AN ABSTRACT OF THE THESIS OF

Robert Andrew Houston for the degree of Master of Science in Geology presented on August 29, 2001. Title: Geology and Structural History of the Butte District, Montana.

Abstract approved: ______________________

John H. Dilles

Ore deposits of the Butte district formed at ca. 66 to 62 Ma within a host rock of Butte Quartz Monzonite (ca. 76 Ma). Deposition of the Lowland Creek Volcanics Formation (ca. 53 to 50 Ma) on top of the Butte Quartz Monzonite and its ores, followed a period of extensive uplift, erosion, and unroofing. The amount of post-mineral tilting related to Cenozoic normal faults has been controversial. In the northwest part of the district, the Lowland Creek Volcanics dip 10° to 50° northwestward. From which data, Proffett (1973, 1979) inferred that the underlying ore deposit is similarly tilted. Paleomagnetic studies of the Butte Quartz Monzonite in the central and western part of the district suggest lesser tilts of 5° to 17° north to northwest (Geissman et al., 1980a, b).

In an effort to resolve the question to the amount of post-mineralization tilting, the structural geology of the Butte district was remapped at 1:12,000 scale. Structural attitudes (n=407) were collected on originally subhorizontal sill-like bodies of aplite

that are cogenetic with the Butte Quartz Monzonite. Examination of these data supports a hypothesis that the amount of tilting related to Cenozoic normal fault block rotation varies spatially across the district. Sheeted sill-like bodies of aplite in the northwest part of the district are tilted 34° northwestward. West of Big Butte, sill-like bodies of aplite are gently tilted 16° northwestward. Sill-like bodies of aplite in the northern and eastern parts of the district are tilted 10° to 15° north to northeastward. In the central part of the district, sill-like bodies of aplite are tilted an average of 14° eastward. In the southern part of the district, sill-like bodies of aplite on Timber Butte are tilted 20° to 25° northeastward.

In the northwest part of the district, the Lowland Creek Volcanics and underlying Butte Quartz Monzonite are tilted 10° to 50° northwestward by closely spaced (0.3 to 0.6 km) northeast-striking, southeast dipping normal faults that exhibit moderate displacements (less than 0.8 km). These northeast striking normal faults exhibit diminishing amounts of offset and northwest tilting southwestward along the faults and successively decreasing amounts of offset and tilting southeastward, perpendicular to the faults. The northeast striking normal faults include some moderate northwest dipping faults. Large north south striking, widely spaced (~9.5 km) Basin-and Range type normal faults cut northeast striking faults. These faults localized deposits of early Miocene and younger clastic sedimentary rocks in their hanging walls. The largest is the Continental-Klepper-East Ridge fault system which shows increased displacement (from ca. 1.5 to >2 km) and eastward tilting of the hanging wall southward along the fault system.

By restoring the orientation of the sill-like bodies of aplite in the northwest part of the district, prior to moderate (10° to 50°) northwest tilting, the sill-like bodies of aplite become gently tilted 10° to 15° northeastward. The restored orientation of the sill-like bodies of aplite is similar to the orientation of the sill-like bodies of aplite southeastward across the district. These observations support the interpretation that the district was gently tilted 10° to 15° northeastward prior to deposition of the Lowland Creek Volcanics Formation.

Analysis of these data identified three episodes of tilting that has tilted different parts of the district in differing amounts supporting both Proffett's (1973, 1979) and Geissman et al.'s (1980a & b) geologic data. The first episode gently tilted the district 10° to 15° northeastward and occurred between 62 Ma (post Main-Stage mineralization) and 59 Ma (pre granite porphyry dike emplacement). The second episode moderately tilted the district 10° to 50° northwest tilting in the northwest part of the district and occurred between 51 Ma (deposition of the Lowland Creek Volcanic Formation) and Basin and Range type normal faulting. Moderate northwest tilting is related to deformation and accommodation along northeast striking normal faults that cut the northwest part of the district. The final episode gently tilted the hanging wall of the Continental fault ~14° eastward and occurred during the middle Miocene related to Basin and Range type normal faulting.

By restoring the district prior to the three episodes of tilting, the orientations of quartz porphyry dikes, Pre-Main Stage veinlets, and zonal patterns related to ca. 66 to 62 Ma mineralization-hydrothermal alteration become vertical and symmetrical. This vertical orientation is consistent with most hypotheses of porphyry copper emplacement. Additionally, the two conjugate fault systems occupied by Main Stage veins (ca. 62 Ma) also restore to become normal oblique-slip faults.

Geology and Structural History of the Butte District, Montana

By

Robert Andrew Houston

A THESIS

Submitted to

Oregon State University

In partial fulfillment of
The requirements for the
Degree of

Master of Science

Presented August 29, 2001
Commencement June 2002

Master of Science thesis of Robert Andrew Houston presented on August 29, 2001.

APPROVED:

Major Professor, representing Geology

Chair of Department of Geosciences

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Robert Andrew Houston, Author

ACKNOWLEDGMENTS

This research was supported by the Atlantic Richfield Company (ARCO), the Tobacco Root Geological Society, and by NSF grants to Dr. John H. Dilles and Dr. Cyrus W. Field of Oregon State University. Reviews by Dr. Cyrus W. Field, Dr. Edward M. Taylor, Dr. Robert S. Yeats, and Dr. Gary Klinkhammer improved the manuscript and are gratefully acknowledged. It is with great pleasure that I thank Dr. John H. Dilles, my advisor, and chair of my thesis committee. He deserves much credit for providing the topic itself, numerous discussions, insight and, most of all, encouragement. Additionally, Steve J. Czehura of Montana Resources Inc. kindly provided me with many informative discussions as well as unpublished data of the Butte district, including geologic maps made by George Burns and John Proffett.

The author is indebted to the residents of the study area who readily gave their permission to traverse their properties. Special thanks go to Julius of Elk Park Pass for much insight on Butte life in the early 1900's and for many pleasant visits; sorry I ran over your dog.

A great deal of support, both financial and personal, came from my parents, Dr. Thomas and Carol Houston, and from Tom and Jan Wareham. Finally, my gratitude is extended to Joni Wareham for believing in my abilities and supporting my commitment.

TABLE OF CONTENTS

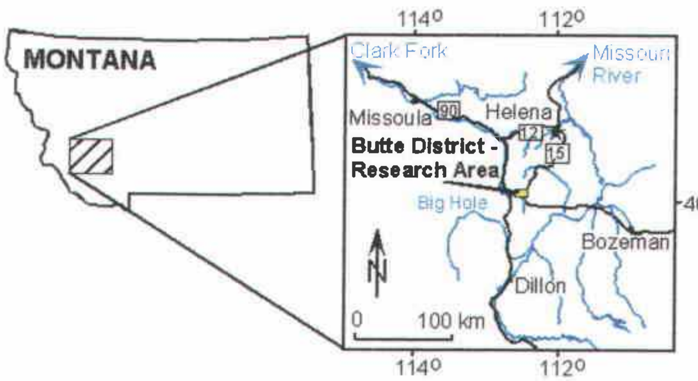
TABLE OF CONTENTS (continued)

LIST OF PLATES

Geology and Structural History of the Butte District, Montana

INTRODUCTION

The Butte porphyry copper-molybdenum and base metal lode deposit is hosted in the late Cretaceous-age Butte Quartz Monzonite (BQM) of the Boulder Batholith, Silver Bow County, Montana.



Location of the Butte district, Montana.

The Butte district is one of the world's largest ore deposits (copper reserves and production greater than 35 million metric tons; Long, 1995) and has been instrumental in building many hypotheses of ore formation (c.f., Weed, 1912; Sales and Meyer, 1948, 1949; Meyer et al., 1968; Miller, 1973). Published and unpublished geologic maps have primarily concentrated on the central parts of the district. These studies include maps of zones of hydrothermal alteration and mineralization. Geological investigations of the peripheral zones and adjacent areas investigated contact relationships and described the Lowland Creek Volcanics Formation (LCV) that disconformably overlie the BQM. Smedes et al. (1962), Smedes (1967, 1968), and Smedes et al. (1988) investigated the distribution of the LCV in the adjacent areas of the district at a scale of 1:48,000, 1:24,000, 1:36,000, and 1:200,000, respectively. Proffett (1973, 1979) and Proffett, J., Burns, G. and others at the Anaconda Minerals Company (unpublished) mapped the LCV and underlying BQM in their geological exploration of the western and northwestern margins of the district (scale: 1:24,000).

Proffett (1973, 1979) and Geissman et al. (1980a, b) proposed contrasting models for style and amount post-mineralization tilting of the district, which this paper addresses. Proffett (1973, 1979) identified 25° to 50° west to northwest tilting of the early Eocene post-ore LCV. Proffett proposed that since no major structural breaks exists between the tilted LCV and the central part of the district, the older underlying BQM and its ores were equally tilted west to northwestward 25° to 50°. In contrast, Geissman et al. (1980a, b) interpreted 5° to 12° northwestward tilting in the center of the district, based on paleomagnetic data obtained on fresh and hydrothermally altered samples of BQM.

This study was undertaken to collect new field data to address the question of the amount and origin of post-ore tilting. New and previous geologic mapping of the Butte district, at a scale of 1:12,000, has been complied as a digital geologic map at 1:24,000 scale (Plate 1). The new field data include, systematic measurements of structural attitudes of aplite sills, description of the LCV stratigraphy, and description of faults and fault offsets. These data reveal that tilting of the LCV and underlying BQM is related to two sets of normal faults one striking northeast, and one striking north-south. Understanding the tilting of the volcanic stratigraphy in relationship to aplite sill orientations is critical to reconstruct the Tertiary geology in the Butte district. These data indicate that the amount of tilting of BQM and host ores varies spatially across the district, from 10° to 50°, generally to the north.

REGIONAL GEOLOGY

The Boulder Batholith crops out over an area of 6,000 km^2 and was shallowly emplaced into the ~80 Ma Elkhorn Mountains Volcanics, Mesozoic to late Proterozoic strata, and Archean metamorphic rocks (Tilling et al., 1968). The Boulder Batholith consists principally of the 76.5 Ma (Martin et al., 1999; Martin and Dilles, 2000; Aleinikoff et al., 2000) BQM and a series of smaller plutons. Cogenetic with and intruded into the BQM are a series of aplite, grano-aplite, and pegmatite dikes and sills. One of these aplites has yield a U/Pb zircon age of 75 Ma (Aleinikoff et al., 2000). A quartz porphyry dike swarm cuts aplites and has yield U/Pb zircon ages ranging from 75$\pm$ 1 Ma to about 65-Ma with a preferred age of 66$\pm$1 Ma (Martin et al., 1999; Aleinikoff et al., 2000; Martin and Dilles, 2000). Emplacement of the quartz porphyry dike swarm is contemporaneous with Pre-Main Stage, porphyry Cu-Mo mineralization and alteration (Roberts, 1973; Brimhall, 1973, 1978; Reed, 1999). One exception is the younger Modoc quartz porphyry plug, which post-dates Pre-Main Stage veins and is cut by polymetallic Cu-Zn-Pb-Ag-As-Mn Main-Stage veins (Proffett, 1973). Main-Stage mineralization and alteration (ca. 62 Ma by $^{40}Ar/^{39}Ar$ on muscovite; Snee et al., 1999) is cut by the east-west trending Mountain View Breccia and associated rhyolite dike (58.8±1.2 Ma by K-Ar on biotite; Martin et al., 1999).

Late Cretaceous to early Tertiary erosion developed a prominent widespread unconformity in the pre Eocene rocks. The 53 to 48 Ma (Dudas et al., 1997; Snee et al., 1999) Lowland Creek Volcanics post-date Main Stage veins and overlie the BQM on the northwest side of the district. The volcanic component comprises six major units, representing a silicic to intermediate volcanic suite that occupies a 2,000 km^2 area north and west of Butte. In the northwest part of the district the Eocene units and all older rocks are now tilted moderately northwestward and are cut by northeast striking, moderately east-dipping normal faults. Younger and larger, north-south striking “Basin and Range” -type normal faults localize fluvial and lacustrine deposits within deep sedimentary basins. Within these basin sedimentary rocks, two major pulses of deposition and associated tectonism are recorded as late Eocene to early Miocene (ca. 37.0 to 20.5-Ma) and middle Miocene (ca. 16.4 to 12.3-Ma) in age (Hanneman and Wideman, 1988).

METHODS

New geologic mapping (at a scale of 1:12,000) of 180 square kilometers describes the complex structural history of the Butte district (Plate 1). Geologic mapping recorded aplite sill and dike orientations in the BQM, the stratigraphic relations of the LCV, and positions and attitudes of faults. All aplite, granoaplite and pegmatite dike and sill-like body orientations identified throughout the Butte district (n=407) were collected and plotted on stereonets, representing twelve structural domains. Eutaxitic foliation of ash-flow tuffs, topographic expression of the geologic contact and primary bedding were used to identify the attitudes of the LCV. Measured sections and cross-sections combined with petrography were used to construct the stratigraphy of the LCV. These new data are compiled with preexisting geological data into a geologic map (1:24,000 scale) of the Butte district (Plate 1). Sources of geologic maps include Proffett, J. Burns, G. and others at the Anaconda Minerals Company (1982 unpublished, 1:12,000); Proffett (1973 at 1:24,000; 1979) Smedes et al. (1962, 1:48,000); Smedes (1967, 1:24,000); and Smedes (1968, 1:36,000) (Plate 1).

