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MAJOR STRUCTURAL CONTROLS ON THE DISTRIBUTION OF PRE-TERTIARY ROCKS, NEVADA TEST SITE VICINITY, SOUTHERN NEVADA

By

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ABSTRACT

The lateral and vertical distributions of Proterozoic and Paleozoic sedimentary rocks in southern Nevada are the combined products of original stratigraphic relationships and post-depositional faults and folds. This map compilation shows the distribution of these pre-Tertiary rocks in the region including and surrounding the Nevada Test Site. It is based on considerable new evidence from detailed geologic mapping, biostratigraphic control, sedimentological analysis, and a review of regional map relationships.

Proterozoic and Paleozoic rocks of the region record paleogeographic transitions between continental shelf depositional environments on the east and deeper-water slope-facies depositional environments on the west. Middle Devonian and Mississippian sequences, in particular, show strong lateral facies variations caused by contemporaneous changes in the western margin of North America during the Antler orogeny. Sections of rock that were originally deposited in widely separated facies localities presently lie in close proximity. These spatial relationships chiefly result from major east- and southeast-directed thrusts that deformed the region in Permian or later time.

Somewhat younger contractional structures are identified within two irregular zones that traverse the region. These folds and thrusts typically verge toward the west and northwest and overprint the relatively simple pattern of the older contractional terranes. Local structural complications are significant near these younger structures due to the opposing vergence and due to irregularities in the previously folded and faulted crustal section.

Structural and stratigraphic discontinuities are identified on opposing sides of two north-trending fault zones in the central part of the compilation region north of Yucca Flat. The origin and significance of these zones are enigmatic because they are largely covered by Tertiary and younger deposits. These faults most likely result from significant lateral offset, most likely in the sinistral sense.

Low-angle normal faults that are at least older than Oligocene, and may pre-date Late Cretaceous time, are also present in the region. These faults are shown to locally displace blocks of pre-Tertiary rock by several kilometers. However, none of these structures can be traced for significant distances beyond its outcrop extent, and the inference is made that they do not exert regional influence on the distribution of pre-Tertiary rocks. The extensional strain accommodated by these low-angle normal faults appears to be local and highly irregular.

INTRODUCTION

The geology of the Nevada Test Site region has been intensely investigated over the last four decades because of the underground nuclear-bomb testing program operated by the U.S. Department of Energy (DOE) and its predecessors (U.S. Department of Energy, 1994). Between the late 1950's and the suspension of testing in 1995, DOE has announced that 828 underground nuclear tests were conducted at the Nevada Test Site (Laczniak and others, 1996). Most of these experiments were performed in the deep alluvial basins beneath Yucca Flat and Frenchman Flat or in the thick Miocene volcanic deposits beneath Rainier Mesa and Pahute Mesa (fig. 1; Laczniak and others, 1996). Test detonations were primarily conducted in unsaturated rock above the water table, but as many as 316 were detonated below the water table or sufficiently close that radioactive byproducts were probably introduced directly into the ground water flow system by the explosions (Laczniak and others, 1996).

Paleozoic sedimentary strata that lie beneath these testing areas largely comprise carbonate rock units of the principal regional aquifer system in southern Nevada (Winograd and Thordarson, 1975; Laczniak and others, 1996). This aquifer system conveys substantial ground water from central Nevada toward the southwest in what is known as the Death Valley ground water flow system (Winograd and Thordarson, 1975; Dettinger, 1989). This regional carbonate aquifer is stratigraphically contained between quartzitic clastic confining units below (Middle Cambrian and older) and shales and siliciclastic confining units above (Late Devonian and younger; Laczniak and others, 1996; Trexler and others, 1996). The continuity of the carbonate aquifer and its physical characteristics that influence ground water flow are strongly influenced by post-depositional folding, faulting, and fracturing (Winograd and Thordarson, 1975).

Studies described in this report were undertaken by the U.S. Geological Survey (USGS) in support of DOE's Environmental Restoration Program for the Nevada Test Site to assist with geological characterization of contaminated environments. This work clarifies the structural and stratigraphic framework of potential pathways that may facilitate the migration of water-borne contaminants from the test areas to points of water discharge or extraction. In particular, the Paleozoic carbonate strata are capable of transporting large quantities of water quickly toward these points of water use (Winograd and Thordarson, 1975; Dettinger, 1989; Laczniak and others, 1996). Knowledge of the structural conditions and stratigraphic relationships within the carbonate aquifer is essential to evaluate risks associated with the manmade contamination resulting from nuclear-weapons testing.

Prior geologic investigations at the Nevada Test Site were focused primarily on the middle Miocene volcanic units of the southwest Nevada volcanic field and the post-volcanic alluvial basins because these were the media for the underground tests. High-quality geologic mapping at 1:24,000-scale and fairly comprehensive stratigraphic studies were completed by USGS staff for the pre-Tertiary rocks in the late 1960's. However,

