AN ABSTRACT OF THE THESIS OF

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Title: Late Cenozoic Structure of the Central Wassuk Range, Mineral County, Nevada.

Abstract approved: Signature redacted for privacy.

At least 105% nearly east-west extension of late Cenozoic age has been accommodated by down-to-the-east normal and oblique-slip faults in the central Wassuk Range. One northwest striking, right-lateral strike-slip fault probably contributes an additional component of WNW-ESE slip. Movement on the normal and oblique-slip faults in this area tilt the Tertiary and Mesozoic section and older faults westward; faults were initiated at high-angles (45-75°) and rotated to shallower dips during movement and by movement on more recent faults.

Late Cenozoic faults can be divided into four age groups: 1) the earliest in the area was a down-to-the-east, spoon-shaped, normal fault, presently dipping gently to the east. This fault dipped moderately to steeply eastward when active and displaces Tertiary and Mesozoic rocks a minimum of 3000 ft. Movement on this fault post-dates eruption of silicic ash-flow tuffs (22-28 Ma), which are tilted moderately to steeply westward (40° to overturned), and pre-dates deposition of Wassuk Group sedimentary rocks and flow rocks (~9 Ma). The Wassuk Group is tilted shallowly to moderately westward (14-64°). 2) Several parallel, northwest striking, moderately dipping, down-to-the-east normal faults were active during deposition of the base of the Wassuk Group (~9 Ma). The sum of movement on these faults is 6150 ± 250 ft. 3) One vertical right-lateral strike-slip fault and two younger, moderately dipping, coeval oblique-slip faults began movement during

deposition of the Wassuk Group, and pre-date eruption of basalt flows (7 Ma). The strike-slip fault has components of vertical and horizontal movement with a maximum horizontal offset of about 11,000 ft. The two oblique-slip faults have an offset of about 13,750 ft. One oblique-slip fault strikes northwest and has components of right- and dip-slip; the second oblique-slip fault strikes northeast to east and has components of dip- and left-slip. One or all of these faults have drag folded parts of the Wassuk Group into a syncline. 4) North-northwest striking, down-to-the-east range-front normal faults were active after eruption of the basalts (7 Ma), which are tilted 5-12° westward. There is evidence of Holocene movement on some of these faults.

The orientation of extension was S85-89°E during the earliest phase of faulting (~22-9 Ma) and underwent a small change in orientation to S69-77°E, before or during movement on the oblique- and strike-slip faults at ~9 Ma. It is uncertain if this extension orientation persisted during movement on the range-front fault system.

Pebble count data suggest that the Cottonwood Springs, Penrod Canyon, and Reese River faults were active during deposition of the Wassuk Group. This, taken in conjunction with the sedimentological evidence (angular clasts, coarse clast size, and poor sorting), suggests that clasts were mostly locally derived and were deposited on alluvial fans adjacent to fault scarps.

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Late Cenozoic Structure of the Central Wassuk Range, Mineral County, Nevada

by

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LATE CENOZOIC STRUCTURE OF THE CENTRAL WASSUK RANGE, MINERAL COUNTY, NEVADA

INTRODUCTION

This study focuses on the Late Cenozoic structure of the central Wassuk Range, located in Mineral County, west-central Nevada (Figures 1 and 2). Late Cenozoic faults observed in the Wassuk Range include down-to-the-east normal and oblique-slip faults, and right-lateral strike-slip faults (Dilles, 1989; and this study). In the Singatse Range to the west, extension has been accommodated primarily by down-to-the-east normal faults (Proffett, 1977). To the east, in the Gabbs Valley and Gillis Ranges, right- and left-lateral faults, kinematically related detachment faults, and normal faults comprise the Cenozoic faults (Hardyman, 1984; and Ekren and Byers, 1984). The Gabbs Valley and Gillis Ranges lie within the center of the Walker Lane belt, which is characterized by northwest-striking right-lateral strike-slip faults (Hardyman, 1984). The study area appears to be transitional between the structural styles of these two areas to the east and west: in the central Wassuk Range, both down-to-the-east normal faults and right-lateral strike- and oblique-slip faults play an integral part in the range's Late Cenozoic structural history.

Strike- and oblique-slip faults have not been recognized previously in the central Wassuk Range. One northwest-striking, high-angle fault, previously mapped as a normal fault by Bingler (1978), is here inferred to be a right-lateral strike-slip fault related to the Walker Lane system. Two other faults, mapped by Bingler (1978) as a thrust fault and normal fault respectively, are interpreted here to be oblique-slip faults; Bingler's (1978) "thrust" fault is a northwest-striking, moderately dipping fault with components of normal- and right-slip. Bingler's (1978) "normal" fault strikes northeast-east and has components of normal- and left-slip.

The purpose of this study was to describe the style, estimate the amount, and constrain the timing of Late Cenozoic extensional faulting in the central Wassuk Range. These objectives were accomplished by detailed mapping of the Cenozoic structure and stratigraphy at a scale of 1:12,000, construction and restoration of balanced cross-sections, and K-Ar and Ar-Ar dating of K-bearing minerals from an air-fall tuff and a basaltic-andesite flow interbedded with Wassuk Group sediments.

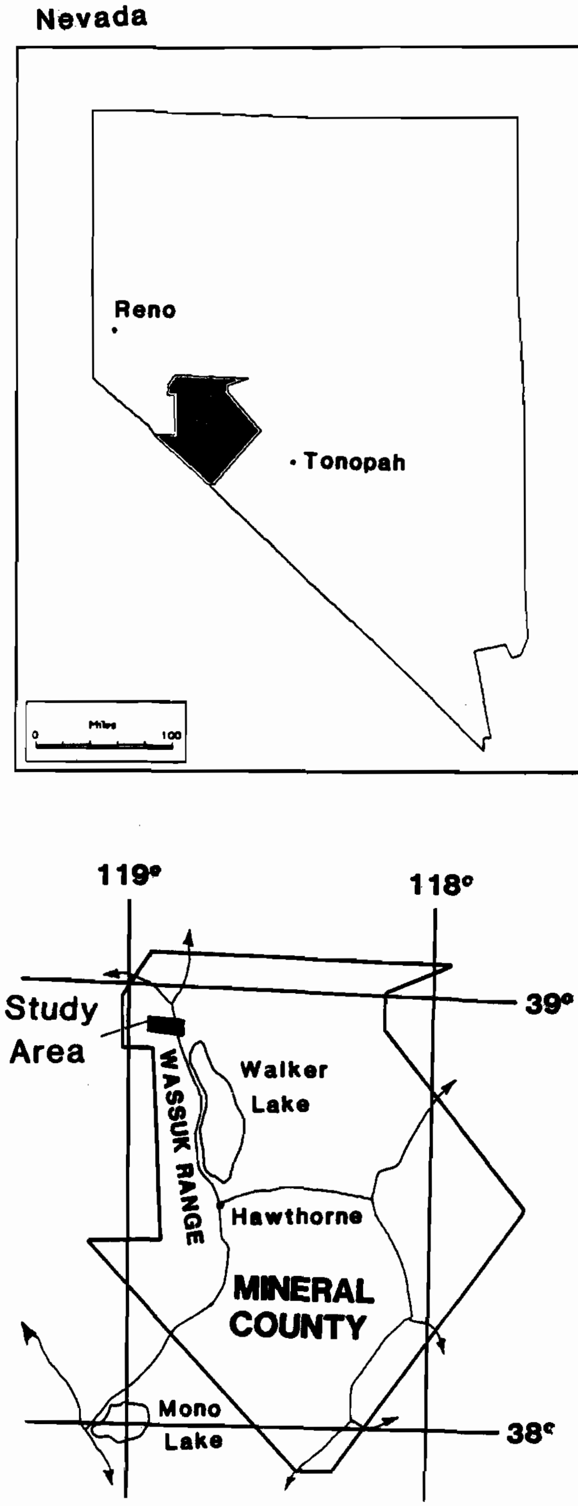


Figure 1. Index map of Mineral County, west-central Nevada.

Quaternary alluvium

Miocene and Quaternary volcanic flows and plugs

Miocene and Pliocene sedimentary rocks and basaltic flows

Miocene intermediate volcanic flows

Oligocene and early Miocene silicic ash-flow tuffs

Mesozoic granitic and metamorphic rocks

Normal fault. Ball on downthrown block. Dotted where covered.

Strike-slip fault. Arrows show relative movement. Dotted where covered.

Thrust fault. Teeth on upper plate.

Contact.

Figure 2. Simplified geologic map of west-central Nevada. The outlined area in the central Wassuk Range is the study area. Data are primarily from Stewart (1978) and partly from Bingler (1978), Proffett and Dilles (1984), Hardyman (1980), Gilbert and Reynolds (1973), and this study.

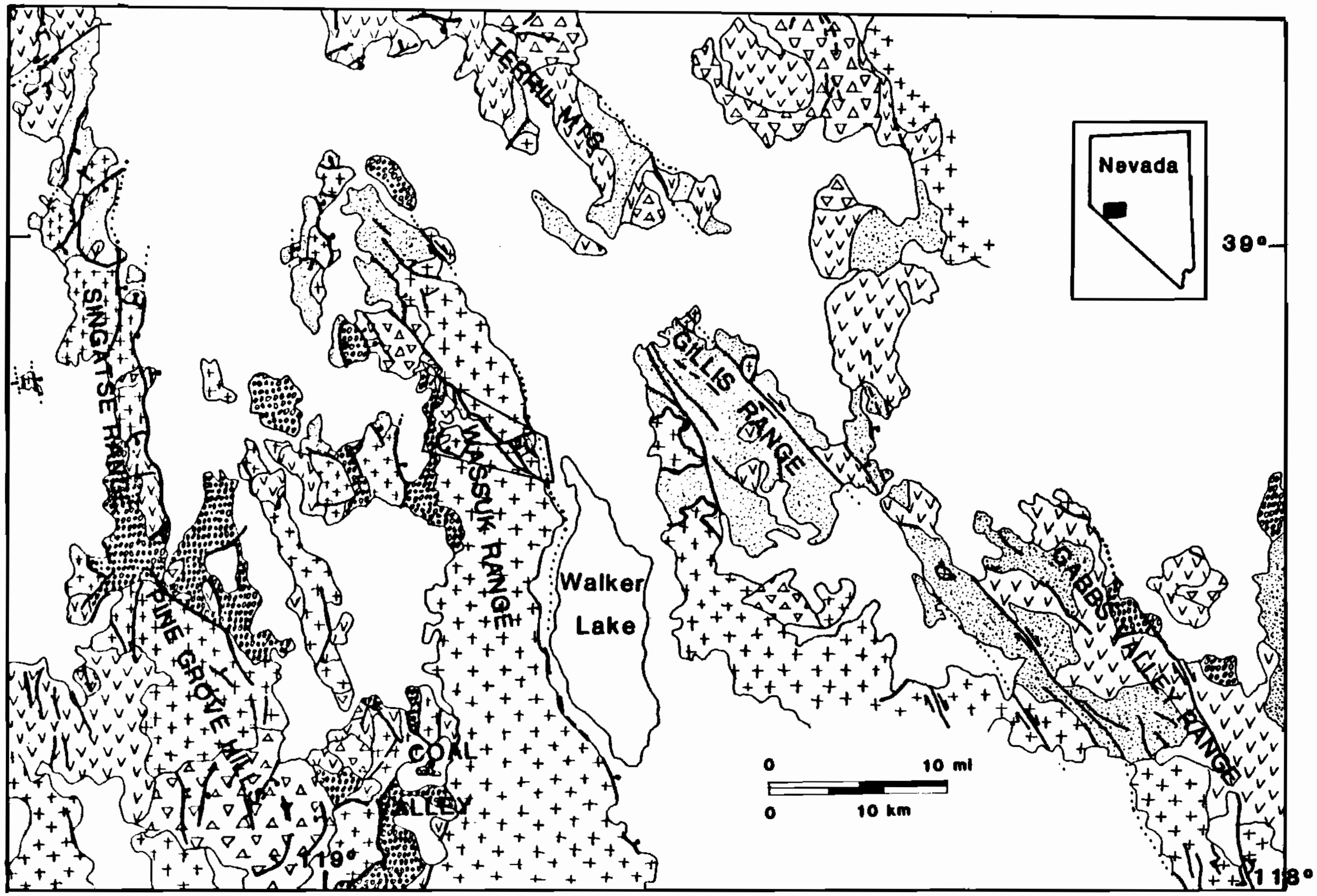

TERRILL MTS
Nevada
39°
SINGATSE RANGE
GILLIS RANGE
WASSUK RANGE
Walker
Lake
GABBS VALLEY RANGE
PINE GROVE HILLS
COAL VALLEY
0
10 mi
0
10 km
119°
118°

Figure 2.

REGIONAL GEOLOGIC SETTING

The Singatse, Wassuk, Gabbs Valley, and Gillis Ranges, Pine Grove Hills, and Coal Valley in west-central Nevada represent a small region within the Cenozoic Basin and Range Province that extends from the eastern flank of the Sierra Nevada in California across Nevada into western Utah, and parts of Idaho, and from south-eastern Oregon southward as far as southern Arizona, New Mexico, and Mexico. Latest Basin and Range faulting resulted in the characteristic regional pattern of alternating alluvial basins and uplifted ranges with a general northerly structural trend. Cenozoic structures of the Basin and Range are superimposed on a wide variety of earlier, mostly compressional structures related to different episodes of Paleozoic and Mesozoic lithospheric plate convergence (Burchfiel and Davis, 1972; Nelson, 1981).

The oldest bedrock exposed in the Singatse, Wassuk, Gabbs Valley, and Gillis Ranges, and in the vicinity of Coal Valley in west-central Nevada are Triassic and early Jurassic shallow marine carbonate and clastic rocks, and volcanic and volcaniclastic rocks and associated plutonic rocks (Ferguson and Muller, 1949; Moore, 1969; Gilbert and Reynolds, 1973; Bingler, 1978; Stewart, 1980; Proffett and Dilles, 1984; and Dilles and Wright, 1988). In the northern Wassuk Range, dioritic plutons were intruded during the Triassic (Dilles and Wright, 1988).During the Jurassic and Cretaceous, the rocks were intruded and thermally metamorphosed by granitic to dioritic plutons, inferred to represent the eastern margin of the Sierra Nevada batholith (Ferguson and Muller, 1949; Moore, 1969; Stewart, 1980; Ekren et al., 1980; and Hardyman, 1984) (Figure 2). At least two phases of folding occurred prior to the Jurassic-Cretaceous intrusions (Ferguson and Muller, 1949; and Hardyman, 1984); the folding may have begun as early as late Triassic or early Jurassic (Stewart, 1980). In the Singatse Range, folding was either synchronous with or slightly predated 169 m.y. old plutons, but was not older than late Early Jurassic

(Dilles and Wright, 1988). In the Gillis and Gabbs Valley Ranges, the metasedimentary and metavolcanic rocks have also been thrust faulted (Ferguson and Muller, 1949; Oldow, 1983; Ekren, 1984; and Hardyman, 1984).

A major unconformity separates the Mesozoic basement rocks from the overlying Tertiary rocks; the unconformity is an erosional surface of moderate relief (Proffett, 1977; and Ekren et al., 1980). In the Singatse Range and the central Wassuk Range, the oldest deposits preserved above the unconformity are conglomerate, breccia, and/or minor basalt (Proffett, 1977; and this study). In the Gabbs Valley and Gillis Ranges, the oldest Tertiary rocks are debris flow deposits and thin (less than 90 ft thick) andesitic flows and flow breccias (Ekren et al., 1980; and Hardyman, 1984).

A thick section of silicic ash-flow tuffs of Oligocene and early Miocene age (~28-22 Ma), interbedded in places with intermediate lavas and tuffaceous sedimentary rocks, overlies the Mesozoic basement and basal Tertiary rocks (Figure 2). Parts of the ash-flow tuff section occur in the Singatse Range, the Coal Valley area, the central and northern Wassuk Range, and eastward into the Walker Lane fault zone in the Gillis and Gabbs Valley Ranges.

According to Hardyman (1984) and Ekren and Byers (1984), the earliest phase of extensional faulting in the Gabbs Valley and Gillis Ranges began during eruption of the youngest ash-flow tuffs (~25 Ma). However, J. H. Dilles (personal communication, 1989) suggests that the timing of this phase of faulting in the Gabbs Valley and Gillis Ranges could be similar to that in the northern Singatse Range (~19-17 Ma). Whether extensional faulting in the Gabbs Valley and Gillis Ranges began during or after the eruption of silicic ash-flow tuffs, this phase of faulting was characterized by northwest striking right-lateral faults, northeast striking left-lateral faults, kinematically related detachment faults, listric and high-angle normal faults, and oblique-slip faults (Ekren and Byers, 1984; Hardyman, 1984; and Keller, 1989).

Overlying the thick ash-flow tuff section are Miocene intermediate lavas of variable thickness (Figure 2). Deposition of these lavas is synchronous with the beginning of widepread extensional faulting in west-central Nevada (Stewart, 1980). For example, in the Singatse Range to the west of the Wassuk Range, Proffett (1977) demonstrated that normal faulting began during an episode of intermediate volcanism at 17-19 Ma.. In Coal Valley, south of the Wassuk Range, an angular unconformity separates 15-18 m.y. old intermediate flows from the 22-28 m.y. old ignimbrites; indicating that tilting of the older rocks along normal faults occurred prior to eruption of the lavas (Gilbert and Reynolds, 1973). In the central Wassuk Range, the timing of faulting with respect to the intermediate flows is unclear; initiation of faulting here is only constrained to have occurred after eruption of the silicic ash-flow tuffs and prior to deposition of sedimentary rocks of the Miocene Wassuk Group (~9 Ma), described below. In the Gabbs Valley and Gillis Ranges, the short-lived period of detachment and listric normal faulting ended during eruption of intermediate lavas, though strike-slip, high-angle normal and oblique-slip faulting continued uninterrupted (Ekren and Byers, 1984; and Keller, 1989).

An angular unconformity separates the intermediate lavas from overlying late Miocene conglomerates, sandstones, siltstones, thin air-fall tuffs, and interbedded lava flows of the Wassuk Group (Figure 2). Thick sections of the Wassuk Group are preserved in Coal Valley, the central and northern Wassuk Range, and the southern Singatse Range, whereas deposits in the N. Singatse Range and the Gabbs Valley and Gillis Ranges are less than 90 ft thick (Ekren et al., 1980, and Proffett, 1977). In the Wassuk Range (Dilles, 1989; and this study) and in Coal Valley and vicinity (Gilbert and Reynolds, 1973), normal and oblique- and strike-slip faults have been documented that were active during Wassuk Group deposition; the Wassuk Group accumulated in basins formed by movement on these Basin and Range faults.

Late Miocene and younger volcanic rocks overlie or intrude the older rocks (Figure 2). In the Singatse Range and Wassuk Range, basalts and basaltic andesite predominate. In the Gabbs Valley Range, Gillis Range, and Coal Valley area, intermediate and silicic flows, and rhyolitic plugs and domes are common, in addition to basalt flows (Ross, 1961; Gilbert and Reynolds, 1973; and Ekren et al., 1980). These volcanic flows and younger Quaternary deposits are tilted gently to the west by high-angle normal faults bounding modern range fronts.

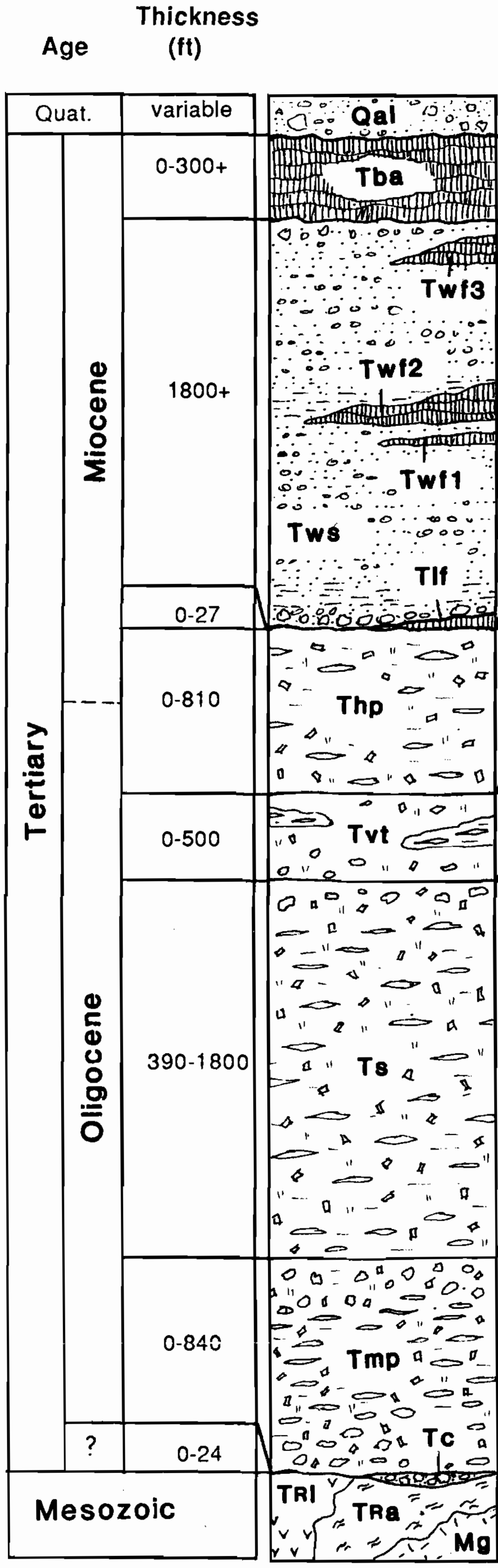
STRATIGRAPHY OF TERTIARY ROCKS

INTRODUCTION

The oldest rocks exposed in the central Wassuk Range are Triassic meta-andesite flow rocks and meta-latite pyroclastic rocks that were intruded and thermally metamorphosed by quartz monzonite and mafic dike rocks in the Middle Jurassic to early Late Cretaceous (Bingler, 1978). A thick section of Oligocene and early Miocene silicic ash-flow tuffs rest unconformably on the Mesozoic basement rocks. A boulder conglomerate derived entirely from Mesozoic basement rocks is present locally below the ash-flow tuff sequence, and, at one location, a thin hornblende latite flow is preserved above the ash-flow tuff sequence. Clastic sedimentary rocks and basaltic-andesite flows of the Miocene Wassuk Group overlie the ash-flow tuffs in angular unconformity. The youngest rocks in the study area are Upper Miocene basaltic-andesite flows. Figure 3 summarizes the stratigraphy of the study area. Except as noted, percent refers to volume percentage from petrographic or hand sample examination.