ROCK UNITS

Butte Quartz Monzonite and Related Intrusions

The medium-grained Butte hornblende-biotite quartz monzonite forms the oldest unit and most abundant rock unit in the district (Plate 2, Appendix). The BQM is intruded by a suite of increasingly silicic phases. An early mafic dike intruded into the still-plastic BQM and disrupted into nodules (UTM: 5101890mN, 381219mE). Dikes and sill-like bodies of aplite cut the mafic dike. Sill-like bodies of aplite are further referred to as aplite sills.

Aplite, granoaplite, and pegmatite dikes and sills typically have sharp contacts with BQM. However, most granoaplites have gradational margins with the BQM. Aplite sills (up to 15 to 20 m wide) commonly exhibit a sheet-like habit with internal zoning from aplite to granoaplite and pegmatite textures (Meyer et al., 1968) (Plate 3). Black tourmaline and molybdenite were identified in vugs. Additionally, Meyer et al. (1968) documented that pyrite, chalcopyrite, and very rarely pyrrhotite occurs with quartz in core zones in the pegmatite. Sheeted aplite sills are abundant in the western and eastern parts of the Butte district and intrude parallel to subhorizontal joint sets observed throughout the Butte district (UTM: 5095085mN, 388121mE).

Quartz Porphyry Dike Swarm and Mineralization

A steeply south-dipping, east-west-striking quartz porphyry dike swarm cuts aplite sills in the central part of the district (UTM: 5096219mN, 383000mE).

Quartz porphyry dikes are up to 20 m wide and contain ca. 50 vol. percent aplitic groundmass and 50 volume percent phenocrysts of plagioclase, quartz, orthoclase, and biotite (Appendix). Pre-Main Stage, porphyry Cu-Mo mineralization and alteration (Meyer et al., 1968; Brimhall, 1977; Reed et al., 1999) is contemporaneous with the emplacement of the quartz porphyry dikes. Reed (1979a, b) identified a large central zone of pervasively quartz-sericite-pyrite-altered rock that post-dates early porphyry Cu-Mo mineralization. This zone is ca. 1 cubic kilometer in volume and identified by long intercepts in deep drill hole #7 (approximately 1.7 km) and in deep drill hole #1A (Plate 1). The quartz-sericite-pyrite-altered rock is located between two Pre-Main Stage Cu-Mo centers and has partially sericitically altered these centers. The Modoc quartz porphyry apparently cuts the sericitic alteration zones. The famous polymetallic Cu-Zn-Pb-Ag-As-Mn Main-Stage veins cut the Modoc porphyry and occupy a complex set of conjugate faults (see Plate 1 & Proffett, 1973).

Granite Porphyry Dike

An east-west trending, porphyritic rhyolite dike and associated Mountain View breccia, cuts Main-Stage mineralization. From east to west, this dike transects the district for >7 km at depth. Normal displacement along the Continental fault has exposed this dike on Rampart Mountain (UTM: 5098085mN, 386134mE).

Lowland Creek Volcanics Formation

At the type locality approximately 12 km northeast of Butte the Lowland Creek Volcanics are approximately 1,800-m thick (Smedes, 1962). In the northwest part of the Butte district, the LCV stratigraphic section is approximately 700-m thick (Plate 2). Smedes' nomenclature is used, but has been slightly modified as noted below.

Basal Sedimentary and Base Surge Tuff Deposits (Tlt)

The oldest rock unit of the formation was named "basal unit" by Smedes (1962) but here is divided into two subunits. A lower, discontinuous subunit consists of siltstone, sandstone, and pebble conglomerate contains abundant BQM detritus and fluvially reworked volcaniclastic sedimentary rocks. An upper subunit, up to 50-m thick, consists of laminated and cross-bedded crystal-poor ash, interpreted to be a base surge tuff. This basal unit was deposited on an irregular erosional surface, locally marked by deeply weathered BQM (grus) surrounding intensely weathered boulders of BQM and aplite (UTM: 5104550mN, 382100mE). Tuffaceous fluvial sediments contain petrified logs indicating a NNE-SSW bi-directional paleo-flow direction.

Quartz Latite Ash-Flow Tuff (Tlw)

A quartz latite ash-flow tuff (UTM: 5098042mN, 378451mE) containing abundant crystals of plagioclase, quartz, hornblende, and biotite (Appendix) is up to 300-m thick and conformably overlies the basal sedimentary and base surge tuff deposits. Smedes (1962) identified this unit as the “welded tuff”. A vitrophyre up to 30-cm thick locally marks the basal contact. Normal grading of lithic fragments occurs as repeated distinct zones upward in the section. In general, hornblende crystal abundances slightly increase, from 1 to 5 volume percent, upwards in the section. The lower ash-flow tuff likely consists of a single cooling unit, but the incompleteness of exposures permits there to be minor cooling breaks.

Volcanic Breccia (Tllb)

A discontinuous volcanic breccia up to 170-m thick overlies the lower ash-flow tuff and is overlain by dacite lava in the northwest part of the district where it was named the “breccia unit” by Smedes (1962). The volcanic breccia consists of a lower matrix-supported part and an upper clast-supported part. The lower part (up to 50-m thick) consists of subangular (less than 1-m diameter) ash-flow tuff and dacite lava fragments (60 vol. %) supported by a devitrified ash matrix (5101850mN, 375700mE). Hoodoo topography is common in the lower sequence and results from moderate silicification of the matrix around brecciated boulders. Locally, zones altered to opal or celadonite represent areas of low temperature alteration that are erosionally resistant. This lower sequence may represent a volcanic debris flow or lahar.

The upper part (up to 120-m thick) of the breccia unit (UTM: 5101500mN, 377900mE) is dominantly framework-supported angular porphyritic dacite lava boulders (90 vol. %) up to 2 m diameter, that are enclosed in a dacite lava matrix. Smedes (1962) proposed that these breccias represent vent agglomerate. However, field relationships suggest that this upper part is an autobrecciated lava along the base of the overlying dacite lava, described below.

Dacite Lava (Tll)

Porphyritic dacite lava flows, in total up to 120-m thick, overlie the volcanic breccia and the lower ash-flow tuff in the northwest part of the district (UTM: 5103350mN, 376675mE). Incomplete exposures did not allow the identification of individual flows; however, from exposures in the type locality Smedes (1962) estimated that individual flows were 6- to12-m thick. Thicker sections of dacite lava may represent local ponding and subsequent inflation of individual flows. The devitrified groundmass (70 vol. %) contains aligned plagioclase phenocrysts (20 vol. %) that exhibit planar flow layering. Biotite, orthopyroxene, and hornblende phenocrysts typically are altered to epidote, chlorite, and clay minerals. Quartz is a sparse phenocryst.

Rhyolite Ash-Flow Tuff (Tlu)

A moderately to densely welded rhyolite ash-flow tuff overlies the dacite lava unit and the Big Butte vent complex in the northwest and western parts of the district (UTM: 5101804mN, 377158mE). This unit is at least 50-m thick and marks the upper most exposures of the LCV in the Butte district. This crystal-rich lapilli ash-flow tuff contains approximately 25 to 35 volume percent crystals (Appendix, up to 3-mm in dia.) of shattered oligoclase-andesine, quartz, biotite, and sanidine. West of Big Butte, a local lithic-rich basal vitrophyre, up to ~5-m thick, grades upward into a densely welded ash-flow tuff (UTM: 5097951mN, 377768mE). The fiammé have an aspect ratio of approximately 6H:1V and are circular in plan view, suggesting simple compaction. The upper ash-flow tuff is petrographically similar to the vent facies tuff described below. In the northwest part of the district, the occurrence of several vitrophyres, up to 5-m thick, suggest multiple cooling units. Smedes (1962) named this the "upper lava unit" and interpreted it as extrusive lava, but field and petrographic criteria reported here indicate the unit is an ash-flow tuff. The tuff is probably correlative with a similar ash-flow tuff described by Frank Dudas (personal communication, 2000) in the upper part of the LCV from exposures south of Anaconda, Montana.

Big Butte Vent Complex

The Big Butte Vent Complex comprises vent facies tuff, breccia, and rhyolite dikes that extends approximately 3.5 km west-northwest from Big Butte to the Rocker Fault (UTM: 5097180mN, 379400mE). Northwest of Big Butte, within the Big Butte Vent Complex, the upper ash-flow tuff overlies rocks of the vent complex.

Vent Facies Tuff (Tiv)

Moderately welded crystal-rich rhyolite tuff contains shattered crystals of quartz, oligoclase-andesine, sanidine, and biotite (up to 3 mm dia.). Post-emplacement compaction partly bent biotite crystals around feldspar and quartz crystal fragments. A vertically lineated fabric is defined by elongation of cognate rhyolite clasts (up to 20 vol. percent) is common throughout the vent-facies tuff. Minor amounts of fiamme are partially flattened (2H:1V to 1.5V aspect ratio) and are orientated parallel to the vertical fabric.

Vent Volcanic Breccia (Tivb, Titb, Ticb, Tiab)

Four types of breccias are associated with the Big Butte vent complex. The first type is vent wall breccia (Tivb) that occurs locally in zones up to 360-m long and 50-m wide at the contact of the vent facies tuff with the BQM (UTM: 5098042mN, 378835mE). Fragments in this breccia (up to 20 cm in diameter and up to 75-vol. %) consist of BQM, aplite, and vent facies tuff enclosed in a matrix of ash and crystal fragments of quartz, plagioclase, sanidine, and biotite. The percentage of BQM and aplite fragments decreases away from the BQM contact, whereas the percentage of brecciated rhyolitic tuff fragments increases toward the main body of the vent facies tuff.

Exposed on the southern flanks of Big Butte (UTM: 5096914mN, 379390mE), the second breccia type consists of entirely welded vent facies tuff fragments (Titb) surrounded by a matrix of similar vent facies tuff. This breccia may represent a previously erupted, welded ash-flow tuff that slumped back into the vent during a later eruption, or alternatively, could represent the brecciation of the vent-wall tuff during a later rhyolitic eruption (Dresser, 2000).

The third type of breccia is exposed on the southeastern flanks of Big Butte, at the Park Street railroad cut (UTM: 5096365mN, 379707mE). This vent-collapse breccia (Ticb) contains blocks, greater than 50 m in diameter, of the lower (hornblende-bearing) quartz latite ash-flow tuff of the LCV. A block of lower ash-flow tuff is cut by tuffasite dikes (Dresser, 2000) and surrounded by vent-facies tuff and vent-wall breccia. Smedes et al. (1973) and Proffett (1973) proposed that these ignimbrite exposures were in-place, and downdropped along an east-dipping normal fault that was later intruded by the Big Butte intrusive. However, no fault offsets or truncations of any veins or aplites in the BQM were identified in association with these mega-lithic ash-flow tuff breccia fragments. Additionally, the eutaxitic texture in the mega-lithic block strikes northwest and dips approximately 20° southwest. This orientation is dissimilar from all other eutaxitic fabric orientations throughout the district and cannot be explained by any local faulting. At other locations within the vent complex, vent facies tuff surrounds blocks of dacite lava, similar to the dacite lava unit in the northwest part of the district. The hypothesis advocated here is that breccia with both lower ash-flow tuff and dacite lava clasts formed by collapse of the lower LCV units into the vent complex during eruption of the vent facies tuffs.

The fourth type of breccia is an autobrecciated dacite lava (Tiab). Fragmented dacitic lava clasts, up to 10 cm in diameter, are enclosed in a matrix of smaller fragments of dacite lava. The fragmented clasts and matrix both contain euhedral plagioclase, biotite, hornblende, and quartz.

Rhyolite Dikes (Ti)

Several steeply dipping porphyritic rhyolite dikes (UTM: 5095329mN, 379390mE), up to 60 meters wide, intrude the BQM south of Big Butte and along strike intrude into the vent facies tuffs at the southeast end of the Big Butte vent complex. These dikes exhibit chilled margins with a lineated flow foliation parallel to the intrusive contacts. North-south striking dikes cut the east-west striking rhyolite dike in the subsurface mine exposures and represent the youngest rocks related to the LCV (Meyer et al., 1968). Rhyolite dikes intrude all unit of the LCV.

Late Eocene to Miocene Sedimentary Deposits (Toa)

Large north-south striking, steeply west-dipping Basin-and-Range type normal faults have localized syn-tectonic sedimentary basins in their hanging walls. Hanneman et al. (1985) identified two fluvial-lacustrine depositional sequences separated by a mid-Tertiary angular unconformity in the ~180-m-thick Rocker basin sedimentary deposit, located west of the Rocker Fault (Plate 1). The lower sequence consists of tuffaceous mudstone and sandstone with minor conglomerate interbeds; the upper sequence consists of tuffaceous mudstone, coarse-grained sandstone, and local pebble conglomerate channel deposits (Hanneman and Wideman, 1988). Smedes (1967) identified gently to moderately tilted (up to 26°E), basin fill sedimentary rocks (Toa) in the hanging wall of the Rocker Fault. These late-Eocene to early-Miocene age rocks contain fossil camel, rhinoceros, horse, and oreodont teeth and bones (Smedes et al., 1973). Similar depositional sequences occur in the adjacent Butte basin (estimated at 100 m thick between the Continental and Berkeley pits by Ratcliff (1973), and thickening southward) lying west of the Continental Fault, and in the Elk Park basin, lying east of the Klepper fault located northeast of Butte. Colluvium deposits occur along the flanks of Rampart Mountain and East Ridge and correlate to Basin and Range type faulting.