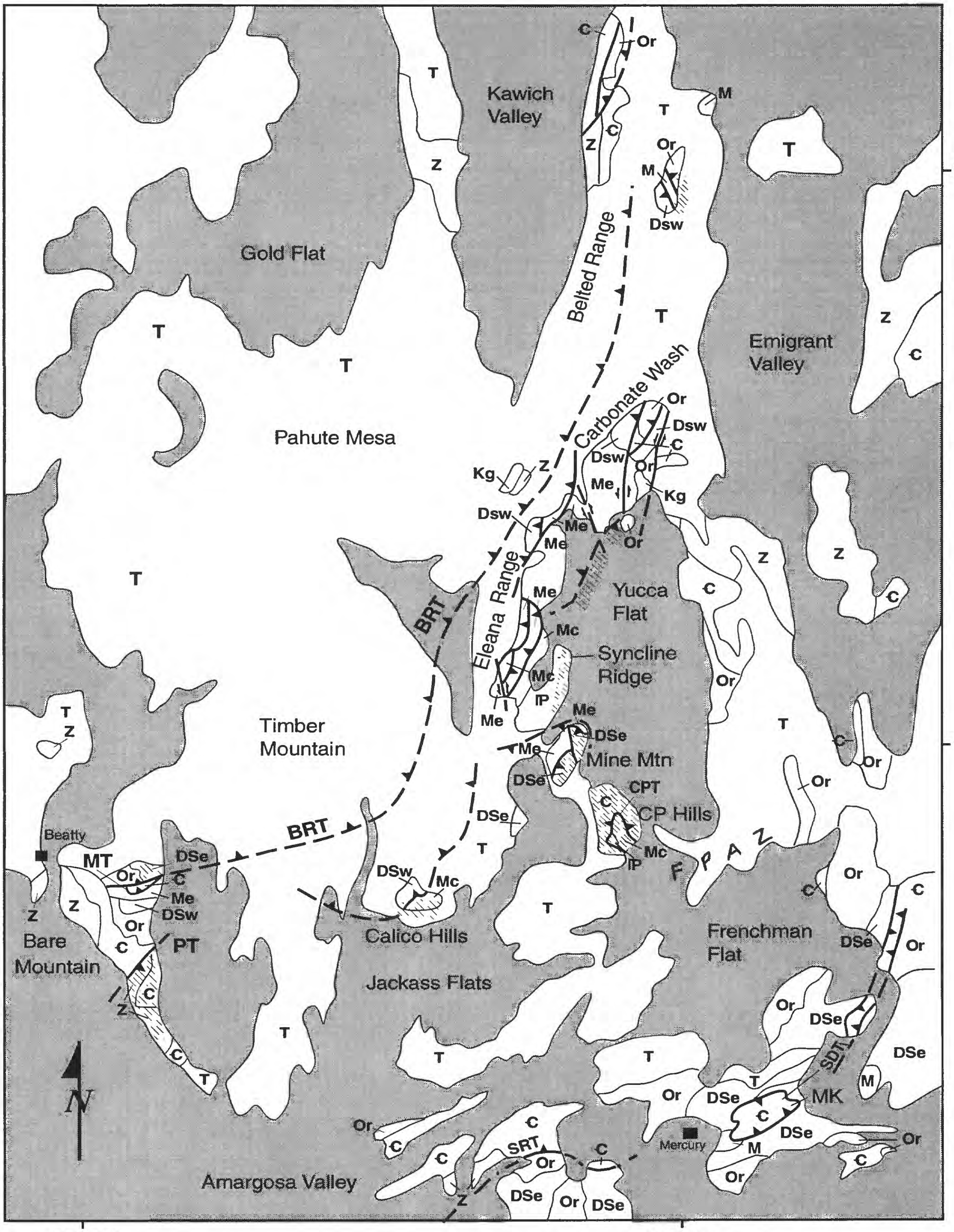

Figure 1.-- Structural summary map of the major contractional features in pre-Tertiary rocks of the Nevada Test Site region. Symbols: shading=Quaternary deposits; T=Tertiary deposits; Kg=Cretaceous granite; IP=Pennsylvanian; Me=Eleana Formation; Mc=Chainman Shale; M=other Mississippian units; DSe=eastern-facies Devonian-Silurian; DSw=western-facies Devonian-Silurian; Or=Ordovician; C=Cambrian; Z=Late Proterozoic; BRT=Belted Range thrust; FPAZ=French Peak accommodation zone; MT=Meiklejohn thrust; PT=Panama thrust; SDT=Spotted Range thrust; SRT=Specter Range thrust. Diagonal-rule pattern indicates areas of hinterland-vergent deformation attributed to the CP thrust system (see text).

little additional DOE-sponsored work was conducted during the 1970's and 1980's because the testing program placed higher priority on studies of younger units (Laczniak and others, 1996). In addition, the Test Site has not been openly accessible to the non-Federal earth science community since the 1950's because of security restrictions. As a result, knowledge of this area has not benefited as much from the collaborative and competitive investigations by industry, academic, State agency, and grant-sponsored scientists as other parts of the Great Basin.

The regional structural and stratigraphic compilation in this report (plate 1) is an outgrowth of coordinated studies by the author and collaborating investigators, principally from the University of Nevada-Reno and the USGS, since the late 1980's. The stratigraphic framework and the evidence for regional facies distributions is described in detail by Cashman and Trexler (1991, 1994), Cole and others (1994), Trexler and others (1996), and Trexler and Cashman (1997). The structural framework and evidence for thrust relationships, structural sequence, and extensional faulting are described in detail by Cole and others (1989, 1993, 1994, 1997), Caskey and Schweickert (1992), and Cole and Cashman (1997).

Acknowledgments

This report draws on considerable pioneering work done by others in this region, but not all of those studies can be directly cited in this report. The author particularly acknowledges the value and utility of the detailed geologic mapping for the Nevada Test Site region at 1:24,000 scale, without which the present work could not have been undertaken and completed in a few years. These maps and the smaller-scale compilations that followed were excellent guides to field relationships, localities to sample for biostratigraphic control, and regional structural patterns (Ekren and others, 1971; Sargent and Orkild, 1973; Maldonado, 1985; Guth, 1989; Frizzell and Schulters, 1990; Monsen and others, 1992; Minor and others, 1993; Wright and Troxel, 1993; Carr and others, 1995; Sawyer and others, 1995; and Wahl and others, 1997). Biostratigraphic control was essential to understanding the regional facies variations and deciphering the structural framework. These studies were done chiefly by Anita Harris of the USGS and published in Grow and others (1994), Trexler and others (1996), and Cole and others (1997). Additional results were obtained from Betty Skipp, Mira Kurka, Alan Titus, Gary Webster, Scott Ritter, and others on various fossil assemblages, many of which are referenced in the publications listed above.

