Tertiary Tectonic Framework and Cenozoic History of the Central Walker Lane, Nevada

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Abstract

The central part of the Walker Lane of western Nevada contains a variety of Tertiary structures that were produced during a complex history of Cenozoic deformation. On the basis of structural analysis of the various styles of Tertiary faults and tilt geometries of the Tertiary section and of the pre-Tertiary basement, the central Walker Lane can be divided into three structural domains. Domain I contains areas characterized by north-south-striking normal faults that cut both Tertiary and pre-Tertiary rocks and in which both the Tertiary and pre-Tertiary sections are strongly tilted. This domain includes the Yerington and Hall districts. Domain II includes those areas bordering the central Walker Lane on both the east and the west, where both pre-Tertiary and Tertiary sections are essentially untilted by late Cenozoic deformation. Domain III includes a large area between Yerington and Tonopah, Nevada that is characterized by a broad zone of through-going strike-slip faults and low-angle detachment faults. This domain is characterized by a slightly to strongly tilted Tertiary section that is nearly everywhere structurally detached from an untilted pre-Tertiary basement. The detachment faults are interpreted to be basal decollement surfaces of transtentional "nappes" developed in Tertiary strata overlying a pre-Tertiary basement that is undergoing strike-slip fault displacement.

Stratigraphic-structural relations in the Tertiary section and structural fabric data in the pre-Tertiary basement, combined with age , paleomagnetic, crosscutting fault, and fault-controlled dike orientation data, provide constraints for an interpretation of the tectonic evolution of the central Walker Lane. These data indicate a 70°-90° clockwise rotation of the least principle stress direction from late Oligocene time to the present. In late Oligocene to early Miocene time the central Walker Lane experienced north-northeast to south-southwest extension that resulted in east-west-trending half-grabens (well preserved in structural domain II) and strike-slip with kinematically related detachment faulting on northwest-trending high-angle faults in structural domain III. The north-northeast to south-southwest oriented extension direction predicts that lateral-slip on northwest-striking faults would have been left-lateral during this time period. During middle to late Miocene time extension was oriented east-west and resulted in the dominant listric-normal or "Yerington"-style faulting characteristic of structural domain I. From late Miocene time to the present the extension direction has been oriented northwest-southeast and has produced right-lateral displacements on northwest-striking high-angle faults.

Northwest-striking high-angle faults are the dominant structural controls for Tertiary mineral deposits in the central Walker Lane. Northwest-striking high-angle faults have been a dominant element of the tectonic framework of the central Walker Lane since Late Jurassic time. Repeated movement on these faults has produced a zone of weakness which favored shallow emplacement of magmas and associated hydrothermal activity.

Introduction

One of the most complex regions in the western Great Basin is the Walker Lane which, together with the Las Vegas Shear Zone, constitute an important Cenozoic tectonic boundary stretching from Las Vegas, Nevada to Honey Lake in northeastern California. This northwest-trending boundary flanks the western Great Basin and separates it from the Sierra Nevada. The Walker Lane, as defined by Locke and others (1940) marks an abrupt physiographic change from the typical north-northeast trending fault-bounded mountains to the east and a terrain of more heterogeneous topographic fabric to the west (Fig. 1). Geologic mapping by several workers (e.g. Ferguson and Muller, 1949; Nielsen, 1963, 1965; Hardyman and others, 1975; Hardyman, 1980, 1984; Ekren and Byers, 1984, 1985a, 1985b, 1986a, 1986b; Ekren and others, 1980) has demonstrated that the central part of the Walker Lane is a zone of pervasive strike-slip faulting.

As defined here, the central Walker Lane extends from the Carson Sink on the north to near Tonopah, Nevada on the south (Fig. 1). This segment of the Walker Lane contains a major fault zone consisting of an en echelon series of linear, throughgoing and range-bounding, northwest-striking faults. Some of the most topographically well defined and best exposed strike-slip faults within the entire Walker Lane occur within this central segment. The fault system dissects a 30-to 3-Ma (Tertiary) volcanic and interlayered sedimentary

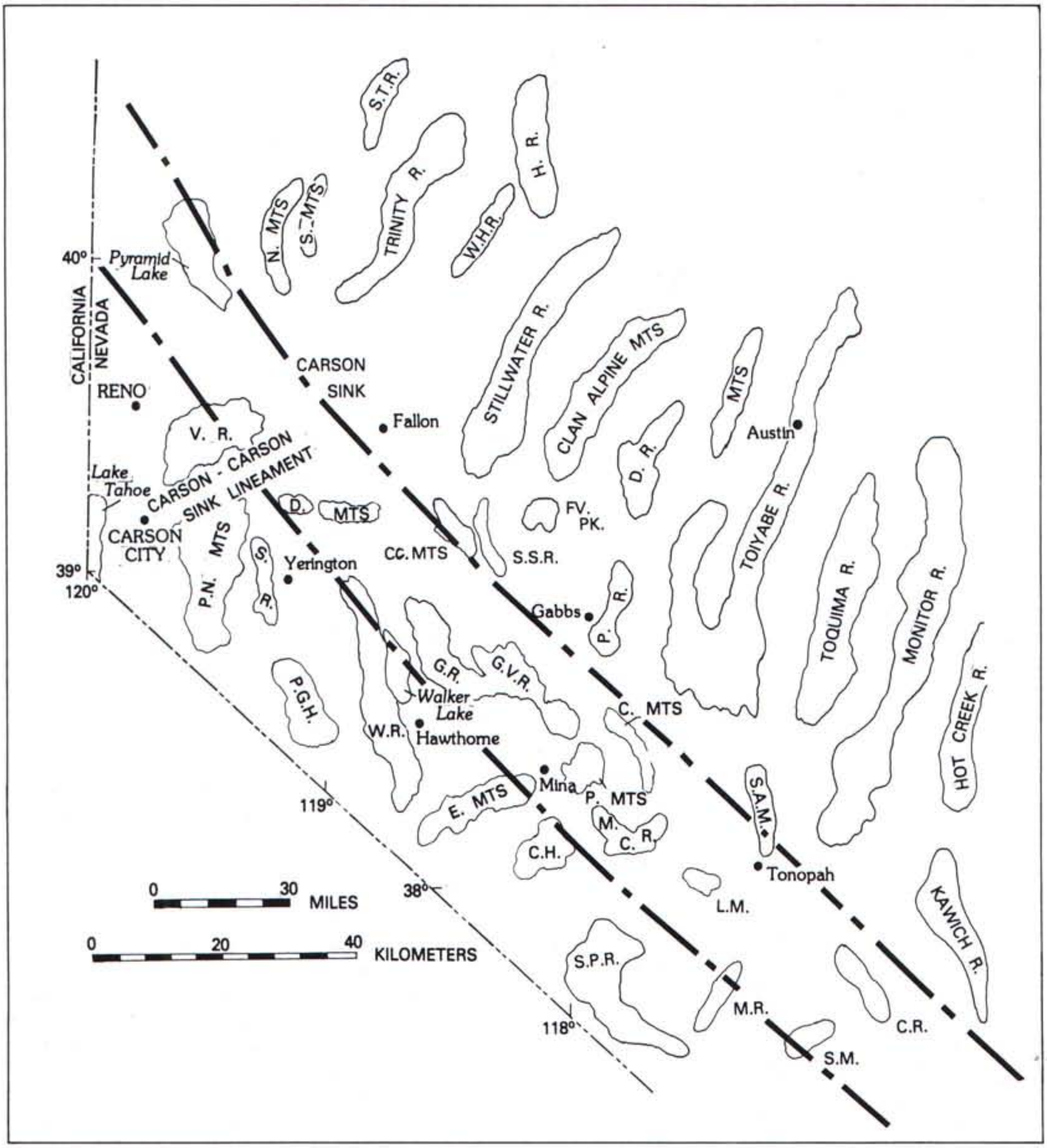


Fig. 1. Index map of western Nevada showing the Walker Lane structural zone (heavy dash-dot lines) and localities referred to in text. Abbreviations: N. MTS -Nightingale Mountains; S. MTS - Shawave Mountains; V. R. - Virginia Range; P. N. MTS - Pine Nut Mountains; S. R. - Singatse Range; D. MTS - Desert Mountains; CC. MTS - Cocoon Mountains; S. S. R. - Sand Springs Range; FV. PK. - Fairview Peak; P. R. - Paradise Range; G. V. R. - Gabbs Valley Range; G. R. - Gillis Range; W. R. - Wassuk Range; P. G. H. - Pine Grove Hills; E. MTS - Excellsior Mountains; P. MTS - Pilot Mountains; C. MTS - Cedar Mountains; C. H. - Candelaria Hills; M. C. R. - Monte Cristo Range; L. M. - Lone Mountain; S. P. R. - Silver Peak Range; M. R. - Montezuma Range; S. M. - Stonewall Mtn; C. R. - Cactus Range; D. R. - Desatoya Mountains; W. H. R. - West Humboldt Range; H. R. - Humboldt Range; S. T. R. - Sant Rosa Range.

sequence unconformably overlying a basement composed of Mesozoic plutons and complexly deformed Paleozoic and Mesozoic sedimentary and volcanic rocks.

In this paper, we focus on the various Tertiary structures of the central Walker Lane and present a summary of our working hypothesis for the Cenozoic history of the region. We also summarize the pre-Tertiary history of west-central Nevada in light of the significance of pre-Tertiary structures to the Cenozoic history. Our interpretation of the Cenozoic history of the central Walker Lane is based on a regional compilation of the structural and stratigraphic relations within the Tertiary section, the structure and stratigraphy of pre-Tertiary rocks, and paleomagnetic data from Mesozoic plutons. Structures affecting the Tertiary rocks, their contact relations with pre-Tertiary rocks, and structural configuration of the pre-Tertiary sections from the Yerington district, across the zone of Walker Lane strike-slip faults, to the Hall deposit near Tonopah are compared. The integration of these relationships is necessary to understand the spatial and temporal development of the tectonic framework for ore deposits in the central Walker Lane.

Pre-Tertiary Tectonic Framework

The pre-Tertiary stratigraphy of the central Walker Lane is dominated by sedimentary and volcanic rocks of the Mesozoic marine province of the northwestern Great Basin (Speed, 1978; Oldow, 1984a). Locally, particularly in the southern part of the central Walker Lane, older units of Paleozoic age are preserved. The lower Paleozoic succession consists of miogeoclinal carbonate rocks structurally overlain by partially coeval chert, argillite, and volcanic units of deep basinal affinity (Stewart, 1980; Oldow, 1984b). Likewise, upper Paleozoic to lowermost Mesozoic rocks are composed of shelf carbonate and clastic units structurally overlain by age-equivalent chert, argillite, and volcanic rocks (Speed, 1977; Stewart, 1980).

The Paleozoic and Mesozoic history of the central Walker Lane is dominated by three major tectonic events; the first two involve episodes of middle Paleozoic and late Paleozoic to early Mesozoic thrusting and the third consists of an episode of thrusting and associated transpressional faulting during the middle Mesozoic (Speed and others, 1988; Oldow and others, 1989). The middle Paleozoic emplacement of the Roberts Mountains thrust interrupted carbonate and clastic deposition in a passive margin setting and resulted in the tectonic juxtaposition of complexly deformed deep-marine sedimentary and volcanic rocks with coeval platformal units (Stewart, 1980; Johnson and Pendergast, 1981; Speed and Sleep, 1982; Oldow, 1984b). During the Permian and Triassic, the Golconda thrust system carried basinal and volcanic rocks (Silberling, 1975; Speed, 1977, 1979; Speed and others, 1988; Miller and others, 1989; Oldow and others, 1989) eastward over coeval shelf to platform carbonate and clastic units. Lower Triassic through Lower Jurassic basinal, volcanic archipelago, and continental shelf successions deposited in and around a marginal basin lying to the east of the Mesozoic Sierran magmatic arc (Speed, 1978; Oldow, 1984b; Oldow and Bartel, 1987) are strongly imbricated in the Luning-Fencemaker thrust belt (Oldow, 1983, 1984a), resulting in profound juxtaposition of rocks deposited in different parts of the Mesozoic marine province. Middle Mesozoic contractional deformation generally is not accompanied by metamorphism, but locally conditions of amphibolite grade were achieved (Chan, 1988) and are associated with exhumed deep parts of the thrust belt. The western boundary of the Luning-Fencemaker thrust belt is marked by the northwesterly-trending Pine Nut transpressional fault system (Fig. 2). The Pine Nut fault system developed together with southeasterly-directed thrusting in the region to the east and served to separate most of the rocks of the marine province from the Sierra Nevada to the west (Oldow and Gelber, 1987; Satterfield and Oldow, 1989).

Within the central Walker Lane, the basal thrusts of the contractional belts are discontinuously exposed across numerous mountain ranges. The trace of the Roberts Mountains thrust is not well defind but is thought to lie in the southern part of the region (Stewart, 1980; Oldow, 1984b; Speed and Sleep, 1982). The Golconda thrust is expressed locally and is overlain by lower Mesozoic volcanic and clastic units. Most exposures of pre-Tertiary rocks in the eastern part of the central Walker Lane are composed of strongly deformed Mesozoic rocks of the upper plate of the Luning-Fencemaker thrust system and the less deformed units of the lower plate (Oldow, 1981, 1983, 1984a). The western part of the central Walker Lane, lying west of the Pine Nut fault system, is underlain by Mesozoic rocks that do not have the same structural history as their counterparts to the east (Fig. 2). Though depositionally related to the Mesozoic marine province, rocks west of the Pine Nut fault share a structural affinity with units of the Sierra Nevada (Oldow, 1983, 1984a; Oldow and others, 1984).

