They probably postdate the most active period of listric normal faulting.

57.1 STOP 5. View listric fault on north side of wash that dips 20-50° west and places Nugent Tuff Member against the Blue Sphinx. Stratigraphic situation, despite continuous 30-50° east dip of strata, is same as where we entered wash 2.1 mi. downstream.

57.65 BRIEF STOP.
(Time permitting). Nugent Tuff here stands vertical--the end product of repetitious listric faulting.

57.93 Cross the trace of Gum Drop Hills fault which, on south side of road, places older fanglomerate against altered tuffs and intrusives - slickensided clay marks trace on south side at 9:00. Light-colored "sanded" younger alluvium marks track on north side.

BRIEF STOP.
(Time permitting). Listric-faulted, extended terrain ends at this fault. Strata to west of fault dip gently east and are not repetitiously faulted.

58.65 Junction with new Nugent Wash road: turn left, proceed to Hawthorne and thence to Reno.

LATE CENOZOIC STRUCTURAL GEOLOGY OF STEWART AND MONTE CRISTO VALLEYS, WALKER LANE OF WEST CENTRAL NEVADA

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ABSTRACT

The Stewart-Monte Cristo fault zone is one of a series of northwest trending right-lateral wrench faults within the central portion of the Walker Lane, west-central Nevada. Deformation along the zone is expressed as a series of discontinuous right-normal-oblique-slip faults which extend for approximately 45 km. along the west side of Stewart Valley into west-central Monte Cristo Valley. The fault zone was initiated post-11.0 m.y. B.P. and is currently active. Folds situated east of the fault zone within the mid-to-late Miocene age Esmeralda Formation are coeval with and genetically related to the faulting, and may be continuing to develop.

Surface faulting associated with the 1932 Cedar Mountain earthquake occurred at the base of pre-existing fault scarps on the southern segment of the fault zone. Fault-related geomorphology provides evidence for at least three and probably five or six surface faulting events during the latest Pleistocene and Holocene; suggesting a recurrence interval on the order of several thousand years.

INTRODUCTION

Stewart and Monte Cristo Valleys are two separate drainage basins which form a continuous, northwest trending topographic depression in eastern Mineral and Esmeralda Counties, west-central Nevada (Fig. 1). The valleys are floored by mid-to-late Miocene volcanic and sedimentary rocks and Quaternary alluvial deposits. The two valleys were the epicentral area of the 1932 Cedar Mountain earthquake (Ms=7.2-7.3) and are situated near the eastern margin of the central portion of the Walker Lane. Gianella and Callaghan (1934a, b) made a detailed report of most of the surface faulting that occurred in 1932 and previous studies in the area (Buwalda, 1914; Mawby, 1965) have only made brief mention of the structural geology within Stewart Valley. The discontinuous pattern of surface faulting and relatively small surface displacements reported by Gianella and Callaghan (1934a, b) are anomalous when compared to other historical earthquakes of similar magnitude.

The purpose of the investigation reported in this paper was to (1) define the late Cenozoic structural geology of the area, (2) refine the work of Gianella and Callaghan, (3) detect any additional

