THE TITUS CANYON FORMATION: EVIDENCE FOR EARLY OLIGOCENE EXTENSION IN THE DEATH VALLEY AREA, CA

by

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ABSTRACT

The Oligocene Titus Canyon Formation, on the east side of the Grapevine Mountains, Death Valley, CA contains laterally sourced alluvial fan and monolithologic megabreccia deposits which interfinger with longitudinally transported fluvial cobble conglomerates, and lacustrine limestones and mudstones. These relations are evidence that the Titus Canyon Formation was deposited in a restricted, fault controlled basin, and that the alluvial fan deposits mark the scarp of the growth fault.

Previously identified Cenozoic faults in the vicinity of the Titus Canyon Formation include the Boundary Canyon detachment (BCD) and a concealed dextral fault zone in Crater Flat (CFFZ). Field relations constrain the BCD to be younger than the Titus Canyon Formation. However, the creation of the Titus Canyon basin by local normal displacement along the CFFZ is consistent with the ages and pre-Boundary Canyon detachment geometries and orientations of the Titus Canyon Formation and the CFFZ. The steep longitudinal gradient required to transport the fluvial cobble conglomerates is consistent with a transtensional origin for the Titus Canyon basin. A mismatch between the clast composition of the fanglomerates and exposures of source rocks can be reconciled by right-lateral oblique-slip displacement along the basin bounding fault.

The Titus Canyon Formation is interpreted as recording Early Oligocene, oblique-slip displacement along the CFFZ. This displacement is older than all previously identified normal faults in the Death Valley area. A 5600 m thick volcanic sequence overlying the Titus Canyon Formation and containing megabreccia deposits like those in the Titus Canyon Formation records activity on the CFFZ that extends well into the Miocene. Displacement along the CFFZ was sub-parallel to and in part coeval with displacement along the Northern Death Valley-Furnace Creek Fault Zone (NFZ). The CFFZ is kinematically similar to and genetically linked with the NFZ, which was instrumental in much of the mid-Miocene extension in the Death Valley area. The deformation along the CFFZ recorded by the Titus Canyon Formation is part of a previously unrecognized, laterally and temporally extensive, early phase of extension in the Death Valley area.

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INTRODUCTION

The Basin and Range Province of western United States (Figure 1) is the best exposed and most extensively studied rift region in the world. Normal faults have been recognized in the region since the earliest investigations (e.g. Ball, 1907; Longwell, 1945), but it was not until the 1970's that geologists began to realize the magnitude of extension (e.g. Anderson, 1971; Proffet, 1977). Now it is generally agreed upon that kinematically linked detachment fault systems and strike-slip fault zones are responsible for large scale extension that began in the latest Eocene or Early Oligocene, was most active during the mid-Miocene, and continues locally today (e.g. Hamilton, 1987; Wernicke et al., 1987).

The interplay of normal and strike-slip fault systems has led to the development of north-trending mountain ranges and intervening sedimentary basins that are characteristic of the Basin and Range Province (e.g. Burchfiel and Stewart, 1966; Wernicke, 1982). Until recently, there have been few combined tectonic and stratigraphic studies of these sedimentary basins (e.g. Alexander and Leeder, 1987; Cemen et al., 1985; Crowell, 1974; Taylor, 1989). Such studies are essential for determining the onset, duration and style of extensional faulting in the Basin and Range Province. Because basin sediments are preferentially preserved while the controlling structures are not, stratigraphic and structural studies of relict sedimentary basins are particularly important for investigating the earliest phases of extension.

In the Death Valley area (Figure 2), the oldest identified normal faults are Early Miocene in age (Cemen et al., 1985). However, Lower Oligocene through Miocene, non-marine sedimentary and volcanic rocks, composing the Titus Canyon Formation and the Timber Mountain volcanic sequence, are exposed along the northeast side of the Grapevine and northern Funeral Mountains (Stock and Bode, 1935). The fanglomerates and megabreccia deposits of the Oligocene - Miocene(?) Titus Canyon Formation are evidence that the Titus Canyon Formation was deposited in a fault-controlled basin. Sediments of the Titus Canyon Formation might record an early, previously unrecognized phase of extension in the Death Valley area and continued deformation is recorded by the overlying Timber Mountain volcanic sequence.

lthough Stock and Bode (1935) called attention to the Titus Canyon Formation as the oldest dated Tertiary formation in the Death Valley area, and Reynolds (1969) suggested that faults bordering the formation might have been active during the Early Oligocene, no previous investigation has addressed the relation between the Titus Canyon Formation and extensional structures in the Death Valley area. A detailed field investigation of the area between upper Monarch Canyon and Daylight Pass, in the northern Funeral Mountains (Figure 2), was carried out in order to determine the temporal and geometrical relation between the Titus Canyon Formation and the Boundary Canyon detachment, the oldest known major detachment in the vicinity (Troxel, 1988). In light of timing and sedimentalogical constraints obtained through that investigation, the tectonic setting of the Titus Canyon basin and its place in the Early Oligocene tectonic development of the Death Valley area can now be assessed.

REGIONAL GEOLOGIC SETTING

The Grapevine and Funeral Mountains, along the east side of Death Valley, are in the center of a highly extended region (Figure 2) which reaches from the Sierra Nevada batholith on the west to the relatively intact Spring Mountains on the east. Low angle detachments, along with high angle and listric normal faults that root into them, have accommodated extension in this region since at least Miocene time (Anderson, 1971; Wernicke, 1982). Northwest-striking dextral and east-northeast-striking sinistral strike-slip fault zones act as intracontinental transforms connecting detachment fault systems.

Block rotation on normal fault systems has lead to the development of tilt-block basins, and divergence along strike-slip fault zones has created deep, transtensional or "pull-apart" basins such as Death Valley itself (Burchfiel and Stewart, 1966).

The Death Valley extended area lies within the bounds of the Upper Proterozoic and Paleozoic miogeoclinal wedge (Stewart, 1970; Wright, 1974), a sequence of westward thickening passive margin strata consisting of a lower clastic part and an upper carbonate part. Dominantly shallow marine strata of the miogeoclinal wedge and the underlying Proterozoic Pahrump Group form the mountain ranges in the Death Valley area. Cenozoic, non-marine sedimentary and volcanic rocks fill the intervening basins.

Although intermittent periods of terrain accretion and crustal shortening dominated the tectonic setting of the western margin of North America from the late Paleozoic to the early Cenozoic (e. g. (Burchfiel and Davis, 1975), the Death Valley area experienced significant thrust faulting and folding only during the Cretaceous Sevier orogeny (Figure 1). Thus, the geometries of the miogeoclinal strata and the Cretaceous age, east vergent thrusts and folds that deform them are simple and distinctive. They provide essential piercing points for piecing together the pre-extensional Death Valley area (e. g. (Wernicke et al., 1988).

Estimates of the amount of Cenozoic extension in the Death Valley area vary from less than 40 percent (Wright, 1983) to greater than 200 percent (Wernicke et al., 1988). Wernicke (1988) estimated that the Death Valley area has been extended by 150 kilometers in the direction N60W. He based his calculations on correlations and reconstructions of a unique Mesozoic fold-thrust system that is exposed through much of the central Death Valley area.

The oldest documented normal faults in the Death Valley area are Early Miocene in age (Cemen et al., 1985), but most of the extension occurred during the mid-Miocene. Generally, extension seems to have progressed from east to west, such that east of the Grapevine and Funeral Mountains most extension had ceased by 11 Ma, but in the central

Death Valley area extension probably continued into the Pliocene, and to the west of Death Valley there has been significant Quaternary extension (Hamilton, 1987).

GEOLOGY OF THE GRAPEVINE AND FUNERAL MOUNTAINS

The geology of the Grapevine and Funeral Mountains is the result of a complex history of Cenozoic extension and volcanism overprinting Mesozoic compression and metamorphism (Figure 3). The mountains are composed predominantly of miogeoclinal rocks. A thick succession of Cenozoic non-marine sedimentary rocks, composed of the Titus Canyon Formation and the Timber Mountain volcanic sequence, flanks their northeast side. Structures present include thrust faults, Mesozoic and Cenozoic folds, and Cenozoic normal and oblique-slip faults. A major Cenozoic extensional structure, the Boundary Canyon detachment, separates the allocthonous northern Funeral and Grapevine Mountains from the metamorphic core of the Funeral Mountain autochthon (Reynolds et al., 1986; Troxel, 1988).

ROCK UNITS

Precambrian and Paleozoic sedimentary and metasedimentary rocks are abundant in the Grapevine and Funeral Mountains (Figure 4). Metamorphosed strata of the Proterozoic Pahrump Group and Johnnie Formation form the core of the Funeral Mountains, while unmetamorphosed miogeoclinal strata from the late Proterozoic Stirling Quartzite, exposed in the south, to the Paleozoic Nopah and Bonanza King Formations exposed in the north, compose the bulk of the Grapevine Mountain allocthon. Late Paleozoic carbonate strata occur in the southern part of the Funeral Mountains. In the Grapevine Mountains, the late Paleozoic rocks are found only at the northern end, in the footwall of the Grapevine thrust (Figure 5).

There is an angular unconformity between the Proterozoic and Paleozoic rocks and the Cenozoic non-marine deposits exposed in the Grapevine and northern Funeral Mountains. The Oligocene - Miocene(?) Titus Canyon Formation lies above progressively younger strata from upper Proterozoic Stirling Quartzite in its southernmost exposures, near the Boundary Canyon detachment, to Ordovician strata in the northern Grapevine Mountains (Figure 5). The Titus Canyon Formation is up to 1000 meters thick. It consists of megabreccia deposits and fanglomerates that interfinger with fluvial, polished cobble conglomerates, and lacustrine mudstones and limestones (Reynolds, 1969).

Unconformably above the Titus Canyon Formation, lie ash-fall tuff, tuffaceous sedimentary rocks and lacustrine mudstones. These volcanic and sedimentary rocks are the base of a thick volcanic sequence that is widely exposed east of the Grapevine Mountains and is here referred to as the Timber Mountain volcanic sequence. A tuff near the base of the sequence has a 22 Ma K/Ar age (Reynolds et al., 1986). The upper part of the volcanic sequence exposed in the Bullfrog Hills includes the 13.9 Ma Crater Flat tuff, the 12.9 Ma Paintbrush Tuff and the 11 Ma Timber Mountain Tuff. These are also exposed at the Bullfrog Hills, Bare Mountain, and have been logged in core samples from Crater Flat and Yucca Mountain (Carr, 1991). The youngest volcanic unit found in the Bullfrog Hills is a 7.6 Ma tuff and basalt flow (Maldonado, 1990). It unconformably overlies the older, deformed Miocene volcanic and sedimentary rocks and is itself undeformed.

STRUCTURE

BOUNDARY CANYON DETACHMENT

The trace of the Boundary Canyon detachment in the northern Funeral Mountains is well exposed. On the western side of the Funeral Mountains it is cut by the diachronous Keene Wonder fault (Troxel, 1988). From there, the trace of the Boundary Canyon detachment runs eastward along the Boundary Canyon road, curves to the south through upper Monarch Canyon, and continues southeastward past Chloride Cliff, until it reaches the alluvium on the eastern side of the Funeral Mountains (Figure 3). The detachment dips to the north under the Grapevine Mountains at a very low angle and forms a gentle anticline with an axis trending approximately N60W (Troxel, 1988; Troxel and Wright, 1989). This trend is similar to the inferred extension direction of the Death Valley area, and probably approximates the tectonic transport direction along the Boundary Canyon detachment (Wernicke et al., 1988).

The Boundary Canyon detachment might extend beneath the alluvium in the Amargosa valley to join with the "Original" Bullfrog fault on the south side of the Bullfrog Hills and the Flourspar Canyon fault on the north side of Bare Mountain (Carr and Monsen, 1988) (Figure 3). Such a geometry would require additional folds of the fault plane along northwest trending axes (Carr, 1991). Carr (1988) suggested that the Grapevine Mountains, Bullfrog Hills and northern Bare Mountain are all part of a single extensional allocthon that moved west-northwestard along an undulating Boundary Canyon- "Original" Bullfrog-Flourspar Canyon low angle detachment system.

Evidence from Bare Mountain and the Grapevine Mountains consistently indicates a mid-Miocene age for extension along the Boundary Canyon detachment. Reynolds (1986) suggested that extensional faulting in the upper plate of the Boundary Canyon detachment occurred between 9 and 5 Ma. Rocks cut by the Flourspar Canyon fault are as young as 10.5 Ma and are overlain by undeformed 7 Ma rocks (Carr and Monsen, 1988). Fission track work on samples collected from the footwall of the Boundary Canyon detachment indicates rapid cooling of the footwall rocks between 10 and 9 Ma which has been attributed to structural unroofing along the Boundary Canyon detachment during that time (Holm and Dokka, 1991).

THE FUNERAL MOUNTAIN AUTOCHTHON

^{40}Ar-^{39}Ar ages of metamorphic minerals from core rocks of the Funeral Mountains indicate an early Cretaceous age for regional metamorphism (DeWitt et al., 1988). A Late Cretaceous age, ductile extensional event brought high pressure, deep crustal rocks to shallower depths (Applegate, 1991). Attenuation of the hanging wall of the Boundary Canyon detachment unroofed the high grade metamorphic rocks in the footwall.

The metamorphic grade in the Funeral Mountain autochthon is highest in the lower part of Monarch Canyon where basement rocks are exposed. Mineral assemblages are of upper greenschist to amphibolite facies (Labotka, 1980). The metamorphic grade decreases toward the southeast. Unmetamorphosed Paleozoic strata compose the southern Funeral Mountains and remnants of Early Miocene alluvial fans are exposed at Bat Mountain, the southern tip of the mountains (Cemen et al., 1985).

Ductile and brittle normal faults, as well as thrusts and folds are present in the Funeral Mountain autochthon. Major structures include the Mesozoic age, east-vergent Clery and Schwaub Peak thrusts and the west-vergent Winters Peak anticline (Figure 3). The west-vergent anticline is unique among the dominantly east-vergent Mesozoic structures in the Death Valley area and plays a key role in the reconstructions by Wernicke (1988, 1989) and Snow et al. (1989) of the pre-extensional Death Valley area.

THE GRAPEVINE MOUNTAIN ALLOCTHON

The structure of the Grapevine Mountain allocthon is dominated by an approximately north-south trending syncline-anticline pair which includes the Corkscrew syncline and the Titus Canyon anticline (Reynolds, 1969) (Figure 3). In the northern Grapevine Mountains, the fold pair deforms the Mesozoic Grapevine thrust (Wernicke et al., 1989). In the southern part of the allocthonous block, the Corkscrew syncline is truncated by the Boundary Canyon detachment.

A dominantly Mesozoic age is attributed to the fold pair (Reynolds, 1969). Snow et al. (1989) suggested that the Titus Canyon anticline is correlative with the Mesozoic Winter's Peak anticline in the Funeral Mountain autochthon. However, the folds in the Grapevine Mountains are closely associated with a Cenozoic age normal fault system.

Cenozoic age extensional structures in the Grapevine Mountains include (Figure 5): 1) a normal fault system that cuts across, and is associated with the fold pair and consists of the low angle Titus Canyon fault and the oblique-slip Thimble fault; 2) a generation of north-south-striking, east-dipping, dextral oblique-slip faults, similar in geometry and orientation to the Thimble fault; and 3) a younger generation of northwest-southeast-striking, west-dipping listric normal faults; and 4) a generation of low angle normal faults that root into the Boundary Canyon detachment (Reynolds, 1969). These structures cut Proterozoic, Paleozoic and Cenozoic strata exposed in the Grapevine Mountains (Reynolds, 1989). None of the structures cut the Boundary Canyon detachment (Troxel, 1988).

TECTONIC IMPLICATIONS

During the Cretaceous Sevier orogeny, the Grapevine and Funeral Mountains area, like the rest of the Death Valley area, was subject to compressional stresses. The numerous thrusts and folds and the regional metamorphism developed during this time. The large scale extension that dominated the Cenozoic tectonic history of the Death Valley area is recorded in the Grapevine and Funeral Mountains by the numerous low angle, listric, high angle and oblique-slip normal faults, the largest and most prominent of which is Boundary Canyon detachment.

Most extension in the Death Valley area is mid-Miocene in age. The Grapevine and Funeral Mountains area seems to have followed a similar pattern; most of the normal faults cut the Oligocene - Miocene(?) Titus Canyon Formation, while strata younger than 7 Ma are little deformed. However, coarse, angular conglomerates and megabreccia deposits of the Titus Canyon Formation, interpreted by Reynolds (1969) as alluvial fan and gravity slide deposits, are inferred to record active, Early Oligocene faulting. The thick sequence of coarse sand and conglomerate that makes up the Titus Canyon Formation is typical of sediments in fault - controlled, extensional basins. In order to understand the place of the Titus Canyon basin within the framework of the Cenozoic tectonic history of the Death Valley area, the nature of the Titus Canyon basin must be determined and, if possible, the controlling fault or faults must be identified.

