southwestern part of the study area. Other exposures of the Wood Canyon Formation are limited to small fault-bounded

blocks scattered peripherally about exposures of Carboniferous strata throughout the southern part of the CP Hills.

Zabriskie Quartzite

The Zabriskie Quartzite was originally described by Hazzard (1937) and defined as a member of the Wood Canyon Formation in the Nopah and Resting Spring Ranges in southeastern California, but was later promoted to the rank of formation by Wheeler (1948). The Zabriskie Quartzite is a clean, homogeneous, light red or pink, medium-to-coarse grained quartzite with minor rusty weathering silty quartzite. The quartzite is commonly planar and cross-laminated, but is locally massive with no distinct sedimentary features. *Skolithos* tubes are common locally.

The Zabriskie Quartzite thickens rapidly to the west regionally from about 6m or less in the Spring Mountains (Cornwall, 1972) to about 350 m at Bare Mountain (Cornwall and Kleinhampl, 1961). Although a complete section of the Zabriskie Quartzite is not exposed in the CP Hills, estimated stratigraphic thickness in the study area is about 20 m.

Although no age diagnostic fossils have been found within the Zabriskie Quartzite, it is assigned an Early Cambrian age because strata above

and below the formation contain trilobites of Early Cambrian age (Stewart, 1970).

The clean quartzites of the Zabriskie Quartzite are generally easily distinguished in the field. However, in structurally complex areas these quartzites may be confused with similar quartzites of the Wood Canyon Formation and the Mississippian Eleana Formation (discussed further below). Because of structural complexities and poor exposure, the Zabriskie Quartzite could rarely be confidently mapped separately from the Wood Canyon Formation in the CP Hills. For this reason, the Zabriskie Quartzite and the Wood Canyon Formation were mapped as a single unit. Nevertheless, the Zabriskie Quartzite is well exposed approximately 80 m due north of the most northerly exposure of Mississippian strata in the central part of the study area (plate 1) and also about 800 m due west of Peak 4856 in the southwest part of the study area (Universal Transverse Mercator coordinates 4086647m N, 580530m E) where the contact with the overlying Carrara Formation is locally well exposed (discussed further below). The base of the Zabriskie Quartzite is not well exposed in the CP Hills, but the formation is presumed to be conformable with the underlying Wood Canyon Formation.

Carrara Formation

The Carrara Formation was originally described and named by Cornwall and Kleinhampl (1961) for exposures at the ghost town of Carrara on the west side of Bare Mountain (fig. 1). Subsequent studies (e.g. Barnes et al., 1962; Stewart, 1970; Palmer and Halley, 1979) have greatly refined the stratigraphy and biostratigraphy of this formation. Barnes et al. (1962) and Palmer and Halley (1979) subdivided the Carrara Formation into seven and nine members, respectively. While specific lithologic details within this formation have proven invaluable in interpreting the structural relations within the CP Hills, a comprehensive stratigraphic study of the Carrara Formation was beyond the scope of this project. Therefore, no attempt was made to delineate members within this formation. Nevertheless, the Carrara Formation is well exposed in the CP Hills and is a heterogeneous unit marking the stratigraphic transition within the miogeocline between earlier dominantly clastic sedimentation and overlying carbonate shelf deposits.

The formation consists of interstratified green, dark brown, and brick-red weathering, micaceous and calcareous shale and siltstone, reddish-orange and grey weathering, oolitic limestone and algal limestone (*Girvanella*), medium-to-dark grey weathering, micritic limestone, olive green weathering,

massive bedded bioclastic (detrital) limestone, thinly bedded rusty-orange and grey weathering planar- and cross-laminated silty limestone, and minor amounts of reddish-brown medium grained calcite cemented quartz sandstone and secondary(?) dolomite. Shales and siltstones are commonly highly bioturbated, evidenced from abundant worm tracks and borings on bedding surfaces. Detrital limestones consist predominantly of chaotically organized fragments of trilobites and other unidentified fossils.

Thickness of the Carrara Formation varies regionally from about 400-600 m (Stewart, 1970). A complete section of the Carrara is not exposed within the CP Hills, but field relations require a minimum stratigraphic thickness of 450 m.

Faunal assemblages of abundant trilobites within the Carrara Formation indicate that the formation generally ranges in age from late Early Cambrian through early Late Cambrian (Barnes et al., 1962; Palmer and Halley, 1979).

The unique lithologic assemblage of strata and an overall rusty-orange to reddish-brown hue make the Carrara Formation one of the most distinctive stratigraphic units within the CP Hills. The Carrara Formation is well exposed in the eastern and southern parts of the CP Hills, although, as

previously noted, no complete sections occur in these areas. The formation is best exposed immediately west of Yucca Pass, where it underlies dolomites of the Bonanza King Formation in a sharp, conformable contact. The base of the formation is locally well exposed approximately 800 m due west of Peak 4856 in the southwest part of the study area, where calcareous and micaceous shales, siltstones, and quartz sandstones of the Carrara Formation are conformable and transitional with underlying silty quartzites of the Zabriskie Quartzite.

Bonanza King Formation

The Bonanza King Formation was first described by Hazzard and Mason (1936) and corresponds to the upper part of the Yucca Flat Formation of Johnson and Hibbard (1957) (Barnes et al., 1962). Barnes et al. (1962) subdivided the Bonanza King Formation on the east side of Yucca Flat (fig. 1) into two members: the Papoose Lake Member and the Banded Mountain Member. McKeown et al. (1976) further subdivided the Banded Mountain Member in the CP Hills into two mappable subunits. This convention proved useful for delineating and interpreting important structures within the study area and is adopted herein. The age of the Bonanza King Formation

is Middle and Late Cambrian based on trilobite assemblage zones (Barnes et al., 1962).

Papoose Lake Member - The Papoose Lake Member is the lowest stratigraphic unit of the Bonanza King Formation and is composed of medium to dark grey and subordinate light grey, thickly to thinly bedded and laminated dolomite and minor amounts of yellow-brown weathering thinly bedded silty dolomite. Laminae are light grey to white and most commonly have irregular cusped morphologies giving the rock a mottled and bioturbated appearance. Prominent clusters of coarse diagenetic(?) dolomite crystals preferentially occupy laminae horizons locally.

Although many similar lithologic features occur throughout the Bonanza King, the Papoose Lake Member in the CP Hills can usually be distinguished from the overlying Banded Mountain Member by its overall darker, smoky grey appearance. The contact with the overlying lower subunit of the Banded Mountain Member is generally sharp and marked by the first appearance of prominent, rusty-orange weathering, silty limestone and dolomite of the Banded Mountain Member. A complete and relatively unfaulted section of the Papoose Lake Member is exposed in the eastern part of the CP Hills. Although this section was not measured in the field, map

relations suggest an approximate thickness of 700 m for this member, which is consistent with a 660 m thickness measured at its type locality (Barnes et al., 1962) east of Yucca Flat. The Papoose Lake Member also crops out extensively in the southern part of the study area as large pervasively fractured and locally brecciated, fault-bounded blocks and smaller isolated fault klippen.

Banded Mountain Member (lower) - The lower subunit of the Banded Mountain Member consists of an alternating sequence of dark grey limestone (minor dolomite) and prominent rusty-orange weathering, calcareous siltstone and silty limestone. Limestones are well-bedded and laminated. Laminae forms are locally similar to those in the Papoose Lake Member. Siltstones and silty limestones are thinly bedded and planar- and cross-laminated. Within the CP Hills, this subunit is the only part of the Bonanza King Formation that contains substantial relict limestone lithologies, suggesting a stratigraphic control to secondary dolomitization.

Thickness of the lower subunit of the Banded Mountain Member varies considerably, from approximately 150 m to less than 60 m and the subunit generally appears to thin gradually toward the west or southwest.

The lower subunit of the Banded Mountain Member is easily distinguished in the field by its prominent rusty-orange color and the

presence of rare limestones. This subunit is exposed extensively in the northern and central parts of the study area, and forms a somewhat confusing outcrop pattern due to structural complexities (discussed later). The contact between the lower subunit and the upper subunit of Banded Mountain Member is sharp and is marked by the first light grey dolomite of the upper subunit.

Banded Mountain Member (upper) - The upper subunit of the Banded Mountain Member is composed of a color banded sequence of light, medium and locally dark grey, well-bedded and thinly laminated dolomite. Dark rusty-brown weathering chert lenses and nodules are common in the lower part of the subunit. Lenses and nodules generally range in thickness or diameter from 1 to 10 cm. Color banding arises from alternating beds of variously tinted grey dolomite, ranging in thickness from less than one to several meters.

A complete section of the upper subunit of the Banded Mountain Member is not exposed in the CP Hills. Structural complications make it difficult to estimate the thickness of this subunit; however, map relations suggest a minimum stratigraphic thickness of roughly 700 m. This estimate is compatible with a 740 m thickness of the Banded Mountain Member (which

includes both upper and lower subunits defined herein) measured at its type locality east of Yucca Flat (Barnes and Palmer (1961) in Barnes et al., 1962).

The upper subunit of the Banded Mountain Member is distinguished in the field from lower units within the Bonanza King Formation by its overall lighter grey hue, its impressive banded appearance, and local occurrences of lenticular and nodular chert which are essentially absent in lower units. The upper subunit of the Banded Mountain Member is widely distributed and moderately well exposed throughout the northern half of the CP Hills.

Devonian/Mississippian

Eleana Formation

The Eleana Formation was described and named by Johnson and Hibbard (1957) for extensive exposures in the Eleana Range, west of Yucca Flat (fig. 1). The stratigraphy and sedimentology have since been studied in greater detail (e.g. Poole et al., 1961, 1965; Nitchman, 1990, in review). In the CP Hills, the Eleana Formation consists of two parts: 1) a lower part of dark brown to greenish brown, thin bedded siliceous mudstone, siltstone, minor sandstone, and rare bioclastic limestone, and 2) an upper part of interstratified clean, white to pink, cross stratified and ripple laminated quartzite, dark grey

to black siliceous mudstone, and olive green weathering, massively bedded bioclastic limestone. Quartzite and limestone beds in the upper part of the section are generally 2-3 m thick. Mudstone units in this section are about 4-7 m thick. Preserved on the tops of quartzite beds are locally abundant molds of crinoid columnal fragments in addition to well-preserved molds of plant stems and fragments (*Calamities* and *Stigmaria*) and large logs (*Lepidodendron*) up to 25 cm in diameter (flora identified by S. Nitchman, personal communication, 1989). Bioclastic limestones are composed largely of macro-scale, randomly organized, and partially fragmented horn corals, crinoid columnals, bryozoans, and brachiopods in a micritic matrix.

The upper part of the Eleana Formation (described above) makes up approximately the upper 90-100 m of the formation in the CP Hills. The base of the formation is not exposed, and therefore an estimate of total stratigraphic thickness is not possible. In the Eleana Range, total thickness for this formation has been estimated between 1500 m (Nitchman, in review) and 2500 m (Poole et al., 1961). However, a maximum exposed thickness of only about 450 m is present in the CP Hills.

The age of the Eleana Formation, constrained by macrofossils (Poole et al., 1961, 1965), ranges from Late Devonian(?) to Late Mississippian (latest

Chesterian). Recently, palynomorphs and conodonts collected from the Eleana Formation have yielded ages ranging from Late Devonian (Famennian) to Early Pennsylvanian (Morrowan) (Cashman and Trexler, 1991).

Rocks of the Eleana Formation are generally easily distinguished in the field, although in structurally complex areas, quartzites of the Eleana Formation may be confused with similar rocks within the Zabriskie Quartzite and the Wood Canyon Formation. Fortunately, quartzites of the Eleana Formation are nearly always (depositionally) associated with bioclastic limestones that contain obvious upper Paleozoic faunal assemblages. These quartzites form resistant ledges and provide good marker horizons. Where laterally persistent, these marker beds were mapped on plate 1. The lower part of the Eleana Formation forms recessive slopes and subcrops.

Exposures of the Eleana Formation in the CP Hills are confined to the south central part of the study area, where this formation and the Pennsylvanian Tippipah Limestone (discussed below) are juxtaposed against Lower and Middle Cambrian strata along the CP thrust and several high-angle normal faults. The depositional contact with the overlying Tippipah Limestone (discussed below) is locally well exposed.

Pennsylvanian

Tippipah Limestone

The Tippipah Limestone was described and named by Johnson and Hibbard (1957) for exposures at Syncline Ridge, approximately 15 km northwest of the CP Hills (fig. 1). This formation is lithologically similar to and largely correlative with the Bird Spring Formation (Cornwall, 1972) which is widely exposed in the Spring Mountains, south of the NTS (fig. 1). Within the CP Hills, the Tippipah Limestone consists of thickly bedded, light-to-medium grey micritic limestone and minor interbeds of light grey weathering platy or fissile limestone and yellow-brown weathering silty limestone. Micritic limestones contain locally abundant dark brown weathering chert lenses ranging in thickness from approximately 3 to 20 cm and spheroidal chert masses ranging from 2 to 25 cm in diameter. Chert masses commonly exhibit irregular shapes with no apparent relation to bedding. Limestones are characterized by local fossiliferous horizons containing abundant gastropods, crinoid columnal fragments, and brachiopods. Limestones also exhibit locally pervasive calcite-filled veins or fractures. Fresh surfaces of fissile limestone are dark grey to black. When broken, these rocks commonly emit a pungent, hydrogen sulfide odor.

The stratigraphic thickness of the Tippipah Limestone cannot be determined in the CP Hills, but field relations suggest that the lowermost 200-300 m of this formation are present. The thickness of an incomplete section of Tippipah Limestone at Syncline Ridge has been estimated at approximately 1060m (Orkild, 1963).

Abundant macrofossils indicate an Early Pennsylvanian (Gordon and Poole, 1968) through Late(?) Pennsylvanian (Poole et al., 1961) age for this formation.

Limestones of the Tippipah Limestone are easily distinguished from other formations in the CP Hills. The Tippipah Limestone is well exposed in the south and southwest parts of the study area (plate 1) together with the Mississippian Eleana Formation (discussed above). The base of the Tippipah Limestone is locally well exposed in the southern part of the study area (Universal Transverse Mercator coordinates 4085590m N, 581700m E) (see plate 1). In this area, the contact with underlying quartzites, limestones, and mudstones of the Eleana Formation forms an abrupt lithologic break marked by the first occurrence of light grey micrites of the Tippipah Limestone. Approximately 900 m to the north, these micrites appear locally to cut out silty bioclastic limestones of the uppermost Eleana Formation. These

observations, together with evidence for a biostratigraphic hiatus at this contact (Gordon and Poole, 1968) suggest that the Tippihah Limestone overlies the Eleana Formation along an erosional disconformity (Gordon and Poole, 1968).

Tertiary volcanic rocks

The NTS lies within the southwest Nevada volcanic field (SNVF) (Christiansen et al., 1977) which was active primarily between 16 and 6 Ma (Christiansen et al., 1977; Carr et al., 1986; Byers et al., 1989). During this time, at least nine voluminous silicic ash flow sheets and many smaller ash flow units and lavas of varying petrology, were erupted from at least four major calderas and were deposited over an area covering approximately 11,000 km² (e.g. Christiansen et al., 1977). Christiansen et al. (1977) estimated the total volume of the SNVF to be greater than 5700 km³. Estimated composite stratigraphic thickness of Miocene volcanic rocks in this region range from 6100 m (Cornwall, 1972) to 9100 m (Ekren, 1968). Stratigraphic nomenclature along with understanding of the volcanology of the SNVF has evolved substantially since the earliest studies in the 1950's and 60's (see discussions in Byers et al., 1989).

The CP Hills are located near the southeast margin of the SNVF. In this area, McKeown et al. (1976) delineated six Miocene volcanic map units. From oldest to youngest these are: 1) **Undifferentiated silicic ash fall and ash flow tuffs**. These tuffs include drill hole occurrences of possible 17.8 Ma(?) **Fraction Tuff** and 15.1 Ma **Redrock Valley Tuff**, and local exposures of 13.7 Ma **Crater Flat Tuff**, although the later may actually be 15.1 Ma **Tuff of Yucca Flat** (see Carr et al., 1986, fig. 2, p. 4); 2) 13.1 Ma **Wahmonie Formation**, rhyodacitic lavas and tuffs; 3) **Topopah Spring Member of the Paintbrush Tuff**, mostly devitrified, densely welded silicic ash flow tuff; 4) **Tiva Canyon Member of the Paintbrush Tuff**, devitrified, densely welded silicic ash flow tuff; 5) **Rainier Mesa Member of the Timber Mountain Tuff**, devitrified, moderately-to-densely welded ash flow tuff; and 6) **Ammonia Tanks Member of the Timber Mountain Tuff**, devitrified, moderately-to-densely welded silicic ash flow tuff. The ages of the Paintbrush and Timber Mountain tuffs range from 11-13 Ma (e.g. Carr et al., 1986). The general stratigraphy for Miocene volcanic rocks in the CP Hills area, and sources for the rock dates given above, are summarized in figure 3.