MICKEY PASS TUFF

The thick Mickey Pass Tuff overlies Mesozoic basement rocks. Abrupt changes in its thickness, from 0-840 ft, indicate that it was deposited in topographic lows. In the study area, the Mickey Pass Tuff consists of a single cooling unit. The percentages of crystals, lithics, and pumice vary considerably from outcrop to outcrop, but, in general, the proportion of phenocrysts is quartz > sanidine > plagioclase > biotite (Table 1). The relative proportion of phenocrysts is similar to that described by Proffett and Proffett



Description	Name
Alluvium, fanglomerate, colluvium, and landslide blocks.	Recent Deposits
Rubbly exposures of black weathering, medium- to dark-grey basaltic-andesite. Contains phenocrysts of plagioclase, clinopyroxene, olivine, and rare resorbed hornblende.	Basaltic Andesite Flows
Light-grey to light-brown conglomerates, sandstones, and siltstones are interbedded with basaltic andesite flows and minor siltstones and mudstones. 0-35 ft thick boulder conglomerates are present locally at the base.	Wassuk Group
Crystal-poor hornblende latite is light-grey to pale-lavendar and weathers a pale orange-brown. Rare quartz xenocrysts, and hornblende and plagioclase phenocrysts are present in a trachytic groundmass.	Hornblende Latite
Red-brown weathering, moderately to densely welded, lavendar-grey, crystal-rich, ash-flow tuff contains sparse pumice and plagioclase, biotite, and clinopyroxene phenocrysts.	Hu-Pwi Rhyodacite
White, light-grey, pink to lavendar-brown, and yellow unwelded to densely welded, crystal-poor vitric tuffs with crystals of quartz, sanidine, plagioclase, biotite, and rare hornblende and variable amounts of pumice/fiamme and lithics.	Vitric Tuff
Red-brown weathering, moderately to densely welded, lavendar-grey, crystal-rich ash-flow tuff contains plagioclase, sanidine, quartz, biotite, and hornblende crystals and minor lithics and buff-colored fiamme. A 0-9 ft thick grey to dark grey vitrophyre is present at the base and contains approximately the same crystal population as the overlying Singatse Tuff plus rare clinopyroxene. 0-120 ft of the top of the Singatse Tuff is bleached and unwelded.	Singatse Tuff
White, buff, grey, and lavendar-grey unwelded to densely welded, crystal-rich ash-flow tuff contains quartz, plagioclase, sanidine, biotite, and traces of hornblende, clinopyroxene, apatite, and allanite near the base plus minor lithics and relatively abundant pumice/fiamme. 0-6 ft thick red vitrophyre is present locally at base of the unit (Tmv).	Mickey Pass Tuff
Locally overlying the Mesozoic metamorphic and igneous rocks is a boulder conglomerate with angular to well rounded clasts from 0.1 in-3 ft in diameter and composed entirely of Mesozoic metamorphic rocks in a matrix of bright red-brown clay-rich sandstone. This conglomerate is overlain by 7.5 ft thick breccia of Mesozoic metamorphic clasts in a light-grey clay-rich sandstone matrix.	Basal Conglomerate
Mesozoic metavolcanic and metasedimentary rocks (Triassic?) intruded by Middle Jurassic to Late Cretaceous quartz monzonites, quartz diorites, and dacite porphyries.	Basement

Figure 3. Stratigraphy of the central Wassuk Range.

Table 1. Phenocryst type and volume percentage of the Mickey Pass Tuff in the central Wassuk Range. Percentages of lithic and pumice/fiamme are included. Abundances are based on point counting one to two thin sections (1000 points per section) for each location (1 to 5) and checked against hand samples.

Rock unit / Mineral	vitrophyre [1]	buff tuff [2]	buff tuff [3]	buff tuff [4]	lavendar-grey tuff [1]	white to buff tuff [5]
plagioclase	<1	3-5	2-4	3-7	5-10	2-3
sanidine	5-10	1-3	2-3	2-5	5-15	5-10
quartz	10-15	5-10	10-15	5-10	5-8	5-10
biotite	1	<1	<1	<1	1	1
hornblende			Tr		Tr	
clinopyroxene			Tr			
allanite			Tr		Tr	
apatite	Tr		Tr			
opaques	1-2		<1			
lithics	<2	2-5	1-2	10	1-2	1-3
pumice/ fiamme	<2	5-10	10-15	5-20	5-15	5

1 NE1/4, SW1/4, Sec. 5, T11N, R28E and NW1/4, Sec. 33, T12N, R28E
2 NE1/4, SW1/4, Sec. 5, T11N, R28E
3 NW1/4, Sec. 33, T12N, R28E and SW1/4, Sec. 28, T11N, R28E
4 NE1/4, Sec. 1, T11N, R28E
5 Sec. 5, T11N, R28E

Tr= Trace

(1976) for unit 2 of the Guild Mine Member of the Mickey Pass Tuff, with which it is probably correlative (Figure 4).

A 0-9 ft thick, red, moderately welded, devitrified vitrophyre is present locally at the base of the Mickey Pass Tuff (Plate 1). The vitrophyre contains <2% lithics and <2% buff, pink or grey pumice both up to 0.8 inches in diameter. Crystals present include 10-15% quartz, 5-10% sanidine, 1-2% opaques, ~1% biotite, <1% plagioclase, and a trace of apatite and zircon.

Overlying either the vitrophyre or Mesozoic basement rocks is a 0-180 ft thick "buff tuff". This is a poorly to moderately welded, devitrified in places, white, buff, grey, pale pink, or yellow ash-flow tuff (referred to as the buff tuff) with 2-20% buff, grey, or pink pumice and fiamme from 0.04-4 in long (average 0.2-0.4 in). The flattening ratio is 1:1 to 1:5 and increases upsection. The ignimbrite contains 1-10% lithics, which are 0.04-4 inches in diameter and consist primarily of Mesozoic metamorphic rocks. It contains 5-15% quartz, 1-10% sanidine, 2-7% plagioclase, <1% biotite, <2% opaque minerals, and traces of hornblende, clinopyroxene, apatite, and allanite.

In the thickest sections of the Mickey Pass Tuff, the buff tuff grades upsection to a 0-270 ft thick "lavendar-grey tuff". This is a moderately to densely welded, devitrified, red-grey weathering, lavendar-grey tuff with 5 to 15% white to buff fiamme up to 6 in long (average 0.4-1.6 in) with a flattening ratio from 1:4 to 1:10 (average 1:6) (Figure 5). The ignimbrite contains 1-2% lithics from 0.04-3.2 in in diameter as well as 5-8% quartz, 5-15% sanidine, 5-10% plagioclase, ~1% biotite, and a trace of hornblende and allanite. In places, the lavendar-grey ash-flow tuff rests directly on Mesozoic basement rocks.

The upper 0-180 ft of the Mickey Pass Tuff is a white to buff ash-flow tuff, which is moderately welded at its base to unwelded and very poorly exposed at its top. The tuff contains ~5% white, grey, or pale pink pumice and fiamme 0.04-0.8 in long with a flattening ratio of 1:1 to 1:6 (highest near the base) and 1-3% lithics 0.04-1.2 in in

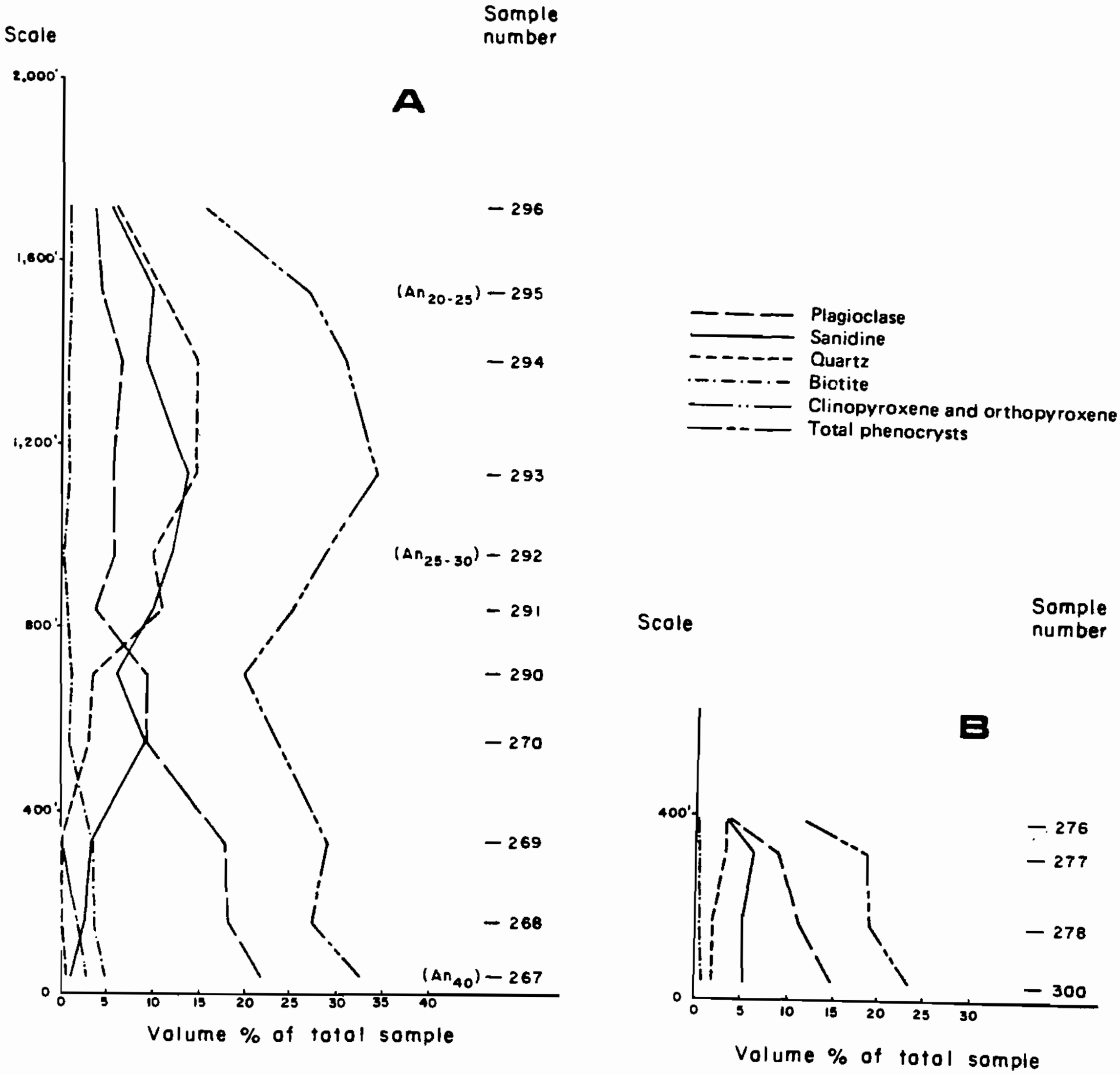


Figure 4. Variation of phenocryst type and abundance for the Mickey Pass Tuff with stratigraphic height. (A) Guild Mine Member of the Mickey Pass Tuff at its type section in the northern Singatse Range. Two thin sections, one parallel to bedding and one perpendicular to bedding were point counted (400 to 500 counts per thin section) under the microscope for each sample. (B) Weed Heights Member of the Mickey Pass Tuff at its type section in the northern Singatse Range. This figure is modified from Proffett and Proffett (1976).

Figure 5. Photograph of very densely welded lavendar-grey Mickey Pass Tuff with prominent buff fiamme. Lens cap is 3 inches in diameter.

diameter (average 0.2 in) of Mesozoic basement rocks. Crystals present include 5-10% quartz, 5-10% sanidine, 2-3% plagioclase, and ~1% biotite.

SINGATSE TUFF

The bulk of the 390-1800 ft thick single cooling unit that makes up the Singatse Tuff is a pink-grey to lavendar-grey, red-brown weathering, mostly devitrified, ridge-forming, densely welded ash-flow tuff. It contains <3% lithics of Mesozoic metamorphic and intrusive rocks, which vary from 0.04 to 3.2 inches in diameter (average 0.2 in) and <5% white, pale pink, or buff fiamme, which are 0.04-2 in long with a flattening ratio of 1:2-1:8. The crystal content is relatively high and constant throughout the unit: 15-20% plagioclase, 5-10% sanidine, 5% quartz, 3-5% biotite, 1-2% hornblende, and <1% opaques.

Locally, near the base of the Singatse Tuff, the lithic content increases to up to 15% with a size variation from 0.04 to 24 in (average 1.2-1.6 in). Proffett and Proffett (1976) noted a corresponding increase in lithics near the base of the Singatse Tuff in the Singatse Range, its type locality. In addition, white to black fiamme content increases locally near the base to up to 10-15%.

In the NE1/4 and SE1/4, Sec. 1, T11N, R28E, and the NE1/4 and NW1/4, Sec. 12, T11N, R28E, a 6-9 ft thick, light-grey to grey-black hypocrystalline vitrophyre is present at the base of the Singatse Tuff. This vitrophyre has <5% lithics, which are 0.04-1.2 in long and composed of Mesozoic metamorphic and intrusive rocks. The vitrophyre also contains <3% white, pale pink, and buff pumice and up to 40% crystals of 20-25% plagioclase, 5-10% sanidine, 5-8% biotite, ~5% quartz, 3-4% hornblende, 1% opaques, and a trace of clinopyroxene.

The upper 0-120 ft of the Singatse Tuff is bleached white to pale pink by vapor phase alteration (Bingler, 1978) and is poorly welded to unwelded with white to pink pumice up to 2 inches in diameter.

VITRIC TUFF

This map unit consists of an unwelded to densely welded ash-flow tuff that overlies the Singatse Tuff and may be as thick as 500 ft. At each outcrop, only a single cooling unit is present.

The base is a white to light-grey, unwelded to poorly welded vitric ash-flow tuff 15 to 55 ft thick (Figure 6). The tuff contains 3-10% lithics that are 0.04-2 in in diameter (average 0.3-0.4 in) and are comprised primarily of Tertiary ignimbrite clasts with lesser Mesozoic metamorphic clasts. 5-25% white, grey, and banded pumice and fiamme are 0.04-4 in long (average 0.4-0.8 in) with a flattening ratio up to 1:10 (average 1:4 to 1:5). This ash-flow tuff contains <5% crystals of quartz, sanidine, plagioclase, and biotite. The flattening ratio, percentage, average length, and dark component of the pumice increase from the bottom to the top of this basal unit. Silicification and red-orange discoloration affect this unit along faults of minor displacement.

Upsection there is a transition to a lavendar, mostly devitrified, densely welded, ridge-forming rhyolite ash-flow tuff, which weathers a dark red-lavendar brown that is 25-60 ft thick. This unit contains 25-40% fiamme that are 0.04-4 in long with a flattening ratio of 1:2 to 1:20. Fiamme are white, pink, and orange, as well as black in the most densely welded portions (Figure 7). It also contains 1-4% lithics that are 0.04 to 1.6 in long comprising Mesozoic metamorphics and intrusives and Tertiary ignimbrites. This tuff is crystal-poor with <5% crystals of quartz, plagioclase, sanidine, and rare biotite and hornblende.

Figure 6. Poorly welded Vitric Tuff with abundant white to grey and banded pumice fragments. Located in SW1/4, SE1/4, Sec. 1, T11N, R28E.

Figure 7. Densely welded Vitric Tuff with distinctive eutaxitic texture. Located in SW1/4, SE1/4, Sec. 1, T11N, R28E.

The top of this unit is a 15+ ft thick, poorly to moderately welded white to pale pink ash-flow tuff with <5% lithics 0.04-0.8 in long; <5% crystals of quartz, plagioclase, sanidine, and biotite; and 3-25% white pumice 0.04-1.2 in long with a flattening ratio of 1:1 to 1:6.

Ignimbrites of the same approximate age and stratigraphic position in the surrounding ranges include the Blue Sphinx Tuff described in the Gabbs Valley Range by Ekren et al. (1980), the tuff of Gabbs Valley in the Gabbs Valley Range (Ekren et al., 1980) the Bluestone Mine Tuff in the Singatse Range (Proffett and Proffett, 1976), and the Nine Hill Tuff (Deino, 1985; and Bingler, 1978). The Vitric tuff is unlikely to correlate with the Blue Sphinx Tuff because it lacks the embayed, resorbed quartz crystals characteristic of the relatively crystal-rich Blue Sphinx Tuff. The mode and crystal contents are permissible for correlation with the Bluestone Mine Tuff, and the partly correlative Nine Hill Tuff and tuff of Gabbs Valley, which are all crystal-poor ash-flow tuffs with 2-10% phenocrysts of sanidine, quartz, plagioclase, and biotite, and variable amounts of lithics and pumice/fiamme. However, according to Deino (1985), the Vitric tuff exposed in Sec. 29, 32, and 33, T12N, R28E is not correlative to the Nine Hill Tuff.

HU PWI RHYODACITE

The Hu Pwi rhyodacite is a red-brown weathering, densely welded, lavendar-grey, crystal-rich, devitrified ash-flow tuff up to 800 ft thick at its only outcrop in the northwestern part of the study area. It contains sparse fiamme and 30-40% plagioclase, 5-8% biotite, 1-2% clinopyroxene, and rare hornblende crystals.

HORNBLENDE LATITE

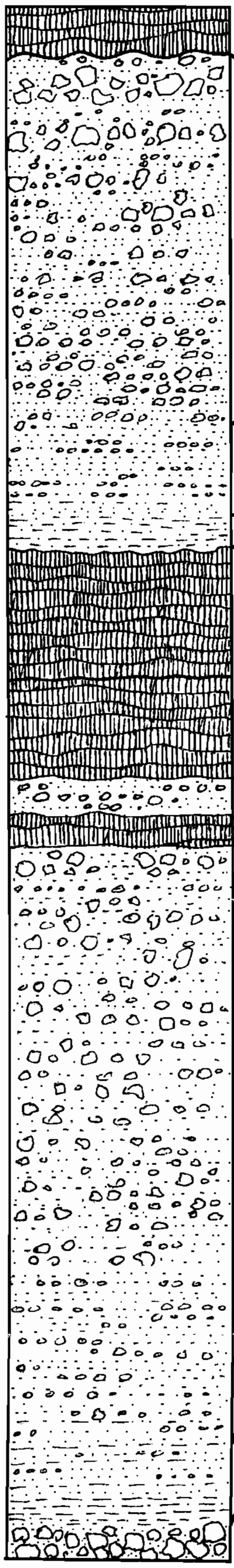
Exposed in the northwestern part of the study area, where it overlies the Vitric Tuff, this crystal-poor hornblende latite flow is approximately 15-30 ft thick. It is light-grey to pale-lavendar and weathers a pale-orange/brown. A trachytic groundmass of plagioclase microphenocrysts and 1-3% clinopyroxene microphenocrysts encloses 1-2% opaque minerals, rare quartz xenocrysts (0.02-0.12 in), rare oxidized hornblende needles (up to 0.08 in), and rare plagioclase phenocrysts (0.02-0.04 in).

This hornblende latite is similar mineralogically to some of the andesites of Lincoln Flat described by Proffett and Proffett (1976) in the Singatse Range, which are 17-19 m.y. old based on K-Ar dating; though Bingler (1978) dated a hornblende latite plug in the northern Wassuk Range at 13.9 $\pm$ 0.4 m.y. old. Despite the apparent age difference, these flows occupy the same stratigraphic position and may be correlative.

WASSUK GROUP

The Wassuk Group is at least 1800 ft thick and is composed predominantly of light-grey to light-brown interbedded conglomerates, sandstones, siltstones, and basaltic-andesite flows (Figure 8). The most complete exposures of the Wassuk Group crop out in Sec.1, T11N, R28E near the mouth of the Reese River canyon and both the descriptions below and in Figure 8 are based on these outcrops. The Wassuk Group has also been described in detail by Axelrod (1956) and Gilbert and Reynolds (1973) in the vicinity of Coal Valley to the south of the study area.

Two samples from the Wassuk Group were dated as a part of this study. K-Ar analysis of biotite from an air-fall tuff yielded an age of 9.44 $\pm$ 0.41 m.y., and ^{40}Ar-^{39}Ar



Unit	Description	Thickness (ft)	dates (Ma)
	Flow 3. Medium- to dark-grey or lavendar-grey basaltic-andesite flow weathers red-brown to lavendar and has plagioclase, hornblende, and clinopyroxene phenocrysts. 6-9 ft of flow breccia occur at the base.	0-75	8.41±1.22
D	1.5-15 ft thick lenses and beds of light-brown to light-grey, medium- to coarse-grained, moderately to well indurated sandstones are interbedded with poorly sorted, clast- and matrix-supported, pebble to boulder conglomerates with subangular to rounded clasts in a poorly sorted, medium to coarse-grained, sometimes clay-rich sandstone matrix. There is some crude normal and inverse grading. Clasts are primarily Mesozoic metamorphic and intrusive rocks, Singatse Tuff, and basaltic-andesite flow rocks (flow 2b). Sandstone:conglomerate ratio varies from 2:8 to 7:3. A few white to light-grey tuffaceous sandstones occur throughout the unit.	>500	
C	0.3-1.5 ft thick lenses and beds of light-grey, moderately to poorly sorted, fine- to coarse-grained, well-indurated, massive sandstones are interbedded with mostly clast-supported, moderately sorted pebble conglomerates, and rare laminated ash-rich siltstones near the base. There is some normal grading of beds from conglomerate upward to laminated fine sandstone and siltstone. Conglomerate clasts are primarily Mesozoic metamorphic and intrusive rocks and Singatse Tuff.	0-90+	
C	Poorly consolidated, massive, light-grey, clay-rich siltstones. Sand dikes occur at one location.	0-45+	
	Flow 2b. Basaltic-andesite flow and flow-breccia of red-brown weathering medium- to dark-grey or lavendar-grey clasts in a pale-lavendar matrix have phenocrysts of plagioclase and clinopyroxene.	0-300+	
	Flow 2a. Medium- to dark-grey or lavendar-grey basaltic-andesite weathers red-brown toward its top and has oxyhornblende, plagioclase, and clinopyroxene phenocrysts. 6-15 ft of flow breccia occur at the base.		
B	Conglomerates interbedded with sandstones.	45-75	
B	Flow 1. Basaltic-andesite flow and flow-breccia with dark-grey clasts that weather grey-black in a light-lavendar matrix have phenocrysts of plagioclase and clinopyroxene.	0-100	
B	0.3-10.5 ft thick lenses and beds of light-grey to light-brown, poorly to moderately sorted, clast- to matrix-supported, pebble to cobble conglomerates with subangular to rounded clasts is interbedded with poorly sorted, poorly to moderately indurated, medium- to coarse grained sandstones and rare grey sandy ash and white tuff beds. There is some crude inverse and normal grading of beds. Conglomerate clasts are predominantly Mesozoic metamorphic and intrusive rocks and Singatse Tuff.	200-500	9.44±0.41
B	Light-grey/brown siltstone grades upward to interbedded fine sandstones and cobble conglomerates in a fine grained, sometimes clayey sandstone matrix.	0-60	
B	0.5-8 in thick well-bedded, organic-rich, dark-lavendar/brown siltstones, mudstones, fine- to medium-grained, moderately indurated sandstones with sparse pebbles are interbedded with light-grey siltstones and sandstones which increases in frequency upsection. Some soft-sediment slumping affects these rocks.	0-70	
A	Very poorly-sorted, clast-supported boulder conglomerate has angular to well rounded clasts primarily of Singatse Tuff and Mesozoic metamorphics in a clay-rich, poorly indurated, poorly sorted, light-brown, coarse grained sandstone matrix.	0-20	
A	Very poorly sorted, clast-supported boulder conglomerate has angular to rounded clasts primarily of Mesozoic metamorphics in a clay-rich, poorly indurated, poorly sorted, brown, coarse grained sandstone matrix.	0-15	

Figure 8. Wassuk Group stratigraphy

analyses of hornblende from basaltic-andesite flow 3 yielded an age of 8.41± 1.22 m.y. (Figure 8, Appendix C). The two dated units were likely deposited within a relatively short time interval. Therefore, an approximate age of 9 Ma is taken for the Wassuk Group.