Exposures of the Titus Canyon Formation are confined, almost exclusively, to a narrow band along the east side of the Grapevine and northern Funeral Mountains, essentially to the hanging wall of the Boundary Canyon detachment (Figure 3). Because the Boundary Canyon detachment is spatially associated with the Titus Canyon Formation, it is the most obvious of possible controlling faults for the Titus Canyon basin. To test this possibility, the relative ages of the Titus Canyon Formation and extension along the Boundary Canyon detachment must be constrained.

GEOLOGY OF THE UPPER MONARCH CANYON - DAYLIGHT PASS AREA

Although there is indirect evidence that the Boundary Canyon detachment was active during the mid-Miocene, probably sometime between 11 and 5 Ma (Holm and Dokka, 1991; Reynolds et al., 1986), constraints on the relative ages of the Oligocene Titus Canyon Formation and all extension along the Boundary Canyon detachment have been ambiguous. The area between upper Monarch Canyon and Daylight Pass, in the northern Funeral Mountains, provides the best exposures of the Boundary Canyon detachment, the late Proterozoic and early Paleozoic strata in the hanging wall, the Titus Canyon Formation, and the lower part of the Timber Mountain volcanic sequence (Figure

5, 6). It is in this area that the closest exposures of the Titus Canyon Formation to the Boundary Canyon detachment are located.

The upper Monarch Canyon - Daylight Pass area was mapped in detail over a period of six weeks during the summer of 1990. The mapping was done at a scale of 1:20,000 using enlarged United States Geological Survey 15' topographic base maps. In order to determine the relative ages of the Cenozoic sediments and the Boundary Canyon detachment as definitively as possible, close attention was paid to areas on geologic maps of the Funeral Mountains by Troxel and Wright (1989), and of the Bullfrog Hills Quadrangle by Cornwall and Kleinhampl (1964), that showed cross-cutting relations between normal faults and the Titus Canyon Formation.

ROCK UNITS

Over 5000 meters of sediments are exposed in the upper Monarch Canyon - Daylight Pass area. Proterozoic Johnnie Formation lies in the footwall of the Boundary Canyon detachment. Miogeoclinal rock units in the hanging wall include the Proterozoic Stirling Quartzite, the late Proterozoic - Early Cambrian Wood Canyon Formation, and the Cambrian Zabriskie Quartzite. Exposures of the Titus Canyon Formation are extensive and form low slopes between hills of miogeoclinal strata. The base of the Timber Mountain volcanic sequence is resistant and forms cliffs above the Titus Canyon Formation.

JOHNNIE FORMATION

The Proterozoic Johnnie Formation was named for exposures near Johnnie, Nevada (Nolan, 1929). It is laterally extensive and widely exposed. Along the eastern side of Death Valley, it occurs only in the metamorphic core of the northern Funeral Mountains where it has been unroofed by extension along the Boundary Canyon detachment.

In the northern Funeral Mountains, the Johnnie Formation is no more than 200 meters thick and is bounded on top and bottom by low angle normal faults (Applegate, 1991). There the Johnnie Formation consists of interbedded gray and tan carbonate and schist that has a shale protolith. There is a distinctive 30 centimeter thick bed of slate-blue colored marble that is distinctive in exposures of the Johnnie Formation near the Boundary Canyon detachment.

The Johnnie Formation is the youngest and lowest grade rock unit in the metamorphic core of the northern Funeral Mountains. In the upper Monarch Canyon - Daylight Pass area, it occurs in the footwall, all along the trace of the Boundary Canyon detachment (Figure 6).

STIRLING QUARTZITE

The Precambrian Stirling Quartzite was named for quartzites exposed on Mount Stirling in southwestern Nevada (Nolan, 1929). In the central Death Valley area, the Stirling Quartzite crops out in the Grapevine Mountains, the northern and southern Funeral Mountains and Bare Mountain. The Stirling Quartzite forms the lowest unit in the hanging wall of the Boundary Canyon detachment. It crops out all along the trace of the detachment in the northern Funeral Mountains (Figure 5, 6).

Stewart (1970) subdivided the Stirling Quartzite into five members. Only the upper three members (C, D and E) occur in the hanging wall of the Boundary Canyon detachment. There they have a combined thickness of approximately 400 meters. Member C is composed of predominantly greenish gray and grayish red siltstone in the lower part and predominantly pale red, cross-stratified quartzite in the upper part. Member D is very conspicuous. It consists of light-gray to pale orange, laminated dolomite that grades upward into interbedded greenish gray siltstone, pale red quartzite and pale orange dolomite. Member E is composed of pinkish gray, medium- to coarse-grained quartzite. Conglomeratic layers consisting of pebbles of quartz and jasper are fairly common. The

Stirling Quartzite is conformably overlain by, and grades upward into the Precambrian to Cambrian Wood Canyon Formation. Locally, in the Monarch Canyon-Daylight Pass area (Figure 6) and in exposures near Chloride Cliff, the Stirling Quartzite is overlain unconformably by the Oligocene Titus Canyon Formation.

WOOD CANYON FORMATION

The Precambrian to lower Cambrian Wood Canyon Formation is named for exposures in Wood Canyon on the west side of the Spring Mountains in southwestern Nevada (Nolan, 1929). The Wood Canyon Formation forms a westward thickening wedge that is approximately 1000 meters thick at the Grapevine Mountains (Reynolds, 1969). Cornwall and Kleinhampl (1964) proposed the name Daylight Formation and Corkscrew Quartzite for strata near Daylight Pass and at Bare Mountain that are now considered part of the Wood Canyon Formation and Zabriskie Quartzite. The Wood Canyon Formation crops out in the northern Funeral Mountains and the southern to central Grapevine Mountains (Figure 5). It forms prominent hills in the Monarch Canyon-Daylight Pass area (Figure 6).

The Wood Canyon Formation consists of lower and upper carbonate members of pale orange- to brown-dolomite and slope forming siltstone, which surround a middle section of siltstone, fine- to medium-grained quartzite and pebbly quartzite. Because the first occurrence of Cambrian fossils is found in the upper carbonate member, the Wood Canyon Formation is considered to be at least in part Cambrian in age (Stewart, 1970). The Wood Canyon Formation is overlain conformably by, and grades into, the Cambrian Zabriskie Quartzite. In the northern Grapevine Mountains, it is unconformably overlain by the Oligocene Titus Canyon Formation (Figure 6).

Zabriskie Quartzite

Hazzard (1937) named the Zabriskie Quartzite for outcrops of quartz arenite interbedded with shale exposed near Zabriskie Point in the Resting Spring Range of southeastern Death Valley. He described it as an upper member of the Wood Canyon Formation. Later, Wheeler (1948) described outcrops of the Zabriskie Quartzite in the Panamint Range and in the Spring Mountains and designated them as a separate formation. The Cambrian Zabriskie Quartzite thickens from 300 meters in its easternmost exposures to 600 meters in its westernmost exposures (Stewart, 1970). The Zabriskie Quartzite is approximately 300 meters thick in the Grapevine Mountains (Reynolds, 1969).

The Zabriskie Quartzite forms a thin brecciated veneer over the southeastern Grapevine Mountains and crops out in a horseshoe-shaped band in the hanging wall of the Titus Canyon fault in the southern and central Grapevine Mountains (Figure 5). In the northern Grapevine Mountains, it lies in the hanging wall of the Grapevine thrust. The Zabriskie Quartzite is the youngest Paleozoic formation exposed in the Monarch Canyon-Daylight Pass area, where it crops out in a narrow brecciated band near Daylight Pass (Figure 6).

The Zabriskie Quartzite consists of light-colored cliff forming quartzite that contrasts sharply with the shales of the underlying Wood Canyon Formation and the overlying Carrara Formation. It is unconformably overlain by the Titus Canyon Formation in the southeastern Grapevine Mountains. In the upper Monarch Canyon-Daylight Pass area, it is separated from the Titus Canyon Formation by a fault (Figure 6).

Titus Canyon Formation

The Titus Canyon Formation comprises brightly colored, interbedded conglomerate, limestone, sandstone and tuff that crops out predominantly in a narrow band on the eastern side of the Grapevine and northern Funeral Mountains (Figure 5). It was first described by Stock and Bode (1935) and was named by them for its typical occurrence near Titus Canyon. Stock and Bode (1935) described the distribution and lithology of the Titus Canyon Formation in their catalogue of mammalian fossils discovered within its the lower part. Aspects of the Titus Canyon Formation were later described by Cornwall and Kleinhampl (1964) in their report on the geology of Bullfrog Hills Quadrangle, by Hunt and Mabey (1966) in their overview of the stratigraphy and structure of Death Valley, and by Reynolds (1969) as part of his doctoral research on the Titus and Titanothere Canyons area of the Grapevine Mountains. Reynolds (1969) designated a reference section for the Titus Canyon Formation in the narrows of Titus Canyon.

As defined by Reynolds (1969), the Titus Canyon Formation lies unconformably above Proterozoic and Paleozoic strata, and unconformably and conformably(?) below an unnamed sequence of volcaniclastic and sedimentary rocks. Stock and Bode (1935) and Reynolds (1969) describe an angular unconformity between exposures of the Titus Canyon Formation in the Grapevine Mountains and the overlying Timber Mountain volcanic sequence. Near Daylight Pass the contact is parallel to the strata, and might be conformable (Figure 6).

The thickness of the Titus Canyon Formation varies (Figure 7). It reaches a maximum of 1000 meters at exposures southeast of Daylight Pass and thins to less than 50 meters south of Chloride Cliff and north of Grapevine Peak (Stock and Bode, 1935) (Figures 7 and 8). At its reference section, Reynolds (1969) measured 640 meters of the Titus Canyon Formation. The variation in thickness is most likely the result of a combination of faulting, erosion and non-deposition.

Stock and Bode (1935) reported the discovery of numerous vertebrate fossils in the red calcareous mudstones of the lower part of the Titus Canyon Formation. These fossils include two types of titanotheres, the horse *Mesohippus,* hydracont rhinoceroses, several types of artiodactyls, and a scinromorph rodent. On the basis of these fossils, Stock and Bode (1935) determined that the lower part of the formation is Early Oligocene in age. No diagnostic fossils have been found in the upper half of the formation but, a tuff near the middle of the formation has been dated as 24 Ma (Reynolds, 1976). Because the upper part of the formation is unconformable with the lower part, Reynolds (1969) suggested that the age of the formation might extend into the Miocene.

Reynolds (1969) divided the Titus Canyon Formation in the Titus and Titanothere Canyons area into informal mapping units: 1) the sedimentary breccia unit at the base of the formation; 2) the variegated unit, which grades laterally into and intertongues with 3) the brown conglomerate unit; and 4) the green conglomerate unit, which forms the upper half of the formation (Figure 6). Reynolds (1969) separately described monolithologic megabreccia deposits which are interbedded with the Titus Canyon Formation and the overlying volcanic rocks. Here, the monolithologic megabreccia deposits within the Titus Canyon Formation are considered part of the Titus Canyon Formation. The monolithologic megabreccia deposits, sedimentary breccia unit, variegated unit and green conglomerate unit, as well as an algal limestone zone described by Stock and Bode (1935) were recognized during recent mapping in the upper Monarch Canyon - Daylight Pass area (Figure 6).

MONOLITHOLOGIC MEGABRECCIA DEPOSITS

Monolithologic megabreccia deposits crop out near the Paleozoic-Cenozoic contact on the northeast side of the Grapevine and northern Funeral Mountains (Figure 8). The monolithologic deposits comprise, for the most part, highly fragmented and brecciated masses of carbonate. The breccia masses are locally as much as 600 meters long and 60 meters thick (Cornwall and Kleinhampl, 1965). Most of the fragments are less than a meter across. The megabreccia deposits also include intact blocks of carbonate that can be up to 120 meters long (Reynolds, 1969). Sedimentary structures are preserved in the blocks, and the bases of the blocks are often parallel to bedding. The intact blocks and the clasts in the brecciated masses consist of dark gray ribbon carbonate. Layers of limestone are burrowed and the burrows are preferentially dolomitized. These rocks are lithologically similar to the Cambrian Bonanza King Formation. The matrix of the breccia masses is also of the same material as the clasts.

In the upper Monarch Canyon - Daylight Pass area, the monolithologic megabreccia deposits lie directly on Cambrian Wood Canyon Formation and, in places, are overlain by the sedimentary breccia unit of the Titus Canyon Formation (Figure 6). Occasional fragments of the Wood Canyon Formation are incorporated into the breccia deposits. In the Titus and Titanothere Canyons area, megabreccia deposits interfinger with the sedimentary breccia unit of the Titus Canyon Formation. Locally, they overlie upturned beds of the Titus Canyon Formation's variegated unit (Reynolds, 1969).

SEDIMENTARY BRECCIA UNIT

The sedimentary breccia unit, like the monolithologic megabreccia deposits, commonly crops out along the Paleozoic-Cenozoic contact in both northern and southern exposures of the Titus Canyon Formation (Figure 8). It interfingers with the variegated unit. In the Titus and Titanothere Canyons area, the sedimentary breccia unit overlies the Bonanza King and Nopah Formations (Reynolds, 1969) (Figure 5), but in the upper Monarch Canyon - Daylight Pass area, it overlies the Wood Canyon Formation (Figure 6).

The sedimentary breccia unit consists of matrix-supported conglomerate with calcareous mudstone matrix and lenses. Abundant large, angular, carbonate clasts are characteristic of the conglomerate. The carbonate clasts vary from small pebble size to boulder size, with occasional blocks as large as 3 meters in diameter. Most clasts are charcoal gray and black, some are tan, green and yellow-brown. The carbonate clasts are lithologically similar to the Carrara, Bonanza King, Nopah, Pogonip and Ely Springs

Formations. In exposures near Monarch Canyon, occasional meter-scale and smaller angular blocks of rose colored quartz arenite, similar to the Zabriskie Quartzite also occur.

VARIEGATED AND BROWN CONGLOMERATE UNITS

The variegated unit is composed of interbedded conglomerate, sandstone, calcareous siltstone and mudstone, and limestone. The conglomerates contain pebbles and cobbles ranging in size from 1 to 10 centimeters across. The clasts are well rounded and polished. Clast compositions include chert, quartzite, carbonate, and granite. The conglomerate beds are lenticular; they often grade laterally into sandstone and occasionally into siltstone. The siltstone, mudstone and limestone deposits, although fairly continuous, also thin and pinch out laterally.

A thick section of yellow-brown weathering conglomerate composes Reynolds' brown conglomerate unit. In addition to clasts similar in composition to those found in the variegated unit, there are also angular blocks of Paleozoic carbonate, and of red calcareous mudstone. The red mudstone is most likely reworked from the Titus Canyon Formation. Reynolds (1969) found exposures of the brown conglomerate unit only in the West Fork of Titus Canyon. In places, the sedimentary breccia unit overlies the brown conglomerate unit. Near Fall Canyon, the brown conglomerate unit grades laterally into, and interfingers with the variegated unit. Reynolds found some evidence for angular discordance between the brown conglomerate unit and the variegated unit.

ALGAL LIMESTONE UNIT

The algal limestone zone of Stock and Bode (1935) marks the top of the brown conglomerate unit and of the variegated unit (Figure 7). It consists of purple and yellow mudstone-siltstone and cream colored algal limestone. Stock and Bode (1935) were able to recognize this horizon in most exposures of the Titus Canyon Formation and use it as a correlation horizon. The algal limestone zone is 30 meters thick and forms a distinctive light colored band in the area between Daylight Pass and Monarch Canyon (Figure 6).

GREEN CONGLOMERATE UNIT

The green conglomerate unit lies above the algal limestone zone and unconformably above the variegated unit in the Titus and Titanothere Canyons area. The unconformity is angular in the central Grapevine Mountains (Reynolds, 1969), but beds are concordant near Daylight Pass (Figure 6). The green conglomerate unit consists of a thick sequence of pebble and cobble conglomerate, sandstone and tuff. The conglomerates and sandstones are commonly tuffaceous. The green conglomerate unit weathers pale green in most areas, hence the name, but near Daylight Pass it weathers light brown and orange. There is a dramatic increase in tuffaceous material from the variegated unit to the green conglomerate unit making the green conglomerate unit easily recognizable. The source of the tuffaceous material has not been identified.