Formation Member	Approximate age (Ma)	References for unit ages
Timber Mountain Tuff ^① Ammonia Tanks Member Rainier Mesa Member	11.5	Kistler (1968) Marvin et al. (1970)
Paintbrush Tuff Tiva Canyon Member ^① Topopah Springs Member ^②	12.8	Sawyer et al. (1990)
Wahmonie Formation ^③	13.1	Carr et al. (1986)
Crater Flat Tuff ^③	13.7	Carr et al. (1986)
Tuff of Yucca Flat ^③	15.1	Sawyer et al. (1990)
Redrock Vally Tuff ^④	15.1	Sawyer et al. (1990)
Fraction Tuff ^④	17.8	Ekren, personal comm. in Cornwall (1972)

Figure 3 - Tertiary volcanic rocks of the CP Hills area. ① - units which do not occur within the study area (see plate 1); ② - unit mapped within the study area; ③ - units mapped collectively as "undifferentiated" on plate 1; ④ - drill hole occurrences (drill hole Ue6e) noted by McKeown et al. (1976).

Detailed description and mapping of Tertiary volcanic units were largely beyond the scope of this project. However, within the study area (plate 1), the Topopah Spring Member of the Paintbrush Tuff and undifferentiated Miocene volcanic rocks of McKeown et al. (1976) are moderately to well exposed and were mapped. Local exposures of Wahmonie Formation (mapped by McKeown et al., 1976) are included with undifferentiated volcanic rocks (plate 1). The contact between the Topopah Spring Member and underlying undifferentiated tuffs is defined in the field, and on aerial photographs, by a prominent 15-20 m thick basal vitrophyre of the Topopah Spring Member. Where determinable, no angular discordance exists between these two map units. The contact between these units is broadly considered to be disconformable.

STRUCTURAL GEOLOGY

Mesozoic Structure

Prior to Tertiary extension, the CP Hills area was part of a Mesozoic fold and thrust belt (Johnson and Hibbard, 1957). Cenozoic extensional faults have greatly disrupted Mesozoic structures in the CP Hills, but Mesozoic folds are locally well preserved and provide the foundation by which much of the Cenozoic deformation can be understood. The most important Mesozoic

structure in the CP Hills is the CP thrust, which was named for exposures in this area (Barnes and Poole, 1968). Paleozoic rocks exposed in the study area comprise two Mesozoic structural levels; 1) strata which lie structurally above the CP thrust (the CP allochthon), including Precambrian(?) and Lower Cambrian Wood Canyon Formation through Upper Cambrian Nopah Formation, and 2) strata structurally beneath the CP thrust (the CP parautochthon), including the Mississippian Eleana Formation and Pennsylvanian Tippipah Limestone. Map scale west-vergent folds occur in both the upper and lower plates of the CP thrust and these structures, together with other arguments presented below, provide constraints on the kinematics of the CP thrust.

The following section outlines the major Mesozoic structural features within the study area. However, in this discussion, brief digressions about pertinent Tertiary faults are necessary. It is also possible that certain Tertiary faults may have originated as Mesozoic structures.

CP Allochthon

The CP allochthon includes all of the lowermost Cambrian (and Precambrian(?)) through Upper Cambrian strata exposed in the CP Hills. In the northern and eastern parts of the study area, a large-scale west-vergent

fold system occurs throughout exposures of the Carrara and Bonanza King formations. The best preserved portion of this fold system in the CP allochthon occurs due west of Yucca Pass (plate 1). In this area, a 400 m thick section of the Carrara Formation forms part of the overturned limb of a west-vergent anticline-syncline pair (see plate 2a,b) that involves a minimum of 2000m of Lower and Upper Cambrian strata when traced to the northeast. Structural data from the Carrara Formation at Yucca Pass indicate the west-vergent anticline in this area has a north-trending and gently plunging orientation (fig. 4a).

Figure 4a illustrates a bimodal distribution of poles to bedding within the Carrara Formation in the Yucca Pass area, whereby east-dipping strata are overturned toward the west and west-dipping strata are upright without exception. In this area, a prominent west-dipping fault bisects the Carrara Formation and everywhere juxtaposes upright, west-dipping strata to the west against overturned east-dipping strata to the east (plate 1). Where exposed, this fault dips between 35 and 40 degrees to the west and is commonly marked by a 1-2 m thick zone of highly fractured and brecciated limestone and localized dolomite. However, locally this fault is a sharp contact where moderately west-dipping strata abruptly overlie steeply

Figure 4 - Equal area, lower hemisphere stereographic projections of structures within the CP allochthon. a) Pi-diagram of poles to bedding, Carrara Formation (Yucca Pass area). b) Hingeline orientations of mesoscopic folds, Carrara Formation (Yucca Pass area). c) Poles to hinge surfaces of mesoscopic folds, Carrara Formation (Yucca Pass area). d) Hingeline orientations of mesoscopic and macroscopic folds within both the hangingwall (HW) and footwall (FW) of the low-angle normal fault (LANF) in the northern part of the CP Hills.

overturned east-dipping strata of the footwall. It is unclear whether this is a Mesozoic or Tertiary structure, although this fault may have a deformation history which includes both eras. Net slip direction and magnitude of displacement are not well constrained for this fault, but a minimum of 180m of normal dip separation appears to be required to produce a viable restored fold geometry in this area (see plate 2a,b).

Close to tight asymmetric parasitic folds are locally abundant within silty layers of overturned Carrara formation where exposed at Yucca Pass. These folds generally exhibit asymmetry which is appropriate for parasitic folds within the overturned limb of a west-vergent fold pair, and so these structures may provide additional constraints on the overall style and orientation of larger-scale folding in this area. Amplitudes and wavelengths of parasitic folds generally range from 5 to 20 cm and these folds commonly exhibit moderate thickening in the hinge zones yielding Class IC and Class 2 fold geometry (Huber and Ramsay, 1987). Hingeline and hinge surface orientations of parasitic folds at Yucca Pass (fig. 4b and c) suggest a gently inclined and gently north-plunging geometry for larger-scale west-vergent folds in this area. This interpretation is consistent with the north-trending

horizontal fold orientation suggested by bedding attitudes (discussed above) within the Carrara Formation at Yucca Pass.

Northwest from Yucca Pass, the west-vergent folds within the CP allochthon are expressed in progressively younger strata of the Bonanza King Formation. In this area, complex Tertiary extensional faulting has greatly disrupted preexisting folds. However, 2 km northwest of Yucca Pass, the hinge zone of a map-scale overturned syncline is well preserved and is delineated by the contact between the upper and lower subunits of the Banded Mountain Member. The overturned limb of this fold is interpreted as a continuation of the west-vergent structure expressed in the Carrara Formation at Yucca Pass.

The overturned syncline 2 km northwest of Yucca Pass (discussed above) lies in the hanging wall of a low-angle normal fault which is interpreted to underlie all of the Bonanza King Formation in the southern half of the study area as well as the Carrara Formation at Yucca Pass (discussed later). This fold appears to have been displaced approximately 1 km from the west where the upper and lower subunits of the Banded Mountain Member occur in the footwall of the low-angle normal fault. Within the footwall of the low-angle normal fault, these strata are highly disrupted by high-angle

Tertiary faults, but they maintain an overall synclinal outcrop pattern. Although the hinge surface trace of this fold is difficult to map precisely, complex smaller scale folds within and around the hinge region and the degree to which strata are overturned within the upper limb leave little doubt that a very large, west-vergent syncline occurs in this area and that this syncline is probably the counterpart of the overturned anticline at Yucca Pass. The overturned syncline in both the hangingwall and footwall of the low-angle normal fault is portrayed in structural sections B-B' and C-C' (plate 3). However, it is necessary to note that fold(s) plunge moderately to the northeast in this area (discussed below), and for this reason, a certain amount of fold distortion is inherent in these structural sections.

Hingeline orientations of mesoscopic and macroscopic parasitic folds within strata of the Banded Mountain Member suggest that the hingeline(s) of the larger-scale fold(s) plunge gently to moderately to the northeast in the northern part of the study area (fig. 4d). These data were collected from folds of varying scales and styles and from both the hangingwall and footwall of the low-angle normal fault discussed above. Despite numerous other Tertiary faults in the area (many of which were too small-scale to map) these data group rather well. The apparent clockwise rotation of the trend of west-

vergent folds in this area relative to those at Yucca Pass (compare figs. 4b and 4d) may be the result of Tertiary deformation in the northern part of the study area which is not presently understood.

No well-defined west-vergent folds have been recognized within the part of the CP allochthon exposed in the southwest part of the study area. However, in this area, particularly along structural section A-A' (plates 1 and 2), strata above the CP thrust exhibit small amplitude, upright, symmetric, north trending folds. These folds represent significant layer parallel shortening, but it is unclear whether these structures formed prior to, after, or somehow concurrent with the west-vergent folds that occur elsewhere in the hangingwall and footwall of the CP thrust.

In the northernmost part of the CP Hills, a possible thrust occurs within the CP allochthon. In this area, overturned strata of the upper subunit of the Banded Mountain Member structurally overlie locally overturned strata of Nopah Formation (see McKeown et al., 1976) in a low-angle fault contact. In the vicinity of 311 Canyon Road, the fault dips gently to the east and is characterized by pervasively fractured and locally brecciated Bonanza King dolomite in the hangingwall. Although these characteristics suggest that Tertiary extensional deformation probably occurred along this fault

surface, structural relations across this structure (i.e. an older on younger age relationship and westward overturned of strata in both the hangingwall and footwall of the fault) indicate that earlier (west-vergent) thrusting along this fault may have occurred. It is reasonable to infer that west-vergent thrust imbrications accompanied large-scale west-vergent folding within the CP allochthon. However, more detailed mapping and structural analysis needs to be done in this area to evaluate the structural relations.

Within the CP allochthon, no penetrative cleavage or foliation associated with large-scale west-vergent folding and thrusting was recognized. However, a moderately well-developed, slaty, hinge surface cleavage is locally associated with smaller scale parasitic folds, particularly where these folds occur within the Carrara Formation at Yucca Pass. Limestones of the Carrara Formation also exhibit locally well-developed bedding-parallel stylolitic solution seams. These stylolites are probably a result of diagenesis.

CP Parautochthon

The CP parautochthon comprises all strata of the Mississippian Eleana Formation and the Pennsylvanian Tippipah Limestone within the study area. These rocks are exposed only in the southern part of the CP Hills and are

primarily juxtaposed along high-angle Tertiary normal faults against downdropped Lower and Middle Cambrian strata of the CP allochthon. However, overturned Mississippian and Pennsylvanian strata structurally underlie rocks of the CP allochthon along the CP thrust in the southwest part of the study area.

The structure of the CP parautochthon is dominated by a large-scale, tight, nearly recumbent, north trending, west-vergent footwall syncline. Although this structure is locally disrupted by high-angle Tertiary normal faults, it can be traced for greater than 2 km throughout exposures of upper Paleozoic strata in the southern part of the study area. Structural relations indicate that this footwall syncline involves a minimum of 670 m of Mississippian Eleana Formation and Pennsylvanian Tippipah Limestone (see plate 2a,b). Structural data collected from these strata (fig. 5a) indicate that the footwall syncline is a fold with the same north-trending, horizontal hingeline orientation as the west-vergent anticline in the CP allochthon at Yucca Pass (discussed above).

The hinge zone of the footwall syncline is very well exposed near the northernmost exposures of upper Paleozoic strata in the south-central part of the study area (fig. 6). In this area, clean quartzites and interbedded bioclastic

Figure 5 - Equal area, lower hemisphere stereographic projections of structures within the CP parautochthon. a) Pi diagram of poles to bedding, Eleana Formation and Tippipah Limestone. b) Hingeline orientations of mesoscopic folds, Eleana Formation and Tippipah Limestone. c) Hingeline orientations of mesoscopic folds, Eleana Formation. d) Hingeline orientations of mesoscopic folds, Tippipah Limestone. e) (next page) Hingeline orientations of problematic, east-trending F1 (?) folds within Tippipah Limestone. f) (next page) Hingeline orientations of figure 5e hypothetically unfolded 144 degrees (clockwise) about a horizontal axis oriented 325 degrees (see text for discussion).

5e

○ Pt F1 (?) hingelines rotated
about 325 (azimuth) by
144 degrees (clockwise angle)

5f

limestones of the uppermost part of the Eleana Formation form a nearly recumbent, slightly north-plunging syncline with a moderately west-dipping, upright lower limb and a moderately to steeply east-dipping, overturned upper limb. Bedding surfaces of the quartzite units exhibit prominent hingeline-perpendicular slickensides. These "movement striae" (Ramsay and Huber, 1987) almost certainly formed parallel to the direction of relative slip between layering within the Eleana Formation during flexural slip folding. Bioclasts (e.g. crinoid columnal fragments and brachiopods) within interbedded limestones locally exhibit a high degree of distortion (strain) which may have resulted from flexural flow deformation related to folding. This type of folding, characterized by both flexural slip and flexural flow, is commonly observed in interlayered competent and incompetent rocks (i.e. quartzite and limestone, resp.) deformed under low-grade metamorphic or nonmetamorphic conditions (Ramsay and Huber, 1987).

The hinge zone of the footwall syncline is also moderately to poorly expressed within the Tippipah Limestone approximately 1.5 km due south of the site mentioned above and immediately west of the large landslide mass of Tippipah Limestone. In this area, strata of the Tippipah Limestone rapidly fold over from moderately west-dipping and upright at the contact with the

Figure 6 - View north-northwest of the hinge zone of the recumbent footwall syncline within clean quartzites of the Eleana Formation within the CP parautochthon in the southern part of the CP Hills.

underlying Eleana Formation (and the overlying landslide mass), to moderately east-dipping and overturned along the north-trending ridge approximately 80 m west of the landslide block. Strata of the Tippipah Limestone are locally complexly folded in this area which is consistent with this area being the hinge zone of the footwall syncline.

Hingeline orientations of mesoscopic folds within the Eleana Formation and the Tippipah Limestone (fig. 5b,c, and d) reflect structural complexities which may be interpreted as resulting from two episodes of contractional deformation in the CP Hills area. Hingelines from the Eleana Formation broadly exhibit two distribution patterns (fig. 5c): 1) a cluster of north-northwest-trending, gently plunging hingelines which also include several south- and southwest-trending, gently-plunging hingelines; and 2) a crude east-northeast to west-southwest trending "girdle" pattern. These two groups of data are also evident when hingelines from the Tippipah Limestone are included (fig. 5b). However, to simplify discussions of the fold data from the Eleana Formation and Tippipah Limestone, data are also shown on separate stereoplots (fig. 5c and d, resp.).

All of the folds with the north-south trending and gently plunging hingelines (mentioned above) (fig. 5c) are close to tight, symmetric and

asymmetric folds developed within quartzites and bioclastic limestones of the uppermost part of the Eleana Formation. In the field, these folds clearly occur within the hinge zone or the overturned limb of the footwall syncline. These folds exhibit appropriate hinge zone symmetry or fold limb asymmetry, depending on where they occur within the footwall syncline, which indicates that these are parasitic folds related to larger-scale, north-trending west-vergent folds within the CP parautochthon.

The hingelines forming the east-northeast to west-southwest trending girdle pattern in figure 5c are all from folds formed within mudstone and siltstone of the poorly exposed lower part of the Eleana Formation. These mesoscopic folds vary widely in style and include open and close symmetrical folds, tight asymmetric folds, and isoclinal folds. Fold amplitudes and wavelengths range from 10 to 50 cm, although small-scale symmetric and asymmetric crenulations (with a wavelength of approximately 1 cm) are also locally associated with some of these folds. The variable orientations of these hingelines could possibly be attributed to the general incompetence of these strata and localized perturbations during larger-scale west-vergent folding. However, the occurrence of locally developed crenulations, together with the existence of several vertical and subvertical folds and a girdled distribution of

these hingelines all suggest that at least two episodes of folding affected these strata. In addition, the girdle pattern appears to be distributed cylindrically about an axis whose trend generally parallels the set of north-northwest and south- and southwest trending hingelines (discussed above). This relation suggests that if two episodes of folding occurred in the CP Hills, north-trending folds related to larger-scale west-vergent folding (discussed above) were superimposed on an earlier set of generally northeast-southwest-trending folds.