Wassuk Group sedimentary rocks (Tws)

The sedimentary rocks of the Wassuk Group are informally divided into units A, B, C, and D in ascending order (Figure 8).

Unit A. Locally, two boulder conglomerates form the base of the Wassuk Group (Figure 9). The lower boulder conglomerate is 0-15 ft thick and contains clasts, up to 6 ft in diameter, primarily of Mesozoic metamorphic lithologies. The upper boulder conglomerate is 0-20 ft thick and contains clasts up to 9 ft in diameter primarily of Singatse Tuff and Mesozoic metamorphic lithologies. Both boulder beds have matrices of very poorly indurated, poorly sorted, coarse grained, clay-rich sandstone.

Unit B. Up to 70 ft of laminated mudstones, siltstones, and sandstones with sparse pebbles overlie the conglomerate of Singatse boulders in NE1/4, Sec.1, T11N, R28E. These fine-grained deposits gradually coarsen upward and are overlain by 200-560 ft of interbedded siltstones, sandstones, and channelized pebble to cobble conglomerates. All beds are lenticular on a scale of one to tens of feet and in general cannot be traced from outcrop to outcrop. The conglomerates are mostly clast supported, moderately sorted with a poorly sorted, medium to coarse grained sandstone matrix. A few large channel-form conglomerates were also observed (Figure 10). This sedimentary sequence is locally overlain by a 0-100 ft thick basaltic-andesite flow (flow 1); this flow is overlain by 45-75 ft of interbedded sandstones and conglomerates, which are overlain by 0-300 ft of basaltic-andesite flows (flows 2a and b).

Figure 9. Wassuk Group sediments (Tws) and flows (Twf1, Twf2a+b, and Twf3). Note the boulder conglomerates (Tsb and Tmb) at the base of the Wassuk Group, the Singatse Tuff (Ts) in the foreground, and Mesozoic crystalline rocks (TRa) in the backgound. This is the eastern part of the field area and the view is to the northeast.

Figure 10. Photograph of channel conglomerates within the Wassuk Group, unit B.

Unit C. Up to 45 ft of fine-grained sandstones and siltstones overlie flow 2b; these are overlain by up to 100 ft of interbedded lenticular sandstone and mostly clast-supported pebble conglomerates (Figure 11), similar to unit B above.

Unit D. The deposits of Unit C grade upward into coarser, more poorly sorted, pebble to boulder conglomerates at least 500 ft thick, accompanied by an increase in the mean bed thickness and the proportion of matrix supported beds (Figure 12).

Depositional Environments of Wassuk Group sedimentary rocks

The Wassuk Group exhibits characteristics of both alluvial fan and braided stream deposits. Poorly sorted deposits, poorly rounded clasts, and the presence of matrix-supported conglomerates and channelized clast-supported conglomerates are all typical of alluvial fans or proximal (Scott-type) braided stream deposits (Boggs, 1987; Appendix A). However, Wassuk Group sediments also exhibit two large-scale, coarsening upward cycles, accompanied by an increase in maximum thickness of beds from the base of the Wassuk Group to flow 2a, and from above flow 2b to the uppermost exposures of the Wassuk Group (Figure 8). According to Walker (1979), Boggs (1987), and Leeder (1982), this is common in alluvial fan deposits, which may coarsen and thicken upward due to active fan progradation. This is unlike braided river deposits, which either have no distinctive pattern or vertical grain-size change or display a fining upward trend (Boggs, 1987), but do not coarsen upward. Therefore, it seems likely the Wassuk Group sediments primarily represent alluvial fan deposits. The change to finer deposits above flows 2a and 2b may represent a minor retrogradation of the fan, followed by progradation as sediments coarsen upward.

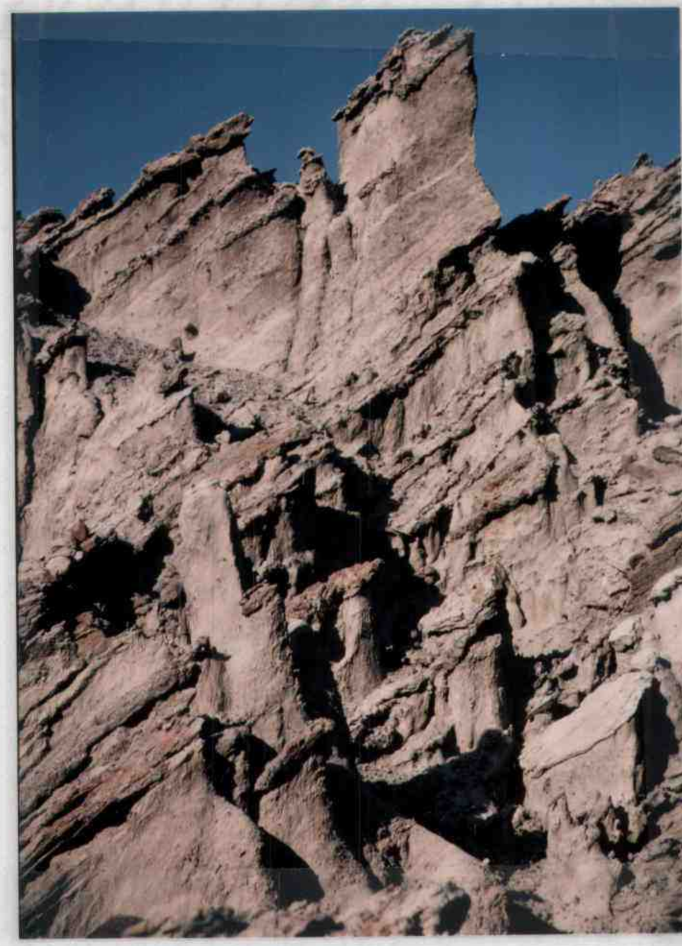


Figure 11. Lenticular pebble to cobble conglomerates and sandstones of the Wassuk Group, unit C. Scale: 1 in = 1 ft.

Figure 12. Wassuk Group cobble conglomerates in a clay-rich matrix, unit D.
Note angular clasts and matric-support. Lens cap is 3 inches in diameter.

The following discussion of depositional environments, corresponding to the lettered unit descriptions above, is based primarily on facies outlined in Appendix A. Additional characteristics of alluvial fan deposits are listed in Table 2.

The extremely poor sorting and large clast size of the Unit A deposits suggests a proximal fluvial origin (braided stream or alluvial fan), or may represent debris flow or landslide deposits.

The fine-grained, well-bedded to laminated rocks at the base of both sequences B and C lack channelized or matrix-supported debris-flow deposits and probably represent shallow lacustrine or distal fan facies (especially sheetflood deposits). Upsection, the coarser, lenticular deposits probably represent sheet flood, stream channel, and minor debris flow deposits from the mid-fan.

The deposits in Unit D display an increase in clast size, bed thickness, and proportion of matrix-supported beds (debris flows), and an associated decrease in sorting, all of which are characteristic of upper fan facies.

Wassuk Group flow rocks (Twf)

Four basaltic-andesite flows are interbedded with Wassuk Group sediments and form a prominent ridge within the exposures in the eastern part of the study area in T11N, R28E, Sec.1 of the Schurz quadrangle (Figure 9).

<u>Flow 1</u>

The oldest flow has a maximum thickness of 100 ft and is predominantly a flow breccia with dark-grey clasts, which weather grey-black, in a light lavendar matrix. The

Table 2. Principle distinguishing characteristics of alluvial-fan deposits. From Boggs (1987).

Characteristic	Description
Texture	Sorting characteristically very poor: great range of grain sizes: clasts poorly rounded. reflecting short distance of transport: rapid downfan decrease in both average and maximum clast size
Composition	Compositionally immature: commonly composed of a wide variety of clast types: mineralogy and clast types dependent upon source rocks. thus composition may change laterally in coalescing fans from different drainage systems
Vertical sequences	Individual beds possibly showing no vertical change in grain size or coarsening or thinning upward: overall. alluvial-fan sequences displaying strong thickening- and coarsening-upward trend or thinning- and fining-upward trend. reflecting either progradation or retrogradation of the fan
Sedimentary structures	Limited suites of sedimentary structures: mainly medium- to large-scale trough or planar cross-bedding and planar stratification: overall. poorly stratified: may display many laterally discontinuous sediment-filled channels and cut-and-fill structures. particularly in upper-fan deposits: paleocurrent patterns radiating outward downfan: complex radiating paleocurrent patterns in coalescing fans
Geometry	Lobate in plan view; lenticular or wedge shaped in cross section: typically forming clastic wedges
Other	Deposits commonly oxidized (red. brown. yellow); contain very little fine organic matter and few fossils except rare vertebrate bones and plant remains: generally composed of a mixture of streamflow and debris-flow deposits–may also contain sieve deposits (gravel lobes) that are unique to alluvial-fan environments

flow is made up of 20-30% plagioclase phenocrysts (0.01-0.04 in), 5-7% clinopyroxene phenocrysts (0.01-0.04 in), 1-2% opaque minerals, 1-2% secondary calcite, and rare oxidized hornblende phenocrysts. Plagioclase and minor clinopyroxene microphenocrysts and glass comprise the hypocrystalline groundmass.

Flow 2

Flow 2 has been subdivided into two units based on its phenocryst population and its megascopic characteristics in the field:

Flow 2a

The basal unit has a maximum thickness of 150 ft, is medium to dark-grey or lavendar-grey, has 5-15 ft of flow breccia at its base, and weathers reddish-brown towards its top. It is composed of 5-10% oxyhornblende phenocrysts (0.01-0.04 in) with oxidized rims, 5-10% plagioclase phenocrysts (0.01-0.04 in), 2-5% clinopyroxene phenocrysts (0.01-0.08 in), 1-2% opaque minerals, and a hypocrystalline groundmass of plagioclase, minor clinopyroxene microphenocrysts, and glass.

Flow 2b

The top unit has a maximum thickness of 150 ft and is predominantly a flow breccia made up of reddish-brown weathering, medium to dark-grey or lavendar-grey clasts in a pale lavendar matrix. Phenocrysts are 20-30% plagioclase (0.01-0.04 in), < 5% clinopyroxene (0.01-0.08 in), and 1-2% opaques; plagioclase and clinopyroxene microphenocrysts and glass comprise the hypocrystalline groundmass.

Flow 3

The uppermost flow has a maximum thickness of 75 ft with 6-10 ft of flow breccia at its base. Fresh surfaces are medium to dark grey or lavendar-grey. The massive flow rocks making up the bulk of this unit weather reddish-brown to lavendar. Phenocrysts are 5-10% plagioclase
(0.01-0.08 in), 5-10% hornblende (0.01-0.3 in) with oxidized rims, 2-5% clinopyroxene (0.01-0.12 in), 1-2% opaques, and <1% secondary calcite. The hypocrystalline groundmass is made up of minor glass plus plagioclase and minor clinopyroxene microphenocryts.

BASALTIC ANDESITE PLUG (Ta)

This grey basaltic-andesite plug weathers a medium brown/grey and intrudes Mesozoic metamorphic rocks and the Cottonwood Springs fault in the northeastern part of the field area approximately 1000 ft south of the mouth of the Reese River canyon. Phenocrysts include ~25% plagioclase (<0.04 in), 10-15% hornblende with oxidized rims (some with zoning) (<0.6 in), 2-5% clinopyroxene (<0.2 in), ~2% opaque minerals, 1-2% secondary calcite, and rare resorbed quartz xenocrysts. Plagioclase and clinopyroxene microphenocrysts make up the groundmass. 0.04-0.6 in thick calcite and zeolite veins are common in outcrop. Locally the hornblende phenocrysts form radial clusters.

BASALTIC ANDESITE FLOWS (Tba)

Medium- to dark-grey basaltic-andesite flow rocks form resistant cuestas of black-weathering, rubbly and blocky outcrops from 45 to 300+ ft thick in the western part of the field area. Phenocrysts present include 30-35% plagioclase (0.01-0.04 in), 4-7% clinopyroxene (0.01-0.08 in), 1-2% olivine (0.01-0.04 in) with red-brown rims (iddingsite alteration), 1-3% opaque minerals, and rare resorbed hornblende; plagioclase, lesser clinopyroxene and olivine microphenocrysts, and minor glass make up the groundmass.

PEBBLE COUNTS

INTRODUCTION

Pebble counts were performed at 24 different localities within the Wassuk Group in the eastern portion of the field area (Figures 13 and 14). Station locations were chosen to obtain the maximum lateral and vertical coverage of the exposed Wassuk Group. Figure 15 shows relative stratigraphic positions of the pebble count stations.

The purpose of conducting pebble counts was to document any vertical or lateral variations in clast composition, which might reflect the sequence of erosional unroofing, though they might also reflect changes in provenance or drainage configuration (Little, 1986). If Wassuk Group sediments were deposited synchronously with movement on adjacent faults, then the changes in clast composition could help constrain the timing of faulting, assuming the clast composition variation resulted from deepening levels of erosion of uplifted footwall blocks.

METHOD

The method used in this study and described below was modified after R.H. Brady (personal communication, 1988). The counting interval (x) determined for each site is 2 times the modal diameter of clasts. At each site, 300 clasts were counted by laying a tape measure parallel to the strike of bedding for a distance equal to 10 times the length of the counting interval, x. Clasts were counted that fell on a multiple of the counting interval, with care being taken that clasts larger than the counting interval were only counted once. Depending on the geometry of the outcrop at each site, the tape was moved laterally and vertically to approximate a square until all 300 clasts were counted. Modal clast sizes

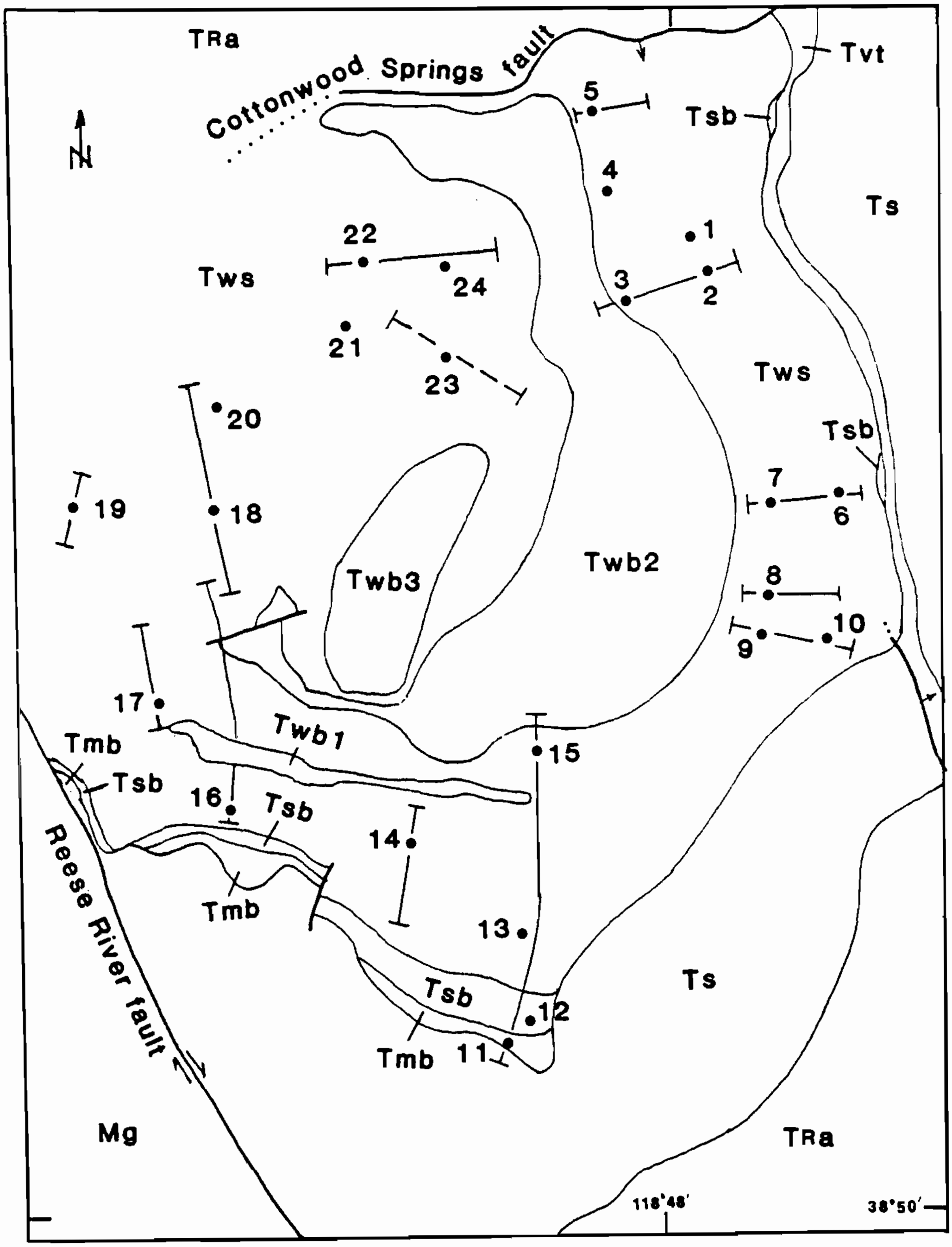


Figure 13. Pebble count locations within the Wassuk Group. Geology simplified from Plate 1. Map unit abbreviations are as on Table 3. Scale 1:12,000.

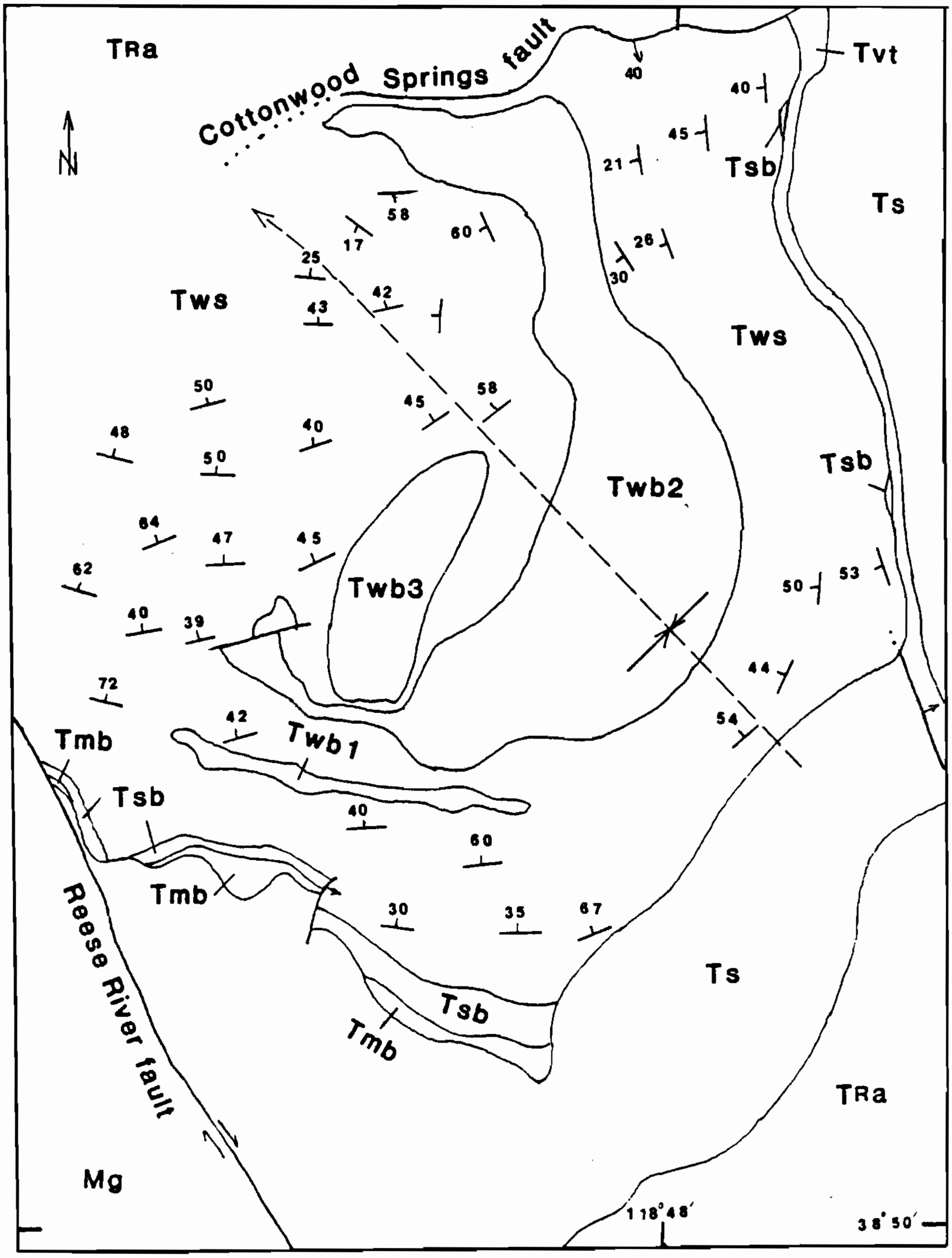


Figure 14. Simplified geologic map of the southeastern portion of the study area (after Plate 1). Map unit abbreviations are as on Table 3. Scale 1:12,000.