Unlike the variegated unit, siltstone mudstone and limestone are minor to absent in the green conglomerate unit. Instead, amalgamated, often tuffaceous conglomerates up to 30 meters-thick are interbedded with tuffaceous sandstone and tuff. The clasts of the conglomerates are well-rounded and polished, and range in size from 2 to 50 centimeters. The clast lithologies are similar to those of the variegated unit, with the exception of the introduction of rhyolite pebbles. In northern exposures, occasional angular blocks of Paleozoic limestone and rhyolite occur in the green conglomerate unit (Reynolds, 1969). The green conglomerate unit fines to the south and is composed mostly of sandstone, tuffaceous sandstone and tuff in the southern exposures.

TIMBER MOUNTAIN VOLCANIC SEQUENCE

Volcanic and sedimentary rocks overlie the Titus Canyon Formation. Cornwall and Kleinhampl (1964) described exposures of the volcanic rocks in the Bullfrog Hills quadrangle and suggested they were derived from a crater there. Reynolds (1969) described an "unnamed tuff sequence" overlying the Titus Canyon Formation in the Titus and Titanothere Canyons area. He traced it laterally to where it meets with the tuffs described by Cornwall and Kleinhample (1964) in the northern Funeral Mountains. The "unnamed tuff sequence" of Reynolds (1969) has been correlated by Maldonado (1990) with the lowest unit of an approximately 5600 meter thick volcanic sequence exposed in the Bullfrog Hills. Volcanic rocks in the upper half of these sequence have been correlated with volcanic rocks at Bare Mountain, and as far east as Timber Mountain and Yucca Mountain (Carr, 1991; Maldonado, 1990). They are sourced from the Timber Mountain - Oasis Valley volcanic complex and the Crater Flat caldera.

The volcanic rocks in the Grapevine and northern Funeral Mountains unconformably overlie the Titus Canyon Formation and Paleozoic strata. In the Bullfrog Hills and Bare Mountain, the volcanic sequence is in fault contact, along the Original Bullfrog and Flourspar Canyon faults, with Paleozoic rocks.The volcanic sequence consists of silicic ash-flow tuff, ash-fall tuff and interbedded volcaniclastic rocks, conglomerate, shale and sandstone. Monolithologic megabreccia deposits, similar to those described in the Titus Canyon Formation, also occur within the volcanic sequence in the northern Grapevine Mountains and the Bullfrog Hills. The base of the sequence in the Grapevines Mountains is defined by Reynolds (1969) as the first thick vitric tuff overlying the Titus Canyon Formation.

STRUCTURE

The upper Monarch Canyon - Daylight Pass area can be divided into three structural blocks separated by Cenozoic normal faults (Figure 9). The southern structural block is the footwall of the gently north dipping - horizontal Boundary Canyon detachment. Hill 5001, and the rock units on strike with and to the northeast of it comprise the northern structural block (Figure 6, 9). The central structural block is bounded by faults (Figure 6). It lies in the hanging wall of a south-dipping normal fault along the south side of hill 5001 and is in the hanging wall of the north dipping Boundary Canyon detachment.

The southern structural block is composed of metamorphosed Johnnie Formation (Figure 6). The central structural block contains Stirling Quartzite, Lower Wood Canyon Formation and the lower half of the Titus Canyon Formation. The Titus Canyon Formation is in depositional and fault contact with the Wood Canyon Formation and the Stirling Quartzite. The northern structural block contains exposures of Stirling Quartzite, Wood Canyon Formation, Zabriskie Quartzite, all units of the Titus Canyon Formation, and the base of Timber Mountain volcanic sequence (Figure 6). The Titus Canyon Formation is in depositional and fault contact with the underlying strata. On the northern side of hill 5001, an almost complete and relatively intact section of the Titus Canyon Formation and the contact with the Timber Mountain volcanic sequence is preserved.

Cenozoic normal and oblique-slip faults, and Mesozoic and Cenozoic folds are present in the upper Monarch Canyon Daylight Pass area. The cross-cutting relations of four generations of Cenozoic faults provide constraints on the age of the Boundary Canyon detachment relative to the Titus Canyon Formation and the base of the Timber Mountain volcanic sequence (Figure 6, 9). The first two generations of Cenozoic faults are confined to the northern structural block. The third generation is represented by the normal fault separating the northern from central structural blocks. The fourth and youngest generation is confined to the central structural block and includes the Boundary Canyon detachment.

Generation One

The oldest generation of faults is represented by an inferred oblique-slip fault on the western side of the northern structural block (Figure 6, 9). It separates the variegated and green conglomerate units of the Titus Canyon Formation from the Wood Canyon

Formation, Zabriskie Quartzite and basal Titus Canyon Formation. The fault plane is not exposed and the contact between the Cenozoic and Paleozoic strata is covered by alluvium. The fault is required to account for the geometry of the Titus Canyon strata which strike into the Paleozoic strata.

The fault strikes northeast and has right-lateral offset such that it displaced rocks of the Titus Canyon Formation and the overlying tuff down to the southeast against the Wood Canyon Formation. North of the map area, the sedimentary breccia unit of the Titus Canyon Formation is in depositional contact with the Wood Canyon Formation and the Zabriskie Quartzite. A maximum of 2 kilometers of offset perpendicular to strike can be accounted for. Toward the south, the fault curves to the east, along the northern face of hill 5001. This first generation fault is probably a member of the generation of north-south striking oblique-slip faults in the eastern Grapevine Mountains which shed blocks of the Titus Canyon Formation down to the southeast (Figure 5).

GENERATION TWO

The second generation of faults consists of a single identified fault which lies on the eastern side of the northern structural block and truncates the first generation fault (Figure 6, 9). In the north, the fault has several splays which separate Titus Canyon Formation from Titus Canyon Formation. To the south, the fault passes through a narrow stream gully on the west side of hill 5001. It separates Titus Canyon Formation and Wood Canyon formation from Wood Canyon Formation and Stirling Quartzite. Again, along much of its trace, the contact is covered by alluvium and rubble. The fault strikes northeast-southwest, has 500 m of separation in a left lateral sense, and has a counterclockwise rotational component.

Generation Three

The third generation fault separates the northern structural block from the southern structural block. The trace runs along the southern side of hill 5001 (Figure 6, 9). The fault strikes northwest-southeast and dips approximately 60 degrees to the south. It has dropped a block of Stirling Quartzite, Wood Canyon Formation and Titus Canyon Formation down to the south. Offset perpendicular to strike is approximately 1500 m. This fault is probably kinematically related to a generation of southwest dipping listric faults in the eastern Grapevine Mountains. Strata of the Wood Canyon Formation in the footwall are folded into an anticline and faulted down to the south. The Titus Canyon Formation in the hanging wall forms a gentle syncline. The anticline-syncline pair is interpreted as a lag feature that developed during movement on the normal fault.

The generation three fault along the south side of hill 5001 truncates the generation two fault. It therefore must be younger than both generations of oblique slip faults in the northern structural block.

Generation Four

The fourth and youngest generation of Cenozoic faults includes the Boundary Canyon detachment and a number of sub-horizontal faults in the southern part of the central structural block that are sub-parallel to, and appear to splay into the Boundary Canyon detachment. Splays of the Boundary Canyon detachment cut exposures of the Titus Canyon Formation and the generation three fault. While the Boundary Canyon detachment does not itself cut the Titus Canyon Formation, it does truncate the generation three fault.

AGE CONSTRAINTS

The progression of cross cutting relations in the upper Monarch Canyon - Daylight Pass area consists of two generations of oblique slip faults that cut the Titus Canyon

Formation and offset the base of the overlying Timber Mountain volcanic sequence, a younger, third generation normal fault which truncates the younger of the two oblique slip faults and cuts the Titus Canyon Formation, and a fourth generation of normal faults which cuts the third generation fault and the Titus Canyon Formation. These cross-cutting relations require that the Boundary Canyon detachment is younger than both the Titus Canyon Formation and the base of the overlying volcanic sequence.

This constraint is consistent with all previous evidence of a mid-Miocene age for the Boundary Canyon detachment. It is possible that one phase of extension along the Boundary Canyon detachment was earlier than or time equivalent with the deposition of the Titus Canyon Formation, but no evidence for such a phase has been found in the upper Monarch Canyon - Daylight Pass area or elsewhere.

BASIN ANALYSIS

The monolithologic megabreccia unit, interpreted as gravity slide deposits, the sedimentary breccia unit, interpreted as alluvial fan deposits, the angular unconformity below the green conglomerate unit and at the top of the Titus Canyon Formation, and the reworked clasts of the Titus Canyon Formation in the brown conglomerate unit are strong evidence for syn-depositional deformation and active tectonic control on the evolving Titus Canyon basin (Reynolds, 1969). However, cross-cutting relations show that the Boundary Canyon detachment, the only major recognized Cenozoic fault that is closely related spatially to exposures of the Titus Canyon Formation, did not create the Titus Canyon basin.

The extent, geometry and provenance of the Titus Canyon Formation's sedimentary facies provide clues to the original geometry and orientation of the Titus Canyon basin. From this information, the style of the controlling structure or structures of the basin can be inferred. Then, the place of the Titus Canyon basin within the tectonic framework of Oligocene Tectonics in the Death Valley area can be analyzed.

SEDIMENTARY ANALYSIS

Four sedimentary facies are identified in the Titus Canyon Formation: gravity slide deposits, alluvial fan deposits, fluvial deposits, and lacustrine deposits (Reynolds, 1969). The gravity slide and alluvial fan deposits are the result of mass wasting from a structural high. The fluvial and lacustrine deposits infilled the adjacent structural low.

ALLUVIAL FAN AND GRAVITY SLIDE DEPOSITS

Environment

The size and angularity of the quartzite and carbonate blocks in the sedimentary breccia unit requires a nearby source and high relief to produce and transport them. A topographic high, separated from the depocenter by a fault scarp is thus inferred. The sedimentary breccia unit is interpreted here, as by Reynolds (1969), as remnants of alluvial fans. The alluvial fan deposits mark the scarp of a growth fault that was active during the deposition of the Titus Canyon Formation (Reynolds, 1969). The sedimentary breccia unit displays many of the same characteristics as quaternary debris flows described in the White Mountains of California (Hubert and Filipov, 1989). These characteristics include poor sorting, matrix support, and a non-erosional base such that the sedimentary breccia unit infills irregularities of the underlying surface. The alluvial fans of the Titus Canyon basin were debris-flow dominated. From this characteristic, it is inferred that the growth fault was steep.

The monolithologic megabreccia deposits also require high relief to transport them. They are probably the result of gravity slides, possibly initiated by earthquakes and also mark the scarp of a growth fault (Reynolds, 1969).

Provenance

Reynolds(1969) noted that the sedimentary breccia unit of the Titus and Titanothere Canyons area thins to the northeast and interbeds with the variegated unit. The number of siltstone lenses and the percentage of matrix increase to the northeast. The size of the fragments in the breccia masses decreases from southwest to northeast. There is a minor component of well-rounded quartzite pebbles and cobbles worked into the sedimentary breccia unit that probably was not locally derived. The abundance of these rounded quartzite clasts increases as the sedimentary breccia member grades into and interfingers with the variegated unit (Reynolds, 1969). Reynolds (1969) inferred from these relations that the alluvial fans and the megabreccias were sourced from a topographic high to the southwest. They interfingered with conglomerates and mudstones of the variegated unit that infilled the adjacent topographic low. The source for these sediments must have been local. Probably, it is the Paleozoic rocks that make up the Grapevine Mountains.

FLUVIAL DEPOSITS

Environment

Reynolds (1969) interpreted the cobble conglomerates and the sandstones of the Titus Canyon Formation as fluvial in origin. The conglomerates represent channels. The lateral gradations into pebbly sandstone and sandstone, especially in the variegated unit, mark the margins of the channels. The siltstones might have been deposited in overbank deposits.

Provenance

The cobbles of the variegated, brown conglomerate and green conglomerate units are well-rounded and polished. Their composition is different from, and more varied than the composition of the clasts in the sedimentary breccia unit. From these characteristics, significant transport and, or possibly reworking of an older conglomerate is inferred (Reynolds, 1969).

Paleocurrent measurements of pebble imbrications and cross-stratification indicate a sediment transport direction from the north or west (Reynolds, 1969). Clast provenance studies by Reynolds (1969) have also provided evidence to constrain the source of the fluvial cobbles. Well-rounded clasts of upper Paleozoic carbonates are abundant in some of the conglomerates. They contain Ordovician, Silurian, Devonian and Permian fossils. Since the clasts are well rounded and polished, they probably were not derived from Ordovician through Devonian rocks exposed in the northern Grapevine Mountains. Permian rocks in the region are now exposed only in the area of Panamint Butte and at Tucki Mountain, but Pennsylvanian rocks are abundant all along the west side of Death Valley. Cobbles of igneous intrusive rocks are also distinctive components of the fluvial conglomerates. There are clasts of fine- to coarse grained quartz monzonite and porphyritic granite. Outcrops of lithologically similar rocks are confined to the areas north and west of the Grapevine Mountains. From these provenance studies, Reynolds inferred a source to the north or west for the fluvial cobble conglomerates of the Titus Canyon Formation.

LACUSTRINE DEPOSITS

Environment

The mudstones and limestones are interpreted as dominantly lacustrine in origin (Reynolds, 1969).They accumulated or precipitated in deeper parts of the basin or during periods of tectonic quiescence. The algal limestone unit of Stock and Bode (1935) is the most distinctive and laterally continuous of the limestone-mudstone lacustrine intervals. It was probably deposited in an extensive, shallow lake.

TECTONIC INTERPRETATION OF SEDIMENTARY FACIES

Many characteristics of the sedimentary facies of the Titus Canyon Formation are distinctive of basins created by oblique-slip displacement along a strike-slip fault (see Christie-Blick, 1985; Sylvester, 1989). Longitudinal as well as lateral basin asymmetry and sediment transport and an apparent sediment-source mismatch are compelling evidence for a strike-slip fault. There is also evidence for episodic subsidence which is typical of strike-slip basins. In addition, the steep faults, debris flow dominated alluvial fans and gravity slide deposits inferred from the Titus Canyon Formation are consistent with strike-slip deformation.

LONGITUDINAL AND LATERAL ASYMMETRY

There appear to be two source areas for the Titus Canyon Formation. The source rocks and the transport direction of the fluvial conglomerates are different from those of the alluvial fan deposits. The megabreccia and alluvial fan deposits of the sedimentary breccia unit were locally derived and consist primarily of angular carbonate clasts and blocks of rock units exposed in the Grapevine Mountains. The alluvial fans and megabreccias were sourced from the southwest. They record local, fault controlled, lateral sediment transport along the short axis of the Titus Canyon basin. The alluvial fan deposits are subordinate to, and interfinger with fluvial cobble conglomerates and sandstones. The fluvial conglomerates were derived from a distil source to the north or west and probably record sediment transport sub-parallel to the long axis of the basin. The stream gradient for the longitudinal transport must have been quite steep because the conglomerate clasts are large. The steepness of the longitudinal gradient is compelling evidence for significant longitudinal asymmetry of the basin floor.

Although many basins that form in half grabens have some longitudinal drainage in addition to lateral alluvial fan facies (Alexander and Leeder, 1987), longitudinal asymmetry is a distinctive characteristic of basins that form along strike-slip faults. The asymmetry results from combined lateral and longitudinal tilting of the basin floor along an oblique-slip fault. It manifests itself in the sedimentary record by dual sediment source areas which feed longitudinally and laterally transported sediment loads (e. g. (Nilson and McLaughlin, 1985). The basin asymmetry often leads to "shingling" of the infilling sediments as the depocenter migrates (Christie-Blick and Biddle, 1985). Although there is little evidence for shingling of the sediments in the Titus Canyon Formation, the size of the cobble conglomerates, and the separate source areas for the alluvial fans and the fluvial sediments are substantial evidence that the Titus Canyon basin developed along a strike-slip fault zone.

SOURCE-SEDIMENT MISMATCH

The clast composition of the alluvial fan and monolithologic megabreccia deposits remains fairly constant from north to south. However, exposures of Paleozoic carbonates are limited to the central and northern Funeral Mountains. Thus, in the south, where the alluvial fan facies is deposited on Stirling Quartzite, Wood Canyon Formation and Zabriskie Quartzite, the nearest possible source area is several kilometers to the northwest. Since the alluvial fan and monolithologic megabreccia deposits are inferred to be sourced from the nearby rocks to the southwest, there is a mismatch between the sediment and an available source.