Structural relations within quartzites of the Eleana Formation approximately 550 m east of peak 4856, along structural section A-A' (plates 1 and 2), also suggest that more than one episode of folding occurred in the CP Hills area. In this area, a map-scale north-trending and plunging sigmoidal "z" fold occurs within the lower limb of the west-vergent footwall syncline. This asymmetric fold is locally overturned toward the east. The sense of asymmetry (and vergence) of this fold indicates that it is probably not related to larger-scale west-vergent folds. Although no obvious cross-cutting relationship exists between this fold and the larger, west-vergent footwall syncline, arguments presented above suggest that this smaller scale fold may have been related to an earlier episode of folding in the CP Hills. However,

localized perturbations resulting in restricted zones of deformation with an opposite sense of vergence during larger-scale west-vergent folding cannot be ruled out.

Hingeline data from the Pennsylvanian Tippipah Limestone also exhibit two distribution patterns (fig. 5d): 1) a cluster of south-(and north-) trending, moderately to gently plunging hingelines; and 2) a cluster of east-trending, moderately plunging hingelines.

The north-south trending hingelines from the Tippipah Limestone (fig. 5d) represent two general types of folds: 1) close to tight, symmetric and asymmetric folds (shown as triangles; and 2) isoclinal folds (shown as squares). Symmetric and asymmetric fold amplitudes and wavelengths range from 15-50 cm, and these folds generally exhibit moderate hinge zone thickening, yielding Class 1C and Class 2 fold geometry (Ramsay and Huber, 1987). These folds are interpreted as parasitic folds related to larger-scale west-vergent folds because they exhibit the appropriate north-trending orientation and hinge zone symmetry or fold limb asymmetry, depending on where they occur within the the west-vergent footwall syncline. Orientations of isoclinal folds also suggest that these folds may be parasitic to larger-scale west-vergent folds. The north-trending isoclinal folds were observed only in deep

drainages incised within the southernmost exposures of Tippipah Limestone. In these locations, these rocks are probably very near the core of the footwall syncline as they exhibit a very high degree of strain manifested as numerous small-scale thrust faults as well as long-limbed isoclinal folds. The occurrence of isoclinal folds near the core of the footwall syncline supports the interpretation of a tight footwall fold geometry (depicted in plate 2a and b).

Folds with east-trending and plunging hingelines (fig. 5d and e) from the Tippipah Limestone are problematic because they all exhibit south-vergent asymmetry. These folds all occur within a distinct silty limestone unit near the base of the Tippipah Limestone within the overturned limb of the footwall syncline. All of these folds are tight to isoclinal asymmetric folds with amplitudes and wavelengths of approximately 25-40 cm. They exhibit moderate thickening within the hinge zones, yielding Class 1C or Class 2 fold geometry (Ramsay and Huber, 1987). Although these south-vergent folds appear to be unrelated to the west-vergent folds, they could reflect south-directed displacement along the CP thrust after or during the development of the west-vergent footwall syncline. However, this interpretation is not very appealing because this would require a 90 degree change in the transport direction of the CP allochthon.

An alternative explanation for these folds is that they developed prior to the west-vergent footwall syncline (i.e. the problematic east-trending folds may be F_1 's and the west-vergent footwall syncline and related folds may be F_2 's). To explore this possibility, the overturned strata of the footwall syncline in which the F_1 folds are developed must be unfolded. Hinge surfaces of F_1 folds are subparallel to overturned bedding within the Tippipah Limestone, so the mean orientation of their hinge surfaces (325, 36E) provides an amount and an approximate axis about which to back-rotate the presently northeast-dipping strata and east-trending hingelines. Upon back-rotating the overturned strata where these folds occur (to a hypothetical upright paleohorizontal orientation), two things happen to the fold set (fig. 5f). First, the fold hingelines take on northeast and southwest trends and gentle to moderate plunges. Secondly, these folds flip around to become northwest-vergent. If this set of folds developed prior to the west-vergent footwall syncline, then the above analysis suggests that these folds represent an earlier episode of northwest-vergent, layer-parallel simple shear deformation. However, it seems likely that any preexisting northwest-vergent folds probably only represent an early phase of progressive, generally west-vergent deformation in this region.

The east-trending set of fold hingelines from the Tippipah Limestone (fig. 5d) fits well into the girdle distribution of fold hingelines from the Eleana Formation (see fig. 5b and c) that has also been interpreted as reflecting deformation prior to large-scale west-vergent folding in the CP Hills area (discussed above). While analysis of the presently east-trending folds in the Tippipah Limestone may suggest that all of the hingelines forming the girdle distribution (fig. 5b) reflect earlier northwest-vergent folding, the existence of map-scale east-vergent folds within the Eleana Formation (discussed above) leaves open the possibility that this distribution may in part be attributed to earlier east-vergent deformation in the CP Hills.

As within the CP allochthon, no penetrative cleavage or foliation associated with large-scale west-vergent folding or thrusting was recognized within the CP parautochthon. However, a moderately well developed slaty hinge surface cleavage is locally associated with most mesoscopic folds. Hinge surface cleavage associated with the previously discussed tight to isoclinal east-trending folds within the Tippipah Limestone (fig. 5d) is also associated with a bedding-parallel fissility (i.e. cleavage) within the limbs of these folds. This bedding-parallel cleavage was observed elsewhere within micrites of the Tippipah Limestone, and could be a penetrative cleavage associated with

deformation related to the presently east-trending fold set. Local crenulations and associated crenulation cleavage within folded mudstone of the Eleana Formation may also require a preexisting bedding-parallel structural fabric within these rocks. Clean quartzites within the Eleana Formation locally exhibit prominent layer parallel stylolitic solution seams. These stylolites occur in both the upper and lower limbs of the footwall syncline and appear to be folded by this footwall structure. It is not clear whether these stylolites are related to layer parallel structural fabrics within other rocks of the CP parautochthon (discussed above). However, because chemical dissolution of quartz is thought to be able to occur at such shallow depths of burial (1-3 km?) and low temperatures ($< 20^{\circ}\text{C}$) (Lewis, 1984, p. 35), these stylolites may possibly be the result of diagenesis related to burial.

CP Thrust

The CP thrust, named for exposures in the CP Hills (Barnes and Poole, 1968) is exposed only in the southwest part of the study area (plate 1, fig. 7). In this area, Lower Cambrian Wood Canyon Formation, Zabriskie Quartzite, and Carrara Formation structurally overlie the east-dipping overturned limb of a large-scale footwall syncline (discussed above) composed mostly of Pennsylvanian Tippipah Limestone, although overturned strata of the

Figure 7 - View north of the CP thrust where exposed in the southwest part of the study area (plate 1). Reddish brown carbonates and silty carbonates of the Carrara Formation overlie grey and rusty-grey limestones of the Tippipah Limestone.

Mississippian Eleana Formation are also exposed locally beneath the CP thrust (plate 1). The actual fault contact in this area is everywhere obscured by colluvium or talus, although the contact can be confidently located to within 1-2 m along the entire mapped trace of the CP thrust. Therefore, the true dip of this fault could not be determined. However, field relations indicate that the CP thrust dips moderately to the northeast in this area.

Localized zones of highly fractured strata of the Carrara Formation as well as locally abundant small-scale north-trending, down-to-the-east, high-angle normal faults within this formation, near the CP thrust contact, indicate that this fault has been somewhat reactivated during east-directed extensional deformation, probably during the Tertiary. The degree to which the CP thrust has been reactivated is uncertain. However, structural and stratigraphic relations across this fault leave no doubt that a major Mesozoic thrust has endured the effects of Tertiary overprinting in the CP Hills area.

Published cross-sections of McKeown et al. (1976), together with interpretations herein, indicate that the CP thrust is a major west-vergent Mesozoic structure. However, as noted earlier, other workers have interpreted the CP thrust, where exposed in the CP Hills, as an east- to southeast-vergent structure (e.g. Barnes and Poole, 1968; Carr, 1984; Hinrichs,

1968; Wernicke et al., 1988; Snow and Wernicke, 1989). Two independent lines of evidence support the interpretation of west-vergence: 1) large-scale, west-facing, recumbent folds occur within both the CP allochthon and the CP parautochthon (discussed earlier); and 2) the CP thrust ramps upsection through hangingwall strata toward the northwest.

Strata of the CP allochthon young progressively toward the northwest, from uppermost Precambrian and Cambrian in the southeastern part of the CP Hills, through uppermost Cambrian and Ordovician strata just north of the study area (McKeown et al., 1976) (fig. 8). Farther northwest, in the Mine Mountain area, Silurian and Devonian carbonates structurally overlie Carboniferous and Permian(?) strata of the lower plate of the Mine Mountain thrust (Orkild, 1968) (fig. 8). The upper Paleozoic units beneath the Mine Mountain thrust are the same as those exposed beneath the CP thrust in the southern part of the CP Hills. Carr (1984) interpreted the Mine Mountain thrust as a Tertiary landslide surface. Although Tertiary displacement along this surface probably occurred, the older over younger relationship at Mine Mountain is probably a remnant of Mesozoic thrusting. In addition, west-vergent folds occur in lower plate rocks both at Mine Mountain (J. Caskey and S. Nitchman, unpublished data) and in the CP Hills. These observations

Figure 8 - Generalized geologic map of the CP Hills and Mine Mountain area. (Modified after Caskey (this paper), McKeown et al. (1976), and Orkild (1968)).

suggest that the CP thrust and the Mine Mountain thrust are correlative thrust faults (collectively referred to herein as the CP thrust), and that this fault ramps upsection through hangingwall strata toward the northwest. This relation offers the most compelling evidence for west-vergent thrusting, since it is a widely accepted rule that thrusts generally cut up through the stratigraphic section in the direction of transport.

Net displacement along the CP thrust is poorly constrained. However, in the CP Hills, the uppermost Precambrian to Lower Cambrian Wood Canyon Formation is thrust over the Pennsylvanian and Permian(?) Tippipah Limestone. This juxtaposition requires a stratigraphic throw of approximately 8.5 km (see fig. 2). Allowance for ramp angle and the fact that the thrust does not appear to exhibit simple ramp geometry within its upper plate in the CP Hills (plates 2a and b), both suggest that net displacement is greater than 8.5 km.

Age of Mesozoic Deformation

The age of thrusting and folding is very poorly constrained in the study area and can only be bracketed between Early Permian (the age of the youngest strata involved in folding and thrusting) and late Tertiary (the age of volcanic rocks that are not involved in folding and thrusting). A comparison with

folds and thrusts whose ages are better known in regions surrounding the NTS (e.g. Burchfiel et al., 1974; Dunne et al., 1978; Fleck, 1970; Fleck and Carr, 1990), suggests that contractional deformation within the study area probably occurred between Late Triassic and Late Cretaceous time (see Caskey and Schweickert (chapter 2; in review) for a more complete review of the ages of regional thrust faulting).

Tertiary Structure

During the Cenozoic, the NTS region was affected by at least two major episodes of extensional faulting (Schweickert and Caskey, 1990). The earliest of these events is represented by low-angle normal faults that predate volcanic rocks of the middle Miocene southwest Nevada volcanic field. The latest of these extensional episodes is represented by generally high-angle normal faults that disrupt rocks of the southwest Nevada volcanic field and have resulted in the present basin and range topography which presently characterizes much of the NTS region. Not all high-angle normal faults within the CP Hills can be shown to postdate middle Miocene rocks, and in all likelihood, many probably do not. However, the major high-angle normal faults within the study area disrupt either Miocene volcanic rocks or preexisting low-angle normal faults, and so for simplicity, all major high-

angle normal faults within the study area are interpreted to represent the same post- middle Miocene extensional episode.

The following sections briefly summarize the major structural features of pre-middle Miocene low-angle normal fault(s) and post- middle Miocene high-angle normal faults that occur within the study area.

Pre-middle Miocene extensional faults

Major pre- middle Miocene extension within the study area is represented by at least one important low-angle normal fault that slices shallowly through strata of the CP allochthon (plate 1). McKeown et al. (1976) previously interpreted this low-angle structure (or structures) as a thrust fault (or faults). However, where exposed, this fault everywhere places younger Cambrian strata upon older Cambrian strata (i.e. an omission of strata) and is nearly everywhere characterized by a 1-5 m thick zone of pervasively fractured or brecciated rock of the hangingwall. Low-angle faults in the Basin and Range with these characteristics of are now commonly interpreted as low-angle normal faults rather than thrust faults (e.g. Longwell, 1945).

Exposures of the low-angle normal fault within the CP allochthon are broadly dispersed throughout the southwestern part of the study area, and this fault is also exposed along an east-west trend in the northern part of the

study area at the latitude of "News Nob" (located along the Mercury Highway) (plate 1). Although high-angle normal faults and local Tertiary volcanic cover make correlations of the low-angle normal fault uncertain, map relations suggest that the low-angle normal fault in the southwestern half of the study area (which structurally underlies nearly all exposures of the Papoose Lake Member of the Bonanza King Formation) is correlative with the low-angle normal fault in the northern part of the study area. This interpretation is supported by the general continuity of Bonanza King strata from the vicinity of Peak 5157 (located at the termination of 311 Canyon Road) to the south (plate 1). In the area of Peak 5157, the upper subunit of the Banded Mountain Member is clearly within the upper plate of the low-angle fault and is stratigraphically continuous with the lower subunit of the Banded Mountain Member and the Papoose Lake Member approximately 300-600 m to the south. Although clear stratigraphic continuity within the Papoose Lake Member is lost in areas farther south due to high-angle normal faults, it appears likely that only minor faults separate continuous strata clearly in the hangingwall of the low-angle normal fault (discussed above) from the Papoose Lake Member to the south, which structurally overlies strata of the Carrara Formation along a low-angle normal fault contact. It is therefore

likely that these low-angle faults are correlative structures. Furthermore, because nearly all other occurrences of the Papoose Lake Member in the southwestern part of the study area are bounded by low-angle normal faults where these rocks structurally overlie older Cambrian strata, these faults are also correlated with the low-angle normal fault in the northern part of the study area.

Map relations suggest that all Paleozoic strata in the eastern part of the study area lie within the hangingwall of the low-angle normal fault. Although rocks in this area are locally highly disrupted by high-angle normal faults, the lower subunit of the Banded Mountain Member appears to be more-or-less continuous from the intersection of structural sections B-B' and C-C' to a point approximately 1.5 km south. From this area east to Yucca Pass, the Banded Mountain Member is stratigraphically continuous with the Papoose Lake Member and the Carrara Formation. The interpretation that these strata lie within the hangingwall of the low-angle normal fault is depicted in structural section A-A' (plate 2a,b).

The dip direction of the low-angle normal fault varies considerably from location to location owing to complexities wrought by superimposed high-angle normal faulting and concomitant tilting (discussed later).

McKeown et al. (1976) showed south and southeast dips of 45 and 15 degrees (respectively) along the low-angle normal fault in the northern part of the study area (although as previously noted they interpreted this structure as a thrust fault). These dips agree well with an approximate 30 degree southeast dip I observed in this area (plate 1). Where exposed to the south, the low-angle normal fault dips gently to the west in areas west of the main exposures of Mississippian Eleana Formation. East of the exposures of Eleana Formation, map relations indicate that the low-angle normal fault dips gently to the east.

At its northern exposures, the low-angle normal fault greatly disrupts a large-scale west-vergent Mesozoic syncline within the CP allochthon (discussed earlier) which involves all three map units of the Bonanza King Formation. This fold occurs in both the hangingwall and the footwall of the low-angle normal fault and therefore provides an excellent marker by which to estimate the magnitude and direction of displacement along this fault. In both hangingwall and footwall, the folds plunge moderately (approximately 15-35 degrees) to the northeast, as previously discussed. Structural section B-B' (plates 1 and 3) crosses the hinge zone of the recumbent syncline where it occurs at the contact between the upper and lower subunits of the Banded

Mountain Member in both the hangingwall and footwall of the low-angle normal fault (i.e. there is an overlap of the hinge zone). Because the section is oblique to the folds, displacement along this fault cannot be restored along section B-B'. Structural section C-C' (plates 1 and 3) shows no overlap of the hinge zone. Therefore, subsequent to restoration of younger high-angle normal faults along this transect (plate 3d), it is possible to restore displacement along the low-angle normal fault (plate 3e). I interpret the east-southeast trend of structural section C-C' to approximate closely the direction of net slip along the low-angle normal fault because only along this general trend can a reasonable restoration of the northeast-plunging syncline be accomplished. Restoration of stratal cutoffs along this fault (plate 3e) indicates that approximately 800 m of top-to-the-east displacement occurred along the low-angle normal fault. Because the fault appears to cut obliquely through the stratigraphic layering (plates 2 and 3), the stratigraphic throw of this fault at northern exposures is estimated to be somewhat less than 800 m.