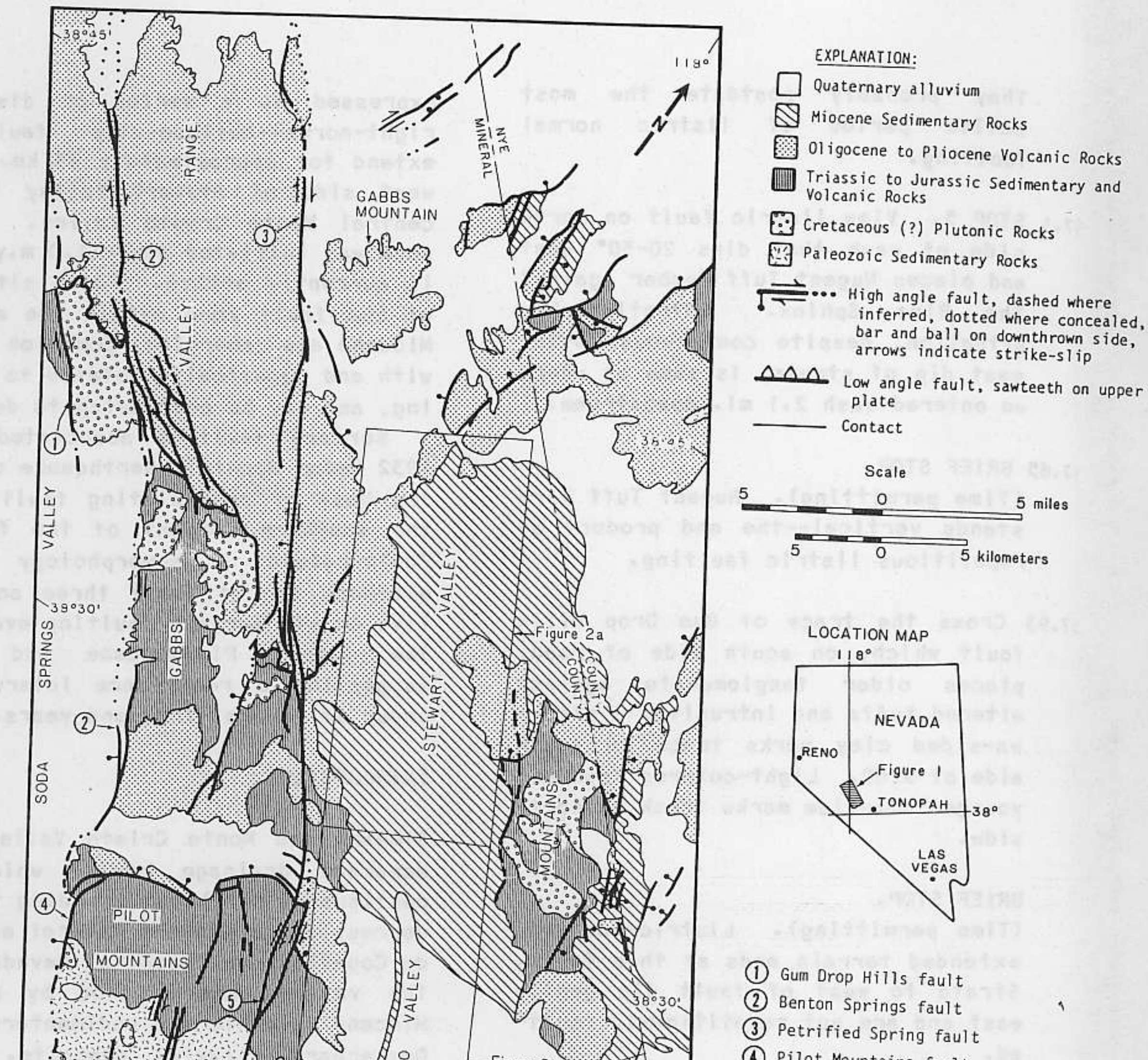

FIGURE 1: Generalized geologic map Stewart and Monte Cristo Valleys a showing major late Cenozoic faults. Figs. 2A and 2B for detail of structu geology in outlined area.

surface faulting which may have occurred in 1932, and (4) determine the space-time relationship of tectonic deformation with respect to nearby areas in the Walker Lane. Ages assigned to Quaternary deposits were estimated by comparing soils formed on geomorphic surfaces with similar soils in the Reno-Carson City area (Bell, 1981). This paper presents a review of the late Cenozoic structural geology and tectonic history of the area and is based on a more detailed report by Molinari (1984).

GEOLOGIC SETTING

Stewart and Monte Cristo Valleys are bounded on the west by the Gabbs Valley Range and Pilot Mountains, on the south by the Monte Cristo Range, on the east by the Cedar Mountains, and by several low hills on the north (Fig. 1). The surrounding mountain ranges consist of late Permian through Jurassic sedimentary rocks, Cretaceous plutonic rocks, late Oligocene and early Miocene silicic ash-flow tuffs, and early-to-mid Miocene lavas and volcanic debris-flow breccias of intermediate composition (Ross, 1961; Nielsen, 1964; Albers and Stewart, 1972; Speed, 1977; Ekren and Byers, 1978; Oldow, 1981).

Lacustrine and fluvial sedimentary rocks of the Esmeralda Formation crop out throughout Stewart Valley (Fig. 1). The Esmeralda Formation consists of at least 445 m. of calcareous and siliceous shale and siltstone, fine- to coarse-grained sandstones, and lesser amounts of limestone, reworked air-fall tuff, chert, diatomite, and tufa (Buwalda, 1914; Mawby, 1965). The basal portion of the Esmeralda Formation interfingers with volcanic debris-flow breccias of intermediate composition along the east flank of the Gabbs Valley Range and at the northwest edge of the Cedar Mountains. Morton and others (1977) obtained K-Ar age dates of 15.1 ± 0.5 m.y. and 15.4 ± 0.5 m.y. from the breccias on the east flank of the Gabbs Valley Range. Two tuffs in the upper portion of the formation were correlated by Mawby (1965) with tuffs exposed on the east flank of the Cedar Mountains that have been K-Ar dated by Evernden and others (1964) at 10.9 m.y. and 11.8 m.y. The mid-to-late Miocene age of the Esmeralda Formation is supported by early Barstovian to early Clarendonian mammalian and molluscan fossil assemblages within the formation (Merriam, 1916; Stirton, 1932; Firby, 1964; Mawby, 1965). During the late Quaternary, several periods of planation were followed by periods of downcutting to form several prominent pediment remnants on the Esmeralda Formation.

Monte Cristo Valley is a closed basin almost completely floored by Quaternary alluvial and playa deposits. The Esmeralda Formation crops out along the northern and southern edges of the valley and in a linear fault-bounded strip along the west side of the valley. Various Tertiary volcanic rocks crop out locally along the western edge and southern portion of the valley (Fig. 1).

STRUCTURAL GEOLOGY

Fig. 2 illustrates the major faults and folds in the Stewart and Monte Cristo Valleys. The structural geology is characterized by a N30°W trending zone of discontinuous faults which extend for approximately 45 km. along the west edge of Stewart Valley and into Monte Cristo Valley to the south edge of Kibby Flat playa. Numerous folds occur east of the faults within the Esmeralda Formation, and the east edge of Stewart Valley is fault bounded.

The southern segment of the N30°W fault zone was reactivated in 1932 and has been informally referred to as the "Cedar Mountain fault" in reference to the earthquake. Since the fault zone is actually located west of the Cedar Mountains in Stewart and Monte Cristo Valleys, it is hereby termed the Stewart-Monte Cristo fault zone (SMCFZ). For the purpose of discussion, the area is divided into three sections (north, central, and south) based on the style and magnitude of deformation along the SMCFZ.