There are Paleozoic carbonate rocks in the southern Funeral Mountains and at Bare Mountain. Because current hypotheses for reconstructing the Death Valley area place the original location of the Grapevine Mountain block above the Funeral Mountains and adjacent to Bare Mountain, it is possible that the alluvial fan and monolithologic megabreccia deposits were sourced from one of these locations. In such a reconstruction, the southern Funeral Mountains and Bare Mountain are part of an autochthon which was unroofed by extension along the Boundary Canyon-Original Bullfrog-Flourspar Canyon detachment system. For the Paleozoic strata in the southern Funeral Mountains or Bare

Mountain to have sourced the alluvial fans in the Titus Canyon Formation, the unroofing must have occurred before or during the deposition of the Titus Canyon Formation. All evidence, including field relations recently mapped in the Monarch Canyon-Daylight Pass area, indicates that extension on the Boundary Canyon detachment is younger than the Titus Canyon Formation. Therefore, the southern Funeral Mountains and Bare Mountain are unlikely sources for the Titus Canyon basins breccias and alluvial fans.

The mismatch between sediment and source might better be explained by syn-depositional, right-lateral, oblique-slip displacement along the inferred fault scarp between the Proterozoic and Paleozoic strata and the Titus Canyon Formation. If alluvial fans in the hanging wall of the fault were sourced from the footwall, then the source area would have been transported away to the north as the footwall migrated beneath them. Thus, the Paleozoic carbonates exposed in the northern Grapevine Mountains could have been the source of the alluvial fans in the Funeral Mountains, but were progressively transported along the basin bounding fault to their present location north of the alluvial fans. Several good examples of similar source, sediment mismatches that resulted from lateral offset along strike-slip basin bounding faults have been described in the literature and include facies relations in the Ventura Basin (Christie-Blick and Biddle, 1985) and the Ridge Basin (Nilson and McLaughlin, 1985) in California.

RAPID, EPISODIC SUBSIDENCE

Lateral heat loss is extremely important in basins associated with strike-slip deformation. Because they are narrow, strike-slip basins tend to lose most of their anomalous heat during rifting (Pitman and Andrews, 1985). Thus, the post-rift, thermal subsidence phase that commonly characterizes other basin types is minor to nonexistent in strike-slip basins. This characteristic leads to episodic subsidence that is very rapid during periods of faulting and is often inconsequential in between. The rapid subsidence phase is recognized by thick accumulations of sediment that were deposited in short periods of time.

Fossils in the Titus Canyon Formation are sparse and the interbedded volcaniclastic rocks have not yet been dated. Thus, exact timing constraints are unknown, and little can be said about the absolute rates of subsidence. However, there is stratigraphic evidence for episodic and rapid sediment accumulation, most compelling of which are the angular unconformities at the base, middle and top of the Titus Canyon Formation.

The transition from a laterally extensive lacustrine environment inferred from the algal limestone zone of Stock and Bode (1935) to renewed fluvial deposition represented by the green conglomerate unit is also interpreted as evidence for rapid and episodic subsidence. Generally, lacustrine facies occur near the locus of subsidence in a basin. The laterally extensive algal limestone zone however, represents lacustrine sedimentation over a widespread area. It might have been deposited on an extensive surface of low relief, during a period of tectonic quiescence. It might also record a period of increased subsidence, during which the Titus Canyon basin deepened and the locus of subsidence grew. Given the latter case, the algal limestone zone would be similar to a marine condensed interval. Coarse fluvial sedimentation above the algal zone recommenced either with renewed tectonic subsidence or as erosion had time to catch up to subsidence.

STEEP FAULT SCARPS

Alluvial fan deposits, such as the sedimentary breccia unit, are often found along fault scarps in basins associated with normal faults and strike-slip faults (e.g. Alexander and Leeder, 1987; Cemen et al., 1985). However, the megabreccia deposits, and the fanglomerates require a steep fault to produce them and might be more consistent with styles of oblique-slip rather than purely normal basin-bounding faults.

Normal fault systems in the Basin and Range Province usually involve block rotation which forms tilt-basins. In tilt-basins, the footwalls rotate away from the hanging walls such that the footwall strata dip away from the developing basin. The fault planes also rotate and become progressively more shallow. That geometry is rare in strike-slip deformation. In fact, because strike-slip faults zones are characterized by near vertical faults, which switch dip-direction (e. g. (Christie-Blick and Biddle, 1985; Sylvester, 1988), it is possible for the footwall to rotate toward the hanging wall. Scarps associated with oblique- or strike-slip faults are therefore steeper than those of normal faults and more conducive to mass wasting. In addition, because the strata can dip toward the basin instead of away, large blocks can slide more easily along bedding planes into the adjacent low.

BASIN GEOMETRY AND EXTENT

It is clear from the alluvial fan and megabreccia deposits that the Titus Canyon Formation was deposited in a locally restricted, tectonically controlled basin. Aspects of the sedimentary facies indicate that the Titus Canyon basin developed during local extension and oblique-slip displacement along a strike-slip fault zone. Alluvial fans, the remnants of which are exposed in the Grapevine Mountains today, formed along the fault scarp. Thus, although there is no direct evidence of a fault, the contact between the megabreccia and sedimentary breccia units of the Titus Canyon Formation and the Proterozoic and Paleozoic formations is interpreted as marking the scarp of a growth fault of the Titus Canyon basin. Most likely the growth fault was steep and fairly straight. The fault was oriented sub-parallel to the trend of exposures of the Titus Canyon Formation and bordered the basin on its western side.

Although most exposures of the Titus Canyon Formation are confined to the eastern Grapevine Mountains, several workers have correlated the Titus Canyon Formation with rocks of similar lithology and stratigraphic position elsewhere in the Death

Valley area. Reynolds (1969) assigned conglomerates on the southwest side of the Funeral Mountains, along the Keene Wonder Fault, to the Titus Canyon Formation (Figure 4). Cornwall and Kleinhampl (1964) described small patches of Titus Canyon Formation unconformably overlying the Carrara Formation in the Bullfrog Hills.

A sequence of alluvial fan, fluvial, lacustrine and volcaniclastic deposits exposed at Bat Mountain might be correlative in part with the Titus Canyon Formation (Cemen et al., 1985) (Figure 4). The section exposed at Bat Mountain, which has been described in detail by Cemen et. al. (1985), is approximately 1300 meters thick and comprises two parts, separated by an angular unconformity. The base of the Bat Mountain section consists of alluvial fan deposits containing angular Cambrian and Devonian clasts in a calcareous siltstone matrix. The fans are inferred to be sourced from the south because the matrix-to-clast ratio increases to the north. The alluvial fan deposits are overlain by a lacustrine unit composed of limestone, siltstone and tuff. A tuff bed low in the unit yielded a K/Ar age of 25 Ma (Cemen et al., 1985). The lacustrine unit is overlain by a fluvial sandstone unit which lies in angular unconformity below a distinctive algal limestone unit that has a 19.8 Ma (biotite, K/Ar (Cemen et al., 1985) tuff at its base. The algal limestone zone is in turn overlain by alluvial fan conglomerates containing angular clasts of the algal limestone and of Proterozoic and Paleozoic formations.

The exposures of Titus Canyon Formation on the west side of the Funeral Mountains are structurally separated from the main band of outcrop of the Titus Canyon Formation and provide no information on the geometry of the basin. The alluvial fan deposits at Bat Mountain, if correlative, might record the southern extent of the Titus Canyon basin during one period of its evolution. The patches of Titus Canyon Formation at Bare Mountain, if correlative with the Titus Canyon Formation, constrain the basin floor to extend at least to Bare Mountain.

BASIN HISTORY

Faulting and development of the Titus Canyon basin had begun by the Early Oligocene. Alluvial fans developed along the fault scarp that formed the western edge of the basin. Gravity slides and debris flows shed slide blocks, megabreccias and coarse, angular fanglomerates down the fault scarp, while fluvial and lacustrine sedimentation infilled the subsiding depression to the east. Episodic faulting disrupted the fluvial and lacustrine sedimentation, producing angular unconformities within the Titus Canyon Formation.

During the middle of Titus Canyon time, volcanic activity in the vicinity increased. The source for the tuffs and the tuffaceous material in the Green Conglomerate unit is not known, however, it is probably closely associated with the group of caldera complexes to the east and north of Bare Mountain that sourced the volcanic material in the thick Timber Mountain volcanic sequence that overlies the Titus Canyon Formation.

The accumulation of a 5600 meter thick Timber Mountain volcanic sequence above the Titus Canyon Formation, and the occurrence of monolithologic megabreccia deposits within that sequence are evidence for continued faulting, volcanic activity and basin formation long after deposition of the Titus Canyon Formation, well into the Miocene. Carr (1990) suggested that the Miocene volcanic and sedimentary rocks overlying the Titus Canyon Formation accumulated in a north-trending volcano-tectonic rift which includes the caldera complexes north and east of Bare Mountain and a caldera complex east of the Black Mountains.

Between 12 and 7 Ma extension along the Boundary Canyon detachment transported the northern Funeral Mountains and the Grapevine Mountains, including the Titus Canyon Formation and the overlying volcanic and sedimentary rocks to the northwest, unroofing the metamorphic core in the Funeral Mountains. Because the Paleozoic and the Cenozoic strata in the Grapevine Mountains both dip steeply and are nearly concordant, it is inferred that rotation of the Titus Canyon sediments was not the result of extension along the bounding fault of the Titus Canyon basin. Block rotation of the Grapevine Mountain allocthon probably occured during transport along the Boundary Canyon detachment. Active extension and volcanism had waned by the late Miocene so that the youngest tuffs exposed in the Bullfrog Hills are 7 Ma and are undeformed.

TECTONIC SETTING OF THE TITUS CANYON BASIN

THE RECONSTRUCTION

In order to understand the place of the Titus Canyon basin and its controlling fault in the extensional history of the Death Valley area, it is essential to determine if the growth fault for the Titus Canyon basin is related to any previously identified faults in the vicinity. It is therefore necessary to know the original orientation and location of the Titus Canyon basin. Here the reconstructions of Wernicke et al.(1988, 1989) and Snow et al. (1989) are used since they are the most detailed and up to date.

The general outline of the reconstruction is that the Cottonwood Mountains were originally adjacent to the Funeral Mountains, the Panamint Range and the Black Mountains were together and were adjacent to the Resting Spring and Nopah Ranges, and the entire structural block reconstructs to the Spring Mountains. This reconstruction hinges on correlations of Proterozoic and Paleozoic facies trends and of a distinctive and regionally unique Mesozoic age thrust-fold system. Segments of the thrust-fold system provide piercing points for calculating the displacement between the Cottonwood Mountains, the Funeral Mountains, Bare Mountain, the Specter Range and the Grapevine Mountains (Schweikert, 1989; Snow et al., 1989; Wernicke et al., 1989; Wernicke et al., 1988) (Figure 9). The major extensional structures that accommodated the displacement of these mountain ranges include the Northern Death Valley-Furnace Creek Fault Zone along the west side of the Grapevine Mountains and the Boundary Canyon detachment (Figure 10).

The Northern Death Valley-Furnace Creek fault zone comprises a zone of dextral, strike-slip offset that is adjacent and sub-parallel to the southwestern side the Grapevine and Funeral Mountains (Stewart, 1983). Movement along the Northern Death Valley-Furnace Creek fault zone is postulated to have begun in the Early Miocene (Cemen et al., 1985). The Northern Death Valley-Furnace Creek fault zone offset the Cottonwood Mountains relative to the Funeral Mountains and is in part responsible for the "pull-apart" origin of Death Valley (Burchfiel and Stewart, 1966).

Wernicke et. al. (1989) suggested that the thrust-fold system composed of the Clery and Schwaub Peak thrusts and the Winters Peak anticline in the Funeral Mountains is equivalent to the Lemoigne and Marble Canyon thrusts and the White Top Mountain fold in the Cottonwood Mountains across the Northern Death Valley-Furnace Creek fault zone (Figure 10). They based their correlations on the uniqueness of a west-vergent backfold among dominantly east vergent Mesozoic structures. They calculated 70 km of displacement across the Northern Death Valley-Furnace Creek fault zone.

The Corkscrew syncline which, in conjunction with the Titus Canyon anticline, forms a syncline-anticline fold pair that runs the length of the Grapevine Mountains, is truncated by the Boundary Canyon detachment. Snow et. al. (1989) suggested that the Corkscrew syncline and the Titus Canyon anticline are also part of the thrust-fold system in the southern Funeral Mountains (Figure 10). By correlating the Stirling Quartzite C member in the hanging wall cut-off of the Boundary Canyon detachment with its first occurrence in the footwall, they calculated that 30 km of displacement has occurred on the Boundary Canyon detachment. Because the folds in the Grapevine and Funeral Mountains are oriented differently, Wernicke et. al. (1989) suggested that the Grapevine Mountains rotated as much as 90 counterclockwise about vertical axes during transport along the Boundary Canyon detachment.

Snow et. al. (1989) suggested a unique correlation between the thrust-fold system in the Funeral Mountains and the Panama thrust and associated fold in Bare Mountain.

They inferred a relatively small displacement of Bare Mountain relative to the Funeral Mountains, which is consistent with hypotheses that both mountains are in the footwall of the Boundary Canyon-Bullfrog-Flourspar Canyon detachment system. They did infer a small amount of clockwise rotation of Bare Mountain relative to the Funeral Mountains.

Schweikert (1989) suggested that the Panama thrust-fold system in Bare Mountain is correlative with an east-trending anticline in the Specter Range (Figure 10). From this correlation, he inferred a minimum of 26 kilometers of separation between Bare Mountain and the Specter Range. He proposed the existence of a dextral fault between the two ranges, hereafter referred to as the Crater Flat fault zone, and suggested that it might be a continuation of the Stewart Valley-Stateline fault exposed south of Amargosa Valley. Because there is little surface expression of the fault in the Amargosa Valley and Crater Flat, Schweikert suggested that much of the displacement predated the 14-10 Ma tuffs in the Crater Flat area.

Reconstructions of the pre-extensional Death Valley area, proposed by Snow et. al. (1989), Wernicke et. al. (1989), and Schweikert (1989), place Bare Mountain adjacent to the Specter Range, the Cottonwood Mountains adjacent to the Funeral Mountains, and the Grapevine Mountains above the Funeral Mountains. The reconstructions require between 60 and 90 degrees of clockwise back-rotation of the Grapevine Mountains in order to properly orient the fold-thrust system. Presumably, since the Titus Canyon Formation pre-dates most of the extension in the area, including extension along the Boundary Canyon detachment, it rotated along with the Grapevine Mountains. If these reconstructions are correct, the growth fault between the underlying Paleozoic strata and the Titus Canyon Formation originally was oriented between north-south and northeast-southwest.

ANALYSIS

The Boundary Canyon detachment is the only recognized, major extensional structure that is close to, and has an orientation similar to that of the inferred bounding fault of the Titus Canyon basin. However, it is rejected as a possible controlling structure for the Titus Canyon Basin because field relations constrain all identifiable extension along it to be younger than the Titus Canyon Formation.

In addition to age constraints, the geometry inferred for the Titus Canyon basin is also inconsistent with any close relation between extension along the Boundary Canyon detachment and the evolution of the Titus Canyon basin. Hamilton (1987) suggested that tilt-block basins are developing today above evolving detachment faults and that similar tilt-block basins developed above earlier detachments. Generally, tilt-block basins develop on listric faults that are synthetic to, and root into the underlying detachment.The reconstruction of Snow et. al (19o;, requires that the bounding fault of the Titus Canyon basin was antithetic to the developing Boundary Canyon detachment and therefore, was not related genetically to movement along the Boundary Canyon detachment. In addition, the listric, normal fault geometry of the Boundary Canyon detachment and its splays is inconsistent with the oblique-slip deformation interpretation of the stratigraphic record of the Titus Canyon Formation.

The Titus Canyon basin could not have developed along the Northern Death Valley- Furnace Creek fault zone either. In both their present and reconstructed orientations, the Grapevine Mountains separate the Titus Canyon Formation from the Northern Death Valley-Furnace Creek fault zone. In addition, if Cemen et. al. (1985) are correct and the alluvial fan deposits at Bat Mountain record the initial movement along the Furnace Creek fault then, the alluvial fan deposits of the Titus Canyon Formation are older than the fault zone.