Quaternary Sedimentary Deposits (Qal)

Unconsolidated sand and gravel form the uppermost deposits in the Butte and Elk Park basins, and extend along Silver Bow Creek and its tributaries along the flanks of Butte hill.

STRUCTURE

Pre-Main Stage Mineralization

Early, disseminated porphyry Cu-Mo mineralization in the Butte district has been called the Pre-Main Stage (Meyer, 1965; Meyer et al., 1968) to distinguish it from the younger, larger Main Stage polymetallic vein mineralization. The Pre-Main Stage mineralization is exposed at the surface in the Continental area, where it has been mined. West of the Continental fault it is downdropped to a depth of more than 500 m below the surface and extending to more than 2 km depth (Reed, 1999).

Two Pre-Main Stage porphyry Cu-Mo domes are concentrically zoned into broadly overlapping shells of centimeter-scale stockwork veinlets. The western Anaconda and eastern Pittsmont domes together form a body about 4 km long east-west by 1.5 km wide prior to offset by the Continental Fault. West of the Continental fault, on the 3,400 and 4,000 levels of the Steward mine, Reed (1979a, b) identified steeply south-dipping, approximately east-west striking, biotite crackle veinlet swarms with a 5 m spacing and a density of 0.4 to 2 per cm over a 5 cm interval. East of the Continental Pit in exposures along highway I-15, the density of early biotite crackle and Cu-Fe sulfide veinlets has decreased to 0.1 to 0.3 per cm. Here, the average strike and dip of the biotite crackle veinlets is N86°E and 73°S, n=14.

Biotite crackle veinlets strike parallel to the synchronous (ca. 66 Ma) quartz porphyry dikes, which strike between N75°W and S80°W (Reed, 1999). These data suggest that emplacement of both dikes and Pre-Main Stage veinlets formed during a stress field where the least principal stress (σ_3) was oriented north-south (Dilles et al., 1999; M.H. Reed, 2000, personal communication). The paleo-stress regime during the Pre-Main Stage was likely σ_1 vertical, σ_2 east-west, and σ_3 north-south.

Main Stage Mineralization and Faulting

Main Stage mineralization forms a large vein network (Anaconda and Blue vein systems) that extends 10 km east-west by 5 km north-south and to depths of ca. 2 km below the center of the district. The east-west striking, steeply north to south dipping, Steward vein of the Anaconda vein system, obliquely right-laterally offsets, Pre-Main Stage biotite crackle veinlets, 33 m north-side-down, at a rake of 35° eastward (Proffett, 1973). Proffett (1973) used the occasional occurrence of en-echelon gaps along the Steward vein, as evidence that the Anaconda system occurred as shear fractures.

Lyden (1925), Hart (1935), and Proffett (1973) showed that the Blue vein system commonly passes through en-echelon gaps in east-west striking Anaconda-age veins. However, Proffett (1973) recognized the majority of fault displacements occurred as pre- and syn-mineralization in both vein systems, with minor post-ore faulting occurring in a similar direction. Proffett concluded that the Anaconda and Blue vein systems represents a synchronous set of conjugate shears. Thus, the Anaconda and Blue vein/fault system accommodated north-south extension through normal displacement, and east-west shortening by strike-slip displacement. The paleo-stress regime during the Main Stage that produced these displacements suggests the major and intermediate principal stresses (σ_1, σ_2) were nearly equal and oriented vertical and ca. east-west. The least principal stress (σ_3) direction was ca. north-south. Thus, Main Stage mineralization and faulting likely developed under a stress field similar to the earlier, Pre-Main Stage veinlets and quartz porphyry dike swarm patterns.

Northeast Striking Normal Faults

Northeast-striking faults represent the oldest normal faults recognized in the district. Northeast-striking, moderately (29° to 35°) east-dipping faults offset the LCV and Main-Stage veins in the northwestern part of the district. The faults form a parallel set within a zone approximately 1 km wide with individual faults spaced at 300 to 600 m. The amount of normal displacement decreases to the southeast from ~800 m to ~100 m along these faults (Plate 1, 4, and 5). Similarly, the amount of northwest tilting in the LCV decreases to the southeast. Tilting of the LCV in the northwest part of the district is here interpreted to be a result of "domino-style" block rotation between closely-spaced normal faults (Proffett, 1973, 1977). Additionally, the tilt of volcanics diminishes to the southeast as the number and spacing of faults decrease (Plate 4). Assuming pure dip-slip normal displacement, the paleo-stress regime of the post-LCV, northeast-striking normal faults was σ_1 vertical, σ_2 northeast-southwest, and σ_3 northwest-southeast. Structural reconstruction of the tilted LCV units do not require a significant amount of strike-slip motion. Therefore, moderate northwest tilting in the northwest part of the district developed under a stress field, different from the earlier quartz porphyry dike swarm patterns, Pre-Main Stage veinlets, and Main-Stage veins.

The Rarus and Milwaukee normal faults and faults 1, 2, and 3 (Plate 1 & 4) also strike northeast but dip to the northwest. The Rarus fault, located in the central part of the district, consist of bifurcating fault traces with gouge zone, up to 15 m wide (Meyer et al., 1968). The fault strikes approximately N45°E, and dips 45° westward. Sales (1914) documented up to 105 m of normal dip-slip movement of Main Stage vein systems. The steeply (~70°) west-dipping Milwaukee fault is located just west of Big Butte. Meyer et al. (1968) identified a rhyolite dike that showed approximately 200 m, down to the west of normal displacement across the fault ~500 m south of the Big Butte vent contact. The strike separation of the N25°W striking, 35° northeast-dipping southern contact of the Big Butte vent complex is 760 m (Plate 1). The strike separation of the northern vent complex contact is approximately 150 m. The intersection of the contact with topography suggests the northern contact strikes east-west and dips steeply southward. Therefore, the approximate amount of normal displacement calculated on the Milwaukee fault is 500 m. Sales (1914) and Meyer et al., (1968) observed normal dip-slip displacement, which demonstrates that strike-slip motion is not present or is unimportant on the Rarus and Milwaukee faults.

Basin and Range Type Normal Faults

The Rocker fault on the west and the Continental, Klepper and East Ridge faults on the eastern side of the district are all large, north-south striking, steeply dipping, Basin and Range type normal faults. Hanneman and Wideman (1988) correlated basin-fill sediments to two major pulses of tectonism associated with the Basin and Range type normal faults. Based on vertebrate material collected from the Rocker basin (~4 km southeast of Big Butte), Hanneman et al. (1985) suggested the lower sequence ranges in age from Chadronian to Arikareean (ca. 37.0 to 20.5 Ma). Fossil mammalian material indicates a Barstovian age (ca. 16.4 to 12.3 Ma) for the upper sequence of sedimentary rocks (Hanneman et al., 1985).

The Continental fault dips approximately 80° westward (Plate 1) and is exposed in the north wall of the Continental Pit. Steve Czehura (personal communication, 1999) has identified nine splays in a 30 to 95 m wide fault zone consisting of fault gouge and brecciated rock fragments. In the central part of the district, Reed (1979a, b) compared Cu-Mo grades and high temperature alteration in zones in the Continental area with the offset equivalent in the Pittsmont area to the west, and estimated 1,100 to 1,400 m of normal displacement on the Continental fault. Meyer et al. (1968) suggested that the lack of significant lateral offset of the quartz porphyry and rhyolite dikes, supported that the movement on the Continental fault must be largely dip-slip. West of the Continental fault, the east-west striking 58.8 ± 1.2 Ma rhyolite dike pinches-out upward at about the 2000 level of the Steward shaft, an elevation of

1,170 m (Proffett, 1973). However, this dike is exposed at the surface on Rampart Mountain at an elevation of 2200 m. This difference provides a minimum normal offset of 1 km, supporting Reed's displacement estimate. The scarp on the Continental fault is larger north of the Continental Pit and is smaller south of the pit. South of the pit the total topographic relief across the accumulative Continental, Klepper and East Ridge faults increases to the south, this indicates great total displacement.

East of the Continental fault, the steeply (~85°) east-dipping, north-south striking Klepper fault, offsets a rhyolite and two quartz porphyry dikes (Ratcliff, 1973). The right-lateral strike separation of the steeply north-dipping (~85°) rhyolite dike is 720 m (Plate 1). The quartz porphyry dikes have a similar strike separation. Reconstruction of the strike separation combined with 1.1 km dip-slip offset based on hornblende barometry data (Dilles et al., 1999) yields an estimated 2.1 km of normal right oblique-slip motion along the Klepper fault.

East of the Klepper fault, the moderately (~60°) west-dipping north-south striking East Ridge fault (UTM: 5095180mN, 387120mE), left-laterally displaces steeply south-dipping quartz porphyry dikes approximately 50 m. Poor resolution between the hornblende barometry data, on either side of the fault, provides no estimate of dip-slip offset.

The Rocker fault dips approximately 80° to 90° west, and bounds the western side of the Butte district. An east-west seismic reflection profile across the Rocker fault, at the Rocker Timber Framing Treatment Plant Operable Unit, near Rocker, identified the contact between the basin-fill sedimentary rocks and the

BQM at 210 ms (Hammar-Klose, 1997). Depending on the density and velocity of these sedimentary rocks, the calculated thickness based on the seismic data for basin-fill sedimentary rocks in the hanging wall of the fault is approximately 180 to 300 m (Debra Hanneman, personal communication, 2001). Additionally, based on greater topographic relief across the fault, displacement increases southward of the town of Rocker.

D. Hanneman (personal communication, 2001) stated that the location of the Rocker fault is in the central part of the Rocker basin, west of the town of Rocker and that the topographic escarpment, just east of the town of Rocker, represents paleotopography that is partly filled with basin sediments. If the escarpment represents paleo-topography, then from west to east the attitudes in the basin-fill sediments would be horizontal then become inclined westward adjacent to the escarpment. However, Smedes (1967) showed that attitudes of the basin-fill sedimentary rocks increase eastward from 10° to 20° toward the escarpment. This increase tilt is typical of increased rotation of the hanging wall proximal to listric or concave upward normal faults (cf., Proffett, 1977). Therefore, Smedes (1967) observations support the interpretation that the Rocker fault is located east of the town of Rocker and traces southward along the north-south trending topographic escarpment (Plate 1, Figure 2).

The north-south striking, west-dipping No. 15 fault, located just east of Big Butte may have as much as 600 meters of normal displacement (Meyer et al., 1968; Proffett, 1973). Rhyolite intrusions along the fault indicate this is a pre-50 Ma fault, but offset of rhyolite dikes indicate some younger displacement (Meyer et al., 1968). It remains unclear whether the reactivation of the No. 15 fault is associated with the older, northeast oriented or younger Basin and Range type normal faulting.

The paleo-stress regime during Basin and Range type faulting was σ_1 vertical, σ_2 north-south, and σ_3 east-west. This stress field is significantly different from the field responsible for earlier faulting, and represents a shift to the regional stress field typical of Basin and Range extension since 15 Ma (Zoback et al., 1981).

Attitude of Eutaxititc Foliation in the Lowland Creek Volcanics

Both attitudes of eutaxitic foliation of ash-flow tuffs and sedimentary bedding in the LCV apparently accurately record similar amounts of moderate northwest tilting of the LCV in the northwest part of the district. At Butte, exposures of eutaxitic compaction foliation in the lower ash-flow tuff are similar to the immediately underlying bedding attitudes of sedimentary rocks (Plate 1). Additionally, compaction foliation attitudes remain consistent throughout individual fault blocks. The eutaxitic foliation is here interpreted to accurately (within 5°) record primary paleo-horizontal, despite documentation (Cas and Wright, 1995) that compaction foliation in welded ash-flow tuffs may partly mantle topography. The consistency of compaction foliation orientations within individual fault blocks suggests the paleo-topography prior to the emplacement of the lower ash-flow tuff was relatively minor. Moreover, the lower ash-flow tuff does not appear to have been deposited on steep topography or within canyons based on relatively uniform thickness of the unit and gradual changes in thickness across the district.

Slight differences of eutaxitic foliation attitudes in adjacent fault-blocks reflect different amount of block rotation particularly associated with the northeast-striking, southeast-dipping normal faults. Overall, primary bedding attitudes and compaction foliation together (n=109) suggest that the northwest part of the district is tilted in amounts ranging from 10° to 50° northwestward (Plate 1 & 4). Steeper attitudes were observed adjacent intrusive contacts and faults.

Attitudes of Aplite Sills Across The District

Orientation of sheeted sill-like bodies has been used to determine approximate paleohorizontal during crystallization of BQM at 7 to 9 km depth at ~76 ma. During crystallization of BQM at 7 to 9 km depth, ~76 ma, σ_1 should be perpendicular to the earth surface and would be near-vertical even with up to 1 km topographic relief over 5 km horizontal. Crystallization of BQM magma would have produced contraction joints allowing aplites to fill planar tensile fractures. At ~76 Ma, east-west shortening from the Laramide fold and thrust belt suggest σ_1 was approximately east-west and σ_2 or σ_3 were vertical.