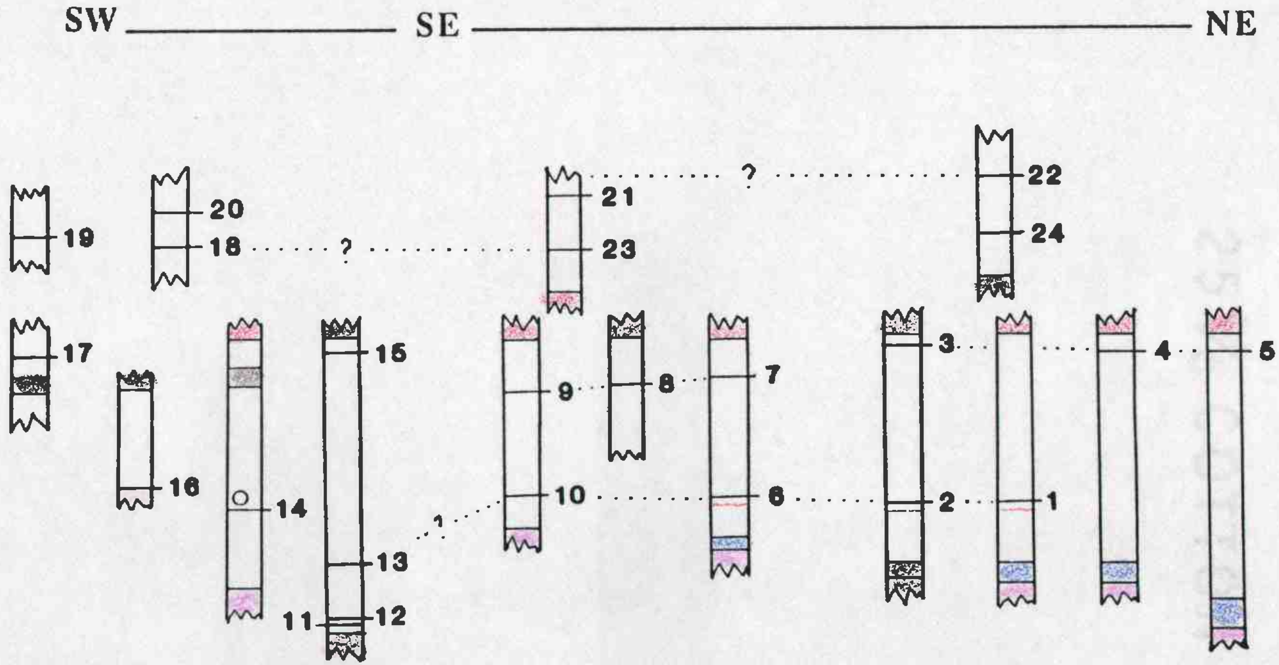


Figure 15. Relative stratigraphic position of Wassuk Group pebble count locations. Vertical scale: 1 in = 500 ft. Horizontal distance is not to scale; positions shown on Figure 13.

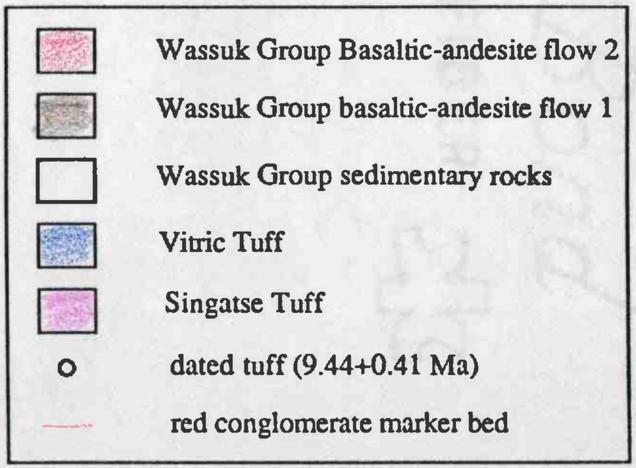


Table 3. Pebble count station data normalized to 100%. Letters in parentheses refer to map unit symbols on Plates 1 and 2.

clast type \ station #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Mesozoic metamorphic rocks (TRa)	76	80	66	64	62	68	58	61	59	53	95	34	32	39	34	43	56	62	63	57	39	34	36	56
Mesozoic intrusive rocks (Mg)	8	9	12	12	14	13	35	24	27	12	<1	14	22	12	31	25	3	1	5	13	10	3	31	3
Singatse Tuff (Ts)	11	10	14	11	16	14	6	14	10	28	2	51	35	36	32	30	39	30	26	14	32	25	24	27
Vitric Tuff (Tvt)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	0	0
Mickey Pass Tuff (Tmp)	<1	<1	1	3	3	0	0	0	2	<1	0	0	3	2	1	1	1	2	1	1	1	5	1	3
Wassuk Group flow (Twf1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	3	2	0	0	0	0
Wassuk Group flow (Twf2b)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	12	12	10	1	1
Wassuk Group flow (Twf2a?)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
Grey tuff (Tsv?)	0	0	0	0	<1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<1	0
poorly welded red tuff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
light-brown to pink tuff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<1	0	<1
vesicular basalt	0	0	2	4	<1	<1	<1	0	<1	2	0	0	0	0	<1	0	0	<1	0	<1	3	2	2	1
andesite (Tlf?)	2	1	5	6	4	4	<1	1	<1	5	0	1	8	11	1	1	<1	4	2	<1	3	3	6	6
white meta-tuff	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0
quartzite	2	0	<1	<1	<1	<1	<1	0	1	0	0	<1	0	0	0	0	0	0	0	0	0	0	0	0
white quartz	0	0	0	0	0	0	0	0	0	<1	0	0	0	<1	0	0	0	0	0	0	0	0	0	0
Counting interval (in) (= 2X modal clast size)	2.8	2	2	2	2.4	1.2	2	1.6	1.6	2.4	2.4	4.3	2	2.4	2.8	2.4	2.8	2	2.4	2	2.8	6.7	1.6	2.8

varied from 0.6 to 3.4 inches in the study area, and thus counting intervals varied from 1.2 to 6.8 in and averaged 2.5 in (Table 3).

Clasts were initially divided into 16 rock type categories; Table 3 lists clast composition data for all 24 stations, normalized to 100%. However, only locally derived clast types are relevant to the determination of the erosional sequence for the study area. Therefore only the first eight of the original categories are considered, and plotted, when analyzing the data for variations in clast composition. In additon, except for the eight categories of locally derived clast types, the other rock type categories make up <10% of the clasts for each station, which would make trends statistically meaningless for these categories. Rock type was plotted against percent of clasts for the pebble count stations to illustrate lateral and vertical clast type variations, or lack thereof (Appendix B; plots 1-6). On the plots, rock types are listed according to their map unit symbols; refer to Table 3 for an explanation of the map symbols.

RESULTS

Bulk composition

62 to 99% of clasts within the Wassuk Group are composed of the Singatse Tuff, Mesozoic metamorphic rocks, and Mesozoic intrusive rocks (Table 3). The remainder of the clasts are composed of the vitric tuff, the Mickey Pass Tuff, Wassuk Group flow rocks (Twf1, Twf2b, and Twf2a?), vesicular basalt, andesite (Tlf?), quartzite, white metamorphosed tuff, grey tuff (Tsv?), brown to red ash-flow tuffs, and white quartz (Table 3).

Changes in clast composition

Lateral changes

At the base of the Wassuk Group, the boulder bed of mostly metamorphic clasts (Pebble count station 11; map unit Tmb) crops out in the southwestern part of the field area, but is absent to the northeast (Figure 13). This may reflect a lateral decrease towards the northeast in the amount of Mesozoic metamorphic clasts or simply a lack of deposition or erosion. Above this, the boulder bed of primarily Singatse Tuff clasts (Pebble count station 12; map unit Tsb) crops out in the southwest and sporadically to the northwest (Figure 13).

In the basal part of the Wassuk Group section 70-150 ft above the boulder conglomerates (Figure 16), there is a northeast to southwest decrease in Mesozoic metamorphic clasts from 76% to 32% from station 1 to 13 and an increase in Singatse Tuff clasts from 11% to 35%, also from station 1 to 13; in addition, the ratio of Mesozoic intrusive rocks to Mesozoic metamorphic rocks increases from the northeast to the southwest (Appendix B: Plot 1).

In the middle of the Wassuk Group section immediately below flow 2, Singatse Tuff clasts show no variation in a north-south direction at the eastern part of the area, but increase from 12 to 35% from east to west. In addition, the ratio of Mesozoic intrusive rocks to Mesozoic metamorphic rocks increases from north to the south (Appendix B: plot 2; Figure 15).

Above flow 2 in the upper Wassuk Group exposures, there are no statistically significant lateral variations (Appendix B: Plots 3 and 4) (Figure 15).

Vertical changes

At the base of the Wassuk Group is the boulder bed with clasts consisting primarily of Mesozoic metamorphic rocks (Pebble count station 11; map unit Tmb). From this point to the Singatse boulder bed immediately upsection (Pebble count station 12; map unit Tsb), there is a dramatic decrease in Mesozoic metamorphic clasts from 95% to 34% with a concomitant increase in Singatse Tuff clasts from 2% to 51% and Mesozoic granitic clasts from <1% to 14% (Appendix B: Plot 5).

From the base to the lower part of the Wassuk group section, upsection an additional 70-150 ft throughout the area , there is a decrease in proportion of Singatse Tuff clasts; for example, in the southwestern part of the pebble count area Singatse Tuff clasts decrease from 51% to 20% (Appendix B: Plot 5; Figure 15).

From this point upsection another 300-600 ft to the base of basaltic-andesite flow 2 in the middle of the section (Appendix B: Plots 5 and 6; Figure 15), the only consistent trends are an increase by 3% to 22% in Mesozoic granitic clasts and an increase in the ratio of Mesozoic granitic clasts to Mesozoic metamorphic clasts.

The only vertical trend that is observed basin-wide from below to above basaltic-andesite flow 2 is the addition of basaltic-andesite clasts (Twb) above flow 2 (Plot 5 and 6, Appendix B; Figure 15).

The vertical variation 100-150 ft further upsection to the uppermost exposures of the Wassuk Group (Appendix B: Plot 5 and 6; Figure 15) is as follows: there is no consistent change in the amount of Singatse Tuff clasts; Mesozoic metamorphic clasts decrease by 5 to 32%; basaltic andesite clasts (Twb) increase by 4-12%; and 17% of vitric tuff clasts appear at station 22, which is at the highest stratigraphic level counted.

Significance of changes in clast composition

Lateral changes

Two significant lateral trends were recognized, which are repeated at more than one stratigraphic level. The first is a northeast to southwest increase in the proportion of Singatse Tuff clasts (Appendix B: Plots 1 and 2), which reflects increasing proximity to the source of Singatse Tuff clasts to the southwest. The Singatse Tuff is exposed at the base of the Wassuk Group in the southwest, probably due to erosion after tilting and uplift on pre-Wassuk Group faults like the Mustang fault. The southwesterly increase in the lower part of the Wassuk Group section was probably due to increasing proximity to exposures of the Singatse Tuff in the footwall of inferred fault Z and the Rattler fault, which cut the lower Wassuk Group at this location. The middle portion of the Wassuk Group section requires a different source of Singatse Tuff clasts since it is younger than fault Z and the Rattler fault. The Singatse Tuff could have been exposed in the footwall of the Reese River fault, which has a normal component of movement and was probably synchronous with deposition of the middle (and lower?) portion of the Wassuk Group section.

The second lateral trend, which is observed near the base of the Wassuk Group, is a north to south increase in the ratio of Mesozoic granitic clasts to Mesozoic metamorphic clasts (Appendix B: Plots 1 and 2). The ratio of Mesozoic granitic rocks to Mesozoic metamorphic rocks is low in the basement north of the Cottonwood Springs fault and high in the basement south of the Penrod Canyon and Reese River faults (Plate 1), where the ratio of Mesozoic granitic rocks to Mesozoic metamorphic rocks increases with depth. If movement on the Cottonwood Springs fault, Penrod Canyon fault, and Reese River fault began during early Wassuk Group deposition, Mesozoic basement could have been exposed in their footwalls. If so, the lateral change in the ratio of Mesozoic granitic clasts to Mesozoic metamorphic clasts can be explained if the clasts were derived from the footwall blocks. This suggests that early Wassuk Group sedimentation was synchronous with movement on the Cottonwood Springs, Penrod Canyon, and Reese River faults.

Vertical changes

A boulder bed with clasts consisting primarily of Mesozoic metamorphic rocks (Tmb) lies at one location at the very base of the Wassuk Group on top of the Singatse Tuff. It is overlain by a boulder bed containing abundant Singatse Tuff clasts (Tsb). This occurrence is enigmatic because the boulder bed of Mesozoic metamorphic clasts sits on the Singatse Tuff, and its Mesozoic metamorphic clasts must be derived from the lower part of the stratigraphic section in the area, which should not be exposed during the early stages of syn-Wassuk Group faulting.

If sufficient relief existed prior to ignimbrite deposition, the ignimbrites might have pinched out against the Mesozoic basement rocks, leaving Mesozoic metamorphic rocks exposed as a viable source for the Wassuk Group basal conglomerate. However, in the study area, the ignimbrites maintain a fairly constant thickness, and, except for the Mickey Pass Tuff, do not pinch out against Mesozoic basement rocks. A more likely scenario is that Mesozoic basement rock was exposed along pre-Wassuk Group faults, like the Mustang fault.

Deposition of the boulder bed of primarily Singatse Tuff clasts (Tsb) above the Mesozoic metamorphic boulder bed requires the existence of local relief to expose the Singatse Tuff as a proximal source of the boulder size clasts up to 10 ft in diameter that characterize this unit. The Singatse Tuff immediately underlies and is in angular unconformity with overlying Wassuk Group sediments in the southwest. Tilting and uplift of the Singatse Tuff occurred due to movement on faults X, Y, and Z, which offset the base of the Wassuk Group; subsequent erosion of the Singatse Tuff exposed in the footwall of these faults provided a source for the boulders.

Upsection, 70-150 ft above the boulder beds, the decrease in percentage of Singatse Tuff clasts is probably related to erosion and decreasing relief of the Singatse Tuff in the source region. This is consistent with the observation (discussed below) that faults X and Y ceased movement early during Wassuk Group deposition, and that the uplifted footwalls of these faults diminished in relief, thus providing fewer clasts. The concomitant increase of Mesozoic clasts suggests that the Mesozoic crystalline rocks were exposed along basin-bounding faults and that the upthrown blocks were subsequently eroded to stratigraphic levels below the Singatse Tuff. There are two ways this could have occurred: (1) If sufficient relief still existed on faults X, Y, etc., Mesozoic basement could have been exposed along these faults, (2) or initiation of movement along the Cottonwood Springs, Penrod Canyon, and Reese River faults could have exposed Mesozoic basement in their footwalls.

The ratio of Mesozoic granitic rock clasts to Mesozoic metamorphic rock clasts increases upward from the base of the section to below flow 2a. The trend likely reflects increasing depth of erosion of Mesozoic crystalline rocks primarily to the south of the Reese River and Penrod Canyon faults or an increase in the percentage of clasts derived from south of the Reese River and Penrod Canyon faults.

Upsection, above flow 2 of the Wassuk Group, the only significant change is the addition of Wassuk Group basaltic-andesite clasts (Twf). Likely explanations include (1) synclinal folding, associated with movement on the Cottonwood Springs and Penrod Canyon faults, which may have warped the basaltic-andesite flows in the hanging walls, causing uplift and erosion; or (2) basaltic-andesite flows on alluvial fans may have been locally eroded in the absence of uplift.

Summary

Pebble count data indicate that the lateral variation in granitic to metamorphic rock ratios reflects derivation from the footwalls of the Cottonwood Springs, Penrod Canyon, and Reese River faults to the north and south of the Wassuk Group pebble count stations. The vertical variations in Singatse Tuff clasts reflect changes in the amount of structural relief and depth of erosion on early syn-Wassuk Group faults adjacent to the pebble count stations. This, taken in conjunction with the sedimentological evidence (angular clasts, coarse clast size, and poor sorting), suggests that clasts were mostly locally derived and were deposted on an alluvial fan adjacent to fault scarps.

NORMAL, STRIKE- AND OBLIQUE-SLIP FAULTS

INTRODUCTION

Four groups of faults offset both the Tertiary and Mesozoic units in the study area: (1) 22-9 m.y. old spoon-shaped low angle normal fault(s); (2) ~9 m.y. old moderately dipping, northwest striking normal faults and high-angle antithetic faults; (3) 9-7 m.y. old, moderately to steeply dipping or vertical, right- and left-lateral oblique- and strike-slip faults; and (4) 7-0 m.y. old, en echelon range-front normal faults. The normal component of motion on faults is predominantly down-to-the-east (Figure 16; Plates 1 and 2).

Fault geometries are well constrained at the earth's surface. Unless there is evidence to the contrary, faults are assumed to be planar at depth (Plate 2).

Rocks in fault zones are brittley deformed and consist of predominantly unconsolidated breccia and gouge, which are sometimes accompanied by bleaching and/or reddish discoloration, and, more rarely, by silicification and/or slickensides. Where faults cut Mesozoic metamorphic rocks and Tertiary basaltic-andesites, copper minerals, such as chrysocolla and malachite, may be present. Quartz monzonites within the Penrod Canyon fault zone are extensively sheared, and are often foliated. On the western edge of the Penrod Canyon shear zone, minor recrystallization has occurred, and alignment of platey minerals (biotite/chlorite) is observed in these relatively cohesive rocks. Where faults cut Mesozoic quartz monzonite or associated mafic dikes, biotite and hornblende are commonly altered to chlorite.

The faults observed in the study area are described below in order of increasing age.

Figure 16. Simplified geologic map of the central Wassuk Range based on data from this study. Data in the outlined area in the northwestern part of the map are from Bingler (1978).

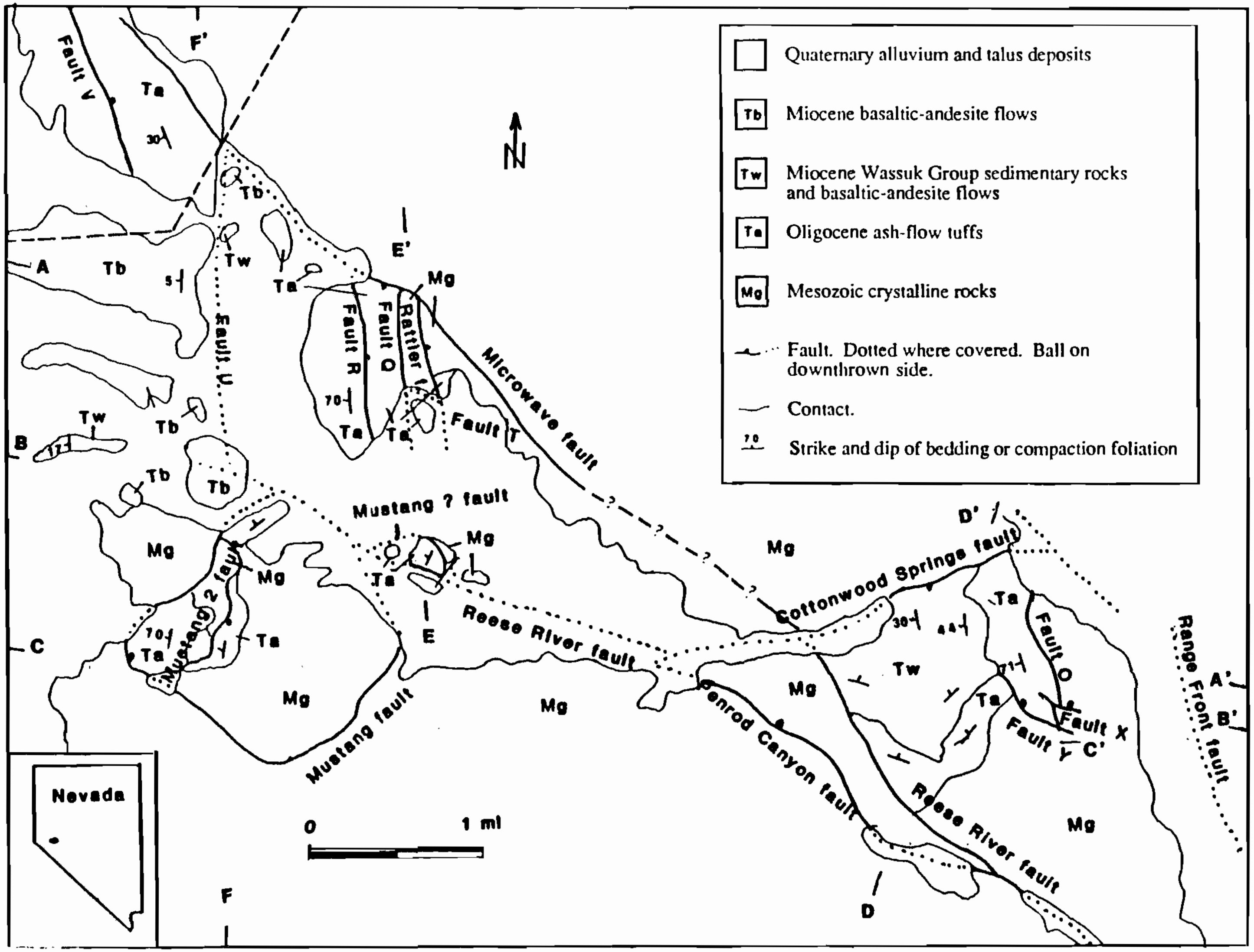

Quaternary alluvium and talus deposits
Tb Miocene basaltic-andesite flows
Tw Miocene Wassuk Group sedimentary rocks and basaltic-andesite flows
Ta Oligocene ash-flow tuffs
Mg Mesozoic crystalline rocks
Fault. Dotted where covered. Ball on downthrown side.
Contact.
70 Strike and dip of bedding or compaction foliation
N
Nevada
0
1 mi
Fault V
F'
Fault U
Fault R
Fault Q
Rattler fault
Fault T
Microwave fault
Mustang ? fault
Mustang ? fault
Mustang fault
Reese River fault
Cottonwood Springs fault
Penrod Canyon fault
Reese River fault
Fault O
Fault X
Fault Y
Range Front fault
A
A'
B
B'
C
C'
D
D'
E
E'
F

Figure 16.

RANGE-FRONT FAULT

A series of en echelon, northwest-striking, high-angle, down-to-the-east normal faults bound the range-front on the eastern edge of the study area and are the youngest structures in the study area. These faults were not mapped directly in this study; Bingler's (1978) placement of the en echelon faults that make up the range-front fault system was used and double-checked with air photos.

Though the range-front fault system does not directly offset the 7 m.y. old basaltic andesites in the study area, it is inferred to be responsible for their 5 to 12 degrees of westward tilt. Moreover, in the northwestern Wassuk Range to the north of the study area, Bingler (1978) mapped several normal faults of similar strike to the range-front fault system that offset the basaltic andesites, primarily down-to-the-east.

According to Bingler (1978), the range-front fault system cuts late Pleistocene alluvial fan and bajada deposits. In addition, at least three of the range-front faults cut Holocene deposits, as documented by Demsey et al. (1988).

COTTONWOOD SPRINGS FAULT

Exposed in the eastern part of the field area near the mouth of the Reese River canyon, the Cottonwood Springs fault has a traceable length of 3500 ft (Plate 1; Figure 16). It strikes ~N70°E and dips ~40°S and appears to be a planar oblique-slip fault with components of left-lateral and normal movement. The Cottonwood Springs fault has at least 13,750 ft of down-to-the-east displacement, where the direction of displacement is constrained by the slip direction.

The Cottonwood Springs fault is cut by the range-front fault, and intruded by an undated basaltic-andesite plug (Ta). Though not directly overlain by 7 m.y. old basaltic-andesites, the minimal dip of the basaltic-andesites (5-12°W) is attributed to movement on the range-front fault system, and, therefore, all Cottonwood Springs fault movement is assumed to be older than the 7 m.y. old basaltic andesite. The Cottonwood Springs fault cuts Wassuk Group sediments (~9 Ma), though it is unclear from field observations if it was active during deposition of the Wassuk Group or entirely post-dates its deposition. Pebble count results suggest that movement on the Cottonwood Springs fault began during deposition of the middle to upper Wassuk Group, about the time of eruption of basaltic andesite flow 2.