The minimum age of deformation in the Luning-Fencemaker thrust belt is constrained by widespread post-kinematic plutons, which generally yield K/Ar ages on biotite and hornblende of about 100 to 75 Ma (Evernden and Kistler, 1970; Robinson and Kistler, 1986). The age of inception of this middle Mesozoic fold-thrust belt is less well established but appears to be Middle Jurassic on the basis of $^{40}Ar/^{39}Ar$ ages from syntectonic amphiboles collected from mylonites associated with thrusting (Chan, 1988).

Three and locally four phases of folds and associated thrusts are recognized in the Luning-Fencemaker belt. The first regionally extensive structures are northeast-trending folds, which were formed during southeasterly directed thrusting (Oldow, 1978, 1981, 1984b). The northeast-trending folds are generally tight to isoclinal, major and minor structures with a penetrative axial-planar cleavage. They are found throughout the part of the central Walker Lane lying to the east of the Pine Nut fault (Fig. 2). Superposed northwesterly-trending open to tight folds, with locally developed spaced cleavage, also are universally developed. A third phase of major and minor, gentle to close folds are sporadically developed and trend north-south and N60oE. Locally, in the areas near the Pine Nut fault system, earlier structures, commonly associated with amphibolite grade dynamothermal metamorphism (Satterfield and Oldow, 1989), are developed. These earlier structures predate the Luning-Fencemaker thrust system and are related to well developed structures in the region lying to the west of the Pine Nut fault (Oldow and Gelber, 1987).

West of the Pine Nut fault, Mesozoic structures are characterized by multiple phases of northwesterly-trending folds (Oldow, 1984b; Oldow and others, 1984). West of the Pine Nut fault, in areas unaffected by large scale Tertiary tilt, one and locally two phases of northwest-trending folds are observed. In areas of Tertiary tilt such as the Yerington region, removal of the Tertiary tilt restores the Mesozoic folds to their original pre-Tertiary northwest-trending orientations. As the Pine Nut fault is approached from the west, recrystallization and the bulk strain in the deformed rocks increase. Locally, northwesterly-trending structures are cross-cut by post-kinematic plutons which have yielded zircons dated at 167 to 169 Ma

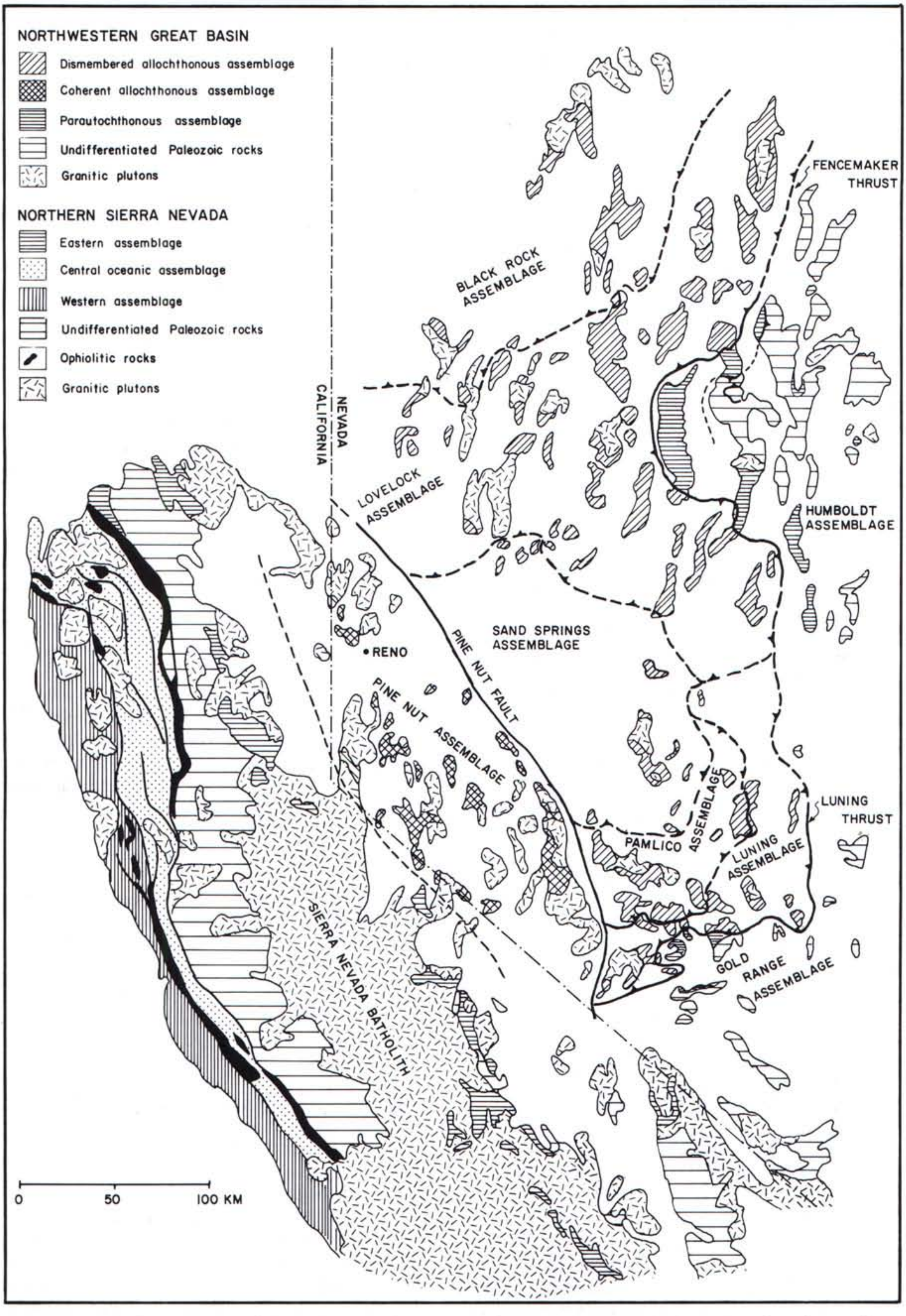


Fig. 2. Generalized geologic map of the northwestern Great Basin and northern Sierra Nevada showing the distribution of pre-Tertiary layered and plutonic rocks. Modified from Oldow (1984a).

(Dilles and Wright, 1988). Volcanic equivalents of the plutons overlie the deformed rocks with angular unconformity and are themselves broadly deformed in northwesterly structures (Dilles and Wright, 1988; Proffett and Dilles, 1984; Oldow, unpublished data).

The Middle Jurassic to mid-Cretaceous northwest-trending Pine Nut fault system is interpreted to be an intra-arc transpressional fault associated with Mesozoic active margin tectonism (Oldow, 1983, 1984a; Ave'Lallemant and Oldow, 1988; Oldow and others, 1989). The trace of the Mesozoic structure is obscured by alluvium, but its location is well constrained by the juxtaposition of coeveal Mesozoic rocks with dramatically different structural histories. The fault system represents a major regional structure and can be considered the ancestor of many of the Cenozoic structures in the central Walker Lane. Certainly, the structural grain associated with this transpressional fault system must have influenced younger structures. Reactivation of northwest-striking faults or lateral-slip on preferentially oriented zones of weakness during north-northeast to south-southwest and later northwest to southeast-oriented Cenozoic extension (discussed below) probably nucleated the dominant northwest-striking Cenozoic strike-slip faults in the central Walker Lane.

Tertiary Tectonic Framework

Cenozoic Stratigraphy

The Cenozoic stratigraphy of the central Walker Lane is dominated by volcanic and volcanogenic sedimentary rocks with an aggregate thickness in excess of 4.5 km. This succession of rocks is divided into three volcanotectonic assemblages consisting of: (1) a lower sequence of intermediate lavas overlain by siliceous ash-flow tuffs and minor sedimentary rocks with a combined thickness between 1.5 to greater than 3.0 km (Proffett and Proffett, 1976; Proffett, 1977; Ekren and others, 1980; Hardyman, 1978; Speed and Cogbill, 1979b; Robinson and Stewart, 1984; John and others, 1989a, 1989b), (2) a middle sequence composed of andesitic flows, lahars, and associated hypabyssal rocks (Proffett, 1977; Dockery, 1982, Garside, 1979; Ekren and others, 1980; Hardyman, unpublished mapping; John and others, 1989a, 1989b) exhibiting great variation in thickness laterally (150 m to greater than 1.0 km), and (3) an upper assemblage composed predominantly of basalt and basaltic appearing flows with aggregate thicknesses of 100 to 150 m and sparse rhyolite flows and domes (Morrison, 1964; Bonham and Garside, 1979; Speed and Cogbill, 1979b; Ekren and others, 1980; Ekren and Byers, 1985b).

The lower succession is dominated by ash-flow tuff units that range in composition from rhyodacite to rhyolite and yield K/Ar ages from 29 to 20 Ma (Proffett and Proffett, 1976; Proffett, 1977; Ekren and others, 1980; McKee and John, 1987). This succession contains numerous ash-flow tuff cooling units separated by unconformities locally marked by bedded tuffaceous sedimentary rocks or thin lava flows. Some of the ash-flow tuff units have regional areal extents and have been correlated across several mountain ranges in the central Walker Lane (Ekren and others, 1980; Proffett and Proffett, 1976; John, 1988; John, unpublished data; Hardyman, unpublished data). Likewise, several of the unconformities within the tuff sections are recognized throughout the region and are important markers (Keller and others, 1987, 1989a, 1989b).

Andesitic rocks overlying the lower ash-flow tuff dominant succession consist mainly of lava flows, flow breccias, mudflow breccias and lahars, and associated dikes and plugs. These younger intermediate-composition volcanic rocks consistently yield 20-to 15-Ma K/Ar isotopic ages (Proffett, 1977; Marvin and others, 1977; Ekren and others, 1980; McKee and John, 1987; John and others, 1989a, 1989b; Oldow, unpublished data) and unconformably overlie and intrude the silicic tuff succession and locally the pre-Tertiary basement. Units of the andesitic succession exhibit dramatic lateral thickness changes (150 m to greater than 1.0 km) interpreted to be related to topography during deposition (Dockery,1982; Meinwald, 1982).

Widespread interbedded basaltic lava and Miocene volcanogenic sedimentary units, ranging in age from about 12 to 3 Ma (Proffett, 1977; Speed and Cogbill, 1979a; Bonham and Garside, 1979; McKee and John, 1987; John and others, 1989b; Fultz and others, 1983; John and McKee, unpublished data) and a few areally restricted rhyolite flows and domes comprise the upper volcanic assemblage in the central Walker Lane. The basaltic rocks depositionally overlie all older Tertiary units and are found in depositional contact with pre-Tertiary basement units. Locally, the younger basaltic rocks lie with marked angular unconformity on steeply tilted rocks of the siliceous tuff and andesitic units in the Yerington district (Proffett, 1977) and elsewhere overlie the andesitic rocks with little disconformity as in the Candelaria Hills (Speed and Cogbill, 1979b).

Cenozoic Structural Domains

Three structural domains (I, II, and III) are recognized in the central Walker Lane (Fig. 3) and are defined on the basis of tilt geometries of the Tertiary section and pre-Tertiary basement and contact relations between pre-Tertiary and Tertiary units (Keller and others, 1987, 1989a, 1989b). The characteristics of each domain are briefly outlined below.

Domain I: Areally restricted regions in which both the pre-Tertiary basement and the unconformably overlying Tertiary section are strongly tilted. This domain includes the Yerington and Hall mining districts.