NORTH SECTION

The north section extends from the northern edge of the area to central Stewart

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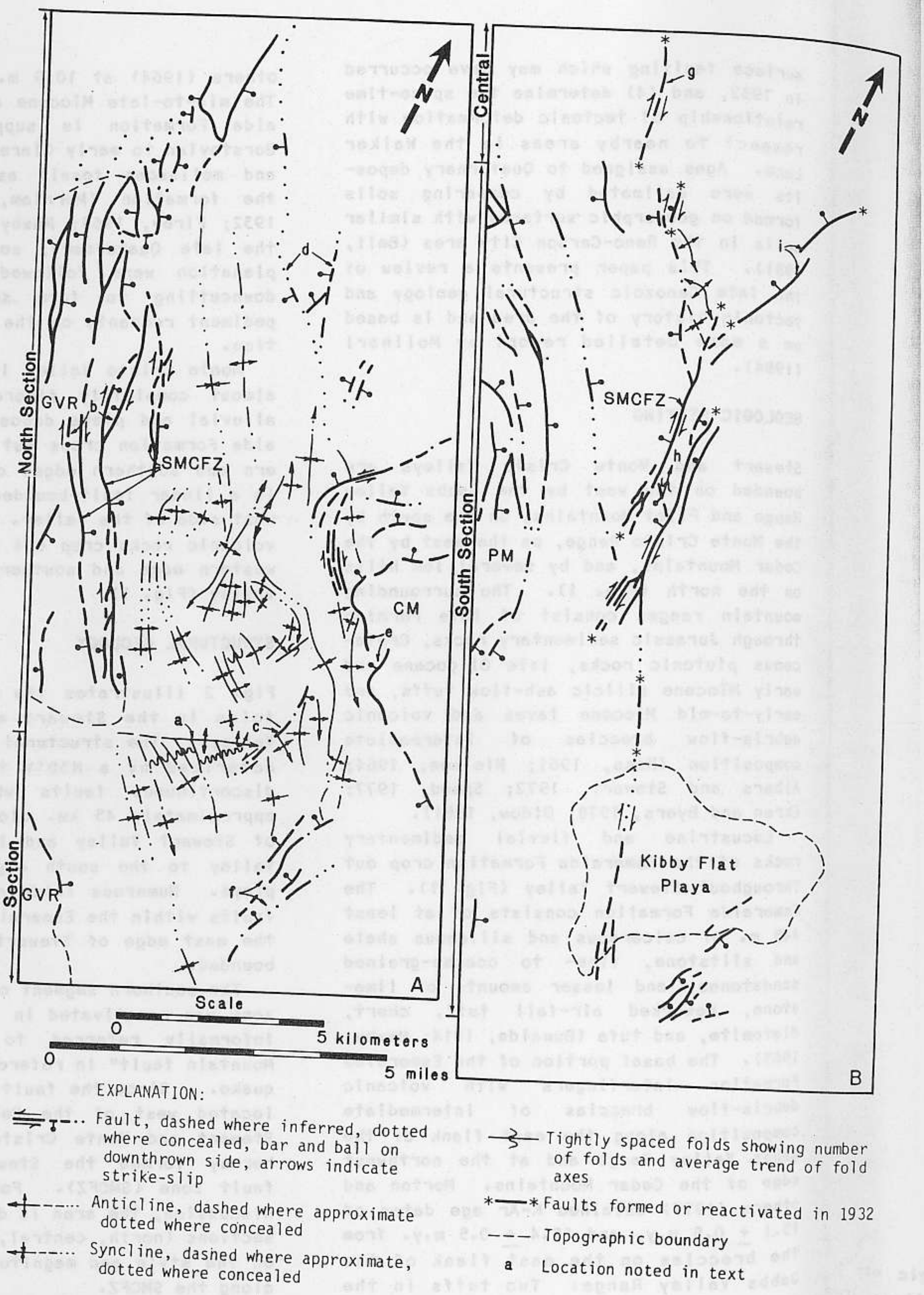

FIGURE 2: Map of late Cenozoic structural geology of Stewart Valley (A) and Monte Cristo Valley (B) (after Molinari, 1984). See Fig. for location. SMCFZ – Stewart-Monte Cristo fault zone, GVR – Gabbs Valley Range, CM – Cedar Mountains, PM – Pilot Mountains.

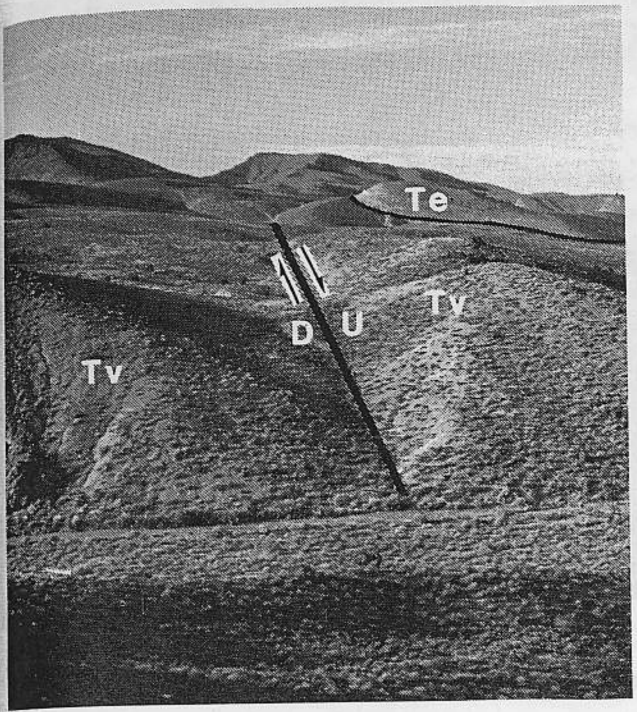

FIGURE 3: Linear hillside valley delineating trace of fault in north segment of the SMCFZ, east flank of the Gabbs Valley Range. Esmeralda Formation (Te) overlies volcanic debris flow breccias (Tv) in right background.