The author gratefully acknowledges the assistance provided by the staff of the U.S. Geological Survey Core Library facility in Mercury, Nevada. In particular, Jerry Magner, Ron Martin, Mark Tsatsa, and Dick Hurlbut were indispensable in retrieving samples of drill core and cuttings for numerous wells from the Nevada Test Site. Field investigations were greatly facilitated by this staff, who unfailingly provided the necessary equipment, vehicles, supplies, and clearances.

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Sources of Information

During the last 40 years, more than 200 exploratory holes have been drilled through the alluvial and volcanic deposits of the Nevada Test Site and into the underlying pre-Tertiary basement rocks. These holes, and numerous shallower borings, were drilled chiefly to obtain engineering, stratigraphic, and structural data to characterize the sites of underground nuclear explosions. The pre-Tertiary rocks were rarely used for nuclear testing (Laczniak and others, 1996), and so many of the exploratory holes only penetrated a few tens of meters below the Tertiary unconformity. Basement samples generally consist only of drill cuttings, supplemented by some bottom-hole core runs. Little systematic work was done under the nuclear-weapons testing program to define the stratigraphy and structure of the pre-Tertiary basement because the primary program emphasis was characterization of the test environments. As a consequence, the large number of drill holes in the central Nevada Test Site and surrounding areas provide relatively little information about stratigraphic positions, bedding attitudes, or structural conditions of the pre-Tertiary formations penetrated.

The sub-crop geologic map in this report (plate 1) is based in large part on substantial new biostratigraphic data obtained through conodont analyses performed by A.G. Harris of the USGS (table 1) on carbonate rocks from exploratory drill holes (Grow and others, 1994; Cole and others, 1997). Conodont fossil assemblages are diagnostic of time periods from the Middle Cambrian through the Pennsylvanian, but they can provide particularly detailed age control for Ordovician and younger rocks. Many of the samples lacked conodonts but contained common to abundant phosphatic brachiopod fragments in the acid-insoluble residues from the sample processing technique. The phosphatic shell composition is distinct to inarticulate brachiopods that are most abundant in Cambrian rocks, reasonably common in the Ordovician, and scarce in younger strata (Moore and others, 1952). Samples that produced phosphatic brachiopods most likely indicate the Nopah Formation, Bonanza King Formation, or Ordovician Pogonip Group (fig. 2). The Nopah and Bonanza King are more than 4,600 ft (1,400 m) thick and consist largely of thick-bedded dolomite and limestone that are essentially indistinguishable from each other in drill cuttings. Rocks of the Pogonip Group tend to be more thinly bedded and silty than the Cambrian formations on the whole, but the distinction cannot always be made with confidence from drill cuttings alone.

Clastic rocks that lack fossils can nonetheless be identified from drillhole samples, with varying degrees of certainty. If the drillhole penetrates sufficient stratigraphic section without structural complication, identification is often possible from knowledge of the local sedimentary stratigraphy. Where little sample is available, lithologic characteristics can be diagnostic in some circumstances. For example, detrital muscovite is a reliable indicator of pre-Ordovician strata. Mica is common in the silty parts of the Carrara Formation and all older units, and is usually detectable in the Dunderberg Shale at the base of the Nopah Formation, but it is scarce to absent in younger formations. The Ordovician Eureka Quartzite is usually identifiable by its well sorted, well rounded character and by well developed secondary quartz overgrowths. Quartzites in the Devonian carbonate units are generally less well sorted and are typically cemented by both calcite and quartz. The