Within the central Walker Lane region, probably the most publicized Cenozoic structures are those of the Yerington mining district. There, a detailed program of mapping, geochronology, and drilling related to min-

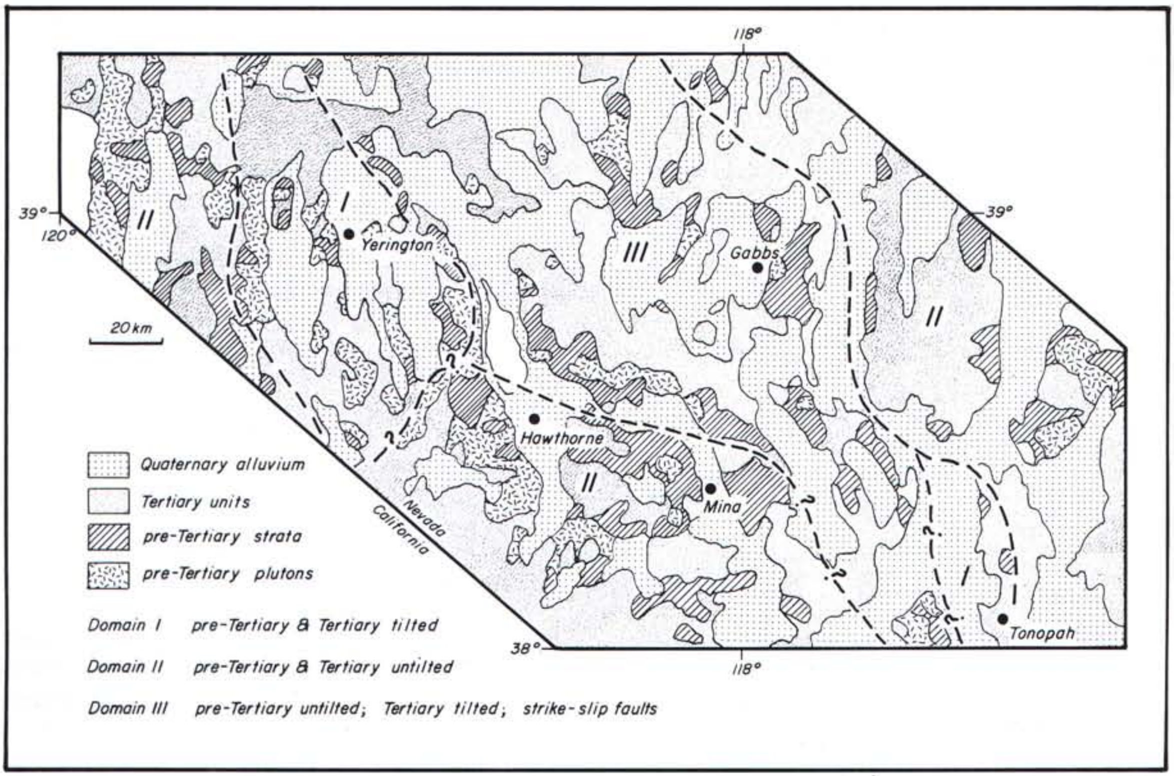


Fig. 3. Generalized geologic map of the central Walker Lane illustrating the distribution of Tertiary structural domains (I, II, III) discussed in the text. Modified from Keller and others (1989a).

eral exploration produced one of the best documented examples of low-angle normal faults in the Great Basin (Proffett, 1977; Proffett and Dilles, 1984). In this area, Tertiary volcanic and sedimentary rocks (the lower and middle Tertiary stratigraphic assemblages outlined above) dip steeply into shallowly dipping to horizontal tectonic contacts which separate Tertiary units from underlying pre-Tertiary basement rocks. Steeply dipping Tertiary rocks are overlain depositionally by shallowly dipping volcanic and associated sedimentary rocks (younger basalt-sediment-rhyolite assemblage of above). In several locations, preserved depositional contacts between the pre-Tertiary basement and the basal Tertiary rocks of the lower assemblage are preserved and have steep dips (Proffett and Dilles, 1984). These preserved depositional contacts and the results of a detailed paleomagnetic study of Jurassic plutons and extrusive equivalent volcanic rocks in the basement (Geissman and others, 1982) conclusively demonstrate that the pre-Tertiary rocks were involved in the deformation that produced the profound tilts of the Tertiary units. Proffett (1977) used the detailed geologic observations to construct the classic Yerington model for successively developed listric normal faults. Similar structures have been documented in the Hall district of the San Antonio Mountains (Shaver and McWilliams, 1987) lying about 20 km north of Tonopah and are inferred by Seedorff (1981; in press, this volume) to exist in the Royston district about 20 km west of the Hall district (Fig. 3).

Although the structural characteristics and the history of structural development of the Yerington district, and to a lesser degree the Hall district, are well established, the boundaries of these structural domains are not well known. The lateral extent of the structures has been addressed in reconnaissance (Keller and others, 1987, 1989a, 1989b) but the boundary regions are often obscured by younger (<10 Ma) volcanic rocks and alluvium. Regardless, regions of large-scale extension underlie relatively restricted and structurally isolated parts of the central Walker Lane region. The Yerington district, which is characterized by westerly tilted strata, and the easterly tilted rocks in the Hall district lie on the flanks and at opposite corners of the northwest-trending zone of strike-slip faults through the central Walker Lane.

Domain II: A broad region bordering the central Walker Lane on both the east and west, in which the pre-Tertiary and Tertiary sections are essentially untilted by Cenozoic structures. In this domain (Fig. 3), Tertiary volcanic and sedimentary rocks have low dips (dips generally less than 25°) and are disrupted by high-angle faults exhibiting only a few tens to hundreds of meters of stratigraphic offset. In these regions, paleomagnetic studies of middle to Late Cretaceous plutons, as well as remagnetized host sedimentary and volcanic rocks, in the pre-Tertiary basement document the lack of significant tilt or vertical axis rotation (Geissman and others, 1984; Geissman, unpublished data; Callian and others, 1988). Paleomagnetic directions from these plutons are in general agreement with predicted directions based on paleomagnetic poles of comparable age for stable North America.

Domain III: A northwest-southeast-trending zone up to 70-km-wide that contains subparallel, strike-slip faults. The zone covers more than 6,000 km2 between Yerington and Tonopah, Nevada. This domain is characterized by a generally strongly tilted Tertiary section (attitudes ranging from 25° to near vertical) that is structurally detached from an untilted pre-Tertiary basement.

Strike-slip faults in this domain are high-angle structures with linear, through-going map traces and exhibit structural and geomorphological characteristics typical of major strike-slip faults. Tertiary strata in this domain display tilt geometries similar to those observed in Tertiary units of the Yerington and Hall districts (Domain I), and in most places, Tertiary rocks dip moderately to steeply into low-angle to flat-lying fault contacts above the Mesozoic basement rocks.

The critical distinction between tilted Tertiary units and associated low-angle faults in domains I and III, however, is that the deformation that produced the tilt and the faults in domain III did not involve the Mesozoic basement. Structural fabrics of polyphased deformed Mesozoic rocks in this domain (Fig. 4a,b) are indistinguishable from those in Domain II, where the Tertiary strata is essentially untilted (Oldow, 1984a; Oldow and others, 1984; Oldow and others, in preparation). Paleomagnetic data from Mesozoic plutons as well as remagnetized host sedimentary and volcanic rocks both in domains II and III (Fig. 4c) indicate that the basement has experienced negligeable tilt or vertical axis rotation (Geissman and others, 1984; Callian and others, 1982, 1985, 1988; Geissman and others, in preparation). Likewise, the faults bounding the tilted Tertiary strata do not penetrate the Mesozoic basement rocks. The Tertiary rocks in Domain III are detached from, and variably tilted above, untilted Mesozoic basement.

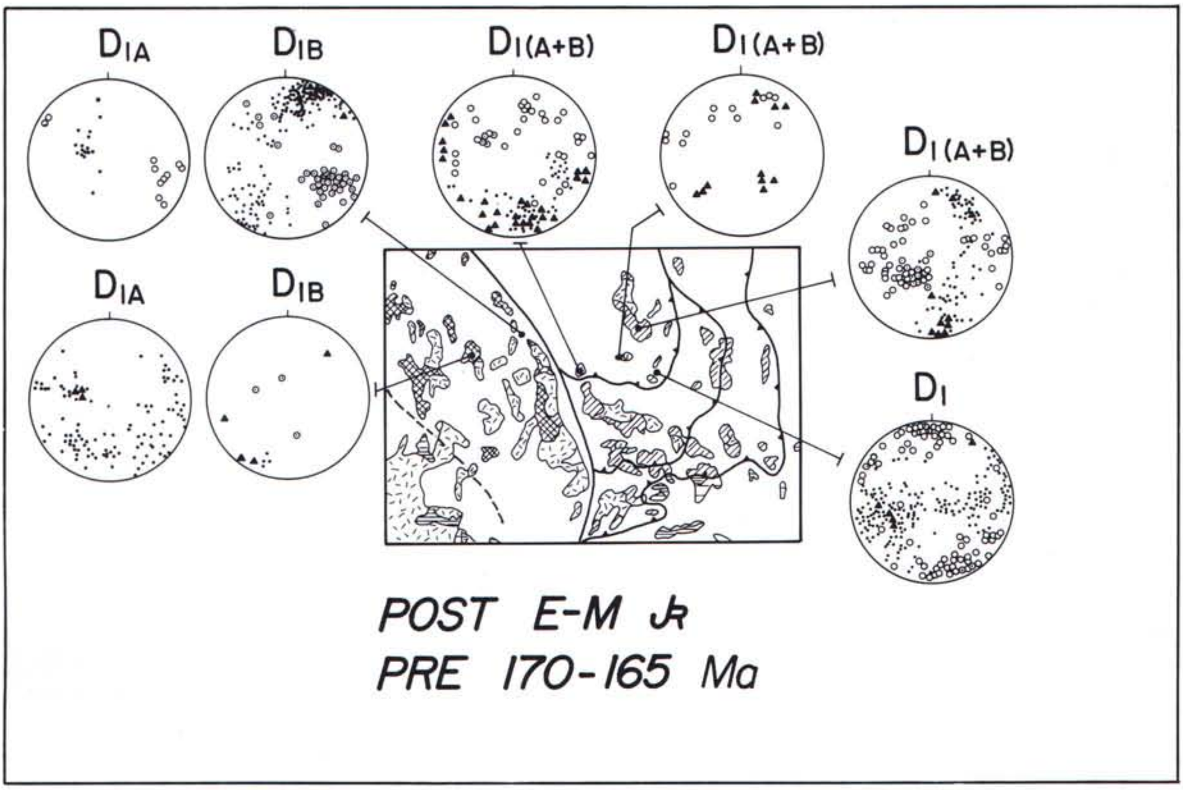
Timing and Styles of Cenozoic Structures

Various styles of faults comprise the Cenozoic structures of the central Walker Lane. They include northwest-striking strike-slip faults, listric normal faults, planar high-angle normal and oblique-slip faults and low-angle detachment faults. In many cases, associations of particular fault styles appear to be genetically related and correspond to particular structural domains outlined above. In addition to the various styles of faults, east-northeast-trending half-grabens occur in the central Walker Lane irrespective of the three structural domains. These half-grabens record an early history of extension largely obscured by later deformation. To integrate the structural characteristics of the three tectonic domains into a comprehesive picture of the tectonic evolution of the region, careful consideration must be given to the field relationships that provide constraints on the timing of various styles of faults and fault related structures. A review of the various styles of faults and related structures is given below.

Half-grabens: Some of the oldest Cenozoic structures in the central Walker Lane are best preserved in the relatively undeformed Tertiary rocks of domain II. In three locales, the Candelaria Hills, northern Pilot Mountains, and northern Garfield Hills, major (1.0 to 1.5 km deep) Oligocene to Miocene half-grabens are exposed. The half-grabens consistently are bound on their southern flank by major down-to-the-north faults which strike east-northeast (Speed and Cogbill, 1979a; Dockery, 1982; Meinwald, 1982; Oldow, 1985; Oldow and Steuer, 1985; Oldow and Speed, 1985). The master fault systems often can be traced for 8 to 10 km and, as in the case of the northern Pilot Mountains, occasionally exhibit dramatic dog-leg morphologies (Fig. 5a). The age of the half-grabens is indicated by Oligocene tuffs as old as 28 Ma (Marvin and others, 1977; Dockery, 1982; Oldow and Steuer, 1985) which thicken dramatically into the axis of the asymmetric basins (Figs. 5b,c, 6, 7). Later extrusion of andesitic rocks apparently straddled the period of active displacement on the bounding master-fault systems. In the Pilot Mountains and northern Garfield Hills (Fig. 6), 19-to 17-Ma andesite flows and mudflow breccias exhibit growth fault relations and thicken into the respective basin axis (Dockery, 1982; Meinwald, 1982; Oldow, unpublished data). In the Candelaria Hills (Fig. 7), on the other hand, younger andesite (17 to 15 Ma) is essentially the same thickness on both sides of the master fault, suggesting that deposition of the younger andesite was not influenced by subsidence of the half-graben (Speed and Cogbill, 1979a, 1979b). Thus, the half-grabens became active at least as early as 28 Ma and possibly before and continued to serve as volcanic depo-centers until 19 to 17 Ma.

The extension direction associated with the development of the half-grabens has been addressed by Dockery (1982) and Meinwald (1982) in the northern Pilot Mountains and differs from the east-west to northwest-southeast direction thought to be active today (Zoback and Zoback, 1980; Zoback, 1989). On the basis of the geometry of the bounding master-fault system, the orientation of andesitic dikes emplaced during basin growth, and depth to pre-Tertiary basement in the basin axis, a northerly or north-northeasterly extension direction is postulated. The extension direction in the central Walker Lane apparently has undergone between 70° to 90° of clockwise rotation since 19 to 15 m.y. ago.