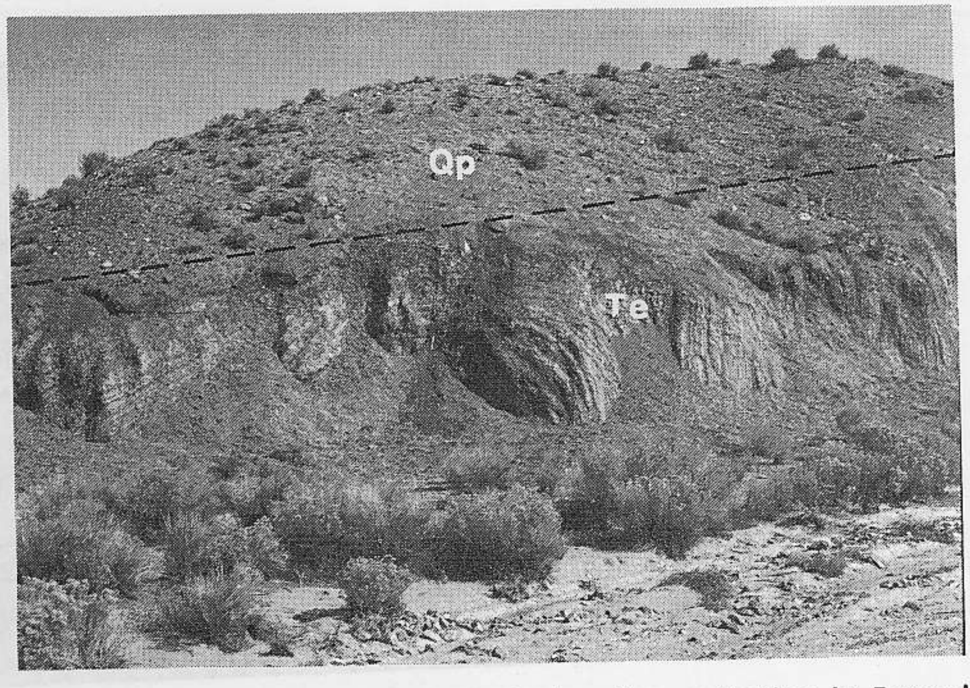

FIGURE 4: Slightly overturned, N75°E trending anticline in Esmeralda Formation (Te) overlain by late Pleistocene pediment gravels (Qp). Limbs dip 33°N and 87°N. See hammer for scale. View to the east in south-central Stewart Valley.

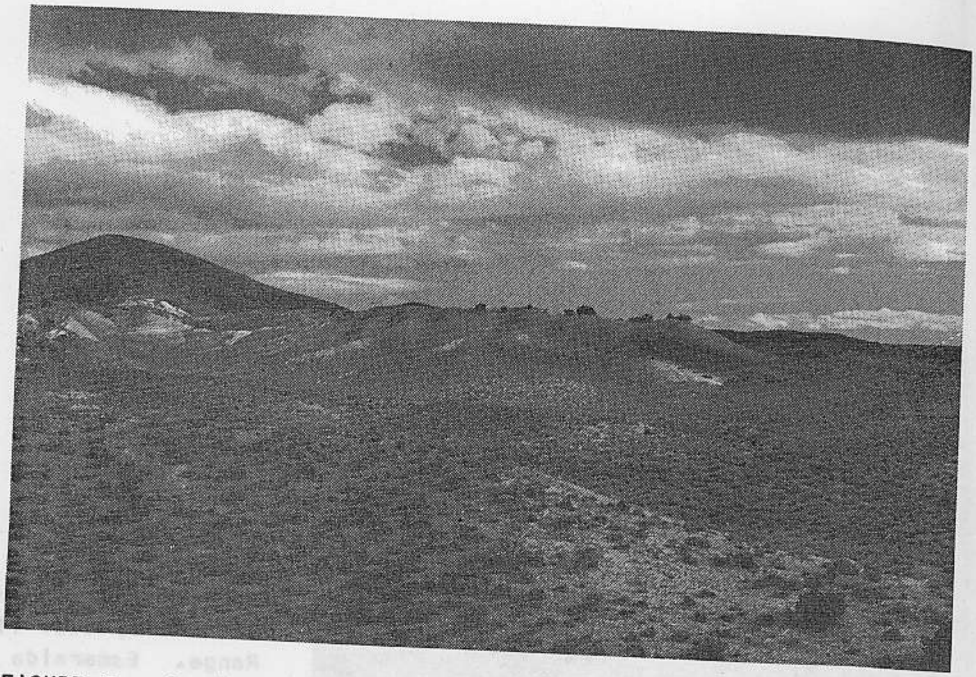

FIGURE 5: Gentle anticline in the Esmeralda Formation, east-central Stewart Valley. Limbs dip 43°E and 18°W. View to the southeast.