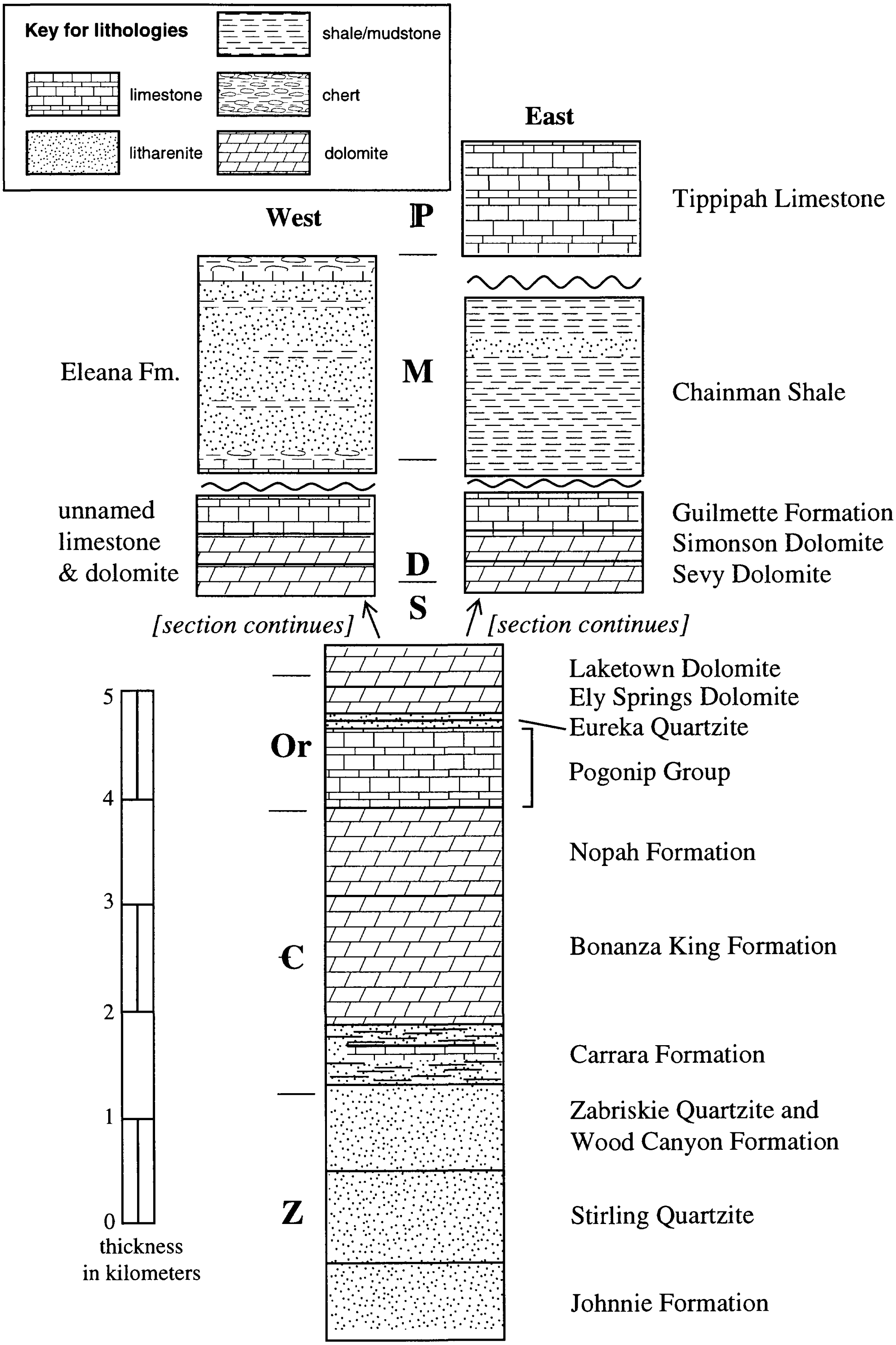

Figure 2.-- Stratigraphic column for pre-Tertiary rocks in the Nevada Test Site region. Nomenclature and average thickness values shown for Silurian and older units are based on eastern, shallow-water facies; thickness values for Devonian and Mississippian units are variable across the region (see text).

Chainman Shale contains some prominent quartzites in its upper part (Scotty Wash Quartzite; Trexler and others, 1996), but they are notably impure, contain detrital tourmaline and zircon, and are not well sorted. The main body of Chainman Shale is distinguished by its extreme uniformity and thickness, by notably higher organic-carbon content than other shales in the section (Barker, 1994; Trexler and others, 1996), and by thin beds of fine, chert-lithic sand.

The distinction between "western" and "eastern" facies in the Silurian and Devonian rocks pertains to environments of deposition and overall stratigraphic context (Trexler and others, 1996). Evidence for these characteristics is generally not available from drillhole samples, particularly when only cuttings are available, as bedding and depositional features are obliterated by drilling. The assignment of rocks from a well to one facies or the other on the map (pl. 1) is based on lithologic character, on the regional structural interpretation of thrust components (Cole and Cashman, 1997), or on inference from nearby holes with better sample material.

STRATIGRAPHIC FRAMEWORK

The pre-Tertiary rocks of the Nevada Test Site area consist of a thick assemblage of siliciclastic and carbonate sedimentary strata that range in age from Late Proterozoic to Early Pennsylvanian (fig. 2). These formations were deposited along the passive margin of the North American continent through Middle Devonian time and include as much as 10,300 feet (3,100 m) of quartzite, shale, and siltstone (Middle Cambrian and older) and 15,200 feet (4,600 m) of limestone and dolomite (Middle Devonian through Middle Cambrian; Trexler and others, 1996). The Antler orogeny altered sedimentation patterns in the region by creating a foreland basin eastward of the advancing Antler orogenic highlands that were accreting to the western margin of North America (Trexler and Cashman, 1991). These highlands, consisting of oceanic and abyssal rocks, were quickly eroded and shed chert-rich sediment southward and southwestward along a submarine fan system into central and southern Nevada (Poole, 1974; Trexler and others, 1996; Trexler and Cashman, 1997).

Rocks deposited during the Antler event through Mississippian time show strong regional facies variations that reflect shelfal depositional environments toward the east and deeper water, slope and submarine-fan depositional environments toward the west (fig. 2; Cole and others, 1994; Trexler and others, 1996). In the Nevada Test Site region, three principal Mississippian depositional environments were present, and each accumulated different assemblages of sediment (Trexler and others, 1996). On the west, the Eleana Formation consists of more than 1,900 m of chert-lithic conglomerate, sand, and silt that were deposited in a submarine fan environment in deep water (Trexler and Cashman, 1997). Farther east, a marginal shelf environment was the site of deposition of more than 1,200 m of uniform clay and silt throughout the Mississippian that are identified as the Chainman Shale (Cashman and Trexler, 1991, 1994; Trexler and others, 1996). On the east in the present-day vicinity of the Spotted Range, the Mississippian is represented by little more than 400 m of section, most of which is limestone deposited in shallow-to-moderate water depths within a carbonate platform and bank setting (Trexler and others, 1996).

PRE-MESOZOIC CONTRACTIONAL ELEMENTS

Contractional deformation, in the form of foreland-vergent folds and thrusts, occurred in this region sometime following the youngest preserved strata (Middle Pennsylvanian) and prior to the oldest intrusions that cut these structures (middle Late Cretaceous; Cole and others, 1993). These structures were previously considered to be middle Mesozoic in age (Barnes , Hinrichs, and others, 1963; Barnes and Poole, 1968), but more recent studies to the west have suggested that the Nevada Test Site structures may correlate with pre-Late Permian folds and thrusts in eastern California (Snow, 1992; Cole and Cashman, 1997). Structures in the Nevada Test Site region related to this convergence have been shown to profoundly influence the distribution of pre-Tertiary sedimentary units, both laterally and with depth (Laczniak and others, 1996; Cole and Cashman, 1997).