Strike-slip Faults: The most prominent Cenozoic structures of the central Walker Lane are northwest-striking transcurrent faults (Fig. 8). These faults are best exposed in the Gillis and Gabbs Valley Ranges (Fig. 9) where five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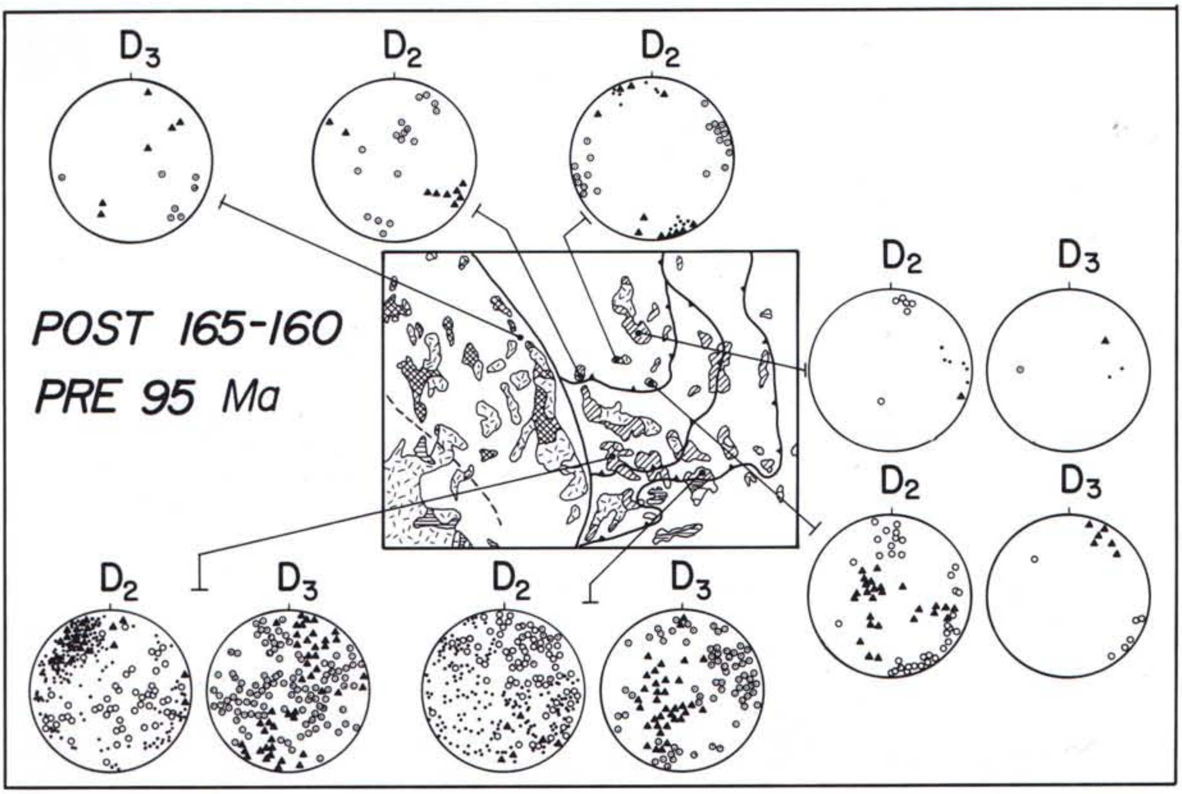
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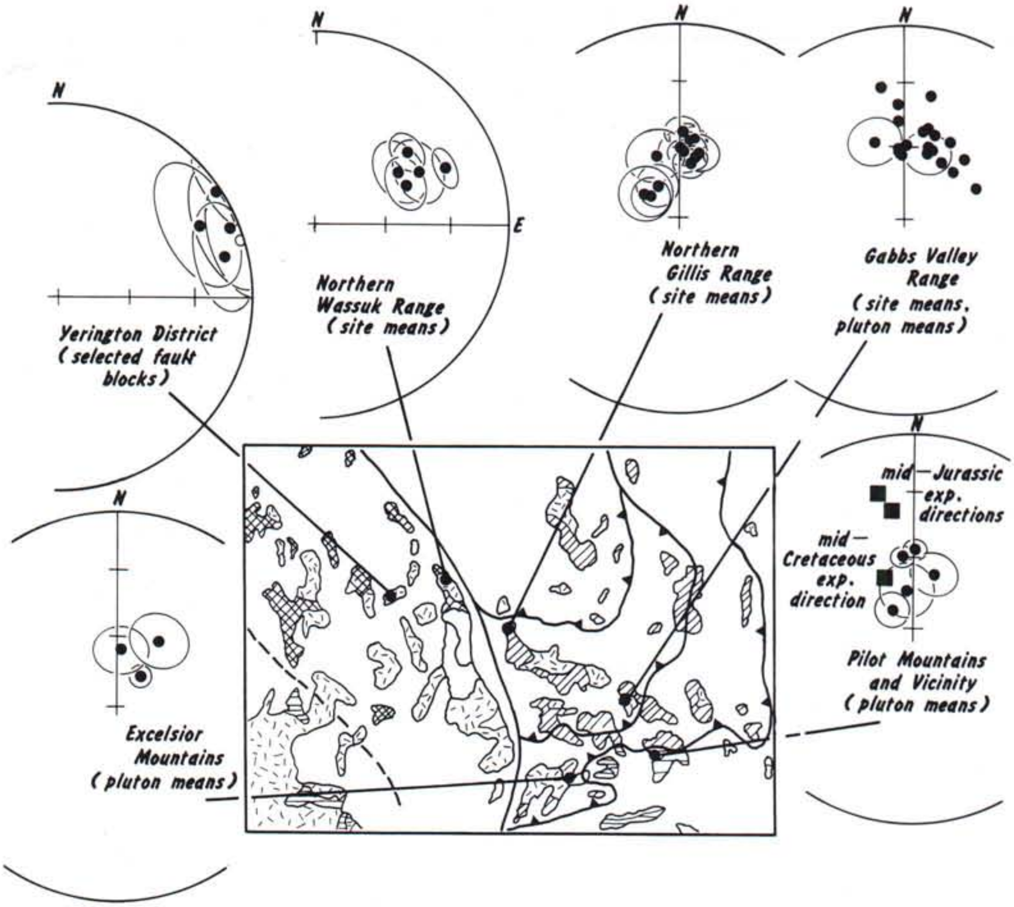
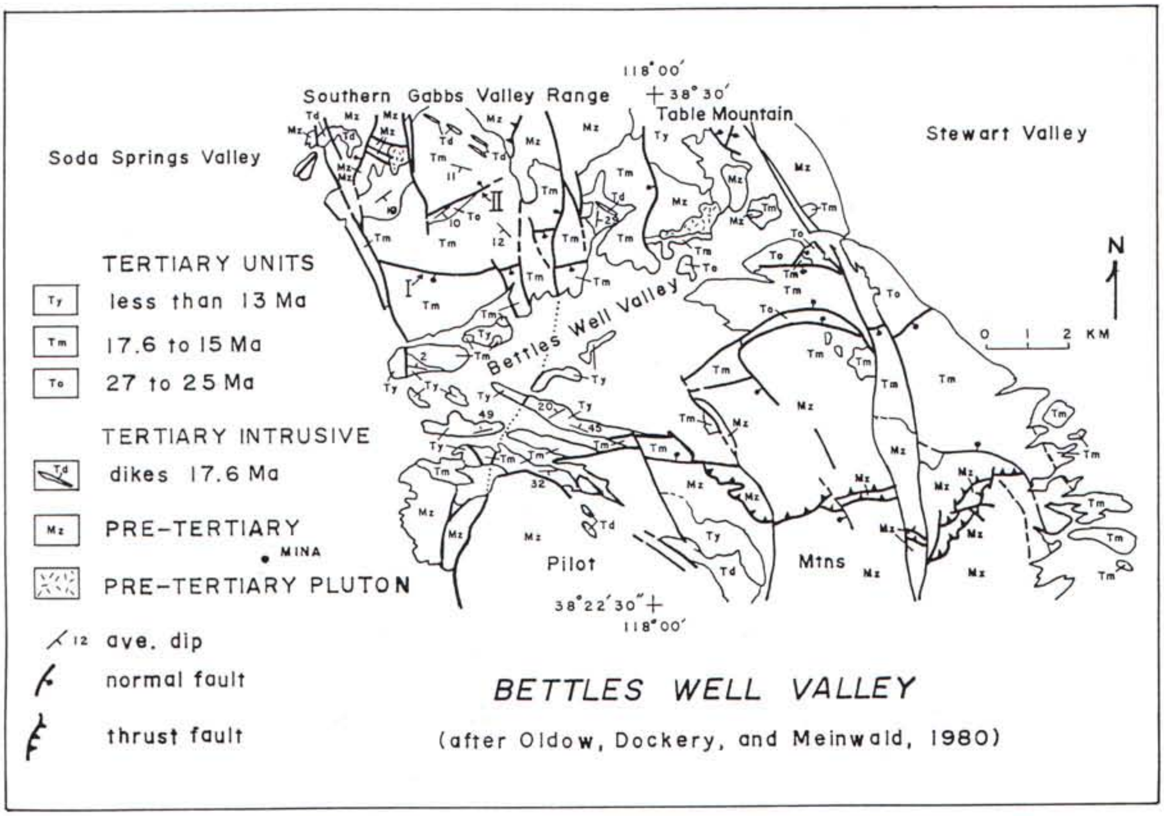


Fig. 4. Fabric diagrams and map locations of early Mesozoic mesoscopic structures of layered rocks and paleomagnetic pole data for Mesozoic plutons and remagnetized layered host rocks in the central Walker Lane. Map patterns are the same as those in Fig. 2. Fabric diagrams are lower hemisphere equal-area projections with the structural elements represented by the following symbols: solid dots, poles to axial planar cleavage; solid triangles, poles to axial planes of folds; open circles, lineations and bedding - cleavage intersections parallel to fold axes; circle-dot, fold axes of minor folds. A: First phase structures (locally sudivided into D_{1A} and D_{1B} in order of decreasing age) formed after the Early to early Middle Jurassic (youngest rocks involved) and before cross-cutting, Middle Jurassic plutons. B: Second and third phase structures (D_2 and D_3) are related to the Luning-Fencemaker fold and thrust belt. D_2 and D_3 structures formed after 165 to 160 Ma and are cross-cut by mid-Cretaceous plutons. D_2 structures are developed only east of the Pine Nut fault (see Fig. 2) and locally are superposed on D_1 folds. Generally, however, D_2 structrues are the first phase of folds recognized in the early Mesozoic rocks of the region east of the Pine Nut fault. D_3 structures are found both east and west of the Pine Nut fault. C: Compilation of paleomagnetic data from mid-Cretaceous plutons and remagnetized host sedimentary and volcanic rocks from the central Walker Lane area. Data from different localities are in the form of equal-area projections of in situ site or locality mean directions of magnetization isolated in progressive alternating field thermal demagnetization and associated projected cones of 95% confidence. In general, the magnetizations are assumed to be of mid-Cretaceous age. Paleomagnetic data from Geissman and others, 1982, 1984; Callian and others, 1982, 1985; Bell and others, 1986; Geissman, unpublished data.

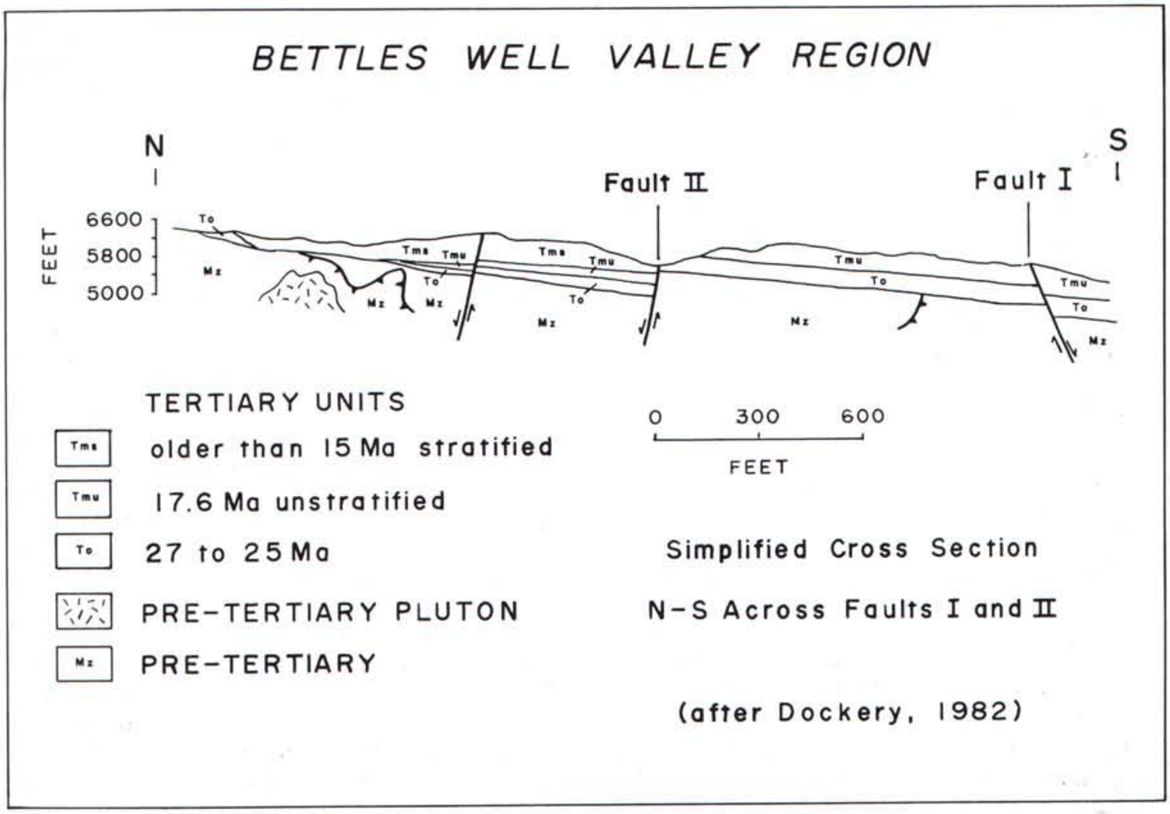
major strike-slip faults are mapped (Hardyman, 1984; Ekren and Byers, 1984). In addition, northwest-striking lateral-slip faults are documented in the northern Wassuk Range (Bingler, 1978; Dilles, 1989), the Terrill Mountains and Rawhide Flats area (Hardyman, unpublished mapping), the east flank of the Pilot Mountains (Nielsen, 1965; Oldow, unpublished mapping), and the east flank of the Cedar Mountains (Brown, 1985; Oldow, unpublished mapping). A major northwest-striking strike-slip fault also is postulated through the Dicalite Summit area into Cirac Valley along the west flank of the Royston Hills (Hardyman and others, in press). Measureable lateral offsets on many of the mapped strike-slip faults yield a combined minimum right-lateral displacement across the central Walker Lane fault zone of 48 to 60 km (Hardyman, 1975, Ekren and Byers, 1984).