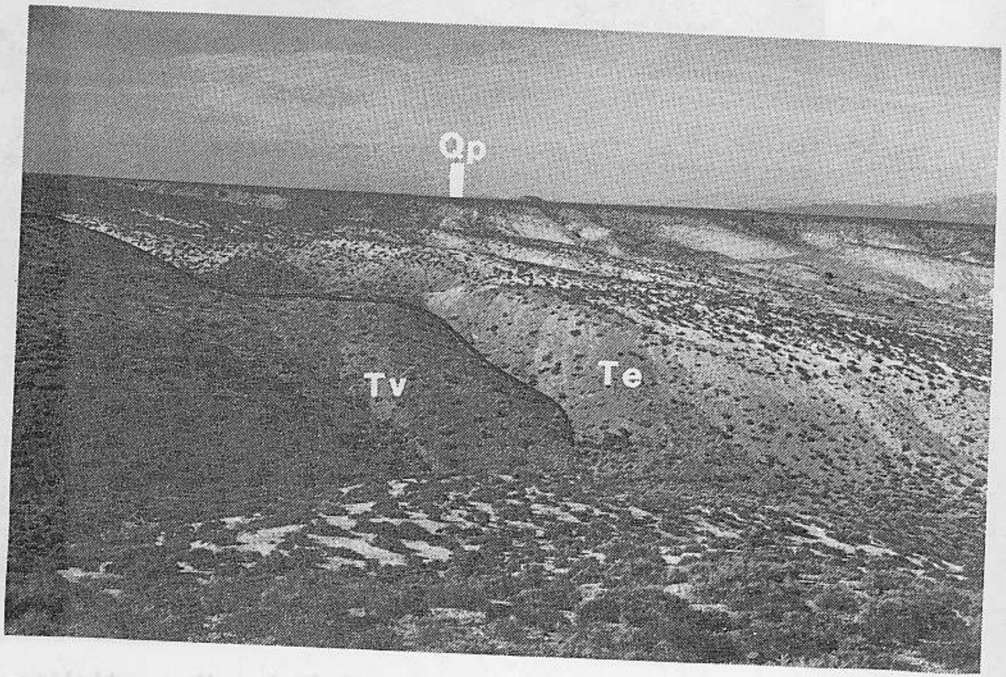

FIGURE 6: Remnant of well developed mid(?)-to-late Pleistocene pediment (Qp) overlying gently dipping Esmeralda Formation (Te), west-central Stewart Valley. Volcanic debris flow breccias (Tv) in buttress unconformity with Esmeralda Formation in foreground.

valley. A major N75°E trending anticline marks the southern terminus of this section (Fig. 2A, location a). Major structures in this section include several northwest trending right-oblique-slip faults of the SMCFZ, numerous northwest trending folds throughout the valley, and several north to northeast trending normal slip and left-oblique-slip faults in the eastern portion of the valley.

The northern segment of the SMCFZ consists of northwest trending, right-oblique-slip faults which extend for approximately 13 km. along the western edge of Stewart Valley (Fig. 2A). The faults dip steeply east or west and occur at or near the contact between the Esmeralda Formation and the volcanic debris flow brecciss. Field evidence for the presence and location of faults include scarps, offset bedding, sheared and brecciated zones in volcanic debris flow breccias, and geomorphic features such as deflected drainages and a linear hillside valley (Fig. 3). The faults are well exposed in the southern portion of the section. Although rarely exposed in the northern portion, the faults are expressed by distinct topographic lineaments visible on aerial photographs.

Accurate estimation of the magnitude of displacement on the northern segment was not possible since the faults parallel the strike of bedding and the breccias are poorly stratified. At several locations, distinctive units can be traced across individual faults and the normal dip separation is on the order of 30 to 40 m. Cumulative normal dip separation is estimated to be at least 100 m. across the fault zone with a similar amount of right-lateral separation. Relative displacements on the faults are both west block upthrown and east block upthrown. Evidence for a component of right-lateral strike-slip includes the rake of striae on slickensided fault scarps, the occurrence of a graben at right-stepping fault traces (Fig. 2A, location b), deflected drainage channels, and the approximately 150 m. of right-lateral separation apparent on the edge of a distinct lava flow offset by one of the faults. The rake of observed striae range from horizontal to 76°, with an average of 43°. The variability of the rake of striae and dip of fault planes are considered to be a result of irregular fault propagation through the heterogenous breccias rather than varying slip directions on the faults at depth.

Similar bedding attitudes on both sides of the fault zone and the conformable contact between the Esmeralda Formation and the volcanic breccias indicate the faults were initiated post-15 m.y. B.P. and probably post-11 m.y. B.P. At one location, an erosional remnant of Esmeralda Formation overlies the volcanic breccias with an angular unconformity of 8°. These sediments are stratigraphically younger than the conformable sediments along the range front. The unconformity is interpreted to be the result of mid-Miocene uplift of the easternmost block of the Gabbs Valley Range on the Petrified Spring fault which is located approximately 4 km. to the west (Fig. 1). The northern segment of the SMCFZ was initiated after deposition of the Esmeralda Formation (post-11 m.y. B.P.). The fault-related geomorphic features and an offset mid(?)-to-late Pleistocene pediment surface indicate late Pleistocene activity but there is no evidence for Holocene activity.