Poles to planar contacts of 407 aplite dikes and sills were collected throughout the district, and grouped on basis of fault boundaries into twelve structural domains. The aplite dikes and sills are plotted on stereonet diagrams using the computer code of Allmendinger (1995) (Plate 6). In the northwest part of the district, attitudes of sheeted aplite sills, immediately underlying northwest-tilted LCV (average attitude: N55°E, 35°NW), have an average strike of N86°E and dip of 34°NW (n=11). Southeastward across the district, the attitudes of sheeted aplite sills strike between N68°E and S58°E and dip from 9° to 14°N (n=276). One exception is in the central part of the district where aplite sill orientations average N5°E, 14°E (n=49). In the central part of the district and just west of the Continental Fault, exposures are very limited due to cover by the Yankee Doodle Tailings Pond, Tertiary basin-fill sedimentary rocks, or restricted access (the Berkeley Pit). Sheeted aplite sills west of Big Butte, collectively strike N35°E to S76°E and dip 14° to 37°N (n=67). South of Butte, Smedes (1962) documented N25°W striking sheeted aplite sills that dip 20° to 25°E in exposures around Timber Butte, (Plate 1 & 6). Assuming that the sill-like aplite sheets were originally emplaced in subhorizontal ($\pm$5) position, as discussed below, the total amount of tilting of the BQM and aplites can be inferred form the present attitudes of the aplite sheets.

Structural contours on the base of the LCV and a second set of contours on the aplite sills (datum in BQM provided by hornblende barometry with error of ca. $\pm$1 km; Dilles et al., 1999) illustrate that the BQM and aplites were tilted prior to deposition of the LCV (Plate 7). Because the amount of northwest tilting diminishes southeastward across the district, due to decrease in numbers of northeast-striking normal faults only the aplite sills immediately underlying the LCV are here restored to remove the amount of tilting post-dating the LCV. Restoration of aplite in structural domains A and B prior to moderately northwest tilting observed in the northwest part of the district yield aplite orientations prior to post-LCV tilting (Figure 8). The orientation of restored aplite sills in structural domains A (N10°W/18°NE) and B (N28°W/18°NE) have gentle northeastward tilts, similar to aplite sill orientations southeastward across the district (Plate 6 & 8).

DISCUSSION

Proffett Hypothesis

Proffett (1973) proposed that the moderately tilted LCV overlie mineralized veins and older BQM unconformably in the northwest part of the district. Because there are no major structural breaks between the tilted LCV and the central part of the district, Proffett (1973) concluded that the entire district is tilted 25° to 50° to the west or northwest. In Proffett's (1979) cross section, an average tilt of 25° west was used to illustrate that the current disturbance of Main-Stage alteration zoning could be due post-mineral tilting.

Geissman Hypothesis

To test Proffett's hypothesis that the entire district is tilted west or northwestward, Geissman et al. (1980a, b) collected and compared paleomagnetic directions from exposures of BQM and LCV. Within the Butte district, samples were grouped into five large structural domains that are demonstrably individually and internally structurally diverse based on recent geologic mapping. Geissman et al. (1980b) did not label individual sampling sites but rather showed sampling areas (greater than 5 sq. km in area) on his sample location map, making it impossible to re-interpret in detail the paleomagnetic data of smaller individual fault block domains distinguished in this study. Based on four BQM sampling sites in the northwest part of the district, Geissman et al. concluded that the "paleomagnetic data from the BQM exposed immediately to the east dictate that the tilting in the Eocene units cannot be attributed to an equal amount of BQM movement in the district" (Geissman et al., 1980b, p. 156). Therefore, Geissman et al. (1980a, b) suggested the 30° to 50° of northwestward tilting in the LCV may in part be controlled by paleotopography, differential compaction, localized fault block rotations of less than 15° and minor 5° to 17° regional northwestward tilting of the entire BQM, perhaps overthrusting of the Idaho batholith. These four BQM samples were collected just east of and parallel to a series of northeast striking, moderately east-dipping normal faults in the northwest part of the district (sites G1, G2, G3, G4, Plate 4). The amount of northwest tilting progressively decreases southeastward across each of the northeast striking faults. The paleomagnetic sampling site locations do not fully represent the complex faulting and block rotation history identified in the northwest part of the district. Specifically, exposures of BQM that likely represent greatest tilting in the district immediately underlying the 40° to 47° northwest tilted basal sedimentary unit of the LCV, and lying between two northeast-striking normal faults, were not sampled (Plate 6, structural domain A). Geissman et al. (1980a, b) also concluded that the central part of the district has not been significantly tilted and suggested that the minor, 5° to 17° northwestward tilting may be related to a more regional tectonism.

Tilting of the District

The field data collected in this and Proffett's (1973, 1979) studies and the paleomagnetic data of Dilles et al. (1999) can be integrated into a tilt history of the Butte district that has three deformational periods: 1) Post-mineralization and Pre-LCV gentle NE tilt; 2) NW tilt of LCV and BQM related to NE-striking normal faults in the northwest part of the district, and 3) minor (<10) of east or west tilt related to young north-south striking Basin and Range type normal faults.

Based on aplite attitudes Geissman et al. (1980a, b) suggested that moderate northwest tilting in the LCV reflects local fault block rotation about a horizontal axis of less than 15° and minor 5° to 17° regional northwest tilting of the entire district. Geissman et al. (1980a, b) added that paleotopography, topographic mantling, and differential compaction of the tuffs produced non-horizontal compaction foliations that might locally exaggerate the degree to which the LCV have been tilted northwestward. However, data in this study indicate that the compaction foliation is concordant ±5° with attitudes in the underlying basal sedimentary unit. Paleotopography and differential compaction produced little (less than 5°) deflection in eutaxitic foliation attitudes within each fault block. Therefore, 10° to 50° northwestward tilting of the LCV resulted from local fault block rotations associated with northeast-striking, moderate southeast-dipping normal faults in the northwest part of the district.

Therefore, the discrepancy between greater northwest-tilting of LCV as indicated by structural attitudes and lesser northwest-tilted based on paleomagnetic data is partly explained by paleomagnetic sampling secondly, as noted above, structural data collected for this study from the LCV are internally consistent and suggest that they are accurate and not affected by paleotopography, differential compaction, and local fault block rotations. Instead, the different structural tilts between LCV and BQM observed by Geissman et al. (1980 a, b) and this study are adequately explained by minor amounts of pre-LCV north and northeast tilting.

In the central and eastern parts of the district, Geissman et al. (1980a, b) proposed that regional tectonism, involving minor 5° to 17° northwest tilting, produced a rough coincidence between the mean BQM paleomagnetic directions and other regionally Late Cretaceous units. This interpretation is supported by mean orientations of 287 sheeted sill-like bodies of aplite identified in the regions east of the Continental fault, north of the Yankee Doodle tailing pond and in the northwest part of the district. However, the mean orientations of 49 sheeted aplite sills from the central part of the district, excluding the area around the Berkeley Pit for lack of access, exhibit a gentle 14° eastward tilt. Smedes (1967) also documented a gentle 20° to 25° eastward tilt of sheeted aplite sills exposed on Timber Butte south of Butte. These aplite sill data combined with southward thickening basin sediments and greater topographic relief across the Continental- Klepper- East Ridge fault systems, suggest that the amount of eastward rotation increases southward in the hanging wall of the Continental-

East Ridge faults. Aplite sills exposed west of Big Butte are gently to moderately tilted northwestward. Combined, the aplite sill data generally indicate gentle (10° to 15°) northeast tilting of BQM and describe a broad, gently northeastward plunging antiform through the central part of the district (Plate 7).

A basic assumption that is consistent with structural geology theory and local observations is that sill-like bodies of aplite must have been emplaced as nearly horizontal bodies across the entire district. Emplacement of the BQM and aplite sills occurred at a paleo-depth of 7- to 9-km (Dilles et al., 1999). Therefore the surface topography at this time would have had little influence on the orientation of the principal stress direction that must be perpendicular to the upper (free) surface of the earth. During emplacement of the sheeted aplite sills, one of the principal stresses, most likely σ_3, would have been vertical (Schmidt, et al., 1990). In exposures along the I-90 roadcut west of Butte, a 3- to 9-cm wide aplite dike intruded along a preexisting vertical joint, then intruded and pinched out along a subhorizontal joint in the BQM. This observation supports that emplacement of the large sill-like sheeted aplites were mainly controlled by the widespread subhorizontal joint sets in the BQM. Therefore, aplite sill orientations represent paleo-horizontal at the time of emplacement and could be used as a proxy for a tilt (strain) marker throughout the district.

Consistent with Proffett's interpretation, northwest of Butte, block rotation along the northeast trending faults moderately tilted bedding planes in the LCV northwestward (an average of N55°E, 35°NW). These tilted micaceous siltstone and mudstone laminations, immediately overlie eleven moderately tilted sheeted aplite sills (N86°E, 34°N; Domain A, Plate 6). By restoring the orientation of the aplite sills in the northwest part of the district, prior to northwest tilting, the aplite sills become gently tilted northeastward (N10°W, 18°NE) (Plate 8). The restored orientation of the aplite sills is similar to the orientation of the sheeted aplite sills southeastward across the district (Plate 6). These observations support the interpretation that the district was gently tilted northeastward prior to deposition of the LCV.

Inferred Tilt of Copper Ores

The Pre-Main Stage mineralization consist of east-west striking, steeply south-dipping quartz porphyry dikes and biotite crackle veinlets. Main-Stage mineralization consists of two conjugate shear fault sets. Multiple, large, east-west striking, steeply south-dipping veins comprise the Anaconda systems. Numerous, northwest-southeast striking, steeply to moderately south dipping veins characterize the Blue vein system. Structural readjustments and accommodation may have tilted the Main-Stage fault blocks and aplite sills gently northeastward throughout the district. The stress field that is required for this northward tilt/accommodation is consistent with the paleo-stress regime of the Blue vein system of Main-Stage mineralization (σ_3 north northeast-south southwest). The gentle northeastward tilt of the district may be related to faulting associated with Main-Stage mineralization. However, Geissman et al (1980a, b) suggested that the gentle northward tilt of the central part of the district may be related to a more regional northward tilt of the entire Boulder Batholith.

The 59 Ma old, east-west striking rhyolite dike and associated Mountain View breccia cuts Main-Stage mineralization. Meyer et al. (1968) observed that the dike contacts are nearly vertical west of the Continental fault. East of the Continental Fault, on Rampart Mountain, dike contacts dip steeply (~85°N) northward. Therefore, the rhyolite dike likely was emplaced after the district was tilted 10° to 15° northeastward. Thus, supporting northeast tilting may have occurred during Main Stage mineralization (62 Ma) or between 62 and 59 Ma.

By restoring the central part of the district prior to the gentle northeast tilting, documented by the aplite sill orientation, the biotite crackle veinlets, quartz porphyry dikes, and zonal patterns of Pre-Main Stage mineralization-hydrothermal alteration become near-vertical. This vertical orientation is generally consistent with other porphyry copper deposit emplacement models (c.f., Dilles, 1987). Note that most of the restored Main Stage veins and faults dip between 55° and 75° south. Thus, these faults remain oblique-slip normal faults, which may have accommodated the 10° to 15° of north to northeastward rotation.

Big Butte Vent Complex

Smedes et al. (1973), Proffett (1973), and Dresser (2000) described these rocks as dikes, lavas, and extrusive tuffs. West of Big Butte, Smedes (1973) used a north-south gravity profile across the vent complex to suggest that more than 350-m of welded tuffs and lavas were down-dropped into a northwest-southeast trending graben. Based on field relations, Proffett (1973) suggested that the Big Butte area is a large flow-banded intrusive complex equivalent to some of the local welded tuffs. Dresser proposed that Big Butte "formed as magma rose through the conduit to emerge as ash-flows or lava flows" (Dresser, 2000, p. 3). Dresser hypothesized "that ground water entered the magma chamber to produce explosions that fragmented the crystal rich magma before it rose through the newly created vent to emerge first as ash flows and then as lava flows" (Dresser, 2000, p. 3).

Field observations supported by petrographic interpretations suggest that the area around Big Butte represents a tilted rhyolitic intra-vent complex. The vent facies rhyolite tuff is exposed on top of Big Butte and extends northwest to the Rocker fault. The ca. 52 Ma vent facies tuff post dates the ca. 53 Ma lower ash-flow tuff, and predates the ca. 52 Ma upper ash-flow tuff (F. Dudas, personal communication, 2000). Additionally, the vertical foliated, crystal-rich vent facies tuff is petrographically identical to the upper rhyolite ash-flow tuff.

Exposures of aplite sills west of Big Butte suggest that this area is gently tilted 16° northwestward. Therefore, paleo-depth increases southeastward along the Big Butte Complex so that over the 3 km length of the complex there is between 0.9 and 1.8 km of structural relief. The contacts of the Big Butte vent complex narrow to the southeast where the vent is intruded by several rhyolite dikes. Additionally, vent wall breccia is exposed along the northern and southern contacts. Contrary to Smedes' graben filled model, these observations described an oblique view of a funnel shaped vent complex that is gently tilted northwestward, consistent with Proffett and Dresser's interpretations.