The transcurrent faults of the central Walker Lane, from the northern Wassuk Range southeast to the San Antonio Mountains, display a southeast-trending, left-stepping en echelon pattern. In part, however, this left-stepping en echelon pattern is the result of these faults only being mapped in bedrock exposed in northwest-trending, left-stepping en echelon mountain ranges. How through-going some of these faults may be, especially to the north-northwest where much of the bedrock is buried by alluvium or consists of younger (<15-10 Ma) volcanic or sedimentary cover is unknown. To the southeast, the westernmost faults of the zone do not



BETTLES WELL VALLEY

(after Oldow, Dockery, and Meinwald, 1980)



BETTLES WELL VALLEY REGION

Simplified Cross Section

N-S Across Faults I and II

(after Dockery, 1982)

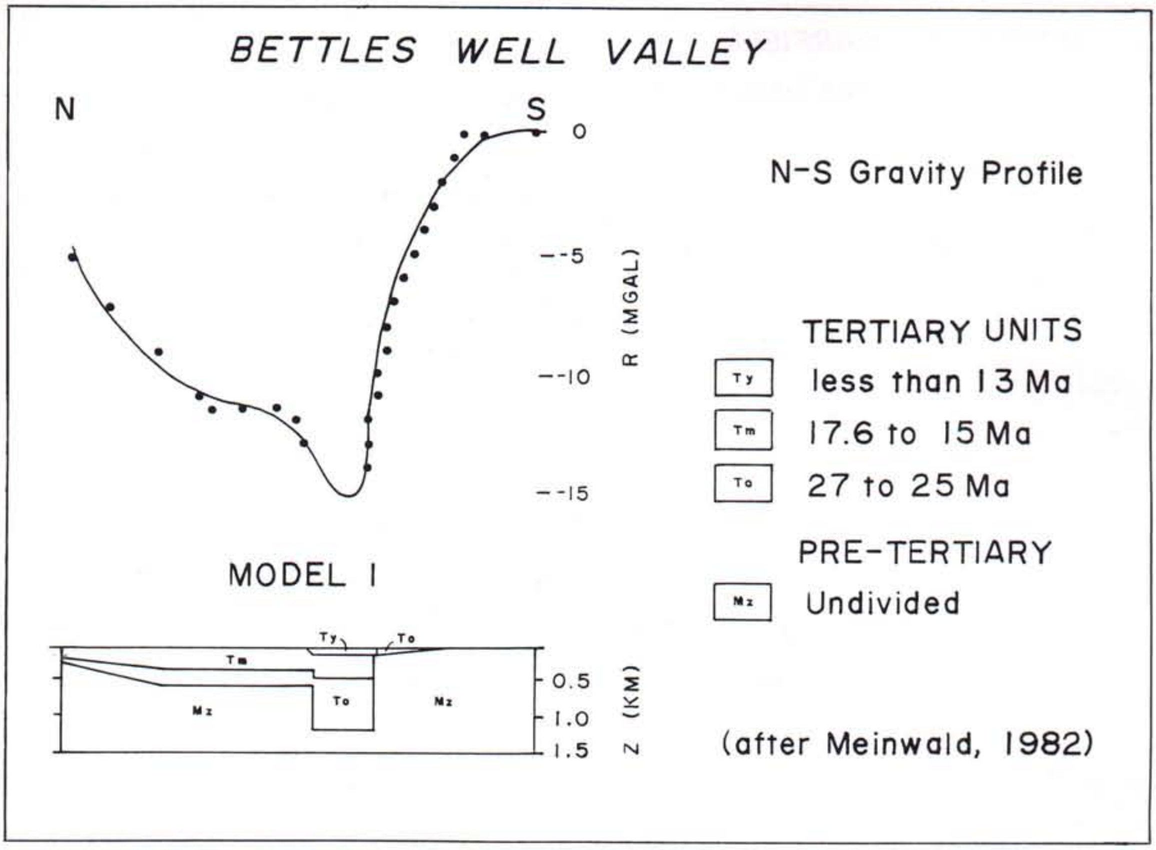


Fig. 5. Simplified geologic map, cross-section, and gravity data of the Bettles Well Valley area, northern Pilot Mountains. A: Simplified geologic map of the Bettles Well Valley area. Modified from Oldow and others, 1980. B: Simplified north-south cross-section across the north side of the Bettles Well Valley region. Modified from Dockery (1982). C: North-south gravity profile and gravity model across Bettles Well Valley, northern Pilot Mountains. Modified from Meinwald (1982).

extend beyond the latitude of Hawthorne and strike-slip displacement steps to faults to the east (Oldow and others, 1980). Certainly, it is difficult to project faults of the central Walker Lane strike-slip fault zone south of the approximate latitude of Tonopah. Lateral-slip on these faults either dies out in the Monte Cristo Range or displacement is stepped east to other faults.

Inception of Cenozoic strike-slip faulting in the central Walker Lane began at least 25 m.y. ago and perhaps as early as 27 m.y. ago and movement on these faults has continued to the present time (Ekren and others, 1980; Ekren and Byers, 1984). How much earlier than this strike-slip faulting may have occured has yet to be resolved. Offsets of Cenozoic units indicate consistent right-lateral displacements on northwest-striking strike-slip faults. Where offsets of Mesozoic units can be measured on these faults they are likewise generally right-lateral and of similar magnitude as offsets of the Cenozoic units. Left-lateral displacement on a northwest-striking strike-slip fault has been documented in one locality, however. On the northeast flank of the northern Wassuk Range a high-angle fault bounding the southwest side of White Mountain displays several hundred meters of normal down-to-the west stratigraphic separation and 2 km of left-lateral separation of a Cretaceous plutonic unit (Bingler, 1978). This fault juxtaposes 23-Ma Tertiary volcanic rocks against the Cretaceous granitic rocks and is intruded by Miocene hornblende andesite dikes (Dilles, 1989), suggesting that movement occurred post 23 Ma and, perhaps, pre-17 to 15 Ma. Thus, the displacement history of the northwest-striking strike-slip faults records both right- and left-lateral motion and appears to have been quite complex.

In the northern Wassuk Range, northwest-striking faults with right-lateral displacement cut and partially bound 13- to 8 Ma syntectonic sedimentary rocks of the Wassuk Group (Axelrod, 1956) which appear to overlie and post-date shallowly dipping, "Yerington"-style normal faults (Dilles, 1989). In the Gabbs Valley Range one of the through-going, northwest-striking, right-lateral strike slip faults (the Gum Drop Hills fault, Fig. 9) beheads a Miocene and Pliocene alluvial fan and is intruded by a 5.8-Ma latite dike which postdates most of the movement on this fault (Ekren and Byers, 1984). In the eastern Pilot Mountains and Gabbs Valley Range, the Bettles Well fault offsets one of the Oligocene to Miocene half-grabens right-laterally about 3 km to the southeast. This fault involves young (< 6 Ma) quartz

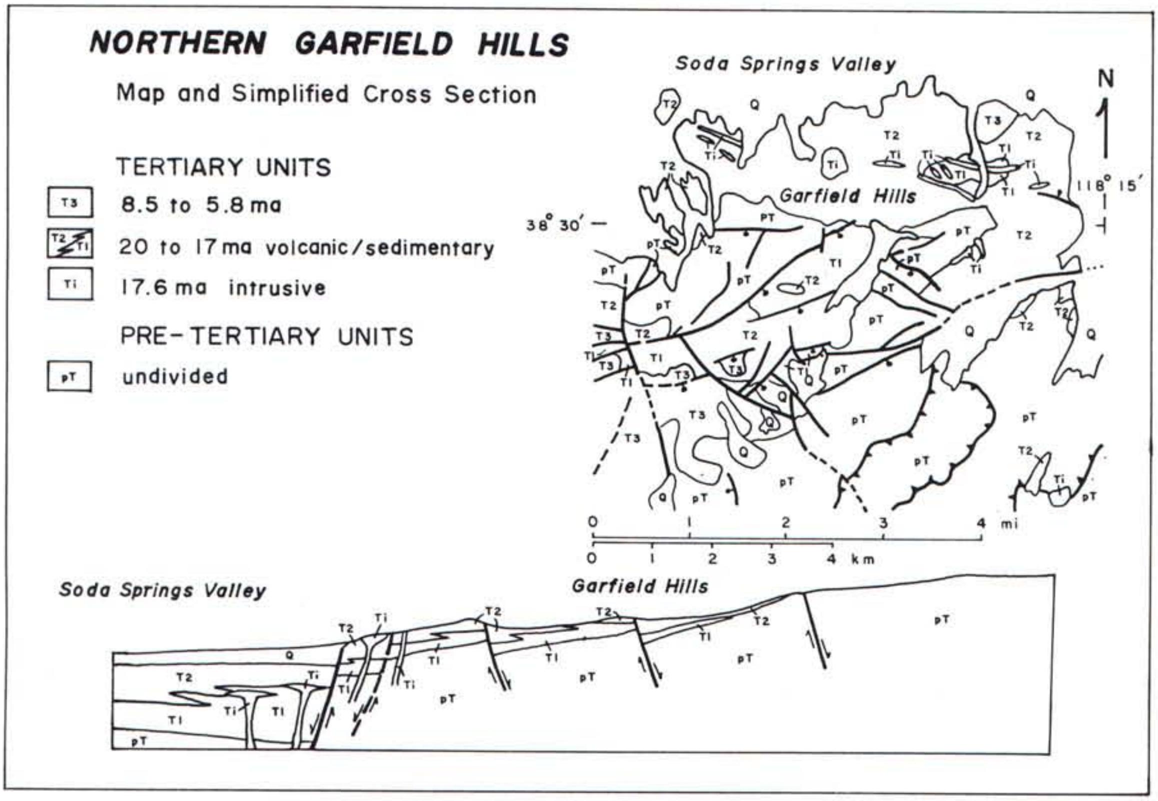


Fig. 6. Simplified geologic map and north-south cross-section of the northern Garfield Hills. Modified from Oldow and Steuer (1985) and Ekren and Byers (1985b).

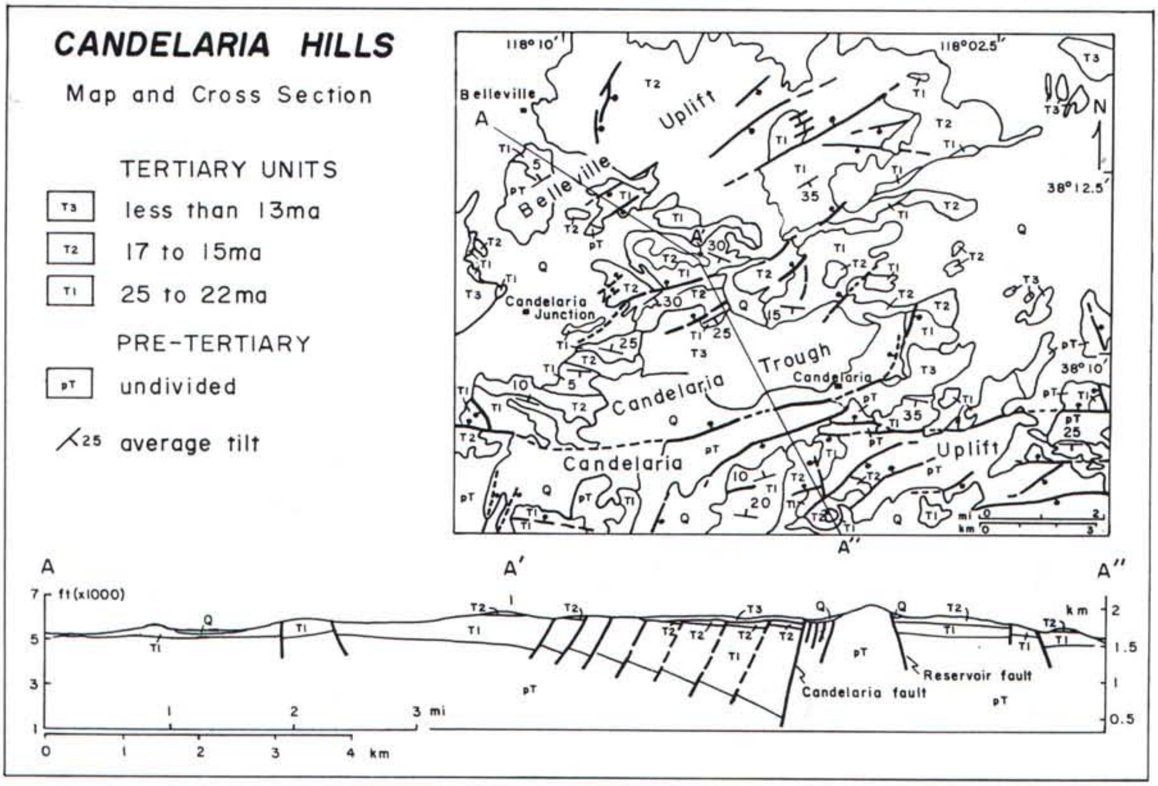


Fig. 7. Simplified geologic map and north-south cross-section of the Candelaria Hills area. Modified from Speed and Cogbill (1979a).

latite flows and appears to cut Quaternary alluvium. Elsewhere in the central Walker Lane, other northwest-striking lateral-slip faults also display geomorphological evidence of right-lateral displacement of young alluvial material (Ekren and Byers, 1984; Molinari, 1984; Hardyman, unpublished data).