Net displacement is not well constrained for the low-angle normal fault where it is exposed in the southern part of the study area. In several locations, a stratigraphic throw greater than the thickness of the Carrara Formation (approximately 450 m) is required because strata of the Papoose

Lake Member are juxtaposed against the Wood Canyon Formation and Zabriskie Quartzite. Structural relations in the area north and northwest of the mapped trace of CP thrust indicate that the low-angle normal fault cuts both up and down through strata in its footwall. This can be explained by the fact that the low-angle normal fault cuts through folded strata of the CP allochthon in this area.

The age of low-angle normal faulting in the study area is poorly constrained. Undifferentiated volcanic rocks depositionally overlie hangingwall and footwall rocks of the low-angle normal fault in several locations (plate 1), and at one location, in the southeast part of the study area, these volcanic rocks appear to overlap the fault itself. These volcanic rocks probably include 13.1 Ma Wahmonie Formation and possible 15.1 Ma Tuff of Yucca Flat (discussed earlier), suggesting that low-angle normal faulting in the CP Hills is pre-middle Miocene in age. A lower age limit for low-angle normal faulting is constrained only as post-Mesozoic west-vergent folding (and thrusting). It seems likely that low-angle normal faulting occurred much later than west-vergent folding and is early to middle Tertiary in age.

Post-middle Miocene extensional faulting

High-angle normal faults are numerous in the CP Hills, and (in general) represent the most recent major deformation within the study area, since they disrupt both preexisting low-angle normal faults and volcanic rocks of the southwest Nevada volcanic field (SWNVF). Strikes of high-angle normal faults widely vary within the study area, although inspection of a larger mapped area (see McKeown et al., 1976), which includes extensive areas of volcanic rocks, shows that north- to northwest-striking high-angle normal faults dominate the structural pattern of most of the CP Hills area. However, patterns of high-angle normal faults are locally more complicated within exposures of Paleozoic strata relative to those patterns within volcanic rocks. This is the case in the central part of the study area (plate 1) and also northwest of 311 Canyon Road where McKeown et al. (1976) mapped complex high-angle fault patterns within the Nopah Formation (note that this area is mapped as undifferentiated Nopah Formation in plate 1). These complex normal fault patterns may represent extension which, in part, occurred prior to eruption of tuffs of the SWNVF, although many of these faults can be shown to post-date low-angle normal faults in the CP Hills.

Movement on Post-volcanic north-to-northwest oriented normal faults within the CP Hills was apparently accompanied by southwest tilting of major fault blocks. This is indicated by prominent southwest dips of bedding and foliation within middle Miocene volcanic rocks (fig. 9). Within the map area, southwest tilting appears to have resulted from down to the northeast displacement along northwest striking normal faults. This structural relation may suggest that listric fault geometry exists at depth (although for simplicity, listric fault geometries are not shown in structural sections). However, west of the study area, in the western part of the CP Hills (see McKeown et al., 1976, and also plate 2), southwest dipping middle Miocene volcanic rocks appear to be associated with closely-spaced, dominantly down-to-the-southwest normal faults resulting in a southwest-facing monoclinical geometry for these strata in this area (plate 2). It is possible that southwest tilting of volcanic rocks in this area predated the high-angle normal faults.

Some of the most important high-angle normal faults in the study area bound a major horst of Mississippian and Pennsylvanian strata in the southern part of the study area (plates 1 and 2). Along structural section A-A' (plates 1 and 2), these faults exhibit approximately 500 m of normal dip-slip displacement and juxtapose rocks of the CP allochthon against underlying

Figure 9 - Equal area, lower hemisphere stereographic projections of poles to foliations in Tertiary volcanic rocks in the CP Hills area (includes both data collected during this study and data from McKeown et al. (1976) within the study area and from other parts of the CP Hills).

rocks of the CP parautochthon. This horst, which includes the structurally lowest rocks exposed within the study area (i.e. relative to the CP thrust), appears to divide the southern part of the CP Hills into an eastern, late Tertiary structural domain of dominantly east-dipping normal faults and a western domain of mostly west-dipping normal faults (see plate 2a,b).

High-angle normal faults that occur within Miocene volcanic rocks in the western and southern parts of the CP Hills outside the study area (see McKeown et al., 1976) have a conspicuous curvilinear map pattern (schematically represented in figure 8). In these areas, dominantly north-northwest trending high-angle normal faults along the western part of the CP Hills appear to bend counterclockwise as much as 75 degrees at the southern end of the CP Hills to become northwest and west-northwest trending. Ander (1984) apparently recognized this curvilinear fault pattern and suggested that these structures are Riedel shears and conjugate Riedel shears (Tchalenko and Ambraseys, 1970) formed during the initiation of a zone of northeast-trending left lateral shear between the Mine Mountain and Cane Spring faults (located north and south of the study area, resp; the left-lateral Mine Mountain fault is shown on fig. 8). However, no evidence of lateral slip was noted along these curvilinear faults by McKeown et al. (1976), nor do map relations suggest

major lateral displacement. Alternatively, these structures could have developed in a non-uniform (arcuate) stress field between the northeast-trending left-lateral faults, or they could have been bent and rotated about a vertical axis in response to left-lateral simple shear along the Cane Spring fault (or related faults) to the south. The rotation hypothesis could easily be tested with paleomagnetic analysis of volcanic rocks at the southern end of the CP Hills.

Although the age of major high-angle normal faulting within the study area is only constrained as post-Paintbrush Tuff (12-13 Ma), much of this faulting probably occurred after eruption of the 11 Ma Timber Mountain Tuff (although, as mentioned above, some high-angle faults within Paleozoic rocks are likely related to earlier extension). This interpretation is based on the fact that north-to-northwest trending faults also cut the Timber Mountain Tuff east, west, and south of the study area. In addition, the middle Miocene volcanic sequence in this area lacks significant angular unconformities arguing against major faulting and tilting coeval with volcanism (Mark Hudson, personal communication). A younger age limit for this latest episode of extensional faulting is constrained only as pre-Quaternary, the inferred age of deposits not affected by high-angle faults within the study area.

However, the generally subdued geomorphology of the region suggests that this area has been relatively quiescent tectonically since perhaps the the early Pliocene.

Quaternary (?) faults

The only possible Quaternary(?) fault within the study area is marked by a prominent northwest-trending vegetation alignment within Quaternary deposits at the northern end of the CP Hills, north of 311 Canyon. This lineament is well expressed on 1:24,000 scale natural color aerial photographs and can be traced for over 2 km along strike. In the field, this lineament is virtually undetectable. However, the mapped trace of this fault locally appears to coincide with the alluvium-bedrock contact. The location of this fault at the alluvium-bedrock contact suggests that down-to-the-northwest normal dip-slip displacement occurred along this structure. However, the northwest trend of this fault (in a region generally characterized by northwest-trending right-slip faults and northeast-trending left-slip faults) and the linear trace of the lineament, suggests a possible component of right-slip on this fault.

Although Recent colluvium and/or erosion everywhere appears to obscure evidence for surface rupture along this fault, this structure is tentatively assigned a Quaternary age.

SUMMARY

The CP Hills have experienced a complex structural history of Mesozoic contractional deformation and superimposed Cenozoic extensional deformation not unlike many areas of the Great Basin. During the Mesozoic, upper Proterozoic and Paleozoic miogeoclinal strata were involved in large-scale west-vergent folding and thrusting. Within the CP Hills, the CP thrust placed allochthonous upper Precambrian and Lower Cambrian strata above parautochthonous Carboniferous strata resulting in a stratigraphic throw of approximately 8.5 km. Structural relations indicate that net displacement along the CP thrust was somewhat greater than this. Large-scale west-vergent folds developed within both the CP allochthon and parautochthon. These folds, together with the observation that the CP thrust ramps up section through hangingwall strata toward the northwest, indicate that the CP thrust is a west-vergent thrust and that it correlates with the Mine Mountain thrust northwest of the study area.

Within the CP allochthon, a large-scale west-vergent overturned anticline-syncline pair involves a minimum of 2000 m of Lower and Middle Cambrian strata. These folds have been strongly disrupted by later Cenozoic extension but they provide markers by which much of this extension can be understood. In the southern part of the CP Hills, a large, nearly recumbent west-vergent footwall syncline is exposed in an erosional window through rocks of the CP allochthon. This fold appears to be tight and involves at least 600 m of Mississippian and Pennsylvanian strata. Structural data from parautochthonous rocks suggests that at least one episode of folding occurred prior to development of the footwall syncline. Analysis of mesoscopic folds within the Pennsylvanian Tippipah Limestone (fig. 5e,f) suggests that this early episode of folding was related to an earlier phase of progressive, generally west-vergent deformation. Other observations suggest an earlier phase of east-vergent deformation. This apparent dilemma has not been adequately resolved herein, although an early phase of west-vergent deformation and a still earlier episode of east-vergent deformation are both possible.

Subsequent to Mesozoic west-vergent folding and thrusting and prior to eruption of volcanic rocks of the southwest Nevada volcanic field,

significant low-angle normal faulting occurred in the CP Hills. This is indicated by at least one low-angle normal fault which strongly disrupts folds within the CP allochthon and which exhibits greater than 800 m of top-to-the-east displacement. Although some high-angle normal faults within the study area may be related to this prevolcanic episode of extension, a later, post- 11 Ma episode of high-angle normal faulting affected all rocks in the CP Hills. Post 11- Ma normal faults are numerous and these structures have resulted in the dominant north-to-northwest structural grain of the CP Hills. Post- 11 Ma faulting was also accompanied by southwest tilting of major fault blocks. This episode of faulting was likely waning by about the early Pliocene. Evidence for Quaternary faulting within the study area is limited to a single northwest-trending vegetation lineament within Quaternary alluvium in the northern part of the CP Hills.

DISCUSSION

Regional extent of west-vergent deformation

The west-vergent CP thrust and associated west-vergent folds are important structural elements of the southern part of the Mesozoic Cordilleran fold and thrust belt. Hinterland-vergent structures probably related to those in the CP Hills form a narrow sigmoidal belt that can be traced

for at least 180km in southern Nevada and southeastern California (Caskey and Schweickert, chapter 2; in review) (see also fig. 1). In this region, hinterland-vergent deformation has been mapped or recognized in the Cottonwood and Grapevine mountains in the Death Valley region (west of fig. 1) (Snow and Wernicke, 1989; Reynolds, 1969), at Bare Mountain (Carr and Monsen, 1988; Monsen et al., 1991), in the Specter Range (Sargent et al., 1970; Schweickert, 1989), in the Calico Hills (McKay and Williams, 1964; J. Caskey and S. Nitchman, unpublished data), Banded Mountain (Barnes et al. 1965; Caskey and Schweickert, in review), and northwest of Oak Spring Butte (Rodgers and Noble, 1969). West-vergent structures mapped in the Egan Range in east-central Nevada (Brokaw and Barosh, 1968) could also be related to this seemingly anomalous, but persistent zone of hinterland-vergent deformation.

Regional correlations of west-vergent structures have important implications for thrust correlations in the NTS region (e.g. Barnes and Poole, 1968; Wernicke et al., 1988a, 1988b; Snow and Wernicke, 1989) and for the regional framework of the Mesozoic fold and thrust belt. However, a detailed description of regional Mesozoic deformation and a comprehensive discussion of thrust correlations and implications thereof are beyond the

scope of this report. For more complete discussions of these topics, see Wernicke et al. (1988a, 1988b) Snow and Wernicke (1989) and Caskey and Schweickert (chapter 2; in review).

Estimates of local extension

Normal faulting and resultant extension have had a profound influence on the geology of the CP Hills. This extensional strain can be estimated in terms of 2-dimensional horizontal extension or percent extension (e.g. % extension = $(l_f - l_o) / l_o \times 100$; where l_f is the final (or present) distance between two reference points along a given transect, and l_o is the original distance between these reference points prior to deformation). It is important to note, however, that l_o is rarely known and an estimate of this value is dependent upon structural interpretations that dictate the outcome of a given restoration (i.e. pre-strain configuration). Furthermore, extension values are dependent upon the proximity of reference points to pertinent extensional structures (e.g. faults). For example, a certain region may have undergone only about 15% extension, although highly faulted smaller areas within the same region may have experienced 100% extension or more. Nevertheless, estimating local values of extension, such as those in the CP Hills, is useful for comparisons of extended regions.

Estimates of extension related to high-angle normal faults in the CP Hills (discussed below) are based on structural section A-A' (plate 2a) and a reconstruction of high-angle Tertiary normal faults along this transect (plate 2b). Note that section A-A' also includes areas adjacent to the study area where mapping by McKeown et al. (1976) was incorporated. The reconstruction of section A-A' was prepared by restoring Paleozoic and Tertiary stratal cutoffs along normal faults. For simplicity, normal faults were modelled as planar faults, and no attempt was made to restore post-middle Miocene tilts of fault blocks. Restoration of high-angle normal faults along section A-A' suggests that the CP Hills as whole have extended by about 15% during (generally) post-middle Miocene deformation, although extension appears to have been slightly greater than this in the central portion of the CP Hills (approximately 20%).

Displacement along the older, low-angle normal fault in the southern part of the study area is not well constrained, and so any estimate of pre-middle Miocene extension in this area would have large uncertainties. Furthermore, structural section A-A' is oriented oblique to the probable direction of net east-southeast displacement along the low-angle normal fault (discussed earlier). Nevertheless, taking into account displacement along this

structure greatly increases the estimate of net Tertiary extension in the CP Hills, and structural relations suggest that total extension on the order of 40% is not unreasonable for the southern part of the CP Hills. Much uncertainty still remains as to the possibility of low-angle normal faults concealed beneath Tertiary volcanic rocks in the western part of the CP Hills.

Regional tectonic implications for pre-middle Miocene extension

Pre-Middle Miocene extension in the NTS and vicinity has only recently gained recognition (Schweickert and Caskey, 1990; Jayko, in press; Guth, personal communication). Jayko (in press) reported pre-Oligocene extension in the Jumble Hills, the Fallout Hills, and the northwestern Pahrangat Range (all located northeast of figure 1 in southwestern Lincoln County). Jayko (in press) also noted that mapping by Barnes et al. (1965) at Jangle Ridge (fig. 1) indicates that flat-lying top-to-the-east faults involve only pre-Tertiary strata and that these faults place younger rocks above older rocks. Jayko argued that these relations suggest that this area had been highly extended prior to the deposition of middle Miocene (16-14 Ma) volcanic rocks (Marvin et al., 1970). Top-to-the-east low-angle normal faults have also been recognized above the Mine Mountain thrust at Mine Mountain (fig. 1) (Guth, personal communication), and these faults are also overlapped by middle

Miocene volcanic rocks (Orkild, 1968). Monsen et al. (1991) showed that major top-to-the-south low-angle normal faults occur above the north-vergent Panama thrust at the southern part of Bare Mountain. Map relations (Monsen et al., 1991) suggest that displacement largely occurred prior to emplacement of 13.9 Ma quartz latite dikes. Approximately 30 km west of Bare Mountain, in the Grapevine Mountains, mapping by Reynolds (1969) indicates that top-to-the-east low-angle normal faults predate the upper Oligocene Titus Canyon Formation (Schweickert and Caskey, 1990), and these faults strongly disrupt large-scale recumbent west-vergent folds.

Exposures of Paleozoic rocks along the eastern, southern, and western margins of the southwest Nevada volcanic field reveal a complex system of pre- middle Miocene extension, although the age of much (or all) of this system may be as old as Oligocene (or older). It therefore seems reasonable to infer that the Miocene southwest Nevada volcanic field conceals a vast and complex older extended terrane (Schweickert and Caskey, 1990). Furthermore, there appears to be a direct correspondence between the structural grain of these low-angle normal faults and that of (hinterland-vergent) Mesozoic deformation.

It is important to note that in southwest Nevada and eastern California, generally north-trending Mesozoic structural trends typical of the southern Great Basin have been rotated clockwise as much as 90 degrees about a vertical axis (e.g. Nelson and Jones, 1987). This phenomenon has been attributed to regional oroflexural bending within the Walker Lane belt (Albers, 1967; Stewart et al., 1968; Stewart, 1988), and also to drag associated with the Las Vegas Valley shear zone and related structures (Longwell, 1960). In the region of maximum "bending," previously north-striking, west-vergent Mesozoic structures (for example) presently strike east and verge to the north, such as at Bare Mountain, as discussed above. The same pattern of orientations appears to hold true for pre- middle Miocene low-angle normal faults. In the Yucca Flat region, where north-trending Mesozoic structures occur at Jangle Ridge, Mine Mountain, and the CP Hills (all interpreted to be west-vergent (this report; Caskey and Schweickert, in review)), these structures are strongly disrupted by top-to-the-east low-angle normal faults. At Bare Mountain, where the Mesozoic structural grain trends east-west, pre-middle Miocene low-angle normal faults are characterized by top-to-the-south displacement. Farther west, in the Grapevine Mountains, the Mesozoic

structural grain has resumed a north-trend, and pre- late Oligocene low-angle normal faults are once again characterized by top-to-the-east displacement.