CONCLUSIONS

New structural and field data support a hypothesis that the amount of post-ore tilting varies spatially across the Butte district. In the northwest part of the district, the LCV and underlying BQM are tilted 10° to 50° northwestward due to rotation along northeast-striking southeast-dipping normal faults. These northeast-striking normal faults exhibit diminishing amounts of northwest tilting southwestward along the faults and successively decreasing amounts of block rotation southeastward, perpendicular to the faults. Other northeast-striking normal faults with northwest dips occur sparsely in the western and central parts of the district. Large north-south striking Basin and Range type normal faults cut the northeast-striking normal faults. Thickening of Cenozoic basin-fill sedimentary deposits and greater topographic relief across the Continental-East Ridge fault system and the Rocker fault, suggest that the amount of eastward rotation and displacement in the hanging wall of the faults increase southward.

Sill-like sheeted bodies of aplite, granoaplite, and pegmatite cogenetic with the 76 Ma BQM record total cumulative tilt of the BQM and host ores across the district. A 15° angular discordance between the attitudes of aplite sills and the LCV was identified in the northwest part of the district. Restoration of the LCV to horizontal produces a gentle northeastward tilt of the aplite sills similar to the 10° to 15° northeast dips of sheeted aplite sills southeastward across the northern, central, and eastern parts of the district. Aplite sills exposed west of Big Butte are gently to moderately tilted northwestward. Aplite sills in the central part of the district exhibit a gentle 14° eastward tilt. South of Butte, sheeted aplite sill exposures on Timber Butte are tilted moderately 20° to 25° eastward.

Analysis of this data identified three episodes of tilting that has tilted different parts of the district in differing amounts supporting both Proffett's (1973, 1979) and Geissman et al.'s (1980a & b) geologic data (Plate 9 and 10). The first episode of tilting gently rotated the district 10° to 15° northeast, perhaps related to overthrusting during the Laramide orogeny. The second episode of tilting rotated the northwest part of the district 10° to 50° northwestward related to post- (48 to 53 Ma) LCV northeast-striking normal faults. The third episode of tilting gently rotated the hangingwall of the Continental fault <10° eastward during Basin and Range Type normal faulting.

By restoring the district prior to these three episodes of tilting, the orientation of the quartz porphyry dikes, Pre-Main Stage veinlets, and Pre-Main Stage zonal patterns of mineralization-hydrothermal alteration in the central part of the Butte district become vertical (Plate 10). This vertical emplacement model of the, Butte porphyry Cu-Mo system is consistent with emplacement models from other porphyry copper deposits.

REFERENCES CITED

Aleinikoff, J.N., Kunk, M.J., Lund, K., Unruh, D.M., Hodges, W.C., and Du Bray, E.A., 2000, Shrimp U-PB and 40AR/39AR age constraints for timing of mineralization in the Boulder Batholith, Montana: Geological Society of America, abstracts, National meeting, v. 32, A112.

Allmendinger, R. (Copyright 1988-1995), Stereonet, version 4.9, Cornell University, Ithaca, New York.

Brimhall, G. H., Jr., 1973, Mineralogy, texture, and chemistry of early wall rock alteration in the deep underground mines and continental area, Butte District, Montana: in *Miller*, R. N., ed., Guidebook for the Butte field meeting of the Society of Economic Geologists, The Anaconda Company, Butte, Montana, p. H-1 to H-5.

Brimhall, G. H., Jr., 1977, Early fracture-controlled disseminated mineralization at Butte, Montana: Economic Geology, v. 72, p. 37-59.

Brimhall, G. H., Jr., 1978, Mechanisms of vein formation at Butte, Montana: element recycling by hypogene leaching and enrichment of low-grade K-silicate protore: Economic Geology, v. 73, p. 1389.

Cas and Wright, 1995, Volcanic Successions-modern and ancient: Chapman and Hall, London, 528 p.

Czehura, S., 1999, personal communication, Montana Resources, Inc., Butte, Montana.

Dilles J.H., 1987, Petrology of the Yerington batholith, Nevada: evidence for the evolution of porphyry copper ore fluids: Economic Geology, v. 82, no. 11, p. 1750-1789.

Dilles, J.H., Reed, M.H., Roberts, S., Zhang, L., Houston, R., 1999, Early magmatic-hydrothermal features related to porphyry copper mineralization at Butte, Montana: Geological Society of America, abstracts, National meeting, v. 31, A380.

Dresser, H., 2000, Stereo Picture Guidebook to Big Butte Volcanics: Field Trip 3: Walking tour of Big Butte and Whiskey Gulch, Tobacco Root Geological Society meeting, Butte, Montana, 73 p.

Dudas, F. O. and Ispolatov, V. O., 1997, Neodymium, strontium, and lead isotopic composition of Lowland Greek Volcanics, west-central Montana: *in* Seventh Annual V. M. Goldschimidt Conference, LPI Contribution No. 921, Lunar and Planetary Institute, Houston, p.62.

Dudas, F.O., 2000, personal communication, Geological Sciences Program, Old Dominion University, Norfolk, Virginia.

Geissman, J. W., Kelly, W. C., Van Der Voo, R., and Brimhall, G., Jr., 1980a, Paleomagnetism Documentation of the Early, High Temperature Zone of Mineralization at Butte, Montana: Economic Geology, V. 75, p. 1210-1219.

Geissman, J. W., Van Der Voo, R., Kelly, W. C., and Brimhall, G., Jr., 1980b, Paleomagnetism, rock magnetism, and aspects of structural deformation of the Butte mining district, Butte, Montana: Journal of Geology, v. 88, p. 129-159.

Hammer-Klose, E., 1997, A high-resolution seismic reflection at Rocker Timber Treatment and Framing Plant site, Rocker, Montana, Department of Geology, Smith College, Northampton, MA.

Hanneman, D.L., Patton, T., Tabrum, A.R., and O'Neill, J.M., 1985, Tertiary geology of the Melrose and Rocker basins, southwestern Montana: Geological society of America, Abstracts with Programs, v. 17, p. 223.

Hanneman, D.L., and Wideman, C.J., 1988, Tertiary-Quaternary basin formation, southwestern Montana: Geological Society of America, Abstracts with Programs, v. 20, p. 419.

Hanneman, D.L., 2001, personal communication, Whitehall Geogroup, Inc., Whitehall, Montana.

Hart, L.H., 1935, The Butte district, Montana: in Copper Resources of the World: Int. Geol. Cong., XVI meeting, v. 1, p. 287-305.

Long, K. R., 1995, Production and reserves of Cordilleran (Alaska to Chile) porphyry copper deposits: *in* Pierce, F. W and Bolm, J. G., eds., Porphyry Copper Deposits of the American Cordillera: Arizona Geological Society Digest 20, p. 35-68.

Lyden, J. P., approx. 1925, Vein fissuring in the Butte district: The Anaconda Company unpublished report, Butte, Montana, 37 p.

Martin, M.W., Dilles, J.H., Proffett, J.M., 1999, U-Pb geochronologic constraints for the Butte porphyry system: Geological Society of America, abstracts, National meeting, v. 31, A380.

Martin, M.W. and Dilles, J.H., 2000, Timing and duration of the Butte porphyry system: Tobacco Root Geological Society meeting, Butte, Montana, p. 1.

Meyer, C., 1965, An early potassic type of wall-rock alteration at Butte, Montana: American Mineralogist, v. 50, p. 1717-1722.

Meyer, C., Shea, I.P., Goddard, C.C., and staff, 1968, Ore deposits at Butte, Montana: *in* Ridge, J.D., ed., Ore Deposits of the United States 1933-1967 (Graton-Sales vol.): New York, Am. Inst. Mining Metall. Petroleum Engineers, v. 2, p. 1363-1416.

Miller, R.N., 1973, Guidebook for the Butte field meeting of the Society of Economic Geologists, The Anaconda Company, Butte, Montana, p. F-1 to F-10.

Proffett, J. M., Jr., 1973, Structure of the Butte district, Montana: *in* Miller, R. N., ed., Guidebook for the Butte field meeting of the Society of Economic Geologists, The Anaconda Company, Butte, Montana, p. G-1 to G-12.

Proffett, J.M., 1977, Cenozoic geology of the Yerington district, Nevada, and implications for the nature and origin of Basin and Range faulting: Geological Society of America Bulletin, v. 88, p. 247-266, 18 figures.

Proffett, J. M., 1979, Ore deposits of the western United States: a summary: Nevada Bureau mines Geology Report 33 (IAGOD 5th Quadrennial Symposium proceedings), v.11, p. 13-32.

Proffett, J. M., Burns, G., and others, 1982, Geologic map of the Butte district (unpublished), the Anaconda Minerals Company, Butte, Montana, 1:12,000.

Ratcliff, M.W., 1973, Copper and molybdenum mineralization in the continental deposit, east Butte district, Montana: *in* Miller, R. N., ed., Guidebook for the Butte field meeting of the Society of Economic Geologists, The Anaconda Company, Butte, Montana, p. I-1 to I-8.

Reed, M.H., 1979a, Pyrite-quartz-sericite mineralization of Late Pre-Main Stage age, Butte, Montana. Anaconda Company report, Butte Montana, 20 p., 7 plates.

Reed, M.H., 1979b, Butte District early stage geology. Anaconda Company report, Butte Montana, 40 p., 24 plates and figures.

Reed, M. H., 1999, Zoning of metals and early potassic and sericitic hydrothermal alteration in the Butte, Montana porphyry copper deposit: [abstract] Geological Society of America, National meeting, v. 31, A380.

Reed, M., 2000, personal communication, University of Oregon, Eugene, Oregon.

Roberts, S.A., 1973, Pervasive early alteration in the Butte District, Montana: in Miller, R. N., ed., Guidebook for the Butte field meeting of the Society of Economic Geologists, The Anaconda Company, Butte, Montana, p. HH-1 to HH-8.

Sales, R. H., 1914, Ore deposits at Butte, Montana: Trans. American Inst. Min. Eng., v. 46, p. 3-109.

Sales, R.H., and Meyer, C., 1948, Wall-rock alteration, Butte, Montana: A.I.M.E.Trans., v. 178, p. 9-35.

Sales, R.H., and Meyer, C., 1949, Results for preliminary studies of vein formation at Butte, Montana: Economic Geology, v. 44, p. 465-484.

Schmidt, C.J., Smedes, H.W., and O'neill, M.J., 1990, Syncompressional Emplacement of the Boulder and Tobacco Root Batholiths (Montana-USA) by Pull-apart along Old Fault Zones. Geological Journal, vol. 25, p. 305-318.

Smedes, H.W., 1962, Lowland Creek Volcanics, an Upper Oligocene formation near Butte, Montana. Journal of Geology, vol. 70, p. 255-266.

Smedes, H. W., Klepper, M. R., Pinckney, D. M., Becraft, G. E., and Ruppel, E.T., 1962, Preliminary geologic map of the Elk Park Quadrangle, Jefferson and Silver Bow Counties, Montana: U.S. Geological Survey map MF-246, Scale 1:24,000.

Smedes, H.W., 1967, Preliminary geologic map of the northeast quarter of Butte south Quadrangle, Montana: U.S. Geological Survey, Open File Map, 1:24,000.

Smedes, H. W., 1968, Preliminary geologic map of part of the Butte North Quadrangle, Silver Bow, Deer Lodge and Jefferson Counties, Montana: U.S. Geological Survey Open-File Report, Scale 1:48,000.

Smedes, H., 1973, Regional geologic setting of the Boulder batholith, Montana: *in* Miller, R. N., ed., Guidebook for the Butte field meeting of the Society of Economic Geologists, The Anaconda Company, Butte, Montana, p. A-1 to A-6.

Smedes, H. W., Klepper, M. R., and Tilling, R. I., 1988, Preliminary Map of plutonic units of the Boulder Batholith, southwestern Montana: Montana Bureau of Mines and Geology, Open-File Report 88 - 283, Scale 1:200,000.

Snee, L., Miggins, D., Geissman, J., Reed, M., Dilles, J., Zhang, L., 1999, Thermal history of the Butte porphyry system, Montana: Geological Society of America, Abstract, National meeting, v. 31, A380.

Tilling, R.I., Klepper, M.R., and Obradovich, J.D., 1968, K-Ar ages and time span of emplacement of the Boulder batholith, Montana: American Journal of Science, v. 266, p. 671-689.

Weed, W.H., 1912, Geology and Ore Deposits of the Butte district, Montana: U.S. Geological Survey Professional Paper 74, p.3-57.

Zoback, M. L., Anderson, R. E., and Thompson, G. A., 1981, Cenozoic evolution of the state of stress and style of tectonism of the Basin and Range Province of the Western United States, *in* Vine, F. J., and Smith, A. G., editors, Extensional tectonics associated with convergent plate boundaries: Philosophical Transactions of the Royal Society of London, Series A: Mathematical and Physical Sciences, vol. 300, No. 1454, p. 407-434.