The dextral Crater Flat fault zone transported Bare Mountain northwestward relative to the Specter Range. It is postulated by Schweikert (1989) to extend from the State Line fault, through the Amargosa Valley to Crater Flat. It is is constrained to lie on the east side of Bare Mountain. Since Bare Mountain was originally adjacent to the Grapevine Mountains (Wernicke et al., 1989), the pre-Boundary Canyon detachment location of the developing Titus Canyon basin was adjacent to the Crater Flat fault zone. The strike of the Crater Flat fault zone is constrained by Bare Mountain and the Specter Range to have been between north-south or northwest-southeast and was therefore orientated sub-parallel to the present orientation, and oblique to the reconstructed orientation of the Titus Canyon basin. The Crater Flat fault zone is for the most part, older than the volcanic material in Crater Flat and therefore, like the Titus Canyon Formation, is older than most of the extension in the Death Valley area. Locally divergent movement along the Crater Flat fault zone could have created the Titus Canyon Basin. Such an origin is consistent with the age and orientation of the Titus Canyon Formation and the Crater Flat fault zone, the style of fault inferred from sedimentary relations to have controlled the evolution of the basin, and with current hypotheses on the extensional history of the Death Valley area.

THE TECTONIC EVOLUTION OF THE TITUS CANYON BASIN

Originally, the Cottonwood Mountains, Funeral Mountains, Grapevine Mountains, Bare Mountain and the Specter Range formed a single structural block (Figure 11 a). Right-lateral displacement along the Crater Flat fault zone began to break the structural block apart between Bare Mountain and the Specter Range. The Titus Canyon Formation records basin formation resulting from Early Oligocene, locally divergent motion along the dextral Crater Flat fault zone (Figure 11 b). There was active faulting at least along the western margin of the basin. The eastern margin of the basin is covered and its geometry is unknown. The inferred fault marked by the alluvial fans along the Titus Canyon Formation - Miogeoclinal strata contact might be the main splay of the Crater Flat fault zone. It is also possible that the Titus Canyon basin was bounded on two sides by faults, and that the main Crater Flat fault passed to the east of the Titus Canyon basin.

The Miocene volcaniclastic and sedimentary rocks that overlie the Titus Canyon Formation and monolithologic megabreccia deposits within them record the continued activity of the Crater Flat fault zone with an accompanying increase in volcanic activity that possibly developed into a volcano-tectono rift on the east side of Bare Mountain. Also during the Early Miocene the Northern Death Valley-Furnace Creek fault zone became active and the Cottonwood Mountains began to break away from and be transported to the northwest relative to the Funeral Mountains (Figure 11 c). Cemen et al. (1986) suggested that alluvial fan deposits at Bat Mountain might record the onset of motion along the Northern Death Valley-Furnace Creek fault zone. Thus, both the Crater Flat fault zone and the Northern Death Valley-Furnace Creek fault zone were active during the Early Miocene, before most of the extension in the area occured. As the Crater Flat fault zone transformed into more of a volcanic rift during the mid-Miocene, the Northern Death Valley - Furnace Creek fault zone continued to be active even into the Pliocene.

Approximately 10 Ma extension on the Boundary Canyon detachment transported the Grapevine Mountain allocthon, including the Titus Canyon Formation and the overlying Miocene volcanic sequence, to its present location northwest of Bare Mountain (Figure 11 d). The metamorphic core of the Funeral Mountains and metamorphic rocks in the Bullfrog hills and Bare Mountain were unroofed.

IMPLICATIONS

Oblique-slip movement along the postulated Crater Flat fault zone is called upon in the above model to explain the origin of the Titus Canyon Formation. The Crater Flat fault zone was active by, at the latest, the Early Oligocene. It accommodated 26 kilometers of displacement, most of which predates the mid-Miocene period of large scale extension in the Death Valley area. Nevertheless, the Crater Flat fault zone is kinematically tied to Death Valley extension.

Deformation along the Crater Flat fault zone was similar in style and orientation to, and was in part coeval with, deformation along the Northern Death Valley-Furnace Creek fault zone, one of the most important extension related structures in the Death Valley area. If the model for the evolution of the Titus Canyon basin is correct, then not only do the sedimentary facies of the Titus Canyon Formation record the earliest identified, extension related deformation in the Death Valley area, but they also contain evidence that the extension was accommodated by a major, only recently identified, Oligocene to Miocene age, strike-slip fault zone. Major detachments associated with the Oligocene strike-slip deformation, if they exist, have not yet been identified. It appears that a phase of predominantly strike-slip deformation preceded the large scale mid-Miocene extension and the mid-Miocene volcanism in the Death Valley area.

Oblique-slip motion along the Crater Flat fault zone during the evolution of the Titus Canyon basin might also explain some of the structural puzzles of the Grapevine Mountains. These puzzles include the varying orientations of folds correlated between the Grapevine, Funeral and Bare Mountains and, renewed Cenozoic age folding and associated low angle faulting along the Corkscrew syncline and Titus Canyon anticline fold pair.

Because the orientation of the fold pair in the Funeral Mountains differs from that of the correlative folds in the Funeral Mountains and Bare Mountain, Snow et. al. (1989) suggested that the Grapevine Mountains rotated clockwise about a vertical axis during transport along the Boundary Canyon detachment. They also suggest a smaller degree of counterclockwise rotation of Bare Mountain. Such block rotation about vertical axes is commonly associated with strike-slip deformation. Transrotational deformation resulting from kinematically linked strike-slip deformation along the Northern Death Valley-Furnace Creek fault zone on the west side of the Grapevine Mountains and the Crater Flat fault zone on the east side is a possible cause of the rotation of the Grapevine Mountains or Bare Mountain (Figure 11 c). However, the dextral sense of the two faults predicts clockwise rotation of the internal block which is inconsistent with the clockwise rotation inferred from the fold geometry in the Grapevine Mountains. In addition, the Funeral Mountain block would be expected to have rotated along with Grapevine Mountain block since they were still joined during the time that the two faults were active. Still, the possibility of block rotation between the Northern Death Valley-Furnace Creek fault zone and the Crater Flat fault zone, particularly clockwise rotation of Bare Mountain can not be ruled out.

The fold pair in the Grapevine Mountains is closely associated with and appears to be kinematically related to an antithetic normal fault system that cuts across it (Reynolds, 1969). Because of the close association of folding and faulting, Reynolds (1969, 1970) inferred that the faults are genetically related to the folds. Snow et. al. (1989) suggest a polygenetic origin for the fold and fault system. The remnant Mesozoic fold pair was refolded and caught up in associated faulting during the transport of the Grapevine Mountains along the Boundary Canyon detachment.

Although the polygenetic origin suggested by Snow et. al. (1989) is reasonable, there is no evidence to restrict renewed folding and extensional faulting to Boundary Canyon detachment time. In fact, available evidence favors an earlier age. With the exception of exposures in the Kit Fox Hills and along the Keene Wonder fault, exposures of the Titus Canyon Formation are restricted to the hanging wall of the Cenozoic fault-fold system and their trend is sub-parallel to the general strike of the fold-fault system (Figure 12). Since the Cenozoic fault-fold system is usually associated with exposures of the Titus Canyon Formation but, never cuts them, the relations suggest that low angle faulting and the renewed folding pre-dates or is contemporaneous with the deposition of the Titus Canyon Formation, and that there is some kinematic link between the evolution of Titus Canyon Formation and the development of the Cenozoic fault-fold system. Early

Oligocene strike-slip faulting during the evolution of the Titus Canyon basin must also be considered as a possible cause for renewed Cenozoic folding in the Grapevine Mountains.

Cenozoic folding in the Grapevine Mountains is consistent with structural trends expected from oblique-slip deformation leading to the evolution of the Titus Canyon basin. Deformation associated with strike-slip fault zones is characterized by a complex combination of synthetic and antithetic compressional and extensional structures. Nevertheless, distinct structural patterns have been recognized and include "en echelon" faults, folds and extensional fractures, which are oblique to the principle zone of strike-slip displacement, and synthetic faults which are subparallel to it (Christie-Blick and Biddle, 1985). 14). Antithetic folds resulting from transpressional stresses associated with the Crater Flat strike-slip fault zone could have nucleated along zones of pre-existing weakness presented by the remnant Mesozoic fold pair and caused renewed folding.

CONCLUSIONS

A tectonic and stratigraphic reinterpretation of the early Oligocene Titus Canyon Formation has important implications for the early extensional history of the Death Valley area. The presence of monolithologic megabreccia deposits and alluvial fan deposits, as well as local angular unconformities in the Titus Canyon Formation is evidence for Early Oligocene faulting during the deposition of the formation. The sedimentary facies relations of the Titus Canyon Formation are indicative of syn-depositional right-lateral displacement, episodic and rapid subsidence, and longitudinal and lateral basin asymmetries, and are evidence that the Titus Canyon Formation was deposited in a limited, fault controlled basin that was created by local divergence along a dextral strike-slip fault zone.

Based on reconstructions of the pre-extensional Death Valley area proposed by Snow et. al. (1989), Wernicke et. al. (1989) and Schweikert (1989), the Boundary Canyon detachment, the Northern Death Valley-Furnace Creek fault zone and the concealed Crater Flat fault zone in the Amargosa Valley and Crater Flat area are the only major recognized faults in the vicinity of the developing Titus Canyon basin. Recent mapping has shown that the Boundary Canyon detachment truncates faults that offset the Titus Canyon Formation and therefore must be younger than the Titus Canyon Formation. Because of its age and geometry, extension along the Boundary Canyon detachment could not have created the Titus Canyon basin. The Northern Death Valley-Furnace Creek fault zone is similarly rejected as a controlling fault. Local normal displacement along the cryptic, dextral Crater Flat fault zone probably controlled the evolution of the Titus Canyon Basin. The age, orientation and location inferred for the Crater Flat fault zone are all consistent with the geometrical, spatial and temporal sedimentalogical and structural relations of Titus Canyon Formation.

The model for the evolution of the Titus Canyon basin, based primarily on the hypothesis that local divergence along the Crater Flat fault zone created the Titus Canyon basin, is also consistent with current hypotheses for the extensional history of the Death Valley area. The Titus Canyon Formation records Early Oligocene, strike-slip displacement on the Crater Flat fault zone, the earliest such displacement identified in the Death Valley area. Later, the Northern Death Valley-Furnace Creak fault zone was activated and deformation along the two fault zones was in part coeval. During the Middle to Late Miocene, the Boundary Canyon detachment transported the Grapevine Mountain allochthon to its current position.

The Crater Flat fault zone is kinematically similar and probably genetically linked with the Northern Death Valley-Furnace Creek fault zone. The initial deformation along the Crater Flat fault zone and later along the Northern Death Valley-Furnace Creek fault zone is older than all identified normal faults in the Death Valley area.The deformation along Crater Flat fault zone recorded by the Titus Canyon Formation and the Timber Mountain volcanic sequence continued from the Early Oligocene to the late Miocene. It is part of a laterally and temporally extensive, early phase of extension in the Death Valley area.

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Figure Captions

Figure 1: Generalized map showing the location of the Basin and Range Province (shaded) and the position of the Death Valley area (boxed) relative to major Mesozoic features (after Hamilton, 1988; Burchfiel and Davis, 1970).

Figure 2: Generalized map of the Death Valley extended area showing the location of major Cenozoic structures (after Hodges et al. 1987). (BCD) Boundary Canyon Detachment; (CFFZ) Crater Flat Fault Zone; (LVVS) Las Vegas Valley Shear Zone; (GM) Grapevine Mountains; (SR) Specter Range; (BM) Bare Mountain; (NFZ) Noethern Death Valley - Furnace Creek Fault Zone; (TM-OV VC) Timber Mountain - Oasis Valley Volcanic Complex; (SLFZ) Stateline Fault Zone. Small boxed area shows location of field study area. Large boxed area shows location of Figure 3. Inset shoes location of the Death Valley extended area relative to Nevada and California.

Figure 3: Generalized map of the north central Death Valley area (after Cemen (1985), showing the location of Oligocene sedimentary deposits, a Mesozoic backfold used in reconstructions of the Grapevine Mountains (GM), Bare Mountain (BM) and the Funeral Mountains FM), and a possible detachment fault system which includes the Boundary Canyon detachment (BCD), the Original Bullfrog fault (OBF) and the Flourspar Canyon fault(FCF). TM is Timber Mountain; SR is the Specter Range; NFZ is the Northern Death Valley - Furnace Creek Fault Zone; CFFZ is a possible location for the buried Crater Flat Fault Zone. Rectangle shows location of field study, Figure 7.

Figure 4: Simplified stratigraphic column of rock units present in the Grapevine and northern Funeral Mountains (after Reynolds(1969)).

Figure 5: Generalized map of the Grapevine and northern Funeral Mountains showing the distribution of major rock units discussed in the text (after Reynolds (1969)).

Figure 6: Geologic map of the area between Daylight Pass and upper Monarch Canyon in the northern Funeral Mountains.

Figure 7: Simplified stratigraphic columns of the Titus Canyon Formation. Approximate locations of measured sections are shown in Figure 10. (1,2,3,4,8,10,11 after Stock and Bode (1935); 5,6,7 after Reynolds(1969)).

Figure 8: Simplified map of exposures of Oligocene rocks (shaded) in the Grapevine and northern Funeral Mountains showing the approximate location of measured stratigraphic columns, breccia deposits in the Titus Canyon Formation, and geographic names mentioned in the text (after Reynolds(1969).

Figure 9: Simplified tectonic map of the upper Monarch Canyon - Daylight Pass area. (1) Paleozoic unmetamorphosed strata, (2) Oligocene - Miocene(?) Titus Canyon Formation, (3) lower part of Miocene Timber Mountain volcanic sequence, (4) metamorphosed Proterozoic strata.

Figure 10: Simplified schematic diagram showing Mesozoic structures used to reconstruct the northern Death Valley area (after Wernicke, 1989).

Figure 11: Schematic diagram showing the evolution of the Titus Canyon basin.

Figure 12: Simplified diagram of structures in the Grapevine Mountains that might be related to strike-slip deformation. (Generalized strain ellipsoid is after Cristie-Blick, 1985)

Figure 1

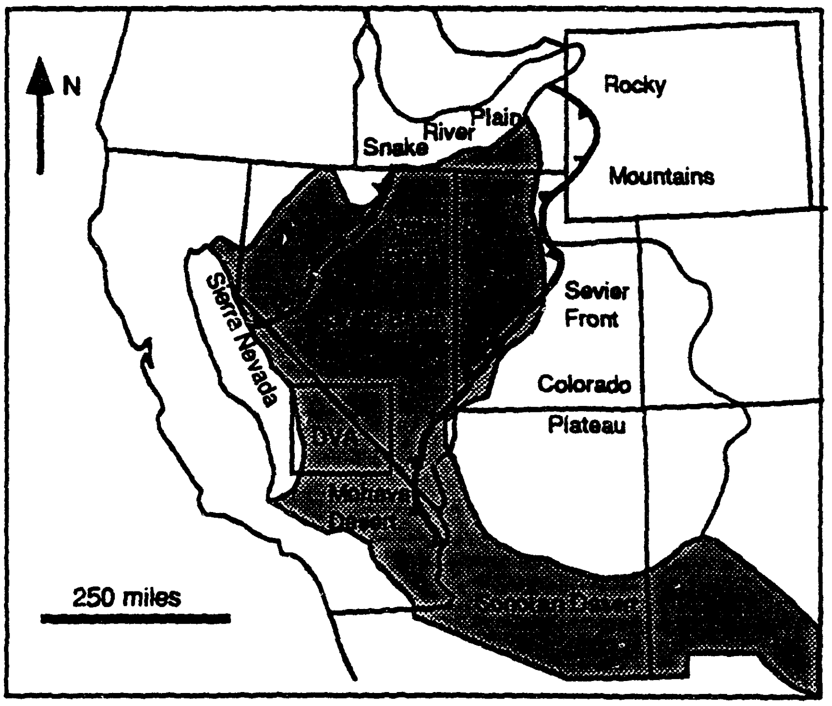
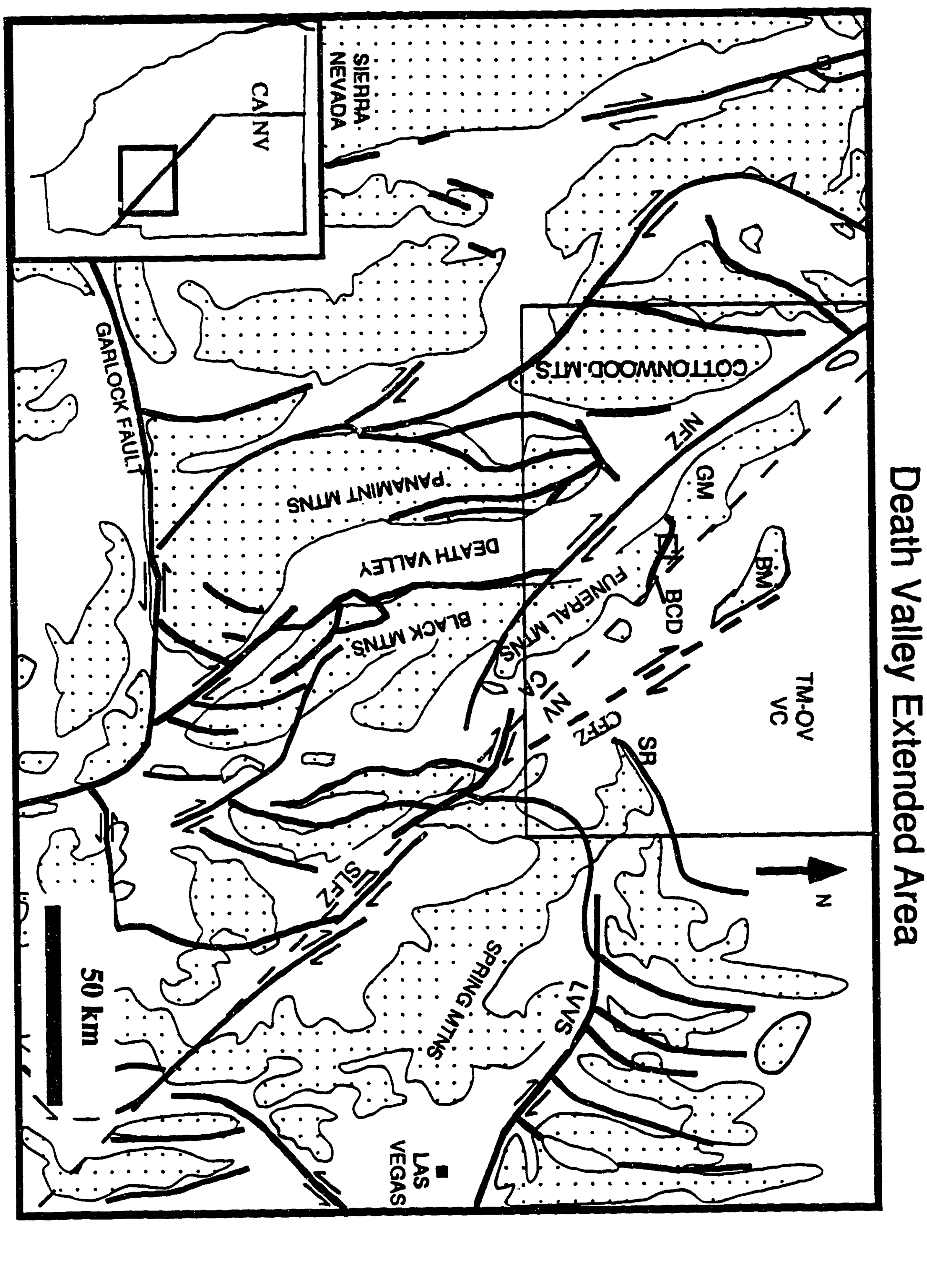