The major foreland-vergent structures in this area are the Belted Range thrust, the Spotted Range thrust, and the Specter Range thrust (fig. 1). The Belted Range thrust emplaced Late Proterozoic Wood Canyon Formation on top of Middle Devonian and Mississippian rocks at the north end of Bare Mountain (Carr and Monsen, 1988; Monsen and others, 1992), in the central Eleana Range, and (by inference) in the central Belted Range near latitude 37°-30' N. In the Eleana Range in particular, the Belted Range thrust is characterized by a broad zone of footwall-duplex structures that shuffle pieces of the footwall section, chiefly those of the Middle Devonian through Middle Mississippian strata (Cole and Cashman, 1997). The easternmost of those footwall faults emplaced the Mississippian Eleana Formation on top of the Mississippian Chainman Shale along most of the west side of Yucca Flat and in the Calico Hills (Cole and others, 1994; Trexler and others, 1996; Cole and Cashman, 1997). The Belted Range thrusts, however, do not appear to have tectonically buried the Chainman Shale and its environs because the shale retains low-thermal maturity indicators that would have been obliterated by deep burial (Cole and others, 1994; Grow and others, 1994; Trexler and others, 1996).

The Specter Range thrust (fig. 1) emplaced Cambrian Bonanza King dolomite on top of Ordovician strata in the Specter Range, and is inferred to die out along strike to the east beneath Mercury Valley (Cole and Cashman, 1997). A separate thrust plate carried Bonanza King over Mississippian carbonate-platform strata in the Mercury klippe in the Spotted Range to the east (Barnes and others, 1982). This Spotted Range structure can be traced northeastward and northward through incompletely mapped terrane in the Ranger Mountains as far as the Papoose Lake Valley (Longwell and others, 1965; Tschanz and Pampeyan, 1970; Guth, 1990). The source of the Spotted Range thrust and the Mercury klippe is not known (Cole and Cashman, 1997).

Two irregular zones of hinterland-vergent folds and thrusts are also recognized in the Nevada Test Site area. One persistent zone occupies a position just west (or northwest) of the leading edge of the Spotted Range thrust; its origin remains enigmatic (Barnes and others, 1982; Cole and Cashman, 1997). A second zone of hinterland-vergent structures can be identified along the outer (eastern and southern) margin of the zone of footwall duplex structures of the Belted Range thrust, and is designated the CP thrust system (Caskey, 1991; Caskey and Schweickert, 1992; Cole and others, 1994; Cole and Cashman, 1997).

Structures of the CP thrust system can be identified in discontinuous outcrop areas along a 130 km trace from near Beatty, NV, on the west, through the Calico Hills and CP Hills, and northward into the central Belted Range (fig. 1; pl. 1). At Bare Mountain, large panels of the Belted Range footwall are folded back toward the north by the Panama thrust and related structures of the CP system (Carr and Monsen, 1988; Monsen and others, 1992; Carr and others, 1995; Cole and Cashman, 1997). In the Calico Hills, recent work has defined a complex zone of interfering structures caused by hinterland-vergent overprinting of the older foreland-vergent thrust (Cashman and Cole, 1996; Cole and Cashman, 1997). In the CP Hills and along the western margin of Yucca Flat, local zones of westward (hinterland)-vergent folds can be traced to the northern end of the basin, and similar westward-vergent thrusting is known from the central Belted Range (Ekren and others, 1971). These folds and thrusts appear to have formed in response to local irregularities in the pre-existing structural stack, and may not have involved great lateral transport (Cole and Cashman, 1997). The hinterland-vergent structures also did not result in tectonic burial of the Chainman Shale because the Chainman retains its low thermal-maturity character everywhere between the east- and west-vergent structural zones (Grow and others, 1994; Cole and Cashman, 1997).

STRIKE-SLIP FAULTS

Regional structural relations suggest that two north-trending strike-slip faults are probably present within the pre-Tertiary basement in the area of northern Yucca Flat and the Belted Range (pl. 1; Cole and Cashman, 1997). These faults, designated the Tippinip fault and the Area 13 fault, are largely covered by Miocene volcanic rocks but can be inferred on the basis of structural and stratigraphic discontinuities on either side. These high-angle structures are interpreted to be wrench faults that are younger than thrusting because they cut across thrust-related folds and they place incompatible folds in side-by-side positions (Cole and others, 1994; Cole and Cashman, 1997). Minor structures formed along the Tippinip fault, including deflections in bedding attitudes and the asymmetry of a few small-scale folds, suggest the displacement is sinistral (Cole and others, 1994).

The Area 13 fault is completely buried by Miocene and younger deposits, but is interpreted to have considerable displacement across it because of stratigraphic differences (Cole and Cashman, 1997). Both the Nopah Formation and the Pogonip Group rocks are dissimilar between the Halfpint Range and the Smoky Hills-Carbonate Wash areas. The Nopah west of the Area 13 fault is generally massive, thoroughly dolomitized, and contains few stromatolites, whereas the same formation to the east is thinner bedded, contains substantial limestone, and documents a shallower water depositional environment by the abundance of oolites and algal stromatolites (Cole and Cashman, 1997). The Pogonip is distinctly less dolomitic and thicker west of the Area 13 fault than in the Halfpint Range. The Silurian and Devonian carbonate sections contain more limestone and slope-facies debris-flow deposits in Carbonate Wash than they do to the east in the Groom Range (Tschanz and Pampeyan, 1971) or in the Spotted Range (Barnes and others, 1982).

The Area 13 fault can also be reliably inferred from structural incompatibilities on opposing sides. Southeast-directed, foreland-vergent folding in the footwall of the Belted Range thrust on the west side of the Area 13 fault lies against north-directed folding to the east (Barnes, Houser, and others, 1963; Rogers and Noble, 1969). Beds in the northern Halfpint Range strike nearly east-west, approximately perpendicular to the Area 13 fault, and define the flanks of a broad fold (Halfpint anticline of Barnes, Hinrichs, and others, 1963, and Carr, 1974, 1984). This fold exposes a significantly deeper structural level than the Smoky Hills-Carbonate Wash block to the west, and exposes the oldest sedimentary rocks in the Nevada Test Site region in its core (Late Precambrian Johnnie Formation). That disparity in structural level across the Area 13 fault was even greater prior to middle Miocene time, as the Miocene volcanic rocks show more than 350 m of down-to-the-east displacement (Barnes, Houser, and others, 1963).