The relationships outlined above indicate that lateral-slip on northwest-striking faults of the central Walker Lane began about 25 Ma or earlier and continues to the present. Limited data suggest that early movement (prior to 17-15 Ma) may have been left-lateral, followed by substantial right-lateral displacement. The onset of right-lateral motion is not well constrained, but may have begun as late as 10 Ma. The merits of this sequence of events, especially the radical premise that northwest-striking Walker Lane faults may once have experienced left-lateral slip, will be evaluated below in developing our hypothesis for the Cenozoic history of the region.

Detachment Faults: Within the broad northwest-trending zone of strike-slip faults some of the most unique and much debated structures of the Walker lane are flat-lying to low-angle detachment faults which separate little tilted to strongly tilted Tertiary strata from the pre-Tertiary basement (Hardyman and others, 1975; Hardyman, 1978, 1984; Ekren and others, 1980; Ekren and Byers, 1984). Detachment faults occur both at the basal Tertiary unconformity and within the Tertiary section. It is now recognized, based on structural fabric data from the deformed pre-Tertiary sedimentary rocks and paleomagnetic data from Mesozoic plutons that cut these rocks (Fig. 4; Oldow, 1984a; Geissman and others, 1984; Keller and others, 1987, 1989a, 1989b; Callian and others, 1988) that the pre-Tertiary basement below the detachment faults and overlying tilted Tertiary strata is virtually untilted. These faults were initiated at flat to low angles and do not cut the basement rocks. They are not, therefore, Yerington-style normal faults that were born at high-angles and subsequently tilted to low angles by large-scale crustal extension (Proffett, 1977). Likewise, the basement below the detachment faults is not mylonitized or pervasively sheared and no chlorite breccia is present as is typical of many of the large scale extension related detachment faults in the lower Colorado River country of Arizona and California (see for example Davis and others, 1980; Frost and others, 1982; Frost, 1981; Lyle, 1982; Mathis, 1982; Rehrig and Reynolds, 1980; Shackelford, 1980; and references therein). In the central Walker Lane, detachment faults are thin-skinned tectonic features, kinematically associated with strike-slip faults and are not the product of large-scale crustal extension (Hardyman, 1978; Keller and others, 1987, 1989a, 1989b).

Elsewhere, in the southwestern Paradise Range low-angle normal faults are conspicuous structures (John, 1988; John and others, 1989b). Here, Tertiary volcanic rocks generally strike north-northwest and are tilted 30-75° east-northeast on moderate to low-angle west-southwest dipping faults. On the east side of the range about 5-40° of tilt occurred between about 21 and 19 Ma (John, 1988). Likewise, farther south, in the northern Pactolus Hills 45-75° of eastward tilting took place about 23 to 19 Ma (John, 1988). Preliminary paleomagnetic data from lower plate rocks of the 5-10° west-southwest dipping Sheep Canyon fault in the southwestern Paradise Range indicate that the pre-Tertiary basement is not significantly tilted (D. A. John and M. R. Hudson, unpublished data). The Tertiary strata above the fault are tilted as much as 70° northeast. This indicates that the Sheep Canyon fault originated as a nearly flat fault. The Sheep Canyon fault and other low-angle faults in the Paradise Range may have formed about 16 Ma. (John, 1988). These faults are cut by north- to northeast-striking high-angle faults.

Within the central Walker Lane a genetic relationship between the detachment faults and strike-slip faults is suggested by: 1) the spatial proximity of the tilted, detached Tertiary section and the areal distribution of the long trace-length strike-slip faults, 2) cross-cutting Tertiary intrusions which establish coeval development of detachment and associated listric faults and the major strike-slip faults, and 3) an axis of symmetry for the dip polarity of listric normal faults defined by the strike-slip faults. Low-angle detachment faults formed at the base and within the Tertiary section during transtensional deformation. Decoupling and tilting of the Tertiary rocks occurred when the underlying basement was being laterally displaced along high-angle strike-slip faults (Fig. 10). As strike-slip faults cut up through the Tertiary units, decoupling, listric fault disruption and associated stratal tilt occured within the Tertiary section. This "transtensional-nappe" model for detachment faulting is consistent with all of the observed structural complexities associated with the detachment faults (Hardyman, 1978, 1984) and allows for variable amounts and polarities of tilt of the Tertiary strata above an untilted pre-Tertiary basement.

Listric Normal Faults: Normal faults that flatten with depth are common both in structural domains I and III in the central Walker Lane. Two varieties of listric normal faults are recognized: 1) those that originated as steep high-angle faults that cut pre-Tertiary and Tertiary rocks and have been tilted to shallow angles by younger listric normal faults; these are "Yerington"-style listric normal faults, and 2) repetitious listric normal faults that cut only the Tertiary strata and merge into detachment faults either tangentially or at small intersection angles.

The well documented listric normal faults at Yerington strike north-south, are shovel or spoon shaped, and consistently dip east and tilt Tertiary and pre-Tertiary rocks 75-90° to the west (Proffett, 1977). Similar faults in the Hall district north of Tonopah (also in Domain I, Fig. 3), also strike north-south but dip west and tilt Tertiary and pre-Tertiary rocks 70-90° to the east (Shaver and McWilliams, 1987). Proffett (1977) convincingly demonstrated that 70-80% of the tilt at Yerington occurred between 17 and 11 Ma. At Hall, 65-75% of the tilt also occurred between 18-17 and 10 Ma (Shaver and McWilliams, 1987).

In contrast to the Yerington and Hall districts, listric

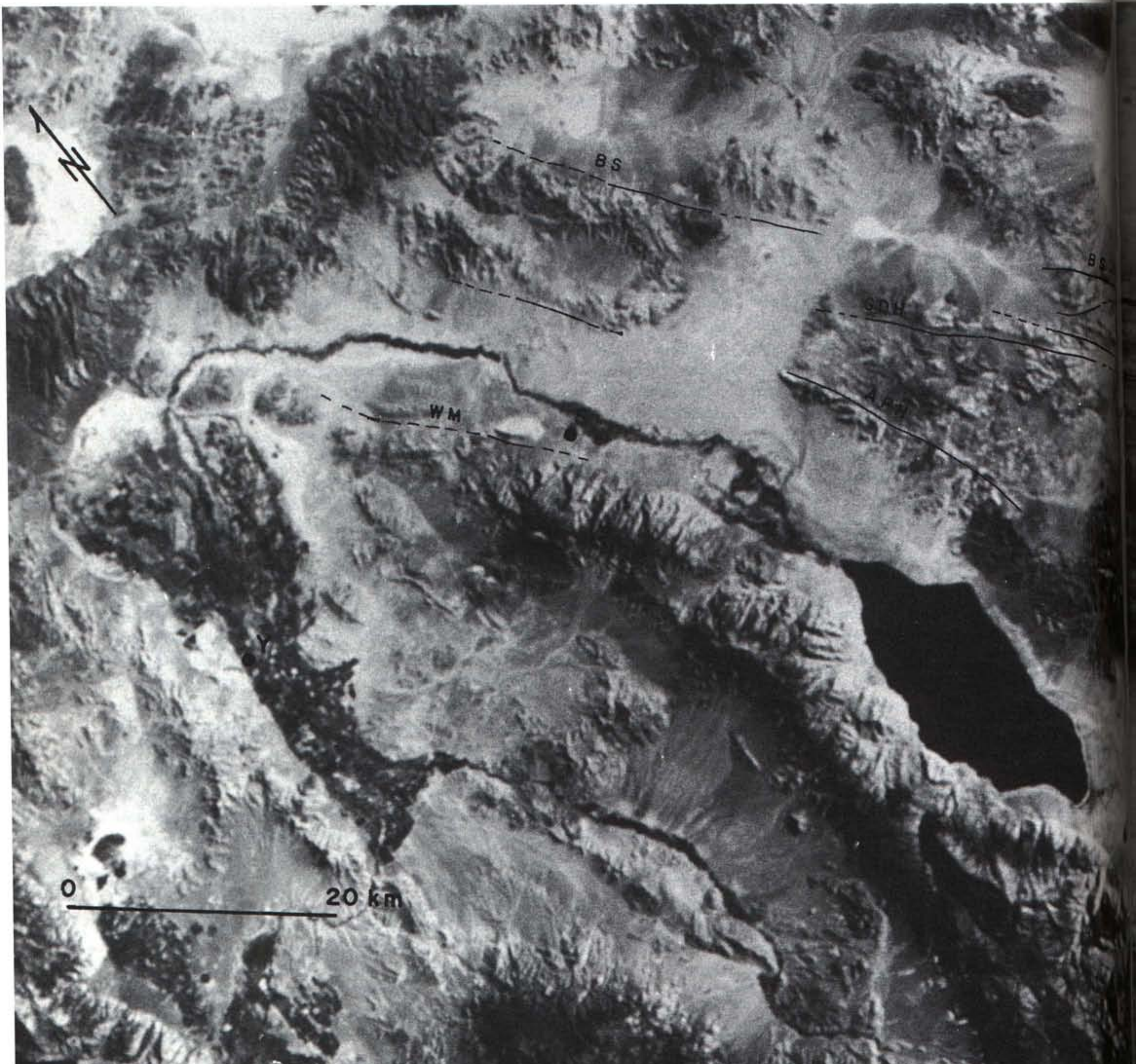
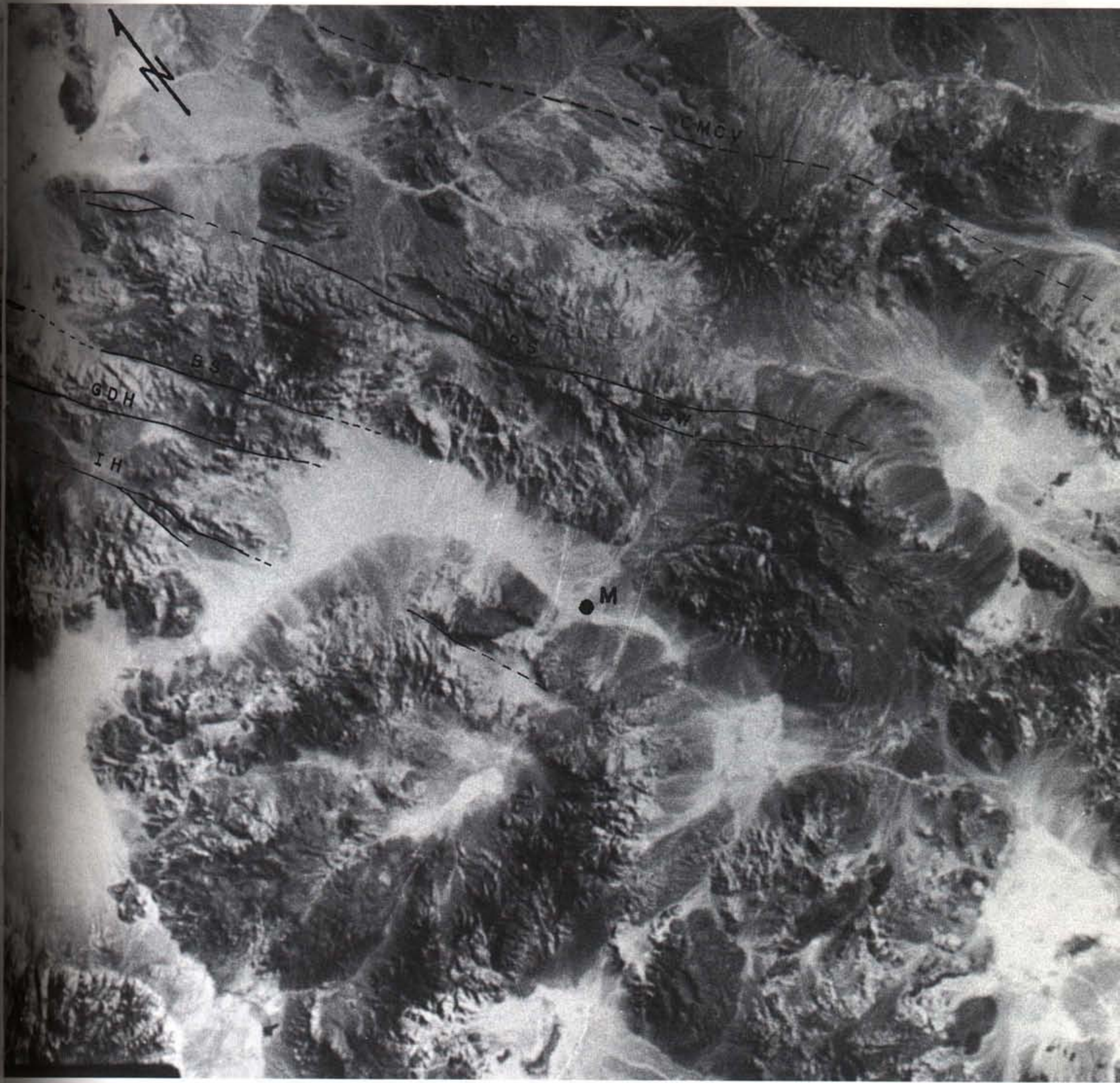


Fig. 8. Satellite photograph of the central Walker Lane region showing the major northwest-trending strike-slip faults. Dashed where approximately located, concealed or inferred. CMCV = Cedar Mountain – Cirac Valley fault, PS = Petrified Spring fault,



BW = Bettles Well fault, BS = Benton Spring fault, GDH = Gum Drop Hills fault, IH = Indian Head fault, APH = Agai Pah Hills fault, WM = White Mountain fault. Y = Yerington, S= Schurz, H = Hawthorne, M = Mina.