N
Rocky
Mountains
Snake River Plain
Sierra Nevada
Sevier
Front
Colorado
Plateau
250 miles

Figure 2



Death Valley Extended Area
SIERRA NEVADA
CA
NV
GARLOCK FAULT
COTTONWOOD MTS.
PANAMINT MTNS
DEATH VALLEY
BLACK MTNS
FUNERAL MTNS
NFZ
GM
BM
BCD
TM-OV VC
SR
CFFZ
SLFZ
SPRING MTNS
LVVS
LAS VEGAS
N
50 km

Figure 3

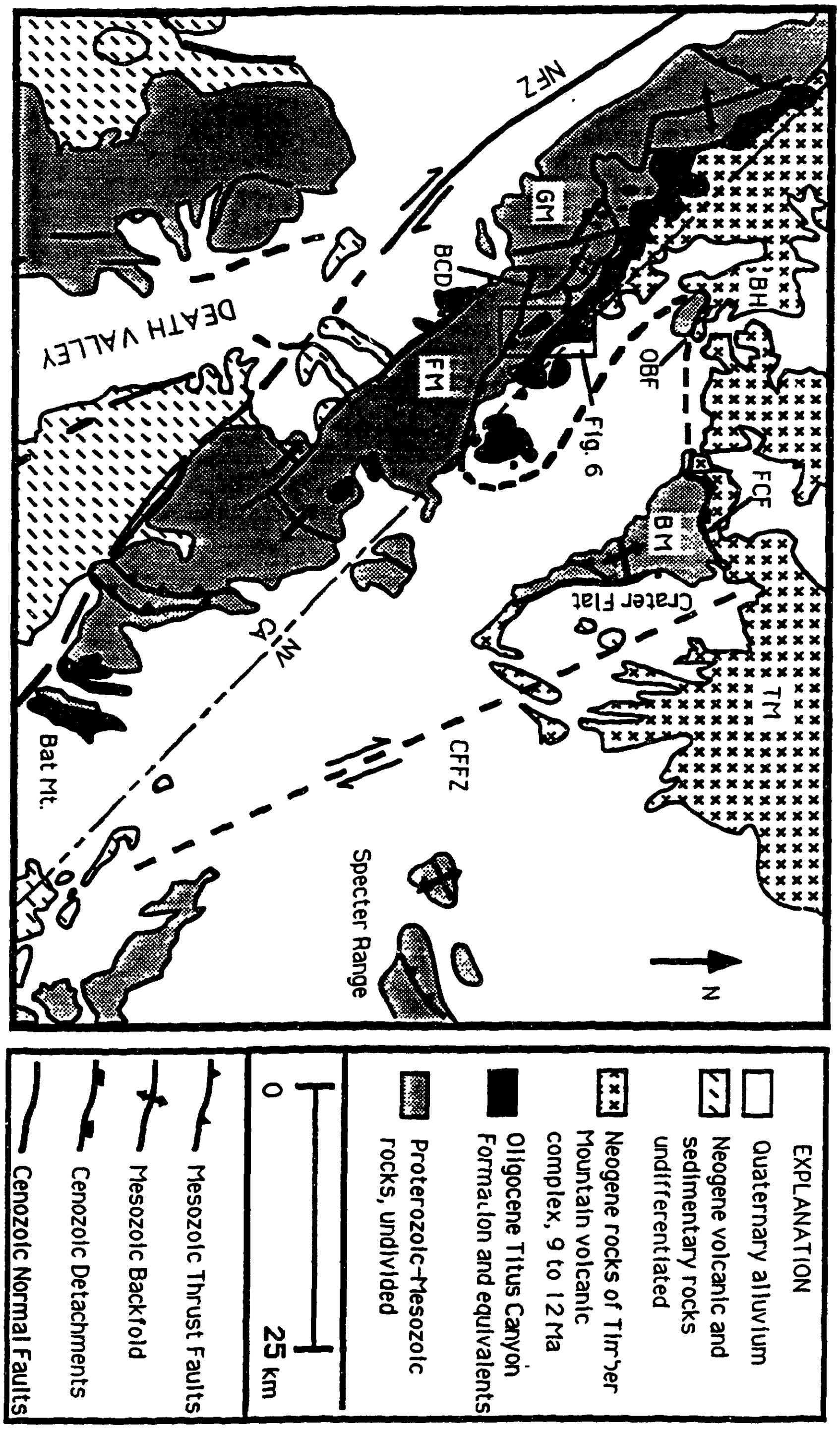

NFZ
DEATH VALLEY
GM
BCD
FM
BH
OBF
Fig. 6
FCF
BM
Crater Flat
TM
CFFZ
Bat Mt.
Specter Range
N
EXPLANATION
Quaternary alluvium
Neogene volcanic and sedimentary rocks undifferentiated
Neogene rocks of Timber Mountain volcanic complex, 9 to 12 Ma
Oligocene Titus Canyon Formation and equivalents
Proterozoic-Mesozoic rocks, undivided
0
25 km
Mesozoic Thrust Faults
Mesozoic Backfold
Cenozoic Detachments
Cenozoic Normal Faults

Figure 4

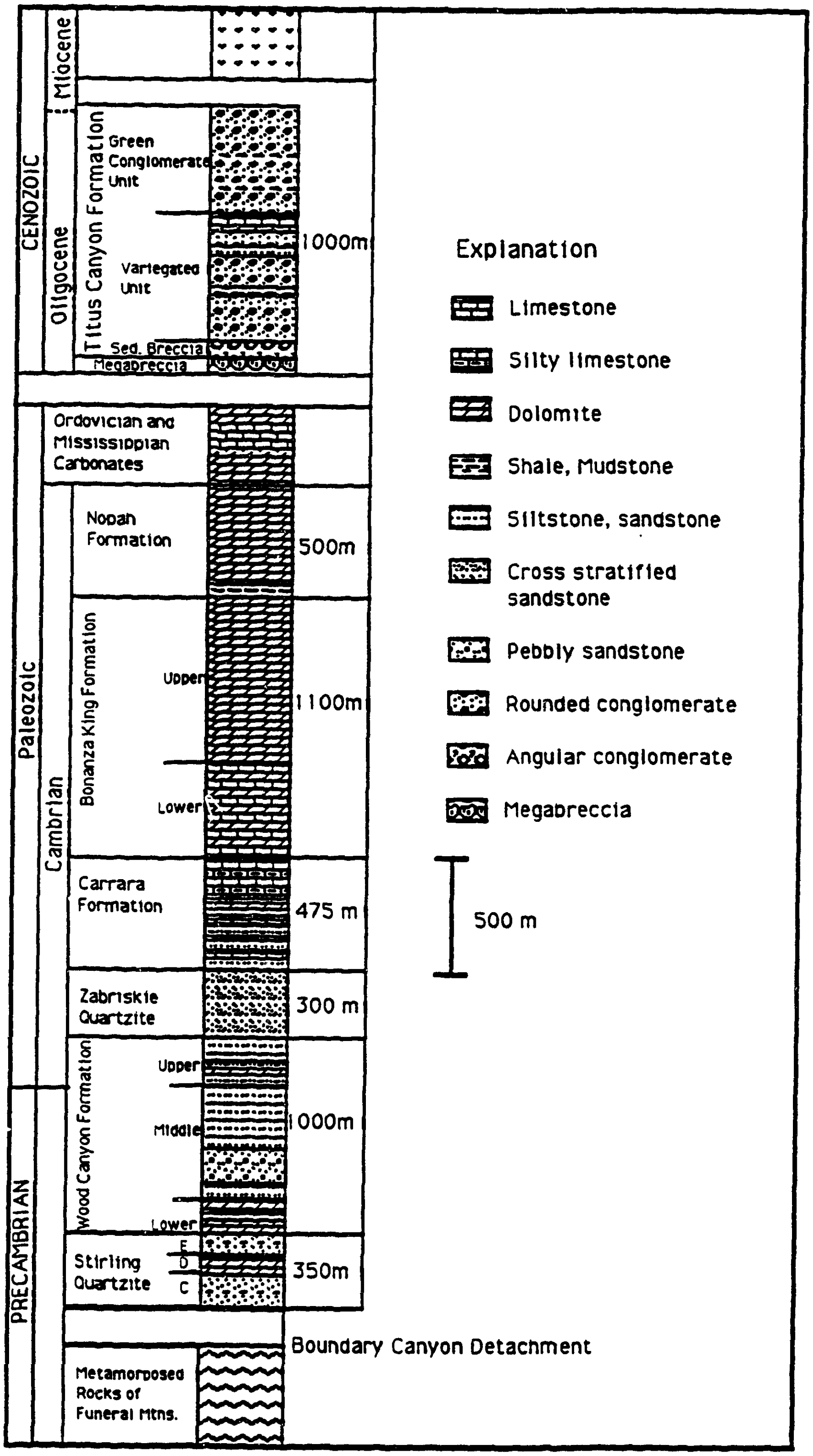
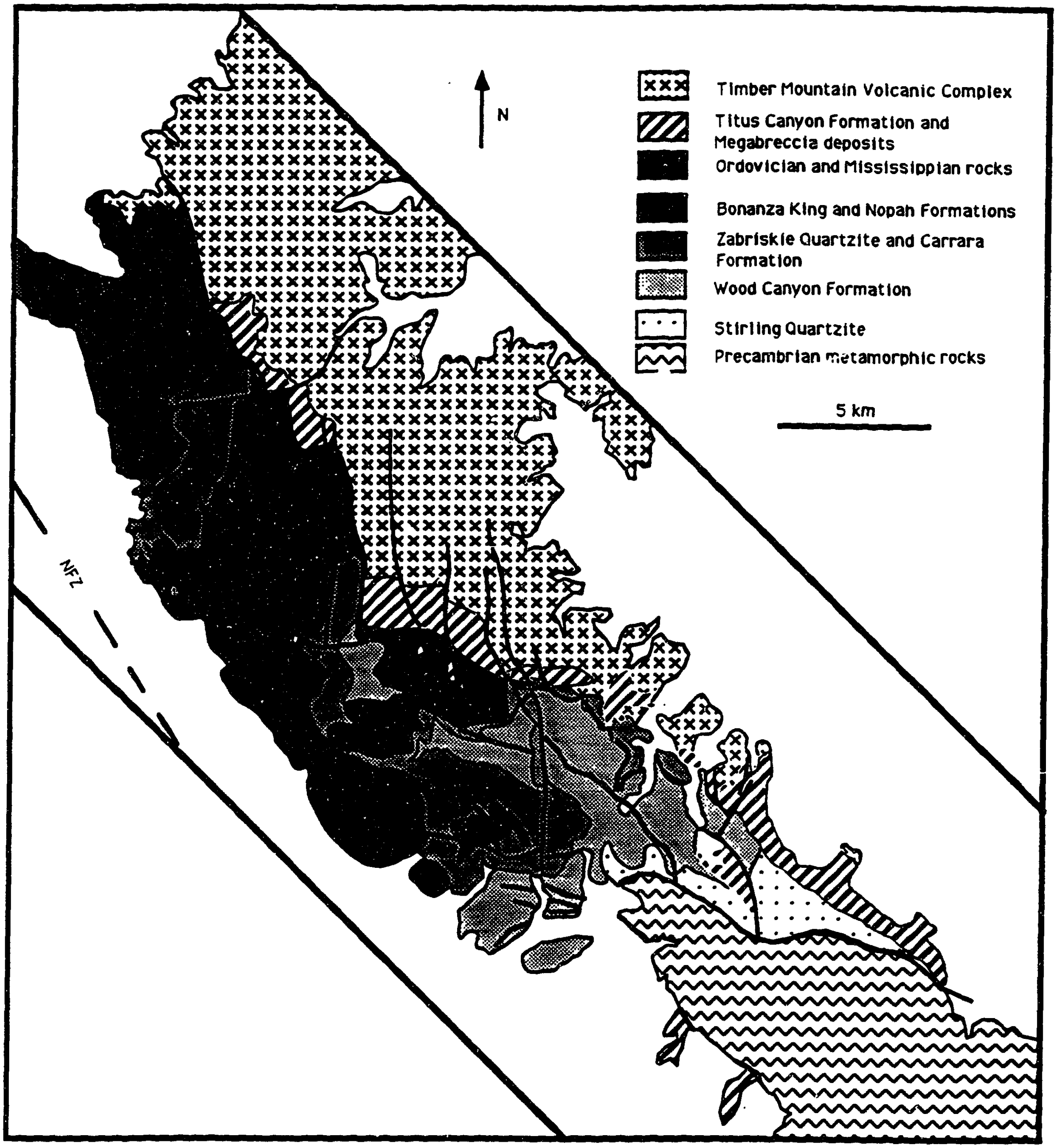
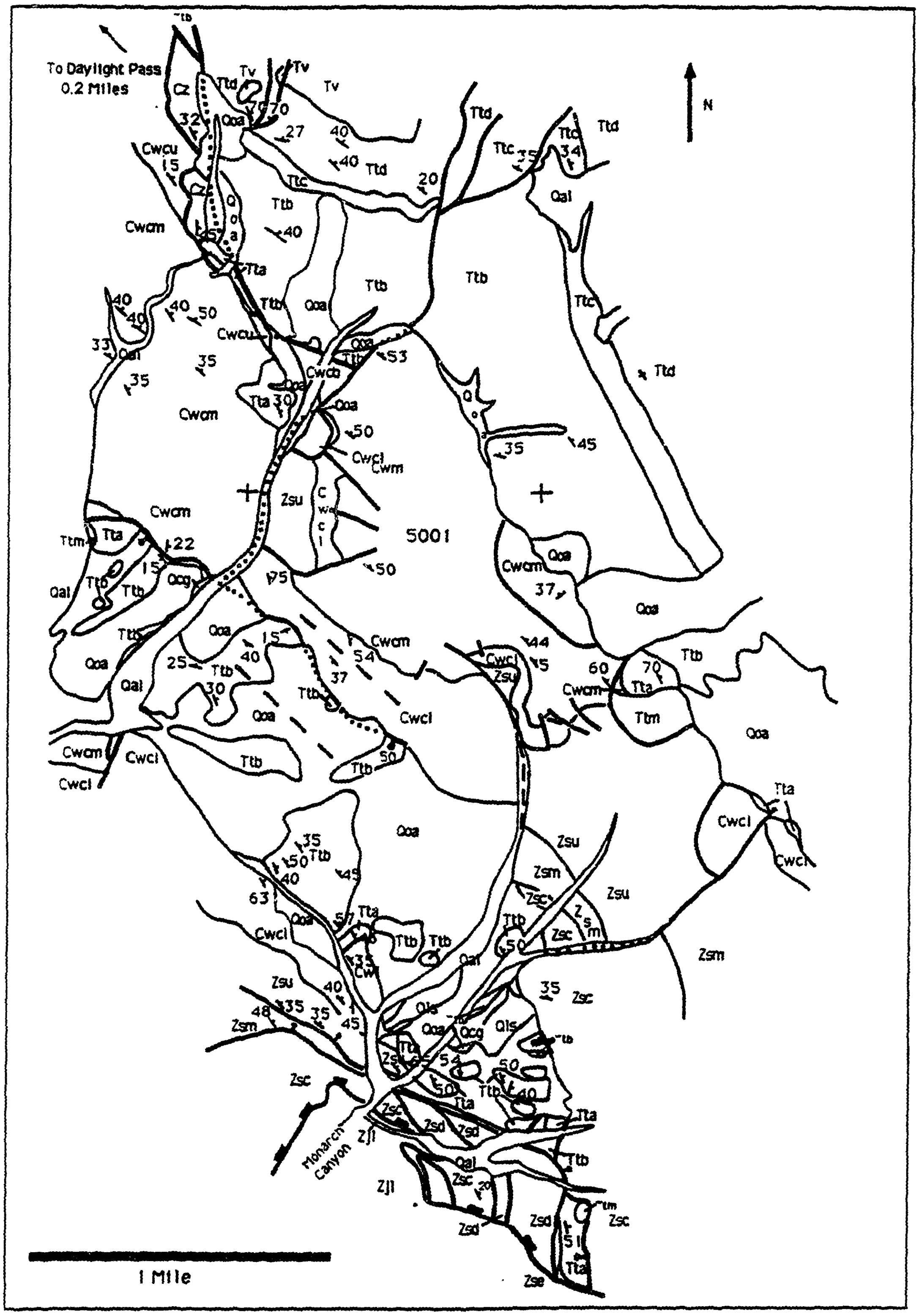