Several explanations (i.e. scenarios) for the above observations are possible: 1) Pre- middle Miocene extensional faults represent regional extension developed more or less concurrently in an appropriate stress regime (for east-west extension), and these faults were later oroclinally "bent" along with preexisting Mesozoic structures; 2) The oroflex predated extension, and pre- middle Miocene faults developed in a variety of tensile stress regimes. In this scenario, the development of pre- middle Miocene extensional faults was likely influenced by a preexisting Mesozoic structural fabric or grain (although this may hold true for both scenarios). In either senario, the regional oroflex is almost certainly pre- middle Miocene, because Miocene volcanic rocks in the southern NTS region do not appear to have been highly rotated about a vertical axis (Hudson and Rosenbaum, 1990; Hudson, personal comm.).

Regional structural relations of major west-vergent folds and thrusts and pre- middle Miocene extensional faulting have important implications for Yucca Mountain (fig. 1), the candidate site for a high-level nuclear waste repository. As previously discussed, Yucca Mountain lies geographically

between Bare Mountain and the CP Hills (fig. 1). Data and interpretations in this report (and also Caskey and Schweickert, in review) suggest that profound structural complexities brought on by intense Mesozoic contractional deformation (e.g. west-vergent folds and thrusts) and superimposed pre-volcanic Cenozoic extensional fragmentation (e.g. top-to-the-east low-angle normal faults) in the CP Hills are regional in extent and broadly correlate with structures at Bare Mountain. Any models of subsurface structure beneath middle Miocene volcanic rocks at Yucca Mountain should incorporate structures in Proterozoic and Paleozoic rocks that are consistent with structural relations at Bare Mountain and the CP Hills.

CONCLUSIONS

- 1) The CP thrust of Barnes and Poole (1968), where exposed in the CP Hills, is a major west-vergent Mesozoic thrust fault with greater than 8.5 km of displacement.
- 2) The CP thrust ramps upsection through hangingwall strata toward the northwest and correlates with the Mine Mountain thrust.
- 3) Rocks within the CP parautochthon were affected by at least one episode of folding prior to the development of large-scale west-vergent folds. This early

episode of folding may have been related to an earlier phase of progressive, generally west-vergent deformation. Other observations suggest an earlier episode of east-vergent deformation.

4) The CP Hills were fragmented by at least two episodes of Cenozoic extensional faulting: 1) an earlier episode of pre- middle Miocene low-angle normal faulting which strongly disrupted west-vergent folds within the CP allochthon; and 2) a later episode of post- 11 Ma high-angle faulting which has resulted in the dominant north-to-northwest structural grain of the CP Hills and the present basin and range topography of the NTS region.

5) The southern part of the CP Hills extended by about 15% during (generally) post- middle Miocene deformation. Net Tertiary extension on the order of 40% is not unreasonable for the southern part of the CP Hills.

6) Pre- middle Miocene low-angle normal faults are regional in extent, and there appears to be a direct correspondence between the structural grain of this low-angle fault system and that of (hinterland-vergent) Mesozoic structures.

7) Mesozoic west-vergent thrusts and folds and Cenozoic low-angle normal faults exposed in the CP Hills broadly correlate with structures at Bare Mountain. Because Yucca Mountain lies between the CP Hills and Bare

Mountain, models of subsurface structure at Yucca Mountain should incorporate structural complexity consistent with structures in Proterozoic and Paleozoic rocks at Bare Mountain and the CP Hills.

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CHAPTER 2

**Mesozoic deformation in the Nevada Test Site
and vicinity; a new perspective from the
CP Hills, Nye County Nevada**

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ABSTRACT

Detailed studies in the CP Hills and Mine Mountain area of the Nevada Test Site (NTS), together with analysis of published maps and cross sections and a reconnaissance of regional structural relations, indicate that the CP thrust of Barnes and Poole (1968) actually comprises two separate, oppositely verging Mesozoic thrust systems: 1) the west-vergent CP thrust which is well exposed in the CP Hills and at Mine Mountain; and 2) the east-vergent Belted Range thrust located northwest of Yucca Flat. Regional structural relations indicate that the CP thrust forms part of a narrow sigmoidal belt of west-vergent folding and thrusting traceable for over 180 km along strike. The Belted Range thrust represents earlier Mesozoic deformation that was probably related to the Last Chance thrust system in southeastern California, as suggested by earlier workers. A pre-Tertiary reconstruction of the Cordilleran fold and thrust belt in the region between the NTS and the Las Vegas Range bears a close resemblance to other regions of the Cordillera and has important implications for the development of hinterland-vergent deformation as well as for the probable magnitude of Tertiary extension north of Las Vegas Valley.

INTRODUCTION

The Nevada Test Site (NTS) (fig.1) of the southern Great Basin lies within the dominantly east-vergent Mesozoic Cordilleran thrust belt near one of the thickest known parts of the Paleozoic Cordilleran miogeocline. Barnes and Poole (1968) and Hinrichs (1968) interpreted several thrust faults that place upper Precambrian and lower Paleozoic rocks over upper Paleozoic rocks as remnants of a single, regional, east- to southeast-vergent thrust system. They named this thrust system the CP thrust for exposures in the Control Point (CP) Hills, south of Yucca Flat (fig. 1). Subsequent work on the Mesozoic structure in the region has been hampered by the general inaccessibility of the NTS and surrounding regions. Later discussions of the regional structural setting of the NTS and vicinity (e.g. Carr, 1984; Wernicke et al., 1988a, 1988b) have therefore relied heavily on these earlier interpretations.

Our detailed studies in the CP Hills and Mine Mountain area (figs. 1 and 4), together with published maps and cross sections by Orkild (1968) and McKeown et al. (1976) and our reconnaissance of regional structural relations, indicate that the CP thrust of Barnes and Poole (1968) actually comprises two separate, oppositely verging thrust systems: 1) the west-vergent CP thrust,

Figure 1 - Location map of the study area showing the distribution of Paleozoic, Tertiary, and Quaternary rocks. Small bodies of Mesozoic intrusive rocks are omitted for clarity (modified after Stewart and Carlson, 1978). Abbreviations: BM - Banded Mountain; CF - Crater Flat; CH - Calico Hills; CPH - CP Hills; CR - Chert Ridge; ER - Eleana Range; MM - Mine Mountain; OSB - Oak Spring Butte; PGR - Pahrnatag Range; PR - Papoose Range; PTK - Paiute Ridge; SH - Striped Hills; SR - Specter Range.

Figure 2 - Major Mesozoic structural features of the NTS region involving Paleozoic rocks (fig. 1). Patterns correspond to different allochthons discussed in text. Abbreviations: BF - Butte fault; CS - Corkscrew syncline; CT - Clery thrust; LVVSZ - Las Vegas Valley shear zone; MPT - Meiklejohn Peak thrust; MT - Montgomery thrust; PT - Pintwater thrust; PWA - Pintwater anticline; SHA - Striped Hills anticline; SPT - Schwab Peak thrust; SRS - Spotted Range syncline; SRT - Spotted Range thrust; SVSFZ - Stewart Valley - Stateline fault zone; TCA - Titus Canyon anticline.

which is well exposed in the CP Hills and at Mine Mountain (figs. 1 and 4), and 2) the southeast-vergent Belted Range thrust, located northwest of Yucca Flat (fig. 1).

Herein, we suggest a revision of nomenclature for thrusts in the NTS region (Earnes and Poole, 1968), and describe the major Mesozoic tectonic features of the NTS and surrounding regions to develop a coherent picture of the pre-Tertiary structural framework.

GEOLOGIC SETTING

The NTS lies within the late(?) Mesozoic Sevier orogenic belt (Armstrong, 1968; Fleck, 1970). However, alluviated extensional basins and Tertiary volcanic and sedimentary rocks (fig. 1) obscure many structural details of the fold and thrust belt. Throughout most of the NTS region, the Mesozoic structural framework has been disrupted by at least two episodes of Tertiary extensional faulting (Ekren et al., 1968; Schweickert and Caskey, 1990), further hindering our understanding of the regional pre-Tertiary tectonic framework. Fortunately, the stratigraphic framework of the Paleozoic Cordilleran miogeocline is well known (e.g. Cornwall, 1972; Ekren, 1968; Longwell et al., 1965; Stewart and Poole, 1972) and forms a good foundation

for unravelling locally complicated Mesozoic and Tertiary structure and for piecing together upper crustal blocks that have been separated as a result of large-scale Tertiary extension (e.g. Wernicke et al., 1988a, 1988b). All seven systems of the Paleozoic are represented in the NTS region and these together with Precambrian strata form a generally conformable stratigraphic section over 38,000 feet (nearly 12,000 m) thick (fig. 3).

The area surrounding Yucca Flat (fig. 1) offers the most extensive exposures of upper Proterozoic and Paleozoic rocks within the NTS. Mesozoic thrusts and folds have been mapped northwest of Yucca Flat (Gibbons et al., 1963; Barnes and Poole, 1968), at the southwest end of Yucca Flat in the CP Hills and Mine Mountain area (Barnes and Poole, 1968; McKeown et al., 1976; and Orkild, 1968), and also just east of the NTS in the Spotted Range (Barnes and Poole, 1968; Barnes et al., 1982; Cornwall, 1972; Longwell et al., 1965; Tschanz and P. mpeyan, 1970). An understanding of the Mesozoic structure of the NTS region, as well as other neighboring regions, is critical to evaluating the regional pre-Tertiary structural framework of the Cordilleran fold and thrust belt at this latitude, the magnitude and style of Tertiary extension, and to interpreting the deep structure beneath Southwest Nevada volcanic field (fig. 1).

Figure 3 - Generalized stratigraphic column for upper Proterozoic and Paleozoic rocks in the Nevada Test Site region (modified after Ekren, 1968).

In the following section, we outline the major structural elements of Mesozoic thrusts and folds that occur in the NTS region and discuss some of the complexities resulting from Tertiary extensional tectonism. We then discuss a regional structural section and a preliminary palinspastic reconstruction to illustrate the pre-Tertiary tectonic framework of the Mesozoic Cordilleran fold and thrust belt at this latitude.

MESOZOIC STRUCTURE

CP thrust

The CP thrust, in the CP Hills (figs. 1 and 4), places uppermost Precambrian and Cambrian rocks above Mississippian through Pennsylvanian strata. Recent studies in the CP Hills and Mine Mountain areas indicate that the CP thrust is a major west-vergent Mesozoic structure. While this interpretation is consistent with published maps and cross sections of McKeown et al. (1976), other workers have interpreted the CP thrust, where exposed in the CP Hills, as an east- to southeast-vergent structure (e.g. Barnes and Poole, 1968; Carr, 1984; Hinrichs, 1968; Wernicke et al., 1988a, 1988b). Two independent lines of evidence support the west-vergent interpretation; 1) large-scale west-facing, nearly recumbent folds occur

in both the hanging wall and footwall of the CP thrust (figs. 4 and 5); and 2) the CP thrust ramps upsection through hanging wall strata toward the northwest.

A north-trending, west-facing recumbent syncline in the footwall of the CP thrust is exposed in an erosional window through upper plate strata in the southern part of the CP Hills (figs. 4 and 5). The recumbent footwall syncline involves at least Upper Mississippian through Pennsylvanian strata and can be traced for several kilometers throughout the window.

Rocks in the upper plate of the CP thrust are imbricately faulted, highly folded, and locally are overturned to the west. In the eastern part of the CP Hills, near Yucca Pass (fig. 4), a north-trending, west-facing, nearly recumbent fold pair in the upper plate involves Lower to Middle Cambrian strata. These folds are similar in scale to the footwall syncline (fig. 5).

Upper plate strata young progressively to the northwest, from uppermost Precambrian and Cambrian strata in the southeastern part of the CP Hills, through upper Cambrian and Ordovician strata at the north end of the CP Hills. Farther northwest, in the Mine Mountain area, Silurian and Devonian carbonates structurally overlie Carboniferous and Permian strata of the lower plate (Orkild, 1968) (fig. 4). These observations indicate that, in

Figure 4 - Generalized geologic map of the CP Hills and Mine Mountain area.
(Modified after Caskey (this paper), McKeown et al. (1976), and Orkild (1968)).

Figure 5 - Simplified structural section SW-NE through the southern part of the CP Hills (see figure 4 for location) with high-angle Tertiary normal faults restored. Upper boundaries of high-angle fault blocks represent modern topography. Labels on the various stratigraphic units correspond to those units shown in figure 4. Patterns do not correspond to those in figure 4. For more details of the structure along this transect refer to plates 1 and 2, chapter 1 (this paper).

general, the CP thrust ramps upsection through upper plate strata to the northwest. This relation offers the most compelling evidence for west-vergent thrusting, because it is a widely accepted rule that thrusts generally cut up through the stratigraphic section in the direction of transport.

The upper Paleozoic units beneath the Mine Mountain thrust are the same as those exposed beneath the CP thrust in the southern part of the CP Hills. Carr (1984) interpreted the Mine Mountain thrust as a Tertiary landslide surface. Although Tertiary displacement along this surface probably occurred, the older over younger relationship at Mine Mountain is probably a consequence of earlier west-vergent thrusting. Similar styles of folding and sense of vergence occur in lower plate rocks at Mine Mountain and in the CP Hills. These combined relations indicate that the CP thrust and the Mine Mountain thrust are correlative west-vergent structures, and these faults are herein collectively referred to as the CP thrust.

Net displacement along the CP thrust is poorly constrained. However, in the CP Hills, the uppermost Precambrian to Lower Cambrian Wood Canyon Formation is thrust over the Pennsylvanian and Permian Tippipah Limestone. This juxtaposition requires a stratigraphic throw of approximately 8.5 km (see fig. 3). Allowance for ramp angle (inferred to exist

east of structural section SW-NE (fig. 5)) and the fact that the thrust does not appear to exhibit simple hanging wall ramp geometry in the CP Hills (i.e. the CP thrust locally cuts open folds within the CP allochthon (see fig. 5)), both suggest that net displacement is greater than 8.5 km.

Belted Range thrust

Northwest of Yucca Flat, published maps and subsurface drill hole data (Gibbons et al., 1963) indicate the presence of a major east-vergent thrust system largely concealed beneath Tertiary volcanic rocks (figs. 1 and 2). In this region, upper Precambrian strata have been thrust over Silurian and Devonian rocks that have in turn been thrust over Mississippian rocks. The Mississippian strata of the footwall are locally folded into a large, southeast-facing recumbent syncline indicating that southeast-directed displacement occurred along this thrust system (Gibbons et al., 1963). Carboniferous rocks within the footwall of the thrust can be traced southward to the Mine Mountain area where they also form the footwall to the CP thrust. Although these oppositely verging thrust systems share a common parautochthon, arguments relating to vergence of footwall (and hangingwall) structures and the northwest younging of strata in the upper plate of the CP thrust (discussed

above) clearly indicate that these are different thrust systems. However, because Barnes and Poole (1968) interpreted the CP thrust (in the CP Hills) as an east-vergent thrust (see also Hinrichs, 1968), they correlated the two thrust systems and collectively termed them the CP thrust. This is clearly a misnomer for the east-vergent thrust northwest of Yucca Flat. We propose the name *Belted Range thrust* for the fault northwest of Yucca Flat, since the major exposures of this east-vergent thrust occur at the southern end of the Belted Range (fig. 1) (Gibbons et al., 1963).

Net displacement along the Belted Range thrust system is poorly constrained. However, a stratigraphic throw similar to that of the CP thrust (>8.5 km) is required. Net displacement along the Belted Range thrust is probably much greater than this, as discussed below.

Spotted Range thrust

The Spotted Range thrust, located in the Spotted Range (figs. 1 and 2) about 30 km southeast of the CP Hills, places Middle Cambrian strata above Upper Devonian and Mississippian rocks which are deformed into a sequence of tight to isoclinal folds overturned to the southeast (Barnes et al., 1982). The sense of vergence of these footwall folds indicates that southeast-directed

displacement occurred along the Spotted Range thrust. This precludes correlation of the Spotted Range thrust with the west-vergent CP thrust in the CP Hills as proposed by Barnes and Poole (1968). A minor west-vergent syncline which involves Devonian and Mississippian strata occurs northwest of thrust klippen exposed at the southwest end of the Spotted Range (Barnes et al., 1982; Johnson and Hibbard, 1957) but it is unclear how this west-vergent fold is related to the surrounding Mesozoic structure. Guth (1990) reported extensive "Tertiary" modification of the Spotted Range thrust, so it is likely that important Mesozoic structural details have been lost through subsequent deformation.