The Tippinip fault is interpreted to be a strike-slip fault because of the local-scale structures mentioned above and because of structural mismatches across its trace. At the north end of Yucca Flat, the block west of the Tippinip fault is an anticline in the Mississippian Eleana Formation with an eastward-overturned limb. In contrast, the block to the east is an anticline in the Ordovician units whose beds steepen toward the west (pl. 1). In the Carbonate Wash area to the north, the block west of the Tippinip fault consists of west-dipping Devonian dolomite while the block to the east is an eastward-overturned syncline of rocks as old as Cambrian (Rogers and Noble, 1969). The Devonian rocks are not likely to have been the thrust hangingwall that caused the overturning in the Cambrian rocks because both units belong to the same Belted Range footwall block (in which the Devonian is younger and structurally higher) and because of the lack of thrust-related deformation near the contact between these units (Cole and Cashman, 1997). The Tippinip fault thus appears to be a structural boundary between blocks whose fold sets are incompatible in terms of a singular contractional stress regime.

The strike-slip mechanism appears to be the most straightforward explanation for the side-by-side placement of otherwise incongruous rocks and fold sets. Rocks east and west of the Area 13 fault differ substantially in their depositional facies, structural level, and structural orientation. The location of older rocks in the synclinal block in Carbonate Wash, flanked on both sides by younger strata of the same thrust sheet, is irreconcilable with simple contractional strain, but can be explained by strike-slip offsets of the previously thrusted blocks.

POST-PALEOZOIC EXTENSIONAL ELEMENTS

Contractional deformation in the region surrounding the Nevada Test Site appears to have ceased by the end of the Paleozoic or middle Mesozoic time (Cole and Cashman, 1997). Subsequent deformation has been extensional or transtensional and has formed normal and strike-slip faults (Minor, 1995). Two groups of extensional structures are recognized: those that are contained within the pre-Tertiary rocks, and those that also offset the Cenozoic volcanic and alluvial deposits.

Work by the author, by Hudson (Cole and others, 1989; Hudson and Cole, 1993), and by Guth (1981, 1990) has shown that some low-angle faults within the pre-Tertiary sections are extensional normal faults. Many of these probably formed as thrusts, or they have displaced blocks from different thrust sheets, but the most recent movement has been in extension. Caskey (1991) documented such structures in the CP Hills (see also Cole and others, 1993, 1994), Cole and Cashman (1997) have identified local extensional fault blocks in the Calico Hills, and the author's reconnaissance of the northern Halfpint Range indicates the mapped faults between the Stirling Quartzite and the Johnnie Formation (pl. 1) are also extensional in nature. Ekren and others (1971), working on the Nellis Air Force Base Gunnery Range north of Yucca Flat (fig. 1), were able to show that local parts of the Ordovician section had been displaced about 500 to 700 meters westward by low-angle normal faults. Author's reconnaissance west of Belted Peak in the central Belted Range (pl. 1) indicates the Cambrian Dunderberg Shale (A.R. Palmer, written commun., 1995) is displaced westward by as much as 4.5 km between two extensional fault blocks.

This extensional deformation pre-dates the oldest volcanic rocks wherever it has been studied. Faults in the Mine Mountain area are pre-middle Miocene (Cole and others, 1989; Hudson and Cole, 1993), and the Belted Range faulting predates Oligocene eruption of the Monotony Tuff (Ekren and others, 1971). Jayko (1990) also identified significant low-angle extensional faults over a broad area to the east that are overlapped by middle Oligocene volcanic rocks. Strong circumstantial evidence in northwestern Yucca Flat indicates similar extensional fault complexes penetrated by the ER-12-1 drillhole (pl. 1; table 1) were intruded by dikes dated at 102 Ma (Cole and others, 1993). By implication, many of these low-angle extensional structures in the region may be pre-Late Cretaceous in age, although there is no compelling reason that all low-angle normal faulting should have occurred during a singular event.

Miocene volcanism has also strongly affected the distribution of older strata. The caldera-forming eruptions of the southwest Nevada volcanic field chiefly between 15 Ma and 9 Ma were responsible for displacing tremendous volumes of the pre-existing crust (Sawyer and others, 1994). Regional gravity data (Healey and others, 1987) and other geophysical datasets show that the caldera system has roots that extend deep through the crust (Grauch and others, 1997). For the purposes of this compilation (pl. 1), the caldera zone boundary is identified as the perimeter of thick volcanic rocks, based on interpretation of the gravity data (Healey and others, 1987; Grauch and others, 1997).

Regional extension continued in the Nevada Test Site area during and following the Miocene eruptive cycle of the southwestern Nevada volcanic field (Minor, 1995). Most of this extension resulted in block tilting, alluvial basin subsidence, and relatively minor lateral displacement of Paleozoic rocks (Barnes and others, 1963; Carr, 1974, 1984; Cole and others, 1997). Extension has been modest for most of the area compiled in the accompanying map (pl. 1), including the Belted Range, Yucca Flat, the Halfpint Range, Calico Hills, and the Spotted Range-Specter Range area (Hudson and others, 1994; Grauch and others, 1997). Paleomagnetic data further demonstrate that most of the area has experienced little or no vertical-axis rotation, except within a northwest-trending zone through the Crater Flat area (Hudson and others, 1994). The north end of Bare Mountain and lands to the north and west are the only areas that show evidence of significant extension and westward translation resulting from the Bullfrog detachment and related structures (Carr and Monsen, 1988; Hamilton, 1988; Grauch and others, 1997).