CENOZOIC
Miocene
Oligocene
Titus Canyon Formation
Green Conglomerate Unit
Variegated Unit
Sed. Breccia
Megabreccia
1000m
Paleozoic
Ordovician and Mississippian Carbonates
Cambrian
Nopah Formation
500m
Bonanza King Formation
Upper
Lower
1100m
Carrara Formation
475 m
Zabriskie Quartzite
300 m
PRECAMBRIAN
Wood Canyon Formation
Upper
Middle
Lower
1000m
Stirling Quartzite
E
D
C
350m
Boundary Canyon Detachment
Metamorposed Rocks of Funeral Mtns.
Explanation
Limestone
Silty limestone
Dolomite
Shale, Mudstone
Siltstone, sandstone
Cross stratified sandstone
Pebbly sandstone
Rounded conglomerate
Angular conglomerate
Megabreccia
500 m

Figure 5



N
Timber Mountain Volcanic Complex
Titus Canyon Formation and Megabreccia deposits
Ordovician and Mississippian rocks
Bonanza King and Nopah Formations
Zabriskie Quartzite and Carrara Formation
Wood Canyon Formation
Stirling Quartzite
Precambrian metamorphic rocks
5 km
NFZ

Figure 6



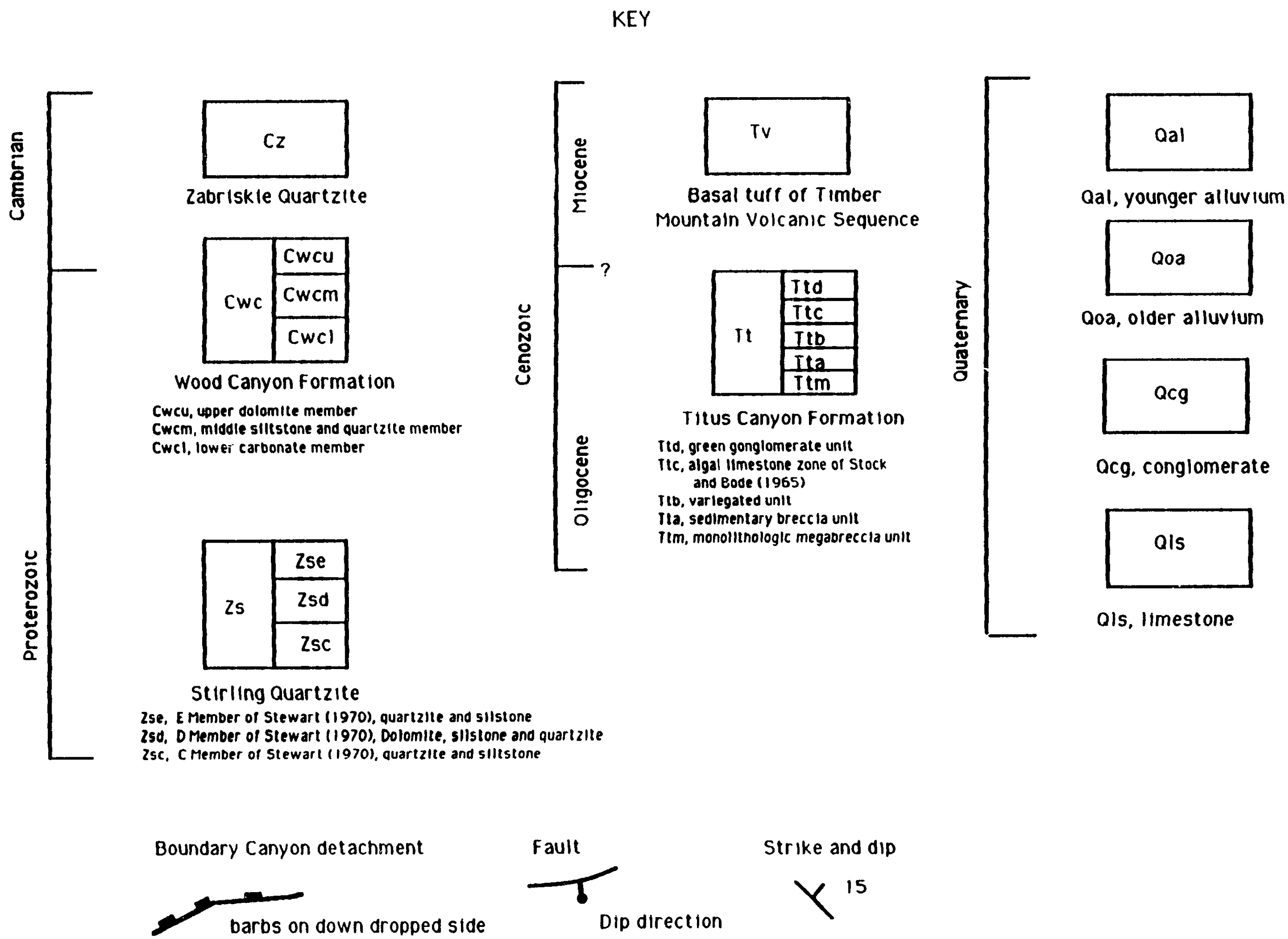

KEY
Cambrian
Proterozoic
Cz
Zabriskie Quartzite
Cwc
Cwcu
Cwcm
Cwcl
Wood Canyon Formation
Cwcu, upper dolomite member
Cwcm, middle siltstone and quartzite member
Cwcl, lower carbonate member
Zs
Zse
Zsd
Zsc
Stirling Quartzite
Zse, E Member of Stewart (1970), quartzite and siltstone
Zsd, D Member of Stewart (1970), Dolomite, siltstone and quartzite
Zsc, C Member of Stewart (1970), quartzite and siltstone
Cenozoic
Miocene
Oligocene
?
Tv
Basal tuff of Timber Mountain Volcanic Sequence
Tt
Ttd
Ttc
Ttb
Tta
Ttm
Titus Canyon Formation
Ttd, green gonglomerate unit
Ttc, algal limestone zone of Stock and Bode (1965)
Ttb, variegated unit
Tta, sedimentary breccia unit
Ttm, monolithologic megabreccia unit
Quaternary
Qal
Qal, younger alluvium
Qoa
Qoa, older alluvium
Qcg
Qcg, conglomerate
Qls
Qls, limestone
Boundary Canyon detachment
barbs on down dropped side
Fault
Dip direction
Strike and dip
15

Figure 6

Figure 7

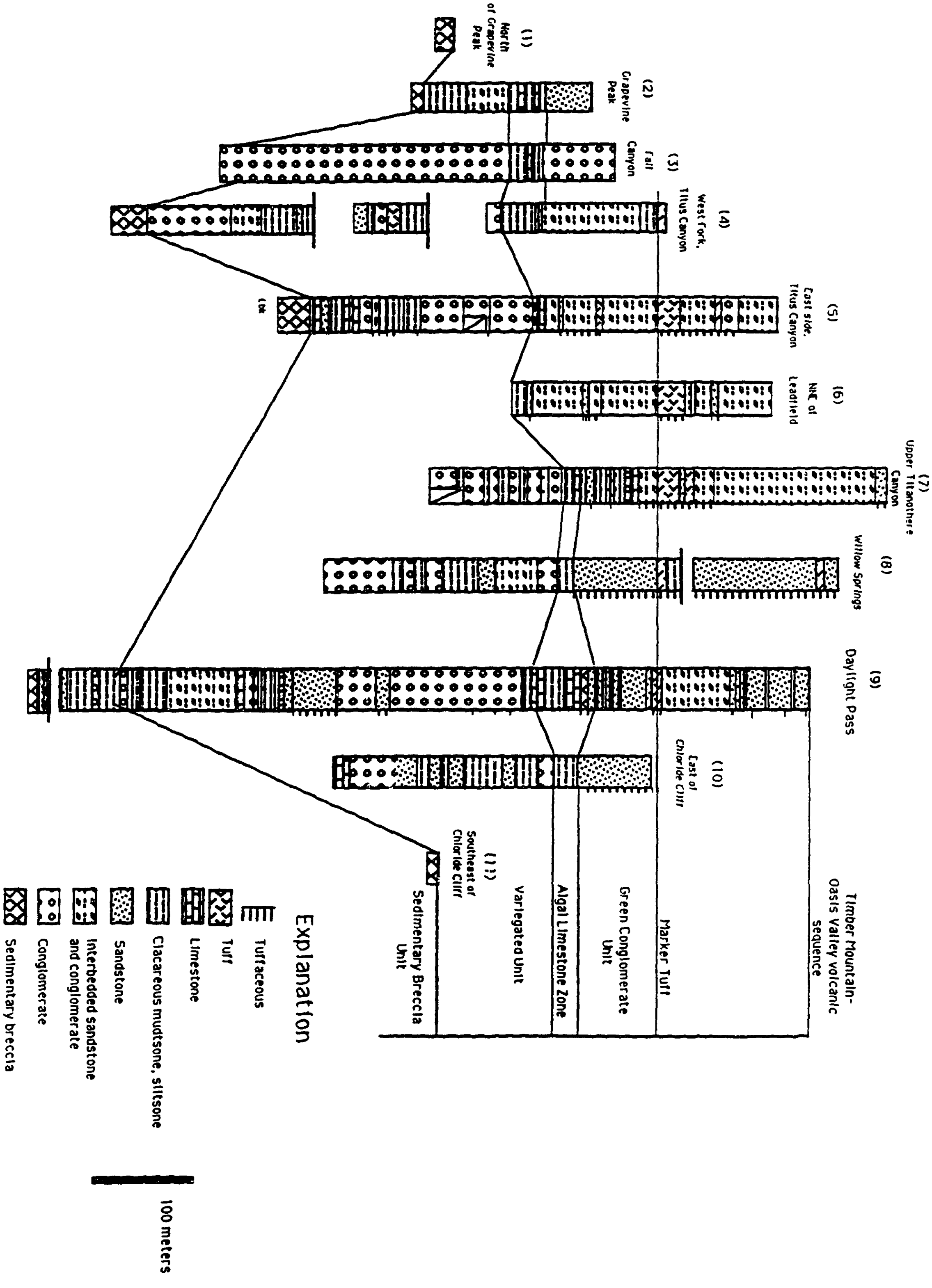

(1) North of Grapevine Peak
(2) Grapevine Peak
(3) Fall Canyon
(4) West Fork, Titus Canyon
(5) East side, Titus Canyon
(6) NNE of Leadfield
(7) Upper Titanothere Canyon
(8) Willow Springs
(9) Daylight Pass
(10) East of Chloride Cliff
(11) Southeast of Chloride Cliff
Timber Mountain-Oasis Valley volcanic sequence
Marker Tuff
Green Conglomerate Unit
Algal Limestone Zone
Variegated Unit
Sedimentary Breccia Unit
Explanation
Tuffaceous
Tuff
Limestone
Clacareous mudstone, siltsone
Sandstone
Interbedded sandstone and conglomerate
Conglomerate
Sedimentary breccia
100 meters

Figure 8

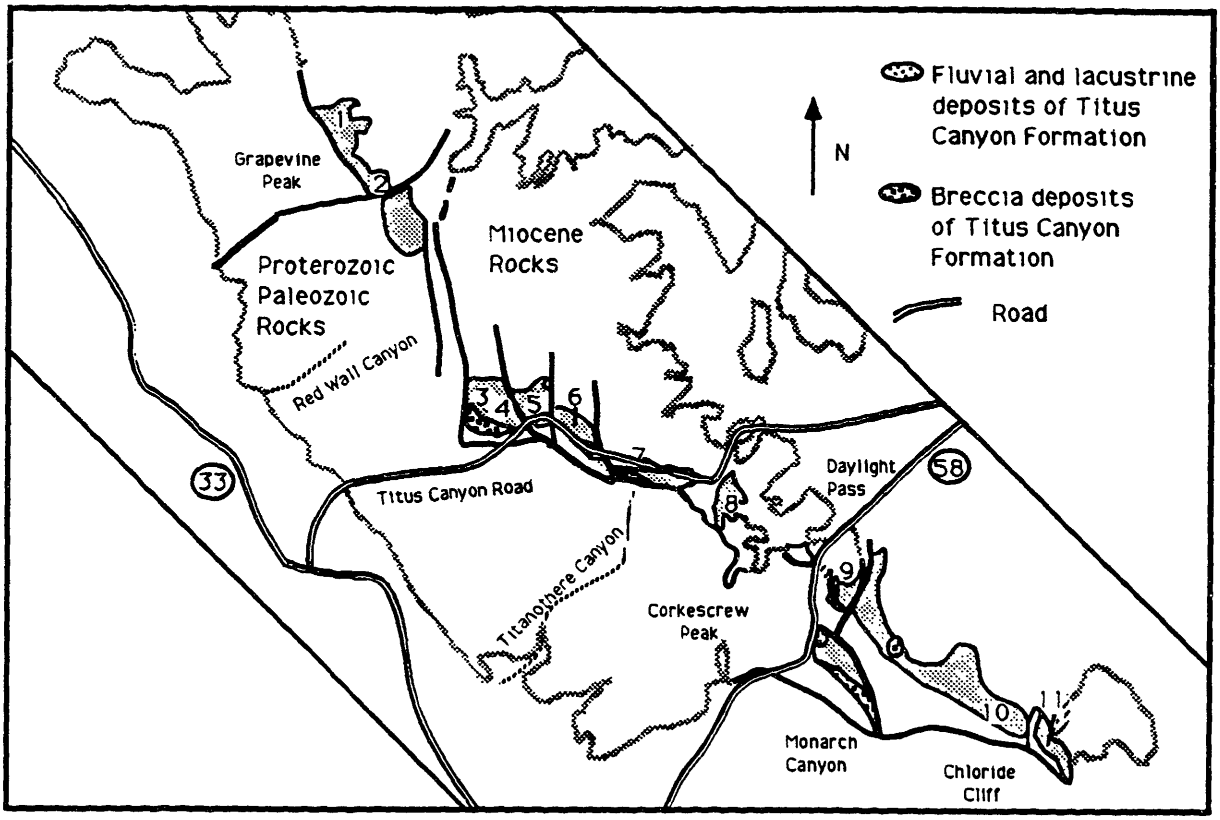

Fluvial and lacustrine deposits of Titus Canyon Formation
Breccia deposits of Titus Canyon Formation
Road
N
Grapevine Peak
Proterozoic Paleozoic Rocks
Miocene Rocks
Red Wall Canyon
Titus Canyon Road
Titanothere Canyon
Corkescrew Peak
Daylight Pass
Monarch Canyon
Chloride Cliff
33
58
1
2
3
4
5
6
7
8
9
10
11