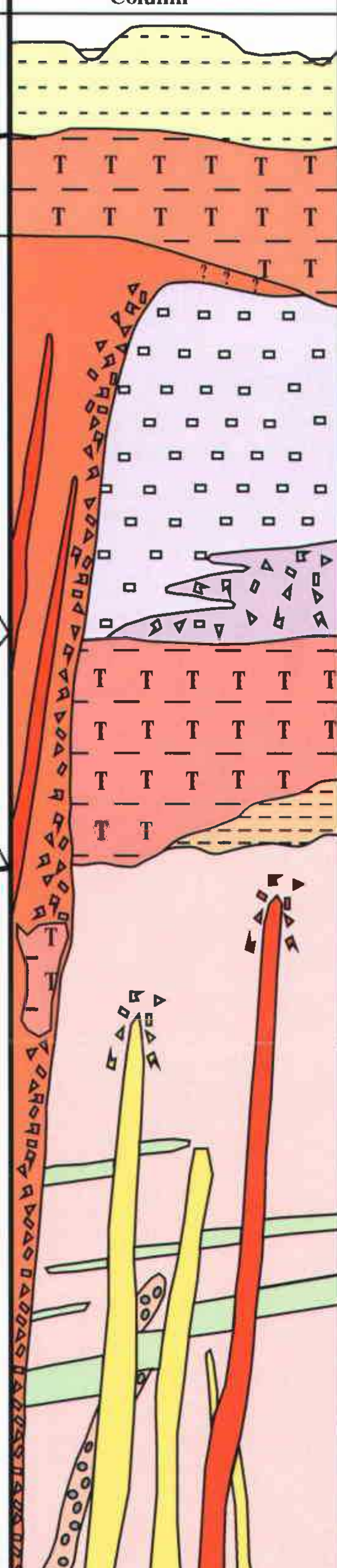
APPENDIX

Mineral modes (Volume %) of the Butte Quartz Monzonite and Lowland Creek Volcanics

	Butte Quartz Monzonite				Lowland Creek Volcanics					
Mineral	Kbq	Kmd	Ka	Kqp*	Tlt	Tlw	Tllb	Tll	Tlu	Tiv
Plagioclase	38.5	60		35 to 4	10 to 15		15	20		
Orthoclase	22.6		43 to 47	1 to 4					20 to 35	26 to 36
Oligoclase-andesine			18 to 22			10 to 15			20 to 25	15 to 17
Quartz	23.7	5	33 to 35	8	3 to 5	5 to 10	1	1	5 to 8	10 to 14
Biotite	7.6	10 to 15	t	1 to 4	1 to 2	1 to 6	3	6	1 to 2	1 to 5
Hornblende	5	15 to 20				1 to 5	2	2		
Orthopyroxene								2		
Magnetite	m	1 to 2		t						

Footnote: m-minor; t-trace (0.1 vol. %)

* all samples are hydrothermally altered and contain pyrite



	Thickness	Age	Description	Name	
Eocene to recent	<300-m		Colluvium, alluvium, lacustrine and terrace sedimentary deposits containing detritus from eroded BQM and the LCV.	Butte basin sedimentary deposits	
			EROSIONAL UNCONFORMITY		
Eocene	>50-m		Moderately to strongly welded, light gray to chalky white, crystal-rich lapilli tuff with shattered crystals of quartz, oligoclase-andesine, biotite, and minor sanidine.	Upper ash-flow tuff	Lowland Creek Volcanics
	0 to 120-m		Porphyritic rhyolite dikes with quartz, biotite and plagioclase phenocrysts.	Rhyolite dikes (Big Butte Vent Complex)	Lowland Creek Volcanics
			Vent wall breccias, collapsed brecciated ash-flow tuff, and dacite lava dome breccia.	Volcanic breccias (Big Butte Vent Complex)	Lowland Creek Volcanics
		51.46+0.8-Ma	Moderately welded, red-brown to light gray, crystal-rich ash flow tuff with quartz, oligoclase-andesine, biotite, and sanidine. Contains abundant steeply dipping flattened cognate inclusions	Vent facies tuff (Big Butte Vent Complex)	Lowland Creek Volcanics
			Brown to purplish red dacite lava with abundant plagioclase, biotite-rich glomerocrysts, orthopyroxene, hornblende, quartz and trace amounts of apatite and opaques entrained in an aphanitic groundmass.	Dacite lava	Lowland Creek Volcanics
	<180-m		Auto-brecciated base of dacite lava unit. Dacite boulders are framework-supported in a light-brown to very pale orange dacite lava matrix.	Upper Volcanic breccia	Lowland Creek Volcanics
			Volcanic mudflow, with boulders of ash-flow tuff and dacite suspended in a lavender-gray devitrified matrix.	Lower Volcanic breccia	Lowland Creek Volcanics
	300-m	~53 Ma	Crystal-rich, moderately to strongly welded, light-gray ash-flow tuff composed of shattered plagioclase, biotite, and hornblende crystals, abundant pumice (fiamme) and lithic fragments.	Lower ash-flow tuff	Lowland Creek Volcanics
	0 to 50-m		Fluvial sandstone, siltstone, and pebble conglomerate sedimentary sequences containing abundant reworked volcanic basal surge tuffs.	Basal sedimentary and base surge deposits	Lowland Creek Volcanics
Late Cretaceous		58.8+1.2 Ma	Porphyritic rhyolite dike contains phenocrysts of plagioclase, quartz, biotite, and rare orthoclase (2 cm) enclosed in an aphanitic groundmass (red).	Granite porphyry	
			EROSIONAL UNCONFORMITY		
		75.6+0.3 Ma to 65 Ma	Quartz porphyry dikes and plugs (3 to 15 m wide) with euhedral plagioclase, rounded quartz eyes, orthoclase and biotite phenocrysts enclosed in a fine-grained groundmass of quartz and orthoclase (yellow).	Quartz porphyry dikes	Butte Quartz Monzonite
		75.0+1 Ma	White to pale pinkish-white, aplite dikes and sills (<15 m wide), and dikes consist medium- to fine-grained, allotriomorphic-granular crystals of perthitic orthoclase, quartz, oligoclase and trace amounts of biotite. Black tourmaline and molybdenite occur in vugs of pegmatitic zones in the centers of aplite sills and dikes. Meyer et al. (1968) reported minor concentrations of pyrite, chalcopyrite, and very rare pyrrhotite in pegmatitic vugs. Aplite sills commonly exhibit internal zoning to grano-aplite and pegmatite phases. West of Big Butte, grano-aplite sills are gradational with the BQM (green).	Aplite, grano-aplite, pegmatite dikes & sills	Butte Quartz Monzonite
			Mafic dike (10 to 20 m) emplaced into and disrupted into dark-green to black ellipsoidal nodules by BQM. Nodules (15 to 50 cm dia.) contain crystals of plagioclase, hornblende, biotite, quartz, magnetite and minor apatite are surrounded by fine grained BQM.	Altered mafic dike	Butte Quartz Monzonite
		76.5+0.3 Ma	Medium to coarse-grained, grayish, anhedral to euhedral crystals of plagioclase, quartz, orthoclase, biotite, hornblende, and accessory magnetite, sphene, ilmenite, apatite, and zircon.	Butte Quartz Monzonite	Butte Quartz Monzonite

Plate 2.

Generalized stratigraphic section of Cenozoic rocks and Eocene-late Cretaceous intrusions of the Butte district, Montana.

A.

B.

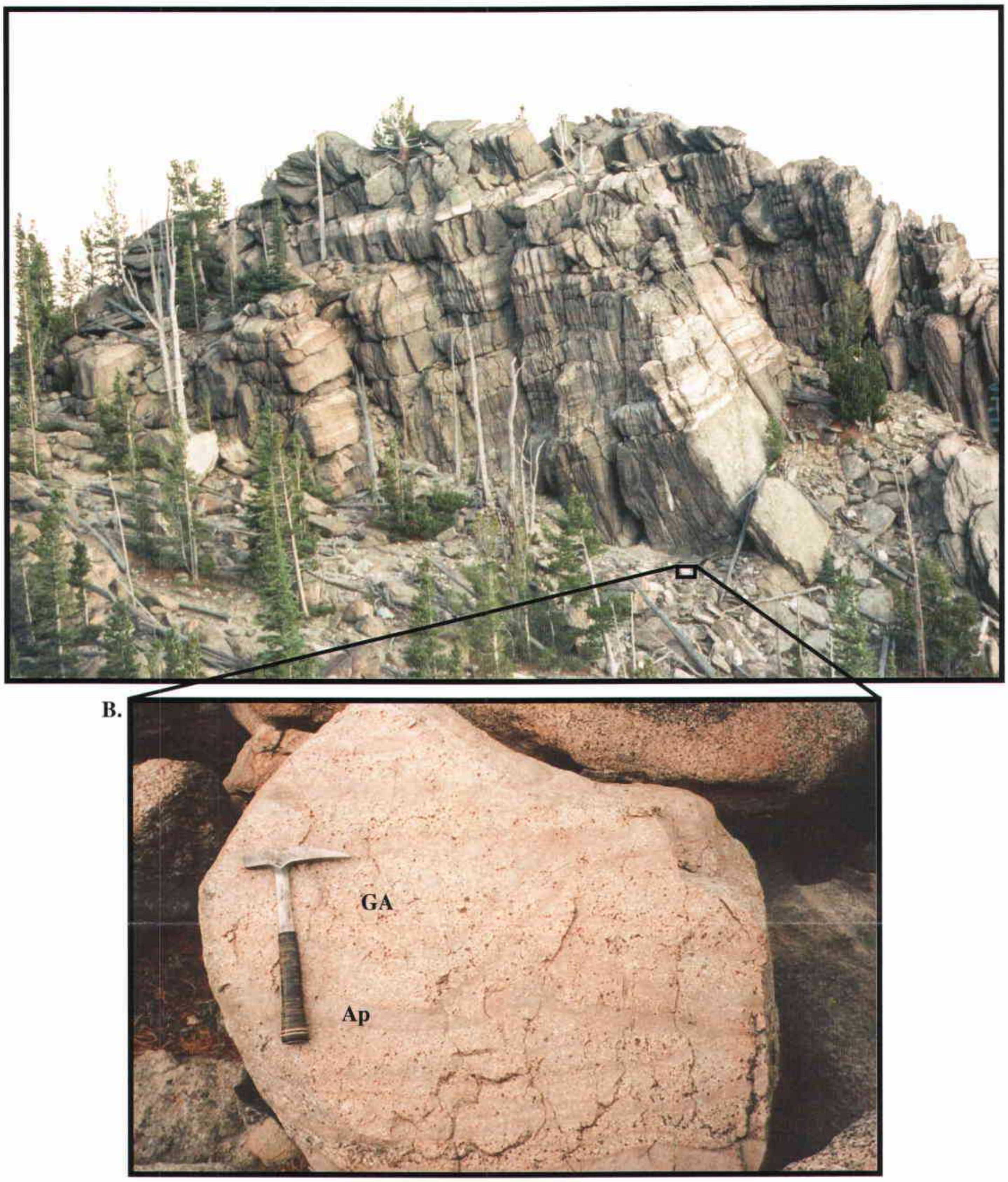


Plate 3. Sheeted aplite sills on top of East Ridge. (View looking south from the "Lady of the Rockies" over-look)

A. Multiple, sill-like injections into BQM that grade from aplite, granoaplite to pegmatite phases. Contacts with BQM are typically sharp; however, some granoaplite sill contacts are gradational. Strike and dip of aplite sills average N69°W/10°NE, n=17. Note sills parallel joints.