A N75°E trending anticline located south of the faults (Fig. 2A, location a) marks the southern boundary of the north section. The fold plunges east and is slightly overturned at its eastern end (Fig. 4) where it is truncated by a north-to-northeast trending fault (Fig. 2A, location c). The presence of a truncated east plunging anticline east of the fault suggests 0.7 km. of left-separation with an undeterminable amount of normal separation. Late Pleistocene pediment gravels are not displaced by the fault but some minor surface fissuring may have occurred in 1932 (Gianella and Callaghan 1934b).

Along the east flank of the Gabbs Valley Range the volcanic breccias consistently dip 20° to 25° east, whereas within Stewart Valley the Esmeralda Formation has been deformed into numerous northwest trending folds which are subparallel to the faults (Fig. 2A). The gentle folds are horizontal to gently plunging with limbs that dip from 5° to as much as 43° (Fig. 5). Lengths of the folds range from approximately 0.5 to 7 km. Several relatively short, north-to-northeast trending, gentle folds occur in the southeast portion of the north section. No unconformities have been detected in the Esmeralda Formation in Stewart Valley; thus, the folding was initiated post-11 m.y. B.P. Undeformed mid(?)-to-late Pleistocene pediment gravels cap the folded Esmeralda Formation (Fig. 6). If the initiation of the folding is assumed to have begun between 5 and 10 m.y. B.P., the amount of post-pediment tilting at locations where pediments are well-preserved would be a maximum of 2°. This value is too small to be distinguished from the natural pediment slope and the folding may be continuing presently.

Local variations in bedding attitudes, the repetition of tuff beds, and one fault exposure in the Esmeralda Formation in northern Stewart Valley indicate the existence of a northwest trending buried fault and a north trending branch fault (Fig. 2A, location d). A cross-section constructed through this area indicates a combined 105 m. of normal dip separation of the tuff beds. The faults do not displace alluvial deposits of Holocene age.

The range front normal fault of the west flank of the Cedar Mountains (Fig. 2A, location e) has a sinuous trace and is delineated by a sharp break in slope, discordant bedding between the Esmeralda Formation on the west and pre-Esmeralda volcanic rocks on the east, and the local emplacement of intrusive breccias along the fault trace. There is no direct evidence for late Pleistocene or Holocene displacement along the fault. At the northwest corner of the range, several minor northwest trending right-oblique-slip faults branch from the main fault. In this area several northeast trending faults juxtapose the Esmeralda Formation against intermediate lavas of probable early-to-mid Miocene age. Stratigraphic relationships within the Esmeralda Formation suggest some left-lateral slip on the northernmost of these faults but the trace of a fold axis crossed by the fault does not appear to be laterally displaced. There is no evidence for late Pleistocene or Holocene movement on these faults.

CENTRAL SECTION

The central section extends for approximately 8 km. southward from the N75°E anticline into northern Monte Cristo Valley (Fig. 2A, 2B). Deformation in the central section is more localized relative to the north. At the northern edge of this section, numerous northwest trending, tightly spaced, gentle to open folds are formed in the Esmeralda Formation on the south limb of the N75°E anticline. Dips of the fold limbs range from 9° to 84° and the average wavelength of the folds is less than 30 m. None of the folds can be traced for more than 2 km.

In southeastern Stewart Valley (Fig. 2A, location f) several northeast trending normal faults, with the east block upthrown, are delineated by distinct lineaments on aerial photography and the repetition of tuff beds within the Esmeralda Formation. Apparent normal dip separation on each of the faults is approximately 30 m. or less. No evidence of lateral slip on these faults was observed, but the discontinuous outcrop pattern of the tuffs prevented resolution of the structural geology. A minor, northwest trending right-lateral strike-slip fault was mapped in the southern portion of the central section (Fig. 2B, location g) based on several surface fissures reported by Gianella and Callaghan (1934b) and a weak photolineament.

SOUTH SECTION

The southern segment of the SMCFZ extends for 24 km. from northwest Monte Cristo Valley to the south edge of Kibby Flat (Fig. 2B). Deformation in the northern 12.2 km. of this section is expressed as a series of prominent north-to-northwest trending fault scarps in mid(?)-to-late Quaternary alluvium with an overall trend of approximately N30°W. In the central portion of the section, northerly trending faults occur in a left-stepping en echelon pattern (Fig. 2B, location h). Vertical displacement on the faults has been great enough to locally juxtapose rocks of the

Esmeralda Formation against various alluvial units. Except where grabens occur, the scarps are west facing. A 65°W dipping fault plane is exposed in a scarp formed in the Esmeralda Formation at one locality. Bedding in the Esmeralda Formation strikes northwest and dips 6° to 65° east except where small, gentle to open folds have formed subparallel to the faults.

A northwest trending vegetation lineament on the west side of Kibby Flat playa is inferred to be fault controlled and represent the southernmost portion of the SMCFZ. The lineament is on trend with the faults northwest of the playa and is transverse to and apparently disrupts bands of vegetation paralleling the playa edge. No displacement of the playa surface was observed.

The surface faults associated with the 1932 earthquake generally formed along pre-existing fault scarps several meters high (Fig. 7). Several new faults were formed and some pre-existing faults were not reactivated. Normal throw of up to 140 cm. was measured on the 1932 scarps and right-lateral slip ranging between 100 to 200 cm. is indicated by offset drainage channels and linear lag deposits of gravel and cobbles perpendicular to the scarps. In addition, a component of right-lateral-slip is indicated by scarp heights which increase downslope on south-facing channel sideslopes perpendicular to the faults.