The Cottonwood Springs fault zone is approximately 6-25 ft thick where it separates the Wassuk Group from Mesozoic metamorphic rocks and up to 45 ft thick where it separates Mesozoic metamorphic rocks from Mesozoic intrusive rocks (Figure 17). 3-10 ft of unconsolidated fault gouge and breccia characterize the fault, with an additional 15-35 ft of coarse brecciation affecting the Mesozoic rocks adjacent to the fault. Bright rust to pink discoloration is seen along the fault in places, as well as some copper mineralization (primarily malachite) within the metamorphic rocks. Slickensides were observed at one station within the Mesozoic intrusive rocks with a plunge and trend of 37°, S 44°E. 10-50 ft thick fault slices of the vitric tuff and the Singatse Tuff are present along the Cottonwood Springs fault at two locations (Plate 1).

PENROD CANYON FAULT

Located in the eastern part of the field area, the Penrod Canyon fault is an oblique-slip fault with components of normal and right-lateral movement. It strikes ~N50°W and dips about 50-60° to the northeast. Evidence for oblique-motion relies primarily on the assumption that the movement vector is S69-77°E, which is discussed later in the text.

Figure 17. The Cottonwood Springs fault separates Wassuk Group sedimentary and flow rocks (Tws) from Mesozoic metamorphic rocks (TRa). Photograph is taken from the Reese River looking to the east.

The Penrod Canyon fault and the coeval Cottonwood Springs fault have at least 13,750 ft of down-to-the-east displacement.

The Penrod Canyon fault is not a discrete fault plane, but a diffuse shear zone within quartz monzonite that is about 1000 to 1700 feet wide. This makes it difficult to determine cross-cutting relationships with certainty. However, south of the intersection of the Reese River fault with the Penrod Canyon fault, there is no fault zone in the quartz monzonite, and I therefore conclude that the Penrod Canyon fault offsets the Reese River fault at this location. In addition, neither the Penrod Canyon fault nor the Cottonwood Springs fault continues west of their intersection (Figure 16; Plates 1 and 2). Coeval movement is inferred to account for the absence of these faults' continuation into the western portion of the field area, perhaps related to the development of a small pull-apart basin associated with a right-step of the Penrod Canyon fault (Figure 18).

On the outer edges of the shear zone, some non-penetrative foliation and coarse brecciation affect otherwise undeformed quartz monzonites and dikes, though the deformed rocks remain cohesive. 20 to 50 ft into the shear zone, mineral alignment of biotite and chlorite is seen in some places within still hard, cohesive quartz monzonites with minor foliation. Further into the shear zone, foliation and mineral alignment are still present together with 0.1-0.6 in thick red or white fractures and veinlets with no preferred orientation, and the still cohesive rock has a milled appearance in places (Figure 19). Density of fractures with associated breccia and gouge, number of dikes, and amount of non-penetrative foliation (parting) increase towards the center of the shear zone, where a high percentage of the rock is unconsolidated and highly deformed (30-80% soft, white or red/lavendar powdery gouge and fine, crumbly breccia in the area of maximum deformation). On the eastern side of the Penrod Canyon fault zone, the intensely sheared rock fabric associated with the Penrod Canyon fault cannot be distinguished from shearing associated with the Reese River fault.

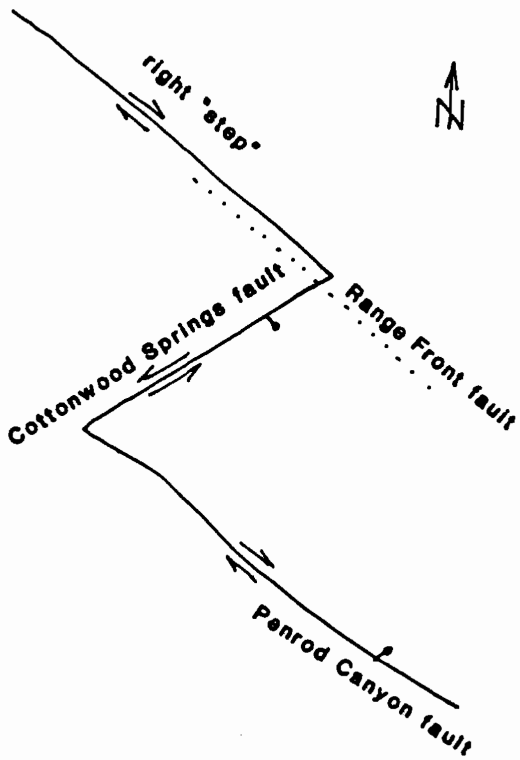


Figure 18. Cartoon showing inferred geometries of faults involved in development of the hypothetical pull-apart basin. The right "step" of the Penrod Canyon fault must be located near the present trace of the range front fault or further east in its footwall. Refer to Figure 16 or Plate 1 for detailed geology.

Figure 19. Milled granitic rock within the Penrod Canyon fault zone. For comparison, relatively undeformed rock is shown in the corners of the upper photograph. Lens cap is 3 inches in diameter.

MINOR FAULTS WITHIN THE HANGING WALL OF THE COTTONWOOD SPRINGS AND PENROD CANYON FAULTS

These faults have inconsistent strikes, moderate to steep dips, and up to 150 ft of apparent normal separation. Some of these faults are probably antithetic to the Cottonwood Springs and Penrod Canyon faults or older faults Y and Z. Because few of these faults can be traced beyond one stream channel exposure, only five are included in Plate 1. The faults are 0.5-12 in thick; within Wassuk Group sediments they consist of clay-rich, friable, dark-lavendar to red-brown gouge, sometimes with cobbles and pebbles incorporated into the fault zone. In addition to gouge and minor brecciation, a fault offsetting the Wassuk Group flow 2 has associated iron staining and precipitation of green copper minerals. Faults within the Singatse Tuff have red to black clay-rich gouge, as well as some bleaching, reddish discoloration, and silicification adjacent to faults.

REESE RIVER FAULT

The Reese River fault has a mappable trace of ~7000 ft in the eastern part of the field area and is inferred to continue westward along the Reese River canyon in the footwall of the Cottonwood Springs fault. The Reese River fault strikes N30°W to N70°W, and dips from 75° to the northeast to 80° to the southwest. Its map trace and field relations indicate that the Reese River fault is a planar, right-lateral strike-slip fault with approximately 11,000 ft of horizontal separation; there may also be a component of dip-slip movement, as discussed below.

Latest movement on the Reese River fault occurred prior to last movement on the Cottonwood Springs and Penrod Canyon faults. If movement on the Cottonwood Springs fault was synchronous with deposition of the Wassuk Group, as interpreted from pebble count data, then the Reese River fault also moved synchronous with deposition of the Wassuk Group.

Brittle deformation associated with Reese River fault movement affects rocks up to 30-60 ft within the Mesozoic intrusive rocks, greater than 45 ft within the Singatse Tuff, 15-45 ft within Mesozoic metamorphic rocks, and 9-15 ft within the Wassuk Group sediments. Rocks in the vicinity of the fault zone are finely to coarsely brecciated, or sheared to a lavendar/red to white powdery gouge with or without associated foliation, which is sometimes accompanied by reddish staining.

In the eastern portion of the field area, where the Reese River fault juxtaposes the Wassuk Group and Singatse Tuff against a Mesozoic quartz monzonite, a 3-12 ft wide hornblende andesite dike intrudes the fault and can be followed intermittently for >3000 ft (Figure 20). It is coarsely brecciated to strongly sheared, indicating emplacement during movement on the Reese River fault.

MICROWAVE FAULT

The Microwave fault is only exposed in trenches in the northwestern portion of the study area, therefore its projection to the southeast is queried on Plate 1. Based on the trench exposures, which are located 3500 ft northwest of a microwave station, it strikes from N20°W to N85°W, and dips from 27 to 57°SW; the average attitude is N48°W, 40°SW.

The subsurface geometry of the Microwave fault is assumed to be planar in cross-sections, though the trench exposures of the Microwave fault may be the northern edge of a down-to-the-east spoon-shaped normal fault, where the fault flattens and then curves upward to the south, similar to the geometry of the Mustang fault (Plate 2: section F-F').

Figure 20. The Reese River fault separating the Singatse Tuff (Ts) and Wassuk Group sedimentary rocks (Tws) to the east from Mesozoic granitic rocks (Mg) to the west. The shearing of the granitic rocks is partially due to movement on the adjacent Penrod Canyon fault. View is to the northwest.

Assuming the slip direction for the Microwave fault is similar to that for other faults in the study area, both of these interpretations require left-lateral slip on the Microwave fault.

However, the Microwave fault is clearly younger than, and probably coeval with, faults Q, R, U, and the Rattler fault, which it truncates. Therefore, the original orientation of the Microwave fault can be determined by removing the approximately 20-30 degrees of westward tilt attributed to movement on younger faults (Table 4). In order to check the relationship between the assumed slip vector and the orientation of the Microwave fault, a stereonet was used to remove the tilt incrementally (Figure 21). After removal of 30° of westward tilt, the Microwave fault strikes approximately E-W and dips about 25°S (Figure 21). Assuming a slip vector of S73$\pm$4°E, then oblique-slip movement occurred on the Microwave fault with components of normal and left-slip.

If the Microwave fault is coeval with faults Q, R, U, and the Rattler fault, then (1) the amount of movement on the Microwave fault would be equal to the sum of the movement on faults Q, R, U, the Rattler fault, and coeval fault V, which is 5900 to 6400 ft; and (2) the Microwave fault, like faults Q, R, U, and the Rattler fault, cuts the base of the Wassuk Group, moved synchronously with lower Wassuk Group sedimentation, and dies out upsection.

In the trenches, white to reddish breccia, sheared, foliated gouge zones and 1-5 inch wide foliated red clay gouge separate Mesozoic metamorphic rocks to the north from the Mickey Pass Tuff and the Singatse Tuff to the south in a 25-50 ft wide zone of thin fault slices. In a shallow prospect pit about 1500 ft southeast of the trenches, the gouge is foliated, and some copper oxide minerals have been precipitated. Faint slickensides were observed on several of the foliation planes, but lacked a consistent trend.

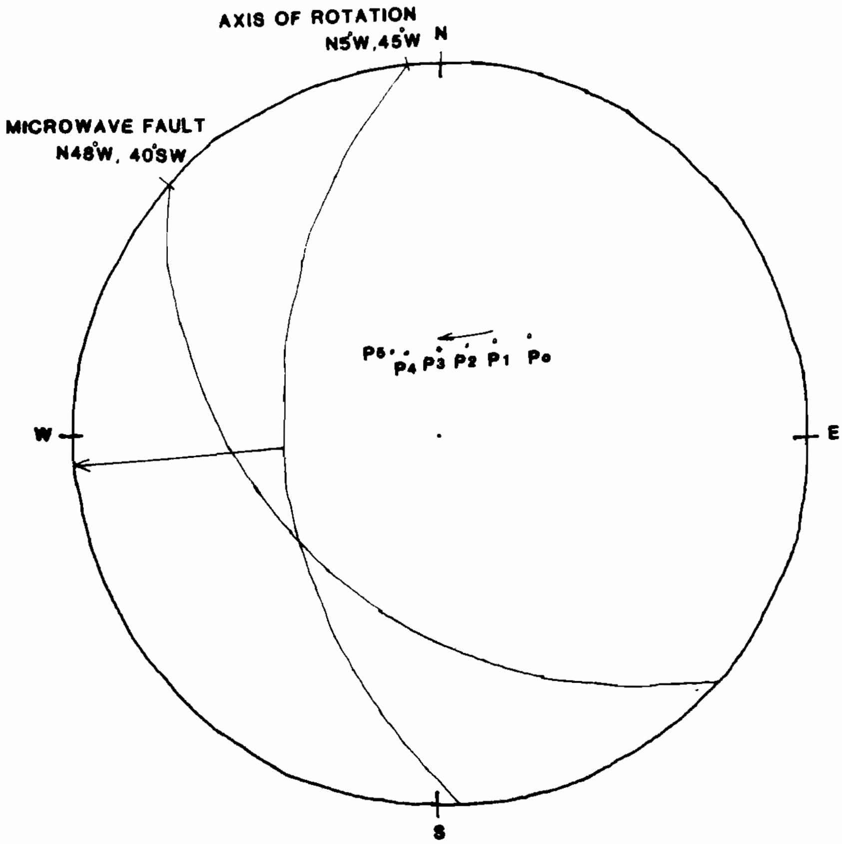


Figure 21. The pole of the Microwave fault (Po) is rotated as westward tilt is removed about the axis of rotation, N5°W. This is the average strike of the Wassuk Group and ash-flow tuffs in the vicinity of the Microwave fault. If Microwave fault movement was coeval with faults Q, R, U, and the Rattler fault, as postulated, then its movement was synchronous with deposition of lower Wassuk Group sediments. Therefore the original orientation of the Microwave fault can be determined by removing the 20-30° of westward tilt attributed to movement on younger faults (Table 4).

	Tilt removed (Total)	Orientation of Microwave fault after removal of tilt
P1	10°	N57°W, 32°SW
P2	20°	N71°W, 28°SW
P3	30°	N88°W, 25°S
P4	40°	N69°E, 25°SE
P5	45°	N61°E, 28°SE

Table 4. Percent extension, slip direction, and amount of westward tilt associated with each fault group.

Age of faults (Ma)	Percent of ~E-W extension	Slip direction	Amount of westward tilting
0-7 [1]	>10	S69-77°E (?)	5-12°
7-9 [2]	60-65	S69-77°E	
7-9 [3]	~34		31-38°
~9 [4]	~30	S69-77°E	
9-22 [5]		S85-89°E	~27°

1= Range-front fault system
2= Cottonwood Springs and Penrod Canyon faults
3= Reese River fault
4= Faults X, Y, Z, R, U, V, Rattler fault, and Microwave fault
5= Mustang fault

FAULTS X AND Y

Exposed in the southeastern part of the field area (Figure 16; Plate 1), fault Y strikes approximately N50°W and dips 37° to the northeast. Fault X, also in the southeastern part of the field area, is poorly exposed, but its topographic expression suggests it is parallel to fault Y. Assuming normal offset, units are displaced approximately 300 ft along fault X and approximately 1300 ft along fault Y (Plates 1 and 2).

Fault Y cuts basal Wassuk Group sediments, but dies out upsection, and therefore is synchronous with deposition of the lower Wassuk Group, but pre-dates deposition of the remainder of the Wassuk Group. Movement on fault X is probably coeval with fault Y.

Both of these faults have >6 ft thick zones of breccia and soft, foliated gouge where they separate Mesozoic and Tertiary rocks, but become untraceable where the fault lies within a single unit.

FAULT O

Fault O is a vertical, down-to-the-west normal fault, with uncertain amount of displacement. It has an irregular strike averaging approximately N25°W and appears to be antithetic to fault Y. Its surface trace follows the Tertiary/Mesozoic contact in the eastern part of the map area, sometimes faulting out the basal vitrophyre of the Singatse Tuff.

Fault O is offset by fault X and truncated by fault Y, which offsets the base of the Wassuk Group; therefore fault O is coeval with fault Y.

The fault plane is 3-9 ft thick and is characterized by soft gouge, which is often foliated parallel to the fault, and breccia. Deformation affects Mesozoic metamorphic rocks to a greater extent than Tertiary ignimbrites.

RATTLER FAULT

The Rattler fault is located in the northwestern portion of the field area in the vicinity of the microwave station, has a strike of approximately N15°W, and dips shallowly to moderately to the east. In cross-sections, a dip of approximately 37 degrees was chosen based on the assumption that movement on the Rattler fault is coeval with fault Y, which has a similar strike and dips approximately 37 degrees to the northeast. Poor exposures and overprinting by deformation associated with the Microwave fault and fault Q make precise location of the trace of the Rattler fault difficult, except where it repeats the thin slice of Singatse Tuff and Mickey Pass Tuff. Displacement on the Rattler fault is about 250 ft south of fault T based on normal offset of the extrapolated Singatse Tuff/Mickey Pass Tuff contact and displacement is a minimum of 800 ft to the north of fault T, based on the offset of the contact between the Mickey Pass Tuff and Mesozoic metamorphic rocks.

The Rattler fault is younger than the 22-28 m.y. old ignimbrites it offsets and older than, or coeval with, the Microwave fault, which truncates the Rattler fault.

Mesozoic metamorphic rocks in the vicinity of the Rattler fault are extensively sheared and brecciated with 1-2 inch thick undulatory fault planes of soft, foliated gouge and a few slickensides with random orientations. Red to white discoloration of the metamorphic rocks is common.

FAULT Q

Fault Q, located in the northwestern portion of the field area in the vicinity of the microwave station, strikes approximately N5°W, and dips from 70 to 90 degrees eastward. Field relations north of fault T suggest apparent reverse displacement, though if post-fault Q westward tilting is removed, fault Q dips approximately 60°W. Therefore fault Q was a down-to-the-west normal fault, probably antithetic to fault R. To the south of fault T, structural complexities make the movement on fault Q appear to be down-to-the-east (Plate 2: section A-A'), which is unlikely.

Fault Q is younger than the 22-28 m.y. old ignimbrites it offsets and older, or coeval with, the Microwave fault, which truncates it. Like fault O, its surface trace coincides with the Tertiary/Mesozoic contact.

Mesozoic metamorphic rocks in the vicinity of fault Q are extensively sheared and brecciated, while the Mickey Pass Tuff is bleached, but less sheared. Red to white discoloration of the metamorphic rocks is common.

MUSTANG FAULT

Poorly exposed in the southwestern part of the field area, the Mustang fault is a spoon-shaped, down-to-the-east normal fault, which dips <3°E (Plates 1 and 2; Figure 22). As discussed in a later section, this fault dipped steeply east when initiated. The movement direction along this fault is S85-89°E based on the orientation of a bend in the fault plane (Figure 22). Minimum amount of displacement is 3000 ft (Plates 1 and 2: section B-B' and C-C').

The Mustang fault offsets the 22-28 m.y. old ash-flow tuffs and does not appear to offset the ~9 m.y. old Wassuk Group; at its northern end, it is buried beneath basaltic-andesite and underlying Wassuk Group.

The 6-50 ft wide fault zone consists of soft, foliated gouge and breccia, though the width of the fault zone and intensity of deformation decrease within Tertiary ignimbrites with respect to Mesozoic metamorphic and intrusive rocks.

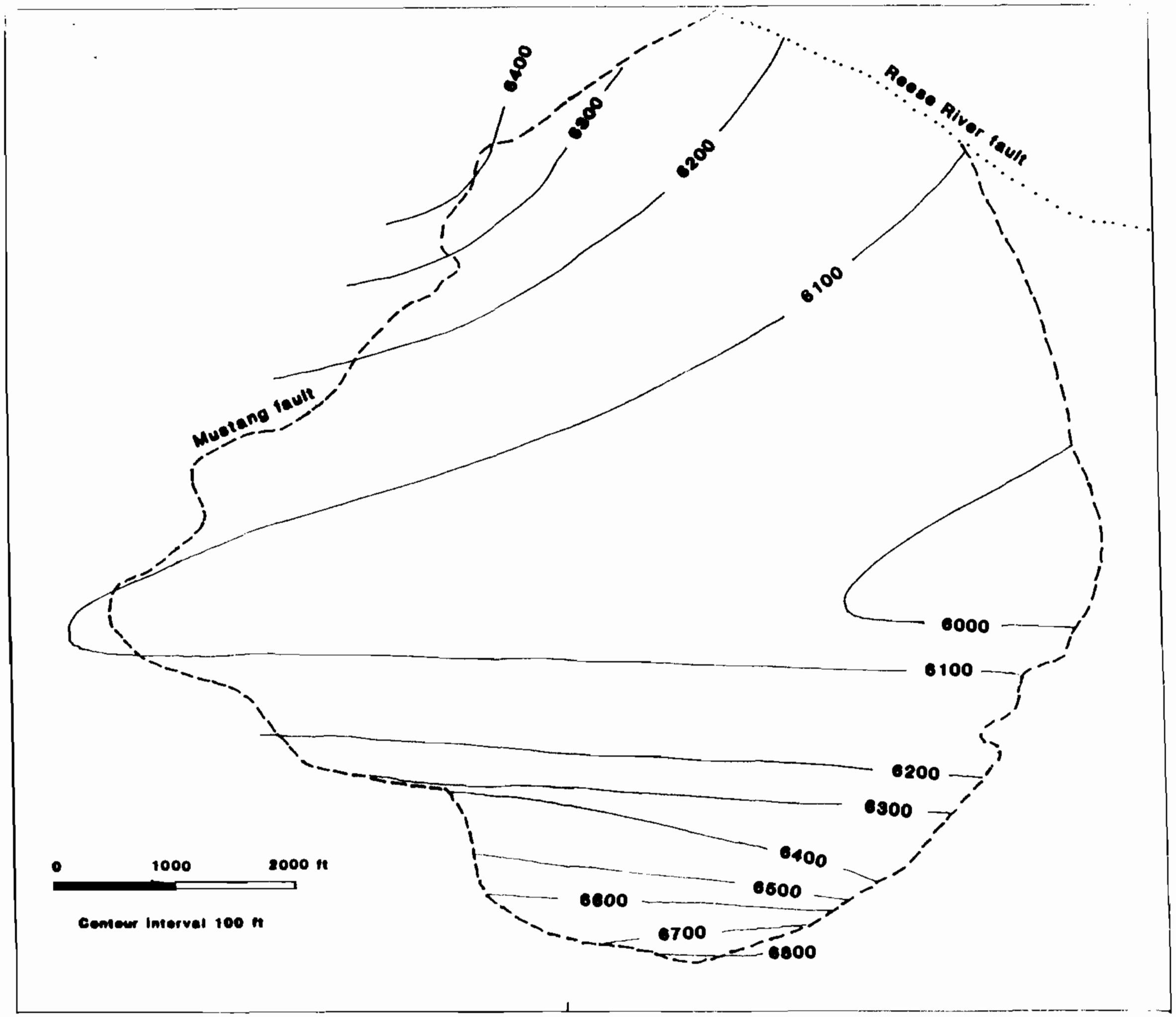


Figure 22. Structure contour map of the Mustang fault. The dashed line corresponds to the surface trace of the Mustang fault from Plate 1; the dotted line is the Reese River fault. Datum is mean sea level.

MUSTANG 2 FAULT

In the southwestern part of the field area, the Mustang 2 fault is a poorly exposed, down-to-the-east normal fault. It appears to sole into the Mustang fault, with which it may have been coeval (Plate 2: section C-C'). Alternatively, the Mustang 2 fault may have been coeval with syn-Wassuk Group faults (e.g. fault R and the Rattler fault). The Mustang 2 fault has accomodated about 800 ft of normal displacement. Where exposed, rocks in the fault zone include breccia to powdery gouge.

MUSTANG FAULT?

In the southwestern half of the field area, south of the microwave station, the very poorly exposed Mustang? fault is a normal fault that dips about 33°SW and may be the northern edge of the Mustang fault offset by the Reese River fault (Figure 16).