B. Interlayered aplite (Ap) and granoaplite (GA) within a single sill.

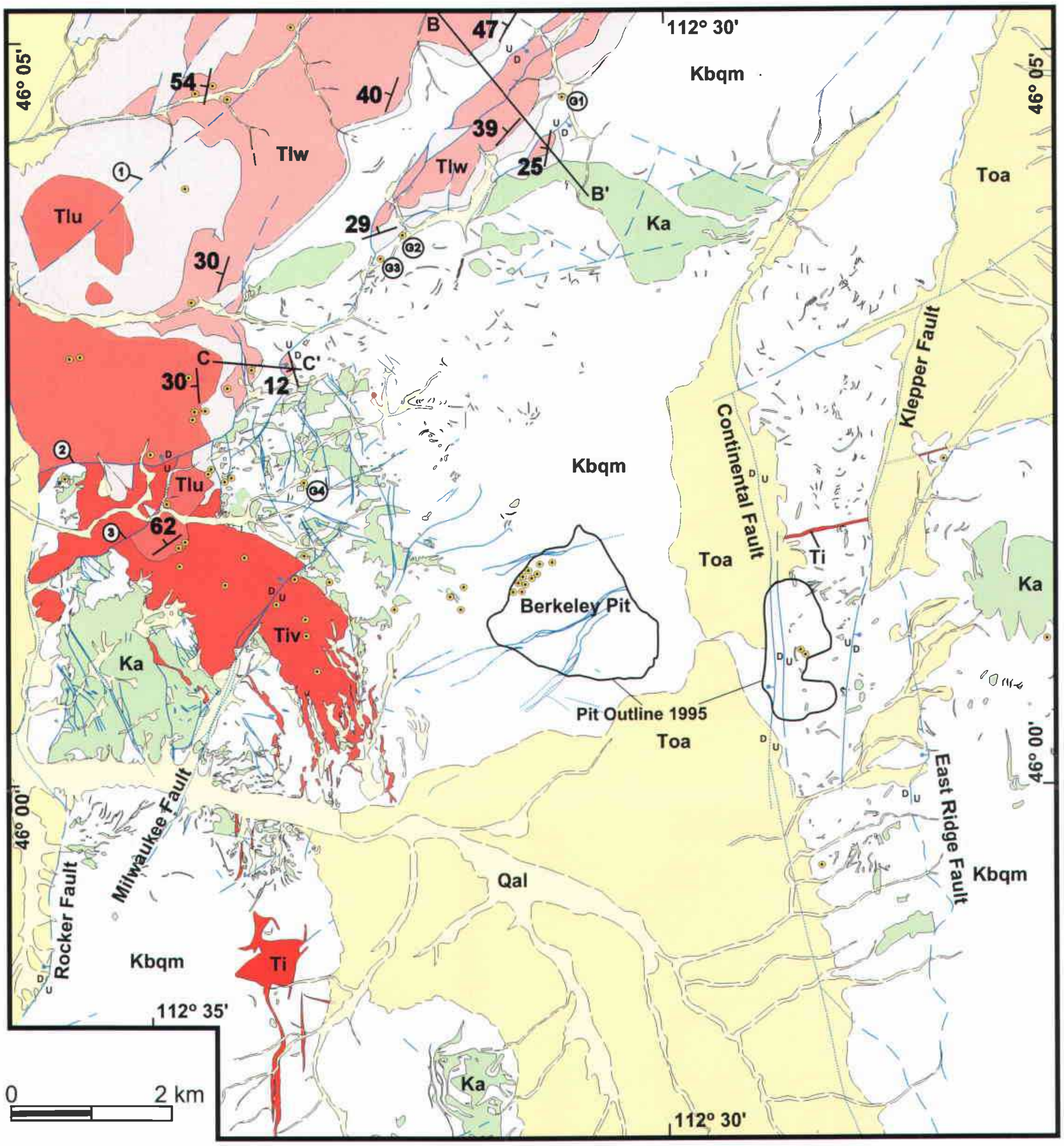
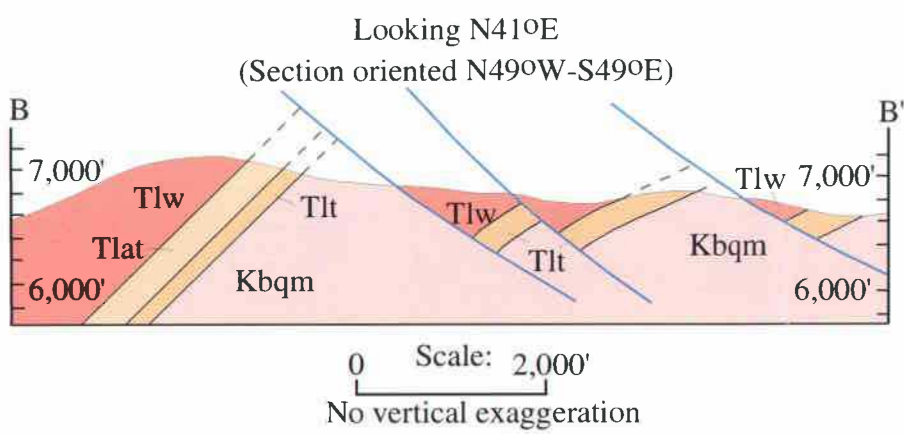


Plate 4. Generalized geologic map of the Butte district, Montana.

Explanation: BQM (Kbqm), aplite dikes and sills (Ka), lower ash-flow tuff (Tlw), upper ash-flow tuff (Tlu), Big Butte vent complex (Tiv), Rhyolite dikes (Ti), Tertiary basin fill sedimentary rocks (Toa) and Quaternary alluvial sedimentary rocks (Qal). Geissman et al. (1980b) paleo-magnetic sampling sites are approximately located (⊙).



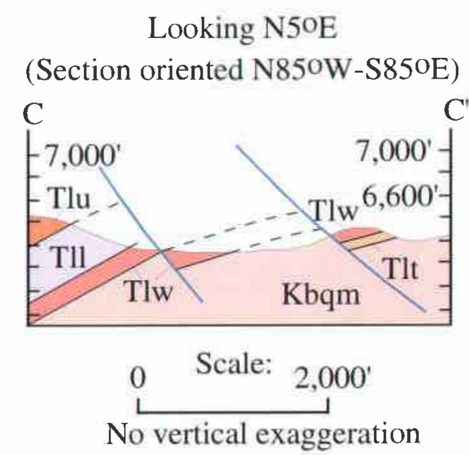


Plate 5.

Section B-B' and section C-C'.

In the northwest part of the Butte district (Plate 4), B-B' lies to the west-southwest of C-C'. Note the different amounts of offset and tilting, at different locations along northeast trending, moderately southeast-dipping rotational normal faults. These rotational normal faults show decreasing displacement and diminishing amounts of northwest tilting southwestward along individual faults. Additionally, from east to west, each individual fault block has successively experienced greater amounts of block rotation. Kbqm = Butte Quartz Monzonite; Tlt = basal sedimentary; Tlw = lower ash-flow tuff; Tll = dacite lava unit; Tlu = upper ash-flow tuff.

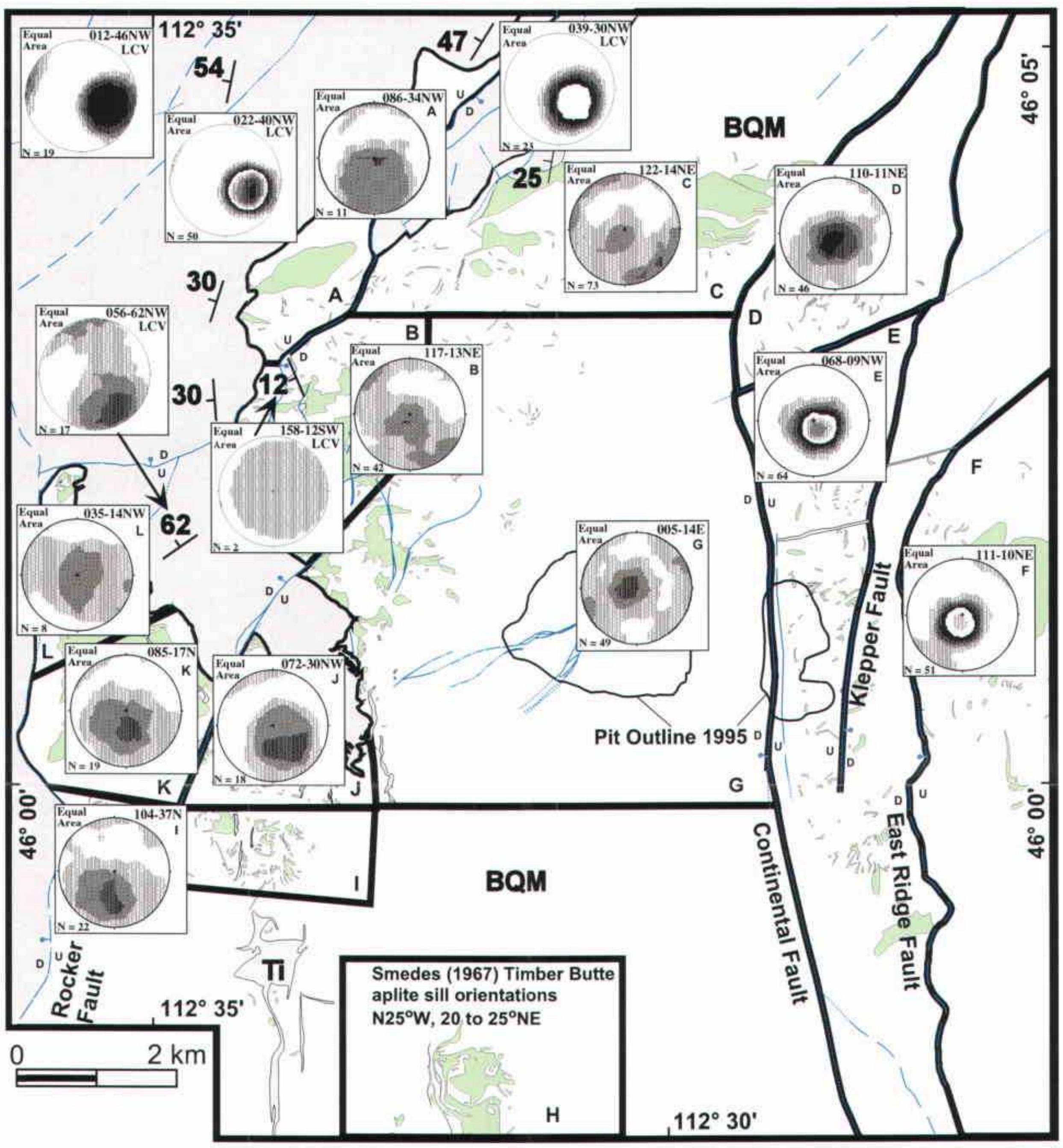


Plate 6. Stereonet plots of aplite dike and sill, and LCV attitudes in the Butte district.

Attitudes of sheeted aplite sills, here inferred to have been emplaced as horizontal sill-like bodies during crystallization of BQM, provide a pre-mineralization tilt marker. The Kamb method was used to contour (contours at 2 sigma) aplite sills and dikes (n=407) and LCV attitudes (n=111) (labeled LCV) into twelve structural domains (labeled A-L) occurring in the Butte district. For each stereonet, the mean strike and dip is shown in the upper right (e.g. 086-34NW). Generalized geologic map of the district; LCV (gray), BQM (white), and aplite dikes and sills (green).

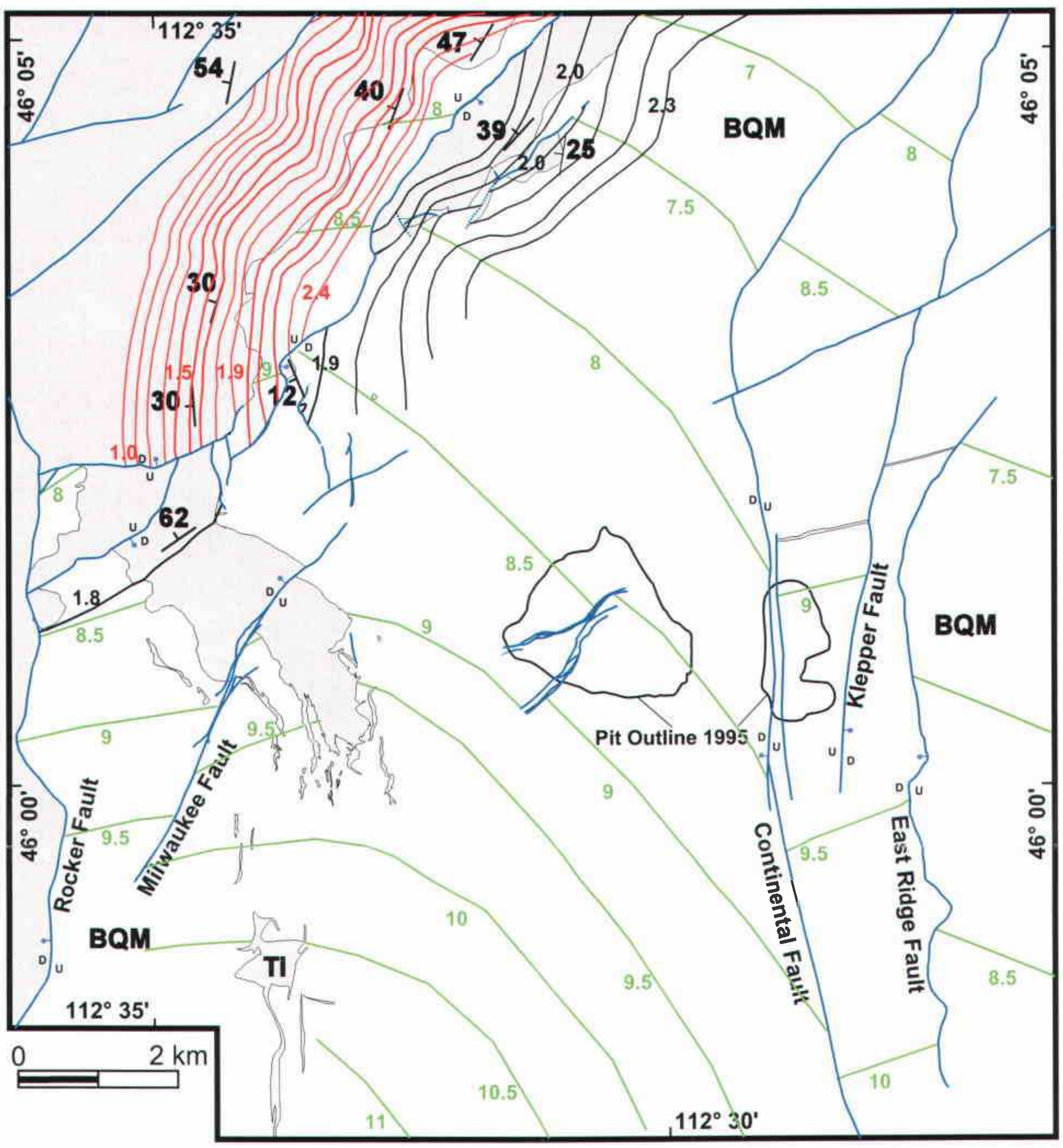


Plate 7. Structural contour map of the Butte district (in km).