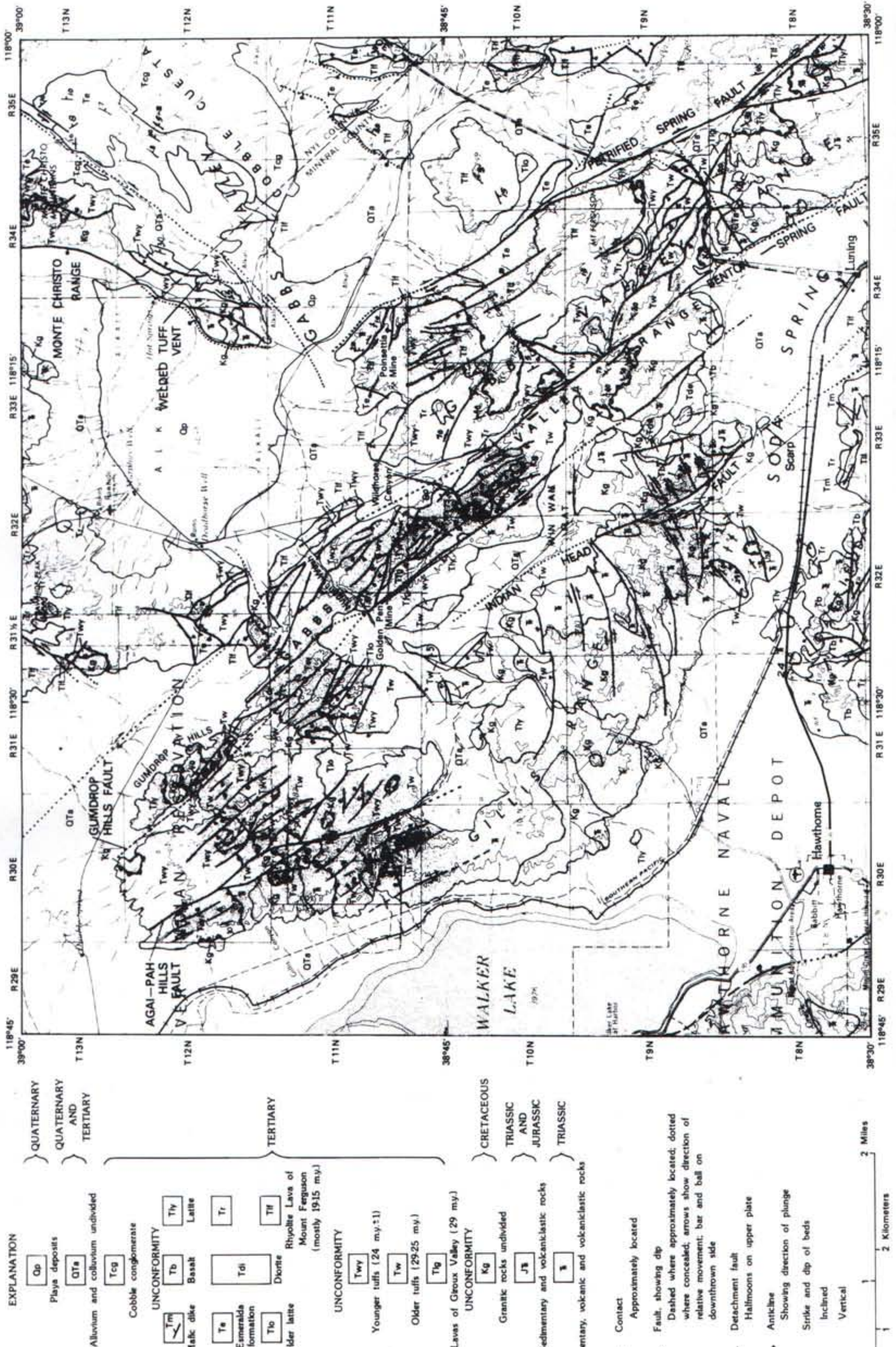


Fig. 9. Generalized geologic map of the Gillis and Gabbs Valley Ranges showing the major northwest-trending strike-slip faults and domains of predominant listric normal faulting. Modified from Ekren and Byers (1984).

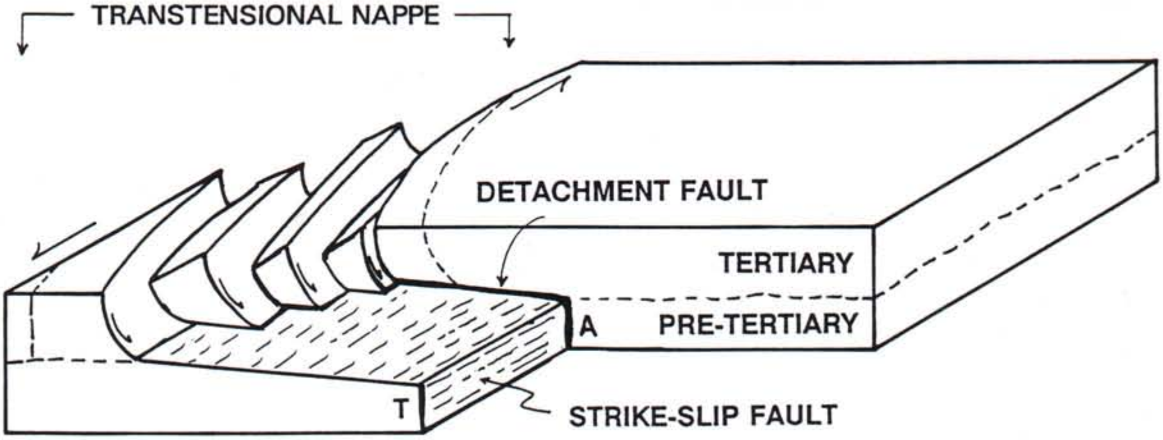


Fig. 10. Diagrammatic model of kinematically related strike-slip, detachment and associated listric normal faults of the central Walker Lane. Modified from Hardyman (1978).

normal faults in structural domain III (Fig. 3) strike northwest and are parallel or subparallel to the northwest-striking strike-slip faults. Unlike the "Yerington"-style faults, listric faults of domain III do not penetrate the pre-Tertiary basement. Fault dips are consistent over areas of several square kilometers or tens of kilometers and generally are either southwesterly and northeasterly. The faults accomodate moderate to steep tilts of Tertiary strata in the hanging wall to the northeast or southwest, and the axes of polarity of the tilted Tertiary strata and listric faults are the traces of the strike-slip faults (Fig. 9). Perhaps the best examples of this style of faulting are in the Gabbs Valley Range (Fig. 9). Here, subdomains of listric normal faults with similar polarity exhibit dips of 60-20° and have displacements of centimeters to several tens of meters or more. These faults repetitiously extend and tilt the Tertiary strata and sole into a detachment fault at the pre-Tertiary-Tertiary interface (Fig. 11). Relatively minor extension, on the order of 20%, is accommodated by these faults.

In the Gabbs Valley Range, listric normal faults cut Tertiary volcanic rocks ranging in age from approximately 29 Ma to 22 Ma, but are conspicuosly few in number in unconformably overlying volcanic rocks that range in age from about 19 Ma to 15 Ma (Ekren and Byers, 1984). If, as appears to be the case, the majority of the listric normal faults in the Gillis and Gabbs Valley ranges are genetically associated with the detachment process and strike-slip faults (see Fig. 10), the field relations indicate that detachment and listric normal faulting occured as a consequence of strike-slip faulting between 24 and 19 Ma.

High-angle Normal Faults: In contrast to the listric normal faults of structural domain III described above that are developed entirely within Tertiary strata, other high-angle normal faults within the central Walker Lane region cut both Tertiary and pre-Tertiary rocks. These faults are steeply dipping, dip-slip and oblique-slip faults that display straight-line map traces and generally trend northwest, but have variable strike orientations. In domain III high-angle normal faults cut low-angle detachment faults and locally bound or cut subdomains of listric normal faults (Hardyman, 1984; Ekren and Byers, 1984). Locally, in the Gillis and Gabbs Valley Ranges, subdomains with rhomb-shaped high-angle normal fault map patterns occur between traces of major strike-slip faults (Fig. 9).

High-angle normal faults that show no flattening at the current erosion level presumably penetrate deep into the Mesozoic crust. This is supported by the observation that these faults, together with strike-slip faults, commonly are conduits for hydrothermal fluids and guide emplacement of Tertiary dike rocks (Hardyman, 1984; Ekren and Byers, 1984).

Tertiary Tectonic Evolution

A coherent tectonic history of the central Walker Lane must integrate the timing of Cenozoic deformation and the styles of faulting characteristic of each of the three structural domains within the region. In particular, the timing of major extension in the Yerington district, accommodated on deeply penetrating "Yerington"-style listric normal faults, must integrate with the timing of lateral displacements on Walker Lane strike-slip faults and genetically associated "thin-skinned" detachment and listric normal faults. Our working hypothesis (summarized below) for the Cenozoic history involves a 70° to 90° rotation in the extension direction in the central Walker Lane since 19 to 15 Ma. Early (28 to 17 Ma) extension was oriented north-northeast -south-southwest and gave way to east-west extension (17 to 11 Ma). After about 10 Ma, extension has been southeast-northwest.

Early Extension: An early northerly or north-northeasterly extension direction is indicated by east-northeasterly-trending half-grabens within the central Walker Lane. These 1.0- to 1.5-km-deep asymmetric structures (Candelaria trough, northern Garfield Hills half-graben, northern Pilot Mountains half-graben) are well preserved in structural domain II. If these structures and associated linear dikes are indicators of regional extension during their formation (28 to 17 Ma) then extension in late Oligocene to early Miocene time was oriented north-northeasterly (Fig. 12). The result of this extension direction is that lateral movement resolved on northwest-striking Walker Lane strike-slip faults would be left-lateral during the time interval of about 28 Ma to 17 Ma. Constraints on the timing of detachment and associated listric normal faulting characteristic of structural domain III indicate that most of these structures also formed during this time interval. Thus, during late Oligocene to early Miocene time east-northeast-trending half-grabens formed in the central Walker Lane in structural domain II and sinistral strike-slip faulting and associated transtensional detachment and shallow listric normal faulting occurred in domain III. The regions in structural domain I were apparently relatively dormant during this time interval.

East-West Extension: East-west directed extension dominated the central Walker Lane from about 17 to 11 Ma. During this period most of the tilt of Tertiary and pre-Tertiary rocks occurred on north-south striking faults in structural domain I (Fig. 12). Approximately 70-80% of the tilt in the Yerington district and 65-75% of the tilt in the Hall district occurred between 17 and 11 Ma. East-west extension probably reactivated some earlier northeast and northwest-trending faults in structural domains II and III, but resulting oblique-slip on these faults probably was minor. Local emplacement of 17- to 15-Ma intermediate to silicic composition dikes and lava flows, however, accompanied this period of east-west extension throughout the central Walker Lane.

Northwest-Southeast Extension: By about 10 to 8 Ma, the regional extension direction had rotated to a northwest-southeast orientation and has apparently remained in this orientation to the present time (Fig. 12). The result of this extension has been dominant right-lateral displacement on pre-exising, northwest-striking, high-angle faults in structural domain III. Pre-existing ("older" Basin and Range), north-south-striking, high-angle faults in domain I experienced subordinate oblique-slip movement and some north-northeast-trending ("younger" Basin and Range) normal faults were formed (Shaver and McWilliams, 1987). Older east-northeast-striking high-angle faults in structural domain II would have experienced subordinate left-lateral motion in this stress regime. Although most of the low-angle detachment faults in domain III probably formed during an earlier period of strike-slip faulting, as outlined above, some of these structures also could have formed during this period of deformation.

Tertiary Tectonic Framework and Ore Deposits

Known ore deposits in the central Walker Lane generally fit into two groups: 1) pre-Tertiary base and/or precious metal deposits and 2) Tertiary epithermal precious metal deposits. The pre-Tertiary deposits range in age from Middle Jurassic to Late Cretaceous and include the Yerington porphyry copper deposit (168 Ma), the Hall porphyry molybdenum deposit (67-70 Ma), and the disseminated silver deposits (approximately 126 Ma) at Candelaria (Dilles, 1983; Shaver and McWilliams, 1987; Silberman and others, 1975). Other base metal skarn and precious metal vein deposits occur in the region and are either controlled by Mesozoic structures or are associated with Mesozoic intrusive bodies. Tertiary structures are important to these deposits in terms of understanding their present geometries and as an exploration tool in predicting the location of offset mineralization and new ore bodies. In the case of the Tertiary ore deposits, Tertiary structures are important in that they: 1) provided the plumbing system for magmatic activity and migration of hydrothermal solutions, 2) locally provided traps for hydrothermal solutions, and 3) have offset mineralization.