INFERRED FAULTS

Fault R

This down-to-the-east normal fault is required to account for the anomalous apparent thickness of the Singatse Tuff in the northwestern portion of the study area, assuming a mean thickness of 1250-1400 ft for the Singatse Tuff in my field area (Figure 16; Plate 1). In addition, a deeply incised, linear gully coincides with the trace of postulated fault R. Fault R is assumed to be approximately coeval with faults X, Y, and the Rattler fault, which have similar attitudes.

Fault T

Near the microwave station, between fault Q and the Rattler fault, the Singatse Tuff terminates, along strike, against Mesozoic metamorphic rocks. This is unusual in the study area, where the Mickey Pass seems to have filled topographic lows, allowing the Singatse Tuff to be deposited on a surface of relatively low relief and with uniform thickness. Therefore, a fault is required to account for the abrupt termination of the Singatse Tuff against the Mesozoic metamorphic rocks. It is possible the knob of Singatse Tuff, shown bounded to the north by fault T on Plate 1, is a late Miocene slide block. Given the observed field relations, it is likely fault T, whether a fault or sliding event, is older than fault Q and the Rattler fault.

Fault U

In the northwesternmost portion of the field area, fault U is required to account for (1) juxtaposition of the Mickey Pass Tuff against the Wassuk Group, and (2) repetition of the Tertiary ignimbrite section (Figure 16, Plate 1). Fault U strikes about N15°W and is parallel to the Rattler fault and inferred fault R, with which it is probably coeval. Its dip is unknown, but is shown in cross sections to be about 40°E, similar to the Rattler fault. As inferred, fault U predates eruption of the 7 m.y. old basaltic-andestite.

RESTORATION AND MAGNITUDE OF FAULT OFFSETS

DATA ON SLIP VECTOR

The movement vectors can be constrained in the study area for two fault systems: (1) the 22-9 m.y. old Mustang fault, a spoon-shaped, low angle normal fault, has a bend that trends S87±2°E (Figure 22); this is the inferred slip direction; (2) because movement on the Cottonwood Springs and Penrod Canyon faults was synchronous, their line of intersection parallels the slip direction (Plate 2: section D-D'). The strike and plunge derived from this intersection is S73±4°E, 25±4°E (Figure 23). This probably represents the slip direction for all syn-Wassuk Group faults (e.g. fault X, Y, etc.).

SECTION A-A'

In order to estimate the amount of extension that has affected the central Wassuk Range, cross-section A-A' with original length of 34,200 ft (between pins) was palinspastically restored (Figure 24). Offsets were removed in sequence as follows:

Post-Wassuk Group:

Displacement on the range-front fault cannot be determined from field data, but the minimum amount of normal displacement on this fault is 5300 ft, the amount required to offset the ~ 7 m.y. old basaltic-andesite from the Wassuk Range to Walker Lake Valley (Plate 2, Figure 24).

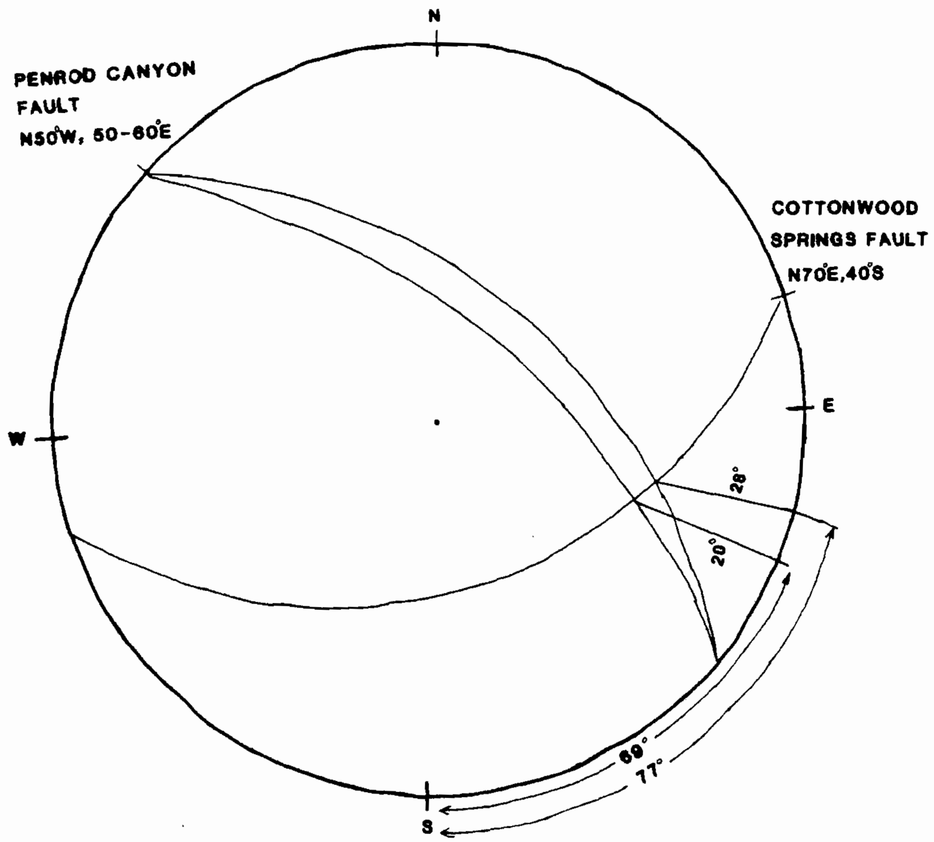


Figure 23. Intersection of the Penrod Canyon and Cottonwood Springs fault is the slip vector: S69-77°E, 20-28°E.

Figure 24. Restoration of section A-A'. A) ~9 Ma, after displacement on the Cottonwood Springs and Penrod Canyon faults and the Range-front fault has been removed. B) Pre-Mustang fault (pre 9 to 22 m.y.) with ignimbrites restored to flat-lying position.

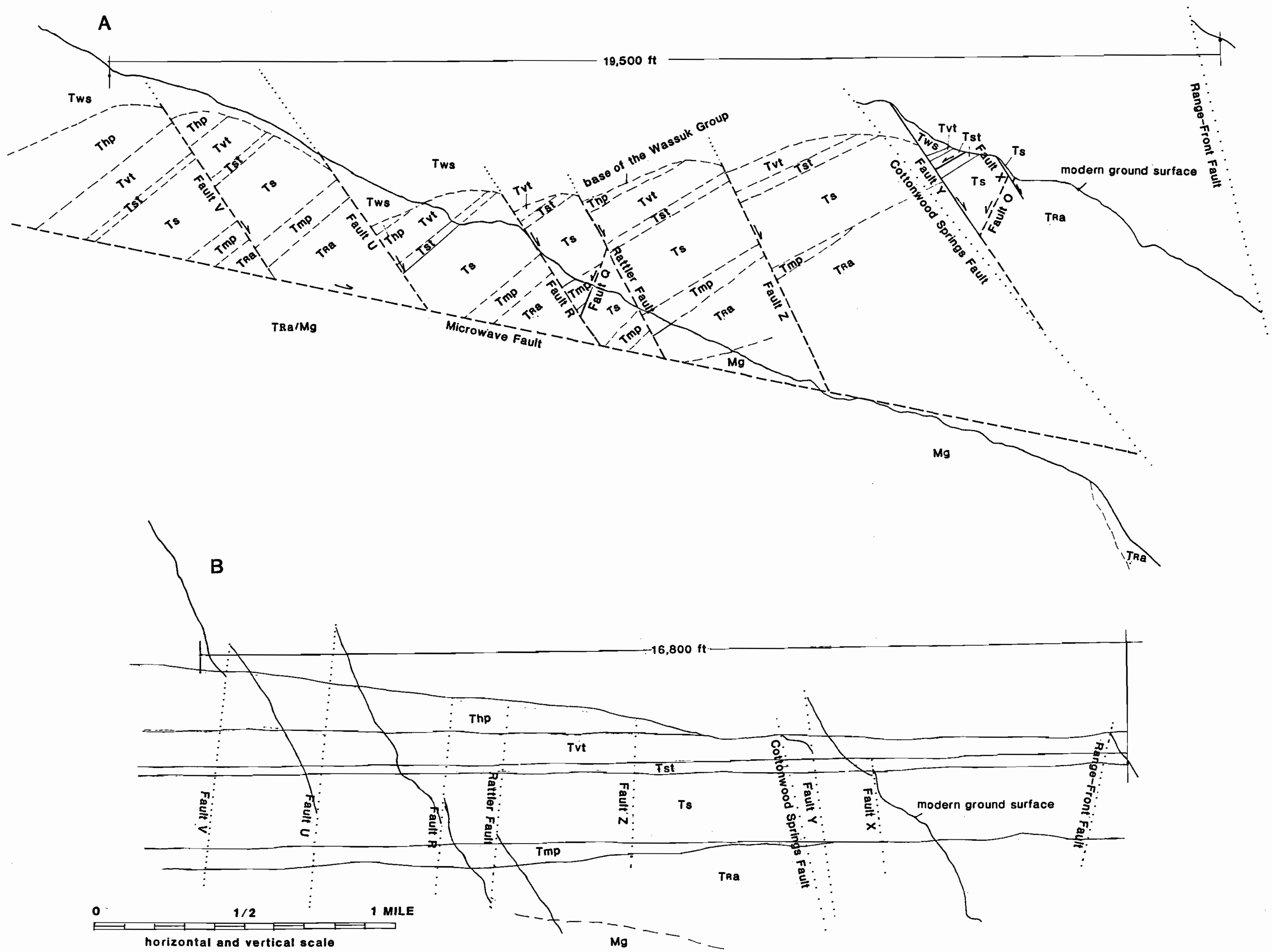

A
19,500 ft
Tws
Thp
Tvt
Tst
Ts
Tmp
TRa
Fault V
Fault U
Fault R
Fault O
Rattler Fault
Fault Z
Fault Y
Fault X
Cottonwood Springs Fault
Range-Front Fault
base of the Wassuk Group
modern ground surface
TRa/Mg
Microwave Fault
Mg
B
16,800 ft
0
1/2
1 MILE
horizontal and vertical scale

Figure 24.

Syn-Wassuk Group:

The 13,750 ft (+/-1000 ft) of displacement on the Cottonwood Springs and Penrod Canyon faults is constrained by the slip vector and by the location of the angular unconformity separating Miocene Wassuk Group sediments from underlying Oligocene ignimbrites (Plate 2). Figure 24 shows cross-section A-A' after removal of this fault set and the range-front fault.

If faults V, U, R, X, Y, and the Rattler fault sole into the Microwave fault as postulated, then the total amount of movement on the Microwave fault should be equal to the sum of movement on these faults, which is 6150 ± 250 ft.

A displacement of 300 ft (+/-100 ft) on fault X is based on the offset of fault O (Plates 1 and 2).

A displacement of 1300 ft (+/-500 ft) on fault Y is constrained by the location of the contact between the Singatse Tuff and the Vitric Tuff (Plates 1 and 2).

Between fault Y and the Rattler fault, the ignimbrite section is inferred to be offset 500-1750 ft by one (or several) normal fault(s) similar in age, orientation, and displacement to faults X, Y, and the Rattler fault (fault Z in Figure 24).

The 200 ft (+/-100 ft) of displacement determined for the Rattler fault, where it crosses section A-A' south of fault T, is based on the offset of the extrapolated Singatse Tuff/Mickey Pass Tuff contact. However, to the north of fault T, the displacement on the Rattler fault is 800 ft based on displacement of the Mickey Pass Tuff/Mesozoic metamorphic basement contact (Plates 1 and 2). The former value is used in this restoration as a conservative limit.

Approximately 750 ft (+/-250 ft) of displacement is required on fault R to account for the observed thickness of the Singatse Tuff, assuming a mean thickness of 1250-1400 ft for the Singatse Tuff (Ts) in the study area (Plates 1 and 2).

There is 3250 (+/-1500) ft of displacement on inferred fault U on the basis of the offset of the Singatse Tuff/Mickey Pass Tuff contact extrapolated from Bingler's (1978) mapping to the northwest of the study area (Figure 16).

Fault V has a displacement of 600 ft (+/-250 ft); its existence is extrapolated from Bingler's (1978) mapping (Figure 16).

Field data is insufficient to determine the amount of displacement on antithetic faults Q and O, though it is assumed to be minor in the restoration.

On the basis of the fault restorations above, section A-A' has undergone a minimum of 104% S73°E-N73°W extension[1]; the length between pins is 34,200 ft at present (e.g. after extensional faulting) and is 16,800 ft before faulting, as measured along paleohorizontal surfaces (Figure 24). Table 4 summarizes the percent extension attributed to each fault group.

[1] Extension was computed using the following equation: $e=(l^{f}-l^{o})/l^{o}$, where e=percentage extension; l^{f}= final, elongated length of the cross-section; and l^{o}= original, pre-extension length of the cross-section (Davis, 1984; and Axen, 1986).

SECTION B-B'

Offsets along faults were removed in sequence as follows:

Post-Wassuk Group:

Displacement on the range-front fault cannot be determined from field data, but the minimum amount of displacement on this fault is 5300 ft, the amount required to offset the 7 m.y. old basaltic-andesite from the Wassuk Range to Walker Lake Valley (Plate 2, Figure 25).

Syn-Wassuk Group:

The 15,200 ft (+/-700 ft) of displacement on the Cottonwood Springs and Penrod Canyon faults is constrained by the slip direction and the location of the Reese River fault in its hanging wall and footwall (Plate 1, Figure 25).

Section B cannot be satisfactorily restored beyond this point due to lack of constraints on the direction of movement on the Reese River fault (Figure 25). The Reese River fault may have a component of normal, down-to-the-north movement, in addition to right-lateral strike-slip movement (Figure 25), but field data are insufficient to constrain the relative amounts. Below, end members for 100% strike-slip motion and 100% normal displacement are calculated and the maximum possible amount of normal movement is discussed. Due to the low angle of intersection between the Reese River fault and the plane of cross-section B-B', only a small error is incurred when calculating the end

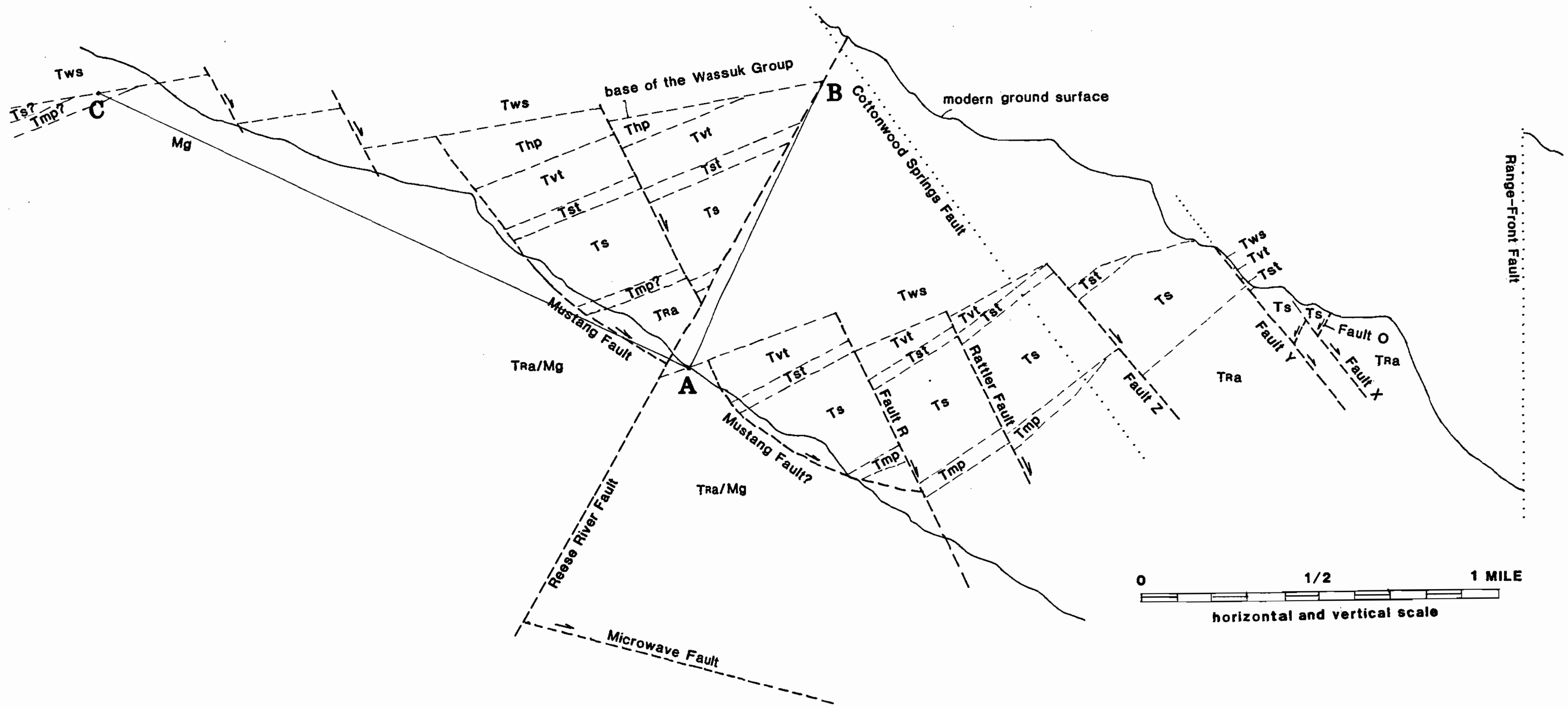


Figure 25. Partial restoration of section B-B'. Restoration of the Range-front fault and Cottonwood Springs fault results in an apparent westward dip of the Reese River fault in the plane of section B-B'. This is an artifact of the low angle (<5°) of intersection between the Reese River fault and the plane of section B-B', which results in a line that rotates as fault displacement is removed. However, the Reese River fault is a plane that remains approximately vertical as it is rotated, and does not dip to the west. A-B represents the maximum amount of vertical displacement possible on the Reese River fault, using the base of the basaltic-andesite as paleo-horizontal. A-C represents the maximum amount of horizontal displacement.

member displacements within the plane of the cross-section (i.e. movement out of the plane of section is small) (see Plate 1).

100% Vertical movement: approximately 4750 +/-1000 ft based on the apparent offset of the base of the Wassuk Group, using the base of the 7 m.y. old basaltic-andesite as horizontal (restoration of points A to B on Figure 25). It is apparent from Figure 25 that movement on the Reese River fault cannot be successfully restored using 100% "vertical" movement because this would juxtapose Mesozoic crystalline rocks faulted against the Singatse Tuff immediately below the base of the Wassuk Group on the north side of the Reese River fault against a thick section of ash-flow tuffs on the south side. In other words, the units do not match across the fault (Figure 25). Therefore, only pure strike-slip movement or a combination of strike-slip and normal movement could have occurred on the Reese River fault. A maximum of 35% of down-to-the-north dip-slip displacement is estimated, the remainder being right-lateral strike-slip (Figure 25).

100% Horizontal movement: 9600 +/-1000 ft based on apparent offset of the base of the Wassuk Group (restoration of points A to C on Figure 25).

Movement on the Reese River fault can be removed assuming approximately 30% down-to-the-north movement, which allows matching the Mustang fault with the Mustang fault? across the Reese River fault

A displacement of 300 ft (+/-100 ft) on fault X is based on the offset of fault O (Plates 1 and 2).

A displacement of 1300 ft (+/-500 ft) on fault Y is constrained by the location of the contact between the Singatse Tuff and the Vitric tuff (Plates 1 and 2).

Between fault Y and the Rattler fault, the ignimbrite section is inferred to be offset 500-1750 ft by one (or several) normal fault(s) similar in age, orientation, and displacement to faults X, Y, and the Rattler fault (fault Z in Figure 25).

The 200 ft (+/-100 ft) of displacement determined for the Rattler fault is determined from section A-A' based on the offset of the extrapolated Singatse Tuff/Mickey Pass Tuff contact to the south of fault T.

Approximately 750 ft (+/-250 ft) of displacement is required on fault R to account for the observed thickness of the Singatse Tuff, assuming a mean thickness of 1250-1400 ft for the Singatse Tuff (Ts) in the study area (Plates 1 and 2).

Two additional normal faults are shown on figure 25 offsetting the base of the Wassuk Group to the south of the Reese River fault. These are inferred faults which account for 1500 ft (+/-800 ft) of displacement.

Pre-Wassuk Group:

The Mustang fault has a minmum displacement of 3000 ft based on minimum offset of the Singatse Tuff (Plates 1 and 2).

Based on the restorations above, which assume approximately 30% down-to-the-north movement on the Reese River fault, section B-B' has undergone approximately 134% extension: the length between pins is 35,500 ft at present and is 15,200 ft after removal of all fault displacements and tilting.

FOLDING

Folds are rare within the Mesozoic metamorphic rocks, which generally lack observable bedding. In the study area, folds (of bedding or foliation) were observed at two locations within the Mesozoic metamorphic rocks. The fold axis of the first trends 268° and plunges ~60°W. After rotating the fold axis back to horizontal by subtracting 60° of Tertiary age westward tilting, the trend of the fold axis is restored to approximately E-W, which would suggest N-S compression, probably related to Mesozoic deformation. However, a second fold axis has a trend and plunge of 8° and ~20°N, and after the fold axis was rotated back to horizontal, its trend was approximately N-S. These two orientations are significantly different, and more data are needed to confidently make deductions about the direction of Mesozoic compression.

Attitudes within the Tertiary section in the eastern part of the field area define a gentle syncline, whose axis trends approximately N20-25°W and plunges approximately 40° to the northwest (Plate 1; Plate 2: section C-C', and D-D'; Figure 26). The syncline is most likely a drag fold that formed in response to movement along the Cottonwood Springs, Reese River, and Penrod Canyon faults.

Figure 26. Gentle synclinal fold of Wassuk Group sedimentary rocks adjacent to the Cottonwood Springs fault. The Reese River can be seen in the center of the photograph. View is the north.

DISCUSSION OF STRUCTURE

SLIP DIRECTION

Study area

The slip direction during movement on the Mustang fault, which was active sometime between 22 and 9 m.y., was S85-89°E, implying an extension direction of N87±2°W-S87±2°E. The slip direction during movement on the Cottonwood Springs and Penrod Canyon fault, active sometime between ~9 and 7 m.y., was S69-77°E; therefore the extension direction during this time period was N73±4°W-S73±4°E. Thus, the extension direction shifted about 15° clockwise, at about 9 m.y.. The slip directions of faults X, Y, Z, R, U, V, the Rattler fault, Reese River fault, and the Microwave fault are not constrained by field observations. However, all of these faults were active during lower Wassuk Group deposition at about 9 m.y. slightly before or synchronous with movement on the Cottonwood Springs and Penrod Canyon faults; therefore, it is likely that these faults have the same slip direction as the 7-9 m.y. old Cottonwood Springs and Penrod Canyon faults, which were also active during Wassuk Group deposition. The strike of the Reese River fault in the footwall of the Penrod Canyon and Cottonwood Springs faults is N70°W. This is approximately parallel to this slip direction, which is consistent with its interpretation as a strike-slip fault; therefore, the Reese River fault accommodated some ~E-W extension parallel to its strike. In the hanging wall of the Penrod Canyon and Cottonwood Springs faults, the strike of the Reese River fault is ~N40°W; drag along the the Penrod Canyon and Cottonwood Springs faults, as evidenced by the folded Tertiary units, may have rotated this segment of the Reese River fault. The movement direction of the range-front fault system, active 7-0 m.y. ago is not known, though it is probably close to the same orientation as for the Cottonwood Springs and Penrod Canyon faults.