The Spotted Range thrust plate is preserved as a series of erosional remnants, or klippen, traceable for over 50 km along the north-to-northeast striking hinge surface trace of a broad regional syncline (Barnes et al., 1982), herein called the Spotted Range syncline (fig. 2). This relation strongly implies that a folding event post-dated the Spotted Range thrust (discussed later). The root zone for the Spotted Range thrust is problematic. Arguments presented below suggest that the lower plate of the Spotted Range thrust is continuous with the upper plate of the west-vergent CP thrust.

At the southwest end of the Spotted Range, Ordovician strata in the lower plate of the Spotted Range thrust crop out almost continuously around the nose of the northeast-plunging Spotted Range syncline and continue northward along the northwestern limb (Barnes et al., 1982; Longwell et al., 1965; Poole, 1965; Tschanz and Pampeyan, 1970). Scattered exposures of Ordovician strata can be tracked discontinuously from there to the east edge of Yucca Flat where they occur in stratigraphic continuity with older rocks at Pahute Ridge and Banded Mountain (fig. 1) (Barnes et al., 1963, 1965; Byers and Barnes, 1967; Hinrichs and McKay, 1965). Strata at Banded Mountain form the steeply dipping western limb of a prominent, northwest-trending, asymmetric anticline involving upper Precambrian through Upper Cambrian strata (Barnes et al., 1963, 1965) which we interpret as the northern continuation of the overturned anticline in the CP thrust plate. Therefore, we equate the lower plate of the Spotted Range thrust with the upper plate of the CP thrust, meaning that the Spotted Range thrust klippen must lie structurally above the CP thrust plate (fig.6).

The apparent continuity of the footwall of the east-vergent Spotted Range thrust to the northeast edge of Yucca Flat indicates that the Spotted Range thrust must root farther to the west and west of the CP thrust. We

Figure 6 - Schematic cartoon structural section which illustrates our interpretations of the relationships between the Belted Range - Spotted Range thrust, the CP thrust, the Gass Peak thrust, and the regional fold pair. Patterns represent different Mesozoic structural levels: stippled-CP/Gass Peak allochthon; stippled with lines-Belted Range/Spotted Range allochthon; dark shading-CP/Belted Range parautochthon; light shading-Gass Peak parautochthon. Different thrust faults are detailed with different teeth patterns for clarity. a) Possible Early Mesozoic structure of the NTS region. b) Possible Late Mesozoic structural geometry in the NTS region.

believe the Spotted Range thrust correlates with the Belted Range thrust.

Barnes and Poole (1968) also suggested that the klippen of the Spotted Range thrust had a root zone northwest of Yucca Flat. Klippen of the Spotted Range thrust lie presently more than 50 km southeast of the trace of the Belted Range thrust. If estimates of more than 100% Tertiary crustal extension in the southern Great Basin (Hamilton and Meyers, 1966; Wernicke et al., 1982, 1988b) are loosely applied to this region, this would still indicate greater than 25 km of net displacement along the Spotted Range/Belted Range thrust system.

If we are correct in correlating the Belted and Spotted Range thrusts, map relations require that the thrust plate was translated across a Mississippian facies boundary separating dominantly siliciclastic rocks, minor carbonates, shales, and orthoquartzites in the Eleana Range (Poole et al., 1961) from calcareous shale and carbonate facies in the Spotted Range (Barnes et al., 1982). The Belted Range thrust apparently rode along a decollement within Mississippian and/or younger strata between the Belted Range and the Spotted Range and once lay above rocks in the CP Hills. Both east- and west-vergent folds occur locally within the footwall of the CP thrust (Caskey, chapter 1), supporting the hypothesis that an east-directed Belted Range thrust

plate once structurally lay above the CP Hills area and was continuous with the Spotted Range thrust (fig. 6a). The presence of tight to isoclinal footwall folds beneath the Spotted Range thrust klippen mapped by Barnes et al. (1982) does not require a footwall ramp zone in the Spotted Range as suggested by Guth (1990), but may suggest rather that upper level decollement-style folds (e.g. Jamison, 1987) and/or minor fault-propagation folds within the lower plate may have initially developed foreland of, or beneath, the eastward-propagating Belted-Spotted Range thrust sheet.

Figure 6 illustrates our interpretation of the structural relations between the east-vergent Belted Range-Spotted Range thrust and the west-vergent CP thrust. Other structural elements shown in figure 6, together with relative timing and cross-cutting relationships (implied in figure) are discussed below.

Gass Peak thrust

East of the Spotted Range, no major thrust faults surface until the Gass Peak thrust in the Las Vegas Range (figs. 1 and 2). The Gass Peak thrust is a regionally extensive east-vergent structure that places Precambrian strata over highly folded and locally overturned Pennsylvanian and Permian carbonates

(Longwell, 1965; Guth, 1981). Wernicke et al. (1984) and Guth (1990)

interpreted the Gass Peak allochthon as a major structural plate that ramps up from a basal decollement of the Sevier orogenic belt. This is supported by published cross sections (Longwell et al., 1965) indicating that the Gass Peak thrust has a hangingwall flat and footwall ramp geometry in the Las Vegas Range. Net horizontal displacement along the Gass Peak thrust is believed to have been in excess of 30 km (Guth, 1981).

A minor thrust or reverse fault has been identified along the west side of the Pintwater Range (fig. 2) (Longwell et al., 1965; the "Pintwater thrust" of Guth, in press). This fault has been highly modified by Tertiary extensional faults because it exhibits both older-on-younger and younger-on-older age relationships (Guth, 1990), and appears to be of little regional importance because it is only traceable for a short distance. Because no major thrusts occur between the Gass Peak thrust and the klippen of the Spotted Range thrust, the lower plate to the Spotted Range thrust (inferred to be the CP allochthon) and the Gass Peak allochthon essentially constitute the same (pre-extensional) structural plate (figs. 2 and 6).

Pintwater anticline/Spotted Range syncline

Aside from the klippen of the Spotted Range thrust (inferred above to be part of the Belted Range thrust plate), the most important Mesozoic structures preserved between the west-vergent CP thrust and the east-vergent Gass Peak thrust are the Pintwater anticline (Longwell, 1945) and the Spotted Range syncline (Barnes et al., 1982) (figs. 2 and 6). These structures both occur within the same structural plate (CP-Gass Peak allochthon) (figs. 2 and 6), and together they constitute a north-trending and plunging regional fold pair whose width now spans four mountain ranges (i.e. the Sheep, Desert, Pintwater, and Spotted Ranges) and which is traceable for nearly 100 km along strike. Longwell (1945), who was the first to recognize the Pintwater anticline, noted that the north ends of the Pintwater Range (the western limb) and the Desert Range (the eastern limb) unite to form the plunging nose of a great fold. As discussed earlier, strata beneath the klippen of the Spotted Range thrust can be traced around the southwest end of the range to form the nose of the Spotted Range syncline to complete the regional fold pair (Longwell et al., 1965; Cornwall, 1972; Barnes et al., 1982).

Wernicke et al. (1984) interpreted the Pintwater anticline as a broad dome related to west-directed Tertiary detachment faulting. Guth (in press)

subsequently interpreted this structure as a ramp anticline formed above a major lower ramp of the Gass Peak thrust concealed beneath Three Lakes Valley (fig. 1). The former interpretation is unlikely because lowest Tertiary sedimentary deposits and younger, Miocene volcanic rocks overlying the western limb of the Pintwater anticline are tilted 25 degrees or more to the east (Tschanz and Pamperyan, 1970; Ekren et al., 1977). The interpretation of a Tertiary "dome" for the Pintwater anticline requires that the western limb or flank of the dome be tilted to the west.

Guth et al. (1988) compiled dip data from Tertiary basin deposits of northwestern Clark County to show that major fault blocks of the Sheep Range detachment system (Wernicke et al., 1984, Guth et al., 1988, Guth, in press) have been rotated an average of 30 degrees to the east during large-magnitude, west-directed Tertiary extension. Because this late Tertiary detachment system strongly disrupted the Gass Peak allochthon, this relation has important implications for the pre-Tertiary geometry of the regional fold pair. At present, Paleozoic strata of the Desert Range, which form the eastern limb of the Pintwater anticline, dip 30 to 50 degrees east (Longwell, 1945; Longwell et al., 1965) (fig. 7a). Paleozoic strata in the Pintwater Range lying west of the anticlinal hinge surface trace (Longwell et al., 1965) dip west an

average of 25-30 degrees, but locally dip as steeply as 50-70 degrees (Longwell, 1945; Longwell et al., 1965; Guth, in preparation). Rocks along the east side of the Spotted Range, which form a continuation of the western limb of the Pintwater anticline and the eastern limb of the Spotted Range syncline, dip an average of 35-45 degrees to the west. The western limb of the Spotted Range syncline generally dips moderately or gently to the east (Tschanz and Pampeyan, 1970).

A structural section oriented NW-SE (fig. 7a) which extends from the Belted Range to the Las Vegas Range illustrates the complex Tertiary extensional overprint and the present structural disposition of pre-Tertiary miogeoclinal strata. The magnitude and style of Tertiary extension west of the Spotted Range is less known than for areas to the east because extensive Miocene volcanic rocks (fig. 1) postdate and conceal much of the evidence for earlier Tertiary extension (Schweickert and Caskey, 1990). In this area, the structural interpretations are therefore regarded as conceptual. However, structural interpretations west of the bend in section are supported by available surface data.

A preliminary palinspastic reconstruction along section NW-SE (fig. 7b) was prepared by restoring Proterozoic and Paleozoic stratal cutoffs across

Figure 7 - A) Interpretive geologic cross section NW-SE (refer to fig. 2 for location). Patterns of stratigraphic units correspond to those at the lower left in figure. Structural interpretations east of the Spotted Range are based primarily on published data of Longwell et al. (1965) and interpretations of Guth (1981, 1990) and Guth et al. (1988). Structural interpretations of the Spotted Range and areas to the west are based on numerous published maps cited in text. Some structures have been projected into the section for emphasis. B) Preliminary pre-Tertiary reconstruction (section NW-SE) of the Mesozoic fold and thrust belt at the latitude of the NTS. Modern topography is shown offset along Tertiary normal faults (shown dashed). Tertiary structure shown concealed beneath Tertiary volcanic rocks between the "bend in section" and the Spotted Range is highly speculative, and therefore a reconstruction of this structure is omitted for clarity. Other details of the structure are discussed in text.

normal faults (making some assumptions about normal fault geometries at depth), and by simultaneously restoring major fault blocks to pre-tilt orientations using published dip data on Tertiary sedimentary and volcanic deposits (Ekren et al., 1977; Guth et al., 1988; Longwell et al., 1965; and Tschanz and Pampeyan, 1970) that depositionally overlie Paleozoic strata. For simplicity, we assumed that Tertiary deposits were originally horizontal.

Upon restoring section NW-SE (fig. 7b), the Pintwater anticline-Spotted Range syncline fold pair take on a substantially different pre-Tertiary geometry. The east limb of the Pintwater anticline, in the Desert Range block when restored 30 degrees to the west acquires a very gentle east dip. The west limb of the Pintwater anticline restored approximately 30 degrees to the west becomes steeply west dipping to locally overturned. In short, our preliminary restoration indicates that, prior to Tertiary extension, the Pintwater anticline and the Spotted Range syncline were a broad regional fold pair of significant structural relief. We suggest that the pre-Tertiary structural relief of the Pintwater "anticlinorium" was likely as great as 7 km, and that simple ramping from a basal decollement of the Gass Peak thrust, as proposed by Guth (1990), cannot account for this structure. Structural thickening related to duplex stacking (e.g. Boyer and Elliot, 1982) and/or folding of the

Precambrian clastic wedge at depth (both shown schematically beneath the Pintwater anticlinorium in fig. 7b), could more likely account for this structural relief (e.g. may be required for balance).

REGIONAL EXTENT OF THRUSTS AND RELATED DEFORMATION

Structures related to the CP thrust

Regional structural relations suggest that west-vergent structures likely related to the CP thrust can be traced along strike throughout the highly extended terrain of the southern Great Basin (see also discussion by Snow and Wernicke (1990)). However, in the region between the southern part of the Las Vegas Range and Bare Mountain (fig. 1 and 2), generally north-trending Tertiary structural blocks and Mesozoic structural trends, typical of the southern Great Basin, have been rotated clockwise as much as 90 degrees about a vertical axis. This phenomenon has been attributed to regional oroflexural bending within the Walker Lane belt (Albers, 1967; Stewart et al., 1968; Stewart, 1988), and also to right-lateral drag associated with the Las Vegas Valley shear zone and related structures (Longwell, 1960). In the region of maximum "bending," previously northerly-trending, west-vergent structures are presently east-trending and north-vergent.

At Bare Mountain (figs. 1 and 2), 50 km west of the CP Hills, major recumbent folds are associated with the north-vergent Panama thrust (Cornwall and Kleinhampl, 1961; Carr and Monsen, 1988; Monsen et al., 1990). The north-vergent folds appear to be tight and involve a several-kilometer-thick package of upper Precambrian through Upper Cambrian strata. It is difficult to provide a realistic estimate of net displacement along the Panama thrust. Lower and Middle Cambrian strata that structurally overlie Mississippian rocks at the north end of Bare Mountain, occupy the same structural position as the Panama thrust at the south end of the range (fig. 2) (Carr and Monsen, 1988; and Monsen, et al., 1990). However, complex Tertiary overprinting has occurred at the north end of Bare Mountain, thus making it difficult to accurately assess the Mesozoic structural framework. If these rocks at the north end of Bare Mountain belong to the north-vergent Panama thrust plate (fig. 2), displacement along the Panama thrust could be comparable to that along the CP thrust in the CP Hills. We interpret the north-vergent structures at Bare Mountain as being broadly correlative with the CP thrust, as defined in this paper.

West of Bare Mountain, in the Grapevine Mountains (figs. 1 and 2), a map-scale, west-vergent recumbent fold pair (e.g. the Titus Canyon anticline

and the Corkscrew syncline (fig. 2)) occurs in the upper plate of the Boundary Canyon normal fault (Reynolds, 1969). These structures have been correlated with the Panama thrust at Bare Mountain and with west-vergent backfolds above the east-vergent Schwab Peak thrust (fig. 2) and Marble Canyon thrust (Wernicke et al., 1988a, 1988b; Snow and Wernicke, 1989) to the south and west, respectively. Because large-scale north-vergent folds occur in both the upper and lower plates of the Panama thrust at Bare Mountain (Monsen et al., 1990), we are uncertain about the structural levels represented by the west-vergent folds in the Grapevine Mountains relative to those to the east (fig. 2).

In the Specter Range (fig. 1), a very large north-vergent anticline occurs whose overturned northern limb, involving a 4.5 km thickness of Lower Cambrian to Devonian strata, is well-exposed in the Striped Hills (Sargent et al., 1970; Sargent and Stewart, 1971; Schweickert, 1989). The scale of the fold, together with the rarity of hinterland-verging structures within the fold belt, suggest that this structure may correlate with recumbent structures in the upper plate of the Panama thrust at Bare Mountain (Schweickert, 1989). If so, this north-vergent structure may have been displaced by a concealed dextral strike-slip fault beneath Crater Flat, east of Bare Mountain. The proposed

dextral fault may be a northern continuation of the dextral Stewart Valley-Stateline fault southeast of the Amargosa Desert (fig. 2) (Schweickert, 1989).

Reconnaissance mapping in the Calico Hills (fig. 1) in the NTS has delineated large-scale north-vergent folds beneath overthrust Devonian carbonates (Caskey and Nitchman, unpubl. data). In this area, lower plate folds involve Upper Mississippian orthoquartzites, shales and carbonate rocks lithologically identical to Mississippian units beneath the CP thrust in the CP Hills. Published cross sections also indicate north-directed displacement along thrust(s) in this area (McKay and Williams, 1964; Orkild and O'Connor, 1970). Approximately 20 km separate Devonian rocks in the Calico Hills from those in the Striped Hills to the south. Although this could be interpreted to mean that an extensive zone of north-vergent folds and thrusts exists in this area, we believe it is also likely that these are upper crustal blocks that have been separated by large-magnitude, northwest-directed extension near the southern and southeastern portions of the Southwest Nevada volcanic field (Schweickert and Caskey, 1990).