Several en echelon northeast trending faults branch from the main trace of the SMCFZ in northern Monte Cristo Valley (Fig. 2B, location I). West facing scarps were formed in 1932 and there is no evidence for pre-existing fault scarps. A 65°W dip was measured on one fault plane where it is exposed in the Esmeralda Formation. Normal throw of up to 75 cm. was measured on the west facing scarps. The consistent scarp height where the faults traverse channel sideslopes suggests little or no lateral slip at this locality.

Several faults are exposed in the

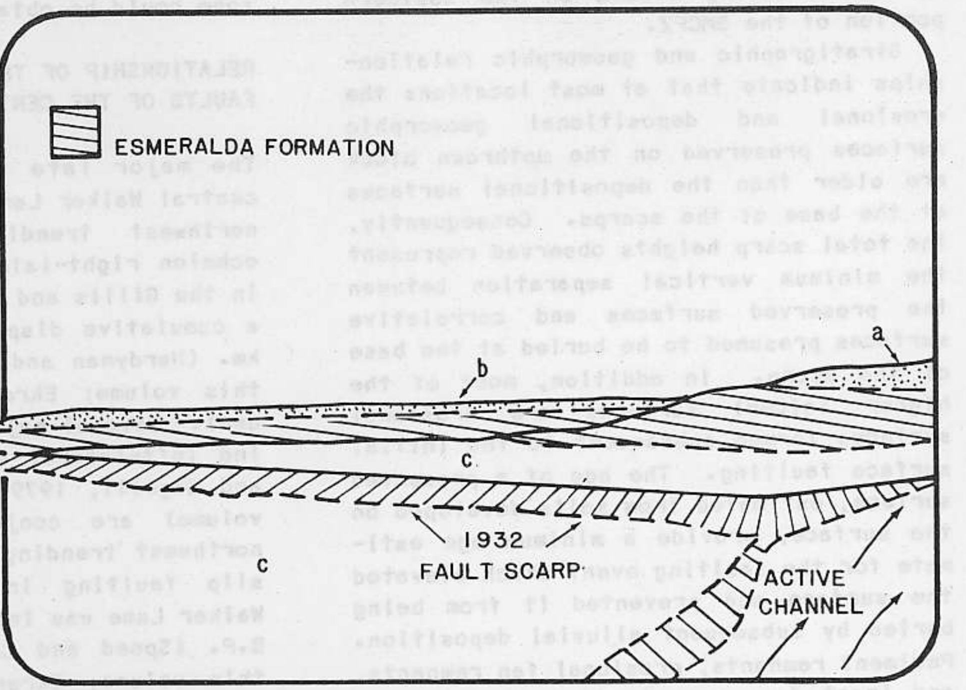

FIGURE 7: Diagram from photograph showing 40 centimeter high 1932 fault scarp at base of pre-existing fault scarp in Monte Cristo Valley. Scarp heights and preserved surfaces provide evidence for several 1932-sized surface faulting events post-surface a prior to surface b, and post-surface b prior to surface c.

Mesozoic sedimentary rocks and Tertiary volcanic rocks which crop out along the west margin of Monte Cristo Valley. The faults exhibit normal displacement and are associated with uplift of the Pilot Mountains. The northwest trending faults may have experienced a component of right-lateral-slip but no direct evidence was observed. None of the late Pleistocene fans deposited across the faults are offset.

LATE QUATERNARY RECURRENT FAULTING ON THE SMCFZ IN MONTE CRISTO VALLEY

Unlike most late Quaternary fault scarps within the Great Basin, the fault scarps along the southern segment of the SMCFZ are antithetic to the nearby range front. Alluvium transported across the piedmont slope has been deposited against and across the fault scarps, or transported and deposited beyond the scarps by ephemeral stream channels eroded through the scarps. The pre-existing scarps and age and number of geomorphic surfaces preserved on the upthrown block provide evidence for multiple late Quaternary surface faulting events on the southern portion of the SMCFZ.

Stratigraphic and geomorphic relationships indicate that at most locations the erosional and depositional geomorphic surfaces preserved on the upthrown block are older than the depositional surfaces at the base of the scarps. Consequently, the total scarp heights observed represent the minimum vertical separation between the preserved surfaces and correlative surfaces presumed to be buried at the base of the scarp. In addition, most of the higher (older) surfaces are erosional surfaces formed subsequent to the initial surface faulting. The age of a preserved surface, estimated from soils developed on the surface, provide a minimum age estimate for the faulting event which elevated the surface and prevented it from being buried by subsequent alluvial deposition. Pediment remnants, erosional fan remnants, and inset fans preserved on the upthrown block (surfaces a, b, and c, respectively, in Fig. 7) have surface soils of Holocene and possibly latest Pleistocene age (less than 35,000 yrs. old).

If it is assumed that the 1932 Cedar Mountain surface faulting event is typical of events on the SMCFZ, then comparison of the 1932 scarps to preexisting scarps provides insight into the number of surface faulting events which occurred during the latest Pleistocene(?) and Holocene. The pre-existing scarps are generally three to five times the height of 1932 scarps at their base (Fig. 7). Scarp profiles measured at several locations suggest at least two or three pre-1932 events with greater-than-1932 vertical displacement. Since the measured scarp heights are minimum values, it is estimated that at least three and probably five or six pre-1932 surface faulting events occurred on the southern portion of the SMCFZ during the latest Pleistocene and Holocene; indicating recurrence intervals on the order of several thousand years. In addition, several older late Pleistocene events are suggested by fault scarps, not reactivated in 1932, which displace older geomorphic surfaces. No reliable estimate for the total displacement on the southern segment of the fault zone could be obtained.