Regional

In the Singatse Range, to the west of the study area (Figure 2), the slip direction for 11 to 19 m.y. old normal faults is S85-90°E, based on the offset of linear features, such as the pinch-out of beds, and offset of features within pre-Tertiary rocks, such as dike swarms, contacts of plutons, and distinctive zones of mineralization (Proffett, 1977). This is consistent with the slip direction for 22-9 m.y old faults in the central Wassuk Range. In addition, Proffett (1977) determined the slip direction for a Holocene age range-front fault to be S65-70°E, based on a sharp bend in a fault plane. This is close to the slip direction for 9 -7 m.y old faults in the study area, and may reflect a similar shift in the slip direction at about 11 m.y. (or later) in the Singatse Range. Thus, data are compatible with similar slip histories in both ranges, marked by a 15° clockwise rotation of slip direction at approximately 11-9 Ma. If this is true, it implies that the 7-0 m.y. old range-front fault system in the Wassuk Range had approximately the same slip direction as the 9 -7 m.y. old faults: S69-77°E.

In the area between Coal Valley and the Pine Grove Hills and into the southern Singatse Range, Gilbert and Reynolds (1973) documented several northwest- to west- and northeast- to east-striking faults. The faults are between 12.5 and 7 m.y. old, and were inferred to be dip-slip faults in the absence of slip direction data. Faults of similar age and orientation in the central Wassuk Range are inferred to be oblique-slip faults, based on a slip direction of about S73°E. It is probable that the slip directions were approximately the same orientation for both areas and, therefore, it seems appropriate to reinterpret many of the faults mapped by Gilbert and Reynolds as oblique-slip faults.

NET EXTENSION

Study area

At least 104% of roughly east-west extension has occurred in the central Wassuk Range, accommodated by movement on down-to-the-east normal and oblique-slip faults. This estimate is based on a stepwise restoration of fault offsets on cross section A-A' (Figure 24). Assuming 30% down-to-the -north movement on the Reese River fault, there was approximately 134% of roughly east-west extension on cross-section section B-B'. The difference in the two estimates of extension is primarily due to slip on the Reese River fault. The amount of extension attributed to each age group of faults, based on the restoration of cross sections A and B, is summarized on Table 4: the 22-9 m.y. old Mustang faults and 9 m.y. old faults X, Y etc. are together responsible for about 30% of extension, the 9 -7 m.y. old Reese River fault contributes about 34%, the 7-9 m.y. old Cottonwood Springs and Penrod Canyon faults contribute 60-65%, and the 0-7 m.y. old range front fault system contributes at least 10% of the total.

Regional

About 130% east-west extension has been documented in the northern Singatse Range by Proffett (1977) and Proffett (1984). This value is close to the estimated amount of extension for the central Wassuk Range based on the restoration of cross-section B-B' and is about 25% greater than the estimate from cross-section A-A'.

TILTING

Rock Units

22-28 m.y. old pre-faulting ash-flow tuffs have all been tilted westward an average of 70°, but dips range from 40°W to steeply overturned to the east. Anomalous ash-flow tuff attitudes not included in average dip calculations are: (1) very low angle dips, (2) dips taken close to the contact of the ash-flow tuffs with the Mesozoic basement rocks, where compaction foliation of the ash-flow tuffs mimics paleotopography, rather than paleohorizontal, and (3) attitudes close to the Reese River fault, which have anomalous northward and eastward dips due to drag folding. All of the ash-flow tuffs have been tilted approximately the same amount (i.e. there are no angular unconformities within the ash-flow tuff section); therefore, it is inferred that faulting initiated after eruption of the ash-flow tuffs, as in the Singatse Range (Proffett, 1977) and Coal Valley and vicinity (Gilbert and Reynold, 1973).

The ~9 m.y. old Wassuk Group, which overlies the ash-flow tuffs, dips moderately to shallowly westward. Fault motion between 9 and 7 m.y occurred during Wassuk Group deposition, which should result in an upsection decrease in dip. No continuous upward decrease can be documented, partly due to complications lent by synclinal folding of the Wassuk Group in the eastern part of the study area. However, it was possible to document that the shallowest dips are at the top of the exposed section in the western and eastern part of the study area. The average dip of the upper Wassuk group exposures is 17°W, and the average for the remainder of the exposures is 43°W, with a range of 15-64°W.

7 m.y. old basaltic andesites have gentle westward dips of 5-12°W, inferred to be largely due to movement on the range-front faults.

Faults

The oldest fault in the study area, the Mustang fault, is constrained to be between 9 and 22 m.y. old. It has an average strike of approximately N3°E and the gentlest dip of any of the faults exposed in the field area; its present dip is nearly horizontal. Tertiary ash-flow tuff strike an average of approximately N5°E and dip an average of 70°W, with a range of 55-90°W, in the vicinity of the Mustang fault trace. If the ash-flow tuffs were approximately horizontal when movement began on the Mustang fault, as inferred, then removal of the 70° of syn- and post-Mustang fault tilt, using N5°E as the axis of rotation, allows the original strike and dip of the Mustang fault to be estimated: N5°E, 55-90°E, or 70°E if the average dip value is used.

Fault Y is the only ~9 m.y. old fault on which a reliable attitude was obtained, and it is assumed to be representative of all of the faults that are inferred to cut the lower Wassuk Group: faults X, Y, Z, R, U, and V. Fault Y strikes N40°W and dips 37°NE. The base of the Wassuk Group was approximately horizontal before movement began on this fault set. The present dip of Wassuk Group bedding averages 42°W and the strike averages approximately N5°W in the vicinity of fault Y. If the 42° of Wassuk Group tilt is removed, then fault Y is returned to its original orientation of approximately N26°W, 74°E. In addition, if the 42° of Wassuk Group tilt is removed from the ash-flow tuffs, presently dipping an average of 70°W, then their dip restores to about 28°W; the Mustang fault must be responsible for this tilt prior to fault Y (Table 4).

It is unclear if the nearly vertical Reese River fault accounts for any of the observed tilt of the rock units, besides the tilt caused by drag folding. The 7-9 m.y. old oblique-slip faults include the Cottonwood Springs fault, which strikes N70°E and dips 40°S, and the Penrod Canyon fault, which strikes N50°W and dips about 50-60°NE. The range front faults are the youngest faults in the central Wassuk Range; by removing the 5-12° of westward tilt attributed to the N13°W striking Range front faults, the pre-Range-front fault orientation of the Cottonwood Springs and Penrod Canyon faults can be determined: the strike of the Penrod Canyon fault is N42-46°W after removal of 5-12°W tilt, and the dip increases to 56-66°NE; the Cottonwood Springs fault's strike changes slightly to N61-66°E, and the dip increases to 43-47°S.

The 9 m.y. old fault set (faults X, Y etc.) and the 7-9 m.y. old oblique slip faults are together responsible for 31-38° of westward tilt (Table 4). This was determined by subtracting the 32-39° of westward tilt accounted for by the Mustang fault and the range front fault from the total amount of tilt on the ignimbrites, using the average value of 70°W. This is in close agreement with the amount of tilt obtained by subtracting 5-12° of range-front fault tilt from the 42° tilt of the Wassuk Group (30-37°W).

GEOLOGIC SUMMARY OF THE STUDY AREA

Mesozoic meta-volcanic rocks and granitic intrusive rocks comprise the basement in the central Wassuk Range. The Cenozoic stratigraphy includes pre-faulting Oligocene and early Miocene ash-flow tuffs, syn-faulting late Miocene sedimentary and volcanic rocks, and late Miocene basalts, which post-date most of the faulting.

The oldest event was eruption of late Triassic (?) and pre-late Triassic meta-andesite flow rocks and pre-late Triassic meta-latite pyroclastic rocks (Bingler, 1978; Dilles and Wright, 1988). Quartz monzonite and mafic dike rocks intruded and thermally metamorphosed the Triassic volcanic rocks in the Middle Jurassic to early Late Cretaceous (Figure16; Bingler, 1978). A boulder conglomerate derived entirely from Mesozoic basement rocks is present locally above the Mesozoic basement rocks and represents the end of a long erosional period. Abundant silicic ash-flow tuffs were erupted in the Oligocene and early Miocene and unconformably overlie the basement rocks (Figure 16). Included in this sequence are the Mickey Pass Tuff, Singatse Tuff, Vitric Tuff, and Hu Pwi Rhyodacite. The Mickey Pass Tuff was localized in Tertiary valleys, whereas the Singatse Tuff retains a relatively uniform thickess and is ubiquitous throughout the study area. Locally hornblende latite flows were erupted disconformably atop the ash-flow tuffs.

The beginning of Basin and Range normal faulting began after eruption of the silicic ash-flow tuff sequence, athough the timing of faulting with respect to the poorly exposed hornblende latite is unclear. The Mustang fault represents this period of faulting within the study area and is a down-to-the-east normal fault, which initially dipped ~70°E but presently dips shallowly eastward (Figure 16).

A later generation of normal faults initiated the creation of the basins in which basal sediments of the Miocene Wassuk Group are preserved; conglomerates, sandstones, and siltstones comprise the Wassuk Group. Movement along these faults continued during lower Wassuk Group deposition with most of the sediments derived from the adjacent upthrown blocks. The faults are all moderately dipping, down-to-the-east, north- to northwest striking normal faults but initially dipped more steeply to the east (Figure 16, Plate 2). These faults are offset by younger northwest-striking right-lateral strike- and oblique-slip faults as well as an east- to northeast-striking left-lateral oblique-slip fault. Both fault sets moved synchronously, creating a basin in which Wassuk Group sediments and intercalated lavas were deposited (Figure 16).

Late Miocene basalt flows post-date both Wassuk Group sedimentation and the above phases of faulting (Figure 16). These rocks have are tilted gently to the west by the most recent episode of faulting, which coincides with the eastern range-front of the Wassuk Range.

CONCLUSIONS

1) This study documents four phases of Late Cenozoic faulting in the central Wassuk Range. These are: (1) down-to-the-east, spoon-shaped, low-angle normal fault(s) active between 22 and 9 Ma; (2) down-to-the-east, moderately dipping, northwest striking normal faults and high-angle antithetic faults active approximately 9 Ma; (3) moderately dipping right- and left-lateral obliqu-slip faults and a vertical right-lateral strike-slip fault active 9 -7 Ma. The oblique-slip faults have a component of down-to-the-east dip-slip movement; and (4) 7-0 m.y. old north-northwest-striking, down-to-the-east normal faults, which coincide with the present range-fronts.

2) The down-to-the-east normal and oblique-slip faults in the study area tilt the Tertiary and Mesozoic section and older faults westward, so that the dips of fault phases (1), (2), and (3) above are not their original dips. Faults were initiated at relatively high angles (45-75°) and rotated to shallower dips during movement and by more recent faults, similar to the faulting sequence described in the Singatse Range by Proffett (1977).

3) Slip vectors of extensional faulting are S85-89°E (22-9 Ma) and S69-77°E (9-7 Ma), and record a 15° clockwise rotation of the extension direction at about 9 Ma. It is uncertain if this orientation persisted during range-front faulting (7-0 Ma).

4) Approximately 104% (~east-west) extension has taken place across the study area in the central Wassuk Range since ~9 Ma, based on the restoration of cross-section A-A'. An additional component of WNW-ESE slip is recorded by the Reese River strike-slip fault.

5) Sedimentology and clast composition data of the ~9-7 m.y. old Wassuk Group suggest these sediments were deposited on alluvial fans adjacent to and synchronous with faults of sets (2) and (3) above.

6) The age of the Wassuk Group in the study area is ~9 Ma.

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APPENDICES

APPENDIX A. ALLUVIAL FAN DEPOSITS

Streamflow and debris-flow are important processes in transport and deposition of alluvial-fan deposits. Streamflow leads to the deposition of three types of fan deposits: STREAM CHANNEL SEDIMENTS accumulate within the channels of streams on the fan's surface. These deposits form long narrow bodies consisting of the coarsest and most poorly sorted of the streamflow deposits. SHEETFLOOD DEPOSITS are formed by surges of sediment-laden water that spread out from the end of a stream channel onto a fan in sheet-like deposits of gravel, sand, or silt that tend to be well-sorted and may be cross-bedded, laminated, or nearly structureless. SIEVE DEPOSITS consist of coarse gravel lobes. They occur on fans where the source supplies relatively little sand, silt, and clay to the fan.

Debris flows and mudflows are common on fans in arid or semiarid regions, in addition to stream-flow deposits. These flows are likely to occur in regions where there is an abundant source of clay, often derived from unconsolidated volcaniclastic or glacial sediment. DEBRIS FLOW DEPOSITS are poorly sorted and lack sedimentary structures. Clasts may be any size and are generally matrix-supported. MUDFLOWS are similar to debris flows but consist mainly of sand-size and finer sediment.

The characteristics of alluvial fan deposits vary depending upon where they are deposited on the fan's surface. In general, there is a down-fan decrease in grain size, bed thickness, and channel depth and an increase in sorting (Leeder, 1982). More specifically, UPPER FAN sediments are coarse and extremely poorly sorted, and streamflow is usually confined to one channel, which may shift position as the channel becomes clogged with streamflow or debris-flow deposits. Upper fan deposits consist of coarse-grained, matrix-supported conglomerates and clast-supported conglomerates, which usually occur within channels. Sediments deposited on the MIDFAN are of intermediate size with respect to upper fan sediments and make up streamflow and debris-flow deposits. Channels are shallower and more numerous than on the upper fan, and sheetlike deposits of sands and gravels are common and may be cross-bedded. Coarse-grained conglomerates are present, including both debris-flow and channeled, streamflow conglomerates. DISTAL FAN deposits occur on the toe of the fan. This part of the fan has the gentlest slopes, finest sediments, and lacks well-defined channels. Sediments are largely sand and silt deposits of sheetflood origin, although thin conglomerate layers may be present. Channeled deposits are rare.

Unless otherwise noted, all of the above material is derived from Boggs (1987).

APPENDIX B. PEBBLE COUNT PLOTS

Pebble count methods are discussed in the text. See Table 3 for pebble count data. Listed below is an explanation of the rock type symbols used on the following plots:

TRa=Mesozoic metamorphic rocks

Mg=Mesozoic intrusive rocks

Ts=Singatse Tuff

Tvt=Vitric Tuff

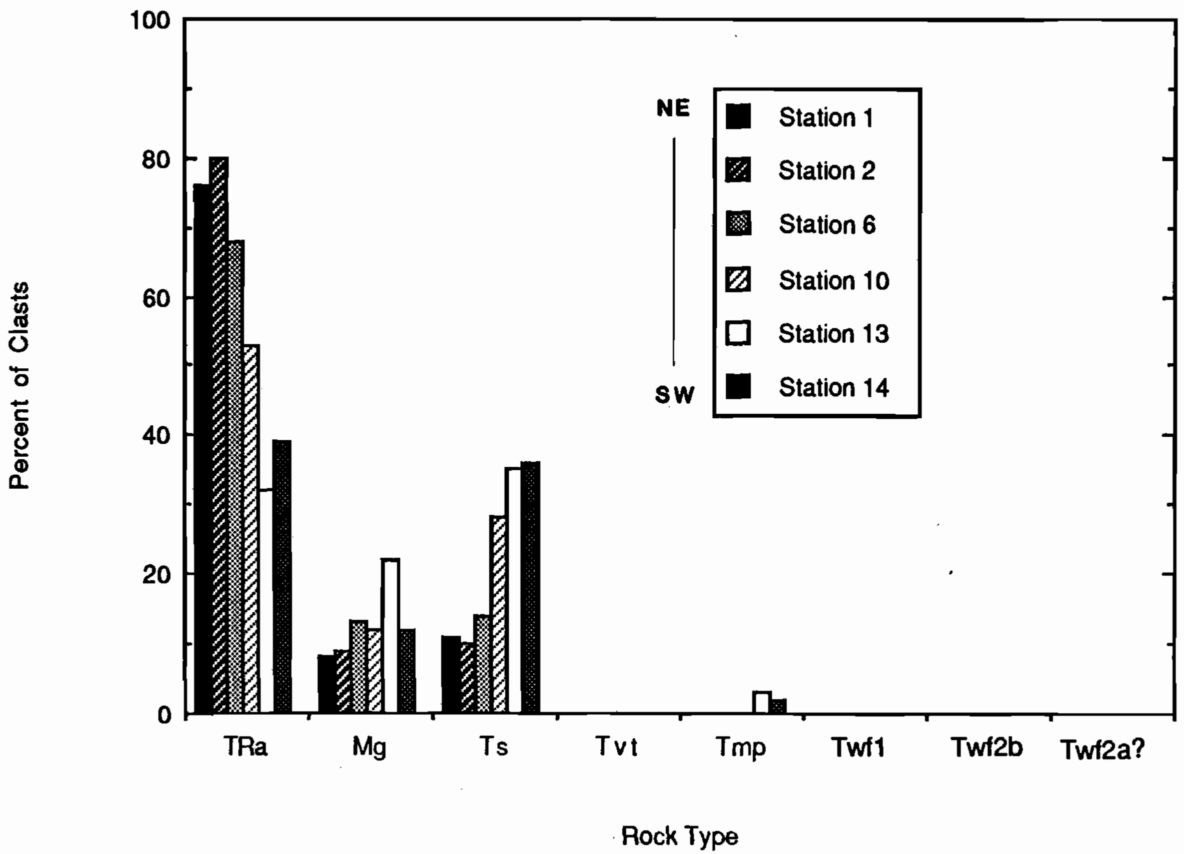
Tmp=Mickey Pass Tuff

Twf1=Wassuk Group flow 1

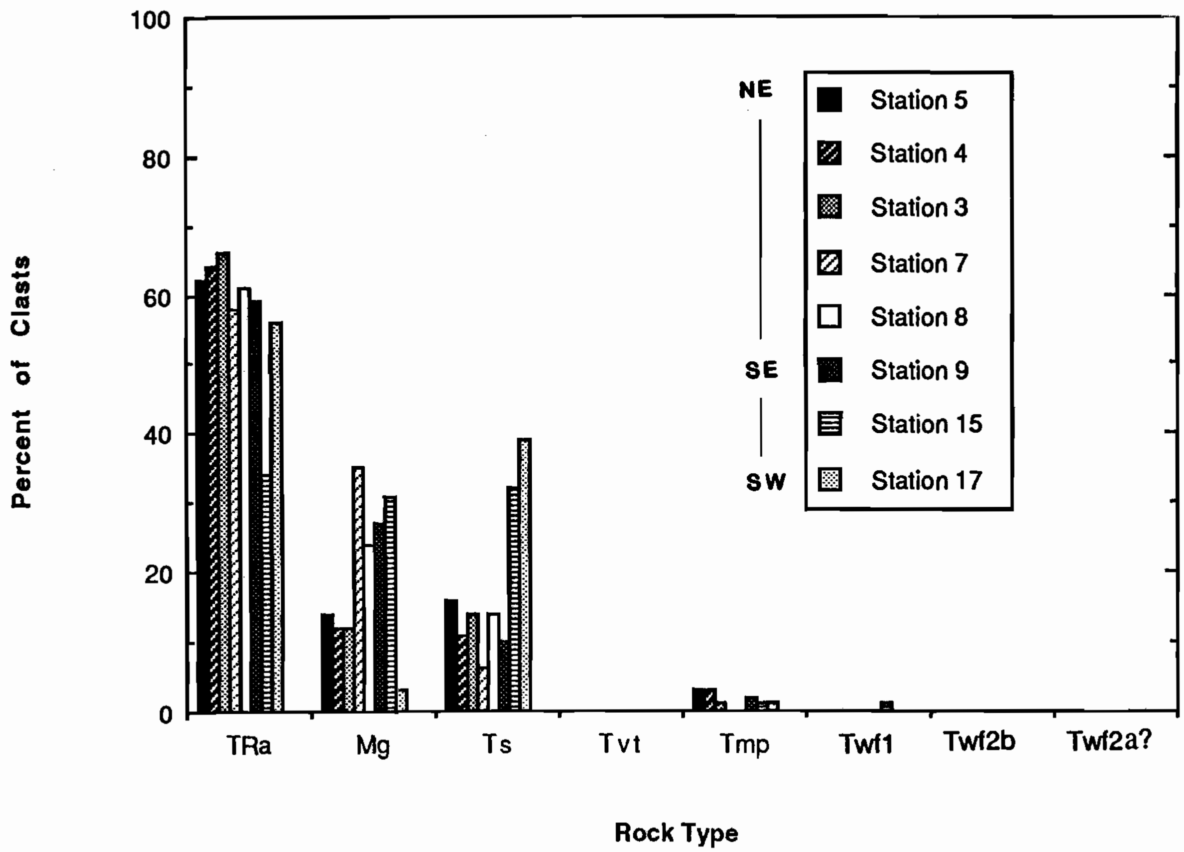
Twf2b=Wassuk Group flow 2b

Twf2a?=Wassuk Group flow 2a?