North of Yucca Flat, a west-facing, overturned syncline northwest of Oak Spring Butte (figs. 1 and 2) involves at least 1.2 km of Ordovician through Devonian strata (Rodgers and Noble, 1969). This syncline, which is

truncated by the Tertiary Butte (normal) fault to the east (fig. 2), probably is a continuation of the west-vergent structures in the CP Hills. Middle Cambrian strata exposed on the downdropped eastern side of the Butte fault lie on trend with and are probably continuous with Middle Cambrian strata at Banded Mountain to the south. As previously discussed, the rocks at Banded Mountain form the western limb of a very large, asymmetric, west-facing anticline which is best interpreted as part of the upper plate of the CP thrust. Johnson and Hibbard (1957) also argued that all the lower Paleozoic rocks in the Yucca Flat region east of Mine Mountain and the Butte fault comprise a major thrust plate, although they were unsure of its sense of displacement. The zone of west-vergent deformation is difficult to trace north of the NTS area because of extensive Tertiary volcanic cover and Tertiary deformation. However, this zone probably exists at least as far north as the Egan Range where major west-vergent folds have been previously mapped (Brokaw and Barosh, 1968).

In summary, regional structural correlations indicate that hinterland-vergent structures probably related to the CP thrust can be traced for at least 180 km along strike in southwest Nevada and eastern California (fig. 2). These west-vergent structures form a z-shaped sigmoidal pattern which

essentially parallels oroflexural bends recognized by Albers (1967) within a "mobile belt" east of the Sierra Nevada. The sigmoidal pattern is disrupted by a possible northward projection of the Stewart Valley-Stateline fault in Crater Flat (fig.1) and also in the northern part of the Amargosa Desert (fig. 2).

Apparent dextral offset of the west-vergent structures across the Amargosa Desert is probably a result of northwest-directed translation of the Titus Canyon anticline-Corkscrew syncline above the Bare Mountain-Bullfrog Hills-Boundary Canyon detachment fault (Carr and Monsen, 1988) (fig. 2).

Dextral offset may, in part, be a result of concealed and as yet unrecognized right-slip faults in the northern part of Amargosa Valley. In any case, east-trending, north-verging structures at Bare Mountain appear to curve sharply westward to become north-trending and west-verging in the Grapevine Mountains, possibly completing the sigmoidal "z" pattern.

Regional extent of other structures

Structurally complicated Tertiary overprinting in areas such as Bare Mountain, extensive volcanic cover, and the fact that thrusts eventually die out along strike all compound the difficulties of correlating thrust faults in this region. Nevertheless, the southeast-vergent Belted Range thrust, as

described here, has previously been correlated to the Meiklejohn Peak thrust at the north end of Bare Mountain and with the Last Chance thrust in eastern California (Burchfiel et al., 1970; Wernicke et al., 1988a, 1988b). This correlation is reasonable, based on the position of both thrusts relative to the west-vergent fold and thrust system, but is not altogether compelling. At the northeast corner of Bare Mountain, exposures of highly sheared and folded Mississippian strata, presumably in the upper plate of the Meiklejohn Peak thrust, suggest the presence of a structurally higher, south-vergent thrust concealed beneath Tertiary volcanic rocks to the north. It is conceivable that the Belted Range thrust may correlate with such a postulated higher thrust and that the Meiklejohn Peak thrust either terminates along strike or represents a thrust imbrication structurally beneath the Belted Range thrust.

As previously mentioned, the klippen of the Spotted Range thrust probably belong to the once extensive Belted Range thrust plate and can be traced for more than 50 km along the hinge zone of the Spotted Range syncline. The northernmost klippe occurs at Chert Ridge, in the northern part of the Spotted Range (figs. 1 and 2) (Tschanz and Pampeyan, 1970; Jayko, 1990). Cambrian strata near the south end of the Spotted Range mapped by Barnes et al. (1982) and Cornwall (1972) appear to represent the southernmost

extent of thrust klippen. An east-trending, south-vergent thrust in the Specter Range (figs. 1 and 2) (Burchfiel, 1965; Sargent and Stewart, 1971) has previously been correlated with the Spotted Range thrust (Wernicke et al., 1988a, 1988b), but this thrust exhibits considerably less stratigraphic throw (i.e. Lower Cambrian over Ordovician strata) than the Spotted Range thrust and appears to us to lie within the lower plate of the Spotted Range thrust.

Burchfiel (1965) also argued that strata in the northern part of the Specter Range including rocks in the upper plate of the thrust in the Specter Range, are continuous with strata in the lower plate of the Spotted Range thrust to the east. He postulated that the thrust in the Specter Range had no counterpart in the Spotted Range and that it may have resulted from late Tertiary compression which accommodated the northwest termination of the right-lateral Las Vegas Valley shear zone (fig. 2).

The Gass Peak thrust is a regionally extensive structure which can be traced for at least 140 km in southern Nevada, from at least the east side of the northern part of the Sheep Range (Longwell, 1965), through the Las Vegas Range to the south, and across the Las Vegas Valley shear zone as the Wheeler Pass thrust (Burchfiel, 1965; Fleck, 1970) in the northwestern part of the Spring Mountains (figs. 1 and 2). Wernicke et al. (1988a, 1988b) correlated

structures as far west as the Slate Range in eastern California with the Wheeler Pass-Gass Peak thrust system. East-vergent structures as far north as the East Pahrangat Range (fig. 1) (Tchaz and Pampeyan, 1970; Jayko, 1990) may also be related to the Gass Peak thrust.

The extent of regional folds related to the Pintwater anticline and Spotted Range syncline is uncertain. North of the study area, Tertiary deformation and extensive Tertiary volcanic cover (Jayko, 1990; Tschanz and Pampeyan, 1970) make ambiguous any correlations of these structures. To the south, extreme bending and attenuation of Mesozoic structures has occurred along the northern terminus of the Las Vegas Valley shear zone (fig. 2) complicating correlation of structures across this region. However, Burchfiel et al. (1983) argued that a large, overturned, east-vergent anticline-syncline pair in the northwestern Spring Mountains (figs. 1 and 2) involving Precambrian Johnnie Formation and Stirling Quartzite correlated with the east-trending Pintwater anticline at the southern end of the Spotted Range. In Burchfiel's (1965, fig. 4, p. 184) interpretation of the structure of the Spring Mountains, he showed that the overturned anticline-syncline pair cores a large anticlinorium (with a structural relief in excess of 6km) within the Wheeler Pass allochthon. Although the Pintwater anticlinorium (fig. 7b)

broadly exhibits a west-facing geometry in our reconstruction, we suggest the pre-Tertiary structural relief and the position of the Pintwater anticlinorium relative to the Gass Peak-Wheeler Pass thrust is essentially identical to that of the anticlinorium in the northwestern Spring Mountains. We therefore support Burchfiel's (1983) correlation and suggest that the magnitude and style of east-vergent structural thickening beneath the anticlinorium in the Spring Mountains is also required farther northeast along strike (fig. 7b).

Figure 2 summarizes correlations of major Mesozoic structures and structural plates proposed in this paper and will be discussed further below.

TIMING OF STRUCTURAL EVENTS

Evidence for relative timing

Several lines of indirect evidence indicate that the west-vergent CP thrust and the regional fold pair to the east postdate emplacement of the east-vergent Belted Range/Spotted Range thrust plate.

1) Two generations of small-scale folds (both west- and east- vergent) have been recognized in rocks beneath the CP thrust in the CP Hills (Caskey, chapter 1). Where determinable, west-vergent folds related to the CP thrust overprint east-vergent folds without exception. Only one generation of (west-

vergent) folds has been recognized in the upper plate of the CP thrust which suggests that these stratigraphically deeper rocks were probably removed from the effects of earlier east-vergent deformation in the CP Hills. Based on our correlation of the east-vergent Belted and Spotted Range thrusts, these relations suggest that deformation related to the west-vergent CP thrust occurred after emplacement of the Belted-Spotted Range thrust plate.

2) Klippen of the Spotted Range thrust are only preserved in a narrow belt along the hinge zone of the Spotted Range syncline. This relation implies that emplacement of the thrust predated formation of the Pintwater anticline/Spotted Range syncline fold pair. Nowhere is the thrust plate, which largely consists of resistant Bonanza King dolomite, preserved on the limbs of the syncline, suggesting it was removed during uplift related to subsequent folding.

There are presently no direct constraints on relative timing between folding related to the Pintwater anticline-Spotted Range syncline and the west-vergent CP thrust to the west. However, the parallelism of the CP thrust, the regional fold pair, and the Gass Peak thrust, as well as arguments discussed later, suggest that they were all genetically related.

Constraints on the absolute age of structural events

The timing of thrust faulting and folding in the NTS region is only widely bracketed between Early Permian (age of the youngest rocks involved in thrusting) and early Tertiary (the inferred age of sedimentary deposits that overlie the Spotted Range thrust (Tschanz and Pampeyan, 1970) and are not folded by the Spotted Range syncline). North of Yucca Flat, 93 Ma quartz monzonite of the Climax Stock (Marvin et al., 1970) intrudes complexly folded Ordovician strata (Houser and Poole, 1960) and places a tighter upper age limit on at least local deformation. Better age constraints on thrusting must be inferred from thrust correlations and age relations established elsewhere in the thrust belt.

In eastern California, Mesozoic thrusts of the Last Chance thrust system (Burchfiel et al., 1970; Dunne et al., 1978, 1983; Dunne, 1986; Corbett et al., 1988) have been shown to predate emplacement of the 167-185 Ma Hunter Mountain batholith (Dunne et al., 1978), and have been interpreted as being Late Triassic to Early Jurassic in age. Corbett et al. (1988) interpreted this thrust system as a manifestation of the Permo-Triassic Sonoma orogeny. More recently, Snow (1990) suggested that the Last Chance thrust system predates the 228 ± 2 Ma White Top stock in the Cottonwood Mountains. If

correlations of the Belted Range thrust to the Last Chance thrust system (as previously discussed) are correct, then the Belted Range thrust may be pre-latest Middle Triassic. Based on relative timing constraints (discussed above), the age of west-vergent deformation related to the CP thrust can be refined only as post-Belted Range thrust and pre- early late Cretaceous (age of the Climax stock).

The age of the Gass Peak/Wheeler Pass thrust system is poorly constrained. However, easternmost thrusts of the Sevier orogenic belt have deformed rocks as young as early Late Cretaceous in the Muddy Mountains (i.e. the Glendale/Muddy Mountain thrust system) (Fleck, 1970) and latest early Cretaceous (~99Ma) in the Spring Mountains (i.e. the Keystone/Contact thrust system) (Fleck and Carr, 1990). Fleck (1970) contended that because the tectonic style is consistent throughout the Sevier orogenic belt, all thrusting represents a single, regional tectonic event. However, an earlier Mesozoic age for the Gass Peak/Wheeler Pass thrust system cannot be ruled out.

SUMMARY

The recognition of an important west-vergent thrust system in the NTS region has led to an improved understanding of the pre-Tertiary

structural framework of the region. Despite large-magnitude Tertiary extension, regionally extensive volcanic cover, and probable strike-slip faults concealed beneath alluviated valleys, hinterland-vergent deformation related to the CP thrust can be traced along strike for at least 180km in southwest Nevada and eastern California (see also discussions in Wernicke et al. (1988a, 1988b). The along-strike sigmoidal "z" pattern of the zone of west-vergent deformation parallels regional curvilinear trends of major folds and the Gass Peak thrust to the east, as well as major structural and stratigraphic trends to the northwest (Albers, 1967).

Structural relations in the NTS region indicate at least two major episodes of Mesozoic deformation occurred. The first is represented by the east-vergent Belted Range thrust northwest of Yucca Flat. We interpret klippen of the Spotted Range thrust to be erosional remnants of a once areally extensive Belted Range thrust plate that were folded and stranded along the hinge zone of the younger Spotted Range syncline. The second episode of Mesozoic deformation is represented by major hinterland-vergent folds and thrusts related to the CP thrust system. The relation of the Pintwater anticline-Spotted Range syncline fold pair to the CP thrust to the west is uncertain, although several lines of evidence (discussed below) suggest that

these folds may have been related to west-vergent folding and thrusting in the CP Hills. The pre-Tertiary structural relief and scale of the Pintwater anticlinorium (fig. 7b) suggests that it may have owed its origin to deeper structural thickening by folding and/or duplexing of Precambrian clastic strata.

DISCUSSION

Implications for the development of hinterland-vergent structures

Structural sections 7a and 7b illustrate our concept of the present and pre-Tertiary structural framework of the NTS region. The structural geometry of the region between the west-vergent CP thrust and the east-vergent Gass Peak thrust bears a close resemblance to the large scale, wedge-like, bivergent geometry recognized elsewhere in the Cordilleran fold and thrust belt (Elison, 1987; Price, 1981). Snow and Wernicke (1989, pp. 1360) also compared a hinterland-vergent backfold in the Death Valley region to structures in the Cordilleran orogen near Calgary, Alberta (Price, 1981). They compared the backfold in the Death Valley region to a west-facing monocline which presumably developed as a result of east-vergent imbricate thrusting of the rapidly westward-thickening Eocambrian clastic wedge (Price, 1981, p. 429,

fig. 2) . However, the Wernicke et al. (1988a, 1988b) and Snow and Wernicke (1989) reconstruction of the Cordilleran orogenic belt showed no direct or indirect evidence of imbricate thrusting or duplexing of the Eocambrian clastic wedge.

Elison (1987) suggested that the location of major thrust belts in north-central Nevada was strongly influenced by downward slopes or inclinations in the regional stratigraphic and structural framework. The west-vergent CP thrust lies above one of the thickest known sections of the Cordilleran miogeocline (Ekren, 1968; Stewart and Poole, 1972). Since maximum subsidence due to sediment loading would be expected in this region, a westward inclination in the layering of the miogeoclinal prism may have once existed. Tectonic loading from earlier thrusting to the west (e.g. the Last Chance thrust system) together with the development of substantial structural relief associated with the formation of the Pintwater anticlinorium to the east would have further promoted a westward slope in the miogeocline between these regions. In Price's (1981) structural section (fig. 2, p. 429), strata lying in the region between the Purcell anticlinorium to the west and the large anticlinorium associated with an inferred hinterland dipping duplex structure (Boyer and Elliot, 1982) to the east exhibit the greatest westward

inclination and correspond to intense west-vergent deformation such as upper crustal folds and thrusts. The anticlinorium associated with the inferred duplex structure in Price's section, exhibits structural relief comparable to or greater than that of the (pre-Tertiary) Pintwater anticlinorium (fig. 7b). It is reasonable to infer that regional horizontal compressional stresses, applied to mechanically anisotropic layering within the miogeocline that dipped significantly to the west, resulted in west-vergent folds and thrusts in both regions. We suggest, as did Snow and Wernicke (1989), that close similarities exist between the structural development and geometry in these two regions of the Cordilleran fold and thrust belt. However, we believe that the magnitude and complexity of the west-vergent structures in the NTS and vicinity are greater than those described in the Death Valley region by Snow and Wernicke.

Implications for previous thrust correlations in the NTS region

Previous workers interpreted thrust fault relations in the NTS region as remnants of a single, regional, east- to southeast-vergent thrust system (Barnes and Poole, 1968). Interpretations of this paper preclude earlier

correlations of the thrust in the CP Hills to southeast-vergent thrusts northwest of Yucca Flat and in the Spotted Range.

Recently, much attention has been given to regional correlations of Mesozoic thrusts for the purpose of palinspastic reconstructions of the highly extended southern Great Basin (Levy and Christie-Blick, 1989; Wernicke et al., 1988a, 1988b). Wernicke et al. (1988b, fig. 5, p. 1743) inferred that five structural levels bounded by major thrust faults identified in the Death Valley region project through the NTS region. Although their estimates of Neogene extension may not be compromised by incorrect details in these particular thrust correlations, we suggest that they are inconsistent with the details of the geology of the Cordilleran fold and thrust belt in the NTS region.

Our studies indicate that only three structural levels exist in the NTS region (fig. 2); 1) strata structurally above the east-vergent Belted Range thrust system (including klippen of the Spotted Range thrust), 2) strata structurally below both the east-vergent Belted Range thrust and the west-vergent CP thrust system, and 3) strata above both the west-vergent CP thrust and the east-vergent Gass Peak thrust.

We agree in general with the Belted Range thrust-Meiklejohn Peak thrust correlation and the Mine Mountain thrust-Panama thrust correlation proposed by Wernicke et al. (1988a, 1988b), although as noted earlier, other possibilities exist for correlations of the Belted Range thrust. However, no geologic evidence exists for the Wernicke et al. (1988a, 1988b) projection of the east-vergent Schwab Peak thrust system (fig. 2) through the southern part of the CP Hills and across the Halfpint Range to the northeast. In addition, the trace of the Clery thrust system (fig. 2) inferred by Wernicke et al. (1988a, 1988b) erroneously transects nearly continuous stratigraphy along the west limb of the Spotted Range syncline at Frenchman Flat. Furthermore, a possible concealed, north-trending strike-slip fault east of Bare Mountain (Schweickert, 1989), as well as an alternative option of a Tertiary origin for the Specter Range thrust (Burchfiel, 1965), as discussed above, may complicate the correlations of the Clery thrust with structures to the east (Wernicke et al., 1988a, 1988b). We suggest that more work needs to be done to understand strike-slip faulting and extension in this region, in order to confidently correlate structures in the Funeral and Grapevine Mountains with structures to the east.