Figure 9

Generalized Tectonic Map of the upper Monarch Canyon Daylight Pass Area

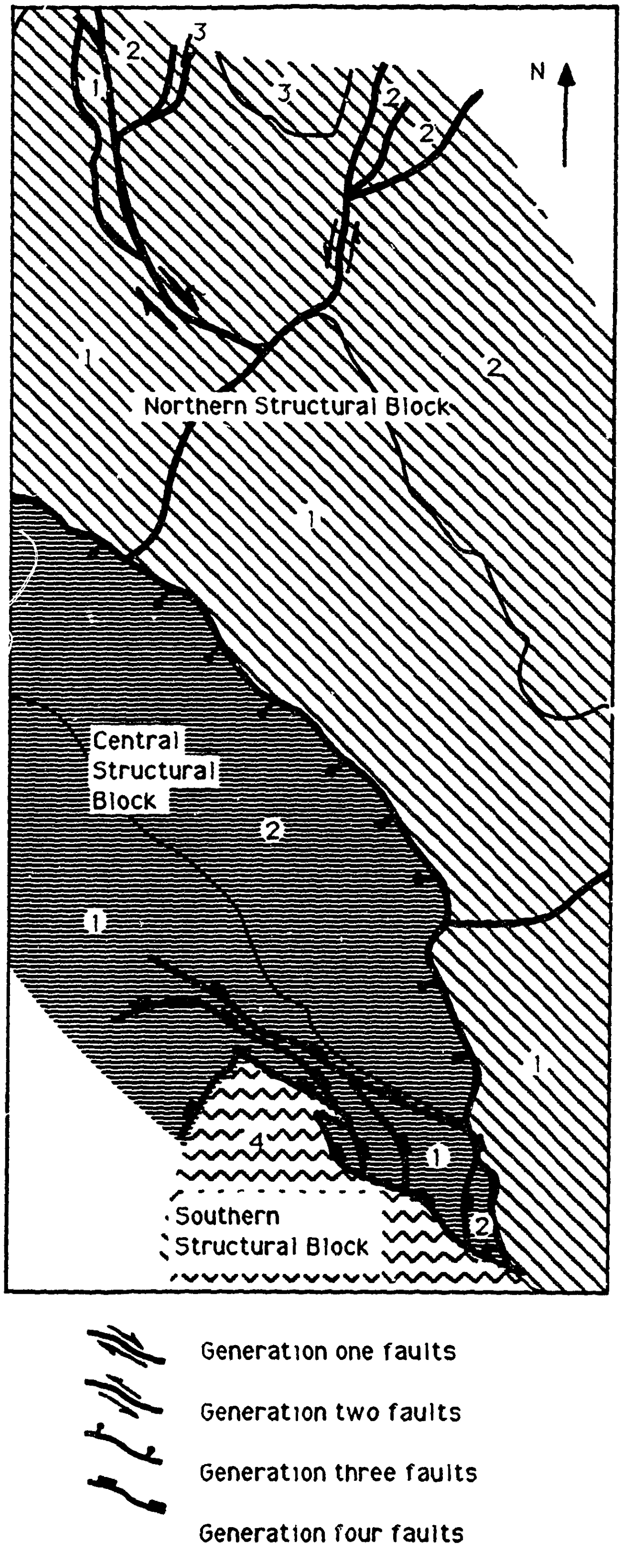
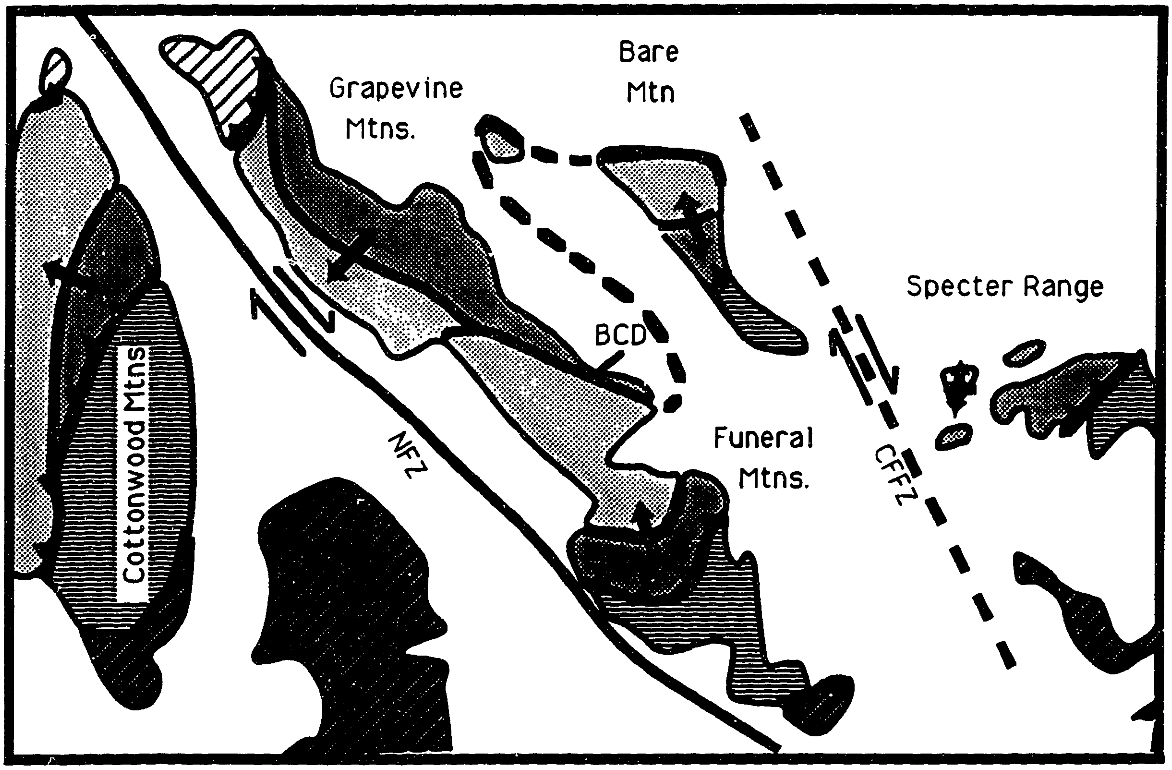


Figure 10



Rocks of Last Chance Thrust plate and equivalents

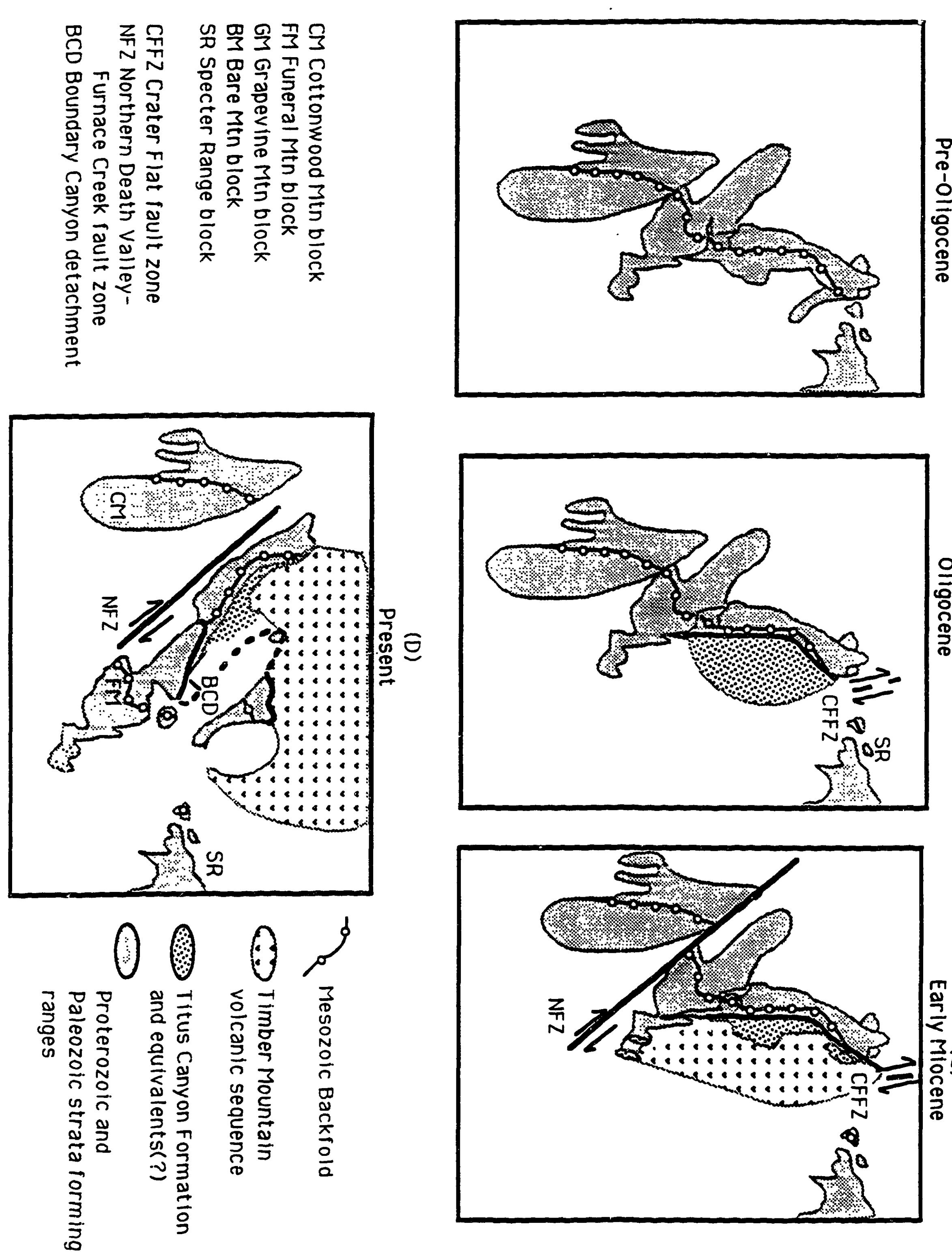
Rocks above Winters Peak anticline

Rocks above Schwaub Peak thrust

Rocks above Clery thrust

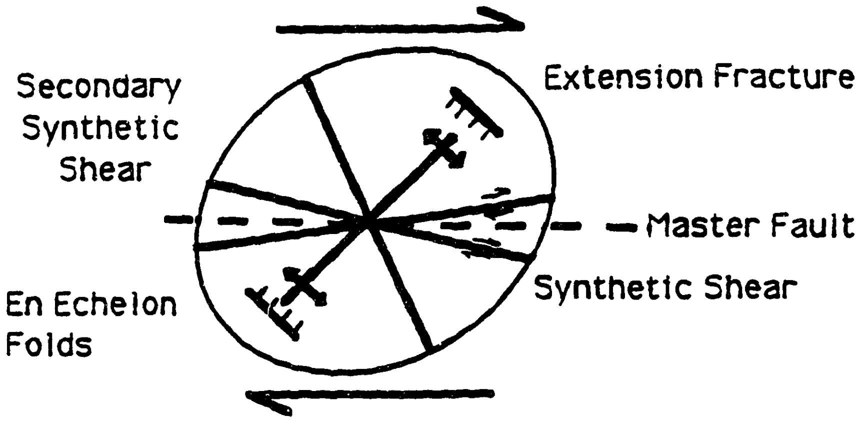
Rocks above Wheeler Pass thrust

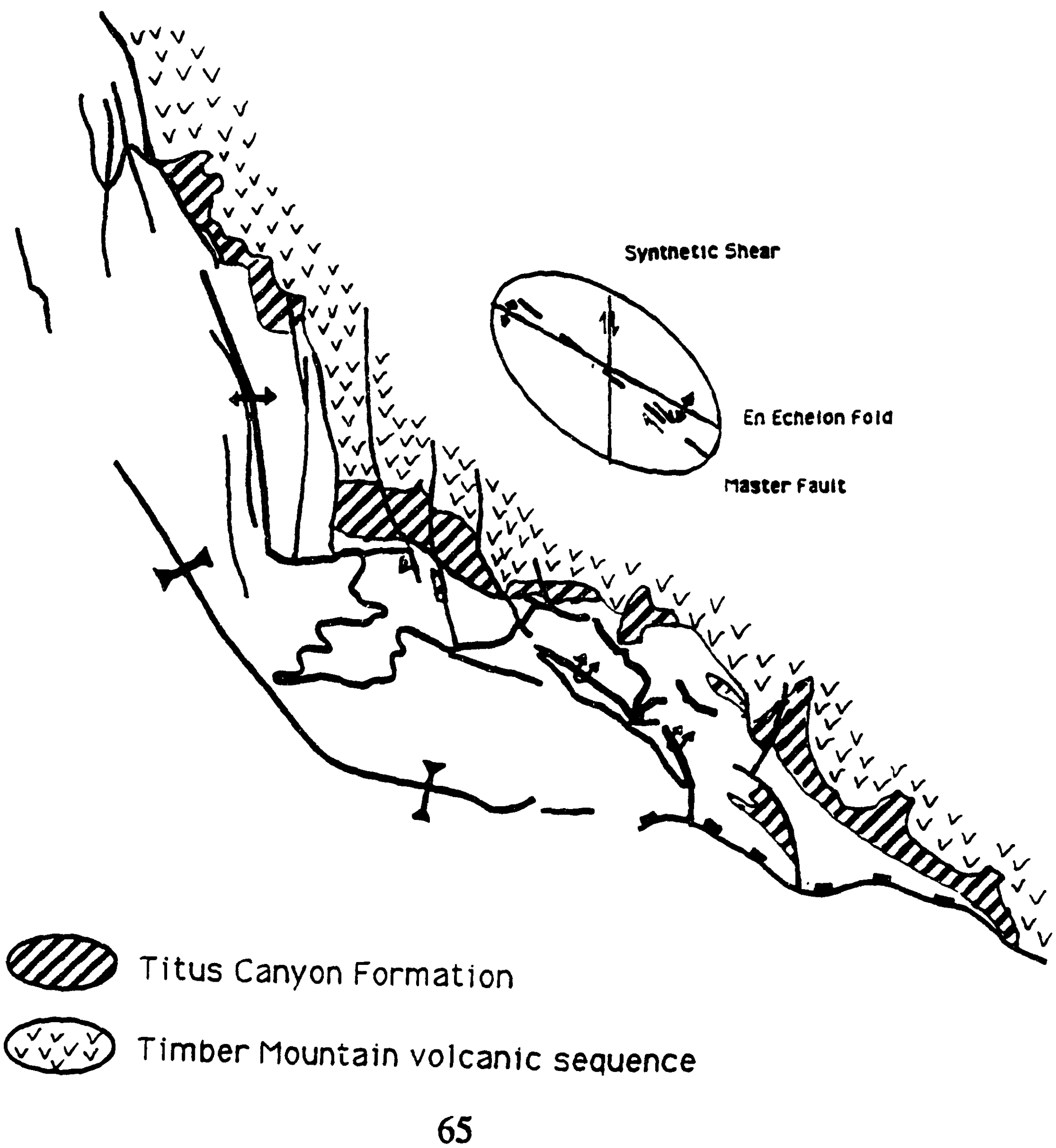
Figure 11



(A) Pre-Oligocene
(B) Oligocene
(C) Early Miocene
(D) Present
CFFZ
SR
NFZ
BCD
FM
CM
Mesozoic Backfold
Timber Mountain volcanic sequence
Titus Canyon Formation and equivalents(?)
Proterozoic and Paleozoic strata forming ranges
CM Cotonwood Mtn block
FM Funeral Mtn block
GM Grapevine Mtn block
BM Bare Mtn block
SR Specter Range block
CFFZ Crater Flat fault zone
NFZ Northern Death Valley-Furnace Creek fault zone
BCD Boundary Canyon detachment

Figure 12


Secondary Synthetic Shear
Extension Fracture
Master Fault
Synthetic Shear
En Echelon Folds


Synthetic Shear
En Echelon Fold
Master Fault
Titus Canyon Formation
Timber Mountain volcanic sequence