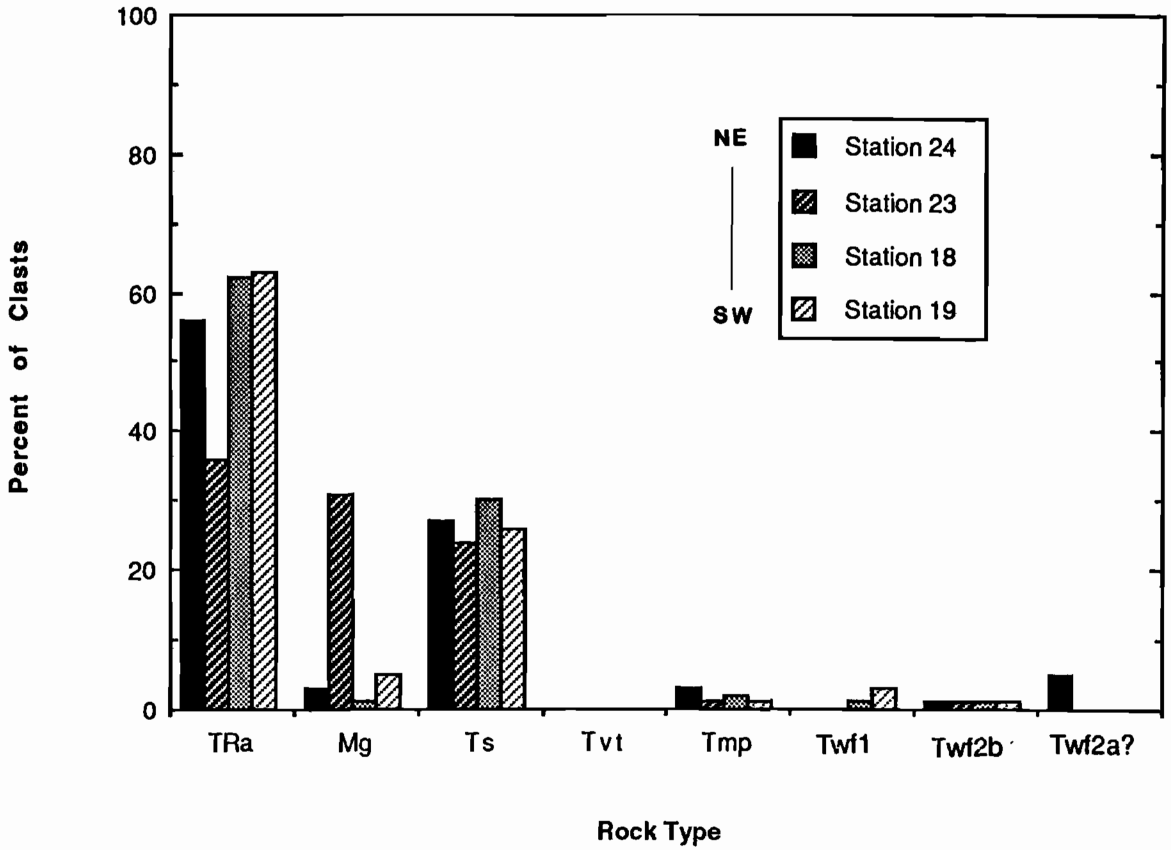
Plot 1. Clast composition data of conglomerates at the same stratigraphic level near the base of the Wassuk Group. Note the northeast to southwest decrease in Mesozoic metamorphic rock clasts (TRa), increase in Singatse Tuff clasts (Ts), and increase in ratio of Mesozoic granitic to Mesozoic metamorphic clasts. See Figure 13 for locations.



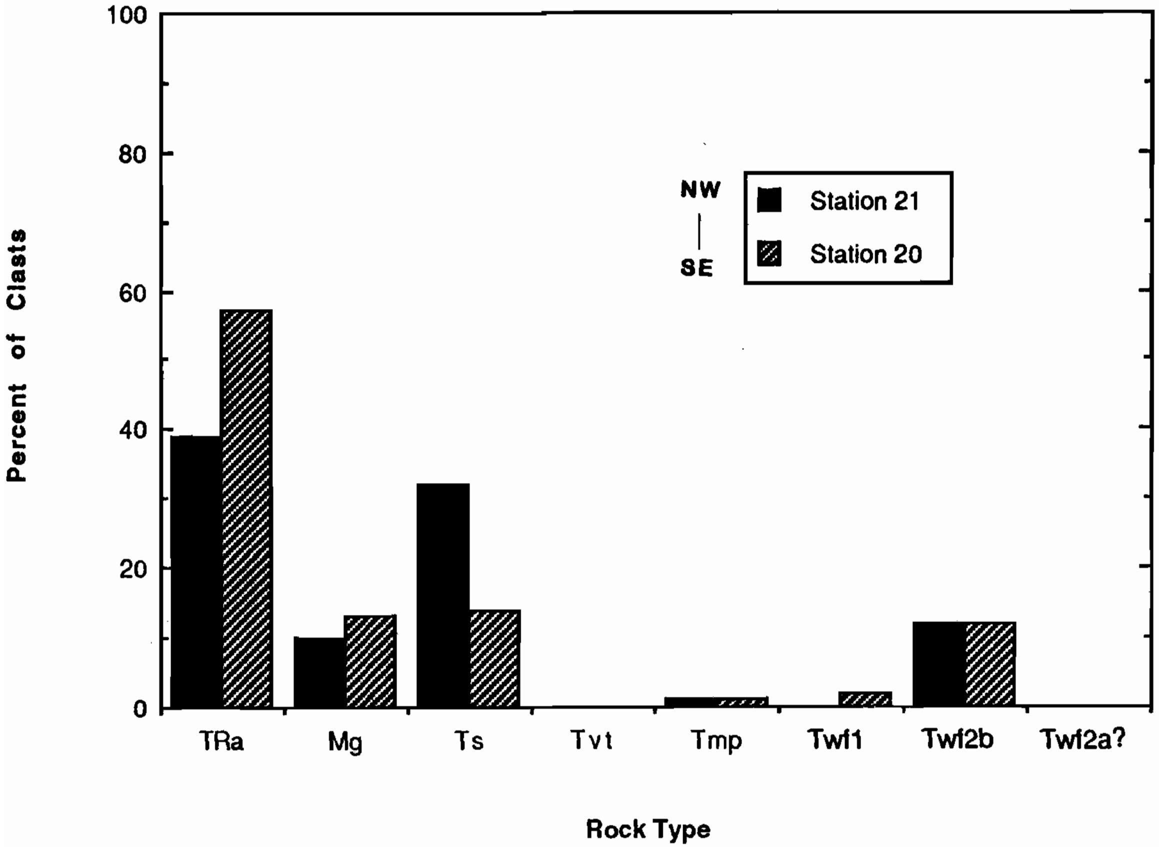
Plot 2. Clast composition data of conglomerates immediately below basaltic-andesite flow 2. Pebble count station 15 and 17, which are located to the west of the other stations, exhibit an increase in Singatse Tuff clasts (Figure 13). In addition, the ratio of Mesozoic granitic to Mesozoic metamorphic clasts increases from north to south.



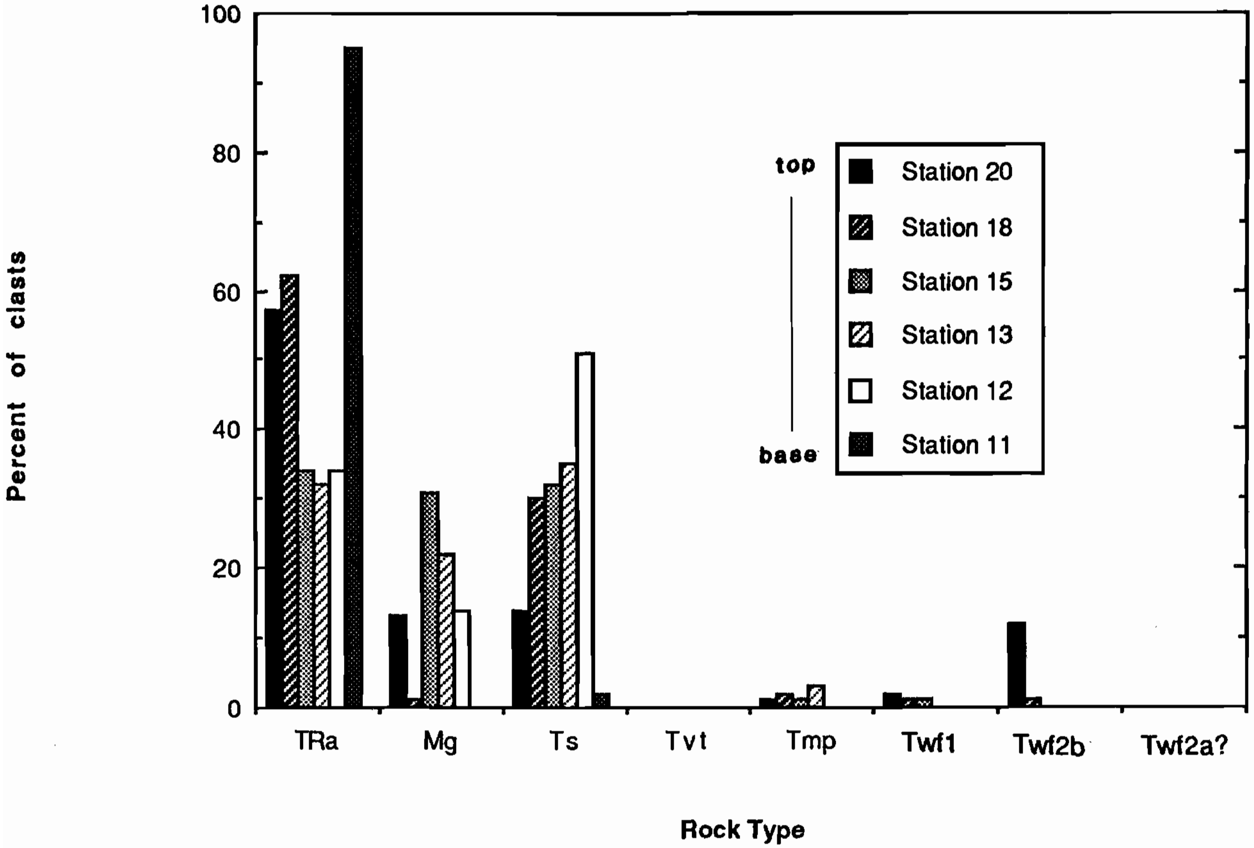
Plot 3. Clast composition data of conglomerates above basaltic-andesite flow 2. Note lack of apparent lateral trends. See Figure 13 for locations.



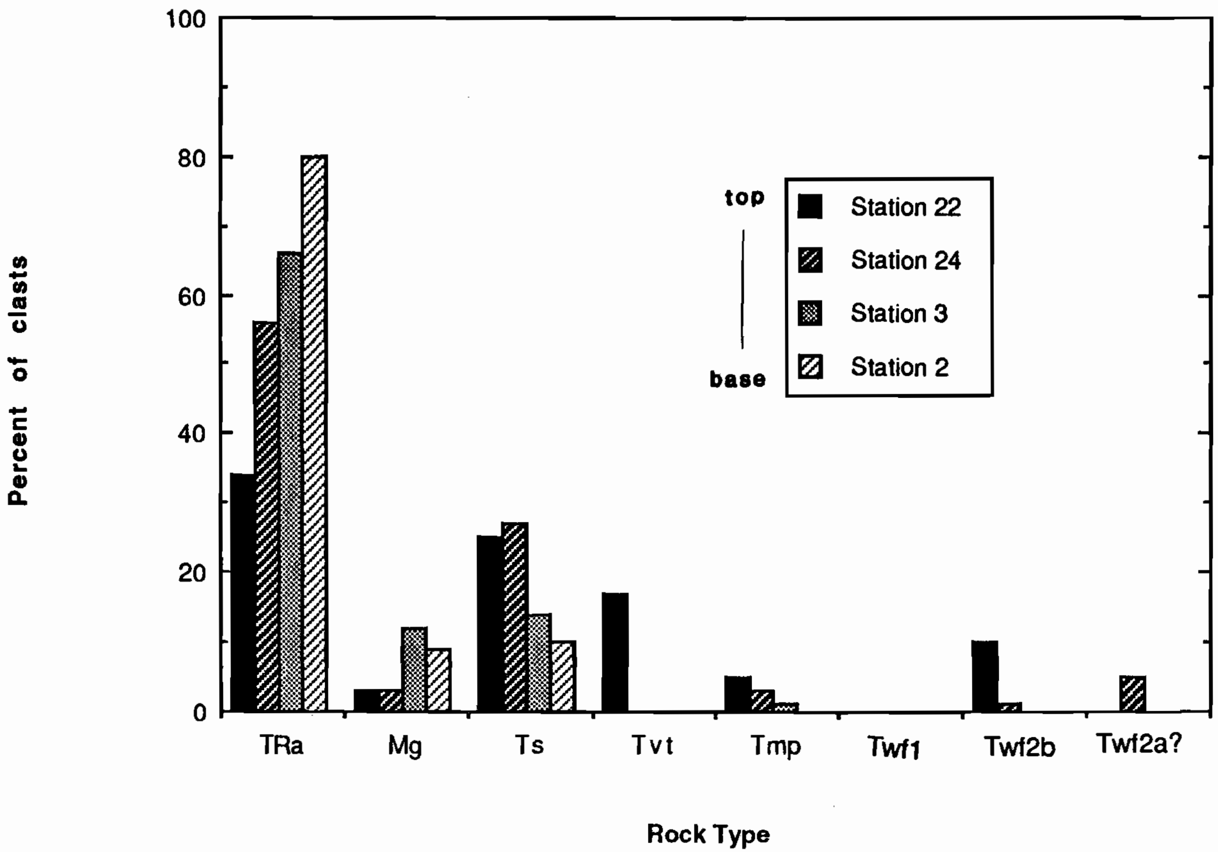
Plot 4. Clast composition data of conglomerates above basaltic-andesite flow 2. See Figure 13 for locations.



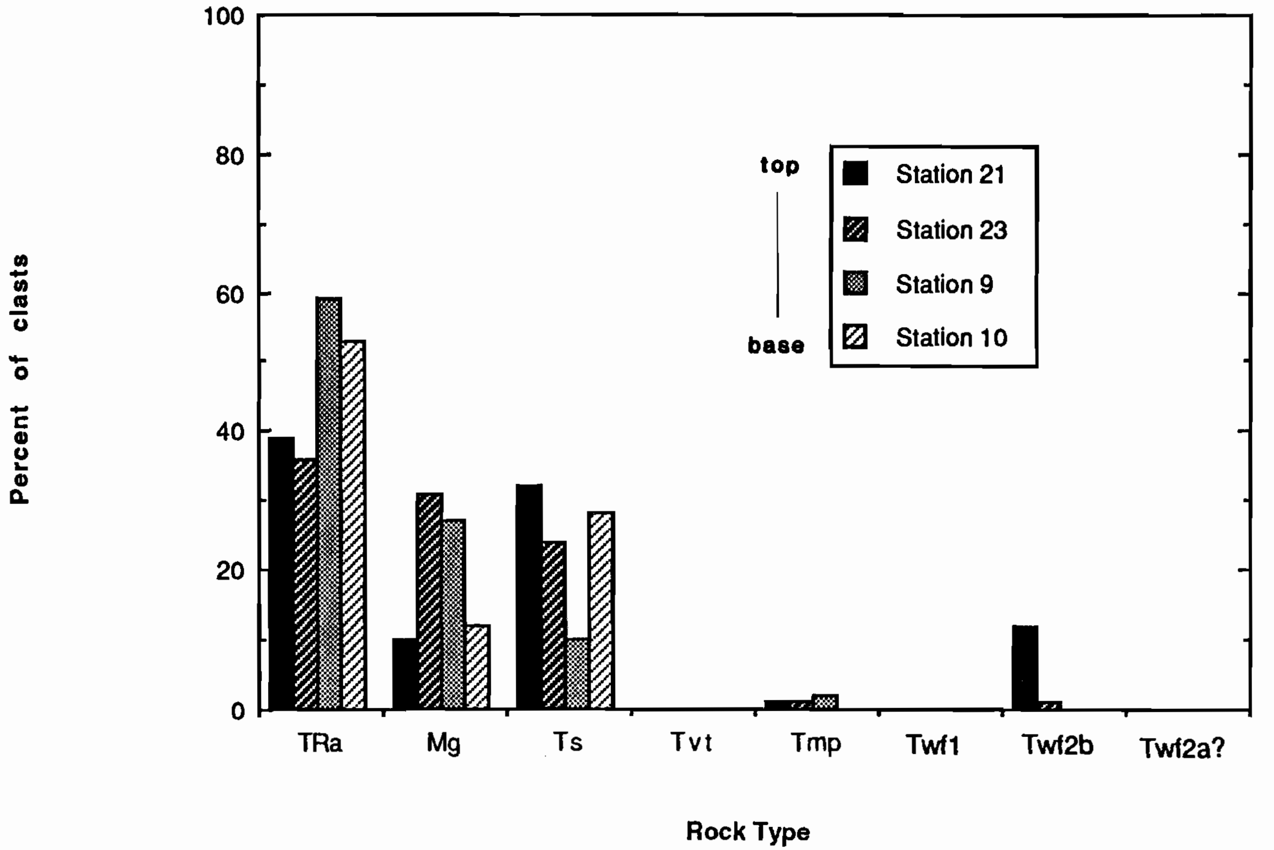
Plot 5. Clast composition data of conglomerates of a vertical section in the southwestern part of the sampling area. See text for discussion of vertical changes in clast composition. See Figure 13 for locations.



Plot 6. Clast composition data of conglomerates of a vertical section in the northeastern part of the sampling area. See text for discussion of vertical changes in clast composition. See Figure 13 for locations.



Plot 7. Clast composition data of conglomerates of a vertical section in the central part of the sampling area. See text for discussion of vertical changes in clast composition.



APPENDIX C. GEOCHRONOLOGY

INTRODUCTION

Two rocks from the Wassuk Group were radiometrically dated as a part of this study. These dates were used, in conjunction with dates of the Tertiary rocks from previous studies, to constrain the timing of Late Cenozoic faulting in the central Wassuk Range. Since most of the faulting in this area occurred during Wassuk Group deposition, the two dates proved especially useful to constrain the ages of the growth faults. The two dates from this study, in addition to dates from previous studies in the Wassuk Range, Singatse Range, Coal Valley, and Gabbs Valley and Gillis Ranges, are listed in Table 5. Dates from Coal Valley and the Singatse Range had to be recalculated for the new decay constants using the tables in Dalrymple (1979).

METHODS

I performed the mineral separates using the facilities in the Geology Department at Oregon State University. The first sample was taken from basaltic-andesite flow 3 of the Wassuk Group and contained hornblende phenocrysts, with thin rims of oxyhornblende containing iron oxides. This sample was ground to 100-120 mesh, slightly finer than required, to ensure removal of iron oxides at the expense of as little of the fresh hornblende as possible. The second was taken from an air-fall tuff near the base of the Wassuk Group. It contained fresh biotites and was ground to 60-100 mesh. Bromoform was used for the initial heavy liquid separation of both samples. After hand magnet removal of metal chips and iron oxides, an excellent separation of biotite was obtained from the tuff by gently shaking the sample over a piece of paper. Further separation of the flow sample was necessary. At this point, the sample consisted primarily of pyroxene and hornblende and minor plagioclase in composite grains. The pyroxene contained fine iron

Table 5. Representative K-Ar dates (Ma) of Cenozoic rocks from west-central Nevada. All of these dates are based on the IUGS constants (Steiger and Jager, 1977; and Dalrymple, 1979). Superscript refers to author.

	Wassuk Range	other localities
Basaltic-andesite flows	7.3±0.4[4]	8.4±1.2[3] 8.8±1.3[3]
Wassuk Group	9.44±0.41[6a] 8.41±1.22[6b] 13.7±2.2[4]	Aldrich Station Fm.: 9.55±0.09 to 13.32±0.39[1] Coal Valley Fm.: 9.38±0.44 to 10.70±0.49[1]
Hornblende latite	13.9±0.4[4]	
Hu-Pwi Rhyodacite	25.2±1.0[4] 22.0±0.5[4]	23.2±0.8[5] 24.7±0.9[2]
Vitric Tuff		25.0±1.0[5] 26.1±0.8[5]
Singatse Tuff	25.9±0.8[4] 25.6±0.8[4]	27.9±1.1[2]
Mickey Pass Tuff		28.5±1.0[2] 26.3±0.9[5] 27.8±0.9[2]

1 Gilbert and Reynolds (1973). Samples are from Coal Valley and vicinity.
2 Proffett and Proffett (1976). Samples are from the Singatse Range.
3 Proffett (1977). Samples are from the Singatse Range.
4 Bingler (1978). Samples are from the Wassuk Range.
5 Ekren et al. (1980). Samples are from the Gabbs Valley and Gillis Ranges.
6 This study (1989). a. K-Ar date. b. Ar-Ar date. Samples are from the central Wassuk Range.

oxide inclusions, making the magnetic susceptibility of pyroxene and hornblende phenocrysts too close for magnetic separation to be successful. Separation of both samples was completed by hand picking. Both mineral separates were hand-picked to 100% purity.

K-Ar and Ar-Ar dating of the minerals was performed by Dr. Alan Deino at the Berkeley Geochronology Center at the Institute of Human Origins.

RESULTS

Hornblende grains from basaltic-andesite flow 3 were analyzed by the 40Ar/39Ar method, which has been described by Dalrymple and Lanphere (1971) and Faure (1986), to name a few. Individual grains yield ages ranging from ~7-11 Ma with 1 sigma errors of ~0.4-1.0 Ma. As the individual hornblende grains yield ages outside of one another's analytical error, the individual radiometric ages do not represent samples of a homogeneous population; rather, the hornblende and oxyhornblende have retained different amounts of argon and potassium. For this reason, the weighted mean is taken as the approximate age. The weighted mean of these 11 determinations (2-4 grains per analysis) is 8.41 m.y. with a 1 sigma error of 1.22 m.y..

K-Ar analysis of biotite from the air fall tuff yielded an age of 9.44±0.41. The biotite sample from the air-fall tuff was analyzed by the K-Ar method, where potassium was determined by flame photometry. Principles and techniques of the K-Ar method have been described by Faure (1986), among others.

The two radiometric dates are within analytical error of one another. For purposes of discussion, the age of the Wassuk Group is referred to as ~9 Ma in the text of the thesis. Radiometric data for the two samples are shown in Tables 6 and 7.

Table 6. Radiometric data for biotite analysis from the air-fall tuff[1]. Refer to Figure 8 and Figure 15 for approximate stratigraphic position of the dated tuff. See Plate 1 for location (*1).

%K+: 6.134±0.07 (1%)

%40Ar*: 20.2

40Ar* (moles/gm): $1.007 \times 10^{-10} \pm 4.200 \times 10^{-12}$

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1 Located in SE1/4, SW1/4, SW1/4, Sec. 1, T11N, R28E

Table 7. Radiometric data for hornblende analyses from basaltic-andesite flow 3[2]. Refer to Figure 8 and Figure 15 for stratigraphic position of the dated sample. See Plate 1 for location (*2).

Run #	37Ar/39Ar	36Ar/39Ar	40Ar*/39Ar	Moles 40Ar	%40Ar*	Age(Ma)	± (1σ)
01	5.7458	0.05840	2.068	5.5 E-15	10.9	7.45	0.96
02	7.6340	0.01746	2.790	3.5 E-15	37.7	10.04	0.55
03	7.7966	0.03800	2.953	5.6 E-15	21.6	10.62	0.69
04	7.4450	0.00484	2.643	1.5 E-15	75.3	9.51	0.39
05	7.1515	0.00479	2.216	1.1 E-15	71.7	7.98	0.45
06	7.2850	0.02050	2.296	1.6 E-15	29.3	8.27	1.04
07	7.1123	0.01027	2.242	1.4 E-15	47.2	8.07	0.69
08	7.2832	0.02406	2.527	4.9 E-15	27.7	9.10	0.54
09	7.4720	0.01028	1.837	2.8 E-15	42.5	6.62	0.37
10	(failed spectrometer run)						
11	8.1513	0.01223	2.258	2.4 E-15	42.9	8.13	0.53
12	7.8083	0.01899	2.047	2.6 E-15	28.9	7.37	0.73

Weighted mean = 8.41
Standard deviation= 1.22

2 Located in NE1/4, SW1/4, SW1/4, Sec. 1, T11N, R28E.