The LCV/BQM unconformity 0.1-km contour interval are in Red & Black relative to current MSL (Mean sea level). The mean average of aplite sill attitudes combined with hornblende barometry data (Dilles, 1999) are contoured at 0.5-km intervals in Green; the Contours are labeled in kilometers estimated paleo-depth of emplacement of the BQM.

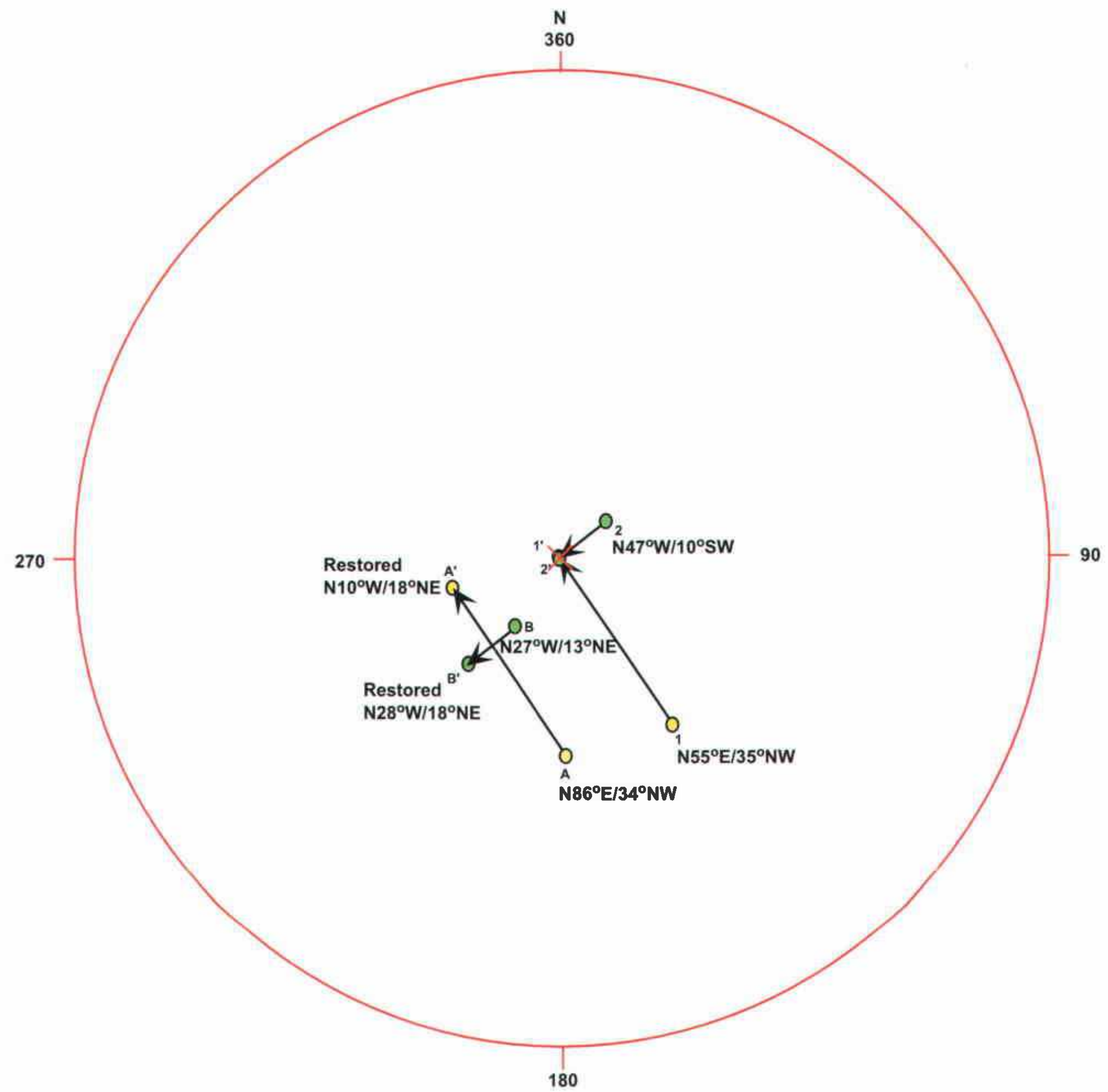
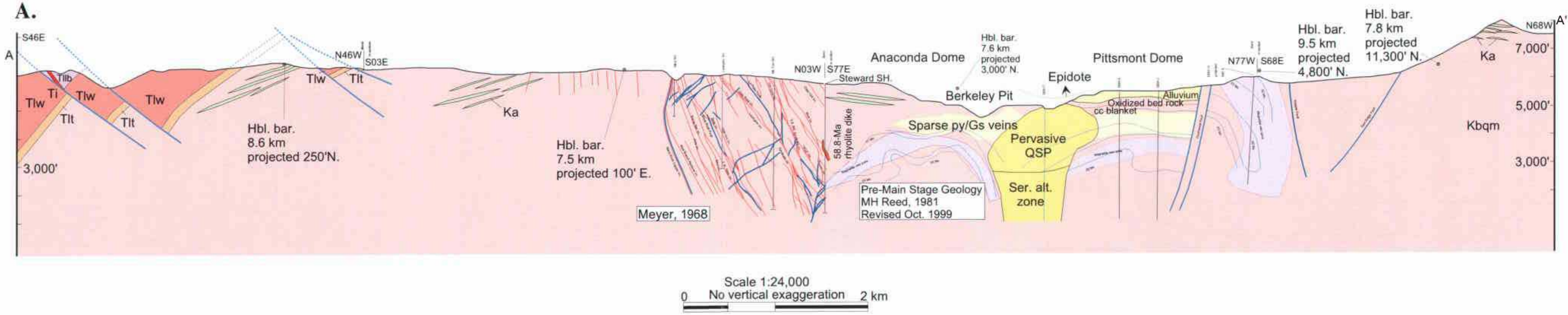


Plate 8. Stereonet plot of average attitudes (poles to bedding planes) of aplite sills in domains A & B and LCV in domains 1 & 2 in the northwest part of the Butte district (Plate 6).

Aplite sills in domain A restore to position A' by removing tilt of the overlying LCV in Domain 1 (restores to flat dip at position 1'). Sills in domain B restore to B' by removing tilt of the overlying LCV in domain 2 (restores to flat dip at position 2').

A.



B.

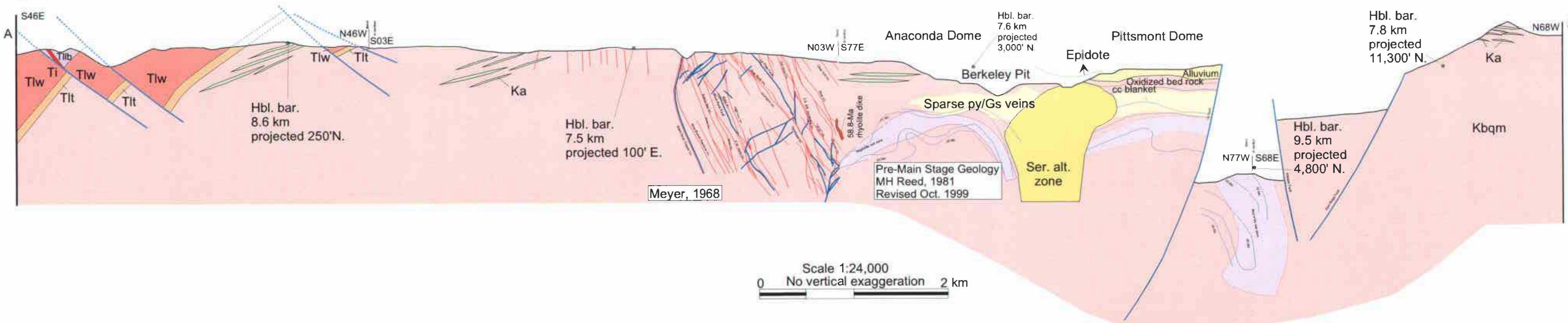


Plate 9. Structural restoreation of section A-A' (Plate 1), Stage 1 and Stage 2.

A) stage 1 is present northwest-southeast section through the Butte district. B) stage 2 represents, structural reconstruction of the Butte district, prior to tilting associated with north-south striking Basin and Range faults, and post-LCV normal faults. Note that restored aplite sill attitudes in the central part of the district are now horizontal to gently tilted northeastward.

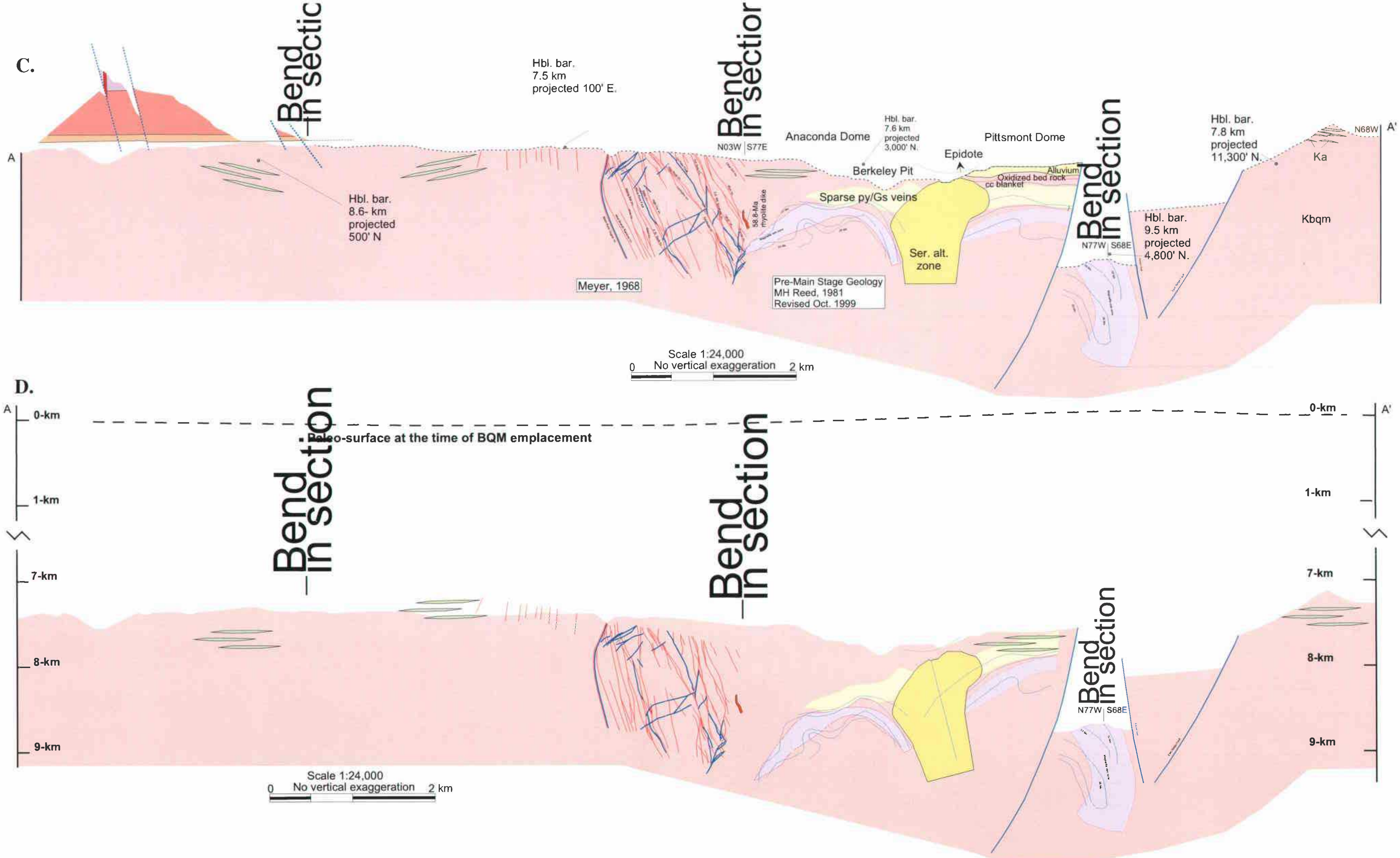


Plate 10. Structural restoreation of section A-A' (Plate 1), Stage 3 and Stage 4.

C) stage 3 represents, structural reconstruction of the Butte district, prior to tilting associated with northeast striking post-LCV normal faults. Note that restored aplite sill attitudes in the northwest part of the district are now gently tilted northeastward. D) stage 4 represents structural reconstruction of the Butte district during Main-Stage mineralization, prior to inferred ~10 to 15 degrees northeast tilting of the district. Paleo-depth is provided by hornblende barometry (±1 km) (Dilles et al., 1999), which is consistent with fluid inclusion pressure estimates form Pre-Main Stage veins (Rusk et al., 1999, 2000).