Certainly some Tertiary mineralization in the Walker Lane was controlled by older Mesozoic structures. The lack of dating of either these deposits or the structures that control them precludes accurate assesment at this time of the control of Mesozoic structures on Tertiary mineralization. The following discussion, therefore, is directed at the known Tertiary structures and their association with known Tertiary mineralization.

High-angle faults are the predominant mineralized Tertiary structures within the central Walker Lane. Hydrothermal alteration and precious metal mineralization are localized along high-angle faults, primarily northwest-striking strike-slip faults, in structural domain III (Ekren and Byers, 1984; Hardyman, 1984). The Gum Drop Hills and Benton Springs faults, for example, are loci for hydrothermal activity from the northern Gillis Range to the southern exposures of these faults in the southern Gabbs Valley Range. Kinematically associated, subparallel, transtensional listric normal faults on the otherhand generally show little control on hydrothermal activity (Ekren and Byers, 1984). Likewise, in the southwestern Paradise Range, northwest-striking high-angle faults are hydrothermally altered whereas low-angle faults are not (John, 1989a). The Paradise Peak mine is located on a prominant northwest-trending lineament and there is a strong northwest-trending structural grain in the mine (John, 1989b; John and others, in press this volume). A northwest-striking high-angle fault zone bounding the southwest side of the Paradise Peak deposit truncates ore grade mineralization (19-18 Ma), but late stage hydrothermal alteration is guided by this fault zone (C. Clark personal communication, 1989; John and others, in press this volume).

Precious metal deposits and volcanic and volcaniclastic

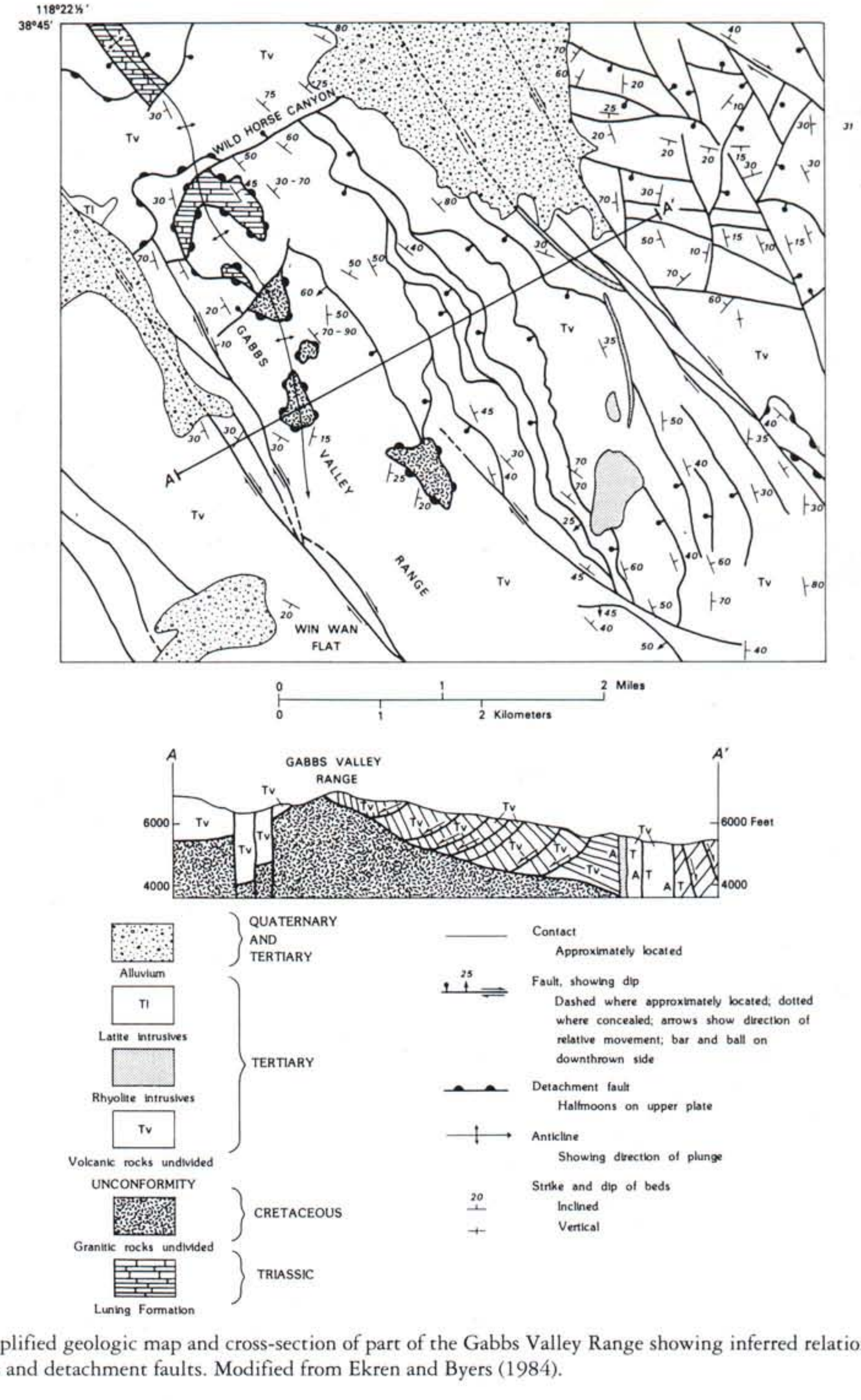


Fig. 11. Simplified geologic map and cross-section of part of the Gabbs Valley Range showing inferred relationship of listric normal faults and detachment faults. Modified from Ekren and Byers (1984).

host rocks at Rawhide are localized along a northwest-striking high-angle Walker Lane structure (Black and Gant, 1987; T. Mancuso, personal commun., 1989; Black and others, in press this volume). Historically mined high-grade gold-silver veins at Rawhide trend north and northeast and are interpreted to be tension gash veins related to the northwest-striking high-angle Walker Lane fault. West-northwest of Rawhide on the east flank of the Terrill Mountains, Tertiary felsic intrusive rocks and precious-metal mineralization also are locallized along a zone of northwest-trending high-angle faults (R. F. Hardyman, unpublished data). Likewise, hydrothermal alteration in the Bovard district, northern Gabbs Valley Range, and precious metal mineralization at the Golden Pen and Rand mines are strongly controlled by northwest-striking high-angle faults (Weaver, 1982).

Northwest-striking high-angle fault control of hydrothermal activity and precious-metal mineralization also include the 19-Ma Santa Fe deposit and 19-Ma mineralization to the northwest along the Benton Spring fault zone in the Gabbs Valley Range. At the Santa Fe

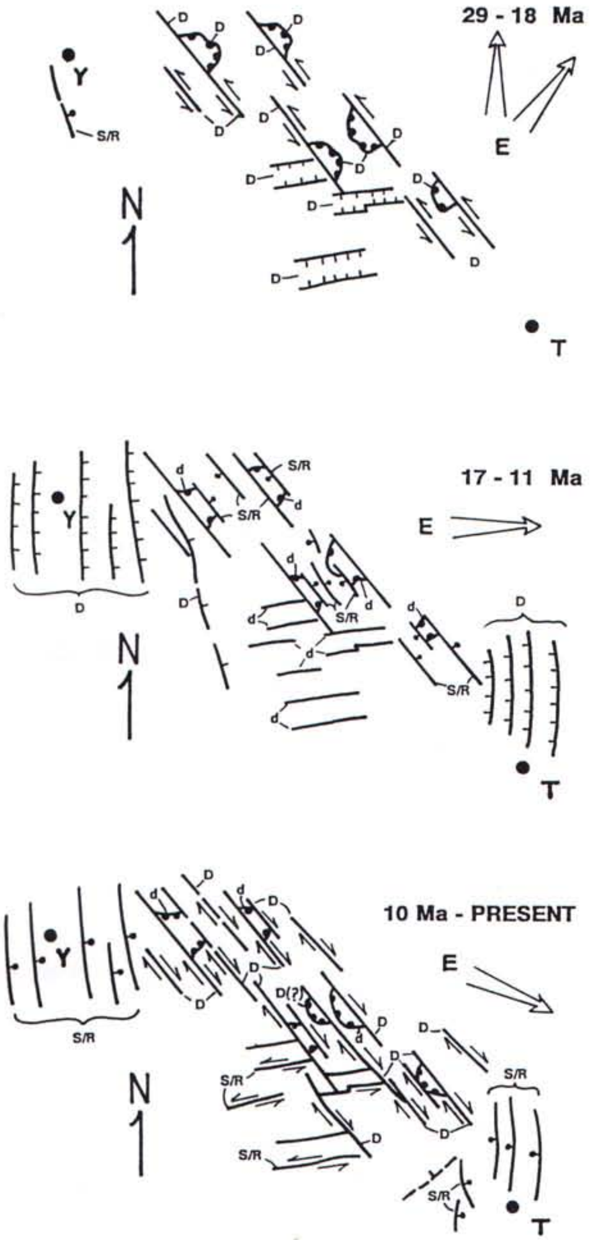


Fig. 12. Diagrammatic models showing the kinematic development of the central Walker Lane from Oligocene time to the present. Modified from Keller and others (1989b). D=dominate d=dormant S/R=Subordinate/Reactivated.

deposit, gold-silver mineralization is controlled by the northwest-trending Santa Fe fault zone (Fiannaca, 1987). This fault zone lies between two splays of the Benton Spring strike-slip fault (Ekren and Byers, 1984, 1985a, 1985b) and has had a complex history of Tertiary oblique and lateral-slip motion (Fiannaca, 1987). Hydrothermal alteration and mineralization in the area of the Isabella Mine, approximately 1 km northwest of the Santa Fe deposit, also is dated at 19 Ma and is localized predominantly along northwest-trending high-angle faults (Diner, 1983). These faults display pre-,syn-,and post-mineralization movement. Likewise, quartz-alunite alteration to the northwest near Rhyolite Pass is adjacent to the northwest-trending, through-going Benton Spring strike-slip fault.

Low-angle detachment faults that are one of the characteristic elements of structural domain III generally are not mineralized (Ekren and Byers, 1984). Detachment faults may be an important element to mineral exploration in the central Walker Lane, however, in that they might act as impervious barriers to hydrothermal fluid flow. In the Santa Fe deposit, for example, impermeable clay fault gouge at the low-angle, northeast-dipping pre-Tertiary-Tertiary contact acted as a seal to early-stage hydrothermal fluid migration in the Santa Fe fault zone and localized mineralization within the carbonate breccia beneath hanging wall volcanic rocks (Fiannaca, 1987). At Rhyolite Pass, quartz-alunite alteration dated at 19.5 Ma (Morton and others, 1977) occurs in an ash-flow tuff that is resting in detachment fault contact above unaltered Mesozoic granite (Ekren and Byers, 1985a, 1985b; Hardyman and others, in press). The detachment fault at the base of the Tertiary rocks at this locality either formed an impermeable barrier to hydrothermal solutions that moved up along the adjacent Benton Spring fault and contained these solutions in the densly welded tuff unit or the altered tuff was tectonically emplaced over the granite from another locality along the northwest-trending Benton Spring strike-slip fault. There is no evidence along the detachment fault contact laterally away from the strike-slip fault to indicate that the hydrothermal system that produced the alteration is rooted in the underlying granite.

As reviewed in this paper, Tertiary structures in the central Walker Lane can be grouped into various styles of faults. These styles of faults, together with their relationship to the structural integrety of the pre-Tertiary "basement", define and characterize structural domains. Although ore deposits occur in the other domains within this tectonic framework, the majority of the Tertiary precious-metal ore deposits appear to occur within structural domain III. This probably reflects the presence of deep-seated faults that were efficient conduits for circulating hydrothermal fluids. Also, this domain has been the focus of transcurrent (transpressional and transtensional) faulting since Late Jurassic to the present time. Northwest-striking faults would be those most favorably oriented to experience the longest duration of repeated movement with rotation of the extension direction from approximately north-south to northwest-southeast during Oligocene to the present time (Fig. 12). Such a long-lived zone of weakness must have favored the rise of magmas to sufficient shallow crustal levels to provide the heat necessary for hydrothermal systems to develop. These magmas also were sources of volatiles and possibly metals (Ashley, 1979; John and others, in press this volume). Not only have the northwest-striking faults in the central Walker Lane experienced the longest history of movement, they were preferred sites for mineralization during the 20-18 Ma time period.

Although the role of high-angle faults as controls on hydrothermal solutions and mineralization is evident, the role of low-angle detachment faults as structural controls to ore deposition is less obvious. Certainly, if they are intimately related to high-angle strike-slip faults, they must be significant controlling structures or traps for mineralization somewhere within the central Walker Lane.

Acknowledgements

The work reported in this paper has benefited greatly from numerous discussions with colleagues and students in academia, industry, and the U.S. Geological Survey who have all worked on pieces of the Walker Lane puzzel. We particularly thank John W. Geissman for stimulating discussions, for sharing unpublished paleomagnetic data, and for providing Fig. 4c. We thank David A. John and John H. Stewart and two anonymous persons for their critical reviews of the original manuscript and their helpful suggestions. John S. Oldow acknowledges the National Science Foundation for funding his work in the western Great Basin.

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