The present-day alluvial basins between the mountain ranges of the area largely formed following the main stage of volcanic activity from the southwest Nevada volcanic field (Barnes, Hinrichs, and others, 1963; Carr, 1974). Drillhole information (for example, table 1) and calculations based on gravity (Healey and others, 1987; Grauch and others, 1997) show that the top of pre-Tertiary rocks in these basins is locally more than 1,000 m below the surface. Map and subsurface data show that the amount of structural relief on the pre-Tertiary surface or on some of the Miocene volcanic horizons locally exceeds 1,700 m (Cole and others, 1997). The deepest parts of the alluvial basins are indicated on the map (pl. 1) by patterns interpreted from gravity data (Healey and others, 1987; Grauch and others, 1997), and by lines inferred to be principal basin-controlling faults.

CONCLUSIONS

The area of southern Nevada surrounding the Nevada Test Site contains a thick pre-Tertiary section that has been greatly altered and reorganized as a result of tectonic deformations. The Late Paleozoic(?) Belted Range thrust was rooted deep in that section and cut up to the highest preserved levels by placing Late Proterozoic rocks on top of Mississippian strata, and folding the Pennsylvanian system in the process. The Devonian and Mississippian footwall rocks of the Belted Range thrust were not passive during this deformation, but rather responded by folding and slicing into numerous local horse blocks that cut upward toward the foreland. The most easterly of these duplex thrusts placed the Mississippian Eleana Formation (submarine-fan facies) eastward and southward on top of the contemporaneously deposited Chainman Shale (marginal shelf facies). None of the Belted Range thrusts is believed to have overridden the principal outcrop area of the Chainman Shale and the overlying Pennsylvanian Tippipah Limestone in western Yucca Flat because of the low-thermal-history record of the Chainman and Tippipah (Trexler and others, 1996; Cole and Cashman, 1997).

Continued contraction led to the formation of various hinterland-vergent folds and thrust faults, collectively designated the CP thrust system. This younger deformation is more irregular than the Belted Range structure, in part because it was superimposed on the foreland-vergent elements, and is characterized by significant local complexity. The overall trace of the CP thrust system is grossly parallel to the Belted Range thrust and appears to be most intensely developed along the leading edge of the foreland-vergent footwall duplex blocks of the Belted Range system.

The CP thrust system is interpreted to be confined to the footwall block (autochthon) of the Belted Range thrust (Cole and Cashman, 1997). This conclusion is based on the stratigraphic similarity between the rocks in the CP allochthonous blocks and the CP footwall, and their dissimilarity to the sections transported in the Belted Range thrust allochthon (Trexler and others, 1996; Cole and Cashman, 1997). The large stratigraphic separations noted across the CP thrust structures (for example, Lower Cambrian hangingwall against overturned Pennsylvanian footwall in the CP Hills) suggest that the faults of the CP system were steep overall and that they cut sharply up through the overlying section. The extreme degree of overturning noted in the Calico Hills, the CP Hills, and the north end of Syncline Ridge suggest that the CP faults flattened as they propagated upward (Cole and Cashman, 1997).

A separate pair of foreland- and hinterland-vergent folds and faults is recognized in the Spotted Range west of Mercury, Nevada. The foreland-vergent Spotted Range thrust carries the Mercury klippe southeastward over an overturned footwall syncline of Mississippian carbonate-shelf-facies strata (Barnes and others, 1982; Trexler and others, 1996). This structure can be traced discontinuously to the northeast and north around the arc of the Ranger Mountains (pl. 1) with the same hangingwall and footwall strata. Immediately north of the Mercury klippe, the Cambrian rocks of the hangingwall are faulted against the same Mississippian carbonate-shelf-facies strata that are folded into a hinterland-vergent, overturned syncline, and this structure can also be traced around the arc of the Ranger Mountains (Cole and Cashman, 1997). The relationships described for the Spotted Range suggest that the Spotted Range thrust plate cannot be tied to the rocks immediately beneath it to the northwest or to the southeast, and its source remains unknown (Cole and Cashman, 1997).

The Specter Range thrust verges southward toward the foreland. It carries Middle Cambrian Bonanza King Formation over a steep to overturned section of Ordovician strata where it is exposed in the Specter Range. Stratigraphic separations across the Specter Range thrust to the west and east (where the trace is not exposed) indicate the throw decreases toward the east, and the structure is interpreted to die out beneath Mercury Valley (Cole and Cashman, 1997). The hangingwall of the Specter Range thrust can be traced through reasonably continuous outcrop across the north side of the Mercury Valley to the footwall of the Spotted Range thrust.

Structural and stratigraphic relationships exposed at the north end of Yucca Flat and northward into the Belted Range suggest significant strike-slip faulting that is younger than the Belted Range and CP thrusts. The Tippinip fault (exposed) and the Area 13 fault (buried) juxtapose rocks that differ markedly in terms of their structural attitudes, structural levels, and stratigraphic facies associations. The mismatches in structural attitudes, in particular, preclude one-directional contractional mechanisms that could account for the observed relationships, and strongly suggest wrench faulting was responsible for bringing the incompatible structures together. Small scale folds and deflections of bedding near the Tippinip fault suggest the sense of motion was sinistral, and a similar sense of dislocation is inferred for the Area 13 fault.

Structures that offset the pre-Tertiary rocks, but post-date the contractional and transpressional deformation, include low-angle normal fault complexes and high-angle block faults. The low-angle normal faults record several kilometers of displacement in some places, but all appear to be essentially local in origin and are not interpreted to affect large-scale lateral displacements within the pre-Tertiary terranes. The high-angle faults formed during and following the voluminous middle Miocene eruptions of the southwest Nevada volcanic field and are responsible for block tilting and subsidence around the present alluvial basins. Structural relief across these young faults is locally greater than 1,700 m.