Implications for the amount of extension north of the Las Vegas Valley shear zone

Although a complete discussion of regional Tertiary extension is beyond the scope of this paper, we believe that an improved understanding of the Cordilleran fold and thrust belt in the NTS and surrounding regions may provide insight as to the magnitude of Tertiary extension north of the Las Vegas Valley shear zone (LVVSZ) (Fig. 2). Earlier workers have estimated the amount of extension using a "tilted block model" (Morton and Black, 1975) which assumes that Paleozoic sedimentary layering in this region was horizontal at the close of Mesozoic thrusting (Armstrong, 1968). Our preliminary reconstruction (fig. 7b) as well as a comparison with Paleozoic rocks south of the LVVSZ in the northwest Spring Mountains (fig 1) where Tertiary extension has been minimal (Burchfiel, 1965) indicates that this assumption is invalid and has led to estimates of extension that are too high.

Guth (1981), using the Morton and Black (1975) model, suggested that between 44% and 58% extension occurred between the Sheep Range and the west side of the Desert Range and that extension increased progressively toward the west. Our preliminary reconstruction of the fold and thrust belt (fig. 7b) indicates that only about 27% extension occurred between the Gass

Peak thrust and the Desert Range. We suggest that overall extension between the Gass Peak thrust and the Spotted Range may be as little as 15% and, in contrast with Guth (1981), extension decreased progressively toward the west between these areas.

As another approach to estimating the amount of regional extension, Guth (1981) compared the relative spacing of correlative structures north and south of the LVVSZ. He noted that north of the LVVSZ the distance (measured perpendicular to strike) between the Gass Peak thrust and the mapped trace of the Pintwater anticline was about 42 km. South of the LVVSZ the distance between the Wheeler Pass thrust and the anticline in the northwest Spring Mountains is only 25 km. Guth concluded that 80% extension was required between the Gass Peak thrust and the Pintwater anticline (although his measurements support only about 70% extension).

A consequence of our preliminary reconstruction is that the mapped trace of the Pintwater anticline (fig. 7a) and the crest of the pre-Tertiary Pintwater anticlinorium (fig. 7b) do not coincide. Instead, the crest of the Pintwater anticlinorium (fig. 7b) lies approximately 26 km from the Gass Peak thrust, essentially identical to the distance between correlative structures south of the LVVSZ. We feel that this coincidence supports our

preliminary reconstruction of the Pintwater anticlinorium and suggests that only about 24% extension has occurred between the Gass Peak thrust and the mapped trace of the Pintwater anticline. We therefore believe that Guth's (1981) estimate of 80% extension across this interval is too large.

CONCLUSIONS

1. The CP thrust of Barnes and Poole (1968) actually comprises two separate, oppositely verging Mesozoic thrust systems; 1) the west-vergent (hinterland-vergent) CP thrust which is well exposed in the CP Hills and at Mine Mountain, and 2) the east-vergent Belted Range thrust located northwest of Yucca Flat.
2. The CP thrust represents part of an important west-vergent Mesozoic fold and thrust system traceable for over 180 km along strike in southwestern Nevada and eastern California. The zone of west-vergent deformation is difficult to trace north of the NTS but probably exists at least as far north as the Egan Range where major west-vergent folds have been previously mapped (Brokaw and Barosh, 1968).
3. Klippen of the Spotted Range thrust are probably erosional remnants of a once areally extensive east-vergent Belted Range thrust sheet whose

emplacement preceded the west-vergent CP thrust and regional folds between the NTS and the Sheep Range.

4. Prior to Tertiary extension, the Pintwater anticline of Longwell (1945) may have been a great anticlinorium with as much as 7 km of structural relief.

This interpretation is consistent with structural interpretations of a correlative structure in the northwest part of the Spring Mountains (Burchfiel, 1965).

5. A region or zone of significant westward inclination within the Cordilleran miogeoclinal framework may have influenced the location and development of the belt of west-vergent folding and thrusting.

6. Previous estimates of Tertiary extension north of the Las Vegas Valley shear zone are too large. A preliminary reconstruction of the fold and thrust belt suggests about 27% extension between the Desert Range and the Gass Peak thrust compared to earlier estimates ranging from 44 to 80% in this area. Overall extension between the Spotted Range and the Las Vegas Range may be as little as 15% although much greater extension certainly occurred locally. More work needs to be done in the entire region, especially in the NTS region, to understand better the magnitude and style of Tertiary extension.

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GENERAL CONCLUSIONS OF THESIS RESEARCH

- 1) The CP thrust of Barnes and Poole (1968) actually comprises two separate, oppositely verging Mesozoic thrust systems; 1) the west-vergent (hinterland-vergent) CP thrust which is well exposed in the CP Hills and at Mine Mountain, and 2) the east-vergent Belted Range thrust located northwest of Yucca Flat.
- 2) Rocks within the CP parautochthon were affected by at least one episode of folding prior to the development of large-scale west-vergent folds. This early episode of folding may have been related to an earlier phase of progressive, generally west-vergent deformation. Other observations suggest an earlier episode of east-vergent deformation.
- 3) The CP Hills were fragmented by at least two episodes of Cenozoic extensional faulting: 1) an earlier episode of pre- middle Miocene low-angle normal faulting which strongly disrupted west-vergent folds within the CP allochthon; and 2) a later episode of post- 11 Ma high-angle faulting which has resulted in the dominant north-to-northwest structural grain of the CP Hills and the present basin and range topography of the NTS region.

- 4) The southern part of the CP Hills extended by about 15% during (generally) post- middle Miocene deformation. Net Tertiary extension on the order of 40% is not unreasonable for the southern part of the CP Hills.
- 5) Pre- middle Miocene low-angle normal faults are regional in extent, and there appears to be a direct correspondence between the structural grain of this low-angle fault system and that of (hinterland-vergent) Mesozoic structures.
- 6) The CP thrust represents part of an important west-vergent Mesozoic fold and thrust system traceable for over 180 km along strike in southwestern Nevada and eastern California. The zone of west-vergent deformation is difficult to trace north of the NTS but probably exists at least as far north as the Egan Range where major west-vergent folds have been previously mapped (Brokaw and Barosh, 1968).
- 7) Klippen of the Spotted Range thrust are probably erosional remnants of a once areally extensive east-vergent Belted Range thrust sheet whose emplacement preceded the west-vergent CP thrust and regional folds between the NTS and the Sheep Range.
- 8) Prior to Tertiary extension, the Pintwater anticline of Longwell (1945) may have been a great anticlinorium with as much as 7 km of structural relief.

This interpretation is consistent with structural interpretations of a correlative structure in the northwest part of the Spring Mountains (Burchfiel, 1965).

- 9) A region or zone of significant westward inclination within the Cordilleran miogeoclinal framework may have influenced the location and development of the belt of west-vergent folding and thrusting.
- 10) Previous estimates of Tertiary extension north of the Las Vegas Valley shear zone are too large. A preliminary reconstruction of the fold and thrust belt suggests about 27% extension between the Desert Range and the Gass Peak thrust compared to earlier estimates ranging from 44 to 80% in this area. Overall extension between the Spotted Range and the Las Vegas Range may be as little as 15%, although much greater extension certainly occurred locally. More work needs to be done in the entire region, especially in the NTS region, to understand better the magnitude and style of Tertiary extension.
- 11) Mesozoic west-vergent thrusts and folds and Cenozoic low-angle normal faults exposed in the CP Hills broadly correlate with structures at Bare Mountain. Because Yucca Mountain lies between the CP Hills and Bare Mountain, models of subsurface structure at Yucca Mountain should

incorporate structural complexity consistent with structures in Proterozoic and Paleozoic rocks at Bare Mountain and the CP Hills.

116°07'30"
37°00'

79°E

North

ARINE MTN. JCT. 3 ABL

33

2763 II SE
(YUCCA FLAT)

'82

'83

'84

GEOLOGIC MAP OF PART OF THE CP HILLS, I NYE COUNTY, NEVADA

by S. John Caskey

(with additions from McKeown et al.,

1991

ROCK UNITS

Quaternary

Qal

Alluvium

Miocene

Tpt

Paintbrush Tuff - Topopah Spring Member
(12.8 Ma) (Sawyer et al., 1990)

Ttu

Undifferentiated volcanic rocks - locally includes
Formation (13.1 Ma) (Carr et al., 1986) and C
Flat Tuff (13.7 Ma) (Carr et al., 1986) and/or
Flat (15.1 Ma) (Sawyer et al., 1990)

Pennsylvanian

Pt

Tippipah Limestone

Mississippian
Upper Devonian

MDa

Eleana Formation - showing quartzite marker beds

Cn

Nopah Formation

Upper Cambrian

Cbbu

Cbbu -Banded Mou

Cbbl

Bonanza King Formation

Cbbl -Banded Mou

Cbp

Cbp -Papoose Lal

Middle Cambrian

Cc

Carrara Formation

Lower Cambrian
Upper Proterozoic

CZzwc

Zabriskie Quartzite and Wood Canyon Form

EXPLANATION OF MAP SYMBOLS

DEPOSITIONAL CONTACT - Dashed where inferred; dotted where

Plate 1

GEOLOGIC MAP OF PART OF THE CP HILLS, NEVADA TEST SITE, NYE COUNTY, NEVADA

by S. John Caskey

(with additions from McKeown et al., 1976)

1991

ROCK UNITS

Quaternary	Qal	Alluvium	
	Tpt	Paintbrush Tuff - Topopah Spring Member (12.8 Ma) (Sawyer et al., 1990)	
Neogene	Ttu	Undifferentiated volcanic rocks - locally includes Wahmonie Formation (13.1 Ma) (Carr et al., 1986) and Crater Flat Tuff (13.7 Ma) (Carr et al., 1986) and/or Tuff of Yucca Flat (15.1 Ma) (Sawyer et al., 1990)	
Silurian	Pl	Tippipah Limestone	
Mississippian or Devonian	MDe	Eleana Formation - showing quartzite marker beds	
	Cn	Nopah Formation	
Cambrian	Cbbu	Bonanza King Formation	Cbbu -Banded Mountain Member (upper subunit)
	Cbbi		Cbbi -Banded Mountain Member (lower subunit)
	Cbp		Cbp -Papoose Lake Member
Cambrian	Cc	Carrara Formation	
Cambrian Proterozoic	CZzwc	Zabriskie Quartzite and Wood Canyon Formation	

EXPLANATION OF MAP SYMBOLS

Lower Cambrian
Upper Proterozoic

CZzwc

Zabriskie Quartzite and Wood Canyon

EXPLANATION OF MAP SYMBOLS

----- DEPOSITIONAL CONTACT - Dashed where inferred; dotted where

36
----- FAULT - Dashed where inferred; dotted where concealed; bar and angle of fault surface; relative vertical movement indicated by arrow; relative horizontal movement indicated by arrow

CP THRUST FAULT - Barbs on upper plate.

PRE- MIDDLE MIOCENE LOW-ANGLE NORMAL FAULT - on upper plate.

LOW-ANGLE FAULT - Classification uncertain (see text); dashed where inferred; dotted where concealed; bar and angle of fault surface; relative vertical movement indicated by arrow; relative horizontal movement indicated by arrow

LANDSLIDE BLOCK BOUNDARY - Dashed where approximate

OVERTURNED WEST-VERGENT ANTICLINE - Showing approximate direction of plunge of hingeline, and dip direction of limbs

OVERTURNED EAST-VERGENT ANTICLINE - Showing approximate direction of plunge of hingeline, and dip direction of limbs

SYNCLINE - Showing approximate hinge surface trace, direction of plunge, and dip direction of limbs

35
OVERTURNED WEST-VERGENT SYNCLINE - Showing approximate direction and amount of plunge of hingeline where known

OVERTURNED EAST-VERGENT SYNCLINE - Showing approximate direction of plunge of hingeline, and dip direction of limbs

AREA OF BRECCIATED ROCK

STRIKE AND DIP OF BEDS

- ① Horizontal and upright
- / Inclined and upright
- | Vertical
- ⌵ Overturned

STRIKE AND DIP OF FOLIATION IN TUFFS

- / Inclined and upright

SCALE 1:12,000

EXPLANATION OF MAP SYMBOLS

- DEPOSITIONAL CONTACT - Dashed where inferred; dotted where concealed.
- FAULT - Dashed where inferred; dotted where concealed; bar and number indicate dip direction and angle of fault surface; relative vertical movement indicated by bar and ball on down-thrown side; relative horizontal movement indicated by paired arrows.
- ▲ CP THRUST FAULT - Barbs on upper plate.
- PRE- MIDDLE MIOCENE LOW-ANGLE NORMAL FAULT - Dashed where inferred; boxes on upper plate.
- △ LOW-ANGLE FAULT - Classification uncertain (see text); dashed where inferred; barbs on upper plate.
- ≡ LANDSLIDE BLOCK BOUNDARY - Dashed where approximate; hash marks on landslide block.
- ↗ OVERTURNED WEST-VERGENT ANTICLINE - Showing approximate hinge surface trace, direction of plunge of hingeline, and dip direction of limbs.
- ↘ OVERTURNED EAST-VERGENT ANTICLINE - Showing approximate hinge surface trace, direction of plunge of hingeline, and dip direction of limbs.
- * SYNCLINE - Showing approximate hinge surface trace, direction of plunge of hingeline where known, and dip direction of limbs.
- 35 ↗ OVERTURNED WEST-VERGENT SYNCLINE - Showing approximate hinge surface trace, direction and amount of plunge of hingeline where known, and dip direction of limbs.
- ↘ OVERTURNED EAST-VERGENT SYNCLINE - Showing approximate hinge surface trace, direction of plunge of hingeline, and dip direction of limbs.
- ▲ AREA OF BRECCIATED ROCK

STRIKE AND DIP OF BEDS

- ① Horizontal and upright
- ↗ Inclined and upright
- ⊥ Vertical
- ↘ Overturned

STRIKE AND DIP OF FOLIATION IN TUFFS

- ↗ Inclined and upright

SCALE 1:12,000

0

1 M

27571 NW
(MINE MOUNTAIN)

88

88

87

unmapped Miocene
volcanic rocks
(see McKeown et al., 1976)

unmapped Miocene
volcanic rocks
(see McKeown et al., 1976)

SCALE 1:12,000

0

0

Sub station

4003

BM Subst

Vows
Vob

Substa

3927

Tanks

4036

Heliport

BM
4050

Yucca Pass

4049

43

8

44

352

Cc

Drill
Hole

3930

4000

X 3958

4100

4000

400

0

1 Mi

0

1 Km

Plate 1
GEOLOGIC MAP OF PART OF THE

Plate 1

A

NNE

2a

The Bench

banic units (Tpc)-Paintbrush Tuff, Tiva Canyon Member, Mountain Tuff, Rainier Mesa Member, and Mountain Tuff, Ammonia Tanks Member do not appear on plate 1. These units and faults in this vicinity were not shown on the line of section from McKeown et al. (1976). The arrows indicate relative separation along fault plane.

CP Hills

SCALE 1:12,000

Vertical Scale = Horizontal Scale

A'

SSW

1 Mi

1 Km

Plate 2

2b

Geolog
No

Plate 2

Geologic Cross Section A - A', CP Hills (Plate 1),
Nevada Test Site, Nye County Nevada

by S. John Caskey
(1991)

- Plate 2a- Geologic cross section A-A'
- Plate 2b- Geologic cross section A-A' with restored
high-angle Tertiary normal faults

B

NW

311 Canyon Road

Elevation (in feet above sea level)

5000

4000

3000

2000

3a

Plate 3

3b

Plate 3

Geologic Cross Sections B-B' at (Plate 1), Nevada Test Site Nye County, Nevada

by S. John Caskey
(1991)

- Plate 3a-** Geologic cross section B
3b- Geologic cross section B
high-angle Tertiary no
3c- Geologic cross section C
3d- Geologic cross section C
high-angle Tertiary no
3e- Geologic cross section C
middle Miocene low-a

3d

:-C', CP Hills

SCALE 1:12,000

Vertical Scale = Horizontal Scale

h restored
aults.

th restored
aults.
th restored pre-
normal fault.

Note: Paired arrows indicate relative separation along fault plane

3e

END

**DATE
FILMED**

6 / 22 / 93