RELATIONSHIP OF THE SMCFZ TO LATE CENOZOIC FAULTS OF THE CENTRAL WALKER LANE

The major late Cenozoic faults of the central Walker Lane consist of a series of northwest trending, left-stepping, en echelon right-lateral strike--slip faults in the Gillis and Gabbs Valley Ranges with a cumulative displacement of at least 48 km. (Hardyman and others, 1975; Hardyman, this volume; Ekren and Byers, this volume). Several major east-northeast trending left-lateral strikeslip faults (Speed and Cogbill, 1979; Ekren and Byers, this volume) are conjugate to the dominant northwest trending faults. Major strike-slip faulting in this portion of the Walker Lane was initiated at least 25 m.y. B.P. (Speed and Cogbill, 1979; Hardyman, this volume; Ekren and Byers, this volume).

The SMCFZ is a N30°W trending right-normal oblique-slip fault located southeast of the major faults in the Gabbs Valley and Gillis Ranges. The southern segment of the fault zone transects the east-west trending Pancake Range lineament (Ekren and others, 1976). This lineament is not expressed in the Esmeralda Formation or Quaternary alluvium of northern Monte Cristo Valley but is well expressed in pre-Esmeralda rocks in the bounding mountain ranges. Some deformation must have occurred in the study area during the early Miocene to form the depositional basin of the Esmeralda Formation and cause an angular unconformity between pre-Esmeralda volcanic rocks and the Esmeralda Formation in the northern Cedar Mountains (Buwalda, 1914; Mawby, 1965). There is no evidence for the existence of the SMCFZ prior to or during the deposition of the Esmeralda Formation, approximately 15.5 to 11.0 m.y. B.P.

The SMCFZ appears to have been the most active of the right-lateral strike-slip faults during the latest Pleistocene and Holocene and deformation is continuing at present as evidenced by the 1932 earthquake and continued seismicity. The relatively young age of the fault zone may represent a southeast expansion of the central portion of the Walker Lane structural zone.

MODEL OF FOLD AND FAULT PATTERN

The timing and pattern of folds and faults is best explained by wrench tectonic models (Tchalenko, 1970; Wilcox and others, 1973; Odonne and Vialon, 1983). Folds associated with right-lateral wrench faults form subparallel (less than 45°) and counterclockwise to the controlling fault. With increasing deformation, the angle decreases and the fold axes may become curved. The folds may result from convergent wrench fault displacement or form when plastic materials overlie materials experiencing brittle deformation along a wrench fault. Since the faults of the SMCFZ display a component of normal slip and the folded Esmeralda Formation overlies Tertiary volcanic and Mesozoic sedimentary rocks which deform brittlely (see Ekren and Byers; Hardyman, this volume), the latter cause is the favored interpretation for the origin of the folds. The major N75°E trending fold in southern Stewart Valley results from strong convergence at the left-step between the north and south segments of the SMCFZ.

The north trending en echelon faults in the southern segment of the SMCFZ (Fig. 2B, location h) could result from a right-step in the fault zone or may be Reidel shears in the "peak structure" stage of evolution (Tchalenko, 1970). Reidel shears form at low angles (less than 30°) to the slip direction during the initial stages of wrench faulting. Pull-apart depressions commonly form at right-steps on right-lateral wrench faults (Crowell, 1974), but since this portion of the SMCFZ is a topographic and structural high the faults are interpreted as Reidel shears. Other north to northeast trending normal and left-normal-oblique-slip faults situated east of the SMCFZ are most likely large scale conjugate Reidel shears. Comparison of the structural development of the SMCFZ to laboratory wrench fault models (Tchalenko, 1970; Wilcox and others, 1973) suggest it is a wrench fault in the initial stage of the early phase of development.

The southern segment of the SMCFZ appears to have been considerably more active than the northern segment during the latest Pleistocene and Holocene and was reactivated in 1932. In addition, the lack of an apparent surface expression of the fault zone in the central section would argue against a genetic relationship between the northern and southern fault segments. This apparent discrepancy can be explained if convergence at the left-step has caused the northern segment to become locked and a new fault to form at depth as a northerly extension of the southern segment (Crowell, 1974; Molinari, 1984). The lack of surface expression of the fault may be a result of the early stage of fault development, poor propagation to the surface due to detachment (Hardyman, 1978; Molinari, 1984), folding, or a combination of these. The presence of a throughgoing fault at depth is supported by the fact that: (1) the length of surface rupture on the southern segment of the SMCFZ associated with the 1932 earthquake is relatively small when compared to other historical earthquakes of similar magnitude; (2) only minor surface faulting occurred within Stewart Valley but occurred on several faults to the north in southern Gabbs Valley (Gianella and Callaghan, 1934a, b); and (3) current microseismicity occurs within Stewart Valley (Gumper and Scholz, 1971; Ryall and Priestley, 1975). A composite focal mechanism from microseismicity recorded in January and February 1969 indicates right-normal oblique-slip on a N27°W trending, 70°SW dipping fault (Gumper and Scholz, 1971). This focal mechanism is entirely consistent with geologic observations.

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