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Table 1. Data for selected drillholes that penetrate pre-Tertiary rock in the Nevada Test Site vicinity

Hole Name[1]	NORTH	EAST	Probable Unit[2]	Elevation @ top of pre-Tertiary	Interval Drilled	Lithology, Biostratigraphy, Structural features	REFERENCE[3]
UE-12p-4	904,748	646,551	DSw	4646 ft	32 ft	Dolomite	This report
UE-12t-8	904,028	642,809	Zws	5351 ft	5 ft	Micaceous shale	This report
UE-12t-3	899,833	641,874	Zws	~ 4600 ft	93 ft	Quartzitic colluvium	Maldonado, Steele, and others, 1979; this report
UE-12t-1	898,949	642,521	DSw	4567 ft	67 ft	Dolomite breccia	Miller, 1970; this report
UE-15d	895,709	682,085	Zws	2815 ft	4225 ft	Stirling Quartzite and Johnnie Fm.	J. Stewart, written commun., 1984; Barnes, 1962; this report
UE-12n-9	895,600	632,309	Zws	5928 ft	95 ft	Mica schist and quartzite	Maldonado, Steele, and others, 1979; this report
UE-12b.07-2	892,715	634,195	DSw	4952 ft	294 ft	Dolomite	Miller, 1970; this report
RMX-1	892,097	629,404	Zws	3731 ft	197 ft	Micaceous phyllite and granite	This report
Hagestad	889,190	631,132	Zws	5589 ft	67 ft	Micaceous quartzite	This report
U12e.03-1	888,264	634,169	DSw	5435 ft	135 ft	Dolomite	This report
UE-10j	887,033	670,453	Cnb	3550 ft	1343 ft	Nopah Fm., Dunderberg Shale, and upper Bonanza King Fm.	McKague, 1980; this report
ER-12-1	886,639	640,540	DSw/ Me/ DSw	5810 ft	3588 ft	Complex structural slices of Devonian, Mississippian, and Ordovician rocks, based on conodonts and lithology	Harris report CRG-92-2; Cole and others, 1993; Russell and others, 1996; this report
U8a-4	884,358	665,735	Mc/ ?dol	3400 ft	710 ft	Chainman Shale over shattered dolomite over more shale; no conodonts recovered	Harris report CRG-92-3; USGS, 1974; this report
ER-19-1	884,237	624,549	Zws	3278 ft	733 ft	Wood Canyon Fm. micaceous quartzite and phyllite	I.T. Corp., 1995b; this report
Test Well 1	876,855	629,310	DSw	2491 ft	531 ft	Dolomite	This report
U2cr	871,800	657,800	Mc	3292 ft	55 ft	Chainman Shale with crinoids and molds of woody plant debris	This report
UE-2ce	871,700	654,900	Cnb-Or	3658 ft	543 ft	Dolomite; phosphatic brachiopods; no younger than Pogonip Group	Harris report CRG-91-1; this report
UE9-U29-1	871,600	683,601	Or	3110 ft	110 ft	Limestone; Early Ordovician conodonts	Harris report CRG-91-1

Table 1. Data for selected drillholes that penetrate pre-Tertiary rock in the Nevada Test Site vicinity (continued)

Hole Name[1]	NORTH	EAST	Probable Unit[2]	Elevation @ top of pre-Tertiary	Interval Drilled	Lithology, Biostratigraphy, Structural features	REFERENCE [3]
UE-2fb	865,600	669,850	Or	1675 ft	191 ft	Flaggy limestone and dolomite; Early to middle Middle Ordovician conodonts	Harris report CRG-91-1; this report
UE-4ac	855,950	659,250	Cnb-Or	2905 ft	112 ft	Dolomite and platy limestone; phosphatic brachiopods; no conodonts recovered	Dixon and others, 1975; Harris report CRG-91-1; this report
U7ae	851,150	692,450	Or	1576 ft	163 ft	Ely Springs Dolomite	Harris report SP-77-1D
UE-4aL	848,700	672,570	Cnb	2485 ft	517 ft	Dunderberg Shale and sheets of shattered dolomite	This report
UE-4ae	847,200	674,500	Or	1775 ft	95 ft	Tan limestone; sparse conodonts, common phosphatic brachiopods	Harris report CRG-91-1
UE-4af	846,300	662,900	Mc	2895 ft	70 ft	Calcareous mudstone with chert sand and siltstone; most likely Chainman Shale	Dixon and others, 1975; this report
UE-3Lj	841,848	680,141	Or	1110 ft	122 ft	Late Early to very earliest Middle Ordovician conodonts; Ninemile Fm equivalent	Harris report CRG-91-1; this report
UE-1L	837,000	654,001	Mc	4260 ft	5139 ft	Chainman Shale; high organic carbon content in shale	McKague, 1980; Barker, 1994; this report
UE-1b	837,000	662,000	Mc	3520 ft	535 ft	Chainman Shale	Emerick, 1983; this report
UE-1e	836,500	663,600	Or	2700 ft	160 ft	Late Early to earliest Middle Ordovician conodonts; Ninemile Fm equivalent	Ross report SP-72-3D; Harris report CRG-91-1; this report
GH-2	834,800	671,650	Or	4048 ft	20 ft	Silty limestone and siltstone; beds dip 15-20 in core; Pogonip Gp. from trilobite fragments	Fernald and others, 1975
ER-3-1	826,811	713,336	Cnb	3558 ft	1654 ft	Lower Nopah Fm., Dunderberg Shale, and upper Bonanza King Fm.	I.T. Corp., 1995a; this report
UE-1p	826,269	662,299	Or	3459 ft	9 ft	Eureka Quartzite	This report
UE-1m	825,408	657,842	Me/Mc	4478 ft	514 ft	Eleana Fm. thrust over Chainman Shale; core shows conspicuous fault near 175 foot depth	This report; D. Herring, written commun., 1994
UE-1h	820,000	675,000	Cnb?	2295 ft	1658 ft	Variable gray dolomite; lower part resembles Banded Mountain Mbr of Bonanza King	This report